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# CHARACTERIZATION OF HLW AND LAW GLASS FORMERS – FINAL REPORT – (U)

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| | |
|---|---|
| ASTM | American Society For Testing and Materials |
| DOE | Department of Energy |
| GFCs | Glass Former Chemicals |
| GFSF | Glass Former Storage Facility |
| HLW | High Level Waste |
| ITS | Immobilization Technology Section |
| J & J | Jenike and Johanson Incorporated |
| LAW | Low Activity Waste |
| MFPV | Melter Feed Preparation Vessel |
| MOC | Material of Construction |
| MSDS | Material Safety and Data Sheets |
| N/A | Not Applicable |
| R & T | Research and Technology |
| RPP-WTP | River Protection Project – Waste Treatment Plant |
| SRTC | Savannah River Technology Center |
| SS | Scoping Statement |
| TGA | Thermal Gravimetric Analysis |
| TS | Test Specification |
| TTP | Technical and Quality Assurance Test Plan |
| U.S. | United States of America |
| VSL | Vitreous State Laboratory |
| WSRC | Westinghouse Savannah River Company |
| WPT | Waste Processing Technology |

# ABSTRACT

A basis of thirteen glass former chemicals (GFCs) was selected upon reviewing existing River Protection Program – Waste Treatment Plant (RPP-WTP) subcontractor documents and after discussions with RPP-WTP R&T, Vitreous State Laboratory (VSL) and Savannah River Technology Center (SRTC) personnel. The thirteen baseline GFCs were approved by RPP-WTP R&T for future use in all RPP-WTP R&T test programs.

SRTC established a contract with Jenike & Johanson Incorporated (J&J), a material handling consultant, to perform the following work scope:

- Measure and report the physical and flow properties of the thirteen individual GFCs, three representative Low Activity Waste (LAW) GFC blends, and two representative High Level Waste (HLW) GFC blends under "as received" and "at rest" conditions. The data obtained from these tests will be used for "information only."
- Review the conceptual design of the RPP-WTP bulk solids handling system.
- Provide functional design parameters needed to achieve mass flow or expanded flow in all 13 storage silos.
- Provide recommendations on the delivery of blended GFCs to the Melter Feed Preparation Vessels (MFPV).
- Provide general recommendations on bulk solids handling issues.

Jenike & Johanson completed this work and issued two technical reports providing their results and recommendations. Their findings and conclusions are summarized and presented in this report.

SRTC recommends that J&J be utilized by RPP-WTP for the following:

- Provide RPP-WTP personnel, involved in the design, engineering, and operations of the bulk solids handling equipment, an overview of dry solids handling techniques and present the results from this report.
- Review vendor bids and provide input in selecting a vendor based on technical merit.
- Provide technical oversight for the installation and initial checkout of the dry bulk solids handling equipment.
- Provide expanded review of proposed delivery methods of adding blended GFCs to the MFPV.

# 1.0 SUMMARY OF TESTING

## 1.1 Objectives

The objectives of this task were to select the baseline glass former chemicals (GFCs) used for testing Low Activity Waste (LAW) and High Level Waste (HLW) feeds, to physically characterize the GFCs and to determine if the selected GFCs impact the conceptual design of the Waste Treatment Plant (WTP) Glass Former Storage Facility (GFSF). In order to accomplish this task it was necessary to carry out the following actions:

- Select GFCs: The GFCs selected for this task were based on a review of existing data from Vitreous State Lab (VSL). The use of these chemicals was agreed upon by WTP Research and Technology (R&T) personnel as well as by VSL and Savannah River Testing Center (SRTC) personnel [1]. These GFCs are recognized as the WTP baseline GFCs and will be used for future R&T work.

- Obtain Design Information: Available preliminary and conceptual design information for the GFC bulk handling system was obtained from Process Engineering [2]. This information can be used to understand the relationship between the design parameters and the measured flow properties of the GFC material.

- Contract with Bulk Solids Flow Consultant: Jenike and Johanson (J&J) was selected to measure the physical and flow properties of 13 individual GFCs, three representative LAW blends, and two representative HLW blends under “as received” and “at rest” conditions. These measurements were performed according to ASTM standards. The RPP-WTP Quality Assurance requirements were not imposed on the development of this data. The J&J data was qualified by comparing the difference in controls between the non-qualified data and current RPP-WTP QA contractual requirements [See Appendix G]. All of the data produced by J&J was qualified. This data can be used in Design Engineering’s Performance Specification to assist vendors with their bid preparations for the “Design and Build” of the entire Glass Former Handling Facility. It has been determined that the QARD requirements under RW-0333P were not necessary [3]. J&J was also tasked to provide the following:
  - A review of the preliminary GFSF conceptual design.
  - Detailed mass flow and expanded flow designs for the thirteen GFC receiving silos.
  - General information on the delivery of dry GFCs to the MFPV.
  - General design issues relative to bulk solids handling.
  - A document on recommendations for handling GFCs by July 2002.[Appendix F]

All test objectives as stated in the test specification and technical task and QA plan were met with the exception noted in Appendix G and Reference[3].

## 1.2 Conduct of Testing

All measurements were performed at J&J's Westford, Massachusetts testing facility. The thirteen baseline GFCs, three representative LAW blends, and two representative HLW blends were characterized at J&J for the physical properties listed in Table 1.1. All GFCs and LAW/HLW blends were characterized under "continuous" flow conditions, in which the measurement of the samples is taken immediately after being placed in the measurement device. The thirteen individual GFCs were also characterized after 7 days "at rest", the three LAW blends after 1 day at rest, and the two HLW blends after 3 days at rest. The "at rest" condition is a static condition in which predetermined loads (consolidating pressures) were placed on the samples for the specified at rest times before the physical properties were measured. All measurements, other than moisture content, were performed at 72°F.

**Table 1.1: Physical Properties Measured at J&J**

| | |
|---|---|
| Cohesive Strength Test | All individual GFCs and GFC blends for "as received" and "at rest" conditions were tested to determine their cohesive strength as a function of consolidating pressure. The "Jenike Shear Test" involved shearing a volume of compressed powder under varying consolidating pressures and measuring the resultant steady state force required to shear the powder in the plane perpendicular to the consolidating pressure. The shear test procedure and data analysis method is described in ASTM Standard D6128-97 [4]. The data derived from these tests are used for determining the critical arching and ratholing dimensions. Methods for calculating arching and ratholing dimensions are not described in the ASTM standard. |
| Wall Friction Test | The samples were tested as a function of consolidating pressure against three different wall surfaces:<br>1. mill finish, mild carbon steel,<br>2. #2B finish, 304 stainless steel, and<br>3. Tivar 88® (also known as ultra high molecular weight polyethylene).<br>This test employed a modified version of the Jenike Shear Tester and measured the force required to shear the compacted powder across the surface of a selected silo material under a given consolidation pressure. The wall friction test procedure and the data analysis method is described in ASTM Standard D6128-97 [4]. The results from this test were used to determine the critical hopper angle(s) required to achieve mass flow. The method to determine these angles is not described in the ASTM standard. |
| Compressibility Test | All GFCs and GFC blends were tested to determine their bulk densities as a function of consolidating pressure. This density/pressure relationship is used to calculate the height of silos and the material induced loads on the silo structure. The method for calculating the density/pressure relationship is described in ASTM Standard D6683 [[5]]. |
| Particle Size Distribution Test | The particle size distribution was measured using a Malvern Mastersizer® 2000 laser diffraction particle size analyzer with a Scirocco dry dispersion unit for all of the individual GFCs. No blends were measured. Tests were performed at 0.0 bar and 3.0 bar conveying pressures. Comparison of the two results provided an indication of the agglomeration tendency of the particles. |
| Permeability Test | The air permeability of eight highly compressible GFCs and all of the GFC blends were measured as a function of consolidating pressure [6]. This test procedure was proprietary to J&J. The information derived from this test was used to determine critical discharge rates from feed hoppers. |
| Chute Angle Test | All blends were tested for the critical chute angle. Weights were applied on a sample blend and then placed on a chute surface in the horizontal plane. The weights were then removed after a short period of time and the horizontal surface was inclined to determine the slope angle of the surface material needed to induce flow of the dry powder under its own weight. The critical chute angle was measured against the same three materials used in the wall friction test for each GFC blend. |
| Angle of Repose | All of the GFCs and GFC blends were tested to determine the angle of repose. This is the angle from horizontal of a slowly formed pile. The results were used to help determine the silo capacity. ASTM Standard D6393-99, Section "Test A" [7] was used to determine this measurement. The angle was determined in four directions around the pile and averaged. Angle of repose is used in bin capacity calculations for final fill. |

## 1.3 RESULTS AND PERFORMANCE AGAINST OBJECTIVES

The selection of GFCs was determined prior to the start of physical testing. During the January 2002 SRTC Quarterly Review, a complete list of GFCs used by all of the RPP-WTP subcontractors was presented based upon a review of Duratek, VSL, PNNL, and SRTC documentation [8-10]. During this meeting, the GFCs were discussed and the basis was determined by RPP-WTP R&T, VSL, and SRTC and subsequently approved by RPP-WTP

R&T [1]. The selected GFCs are shown in Table 1.2. This list of materials may be refined and altered as the RPP-WTP R&T programs progress.

### Table 1.2: Present Baseline Glass Former Chemicals

| No. | Oxide Added | Mineral | Grade | Vendor |
|---|---|---|---|---|
| 1 | $Al_2O_3$ | Kyanite - $Al_2O_2$-$SiO_2$ | Raw –325 Mesh | Kyanite Mining Corp. |
| 2 | $B_2O_3$ | Boric Acid - $H_3BO_3$ | Technical Grade-Granular | U.S. Borax |
| 3 | $Na_2O/B_2O_3$ | 10M Borax - $Na_2B_4O_7$-$10H_2O$ | Technical 10 Mole Borax | U.S. Borax |
| 4 | $Na_2O$ | $Na_2CO_3$ Anhydrous | Dense Soda Ash | Solvay Minerals |
| 5 | CaO | Wollastonite - $CaSiO_3$ | NYADM325 | NYCO |
| 6 | $Fe_2O_3$ | $Fe_2O_3$ | 5001 | Prince Mfg. Co. |
| 7 | $Li_2O$ | $Li_2CO_3$ | Technical Grade | Chemettal-Foote |
| 8 | MgO | Olivine | #180 | Unimin Corp. |
| 9 | $SiO_2$ | $SiO_2$ | SCS-75 | U.S. Silica |
| 10 | $TiO_2$ | Rutile $TiO_2/Fe_2O_3$ | Air Floated Rutile 94 | Chemalloy Co. |
| 11 | no | no | Kadox 920 | Zinc Corp America |
| 12 | $ZrO_2$ | $ZrSiO_4$ | Zircon flour | American Mineral Inc. |
| 13 | $C_{12}H_{22}O_{11}$ | Sugar | Granular | Amalgamated Sugar Co. |

Table 1.5 through Table 1.17 are summary data sheets for each of the GFCs. These summary data sheets have the following vendor information as listed in Table 1.3, if provided.

### Table 1.3: Vendor Provided Information in Summary Data Sheets

| | | | |
|---|---|---|---|
| Name of material | Grade | Vendor location | Cost |
| Bulk density | Particle density | Formula weight | Chemical composition |
| Vapor pressure | Solubility in water | Particle size | Critical dust concentration |
| Weight loss | Heat of solution | Melting point | Ignition temperature of dust |

These individual GFC data sheets, as well as the data sheets shown in Table 1.18 through Table 1.22 for each GFC blend, summarizes the J&J data and analyses, which include the items listed in Table 1.4.

**Table 1.4: J&J Data Provided in Summary Data Sheets**

| | | | |
|---|---|---|---|
| Moisture content | Powder density | Air permeability coefficient | Volume particle size distribution |
| Number particle size distribution | Rathole dimension for "continuous" and "at rest" conditions with 10 feet effective head for all GFCs and GFC blends. | Arching dimension for "continuous" and "at rest" conditions for all GFCs and GFC blends with a P-factor = 1.0 for conical and transition mass flow hopper designs. | Hopper angle required for mass flow using conical and transition hoppers with a 1-ft hopper diameter opening for both "continuous" and "at rest" conditions. |
| | Critical discharge rates for conical hopper with the following hopper opening (diameter):<br>GFCs 1.0 ft<br>GFC Blends 2.0 ft. | Critical discharge rates for transitional hopper with the following hopper span opening/length:<br>GFCs 1.0 ft. / 0.785 ft.<br>GFC Blends 2.0 ft. / 1.57 ft. | Minimum Chute angles for all GFC blends. |

The J&J results from Table 1.5 through Table 1.22 are generalized below:

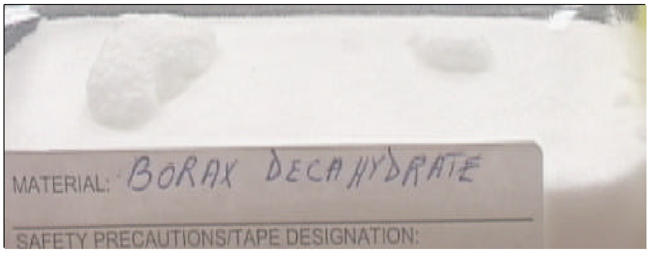
- Materials that are cohesive are also very compressible (density is a strong function of consolidating pressure ($\sigma_1$)).
- The majority of the baseline GFCs and all GFC blends are cohesive and exhibit the following potential flow problems:
  - Ratholing will exist in funnel flow hoppers, unless the outlet of the hopper is larger than the ratholing dimension.
  - Ratholing dimension increased as the material was allowed to rest.
  - Arching dimension increased as the material was allowed to rest.
- Particle size analyses showed that higher conveying pressure (e.g. higher velocity) resulted in breaking up of agglomerates, removal of fine particles loosely bonded to coarse particles, and attrition of weak particles.
- Angle of repose can not be used directly to determine flow properties.
- The air permeability data indicated that some of the materials were highly impermeable, which limited the material discharge rate from the hopper.
- Comparison of conical and transitional mass flow hoppers showed the following:
  - Conical hoppers required a steeper slope. This was due to how the flow converges in the different hopper designs.
  - Given the same hopper span opening and equal discharge area, the transitional hopper provided a higher mass flow rate in all cases.
  - Conical hoppers had larger arching dimensions.
- No single hopper material was shown to be optimal for all the GFCs and GFC blends tested, given the 1-foot hopper diameters.
- Tivar®-88 is the preferred chute material for the GFC blends.

J&J reviewed the preliminary conceptual design of the 13 storage silos as provided by RPP-WTP process engineering [2]. The conceptual designs were developed as a starting point. All of the storage silos in the conceptual design had conical hopper sections made of carbon steel, sloped walls that were 30 degrees (from vertical), and discharge openings with 1-foot diameters. J&J's assessment of the initial silo designs are summarized in Table 1.23, which shows that all of these hoppers would produce funnel flow and ratholing after 7 days of "at rest" conditions. Materials that could potentially exhibit flooding were also flow rate limited and could not achieve the proposed design throughput rates.

J&J also reviewed the utilization of a conceptual chute that moves the GFC blend from the final feed hopper and delivers it to the MFPV. J&J's recommendations are summarized in Table 1.24, given the limited design information available [19]. The present method of adding the dry GFCs to the mixing vessel may create excessive dusting. Items that can impact dusting are listed in Table 1.25 and this list is not all-inclusive. The impact of dusting is considered process specific, and must be properly evaluated to mitigate consequences of dusting that may be unacceptable for both short term and long term operations.

A summary of J&J mass flow and expanded flow hopper design characteristics for the 13 storage silos are shown in Table 1.26. All of the hopper designs have associated mass flow screw augers. J&J recommends that cost savings can be achieved by standardizing the designs into 4 or 5 general silo/hopper designs. Details on the 13 storage silo designs and general bulk handling design information can be found in Appendix F.

## Table 1.5: Summary Data Sheet - Borax Decahydrate

| | | |
|---|---|---|
| *Mineral* | 10 Mole Borax<br>$Na_2B_4O_7 \cdot 10H_2O$ |   MATERIAL: BORAX DECAHYDRATE<br>SAFETY PRECAUTIONS/TAPE DESIGNATION: |
| *Grade:* | Technical | |
| *Oxides Provided:* | $Na_2O$, $B_2O_3$ | |
| *Vendor & Address:* | U.S. Borax Inc.<br>26877 Tourney Rd.<br>Valencia, CA 91355<br>805-287-5400 | |
| *Cost:* | $0.17/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 63 lbm/ft$^3$ | *Particle Density:* | 107.95 lbm/ft$^3$ |
| *Formula weight:* | 381.37 g/g-mole | *Melting Point:* | 67°C |
| *Vapor Pressure:* | Negligible | *Solubility in Water:* | 20°C 5.8%<br>100°C 65.6% |
| *Heat of Solution:* | 222 BTU/lbm | *Particle size:* | < 0.1 % retained in 2380 µm (#8 Mesh) |

*Chemical Properties (weight percent)*

| $B_2O_3$ | $Na_2O$ | $SO_4$ | Cl | Fe | $H_2O$ | N/A | N/A |
|---|---|---|---|---|---|---|---|
| 37.5 | 16.7 | <600 ppm | <700 ppm | <30 ppm | Remaining | N/A | N/A |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.0 % | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (29° – 33°) / 31° Average | Minimum 48.2 | Range ( $s_1 = 44$ *to* $2362 \frac{lbf}{ft^2}$<br>$r = 51.7$ *to* $53.5 \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:* | Not Measured | | Density fit to range above:<br>$r = -3\times10^{-7}\cdot s_1^2 + 0.0015\cdot s_1 + 51.775$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 229.7 µm | 389.3 µm | 627.6 µm | 36.3 µm | 48.5 µm | 256.2 µm |
| 3 bar | 59.6 µm | 275.6 µm | 549.1 µm | 3.2 µm | 4.5 µm | 8.6 µm |

*Cohesive strength*

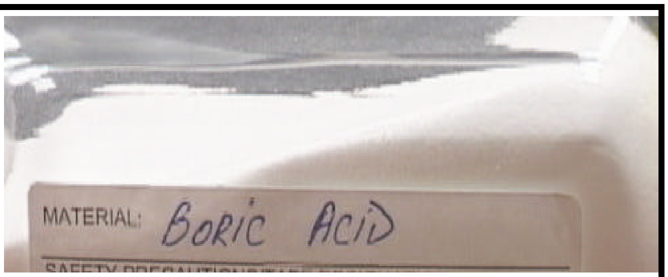
| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 2 ft. | 12 ft. | Conical | 0.0 ft. | 3.0 ft. |
| | | Transitional | 0.0 ft. | 1.4 ft. |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | None | None | 17° | 17° |
| Mild carbon steel plate, mill finish | 9° | 5° | 21° | 20° |
| TIVAR –88 | 14° | 9° | 26° | 21° |

| | |
|---|---|
| *Critical Flow Rate – Mass flow hopper containing 10 ft. of effective head using air permeability data:* | No $K_{air}$ obtained, hence no data. |

## Table 1.6: Summary Data Sheet - Boric Acid

| | | |
|---|---|---|
| *Mineral* | Boric Acid<br>$H_3BO_3$ |  |
| *Grade:* | Technical | |
| *Oxides Provided:* | $B_2O_3$ | |
| *Vendor & Address:* | U.S. Borax Inc.<br>26877 Tourney Rd.<br>Valencia, CA 91355<br>805-287-5400 | |
| *Cost:* | $0.36/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 56.8 lbm/ft$^3$ | *Particle Density:* | 94.22 lbm/ft$^3$ |
| *Formula weight:* | 61.84 g/g-mole | *Melting Point:* | 170.9°C (in closed space) |
| *Vapor Pressure:* | Negligible @ 20°C | *Solubility in Water:* | 20°C 4.7%<br>100°C 27.5% |
| *Particle size:* | < 2.0 % retained in No. 20 U.S. standard sieve | | |

*Chemical Properties (weight percent)*

| $B_2O_3$ | $SO_4$ | Cl | Fe | $H_2O$ | N/A | N/A | N/A |
|---|---|---|---|---|---|---|---|
| 56.53 | < 350 ppm | < 18 ppm | < 6 ppm | Remaining | N/A | N/A | N/A |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.0 % | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (27° – 36°) / 32°- Average | Minimum | Range ( $s_1 = 44 \text{ to } 2362 \frac{lbf}{ft^2}$<br>$r = 54.8 \text{ to } 59.0 \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:* | Not Measured | 54.6 | Density fit to range above:<br>$r = -5\times10^{-7}\cdot s_1^2 + 0.002\cdot s_1 + 56.858$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 130.8 µm | 336.1 µm | 750.1 µm | 17.7 µm | 28.7 µm | 115.3 µm |
| 3 bar | 48.6 µm | 183.7 µm | 487.0 µm | 3.4 µm | 4.7 µm | 9.8 µm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 1 ft. | 5 ft. | Conical | 0.0 ft. | 0.0 ft. |
| | | Transitional | 0.0 ft. | 0.0 ft. |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 33° | 19° | 47 | 33 |
| Mild carbon steel plate, mill finish | 28° | 24° | 42° | 38° |
| TIVAR –88 | 29° | 29° | 45° | 43° |

| | |
|---|---|
| *Critical Flow Rate – Mass flow, cone, 1 ft. outlet diameter, cylinder containing 10 ft. of effective head using air permeability data:* | No $K_{air}$ obtained, hence no data. |

## Table 1.7: Summary Data Sheet - Iron Oxide

| | |
|---|---|
| *Mineral* | Iron Oxide |
| *Grade:* | 5001 |
| *Oxides Provided:* | $Fe_2O_3$ |
| *Vendor & Address:* | The Prince Manufacturing Company<br>One Prince Plaza<br>P.O. Box 1009<br>Quincy, IL 62306<br>217-222-8854 |
| *Cost:* | $0.30 to 0.50/lbm |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 70 lbm/$ft^3$ – loose<br>170 lbm/$ft^3$ – compacted | *Particle Density:* | 280.8 to 312 lbm/$ft^3$ |
| *Formula weight:* | | *Melting Point:* | 1565 °C |
| *Vapor Pressure:* | N/A | *Solubility in Water:* | Insoluble |

*Particle Size Distribution (microns)*

| *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|
| *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 1.6 µm | 23.06 µm | 42.86 µm | 0.46 µm | 0.56 µm | 0.96 µm |

*Chemical Properties (weight percent)*

| $Fe_2O_3$ | $Al_2O_3$ | $SiO_2$ | P | MgO | Mn | CaO | S |
|---|---|---|---|---|---|---|---|
| 97.0 | 1.50 | 1.35 | 0.115 | 0.10 | 0.09 | 0.04 | 0.032 |

**JENIKE & JOHANSON DATA:**

| | | *Bulk Density ($lbm/ft^3$)* | |
|---|---|---|---|
| *Moisture Content:* | 0.3 % | | |
| *Angle of repose (range) / average:* | (36° – 41°) / 38° Average | Minimum<br>88.9 | Range ( $s_1 = 44 \ to \ 2362 \ \frac{lbf}{ft^2}$, $r = 110.6 \ to \ 140.9 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant:*<br>$r = 101.8 \ to \ 149.6 \ \frac{lbm}{ft^3}$ | $K_{air} = 0.001532 \left( \frac{r}{100.4} \right)^{-0.5.35} \ \frac{ft}{sec}$ | | Density fit to range above:<br>$r = 103.96 \cdot \left( \frac{s_1}{13.00} \right)^{0.06065}$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 4.76 µm | 23.86 µm | 69.96 µm | 0.636 µm | 0.966 µm | 2.196 µm |
| 3 bar | 2.06 µm | 21.36 µm | 58.76 µm | 0.326 µm | 0.436 µm | 0.806 µm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 8 ft. | 8 ft. | Conical | 0.5 ft. | 0.5 ft. |
| | | Transitional | 0.2 ft. | 0.2 ft |

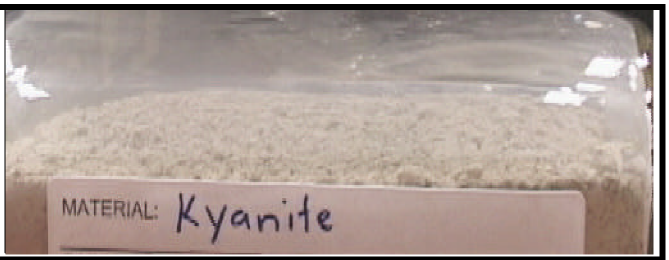
*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 8° | 7° | 21° | 20° |
| Mild carbon steel plate, mill finish | 10° | 7° | 22° | 19° |
| TIVAR –88 | 11° | 8° | 22° | 20° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 820 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 1100 lbm/hr |

## Table 1.8: Summary Data Sheet - Kyanite

| | | |
|---|---|---|
| *Mineral* | Raw Kyanite |  |
| *Grade:* | < 325 Mesh | |
| *Oxides Provided:* | $Al_2O_3$, $SiO_2$ | |
| *Vendor & Address:* | Kyanite Mining Corp.<br>Hwy 15S<br>Dillwyn, VA, 23936<br>434-983-2043 | |
| *Cost:* | $0.068 to 0.083/lbm | |

| **VENDOR DATA:** | | | |
|---|---|---|---|
| *Bulk Density:* | 65.5 lbm/ft$^3$ | *Particle Density:* | 199.7 - 224.6 lbm/ft$^3$ |
| *Formula weight:* | | *Melting Point:* | 1595°C |
| *Vapor Pressure:* | N/A | *Solubility in Water:* | Insoluble |

| *Particle Size Distribution (microns)* | |
|---|---|
| *200 to 325 Mesh* | *< 325 Mesh* |
| *8.2 %* | *91.8 %* |

| *Chemical Properties (weight percent)* | | | | | | | |
|---|---|---|---|---|---|---|---|
| $Al_2O_3$ | $SiO_2$ | $TiO_2$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ |
| 54.0 – 60.0 | 39.0 – 42.0 | 0.5 – 1.6 | 0.42 – 1.0 | < 0.04 | < 0.04 | < 0.04 | < 0.07 |

| **JENIKE & JOHANSON DATA:** | | | |
|---|---|---|---|
| *Moisture Content:* | 0.1 % | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (40° – 43°) / 41° Average | Minimum<br>56.1 | Range ( $s_1 = 44 \ \ to \ \ 2362 \ \frac{lbf}{ft^2}$ ,<br>$r = 76.2 \ \ to \ \ 101.1 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant:*<br>$r = 67.5 \ \ to \ \ 94.9 \ \frac{lbm}{ft^3}$ | $K_{air} = 0.0203 \cdot e^{-0.0488\, r} \ \frac{ft}{sec}$ | | Density fit to range above:<br>$r = 6.2747 \cdot Ln(s_1) + 53.34$ |

| *Particle Size Distribution (microns)* | | | | | | |
|---|---|---|---|---|---|---|
| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 2.2 µm | 13.8 µm | 54.2 µm | 0.33 µm | 0.46 µm | 1.01 µm |
| 3 bar | 1.4 µm | 11.3 µm | 56.9 µm | 0.32 µm | 0.45 µm | 0.90 µm |

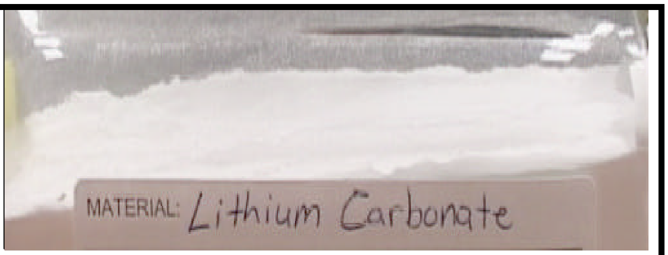
| *Cohesive strength* | | | | |
|---|---|---|---|---|
| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 6 ft. | 6 ft. | Conical | 0.6 ft. | 1.1 ft. |
| | | Transitional | 0.3 ft. | 0.6 ft. |

| *Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time* | | | | |
|---|---|---|---|---|
| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 9° | 9° | 22° | 22° |
| Mild carbon steel plate, mill finish | None | None | None | None |
| TIVAR –88 | 3° | 3° | 17° | 16° |

| *Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:* | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 220 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 314 lbm/hr |

## Table 1.9: Summary Data Sheet - Lithium Carbonate

| | |
|---|---|
| *Mineral* | Lithium Carbonate |
| *Grade:* | Technical, min 99% |
| *Oxides Provided:* | $Li_2O$ |
| *Vendor & Address:* | Chemettal-Foote<br>348 Holiday Inn Drive<br>Kings Mt., NC 28086<br>704-734-2501 |
| *Cost:* | $1.00/lbm |



**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 49.3 $lbm/ft^3$ | *Particle Density:* | 131.7 $lbm/ft^3$ |
| *Formula weight:* | 73.89 g/g-mole | *Melting Point:* | 732 °C |
| *Vapor Pressure:* | N/A | *Solubility in Water*<br>*$gLi_2CO_3$/100g*<br>*(0 °C < T < 100 °C):* | $k = 2 \cdot 10^{-5} \cdot T^2 - 0.0099 \cdot T + 1.5343$ |

*Typical Mass Particle Size Distribution (microns)*

| *> 840* | *420 – 820* | *250 – 420* | *149 – 250* | *105 -149* | *74 – 105* | *< 74* |
|---|---|---|---|---|---|---|
| 0.3% (0.8% max) | 47 % | 21 % | 12 % | 2 % | 0.7 % | 17 % (25 % max) |

*Typical Chemical Properties (weight percent)*

| $Li_2O$ | $CO_2$ | Cl | Na | Mg | $SO_4$ | $Fe_2O_3$ | Ca |
|---|---|---|---|---|---|---|---|
| 40.2 | 59.2 | 0.01 | 0.0003 | 0.06 | 0.004 | 0.04 | 0.001 |

**JENIKE & JOHANSON DATA:**

| | | *Bulk Density ($lbm/ft^3$)* | |
|---|---|---|---|
| *Moisture Content:* | 0.1 % | | |
| *Angle of repose (range) / average:* | (34° – 42°) / 38° Average | Minimum 53.1 | Range ( $s_1 = 44 \ to \ 2362 \ \frac{lbf}{ft^2}$, $r = 61.8 \ to \ 72.2 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant:*<br>$r = 53.5 \ to \ 69.6 \ \frac{lbm}{ft^3}$ | $K_{air} = 0.002209 \cdot \left(\frac{r}{58.4}\right)^{-4.60} \frac{ft}{sec}$ | | Density fit to range above:<br>$r = 2.5559 \cdot Ln(s_1) + 52.66$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 16.0 µm | 197.0 µm | 470.9 µm | 3.1 µm | 5.4 µm | 12.4 µm |
| 3 bar | 5.9 µm | 59.0 µm | 308.2 µm | 0.8 µm | 1.1 µm | 2.5 µm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 5 ft. | 5 ft. | Conical | 0.5 ft. | 0.5 ft. |
| | | Transitional | 0.2 ft. | 0.2 ft. |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

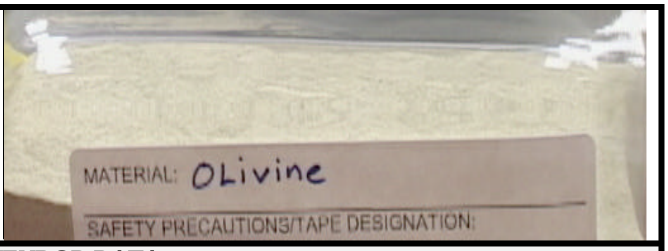
| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 16° | 16° | 27° | 27° |
| Mild carbon steel plate, mill finish | 17° | 15° | 28° | 27° |
| TIVAR –88 | 16° | 15° | 27° | 26° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 1260 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 1571 lbm/hr |

## Table 1.10: Summary Data Sheet - Olivine

| | |
|---|---|
| *Mineral* | Olivine |
| *Grade:* | 100 x 200 |
| *Oxides Provided:* | MgO, $SiO_2$, $Fe_2O_3$ |
| *Vendor & Address:* | Unimin Corp.<br>Hamilton, Wa<br>800-243-9004 |
| *Cost:* | $0.02 to 0.05/lbm |



**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 90 - 109 $lbm/ft^3$ | *Particle Density:* | 143.5 – 224.6 $lbm/ft^3$ |
| *Formula weight:* | | *Melting Point:* | 1538 to 1760°C |
| *Vapor Pressure:* | Not applicable | *Solubility in Water:* | Insoluble |

*Particle Size Distribution (microns)*

| *420 – 595* | *297 – 420* | *210 – 297* | *149 – 210* | *105 – 149* | *74 – 105* | *53 – 74* | *< 53* |
|---|---|---|---|---|---|---|---|
| 0.4% | 1.5% | 9.0% | 32.5% | 33.0% | 16.0% | 5.0% | 2.6% |

*Chemical Properties (weight percent)*

| MgO | $SiO_2$ | $Fe_2O_3$ | CaO | $Cr_2O_3$ | $Al_2O_3$ | $K_2O$ | $Na_2O$ | NiO |
|---|---|---|---|---|---|---|---|---|
| 48.01 | 42.52 | 7.68 | 0.02 | 0.13 | 0.19 | 0.01 | 0.02 | 0.37 |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.2 % | *Bulk Density ($lbm/ft^3$)* | |
| *Angle of repose (range) / average:* | (28° – 30°) / 29° Average | Minimum<br>89.3 | Range ( $s_1 = 44$ to $2362\ \frac{lbf}{ft^2}$, $r = 94.5$ to $97.9\ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:* | Not Measured | | Density fit to range above:<br>$r = -8\times10^{-7}\cdot s_1^2 + 0.0033\cdot s_1 + 94.384$ |

*Particle Size Distribution (microns)*

| Conveying Pressure | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 61.9 μm | 104.3 μm | 171.0 μm | 44.4 μm | 66.3 μm | 109.8 μm |
| 3 bar | 47.2 μm | 92.9 μm | 164.1 μm | 6.1 μm | 8.8 μm | 19.2 μm |

*Cohesive strength*

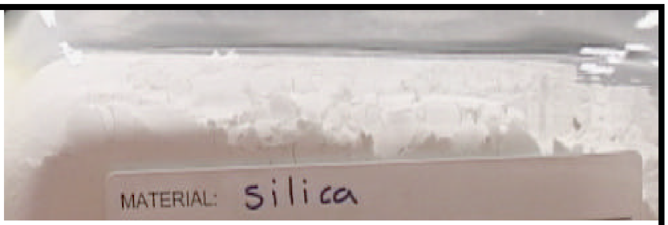
| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 2 ft. | 2 ft. | Conical | 0.0 ft. | 0.0 ft. |
| | | Transitional | 0.0 ft | 0.0 ft |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 17° | 17° | 31° | 31° |
| Mild carbon steel plate, mill finish | 6° | None | 21° | None |
| TIVAR –88 | 22° | 20° | 35° | 33° |

| | |
|---|---|
| *Critical Flow Rate – Mass flow hopper containing 10 ft. of effective head using air permeability data:* | No $K_{air}$ obtained, hence no data. |

## Table 1.11: Summary Data Sheet - Silica

| | | |
|---|---|---|
| *Mineral* | Silica |  |
| *Grade:* | Sil-Co-Sil 75 | |
| *Oxides Provided:* | $SiO_2$ | |
| *Vendor & Address:* | U.S. Silica<br>Mill Creek, OK<br>800-243-7500 | |
| *Cost:* | $0.009/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 59.3 $lbm/ft^3$ | *Particle Density:* | 165.4 $lbm/ft^3$ |
| *Formula weight:* | | *Melting Point:* | 1705 °C |
| *Vapor Pressure:* | N/A | *Solubility in Water:* | Insoluble |

*Typical Mass Particle Size Distribution (microns)*

| *106 – 150* | *75 – 106* | *53 – 75* | *45 – 53* | *< 45* |
|---|---|---|---|---|
| 0.2 % | 1.3 % | 5.9 % | 5.6 % | 87 % |

*Typical Chemical Properties (weight percent)*

| $SiO_2$ | $Fe_2O_3$ | $Al_2O_3$ | $TiO_2$ | CaO | MgO | $Na_2O$ | $K_2O$ |
|---|---|---|---|---|---|---|---|
| 99.7 | 0.016 | 0.135 | 0.008 | 0.008 | 0.008 | 0.002 | 0.017 |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.1 % | *Bulk Density ($lbm/ft^3$)* | |
| *Angle of repose (range) / average:* | (36° – 45°) / 40° Average | Minimum<br>49.6 | Range ( $s_1 = 44 \ to \ 2362 \ \frac{lbf}{ft^2}$, $r = 69.1 \ to \ 88.9 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant:* $r = 60.6 \ to \ 91.5 \ \frac{lbm}{ft^3}$ | $K_{air} = 0.000630 \cdot \left(\frac{r}{64.9}\right)^{-4.52} \frac{ft}{sec}$ | | Density fit to range above:<br>$r = 5.004 \cdot Ln(s_1) + 50.965$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 2.8 µm | 21.5 µm | 72.0 µm | 0.3 µm | 0.5 µm | 1.0 µm |
| 3 bar | 1.9 µm | 19.8 µm | 58.5 µm | 0.3 µm | 0.5 µm | 0.9 µm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 6 ft. | 6 ft. | Conical | 0.6 ft. | 1.1 ft. |
| | | Transitional | 0.3 ft. | 0.5 ft. |

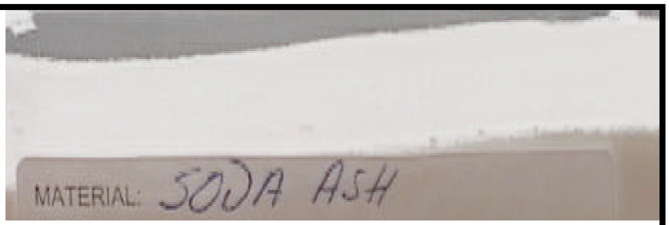
*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 10° | 10° | 23° | 23° |
| Mild carbon steel plate, mill finish | None | None | 17° | 17° |
| TIVAR –88 | 7° | 6° | 21° | 21° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 240 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 436 lbm/hr |

## Table 1.12: Summary Data Sheet – Soda Ash

| | | |
|---|---|---|
| *Mineral* | Soda Ash |  |
| *Grade:* | Dense Anhydrous | |
| *Oxides Provided:* | $Na_2O$ | |
| *Vendor & Address:* | Solvay Mineral<br>Houston TX<br>713-525-6800 | |
| *Cost:* | $0.033/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 56 – 66 lbm/ft$^3$ | *Particle Density:* | 158.1 lbm/ft$^3$ |
| *Formula weight:* | 105.99 g/g-mole | *Melting Point:* | 851°C |
| *Vapor Pressure:* | N/A | *Solubility in Water:* | 33% maximum by weight |

*Typical Mass Particle Size Distribution (microns)*

| *> 841* | *595 – 841* | *420 – 595* | *149 – 420* | *74 – 149* | *< 74* |
|---|---|---|---|---|---|
| 1% | 1% | 13% | 78% | 6% | 1% |

*Chemical Properties (weight percent)*

| $Na_2O$ | $CO_2$ | $Na_2SO_4$ | NaCl | $H_2O$ Insoluble | Fe | Ca | Mg |
|---|---|---|---|---|---|---|---|
| 58.37% | 41.43% | 0.01% | 0.03% | 0.02% | 2 ppm | 35 ppm | 25 ppm |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.2 % | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (30° – 35°) / 33° Average | Minimum 64.2 | Range ( $s_1 = 44$ *to* $2362\ \frac{lbf}{ft^2}$, $r = 66.3$ *to* $67.5\ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:* | Not Measured | | Density fit to range above: $r = -2\times10^{-7}\cdot s_1^2 + 0.0009\cdot s_1 + 66.342$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 164.0 | 287.4 | 456.5 | 24.7 | 33.9 | 191.4 |
| 3 bar | 19.8 | 147.5 | 380.6 | 0.9 | 1.2 | 2.5 |

*Cohesive strength*

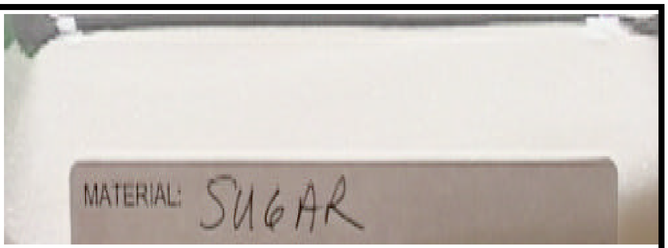
| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 1 ft. | 3 ft. | Conical | 0.0 ft. | 0.3 ft. |
| | | Transitional | 0.0 ft. | 0.2 ft. |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 14° | 14° | 26° | 26° |
| Mild carbon steel plate, mill finish | 10° | 10° | 22° | 22° |
| TIVAR –88 | 13° | 13° | 25° | 25° |

| | |
|---|---|
| *Critical Flow Rate – Mass flow hopper containing 10 ft. of effective head using air permeability data:* | No $K_{air}$ obtained, hence no data. |

## Table 1.13: Summary Data Sheet - Sugar

| | | |
|---|---|---|
| *Mineral* | Sugar |  |
| *Grade:* | Fine Granulated Sugar | |
| *Oxides Provided:* | Carbon ($C_{12}H_{22}O_{11}$) | |
| *Vendor & Address:* | The Amalgamated Sugar<br>Company, LLC<br>Ogden, UT<br>801-399-3431 | |
| *Cost:* | $0.35/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | | *Particle Density:* | 96.7 lbm/$ft^3$ |
| *Formula weight:* | 342 g/g-mole | *Melting Point:* | 186°C |
| *Solubility in Water:* | 200 grams/100 cc $H_2O$ @ 20°C | N/A | N/A |
| *Critical Dust Concentration:* | 0.045 oz/$ft^3$ | *Ignition Temperature Dust:* | 420°C |

*Typical Mass Particle Size Distribution (microns)*

| *> 841* | *595 - 841* | *420 – 595* | *297 –420* | *210 – 297* | *149 – 210* | *< 149* |
|---|---|---|---|---|---|---|
| 0.2% | 2.8% | 27% | 45% | 17% | 6% | 2% |

*Chemical Properties (weight percent)*

| C | $H_2O$ | N/A | N/A | N/A | N/A | N/A | N/A |
|---|---|---|---|---|---|---|---|
| 42.11% | 57.89% | N/A | N/A | N/A | N/A | N/A | N/A |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.1 % | *Bulk Density (lbm/ft³)* | |
| *Angle of repose (range) / average:* | (29° – 31°) / 30° Average | Minimum 52.6 | Range ( $s_1 = 44 \ to \ 2362 \ \frac{lbf}{ft^2}$, $r = 54.2 \ to \ 55.9 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:* | Not Measured | | $r = -53.65 \cdot \left( \frac{s_1}{13.00} \right)^{0.00753}$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 245.5 µm | 381.3 µm | 637.3 µm | 182.3 µm | 267.4 µm | 433.7 µm |
| 3 bar | 90.1 µm | 336.0 µm | 609.5 µm | 4.3 µm | 5.9 µm | 12.1 µm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 2 ft. | 3 ft. | Conical | 0.1 ft. | 1.0 ft. |
| | | Transitional | 0.0 ft | 0.5 ft. |

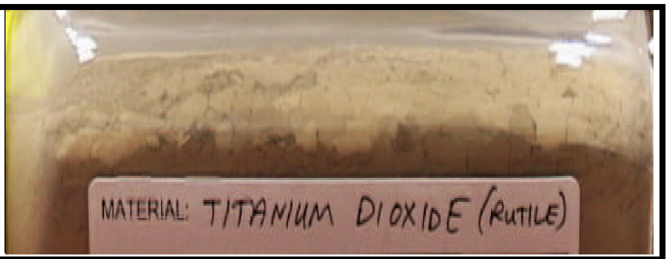
*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | None | None | None | None |
| Mild carbon steel plate, mill finish | None | None | None | None |
| TIVAR –88 | 10° | 10° | 24° | 24° |

| | |
|---|---|
| *Critical Flow Rate – Mass flow hopper containing 10 ft. of effective head using air permeability data:* | No $K_{air}$ obtained, hence no data. |

## Table 1.14: Summary Data Sheet – Titanium Dioxide

| | |
|---|---|
| *Mineral* | Titanium Dioxide |
| *Grade:* | Rutile Air Floated 94 |
| *Oxides Provided:* | $TiO_2$, $ZrO_2$, $Fe_2O_3$ |
| *Vendor & Address:* | Chemalloy Company<br>Bryn Mawr, PA<br>610-527-3700 |
| *Cost:* | $0.20 to 0.23/lbm |



**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | | *Particle Density:* | 268.3 – 312 lbm/ft$^3$ |
| *Formula weight:* | | *Melting Point:* | 1650 °C |
| *Vapor Pressure:* | N/A | *Solubility in Water:* | Insoluble |

*Typical Mass Particle Size Distribution (microns)*

| *44 – 177* | *< 44* |
|---|---|
| 10% | 90% |

*Typical Chemical Properties (weight percent) – First Column of Data is Nominal wt. %*

| *$TiO_2$* | *$ZrO_2$* | *$Fe_2O_3$* | *$SiO_2$* | *$Al_2O_3$* | *$V_2O_5$* | *$Cb_2O_5$* | *$Cr_2O_3$* | *S* | *P* |
|---|---|---|---|---|---|---|---|---|---|
| 92.8 – 93.6 | 1.9 | 0.7 | 2.0 – 2.4 | 0.5 | 0.45 | 0.40 | 0.16 | 0.01 | 0.02 |
| Min 92.0 | Max 2.5 | Max 2.0 | Max 2.5 | Max 0.75 | Max 0.75 | Max 0.75 | Max 0.5 | Max 0.02 | Max 0.03 |

**JENIKE & JOHANSON DATA:**

| | | *Bulk Density (lbm/ft$^3$)* | |
|---|---|---|---|
| *Moisture Content:* | 0.2 % | | |
| *Angle of repose (range) / average:* | (40° – 43°) / 41° Average | Minimum 91.2 | Range ( $s_1 = 44 \ to \ 2362 \ \frac{lbf}{ft^2}$, $r = 110.3 \ to \ 135.2 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant:* $r = 92.7 \ to \ 139.2 \ \frac{lbm}{ft^3}$ | $K_{air} = 0.000696 \cdot \left(\frac{r}{104.5}\right)^{-3.79} \frac{ft}{sec}$ | | Density fit to range above: $r = 6.2823 \cdot Ln(s_1) + 87.207$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 4.7 μm | 19.9 μm | 49.1 μm | 0.5 μm | 0.8 μm | 2.1 μm |
| 3 bar | 2.5 μm | 20.1 μm | 52.8 μm | 0.3 μm | 0.4 μm | 0.9 μm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 7 ft. | 7 ft. | Conical | 0.1 ft. | 0.2 ft. |
| | | Transitional | 0.1 ft. | 0.1 ft. |

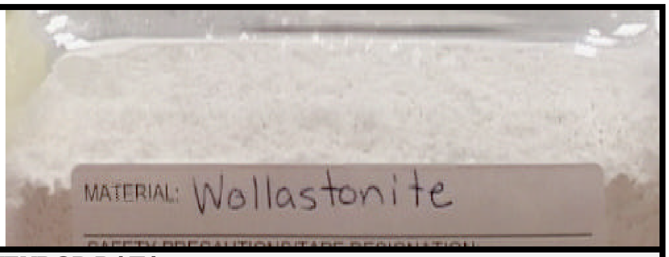
*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 5° | 5° | 21° | 21° |
| Mild carbon steel plate, mill finish | None | None | 17° | 16° |
| TIVAR –88 | None | None | 18° | 17° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 860 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 911 lbm/hr |

## Table 1.15: Summary Data Sheet - Wollastonite

| | | |
|---|---|---|
| *Mineral* | Wollastonite |  |
| *Grade:* | NYAD@ 325 | |
| *Oxides Provided:* | CaO, $SiO_2$ | |
| *Vendor & Address:* | NYCO<br>Wilsboro, NY<br>518-963-4262 | |
| *Cost:* | $0.10 to 0.13/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 45 – 70 lbm/$ft^3$ | *Particle Density:* | 181 lbm/$ft^3$ |
| *Formula weight:* | 116 g/g-mole | *Melting Point:* | 1540 °C |
| *Vapor Pressure:* | N/A | *Solubility in Water:* | 0.0095g / 100 cc $H_2O$ |
| *Weight Loss:* | 0.68 wt. % at 1000°C | | |

*Typical Mass Particle Size Distribution (microns)*

| < 10% | < 50% | < 90% |
|---|---|---|
| 1.9 µm | 10.0 µm | 27.0 µm |

*Typical Chemical Properties (weight percent)*

| CaO | $SiO_2$ | $Fe_2O_3$ | $Al_2O_3$ | MnO | MgO | $TiO_2$ |
|---|---|---|---|---|---|---|
| 47.5 | 51.0 | 0.4 | 0.2 | 0.1 | 0.1 | 0.02 |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.2 % | *Bulk Density (lbm/$ft^3$)* | |
| *Angle of repose (range) / average:* | (35° – 38°) / 36° Average | Minimum<br>46.4 | Range ( $s_1 = 44$ to $2362 \frac{lbf}{ft^2}$, $r = 58.5$ to $76.8 \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant:* $r = 55.4$ to $77.2 \frac{lbm}{ft^3}$ | $K_{air} = 4286.9 \cdot (r)^{-3.8827} \frac{ft}{\sec}$ | | Density fit to range above:<br>$r = 4.5674 \cdot Ln(s_1) + 41.825$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 2.7 µm | 15.5 µm | 45.0 µm | 0.3 µm | 0.5 µm | 1.1 µm |
| 3 bar | 1.6 µm | 11.2 µm | 42.6 µm | 0.3 µm | 0.5 µm | 0.9 µm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 7 ft. | 11 ft. | Conical | 0.8 ft. | 3.9 ft. |
| | | Transitional | 0.4 ft | 1.9 ft |

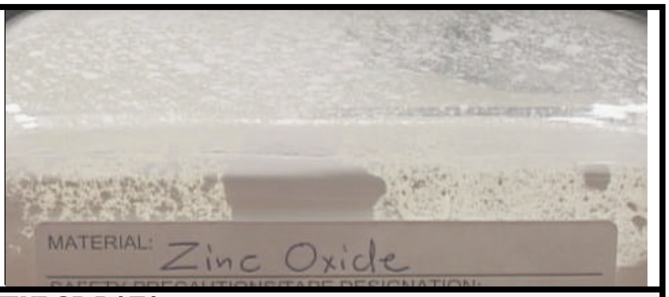
*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 6° | 6° | 18° | 18° |
| Mild carbon steel plate, mill finish | None | None | None | None |
| TIVAR –88 | 5° | 5° | 16° | 16° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 180 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 346 lbm/hr |

## Table 1.16: Summary Data Sheet – Zinc Oxide

| | | |
|---|---|---|
| *Mineral* | Zinc Oxide |  |
| *Grade:* | Kadox-920 | |
| *Oxides Provided:* | ZnO | |
| *Vendor & Address:* | Zinc Corporation of America<br>Monaca, PA<br>412-774-1020 | |
| *Cost:* | $0.80/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 35 lbm/ft$^3$ | *Particle Density:* | 349.4 lbm/ft$^3$ |
| *Formula weight:* | | *Melting Point:* | 1975 °C |
| *Vapor Pressure:* | N/A | *Solubility in Water:* | Negligible |
| *Mean Particle size:* | 0.21 microns | N/A | N/A |

*Typical Chemical Properties (weight percent)*

| *no* | *PbO* | *CdO* | *CuO* | *MnO* | *$Fe_2O_3$* | *Soluble salts* |
|---|---|---|---|---|---|---|
| 99.8 | 0.001 | 0.005 | <0.0005 | <0.0005 | 0.001 | 0.02 |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.2 % | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (31° – 34°) / 33° Average | Minimum<br>33.8 | Range ( $s_1 = 44 \ \ to \ \ 2362 \ \frac{lbf}{ft^2}$, <br>$r = 42.5 \ \ to \ \ 66.1 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant:*<br>$r = 55.4 \ \ to \ \ 77.2 \ \frac{lbm}{ft^3}$ | $K_{air} = 4286.9 \cdot (r)^{-3.8827} \ \frac{ft}{sec}$ | | Density fit to range above:<br>$r = -4 \cdot 10^{-6} \cdot s_1 + 0.0185 \cdot s_1 + 43.109$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 2.7 µm | 15.5 µm | 45.0 µm | 0.3 µm | 0.5 µm | 1.1 µm |
| 3 bar | 1.6 µm | 11.2 µm | 42.6 µm | 0.3 µm | 0.5 µm | 0.9 µm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 18 ft. | 22 ft. | Conical | >13.7 ft. | >16.7 ft. |
| | | Transitional | >27.5 ft. | >33.4 ft. |

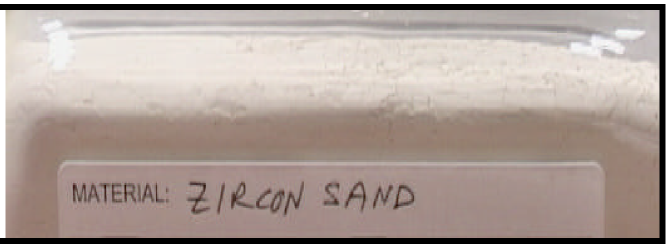
*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 2° | 2° | 14° | 14° |
| Mild carbon steel plate, mill finish | None | None | None | None |
| TIVAR –88 | 15° | 13° | 28° | 26° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 13600 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 13666 lbm/hr |

## Table 1.17: Summary Data Sheet - Zircon

| | | |
|---|---|---|
| *Mineral* | Zircon Flour | <br> |
| *Grade:* | < 325 Mesh | |
| *Oxides Provided:* | $ZrO_2$, $SiO_2$ | |
| *Vendor & Address:* | American Mineral Inc.<br>King of Prussia, PA<br>610-962-5050 | |
| *Cost:* | $0.20/lbm | |

**VENDOR DATA:**

| | | | |
|---|---|---|---|
| *Bulk Density:* | 170 - 180 lbm/ft$^3$ | *Particle Density:* | 287 - 300 lbm/ft$^3$ |
| *Formula weight:* | 183.3 g/g-mole | *Melting Point:* | 2200 °C |
| *Solubility in Water:* | Insoluble | *Mean Particle size:* | 95 wt. % < 44 microns |
| *Angle of repose:* | 30 degrees | | |

*Typical Chemical Properties (weight percent)*

| $ZrO_2$ (+$HfO_2$) | $Fe_2O_3$ | $TiO_2$ | $Al_2O_3$ | $SiO_2$ | *Free Silica* | *U + Th* |
|---|---|---|---|---|---|---|
| 65 - 66.0% | 0.06-0.09% | 0.07 –0.14% | 0.1-0.4% | 32.0-32.5% | 0.01-0.2% | 400-500 ppm |

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | 0.2 % | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (40° – 47°) / 43° Average | Minimum<br>96.0 | Range ( $s_1 = 44$ *to* $2362\ \frac{lbf}{ft^2}$, $r = 121.9$ *to* $154.9\ \frac{lbm}{ft^3}$) |
| *Air Permeability constant:*<br>$r = 112.6\ to\ 161.5\ \frac{lbm}{ft^3}$ | $K_{air} = 0.000993 \cdot \left(\frac{r}{115.0}\right)^{-5.09} \frac{ft}{sec}$ | | Density fit to range above:<br>$r = 8.2935 \cdot Ln(s_1) + 91.989$ |

*Particle Size Distribution (microns)*

| *Conveying Pressure* | *Volume Percent* | | | *Number Percent* | | |
|---|---|---|---|---|---|---|
| | *≤10%* | *≤50%* | *≤90%* | *≤10%* | *≤50%* | *≤90%* |
| 0 bar | 3.2 μm | 17.8 μm | 50.0 μm | 0.3 μm | 0.5 μm | 1.1 μm |
| 3 bar | 1.8 μm | 18.9 μm | 52.7 μm | 0.3 μm | 0.4 μm | 0.8 μm |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 6 ft. | 6 ft. | Conical | 0.6 ft. | 0.6 ft. |
| | | Transitional | 0.3 ft. | 0.3 ft. |

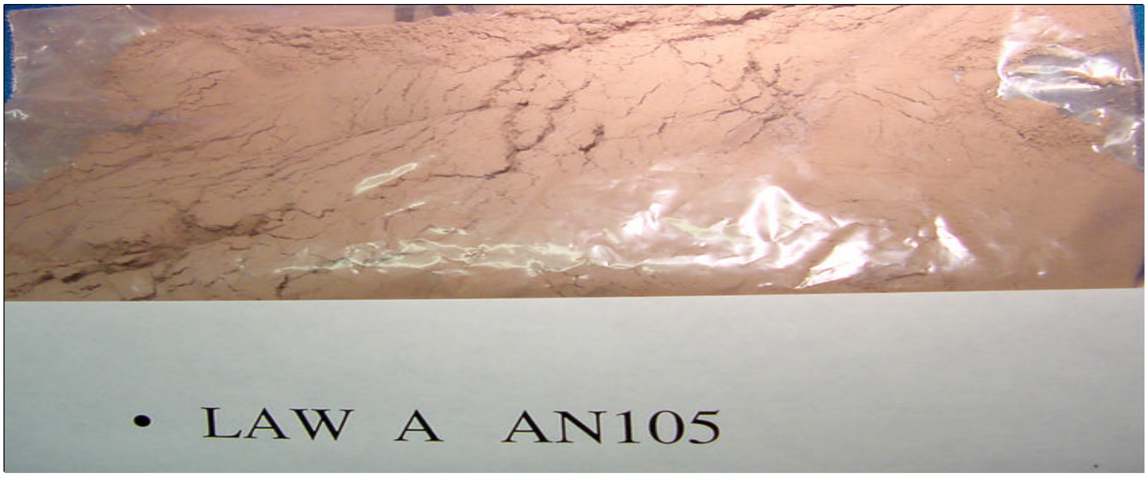
*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 1 ft opening* | | *Transition hopper 1 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 8° | 8° | 21° | 21° |
| Mild carbon steel plate, mill finish | 4° | 4° | 18° | 18° |
| TIVAR –88 | 6° | 6° | 19° | 19° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 1 ft. outlet diameter* | 620 lbm/hr |
| *Transition hopper, 1 ft width, 0.785 ft length* | 880 lbm/hr |

# Table 1.18: Summary Data Sheet – LAW A AN-105



**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | Not Measured | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (41° – 45°) / 43° Average | Minimum 56.1 | Range ( $s_1 = 44$ *to* $2362 \frac{lbf}{ft^2}$<br>$r = 70.1$ *to* $89.5 \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant* $K_{air}$:<br>$r = 61.3$ *to* $84.3 \frac{lbm}{ft^3}$ | $K_{air} = 0.000719 \cdot \left(\frac{r}{65.8}\right)^{-5.40} \frac{ft}{sec}$ | | Density Fit to range above:<br>$r = 4.9064 \cdot Ln(s_1) + 52.092$ |
| *Particle Size Distribution (microns)* | | Not Measured | |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 8 ft. | 8 ft. | Conical | 0.4 ft. | 1.0 ft. |
| | | Transitional | 0.2 ft. | 0.5 ft. |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 2 ft opening* | | *Transition hopper 2 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 12° | 12° | 24° | 24° |
| Mild carbon steel plate, mill finish | 7° | 7° | 22° | 21° |
| TIVAR –88 | 9° | 8° | 23° | 22° |

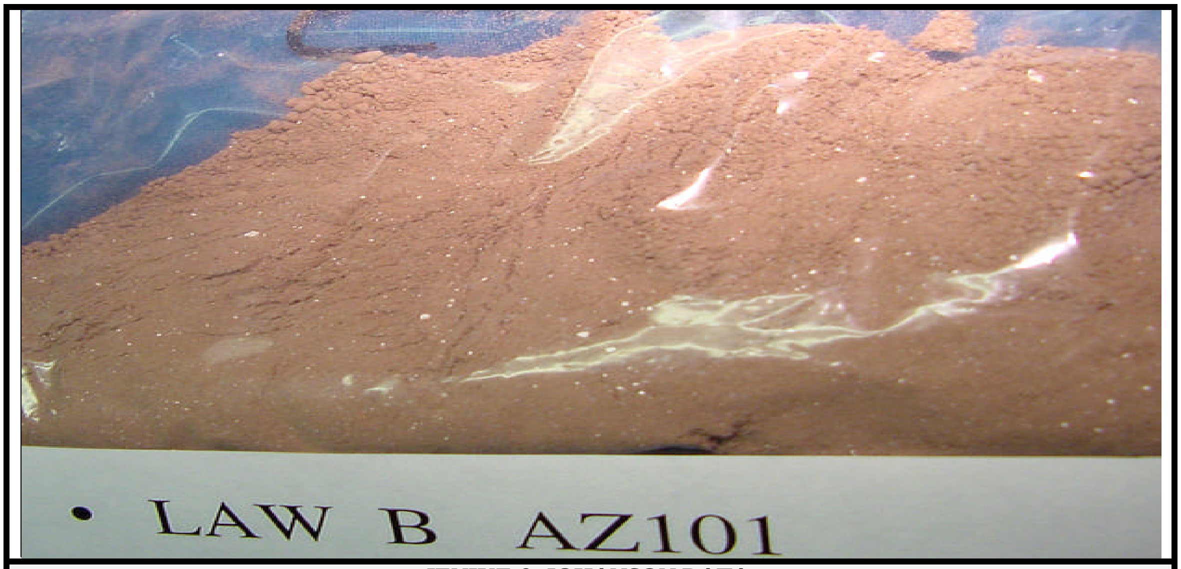
*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 2 ft. outlet diameter* | 1980 lbm/hr |
| *Transition hopper, 2 ft width, 1.57 ft length* | 2136 lbm/hr |

*Minimum Chute Angle from Horizontal in Degrees Given Different Impact Pressures*

| *Hopper Material* | *Impact Pressure* $\frac{lbf}{ft^2}$ | | | |
|---|---|---|---|---|
| | *3.5* | *42.6* | *81.7* | *159.9* |
| 304 #2B finish stainless steel sheet | 36° | 37° | 37° | 37° |
| Mild carbon steel plate, mill finish | 36° | 38° | 46° | 45° |
| TIVAR –88 | 41° | 39° | 38° | 39° |

## Table 1.19: Summary Data Sheet – LAW B AZ-101



| JENIKE & JOHANSON DATA: | | | |
|---|---|---|---|
| *Moisture Content:* | Not Measured | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (41° – 45°) / 43° Average | Minimum<br>49.6 | Range ( $\sigma_1 = 44 \;\; to \;\; 2362 \;\; \frac{lbf}{ft^2}$<br>$\rho = 58.1 \;\; to \;\; 74.4 \;\; \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant K$_{air}$:*<br>$\rho = 50.6 \;\; to \;\; 65.2 \;\; \frac{lbm}{ft^3}$ | $K_{air} = 0.007376 \cdot \left( \frac{\rho}{53.4} \right)^{-6.15} \;\; \frac{ft}{\sec}$ | | Density Fit to range above:<br>$\rho = 53.39 \cdot \left( \frac{\sigma_1}{13.00} \right)^{0.06318}$ |

| *Particle Size Distribution (microns)* | Not Measured |
|---|---|

| *Cohesive strength* | | | | |
|---|---|---|---|---|
| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 15 ft. | 19 ft. | Conical | 0.2 ft. | 0.6 ft. |
| | | Transitional | 0.1 ft. | 0.3 ft |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 2 ft opening* | | *Transition hopper 2 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 10° | 6° | 23° | 18° |
| Mild carbon steel plate, mill finish | 8° | 8° | 20° | 19° |
| TIVAR –88 | 11° | 10° | 23° | 21° |

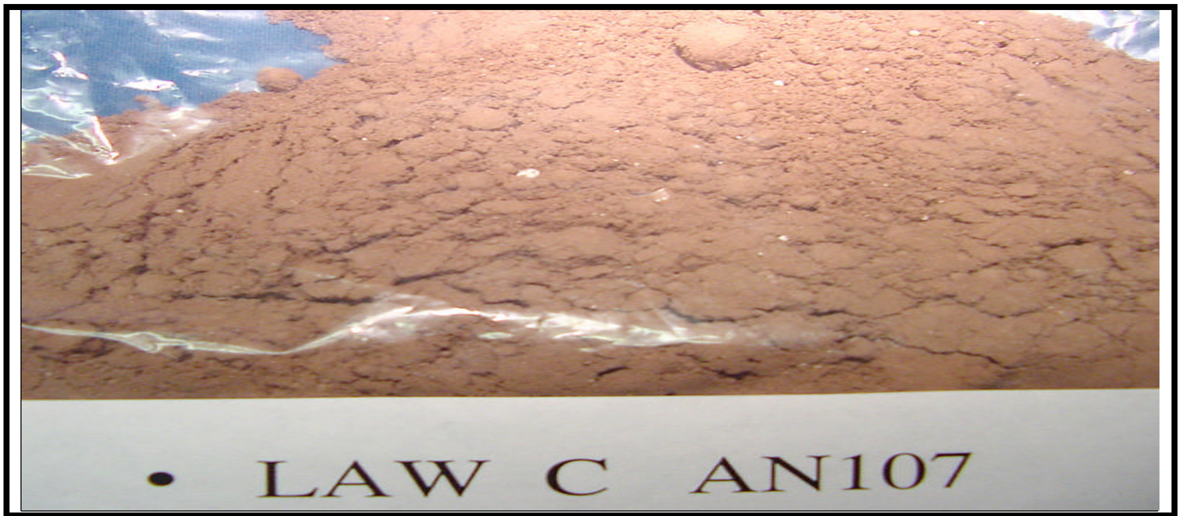
*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 2 ft. outlet diameter* | 20000 lbm/hr |
| *Transition hopper, 2 ft width, 1.57 ft length* | 22305 lbm/hr |

*Minimum Chute Angle from Horizontal in Degrees Given Different Impact Pressures*

| *Hopper Material* | *Impact Pressure* $\frac{lbf}{ft^2}$ | | | |
|---|---|---|---|---|
| | *3.5* | *42.6* | *81.7* | *159.9* |
| 304 #2B finish stainless steel sheet | 34° | 39° | 39° | 40° |
| Mild carbon steel plate, mill finish | 37° | 40° | 45° | 60° |
| TIVAR –88 | 35° | 44° | 48° | 52° |

## Table 1.20: Summary Data Sheet – LAW C AN107



| **JENIKE & JOHANSON DATA:** | | | |
|---|---|---|---|
| *Moisture Content:* | Not Measured | *Bulk Density (lbm/ft$^3$)* | |
| *Angle of repose (range) / average:* | (33° – 34°) / 33° Average | Minimum<br>47.0 | Range ( $s_1 = 44 \ to \ 2362 \ \frac{lbf}{ft^2}$<br>$r = 53.1 \ to \ 71.5 \ \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:*<br>$r = 43.3 \ to \ 71.4 \ \frac{lbm}{ft^3}$ | $K_{air} = 0.024481 \cdot \left(\frac{r}{48.0}\right)^{-5.89} \frac{ft}{sec}$ | | Density Fit to range above:<br>$r = 48.01 \cdot \left(\frac{s_1}{13.00}\right)^{0.07566}$ |

| | |
|---|---|
| *Particle Size Distribution (microns)* | Not Measured |

| *Cohesive strength* | | | | |
|---|---|---|---|---|
| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 15 ft. | 19 ft. | Conical | 0.9 ft. | 1.8 ft. |
| | | Transitional | 0.4 ft | 0.8 ft. |

| *Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time* | | | | |
|---|---|---|---|---|
| *Hopper Material* | *Conical Hopper 2 ft opening* | | *Transition hopper 2 ft oval width* | |
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 9° | None | 20° | 14° |
| Mild carbon steel plate, mill finish | 5° | 2° | 17° | 14° |
| TIVAR –88 | 18° | 14° | 29° | 25° |

| *Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:* | |
|---|---|
| *Conical hopper, 2 ft. outlet diameter* | 32000 lbm/hr |
| *Transition hopper, 2 ft width, 1.57 ft length* | 37699 lbm/hr |

| *Minimum Chute Angle from Horizontal in Degrees Given Different Impact Pressures* | | | | |
|---|---|---|---|---|
| *Hopper Material* | *Impact Pressure $\frac{lbf}{ft^2}$* | | | |
| | *3.5* | *42.6* | *81.7* | *159.9* |
| 304 #2B finish stainless steel sheet | 38° | 46° | 49° | 57° |
| Mild carbon steel plate, mill finish | 37° | 44° | 63° | 70° |
| TIVAR –88 | 35° | 40° | 41° | 44° |

## Table 1.21: Summary Data Sheet – HLW AZ102

**JENIKE & JOHANSON DATA:**

| | | | |
|---|---|---|---|
| *Moisture Content:* | Not Measured | *Bulk Density (lbm/ft³)* | |
| *Angle of repose (range) / average:* | (28° – 43°) / 37° Average | Minimum<br>52.4 | Range ( $s_1 = 44 \;\; to \;\; 2362 \; \frac{lbf}{ft^2}$<br>$r = 53.1 \;\; to \;\; 71.5 \; \frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:*<br>$r = 57.0 \;\; to \;\; 83.9 \; \frac{lbm}{ft^3}$ | $K_{air} = 0.001295 \cdot \left(\frac{r}{59.9}\right)^{-4.88} \frac{ft}{sec}$ | | Density Fit to range above:<br>$r = 4.6364 \cdot Ln(s_1) + 48.831$ |

| | |
|---|---|
| *Particle Size Distribution (microns)* | Not Measured |

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 8 ft. | 13 ft. | Conical | 0.2 ft. | 4.0 ft. |
| | | Transitional | 0.1 ft. | 2.0 ft. |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 2 ft opening* | | *Transition hopper 2 ft oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 15° | 14° | 27° | 26° |
| Mild carbon steel plate, mill finish | 14° | 9° | 25° | 21° |
| TIVAR –88 | 16° | 10° | 27° | 21° |

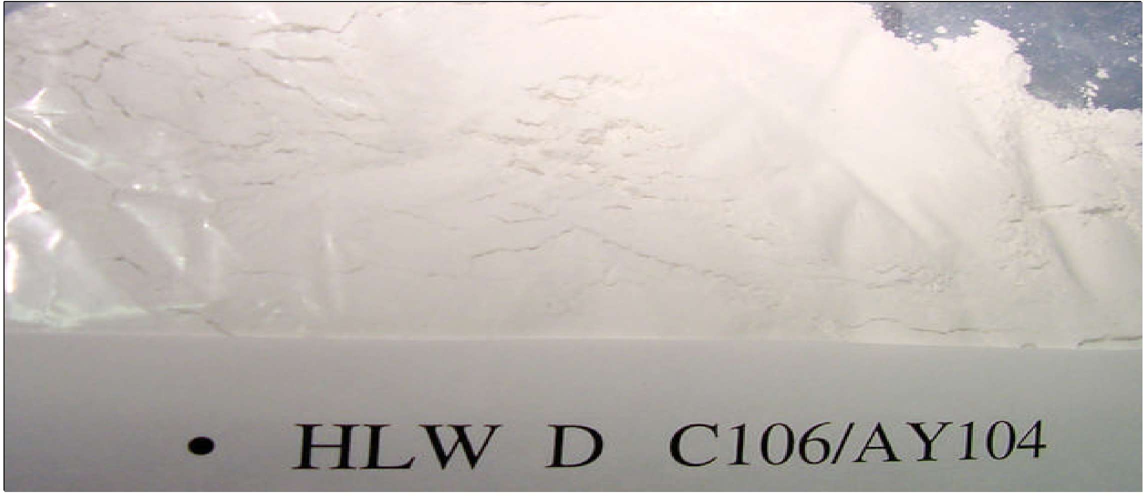
*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 2 ft. outlet diameter* | 3400 lbm/hr |
| *Transition hopper, 2 ft width, 1.57 ft length* | 3456 lbm/hr |

*Minimum Chute Angle from Horizontal in Degrees Given Different Impact Pressures*

| *Hopper Material* | *Impact Pressure* $\frac{lbf}{ft^2}$ | | | |
|---|---|---|---|---|
| | *3.5* | *42.6* | *81.7* | *159.9* |
| 304 #2B finish stainless steel sheet | 35° | 50° | 51° | 50° |
| TIVAR -88 | 38° | 39° | 40° | 39° |
| Mild carbon steel plate, mill finish | 39° | 53° | 64° | 67° |

## Table 1.22: Summary Data Sheet – HLW D C106/AY104



**JENIKE & JOHANSON DATA:**

| *Moisture Content:* | Not Measured | *Bulk Density (lbm/ft$^3$)* | |
|---|---|---|---|
| *Angle of repose (range) / average:* | (26° – 51°) / 37° Average | Minimum 47.2 | Range ( $s_1 = 44$ *to* $2362$ $\frac{lbf}{ft^2}$ <br> $r = 55.0$ *to* $76.6$ $\frac{lbm}{ft^3}$ ) |
| *Air Permeability constant $K_{air}$:* <br> $r = 44.0$ *to* $65.8$ $\frac{lbm}{ft^3}$ | $K_{air} = 0.004634 \cdot \left(\frac{r}{52.0}\right)^{-6.03} \frac{ft}{sec}$ | | Density fit to range above: <br> $r = 5.2787 \cdot Ln(s_1) + 37.026$ |

| *Particle Size Distribution (microns)* | Not Measured |
|---|---|

*Cohesive strength*

| *Critical rathole diameter (DF) at 10 ft. effective head for funnel flow hopper* | | *Minimum outlet diameter required to prevent arching in mass flow hoppers* | | |
|---|---|---|---|---|
| Continuous flow | 7 days at rest | Hopper Type | Continuous flow | 7 days at rest |
| 12 ft. | 22 ft. | Conical | 0.6 ft. | 6.0 ft. |
| | | Transitional | 0.3 ft. | 2.2 ft. |

*Mass Flow Hopper Angles (degrees) from Vertical for Given Wetted Material, Hopper design, and Storage time*

| *Hopper Material* | *Conical Hopper 2 foot opening* | | *Transition hopper 2 foot oval width* | |
|---|---|---|---|---|
| | *0.0 hrs* | *168 hrs* | *0.0 hrs* | *168 hrs* |
| 304 #2B finish stainless steel sheet | 13° | None | 24° | None |
| Mild carbon steel plate, mill finish | 11° | None | 23° | None |
| TIVAR –88 | 15° | 14° | 25° | 25° |

*Critical Flow Rate – Mass flow hoppers containing 10 ft. of effective head using air permeability data:*

| | |
|---|---|
| *Conical hopper, 2 ft. outlet diameter* | 7200 lbm/hr |
| *Transition hopper, 2 ft width, 1.57 ft length* | 8168 lbm/hr |

*Minimum Chute Angle from Horizontal in Degrees Given Different Impact Pressures*

| *Hopper Material* | *Impact Pressure* $\frac{lbf}{ft^2}$ | | | |
|---|---|---|---|---|
| | *3.0* | *42.1* | *81.2* | *159.5* |
| 304 #2B finish stainless steel sheet | 39° | 63° | 77° | 77° |
| TIVAR –88 | 36° | 47° | 38° | 40° |
| Mild carbon steel plate, mill finish | 39° | 62° | 64° | 79° |

## Table 1.23: J&J Analysis of RPP-WTP Silo Design Basis as of February 2002

| Material | Discharge flow type: funnel (f) or mass (m) | Bridging | | Rathole | | Exhibit Flooding behavior when rathole collapses | Exhibit flow rate limitations (Flow deficient factor FD*) |
|---|---|---|---|---|---|---|---|
| | | At rest for 0 hrs | At rest for 7 days | At rest for 0 hrs | At rest for 7 days | | |
| (Borax)** | f | N | Y | Y | Y | NL | NL |
| Boric Acid | f | N | N | N | Y | NL | NL |
| Iron Oxide | f | N | N | Y | Y | WL | Y (6) |
| Kyanite | f | N | N | Y | Y | WL | Y (50) |
| Lithium Carbonate | f | N | N | Y | Y | WL | Y (10) |
| Olivine | f | N | N | Y | Y | NL | NL |
| Silica | f | N | N | Y | Y | WL | Y (185) |
| Soda Ash | f | N | N | N | Y | NL | NL |
| Sugar | f | N | N | Y | Y | NL | NL |
| Titanium dioxide | f | N | N | Y | Y | WL | Y (2) |
| Wollastonite | f | N | Y | Y | Y | WL | Y (70) |
| Zinc Oxide | f (if any) | Y | Y | Y | Y | NL | NL |
| Zircon Flour | f | N | N | Y | Y | WL | Y (8) |

N = No, NL = Not likely, WL = Will likely, Y = Yes
*FD = DB mass flowrate provide by WTP divided by J&J calculated limited mass flow rate
** Not included in February 2002 Design Basis

## Table 1.24: J&J Summary on RPP-WTP Chute Concept

| Details of the chute design were not available at the time requested. WTP provided location (vertical) of final hopper and melter feed vessels. Recommendation provided based on GFC properties and location of equipment. | |
|---|---|
| 1. | Based on the measured flow properties, two modes of flow could result, either fluidized or de-aerated. |
| 2. | Recommends de-aerated method to delivery GFC. Fluidization will promote the entrainment of dust particles. |
| 3. | All methods of GFC addition, other than slurrying the GFCs in another vessel and then pumping the slurry to the MFPV, will generate dust. |

## Table 1.25: Physical Properties and Process Conditions That Could Affect Dusting

| Physical property | Process Condition |
|---|---|
| Particle size distribution | Fluidization of the glass former chemicals |
| Particle density | Pipe drop and angle, causing particles to accelerate |
| Flow properties | Purge air in chute |
| Cohesive strength | Distance between discharge at top of tank to top of liquid level |
| N/A | Purge air rate and location in mixing vessel |
| N/A | Air movement produced by agitation |
| N/A | Attrition of particles due to blending/transport |
| N/A | Mass flow rate of GFC addition to MFPV |

**Table 1.26: J&J Recommended Hopper Design Characteristics for Storage Silos**

| Silo | Hopper MOC | I.D of Silo | Overall silo height* | Silo Working Capacity | Hopper angle from vertical | | Hopper Outlet | | Mass flow Screw Feeder** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $\theta_c$ | $\theta_p$ | Width | Length | Bulk density | Number of screw feeders | | | |
| | | Inches | Inches | $ft^3$ | Degrees | Degrees | Inches | Inches | $lbm/ft^3$ | | | | |
| **Borax** | CS | 96 | 350 | 1,200 | 0 | 20 | 18 | 96 | 52 | 1 | Rate lbm/hr | 14,500 | 16,000 |
| | | | | | | | | | | | RPM | 2.5 | 3 |
| | | | | | | | | | | | R.T. in. lb. | 44,500 | 44,500 |
| | | | | | | | | | | | Motor HP | 5 | 5 |
| **Boric Acid** | CS | 168 | 572 | 5,500 | 0 | 30 | 12 | 72 | 57 | 1 | Rate lbm/hr | 14,500 | 16,000 |
| | | | | | | | | | | | RPM | 7 | 8 |
| | | | | | | | | | | | R.T. in. lb. | 11,400 | 11,400 |
| | | | | | | | | | | | Motor HP | 3 | 3 |
| **Iron Oxide** | CS | 96 | 272 | 800 | 5 | 20 | 9 | 75 | 119 | 1 | Rate lbm/hr | 4,100 | 5,800 |
| | | | | | | | | | | | RPM | 2.5 | 4 |
| | | | | | | | | | | | R.T. in. lb. | 11,000 | 11,000 |
| | | | | | | | | | | | Motor HP | 1.5 | 2 |
| **Kyanite** | CS | 132 | 368 | 2,200 | 0 | 20 | 25 | 132 | 81 | 2 | Rate lbm/hr | 2,400 | 10,000 |
| | | | | | | | | | | | RPM | 0.5 | 1.5 |
| | | | | | | | | | | | R.T. in. lb. | 83,000 | 83,000 |
| | | | | | | | | | | | Motor HP | 2 (total) | 7.5 (total) |
| **Carb.** | CS | 156 | 449 | 3,600 | 10 | 25 | 12 | 102 | 63 | 1 | Rate lbm/hr | 2,700 | 13,000 |
| | | | | | | | | | | | RPM | 4 | 6 |
| | | | | | | | | | | | R.T. in. lb. | 17,300 | 17,300 |
| | | | | | | | | | | | Motor HP | 3 | 5 |
| **Olivine** | CS | 108 | 299 | 1,100 | 4 | 20 | 9 | 90 | 95 | 1 | Rate lbm/hr | 3,700 | 5,600 |
| | | | | | | | | | | | RPM | 3 | 4 |
| | | | | | | | | | | | R.T. in. lb. | 10,300 | 10,300 |
| | | | | | | | | | | | Motor HP | 1.5 | 2 |
| **Silica** | CS/SS | 216 | 647 | 10,200 | 0 | 20 | 56 | 180 | 75 | 3 | Rate lbm/hr | 29,000 | 40,500 |
| | | | | | | | | | | | RPM | 1.5 | 2.5 |
| | | | | | | | | | | | R.T. in. lb. | 697,000 | 697,000 |
| | | | | | | | | | | | Motor HP | 25 (total) | 25 (total) |

MOC – Material of construction, CS – Mild carbon steel with a #1 mill finish, SS –304 stainless steel with a #2B finish, $\theta_c$ – Cone side, $\theta_p$ - Wedge side, R.T. – Running Torque, * - Does not include height of slide gate and trough, ** - Starting torque and power can be 2.5 times values specified.

## Table 1.27: J&J Recommended Hopper Design Characteristics for Storage Silos - Continued

| Silo | Hopper MOC | I.D of Silo | Overall silo height* | Silo Working Capacity | Hopper angle from vertical | | Hopper Outlet | | Mass flow Screw Feeder** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | $\theta_c$ | $\theta_p$ | Width | Length | Bulk density | Number of screw feeders | | | |
| | | Inches | Inches | Ft$^3$ | Degrees | Degrees | Inches | Inches | lbm/ft$^3$ | | | | |
| **Soda Ash** | CS | 108 | 374 | 1,500 | 4 | 20 | 9 | 90 | 66 | 1 | Rate lbm/hr | 1,500 | 12,400 |
| | | | | | | | | | | | RPM | 1.5 | 13 |
| | | | | | | | | | | | R.T. in. lb. | 7,200 | 7,200 |
| | | | | | | | | | | | Motor HP | 1 | 3 |
| **Sugar** | CS | 132 | 394 | 2,300 | 0 | 20 | 14 | 132 | 54 | 1 | Rate lbm/hr | 6,600 | |
| | | | | | | | | | | | RPM | 3 | |
| | | | | | | | | | | | R.T. in. lb. | 28,000 | |
| | | | | | | | | | | | Motor HP | 3 | |
| **Titan. Dioxide** | SS | 120 | 411 | 1,800 | 0 | 20 | 9 | 84 | 117 | 1 | Rate lbm/hr | 1,300 | 1,800 |
| | | | | | | | | | | | RPM | 1 | 1.5 |
| | | | | | | | | | | | R.T. in. lb. | 12,200 | 12,200 |
| | | | | | | | | | | | Motor HP | 1 | 1 |
| **Wollast.** | SS | 156 | 503 | 4,200 | 5 | 20 | 25 | 124 | 60 | 2 | Rate lbm/hr | 4,000 | 12,600 |
| | | | | | | | | | | | RPM | 1 | 3 |
| | | | | | | | | | | | R.T. in. lb. | 61,400 | 61,400 |
| | | | | | | | | | | | Motor HP | 3 (total) | 7.5 (total) |
| **Zinc Oxide** | SS | 120 | 385 | 2,000 | 5 | 20 | 32 | 100 | 43 | 3 | Rate lbm/hr | 2,600 | 2,800 |
| | | | | | | | | | | | RPM | 1 | 1 |
| | | | | | | | | | | | R.T. in. lb. | 43,200 | 43,200 |
| | | | | | | | | | | | Motor HP | 2 (total) | 2 (total) |
| **Zircon** | CS | 96 | 297 | 900 | 5 | 20 | 9 | 75 | 133 | 1 | Rate lbm/hr | 4,000 | 4,400 |
| | | | | | | | | | | | RPM | 2 | 2.5 |
| | | | | | | | | | | | R.T. in. lb. | 12,200 | 12,200 |
| | | | | | | | | | | | Motor HP | 1.5 | 1.5 |

MOC – Material of construction, CS – Mild carbon steel with a #1 mill finish, SS –304 stainless steel with a #2B finish, $\theta_c$ – Cone side, $\theta_p$ - Wedge side, R.T. – Running Torque, * - Does not include height of slide gate and trough, ** - Starting torque and power can be 2.5 times values specified.

## 1.4 QUALITY REQUIREMENTS

This work conducted at SRTC was in accordance with the RPP-WTP QA requirements specified for work conducted by SRTC as identified in DOE IWO MOSRLE60. SRTC has provided matrices to WTP demonstrating compliance of the SRTC QA program with the requirements specified by WTP. Specific information regarding the compliance of the SRTC QA program with RW-0333P, Revision 10, NQA-1 1989, Part 1, Basic and Supplementary Requirements and NQA-2a 1990, Part 2.7 is contained in these matrices. The data produced by J&J were obtained without imposing the RPP required NQA-1-1989 and 1990 programmatic requirements. The lack of contractually not imposing a formal QA Program on J&J was documented on WSRC deficiency document 2003-PIR-11-00052 and on an RPP deficiency document 24590-SCAR-QA-03-007. As a result, the data produced by J&J were reviewed and qualified, and determined that the non-qualified data meets the current documentation and NQA-1-1989 and 1990 requirements [See Appendix G]. Based on this the data has been determined to be qualified and acceptable for use by RPP. The ASTM and other experimental requirements were described in the Statement of Work in Requisition 0F0806..

The instrumentation used to perform the measurements at J&J were checked as described in Table 1.28.

**Table 1.28: J&J Control Program**

| | |
|---|---|
| 1 | Jenike Direct Shear Tester<br>• Utilize span setting device to calibrate load cell.<br>• Calibrate at 0 lb. and 9 lb. setting using pre-calibrated weights.<br>• Calibrations performed weekly |
| 2 | Compressibility Tester<br>• Utilize 0.75 in. gauge block to calibrate dial indicator.<br>• Performed before each test |
| 3 | Laboratory Electronic Scales<br>• Use 200 or 600 gram calibrated weights to calibrate scales.<br>• Performed monthly |
| 4 | Permeability Tester – Proprietor Instrument<br>• Leak check performed semi-annually |
| 5 | Chute Tester<br>• Calibration not required |
| 6 | Angle of Repose<br>• Calibration not required. |
| 7 | Malvern Particle Size Analyzer<br>• Calibration performed by vendor with reference material |

## 1.5 ISSUES

Designing the 13 storage silo hoppers and screw feeders for mass flow conditions helps to eliminate the occurrence of ratholing and bridging for both individual GFCs and GFC blends and to ensure that the attainment rates specified by RPP-WTP for the individual GFCs in the conceptual design [2] can be achieved under controlled conditions. Reduced GFC flow rates would drastically impact the throughput of the Glass Former Handling Facility and overall plant performance.

The 7 days at-rest tests for the individual GFCs were performed to obtain information on property changes that occur as a result of storing dry bulk materials under static conditions. The 1-day "at rest" tests were performed on the 3 LAW blends and 3-day "at rest" tests were performed on the 2 HLW blends. These durations were based on the length of time each of these blends could potentially remain in the final feed hopper while waiting to be delivered to the respective MFPVs. If these materials are expected to be in the silos/hopper for an extended period of time (in excess of 1, 3, or 7 days) without any processing, then the materials would need to be re-characterized by the methods used by J&J for that extended period of time. This characterization data should be provided for or characterized by the vendor who supplies the final design/equipment to RPP-WTP for the GFSF.

The currently proposed method of adding dry GFCs to the LAW and HLW MFPVs will definitely generate dust. The amount of dust generation is dependent on both the physical properties of the GFC blends and the process conditions listed in Table 1.25. Changes to the GFCs physical properties, such as increasing the particle size will impact downstream processes, but may not necessarily resolve the dusting issue since particle attrition can cause additional fines to be produced [23]. Presently R&T has a test [25] that will look at the potential of dusting which is limited to looking at only one HLW GFC composition. The present method of adding GFCs should be further addressed to determine if there are issues related to:

- The effectiveness of removing matted material
- Carryover and its impact on downstream equipment/processes
- Quantity/quality/frequency of flush water,
- Are there wetted/dry areas that could be operational issues?

The LAW and HLW blends selected and characterized in this report may not necessarily be the extreme cases in which the design of the RPP-WTP should be designed within. The unknowns include:

- The tanks at Hanford that have not been characterized to date
- The processing of the waste steams and blending in pre-treatment, yielding a final product to vitrification
- Utilization of GFCs may vary over time.
- Actual process time.

The physical characterization data and preliminary design data reported in this document are based solely on the RPP-WTP R&T baseline GFCs and selected blends. The following issues may result if deviations occur from the baseline GFCs and additional testing will be required to determine the impact to the various RRP-WTP processes:

- Utilization of different GFC particle sizes and/or chemical form must be evaluated on unit operations that are affected by such a change. Time dependent effects should also be considered.
- Increasing the particle size of the GFCs distribution could change the classification of the slurry, from a homogeneous to a non-homogenous slurry, in

which case both agitator speed (to obtain homogeneity) and critical velocity (pipe) increases.

- Physical characterization of the individual GFCs and blended compositions should be performed to determine the impact on the processing of this material using the RPP-WTP dry handling process.

## 2.0 CD-ROM ENCLOSURES

N/A

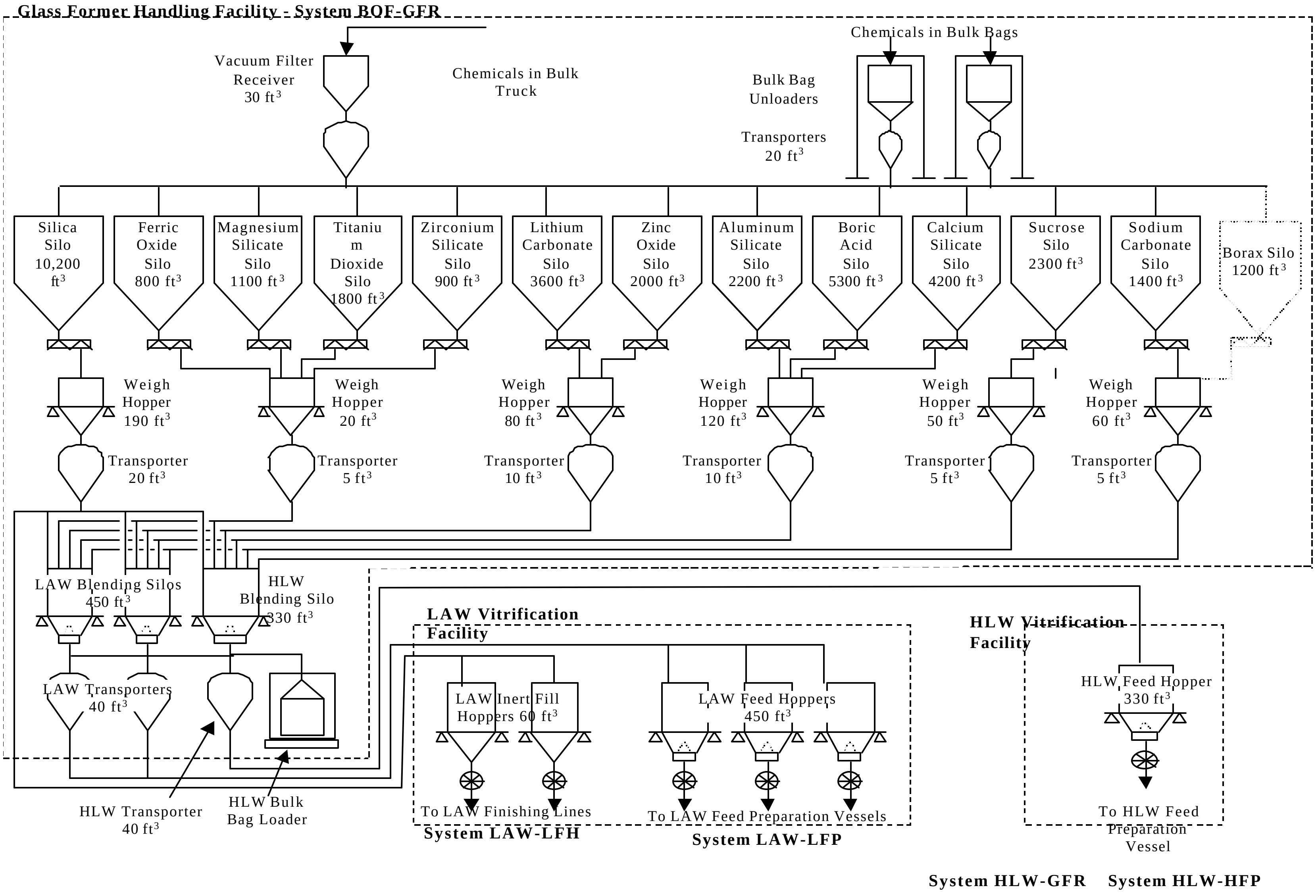
# 3.0 DISCUSSION

### 3.1 Purpose

The purpose of this task was to specify the GFCs for both the HLW and LAW waste streams in order to support vendor tests, pilot-scale mixing tests, and general R&T test programs. This effort required obtaining a consensus by the RPP-WTP R&T team on a single list of GFCs, which can be employed throughout the R&T program. The selection of the GFCs was based on existing information contained in reports provided by VSL [8,9] and SRTC's physical and flow characterization of preliminary RPP-WTP GFCs [10]. These initial GFCs were screened further on the basis of material cost, availability, chemical purity, physical properties, and slurry characteristics (specifically related to the LAW waste streams blended with GFCs).

The initial RPP-WTP conceptual design for the GFSF was to use a series of cylindrical carbon steel silos and hopper sections, sized to meet the storage requirements for each GFC material to be processed based on providing a minimum hands on material inventory for a specified period of time [2]. The GFC storage silos were all fitted with conical hopper sections, where the sloped section was 30° from vertical and constructed of carbon steel. All the GFC storage silo discharge outlet diameters for the hopper sections were one foot. The HLW and LAW blend and final feed silos were of similar design except that the outlets were two feet in diameter, due to the installation of a pneumatic blend head at the opening. The pneumatic blend heads are used to blend the GFCs in the blend silos and to have the capabilities to fluidize the blended GFCs prior to feeding the GFCs through a rotary feeder valve in the final feed silos/hoppers. Load cells are attached to the weighing, blending, and feed silo/hoppers to ensure complete transfer of material by pneumatic means within the specifications as stated in reference [20]. Figure 2.1 is a simplistic schematic of the WTP – Glass Former Storage Facility, which also include the borax silo.

## Figure 2.1: Schematic of WTP - Glass Former Storage Facility



Before discussing J&J's results, it is necessary to discuss general concepts of bulk solids flow through silos and hoppers. Basically, there are three primary flow patterns that can develop in a bulk solids bin:

- "funnel flow"
- "mass flow"
- a combination of these two flow patterns called "expanded flow"

In funnel flow, an active flow channel forms above the outlet and along the central axis of the silo, with stationary, non-flowing material at the periphery. As the level of material in the bin decreases, layers of the non-flowing material may or may not slide into the flowing channel. This can result in the formation of stable "ratholes", leaving stagnant material on the sides. In addition, funnel flow can lead to product caking with time and provides a first-in-last-out flow sequence of materials. Ratholing occurs when a stable empty channel forms within the material in a funnel flow bin, running from the outlet of the hopper to the top surface of material in the silo. Ratholing can occur when cohesive materials are handled in funnel flow bins. However, stable ratholing will not occur with free-flowing materials discharging in funnel flow. Additional problems with funnel flow include:

- uncontrolled flow (flooding) of powders from the feeder typically due to the collapse of a rathole
- segregation of particle mixtures
- reduced useable silo capacity which can be significantly less than the design capacity
- caking and spoilage of bulk solids in the stagnant zones
- the potential for structural silo failures due to the collapse of ratholes resulting in unbalanced forces on the silo

In mass flow, all of the material in the silo is in motion whenever any material is withdrawn from the hopper. Material from the center as well as the periphery moves toward the outlet at about the same velocity. Mass flow hoppers provide a first-in-first-out flow sequence, eliminate stagnant material, reduce sifting segregation, and provide a steady discharge with a consistent bulk density which is well controlled. Ratholing cannot occur in a mass flow bin. Requirements for achieving mass flow include sizing the outlet large enough to prevent arching and ensuring the hopper walls are sufficiently smooth and steep enough to promote flow at the walls. Arching, also known as bridging, causes stoppage of solids flow and thus leads to unstable operations of the bulk handling process [21]. For more details about mass flow hoppers, see references [11-13]. These references also describe some of the details that plant operations must go through in order to correct for improper hopper/silo designs.

The third type of flow pattern, called "expanded flow", can develop when a mass flow hopper is placed beneath a funnel flow hopper. The mass flow hopper is designed to activate a flow channel in the conical funnel flow hopper, which is sized to prevent the formation of a stable rathole. The major advantage of an expanded flow discharge pattern is the savings in headroom. The wall angles of the funnel flow hopper are shallower than the angles necessary for a mass flow hopper, therefore, the height of the funnel flow hopper section is decreased. The mass flow hopper beneath the funnel flow hopper still has the benefits of discharging material with a consistent bulk density while preventing flooding.

Through proper characterization of the physical and flow properties of the bulk solids, and designing bins and hoppers based on these characterizations, most bulk solids flow problems can be prevented or eliminated [4,6,11-13,22]. Generally this is achieved by designing hoppers for "mass flow" conditions.

Additional bulk solids handling problems may occur during feeding from the hopper, pneumatic transfer of the materials, and dust generation. Also, there is a potential for explosions with certain organic materials [14, 23].

Table 2.1 depicts the purpose of this work, the driver documents associated with this work, (Scoping Statement (SS), Test Specification (TS), and Task Technical Plan (TTP)), and where/how this work was accomplished to satisfy the purpose.

**Table 2.1: Purpose, Driver Documents, and How the Completed Testing Met the Purpose**

| | Purpose | Driver Documents | Completed testing met purpose |
|---|---|---|---|
| 1 | Obtain consensus with RPP-WTP, VSL, and SRTC concerning which glass former chemicals are to be utilized during this testing and for future RPP-WTP R&T work. GFCs will be based on documents that have been issued by VSL and WTP concerning utilization of GFCs. | SS, TS, TTP | RPP-WTP, VSL and SRTC discussed this issue at SRTC in January 2002 and agreed upon a baseline of GFCs for utilizing in the WPT-RPP R&T programs. [1] |
| 2 | GFCs to be screened further on the basis of cost, availability, purity, and physical properties | SS, TTP | [1], Appendix A and Appendix B of this document |
| 3 | Selection of GFCs to support HLW and LAW vendor and pilot-scale mixing tests. | SS | [1] and this document |
| 4 | Contact glass former vendors and obtain background information. | TTP | Appendix A and B of this document |
| 5 | RPP-WTP design basis of the glass former staging, blending, and final hoppers | TTP | RPP-WTP issued document February 2002, [2] |
| 6 | Obtain GFCs. Characterize GFCs and representative LAW and HLW blends. | TTP | GFC and representative LAW and HLW blend recipes sent to J&J for characterization. SRTC ordered materials and verified materials received at J&J. |
| 7 | The identification of flow properties and the potential flow problems associated with these selected GFCs and GFC blends | TTP | J&J characterized GFCs and blends, provided design for all incoming silos, and provided general processing issues related to the handling of these GFCs.<br>Appendix D and Appendix F |
| 8 | Final selection of GFCs for RPP-WTP R&T functions. | TTP | This document. |

## 3.2 Conduct Of Testing

To properly determine and interpret the bulk solids flow characteristics of the GFCs, a specialist in bulk solids handling was contracted to measure the properties of the individual GFCs and representative GFC blends to predict any potential bulk solids handling problems given the conceptual RPP-WTP bulk process. The bulk solids specialist selected was Jenike

& Johanson, Inc. (J&J), One Technology Park Drive, Westford, MA 01886-3189. This company is a widely experienced engineering consulting firm that deals specifically with the characterization of bulk solids, trouble shooting bulk solids handling issues at existing plants, providing designs of bulk handling processes, and consulting in the design of bulk handling processes. J&J is not a vendor that makes process equipment or designs buildings and accessories that contain solids handling equipment.

SRTC contracted with J&J to measure bulk solids physical and flow properties and to evaluate the flowability of the bulk solids within the silos, hoppers, and chutes of the WTP Glass Former Handling Facility using ASTM standards, where available. The contract was requested under Requisition No. 0F0806 and issued under Subcontract No. AC30047 (3/25/02). This contract was modified twice under Purchase Requisition Change Notices: (PRCN) 44241P (4/22/02) and PRCN 44583P (5/24/02). The PRCN's expanded the testing to cover additional GFCs and additional blend testing. All tests were carried out at J&J's Westford, MA facility using ASTM or J&J's proprietary test procedures.

### 3.2.1 Selection of GFCs

The same glass forming components (oxides) can be obtained from a large population of chemicals and minerals including various oxides, silicates, borates, and carbonates. In addition, there are numerous potential suppliers, both inside and outside of the United States, which can supply different grades of the materials. Some level of selection was already available based on previous work performed at VSL and SRTC [8-10]. The selection of the final set of glass former chemicals was based on the following criteria:

- Consultation with VSL and RPP-WTP R&T personnel
- Supplier must be a major supply source with adequate reserves.
- Reasonable distance from production facility to Richland, Washington
- Acceptable chemical impurity levels in the GFCs
- Other physical properties
- Impact of slurry rheology

The availability, reserves and background for the various GFCs are described in detail in Appendix A. The chemical compositions of the GFCs including trace elements are presented in Appendix B and in Table 1.5 through Table 1.17. The presence of trace elements in the GFC analyses is not critical due to the presence of a wide variety of chemical constituents in the waste streams. For the LAW GFCs the presence of alkali, particularly sodium, was not desirable due to the high sodium concentration in these waste streams. The presence of significant quantities of RCRA elements was also a consideration in the GFC selection process. In addition, carbonates were avoided in order to reduce the possibility of foaming during the vitrification process.

Table 1.2 lists the selected GFCs per the Technical Task Plan. RPP-WTP R&T, VSL and SRTC personnel approved this list [1]. This document has been distributed to the various RPP-WTP R&T contractors that need to use GFCs to support present and future RPP-WTP R&T work scope.

### 3.2.2 Procurement of GFCs for the J&J Testing

All of the GFCs listed in Table 1.2 were obtained by SRTC and shipped directly to J&J for characterization. Due to the small quantities required for this characterization (100 to 200 lbs.), many of the raw materials in Table 1.2 were procured directly from the distributors listed in Table 2.2, which are the local distributors for the southeast region of the nation.

**Table 2.2: Distributors for Glass Forming Chemicals and Minerals**

| GFC | Distributor | City | Phone |
|---|---|---|---|
| Boric Acid, Technical Grade | Brenntag Southeast | Charlotte, NC | 800-849-7000 |
| Ten Mole Borax, Technical Grade | | | |
| Soda Ash, Dense Technical Grade | | | |
| Wollastonite, NYAD 325 | Ed Simal & Assoc. | East Point, GA | 404-761-7961 |
| SilCoSil-75, Mill Creek, OK | T&S Materials | Gainesville, TX | 940-665-2433 |
| Zinc Oxide, Kadox 920 | Deeks & Co. | High Point, NC | 800-849-255 |
| Zircon Flour (-325M) | Amer.Miner. Inc. | King of Pruss. PA | 856-963-1811 |
| Sugar, Granular | Amalgamate | Chicago, IL | 847-215-1113 |

MSDS and vendor technical data sheets were forwarded to J&J and are presented in Appendix B.

### 3.2.3 Recipes for the HLW and LAW, GFC Blends

VSL was requested to supply “typical” or “representative” blend recipes for the GFCs for both the LAW and HLW feed streams. Four HLW blends were provided, of which two were selected as representing the range of GFCs used in the recipes. The HLW blends include the AZ-102 Tank (HLW98-61) and the C-106/AY104 Tank (HLW98-34). Three different LAW blends were also provided; AN-105 (LAWA44), AZ-101 (LAWB45), and AN-107 (LAWC22) tank waste streams. All the blend formulations as received from VSL are presented in Laboratory Notebooks [16-17] along with other pertinent information on this task. The blend formulations used at J&J are shown in Table 2.3 for the LAW blends and Table 2.4 for the HLW blends. Appendix C contains the calculations, weight factors, and actual weighed quantities for each of the blends tested at J&J.

### Table 2.3: LAW Blend Formulations for J&J Evaluations

| | | Envelope, Identification, and Tank | | | | | |
|---|---|---|---|---|---|---|---|
| | GFCs | LAW A, LAWA44, AN105 | | LAW B, LAWB45, AZ101 | | LAW C, LAWC22, AN107 | |
| | | Grams | Wt. % | Grams | wt. % | Grams | wt. % |
| 1 | Kyanite, -325Mesh, Raw | 37.586 | 4.26% | 93.822 | 8.42% | 98.06 | 10.09% |
| 2 | Boric Acid, Tech. Grade, Gran. | 162.051 | 18.35% | 222.108 | 19.93% | 181.335 | 18.65% |
| 3 | Ten Mole Borax, Tech Grade | N/A | N/A | N/A | N/A | N/A | N/A |
| 4 | Sodium Carbonate, Dense | N/A | N/A | N/A | N/A | N/A | N/A |
| 5 | Wollastonite, NYAD325 | 42.086 | 4.77% | 140.382 | 12.60% | 107.597 | 11.07% |
| 6 | Iron Oxide, 5001 | 67.938 | 7.69% | 47.861 | 4.30% | 51.942 | 5.34% |
| 7 | Lithium Carbonate, Tech.Grade | N/A | N/A | 115.654 | 10.38% | 62.894 | 6.47% |
| 8 | Olivine, #180 Grade | 41.923 | 4.75% | 62.45 | 5.60% | 31.768 | 3.27% |
| 9 | Silica, SilCoSil 75 | 376.643 | 42.65% | 328.613 | 29.49% | 343.156 | 35.30% |
| 10 | Air Floated Rutile Ore, "94" | 21.38 | 2.42% | N/A | N/A | 12.241 | 1.26% |
| 11 | Zinc Oxide, Kadox 920 | 29.718 | 3.37% | 31.604 | 2.84% | 30.71 | 3.16% |
| 12 | Zircon Flour 325 Mesh | 45.759 | 5.18% | 48.223 | 4.33% | 46.218 | 4.75% |
| 13 | Sugar, Granular | 58.038 | 6.57% | 23.618 | 2.12% | 6.151 | 0.63% |
| | Total | 883.122 | 100% | 1114.335 | 100% | 972.072 | 100% |

### Table 2.4: HLW Blend Formulation for J&J Evaluation

| | | Envelope and Tank | | | |
|---|---|---|---|---|---|
| | GFCs | HLW D AZ102 | | HLW D C106/AY104 | |
| | | Grams | wt. % | Grams | wt. % |
| 1 | Kyanite, -325Mesh, Raw | N/A | N/A | N/A | N/A |
| 2 | Boric Acid, Tech. Grade, Gran. | N/A | N/A | 17.157 | 13.71% |
| 3 | Ten Mole Borax, Tech Grade | 16.011 | 12.61% | 12.216 | 9.76% |
| 4 | Sodium Carbonate, Dense | 19.987 | 15.75% | N/A | N/A |
| 5 | Wollastonite, NYAD325 | N/A | N/A | N/A | N/A |
| 6 | Iron Oxide, 5001 | N/A | N/A | N/A | N/A |
| 7 | Lithium Carbonate, Tech.Grade | 18.682 | 14.72% | 20.059 | 16.03% |
| 8 | Olivine, #180 Grade | N/A | N/A | N/A | N/A |
| 9 | Silica, SilCoSil 75 | 72.247 | 56.92% | 71.645 | 57.24% |
| 10 | Air Floated Rutile Ore, "94" | N/A | N/A | N/A | N/A |
| 11 | Zinc Oxide, Kadox 920 | N/A | N/A | 4.088 | 3.27% |
| 12 | Zircon Flour 325 Mesh | N/A | N/A | N/A | N/A |
| 13 | Sugar, Granular | N/A | N/A | N/A | N/A |
| | Total | 126.927 | 100% | 125.165 | 100% |

### 2.2.4 Preparation of Blends at J&J

Before the blends were weighed out, the moisture content of the individual GFCs was determined by first pre-weighing pulled samples, placing the sample in a forced convection oven at 107°C for two hours, and then weighing the dried sample. The percent moisture content was then determined by subtracting the dried sample mass from that of the original sample mass, dividing this difference by the original sample mass and then multiplying by 100%. The calculated moisture contents are presented in Table 2.5 along with the range of bulk densities based on consolidating pressures ranging from loose fill to 2362 $lb_f/ft^2$. Since the boric acid, ten-mole borax, and sugar contained chemically bound water, a Thermal Gravimetric Analysis (TGA) was performed on these materials. The ten-mole borax had a significant loss in weight at temperatures below 100°C. Literature [18] states that ten mole borax releases 5 moles of water at 62°C, 2 moles at 130°C, and additional losses of one mole at 150°, 180° and 318°C. The boric acid also had a small weight loss below 100°C. Contact with U.S. Borax advised that the boric acid should be tested at 60°C and should have only 0.1% or less moisture content. The literature notes that dehydration of boric acid starts at 100°C, but complete dehydration occurs at 1050°C. The TGA results for sugar showed that weight was lost below 100°C.

**Table 2.5: Moisture Content and Range of Density of GFCs and GFC Blends.**

| GFC Material | Moisture Content | Density Range |
|---|---|---|
| | Wt. % | $lb_m/ft^3$ |
| Borax – 10 Mole | 0.0* | 48 – 54 |
| Boric Acid | 0.0* | 55 - 59 |
| Iron Oxide | 0.30 | 89 – 141 |
| Kyanite | 0.14 | 56 - 101 |
| Lithium Carbonate | 0.07 | 53 – 72 |
| Olivine | 0.20 | 89 – 98 |
| Silica | 0.10 | 50 - 89 |
| Soda Ash | 0.20 | 64 – 68 |
| Sugar* | 0.0* | 53 - 56 |
| Titanium Oxide (Rutile) | 0.20 | 91 – 135 |
| Wollastonite | 0.18 | 46 - 77 |
| Zinc Oxide | 0.15 | 31 – 66 |
| Zircon | 0.20 | 96 – 155 |
| LAW A:AN105 | N/A | 56 – 90 |
| LAW B:AZ101 | N/A | 50 – 74 |
| LAW C:AN107 | N/A | 47 – 72 |
| HLW D:AZ102 | N/A | 52 – 84 |
| HLW D:C106/AY104 | N/A | 47 – 77 |

* See Text

The blends were prepared by adding the pre-weighed quantities of individual GFCs (Appendix C) from plastic bags into a Hobart blender. The easiest flowing materials (materials having small density range) were added first, followed by the finer powders or more cohesive materials (materials with a large density range). The Hobart paddle blender was operated at its lowest speed (to minimize dusting) with a vacuum hose placed near the bowl to collect any generated dust. Dusting was observed during the mixing process, particularly when the Hobart was set to its next highest speed to observe whether or not dusting was more prevalent. The blender was turned off several times to stir the materials by hand using a spatula to ensure complete mixing. After mixing was complete, the blend was stored in sealed double plastic bags to protect the blend from adsorbing moisture.

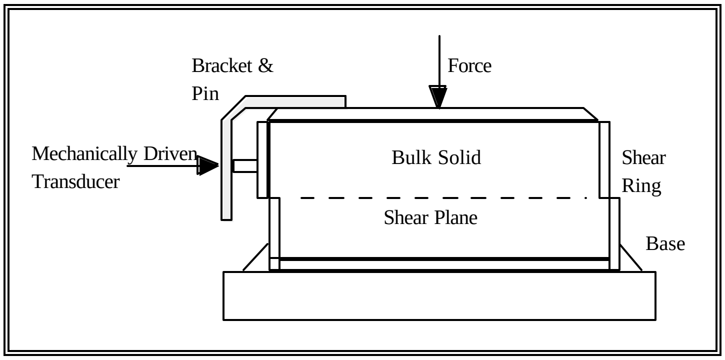
### 3.2.5 J&J Testing

J&J was tasked to:

- analyze the individual GFCs and 5 GFC blends as described in Table 1.1
- make up the blended GFCs
- dispose of the materials tested
- issue a report of the physical/flow properties of the individual GFCs and blend
- write another report that interprets the physical/flow property results in providing engineering recommendations for handling the bulk solids in the receiving hopper/silos and final feed hopper/MFPV transfer chutes as compared to the RPP-WTP conceptual GFSF design

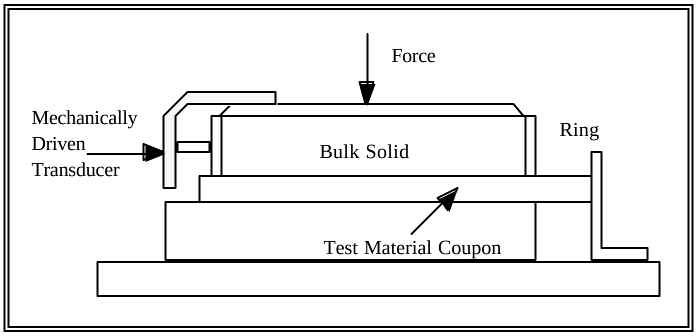
The Jenike Shear Cell presented in Figure 2.2 was utilized to measure the instantaneous cohesive shear strength and the cohesive shear strength after storage. The cell consisted of two steel shear rings, which were slightly offset. The bulk solids were then uniformly distributed into the cell and the excess solids were removed to be flush with the top shear ring. The lid (bracket & pin) was then placed on top of the sample, making sure no contact was made with the shear ring and a vertical force (resulting in consolidating pressure) was applied to the lid, compressing the bulk solids. The mechanically driven transducer then drove the bracket at a constant speed and the resulting force was measured (via a force transducer) and recorded. The measurement stopped once a steady shearing force was obtained. This measurement was repeated with different vertical loads (directly related to consolidated pressure), resulting in a shear stress versus consolidating pressure curve. Details about this measurement and parameters that can be calculated from these measurements are described in ASTM Standard D6128 [45]. The force transducer was calibrated with a separate calibration device shown in the ASTM Standard D6128. The calculated information from these measurements was then used to determine the arching and bridging dimensions. The methods used to calculate the arching and bridging dimension are not described in the ASTM Standard D6128.

**Figure 2.2: Jenike Shear Cell in Initial Offset Position.**



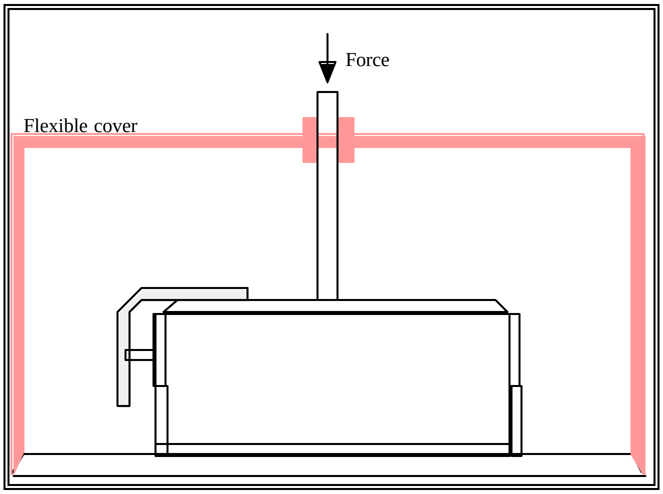
The wall friction test device is shown in Figure 2.3. The test material coupon is that of the hopper material. A steel ring was placed onto the test coupon and filled with the bulk solid as described in the above paragraph. The ring was then raised slightly off the test coupon and the lid (bracket & pin) was placed on top of the sample, making sure that it did not make contact with the ring. A large vertical force (consolidating pressure) was applied/maintained to the top of the ring. The mechanically driven transducer then drives the bracket at a constant speed (horizontally) and the resulting force is measured and recorded. The measurement stops once a steady shearing force is obtained. This measurement was repeated by removing the vertical force in a stepwise fashion and recording the steady shearing force. Details about this measurement are described in ASTM Standard D6128-97 [4]. The force transducer was calibrated with a separate calibration device as shown in the ASTM Standard D6128. The calculated information from these measurements was then used to determine the angle necessary to achieve mass flow in a hopper. The method used to calculate the mass flow hopper angle is not described in the ASTM Standard D6128.

**Figure 2.3: Schematic of Wall Friction Test**



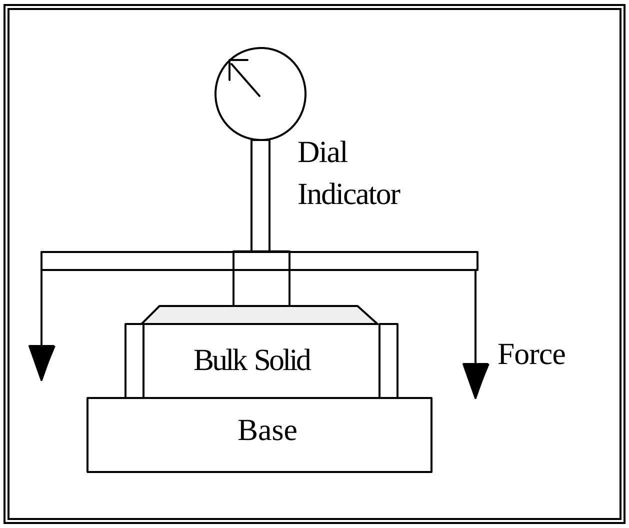
For the “at rest” conditions, the bulk solid samples were placed into the appropriate apparatus (either the shear or wall friction test configurations) and the apparatus was then placed onto a consolidating bench station. A flexible cover was placed over the apparatus as shown in Figure 2.4. This flexible cover was designed to prevent interference caused by environmental effects such as evaporation or humidification that would impact the “at rest” results. Predetermined loads (forces) were then placed onto the sample for the given “at rest” times. After reaching the “at rest” times, the loads were removed and the apparatus was carefully removed from the consolidating bench station. The shear strength or wall friction tests were then performed as described above.

**Figure 2.4: Consolidating Bench Station for At Rest Conditions**



The compressibility test was performed to determine the change in bulk density as a function of consolidating pressure. Figure 2.5 shows the apparatus used for this determination. The area and height of the cell are known. The bulk solid was loosely loaded into the cell and the excess solid removed. A load was then applied to the bulk solid and after a steady state reading from the dial indicator (used to measure the height of the cell lid) was obtained, the load and dial displacement were recorded. This sequence was repeated for different loads, where both the load and height of the lid were recorded. Upon completion of testing, the bulk solid in the cell was weighed. The loosely packaged density was calculated from the original volume of the sample, prior to any consolidation pressure. Based on knowing the height of the cell lid, the volume was calculated for a given load, hence its density. This method of measuring the bulk solids density is described in ASTM Standard 6683 [5]

**Figure 2.5: Bulk Density Measured as a Function of Consolidating Pressure.**



The particle size analysis provided by J&J was provided as volume percent, as described in Table 1.1. This data was manipulated to provide the number percent data and distribution, using the following equations as shown in Table 2.6 and using Microsoft Excel.

The results and graphs are in Appendix E. The volume and number percents for less than 10%, 50%, and 90% were calculated by linearly interpolating between the mean bin diameters that provided these values. These results are in Appendix E and in Table 1.5 through Table 1.17 for the different conveying pressures as described in Table 1.1.

**Table 2.6: Method for Calculating the Number of Particles for a Given Bin Size**

| | | |
|---|---|---|
| A: | Calculate mean bin diameter: | $\bar{d}_i = \frac{d_i + d_{i+1}}{2}$ |
| B: | Calculate number of particles in bin: | $n_i = \left( \frac{6 \cdot V_i}{p \cdot \bar{d}_i^3} \right)$ |
| C: | Calculate number percent for each bin: | $N_i = 100\% \cdot \frac{n_i}{\sum_{j=1}^{I} n_j}$ |
| Where: | | $D_i$ = lower bin diameter for bin I<br>$D_{i+1}$ = upper bin diameter for bin i<br>$V_i$ = volume % for material between bin diameter $d_i$ and $d_{i+1}$.<br>$N_i$ = number % for material between bin diameter $d_i$ and $d_{i+1}$.<br>I = total number of bins |

## 3.3 Results

### 3.3.1 J&J Silo/Hopper Designs

The GFCs for the RPP-WTP program were selected and are presented in Table 1.2. A report covering the bulk solids flow properties for all thirteen individual GFCs and the five LAW and HLW blends was received from Jenike and Johanson on June 26, 2002. This report is presented in Appendix D. A summary of the J&J data is presented in Table 1.5 through Table 1.22. The following summarizes these results.

The results of the cohesive strength tests for the GFCs indicated that the diameter of the hopper openings required to prevent ratholing would be unrealistically large, (i.e. generally greater than two feet.) This was based on the RPP-WTP conceptual conical hopper design, which had sloped walls (30° from vertical) and one-foot diameter outlets. Functionally, these conceptual hoppers will induce “funnel flow” behavior. Funnel flow is unacceptable for the WTP since it is a batch process. To induce mass flow, the outlet diameters for both the HLW and LAW blend hoppers would need to be greater than eight feet, given a conical hopper design. It was concluded that the conical hoppers should not be employed and that some type of “mass flow” design be employed since all the feed in these hoppers must be removed. In general the results indicated that the materials were found to be:

- Highly cohesive, and thus prone to flow obstructions such as bridging and ratholing
- Highly frictional, and thus prone to discharge in a funnel flow pattern
- Highly compressible, and thus prone to have erratic variations in bulk density
- Highly impermeable, and thus prone to discharge rate limitations; if aerated, material may remain fluidized for extended times and could result in flushing from the screw feeders.

J&J, using the data supplied [Appendix D], prepared an additional report presenting design recommendations for hopper/silos and feeders for the thirteen storage hopper/silos. The conceptual preliminary storage silo specifications from RPP-WTP [2] were utilized in developing the functional designs of the GFC storage silos. The summary of results from J&J is presented in Table 1.23 and Table 1.24. See Appendix F for the J&J design recommendations.

The majority of the GFC silos can be fabricated from mild carbon steel; however, for the GFCs that possess extreme frictional properties, hoppers lined with 304 stainless steel sheet (#2B finish) will be required. Along with each GFC silo design provided in Appendix F, there is functional design for each screw feeder. Improperly designed screw feeders can cause a mass flow hopper to revert to a funnel flow hopper. Note that some of the screw feeders use multiple screws, which is due to material impermeability and difficulty in achieving the desired feed rate [2]. A multiple screw system must operate simultaneously in the direction shown in the designs provided in Appendix F. Note that if these designs are used, it is highly recommended that J&J formally review the design drawings prior to construction.

To minimize fabrication and maintenance cost, some of the GFC hoppers and feeders could potentially share a common design basis. J&J can perform this evaluation, if required. Several of the fine impermeable materials, such as silica, kyanite, and iron oxide may have the ability to be handled in the "fluidized mode". In order to determine feasibility of additional fluidization, further tests at J&J would be required.

### 2.3.2 Blend Transfer Chute Analysis

Based on available information at the time, a circular six-inch diameter pipe (chute) was selected for transferring the LAW and HLW GFC blends to their respective LAW and HLW MFPVs. Based on the flow properties of the five GFC blends tested at J&J and the proposed chute geometry, two modes of flow could result; either fluidized or deaerated. Due to the state of the design on the chute [18], no effort was made by J&J to determine how the GFCs would flow in the chute. In any case, without full-scale modeling of the proposed chute configuration, it is difficult to predict the exact behavior.

- <u>Fluidized:</u> The GFC blends will be aerated and behave much like a fluid. If this occurs, the GFC blends should not plug the transfer chutes. However, <u>severe dusting in the MFPV is likely</u>. Once the fast moving stream (approximately 30 ft/sec) of fluidized material strikes the liquid/slurry interface in the vessel, large amounts of air will be released from the stream and will carry away the fine particles as dust. The dust will then migrate towards the circumference of the vessel and also towards the demister filter where a vacuum is being drawn. It is expected that this filter could become heavily clogged with the dust, which could affect its process efficiency, which is to remove moisture.

- <u>Deaerated:</u> the GFC blend will act as a cohesive bulk solid and has the potential to pack and plug the chute. As long as the GFC blend stream does not hang up on the 60-degree pipe bend, then plugging should not result. However, if buildup occurs over time, then material will collect in this pipe if it is not sufficiently steep or low enough in friction to clean itself off, causing plugging to occur.

Several recommendations were presented in the J&J report [Appendix F], which are helpful for eliminating potential bulk solids problems. Examples of these recommendations include:

- Install a "kick-plate" at the inlet to the MFPV to direct the aerated stream into a paddle-induced vortex within the liquid. This would not help dusting.
- Incorporate a large dust collector in the mix vessel to handle the high dust loading, with the capability of cleaning its filters of dust cake and dropping the cake back into the mix vessel.
- Design a spiral or "ski-jump" type chute whereby the material is not allowed to aerate, thus not creating as much dust. The material stream will always be kept in contact with the chute. The main issue with this method is that if the chute becomes plugged, it may be very hard to unplug.
- Pre-slurry the GFCs and feed the slurry to the MFPV. This will eliminate the dusting and plugging issue in the MFPV.

J&J has made numerous additional recommendations pertaining to the silo/hopper construction and design. These recommendations are located in Appendix F.

### 3.3.3 Additional Considerations

Mechanical flow aids, such as mechanical vibrators, air cannons, etc. can be helpful at times to get some materials flowing; however, they are usually ineffective with extremely cohesive, non free flowing materials such as the GFCs and GFC blends. Incorrect application of these devices may result in compounding the problems. Inorganic chemical flow aids can also be substituted for some of the GFCs to improve flowability of the HLW and LAW blends. When these materials are added at levels less than one weight percent they can increase flowability by increasing particle separation and reducing moisture absorption. The GFC recipe can be compensated for the additional chemical constituents by slightly reducing the amount of the respective GFCs.

Some of the GFCs have a tendency to clump if exposed to high humidity. See Table 1.5 and Table 1.18 through Table 1.20 for photographs of clumps. Notable examples are the ten-mole borax, boric acid, and sugar. Other GFCs, which may clump under humid environments, are sodium and lithium carbonate. It is recommended that all the powders be maintained in dry – low relative humidity environment. See appropriate MSDS in Appendix B for additional information.

The pneumatic transfer of GFCs is a science and extreme attention must be paid to pipe dimensions, changes in directions of flow, material velocities, and pipe erosion. Pipe couplings must not provide interference with the direction of powder flow.

The potential for dust explosions from the handling of materials, such as sugar, must also be considered in the engineering design [13]. The pneumatic transfer of granular sugar will inevitably produce some level of fine powder. The explosiveness of these powders must be considered when handling this bulk solid. Once the sugar is blended with other GFCs the potential for an explosion is greatly reduced but the hazard is still unknown.

Results from the particle size distribution show that there is a very broad distribution of particle size for each GFC. Additionally, both the volume and number percents show that as the conveying pressure increases, the size of the particles decrease, indicating that higher conveying pressures may result in breaking up agglomerates, removing fine particles loosely bonded to coarse particles, or attrition of weak particles. For the conveying pressures used, only the iron oxide, kyanite, silica, and zircon flour showed a small change. The others showed a large impact of conveying pressure on particle size distribution. Other means of particle attrition can also contribute to the process [23, 24].

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# APPENDIX A. GLASS FORMER CHEMICAL SURVEYS

The following sections provide background information on the selected GFC sources, their major uses, availability, and average market price. The major reference source was the U.S. Geological Survey - Minerals 2000 Yearbook and various associated literature. Some commercial vendor literature was also employed. Special attention was paid to domestic sources, but world resources were presented when they were necessary.

## Aluminum Source

### $Al_2O_3$

### Kyanite (57% $Al_2O_3$) [A-1]

Kyanite, andalusite, and sillimanite are natural anhydrous aluminosilicate minerals with the same chemical formula ($Al_2SiO_5$) but different crystal structures and physical properties. These minerals also contain minor amounts of iron oxide, titania, and alkalis. Mullite ($3Al_2O_3$-$2SiO_2$) is a refractory material obtained when aluminosilicate minerals are heated to temperatures between 1500 to 2000°C. Refractories are the largest end use of kyanite, andalusite, mullite, and synthetic mullite in the U.S. and worldwide. Mullite in refractories increases the fired strength, resistance to deformation under load, and thermal resistively.

The U.S. has the largest production of kyanite at about 90,000 ton per year valued at $13.4 million (before any material was converted to mullite). **Kyanite Mining Corp.** the world's largest supplier of kyanite, operated two open pit mines in Buckingham County, VA, and beneficiated the ore into marketable kyanite. Some of the kyanite was calcined for conversion into mullite. Their reserves are reported to be sufficient to last well into the 21st century. **C-E Minerals Inc.** produces a synthetic mullite mineral from calcined bauxite kaolin. Estimated U.S. production was about 40,000 t/year. **Piedmont Minerals Co., Inc.** mined a deposit containing andalusite combined with pyrophelite and sericite. The company sells products containing blends of the three minerals to refractories and ceramics producers. While the U.S. is a major exporter of kyanite products approximately 6,200 ton of andalusite was imported from South Africa. India has supplied most of the world's sillimanite. Raw kyanite ground to 35 to 325 mesh has a price between $149 to $182/Mt ($0.068 to $0.083/lb)

Kyanite contains varying amounts of crystalline silica, a declared carcinogen, which may present a health hazard if inhaled over long periods of time.

### Alumina (99+% $Al_2O_3$) [A-2]

Alumina ($Al_2O_3$) is derived by a wet chemical leaching process from natural bauxite (alumina hydroxides) and sold as specialty alumina products, which are converted into aluminum metal. Total reported world reserves of bauxite are sufficient to meet cumulative world, primary aluminum metal demand well into the 21st century.

In the year 2000, Reynolds Metals Co. announced that they would merge into **Alcoa Inc.** Alcoa is the leading supplier of quality alumina-based chemical products. The other major suppliers are **Alcan Aluminum Ltd.** and **Kaiser Aluminum & Chemical Corp.** An estimated 90% of the alumina shipped by U.S. alumina plants went to domestic, primary aluminum smelters for metal production. Consumption by the abrasives, chemicals, refractories, and specialties industries accounted for the remainder of alumina use. Alumina prices range from $500 to $1000/ton depending on particle size and purity of the product ($0.25 to 0.50/lb).

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[A-1] Potter, M.J., "Kyanite and Related Materials," USGS, Minerals Yearbook, 2000.
[A-2] Plunkert, P.A., "Bauxite and Alumina," USGS, Minerals Yearbook, 2000.

## Boron Source

### $B_2O_3$ [A-3]

Boron produced domestically during 2000 totaled 546,000 Mt of boron oxide. The glass industry remains the largest domestic market for boron production and in 2000, accounted for 76% of boron consumption. A small percentage is used in detergents and other products. Boron compounds and minerals sold were produced by surface and underground mining, in-situ and from brine. **American Borate Company** mined small amounts of colemanite and ulexite-probertite from the Billie Mine in Death Valley, CA. Reported employment was 110 employees. **Fort Cady Minerals Corp.** used an in situ process near Hector CA to produce a product containing 48% boron oxide. Because it was chemically precipitated, this product has advantages in the consistency of its chemical composition. This product contained 48% boron oxide, 25% calcium oxide, 0.8% sulfur, etc. In 2000, **IMC Global Inc.** operated the Trona and the Westend plants at Searles Lake in San Bernardino County, CA. IMC produced refined sodium borate ($Na_2B_4O_7$) and boric acid ($H_3BO_3$) as a co-product of soda ash and sodium sulfate from the mineral rich lake brines. **U.S. Borax Inc**., which was a member of the Rio Tinto Borax Group, mined borate ores at Boron, CA; operated by open pit methods. At Boron, reserves containing the minerals kernite and tincal were reportedly in excess of 100 million metric tons. Production was reported to be 570,000 ton during 2000. The ore was processed into sodium borate or boric acid products in the refinery complex adjacent to the mine. An onsite plant also produced anhydrous sodium borate and boric oxide. A new $10 million plant at Boron was projected to be able to process more than 1,400 Mt per day for the sodium borate process. U.S. Borax employs approximately 1,100 people in its California operations. Boric Acid ($H_3BO_3$, 56.5% $B_2O_3$)) technical grade in bulk sells at just below $800/Mt ($0.36/lb). Borax decahydrate [$Na_2B_4O_7$-$10H_2O$ (37.5% $B_2O_3$)], technical grade, in bulk sells at about $375/Mt ($0.17/lb). Borax pentahydrate [$Na_2B_4O_7$-$5H_2O$ (47.8% B2O3)] has a similar sales price to the decahydrate in bulk and may offer an economic advantage.

## Sodium Source

### $Na_2O$

**Soda Ash (58.5% $Na_2O$)** [A-4]

Annual production of soda ash ($Na_2CO_3$) in the U.S. averages about 10 million metric tons which is the largest capacity in the world. About 50% of this capacity is used by the glass industry while chemicals and detergents required the remainder. The U.S. production of soda ash is obtained from Trona and sodium carbonate-rich brines. After mining, soda ash is dissolved and recrystallized to provide a pure and consistent material. There are two physical forms of soda ash: dense and light. All glass producers use the dense form. The world's largest deposit of Trona is in the Green River Basin of Wyoming. About 47 billion metric tons of identified soda ash resources could be recovered. In addition, Searles Lake and Owens Lake in California contain an estimated 815 million tons of soda ash reserves. Four companies in Wyoming, one in California and one in Colorado composed the U.S. soda ash industry. The four companies in Wyoming are **FMC Wyoming Corp**., **General Chemical Partners**, **OCI Chemical Corp**, and **Solvay Minerals Inc**. **IMC Chemical** is located in Trona, CA and **American Soda LLP** is located in Parachute, CO. **Solvay Minerals** is a member of the Solvay

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[A-3] Lyday, P.A., "Boron," USGS, Minerals Yearbook, 2000.

[A-4] Kostick, D.S., "Soda Ash," USGS, Minerals Yearbook, 2000.

Group, an $8 billion, 138-year-old group of chemical and pharmaceutical companies based in Brussels, Belgium. Solvay began producing soda ash in 1982 with an original plant capacity of one million tons per year. Solvay and Asahi Glass of Japan, one of the world's largest flat glass producers, entered into a joint venture in the early 90's. Today Solvay Minerals expects capacity to reach 2.3 million tons per year, with an eventual capacity approaching 3.5 million tons.

The average annual value for bulk, dense natural soda ash (f.o.b.) Green River WY and Searles Valley CA, was $73 per metric ton ($0.033/lb). The list price for Wyoming bulk, dense soda ash has not changed since it was raised July 1, 1995. The price has been relatively steady because of an increased use of plastic in bottles and the recycle of glass containers, which reduced glass industry requirements.

## Calcium Source

## CaO

### Wollastonite [A-5] (48.3%CaO)

Wollastonite, a calcium metasilicate ($CaSiO_3$), may contain traces of aluminum, iron, magnesium, manganese, potassium and sodium. U.S. deposits have been found in Arizona, California, Idaho, Nevada, New Mexico, New York, and Utah. Wollastonite is used primarily in ceramics, automotive friction products, metallurgy, paint, and plastics. Some of the properties that make it so useful are its high brightness and whiteness, low moisture, and oil absorption, low volatile content and the acicular nature of some wollastonites.

Wollastonite has been mined commercially in California and New York. The California deposits, which were in Inyo, Kern, and Riverside Counties, were mined between 1930 and 1970. Wollastonite deposits in New York have been mined for more than 50 years. U.S. production was estimated to be on the order of 130,000 metric tons per year. Two companies currently are mining wollastonite: **NYCO Minerals Inc.** operates a mine in Essex County, and **R.T. Vanderbilt Co. Inc.** operates a mine in Lewis County, NY. NYCO also chemically modifies the surfaces of some of its wollastonite products to improve their performance. The R.T. Vanderbilt deposit is processed at its Balmat plant where it is milled and air classified. Domestic wollastonite production decreased from that of 1999. Much of the decrease occurred because NYCO Minerals began supplying powder-grade wollastonite to some of its North American customers from its operation in Sonora, Mexico. Other imports can be obtained from India, Finland, and China. One company, **Intercorp, Inc.** will be stocking product from India, in either Portland, OR or Seattle, WA.

Prices per metric ton for domestically produced acicular wollastonite, ex-works, were $209 for 200 mesh, $258 for 325 mesh, and $284 for 400 mesh ($0.10 to 0.13/lb).

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[A-5] Virta, R.L., "Wollastonite," USGS, Minerals Yearbook, 2000.

## Iron Source

### $Fe_2O_3$ [A-6]

Natural iron oxides are derived from hematite, which is a red iron oxide mineral ($Fe_2O_3$); limonites ($HFeO_2$), which vary from yellow to brown, and magnetite($FeO$-$Fe_2O_3$) which is a black iron oxide. Synthetic iron oxide compounds are produced from basic chemicals. U.S output of natural, mined iron oxide pigments (IOPs) in 2000 was 87,000 metric tons. Finished synthetic IOPs accounted for 84,000 metric ton and total U.S. imports of IOPs were 91,00 metric ton. U.S. consumption was about 254,000 metric tons. The largest end-use continued to be construction with 32% and coatings with 22%. Prices for the red iron oxide, f.o.b. warehouse, ranged from $0.65 to 1.10/ kg. Table A.1 lists most of the known suppliers in the U.S.

### Table A.1: Producers of Iron Oxide Pigments

| Producer | Plant Location |
|---|---|
| **Finished Pigments** | |
| Alabama Pigments Co. | Green Pond, AL |
| Arizona Oxides LLC | El Mirage, AZ |
| Bayer Corp | New Martinsville, WV |
| Dynamic Color Solutions, Inc | Milwaukee, WI |
| Elementis Pigments Inc. | Emeryville, CA; E. St Louis IL; Easton, PA |
| Hoover Color Corp. | Hiwassee, VA |
| New Riverside Ochre Co. Inc. | Cartersville, GA |
| Pea Ridge Iron Ore Co. | Sullivan, MO |
| Prince Manufacturing Co., Inc. | Quincy, IL and Bowmanstown, PA |
| Rockwood Pigments Inc. | Beltsville, MD and St. Louis, MO |
| Solomon Grind-Chem Services, Inc | Springfield, IL |
| **Crude Pigments** | |
| Alabama Pigments Co | Green Pond, AL |
| Arizona Oxides LLC | El Mirage, AZ |
| Hoover Color Corp | Hiwassee, VA |
| New Riverside Ochre Co. Inc | Cartersville, GA |
| Pea Ridge Iron Ore Co. | Sullivan, MO |
| **Regenerator and Steel plant waste iron oxides** | |
| Bailey-PVS Oxides, LLC | Fairfield, AL |
| International Steel Services, Inc. | Allenport,PA |
| Wirton Steel Corp. | Weirton, WV |

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[A-6] Potter, M.J., “Iron Oxide Pigments,” USGS, Minerals Yearbook, 2000.

## Lithium Source

## $Li_2O$[A-7]

**Lithium Carbonate, (40%$Li_2O$)**
**Lithium Hydroxide, (35 to 62%$Li_2O$)**

The latest commerce data indicates that Chile was again the world's leading producer of lithium carbonate with production at its two lithium operations in the Andes Mountains. U.S. imports of lithium carbonate from Chile were about 13,500 metric tons in 2000. There was one lithium carbonate plant in Argentina, which operated at a level far below its capacity. One lithium carbonate plant continued to operate in Nevada. Chinese and Russian lithium carbonate production continued while Australia, Canada, and Zimbabwe were important sources of lithium ore concentrates. The United States was the leading producer of lithium materials for most of the 20th century, with spodumene mines in North Carolina. Chile overtook the U.S. as the world's leading producer in 1998, the year the final spodumene operation closed. The major uses of lithium are in the aluminum, ceramics and glass, lubricating grease, and synthetic rubber industries. The largest use of lithium in the U.S. was in additions to ceramics and glass manufacturing processes. These additions which can be made with either lithium carbonate or ore concentrates lower glass melting points and alter physical properties. Until 1997, lithium ore concentrates were the only lithium products that were acceptable for most ceramics and glass applications because of their low cost in comparison to lithium carbonate. When the lithium carbonate price was cut to about one-half of its previous level, the specialty glass producers were able to change their glass formulations. There are four major producers of lithium aluminosilicate minerals: **Gwalia Consolidated** in Western Australia, the largest producer of spodumene; **Tantalum Mining Corp.** in Manitoba, Canada, spodumene; **Bikita Minerals** in Zimbabwe is the largest producer of petalite; and **Sociedad Mineria De Pegmatites,** Portugal, producers of lepidolite.

**Chemetall Foote Corp.**, a subsidiary of the German company Chemettall GmbH, produced lithium carbonate from brines near Silver Peak, NV. The company's other lithium operations included a lithium hydroxide plant in New Johnsonville, TN and facilities producing downstream lithium compounds at the site of an idle spodumene deposit in Kings Mountain, NC. Domestic production of lithium carbonate is now limited to Chemetall Foote's brine operation in Nevada.
**FMC Corp.**, Lithium Division, produced a full range of downstream compounds, at its facilities in Messemer City, NC and Bayport, TX. FMC also operated a lithium carbonate plant and spodumene mine in NC until 1998. Since 1999, FMC has met its lithium carbonate requirements through a long-term agreement with Chilean producer **Sociedad Quimicay Minera de Chile, (SQM)** which supplies lithium carbonate produced at its brine operation. SQM owns the largest economic reserves of lithium in the world with a lithium carbonate capacity of 22,000 metric tons per year.

With the import of more South American lithium carbonate the price has brought about nation-wide price reductions by SQM, Chemetall Foote, and FMC. The present prices are variable, but are around $1.00/lb.

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[A-7] Ober, J.S., "Lithium," USGS, Minerals Yearbook, 2000.

## Magnesium Source

### MgO[A-8]

#### Olivine, (48% MgO)

Of the total U.S. magnesium compounds production, about 60% came from seawater and well or lake brines. The remainder was recovered from magnesite, dolomite, olivine, and brucite ores. About 69% of the total consumption of magnesium compounds was for refractory applications. The remaining 31% is used in agricultural, chemical, environmental and other applications.

Olivine is a magnesium containing mineral composed of forsterite ($Mg_2SiO_4$) and fayalite ($FeSiO_4$). This mineral finds use in foundry sands and refractories. Foundry uses remained the largest application for olivine in the U.S., accounting for 87% of consumption of domestically produced material. Refractory applications accounted for 7% of U.S. consumption. Two companies in the U.S. produced olivine sands: **Unimin Corp** and **Olivine Corp.** Unimin operated two mines, one in North Carolina and one in Washington, and processing plants in Indiana, North Carolina, and Washington. Olivine Corp operated one mine and one processing plant in Washington. Norway is the world's principal producer and supplier of olivine. Other producers include Australia, Italy, Japan, Mexico, Pakistan, Spain and the U.S.

Olivine may contain a small amount of nickel, chrome, and crystalline silica. Appropriate respiratory protection for respirable particulate should be used when handling materials.

The cost of foundry grade olivine, f.o.b. from plant was between $60 to 110 per metric ton ($0.02 to 0.05/lb).

## Silica Source

### $SiO_2$[A-9]

#### Silica Sand

Industrial sand often called "silica," "silica sand," and "quartz sand," includes sands with high silicon dioxide ($SiO_2$) content. These sands are used in glassmaking, foundry, abrasive, and oil drilling-hydraulic fracturing applications. The regulation of respirable silica continued to concern miners and consumers of the many minerals that contain crystalline silica. Scientists have known for decades that prolonged and excessive exposure to crystalline silica dust can cause silicosis, a non-cancerous lung disease. During the 1980's studies suggested that crystalline silica was also a carcinogen. In 1987, the International Agency for Research on Cancer labeled crystalline silica as a "2A substance," a probable human carcinogen. This was upgraded to a 1A substance, a known human carcinogen, following a review of the health literature in 1996. Crystalline silica was regulated under OSHA as a carcinogen.[A-9] Kyanite, silica, olivine, rutile, and zircon are all GFC minerals that contain some level of free crystalline silica.

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[A-8] Kramer, D.A., "Magnesium Compounds," USGS, Minerals Yearbook, 2000.

[A-9] Dolley, T.P. and Wallace, P.B., "Silica," USGS, Minerals Yearbook, 2000

About 82% of the total industrial sand and gravel was produced by 51 operations, each with production of more than 200,000 tons per year. The five leading producers of industrial sand, in descending order, were Unimin Corp., U.S. Silica Co., Fairmount Minerals Ltd., Oglebay Norton Industrial Sands Co., and Badger Mining Corp. The share of silica sold for all types of glass making as a percentage of all silica sold was a little more than 38%. The plant location, grade, and method of shipment for Unimin Corp and U. S. Silicate are listed in Table A.2.

The f.o.b. plant price of U.S. industrial sand increased by 4.7% to $19.57 per metric ton in 2000.

### Table A.2: Plant Locations for Unimin Corp and U.S. Silica

| Location | Wt. % $SiO_2$ in Feed | Method $SiO_2$ Shipped |
|---|---|---|
| **Unimin:**<br>Grade: Glassil | | |
| Byron, California | 91.5% $SiO_2$ | Bulk Only |
| Emmett, Idaho | 87.4% $SiO_2$ | Bulk Only |
| Lugoff, S. Carolina | 99.6% $SiO_2$ | Bulk Only |
| Additional Plants: AL, AK, CA(2), GA, IL(3), MN(2), MO, NJ, NC, OK, TN, TX(2), VA, WI | | |
| **U.S. Silica:**<br>Grade: Sil-Co-Sil™ | | |
| Mill Creek, Oklahoma | 99.7% $SiO_2$ | Call Vendor |
| Pacific, Missouri | 99.7% $SiO_2$ | Call Vendor |
| Ottawa, Illinois | 99.8% $SiO_2$ | Call Vendor |
| Columbia, S. Carolina | 99.5% $SiO_2$ | Call Vendor |
| Berkely Springs, W.Virginia | 99.6% $SiO_2$ | Call Vendor |
| Additional Plants: AL, LA, MI, NJ, OH, PA, TN, TX | | |

## Titanium Source

## TiO2[A-10]

### Rutile

Approximately 95% of titanium is consumed as $TiO_2$ pigment for paints, paper, and plastic. The remainder is employed in ceramics, glass, steel, titanium metal, and welding rod coatings. Titanium is found in nature in the mineral form as oxides, titanates, and silicotitanates. It is the ninth most abundant element in the Earth's crust and is present in most rocks and soils. The titanium-bearing minerals that have significant economic importance include ilmenite($FeTiO_3$), leucoxene ($TiO_2.H_2O$), and rutile ($TiO_2$). U.S. consumption of titanium bearing minerals is approaching two million metric tons per year with the majority being imported from Australia or South Africa.

Commercial forms of titanium mineral concentrates are usually mined. Gravity spirals are used for wet separation of the heavy minerals, while magnetic and high-tension separation are used to separate the constituents. Australia, Canada, India, Norway, and South Africa led the world's production of titanium mineral concentrate. U.S. mineral concentrate producers included **E.I. du Pont de Nemours & Co.**(DuPont), **Kerr-McGee Chemical Corp.**, and **Iluka Resources Inc.** DuPont's operations in

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[A-10] Gambogi, J., "Titanium," USGS, Minerals Yearbook, 2000.

Starke, FL produced a mixed product containing ilmenite, leucoxene, and rutile that was used as a feedstock in DuPont's $TiO_2$ pigment operations. Iluka"s mining operations in Green Cove Springs, FL and Stony Creek, VA, produced both rutile and ilmenite concentrates. Kerr-McGee's operation in Mobile, AL produced synthetic rutile from purchased ilmenite concentrate. **Altair International Inc.** was proceeding with feasibility studies at it heavy mineral deposits near Camden, TN. If further studies are successful, Altair Expects to produce 250,000 ton of a high TiO2 mineral concentrate. Iluka Resources studied the feasibility of increasing capacity by 70% at its Florida and Virginia mineral operations.

The year 2000 published price range for bulk rutile mineral concentrates was $470 to $500 per ton ($0.20 to 0.23/lb). Air floated rutile contains a small amount of crystalline silica and steps should be taken to avoid inhalation of dusts.

## Sugar Source

### Sugar[A-11]

Sugar (sucrose, $C_{12}H_{22}O_{11}$) in the vicinity of Richland Washington is produced from sugar beets grown in eleven western states – California, Colorado, Idaho, Michigan, Minnesota, Montana, Nebraska, N.Dakota, Oregon, Washington, and Wyoming. Sugar beets are processed in 30 factories that are necessarily located near the producing regions. They are also seasonal operations that normally run from September through January. Beet sugar production in 1999/00 is estimated to be about 4.6 million short tons, raw value. In the southern regions of the country sugar is produced from sugar cane.

The five largest sugar beet processors are **Amalgamated Sugar Co**, **American Crystal Sugar Co., Holly Sugar Corp., Michigan Sugar Co.** and **Western Sugar Co.** The second largest beet sugar processing company, **Amalgamated Sugar**, has plants in Oregon and Idaho. Total capacity is 31,400 tons of beets per day. An cost for granulated sugar from Amalgamated Sugar Co. shipped directly from the plant in 2,000 lbm tote sacks in truckload quantities is approximately $0.35/lbm.

Sugar may form combustible or explosive dust concentrations when distributed in air.

## Zinc Source

### ZnO[A-12]

**Zinc Oxide**

In 2000, domestic zinc mine production, expressed in zinc metal content of ore, increased by nearly 2% from that of 1999, mainly due to increased production in Alaska and Missouri. On the basis of recoverable content and annual average U.S. price, the value of zinc mine production was estimated to be about $1 billion (1 million metric tons). Zinc was extracted from 19 mines in 6 states by 8 companies. Table A.3 list the top producing plants in the U.S.

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[A-11] www.sugar.org and www.amalgamatedsugar.com
[A-12] Plachy, J., "Zinc," USGS, Minerals Yearbook, 2000.

World production of zinc concentrate by 41 countries increased about 9% in 2000 to more than 8.7 million metric tons. The largest producers were, in decreasing order of magnitude, China, Australia, Canada, Peru, and the U.S.

Zinc oxide production in the U.S. decreased from 114,000 metric tons in 1999 to 102,000 metric tons in 2000. Zinc oxide is used in ceramics, chemicals, paints, agriculture, and rubber. The value of zinc oxide obtained from export marketing figures was about $0.80 per pound.

**Table A.3: Top Ten Leading Zinc Producing Mines in the U.S. in 2000**

| Mine* | Operator | County and State |
|---|---|---|
| Red Dog | Cominco Alaska Inc | NW Arctic, AK |
| Greens Creek | Kennecott Green Creek Mining Co | Admiralty Island, AK |
| Balmat | **Zinc Corporation of America** | St. Lawrence, NY |
| Gordonsville | Pasiminco Ltd | Smith, TN |
| Young | ASARCO Inc. | Jefferson, TN |
| Montana Tunnels | Apollo Gold Co. | Jefferson, MT |
| Brushy Creek | Doe Run Resources Corp. | Reynolds, MO |
| Pierrepont | **Zinc Corporation of America** | St. Lawrence, NY |
| Immel | ASARCO Inc. | Knox, TN |
| Buick | Doe Run Resources Corp. | Iron, MO |

* Listed in Order of Output

## Zircon Source

## $ZrO_2$[A-13]

**Zircon (65% $ZrO_2$)**

The principal source of zirconia is the zirconium silicate mineral, zircon ($ZrSiO_4$). Zircon is also the primary source of all hafnium. Zirconium and hafnium are contained in zircon at a ratio of about 50 to 1. Zircon is a co-product or byproduct of the mining and processing of heavy-mineral sands for the titanium minerals, ilmenite and rutile or tin minerals. The major end uses of the mineral zircon are refractories, foundry sands, and ceramic opacification. Zirconium metal is used in nuclear fuel cladding, chemical piping in corrosive environments, heat exchangers, and various specialty alloys.

In 2000, U.S. mine producers of zircon were **E.I. du Pont de Nemours and Co.** (DuPont) and **Iluka Resources, Inc.** (previously RGC Mineral Sands), a subsidiary of the Australian company Iluka Resources Limited. DuPont produced zircon from its Highland and Maxville sands deposits near Starke, FL. Iluka produced zircon from it operations at Green Cove springs, FL and Stony Creek, VA. **Altair International Inc.** announced that it had broken ground on the construction of a pilot plant at its two sand deposits near Camden, TN.

Approximately 95% of all zirconium consumed is in the form of zircon, zirconium oxide, or other zirconium chemicals. The remainder is consumed as zirconium metal and zirconium containing alloys. Excluding U.S. production, world production of zirconium mineral concentrates in 2000 is

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[A-13] Hedrick, J.B., "zirconium and Hafnium," USGS, Minerals Yearbook, 2000.

estimated to be 760,000 tons. Australia and South Africa supplied about 82% of all production outside the United States.

In 2000, the increased demand for zircon concentrates resulted in an increase in price. The average value of imported ore and concentrates increased by 27% to $396 per ton.

The mineral zircon contains a small amount of free crystalline silica and breathing of dusts should be avoided.

Table A.4 is a summary of the estimated price per lbm for the raw materials tested.

**Table A.4: Estimated Costs for Raw Materials**

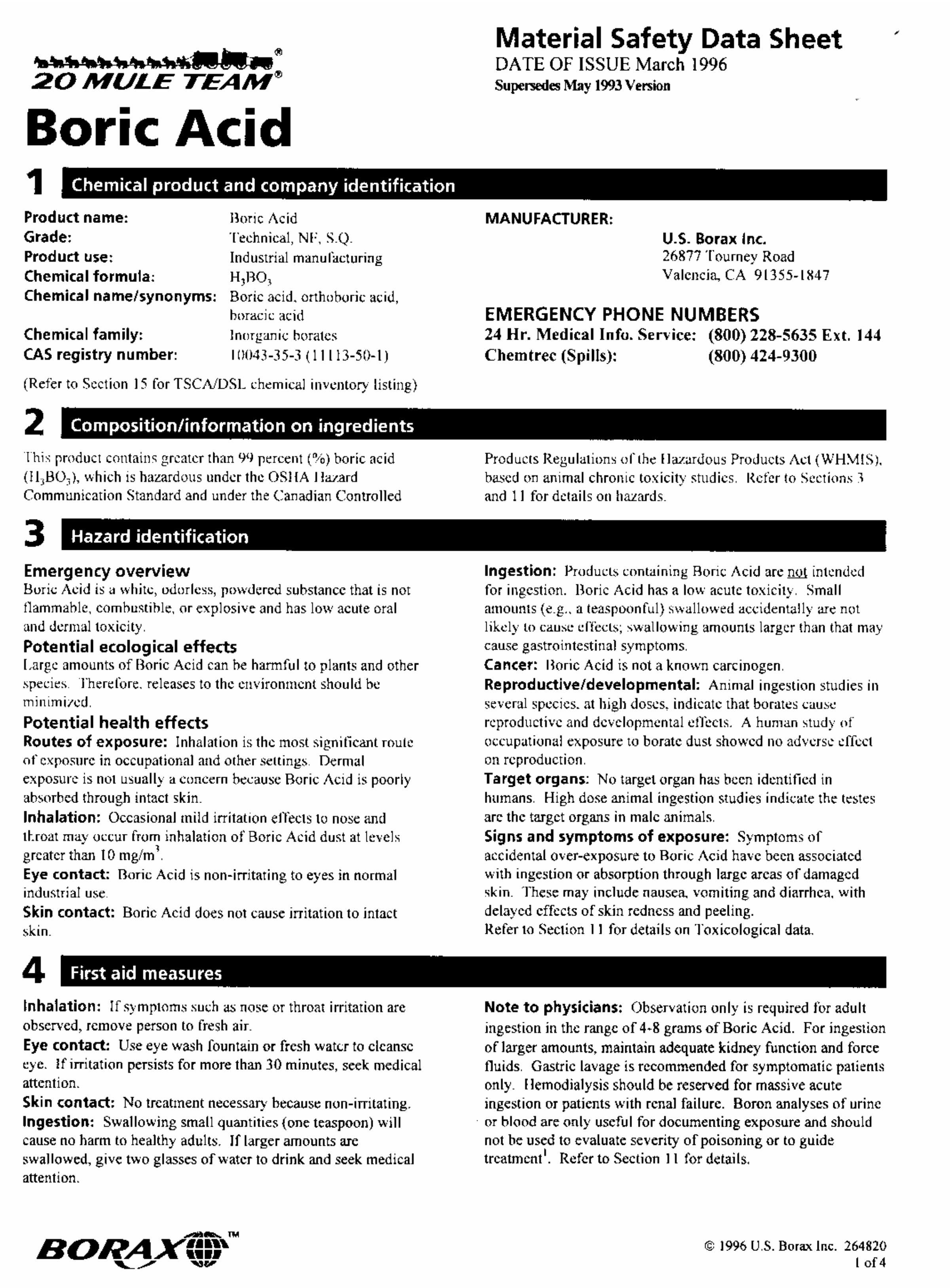
| Raw Material | Estimated Cost* From Available Data ($/lbm) |
|---|---|
| Alumina | 0.25 to 0.50 |
| Borax – Ten Mole | 0.17 |
| Boric Acid | 0.36 |
| Iron Oxide | 0.30 to 0.50 |
| Kyanite | 0.068 to 0.083 |
| Lithium Carbonate | 1.00 |
| Olivine | 0.02 to 0.05 |
| Silica | 0.01 |
| Soda Ash | 0.033 |
| Titanium Oxide – Rutile | 0.20 to 0.23 |
| Wollastonite | 0.10 to 0.13 |
| Zinc Oxide | 0.80 |
| Zircon | 0.20 |
| Sugar | 0.35 |

* Cost does not include transportation

# APPENDIX B. MSDS AND TECHNICAL DATA SHEETS FOR GFCS

**Data from MSDS and may not be qualified.**

Figure B.1: Boric Acid - MSDS



20 MULE TEAM®

# Boric Acid

# Material Safety Data Sheet

DATE OF ISSUE March 1996
**Supersedes May 1993 Version**

## 1 Chemical product and company identification

| | |
|---|---|
| **Product name:** | Boric Acid |
| **Grade:** | Technical, NF, S.Q. |
| **Product use:** | Industrial manufacturing |
| **Chemical formula:** | $H_3BO_3$ |
| **Chemical name/synonyms:** | Boric acid, orthoboric acid, boracic acid |
| **Chemical family:** | Inorganic borates |
| **CAS registry number:** | 10043-35-3 (11113-50-1) |

(Refer to Section 15 for TSCA/DSL chemical inventory listing)

**MANUFACTURER:**

**U.S. Borax Inc.**
26877 Tourney Road
Valencia, CA 91355-1847

**EMERGENCY PHONE NUMBERS**

| | |
|---|---|
| **24 Hr. Medical Info. Service:** | **(800) 228-5635 Ext. 144** |
| **Chemtrec (Spills):** | **(800) 424-9300** |

## 2 Composition/information on ingredients

This product contains greater than 99 percent (%) boric acid ($H_3BO_3$), which is hazardous under the OSHA Hazard Communication Standard and under the Canadian Controlled Products Regulations of the Hazardous Products Act (WHMIS), based on animal chronic toxicity studies. Refer to Sections 3 and 11 for details on hazards.

## 3 Hazard identification

### Emergency overview

Boric Acid is a white, odorless, powdered substance that is not flammable, combustible, or explosive and has low acute oral and dermal toxicity.

### Potential ecological effects

Large amounts of Boric Acid can be harmful to plants and other species. Therefore, releases to the environment should be minimized.

### Potential health effects

**Routes of exposure:** Inhalation is the most significant route of exposure in occupational and other settings. Dermal exposure is not usually a concern because Boric Acid is poorly absorbed through intact skin.

**Inhalation:** Occasional mild irritation effects to nose and throat may occur from inhalation of Boric Acid dust at levels greater than 10 mg/m$^3$.

**Eye contact:** Boric Acid is non-irritating to eyes in normal industrial use.

**Skin contact:** Boric Acid does not cause irritation to intact skin.

**Ingestion:** Products containing Boric Acid are not intended for ingestion. Boric Acid has a low acute toxicity. Small amounts (e.g., a teaspoonful) swallowed accidentally are not likely to cause effects; swallowing amounts larger than that may cause gastrointestinal symptoms.

**Cancer:** Boric Acid is not a known carcinogen.

**Reproductive/developmental:** Animal ingestion studies in several species, at high doses, indicate that borates cause reproductive and developmental effects. A human study of occupational exposure to borate dust showed no adverse effect on reproduction.

**Target organs:** No target organ has been identified in humans. High dose animal ingestion studies indicate the testes are the target organs in male animals.

**Signs and symptoms of exposure:** Symptoms of accidental over-exposure to Boric Acid have been associated with ingestion or absorption through large areas of damaged skin. These may include nausea, vomiting and diarrhea, with delayed effects of skin redness and peeling.
Refer to Section 11 for details on Toxicological data.

## 4 First aid measures

**Inhalation:** If symptoms such as nose or throat irritation are observed, remove person to fresh air.

**Eye contact:** Use eye wash fountain or fresh water to cleanse eye. If irritation persists for more than 30 minutes, seek medical attention.

**Skin contact:** No treatment necessary because non-irritating.

**Ingestion:** Swallowing small quantities (one teaspoon) will cause no harm to healthy adults. If larger amounts are swallowed, give two glasses of water to drink and seek medical attention.

**Note to physicians:** Observation only is required for adult ingestion in the range of 4-8 grams of Boric Acid. For ingestion of larger amounts, maintain adequate kidney function and force fluids. Gastric lavage is recommended for symptomatic patients only. Hemodialysis should be reserved for massive acute ingestion or patients with renal failure. Boron analyses of urine or blood are only useful for documenting exposure and should not be used to evaluate severity of poisoning or to guide treatment[1]. Refer to Section 11 for details.

BORAX™

## 5 Fire fighting measures

**General hazard:** None, because Boric Acid is not flammable, combustible or explosive. The product is itself a flame retardant.

**Extinguishing media:** Any fire extinguishing media may be used on nearby fires.

**Flammability classification (29 CFR 1910.1200):** Non-flammable solid.

## 6 Accidental release measures

**General:** Boric Acid is a water-soluble white powder that may, at high concentrations, cause damage to trees or vegetation by root absorption. (Refer to Ecological information, Section 12, for specific information.)

**Land spill:** Vacuum, shovel or sweep up Boric Acid and place in containers for disposal in accordance with applicable local regulations. Avoid contamination of water bodies during cleanup and disposal. No personal protective equipment is needed to cleanup land spills.

**Spillage into water:** Where possible, remove any intact containers from the water. Advise local water authority that none of the affected water should be used for irrigation or for the abstraction of potable water until natural dilution returns the boron value to its normal environmental background level. (Refer to Sections 12, 13 and 15 for additional information.) Boric Acid is a non-hazardous waste when spilled or disposed of, as defined in the Resource Conservation and Recovery Act (RCRA) regulations (40 CFR 261). (Refer to Regulatory information, Section 15, for additional references.)

## 7 Handling and storage

**General:** No special handling precautions are required, but dry, indoor storage is recommended. To maintain package integrity and to minimize caking of the product, bags should be handled on a first-in, first-out basis. Good housekeeping procedures should be followed to minimize dust generation and accumulation.

| | |
|---|---|
| **Storage temperature:** | Ambient |
| **Storage pressure:** | Atmospheric |
| **Special sensitivity:** | Moisture (caking) |

## 8 Exposure controls/personal protection

**Engineering controls:** Use local exhaust ventilation to keep airborne concentrations of Boric Acid dust below permissible exposure levels.

**Personal protection:** Where airborne concentrations are expected to exceed exposure limits, NIOSH/MSHA certified respirators should be used. Eye goggles and gloves are not required for normal industrial exposures, but may be warranted if environment is excessively dusty.

**Occupational exposure limits:** Boric acid is treated by OSHA, Cal OSHA and ACGIH as "Particulate Not Otherwise Classified" or "Nuisance Dust". The OSHA/PEL (Permissible Exposure Level) is 15 mg/m$^3$ total dust and 5 mg/m$^3$ respirable dust. The Cal OSHA/PEL is 10 mg/m$^3$. The ACGIH/TLV (Threshold Limit Value) is 10 mg/m$^3$.

## 9 Physical and chemical properties

| | |
|---|---|
| **Appearance:** | White, odorless, crystalline solid |
| **Specific gravity:** | 1.51 |
| **Vapor pressure:** | Negligible @ 20°C |
| **Solubility in water:** | 4.7% @ 20°C; 27.5% @ 100°C |
| **Melting point:** | 170.9°C (340°F) (heated in closed space) |
| **pH @ 20°C:** | 6.1 (0.1% solution); 5.1 (1.0% solution); 3.7 (4.7% solution) |
| **Molecular weight:** | 61.84 |

## 10 Stability and reactivity

**General:** Boric Acid is a stable product, but when heated it loses water, first forming metaboric acid ($HBO_2$), and on further heating it is converted into boric oxide ($B_2O_3$).

**Incompatible materials and conditions to avoid:** Boric Acid reacts as a weak acid which may cause corrosion of base metals. Reaction with strong reducing agents, such as metal hydrides or alkali metals, will generate hydrogen gas, which could create an explosive hazard.

**Hazardous decomposition:** None.

## 11 Toxicological information

### Acute toxicity

**Ingestion:** Low acute oral toxicity; $LD_{50}$ in rats is 3,500 to 4,100 mg/kg of body weight.

**Skin/dermal:** Low acute dermal toxicity; $LD_{50}$ in rabbits is greater than 2,000 mg/kg of body weight. Boric acid is poorly absorbed through intact skin.

**Inhalation:** Low acute inhalation toxicity; $LC_{50}$ in rats is greater than 2.0 mg/L (or $g/m^3$).

**Skin irritation:** Non-irritant.

**Eye irritation:** Draize test in rabbits produced mild eye irritation effects. Fifty years of occupational exposure to Boric Acid indicates no adverse effects on human eye. Therefore, Boric Acid is not considered to be a human eye irritant in normal industrial use.

**Sensitization:** Boric acid is not a skin sensitizer.

### Other

**Reproductive/developmental toxicity:** Animal feeding studies in rat, mouse and dog, at high doses, have demonstrated effects on fertility and testes[2]. Boric acid studies in rat, mouse and rabbit, at high doses, demonstrate developmental effects on the fetus, including fetal weight loss and minor skeletal variations[3, 4]. The doses administered were many times in excess of those to which humans would normally be exposed[5].

**Carcinogenicity/mutagenicity:** No evidence of carcinogenicity in mice[6]. No mutagenic activity was observed for boric acid in a battery of short-term mutagenicity assays.

**Human data:** Human epidemiological studies show no increase in pulmonary disease in occupational populations with chronic exposures to boric acid dust and sodium borate dust. A recent epidemiology study under the conditions of normal occupational exposure to borate dusts indicated no effect on fertility[7].

## 12 Ecological information

### Ecotoxicity data

**General:** Boron (B) is the element in boric acid which is used by convention to report borate product ecological effects. It occurs naturally in sea-water at an average concentration of 5 mg B/L and generally occurs in fresh water at concentrations up to 1 mg B/L. In dilute aqueous solutions the predominant boron species present is undissociated boric acid. To convert boric acid into equivalent boron (B) content, multiply by 0.1748.

**Phytotoxicity:** Boron is an essential micronutrient for healthy growth of plants; however, it can be harmful to boron sensitive plants in high quantities. Care should be taken to minimize the amount of Boric Acid released to the environment.

**Algal toxicity:**

Green algae, *Scenedesmus subspicatus*
96-hr $EC_{10}$ = 24 mg B/L†

**Invertebrate toxicity**[8]**:**

Daphnids, *Daphnia magna straus*
48-hr $LC_{50}$ ~ 133 mg B/L‡
21-day NOEC-LOEC = 6-13 mg B/L‡

**Fish toxicity:**

Sea-water[9]:
Dab, *Limanda limanda*
96-hr $LC_{50}$ = 74 mg B/L†

Fresh water[10]:
Rainbow trout, *S. gairdneri* (embryo-larval stage)
24-day $LC_{50}$ = 150 mg B/L‡
32-day $LC_{50}$ = 100 mg B/L‡
Goldfish, *Carassius auratus* (embryo-larval stage)
7-day $LC_{50}$ = 46 mg B/L‡
3-day $LC_{50}$ = 178 mg B/L‡

### Environmental fate data

**Persistence/degradation:** Boron is naturally occurring and ubiquitous in the environment. Boric Acid decomposes in the environment to natural borate.

**Octanol/water partition coefficient:** Log $P_{ow}$: -0.7570 at 25°C.

**Soil mobility:** Boric Acid is soluble in water and is leachable through normal soil.

Test substance: † sodium tetraborate
‡ boric acid

## 13 Disposal considerations

**Disposal guidance:** Small quantities of Boric Acid can usually be disposed of at landfill sites. No special disposal treatment is required, but local authorities should be consulted about any specific local requirements. Tonnage quantities of product are not recommended to be sent to landfills. Such product should, if possible, be used for an appropriate application.

**RCRA (40 CFR 261):** Boric acid is not listed under any sections of the Federal Resource Conservation and Recovery Act (RCRA).

**NPRI (Canada):** Boric acid is not listed on the Canadian National Pollutant Release Inventory.

Refer to Section 15 for additional regulatory information.

## 14 Transport information

**DOT hazardous classification:** Boric acid is not regulated by the U.S. Department of Transportation (DOT) and is therefore not considered a hazardous material/substance.

**TDG Canadian transportation:** Boric acid is not regulated under Transportation of Dangerous Goods (TDG).

**International transportation:** Boric acid has no UN Number, and is not regulated under international rail, road, water or air transport regulations.

## 15 Regulatory information

**OSHA/Cal OSHA:** This MSDS document meets the requirements of both OSHA (29 CFR 1910.1200) and Cal OSHA (Title 8 CCR 5194 (g)) hazard communication standards. Refer to Section 8 for regulatory exposure limits.

**WHMIS classification:** Boric Acid is classified as Class D-Division 2A under Canadian WHMIS guidelines.

**Chemical inventory listing:** Boric acid (10043-35-3) appears on several chemical inventory lists (including the EPA TSCA inventory, Canadian DSL, European EINECS, Japanese MITI, Australian and Korean lists) under the CAS No. representing the anhydrous form of this inorganic salt.

| | |
|---|---|
| **U.S. EPA TSCA Inventory** | 10043-35-3 |
| **Canadian DSL** | 10043-35-3 |
| **EINECS** | 233-139-2 |
| **South Korea** | 1-439 |
| **Japanese MITI** | (1)-63 |

**RCRA:** Boric acid is not listed as a hazardous waste under any sections of the Resource Conservation and Recovery Act (RCRA) or regulations (40 CFR 261 *et seq*).

**Superfund:** CERCLA/SARA. Boric acid is not listed under CERCLA (Comprehensive Environmental Response Compensation and Liability Act) or its 1986 amendments, SARA (Superfund Amendments and Reauthorization Act), including substances listed under Section 313 of SARA, Toxic Chemicals, 42 USC 11023, 40 CFR 372.65, Section 302 of SARA, Extremely Hazardous Substances, 42 USC 11002, 40 CFR 355, or the CERCLA Hazardous Substances list, 42 USC 9604, 40 CFR 302.

**Safe Drinking Water Act (SDWA):** Boric acid is not regulated under the SDWA, 42 USC 300g-1, 40 CFR 141 *et seq*. Consult state and local regulations for possible water quality advisories regarding boron compounds.

**Clean Water Act (CWA) (Federal Water Pollution Control Act):** 33 USC 1251 *et seq*.

a) Boric acid is not itself a discharge covered by any water quality criteria of Section 304 of the CWA, 33 USC 1314.
b) It is not on the Section 307 List of Priority Pollutants, 33 USC 1317, 40 CFR 129.
c) It is not on the Section 311 List of Hazardous Substances, 33 USC 1321, 40 CFR 116.

**Canadian drinking water guideline:** An "Interim Maximum Acceptable Concentration" (IMAC) for boron is currently set at 5 mg B/L.

**IARC:** The International Agency for Research on Cancer (IARC) (a unit of the World Health Organization) does not list or categorize boric acid as a carcinogen.

**NTP Biennial Report on Carcinogens:** Boric acid is not listed.

**OSHA carcinogen:** Boric acid is not listed.

**California Proposition 65:** Boric acid is not listed on the Proposition 65 list of carcinogens or reproductive toxicants.

**Federal Food, Drug and Cosmetic Act:** Pursuant to 21 CFR 175.105, 176.180 and 181.30, boric acid is approved by the FDA for use in adhesive components of packaging materials, as a component of paper coatings on such materials, or for use in the manufacture thereof, which materials are expected to come in contact with dry food products.

**Clean Air Act (Montreal Protocol):** Boric acid was not manufactured with and does not contain any Class I or Class II ozone depleting substances.

## 16 Other information

### References

1) Litovitz T L, Norman S A, Veltri J C, Annual Report of the American Association of Poison Control Centers Data Collection System. Am. J Emerg. Med. **4**: 427-458 (1986).
2) Weir R J, Fisher R S, Toxicol. Appl. Pharmacol. **23**: 351-364 (1972).
3) Fail *et al.*, Fund. Appl. Toxicol. **17**: 225-239 (1991).
4) Price *et al.*, J. Am. Coll. Toxicol. **14**: (2), 173 (Abst. P-17) (1995).
5) Murray F J, Regul. Toxicol. Pharmacol. (Dec. 1995).
6) National Toxicology Program (NTP) –Toxicology and carcinogenesis studies of boric acid in $B6C3F_1$ mice, Tech. Report Ser. No. 324, U.S. Dept. of Health and Human Services. NIH Publ. No. 88-2580 (1987).
7) Whorton *et al.*, Occup. Environ. Med. **51**: 761-767 (1994).
8) Schöberl *et al.*, Tenside Surfactants Detergents **25**: 99-107 (1988).
9) Hugman S J, Mance G, Water Research Centre Report 616-M (1983).
10) Butterwick L, de Oude N, Raymond K, Ecotoxicol. Environ. Safety **17**: 339-371 (1989).

For general information on the toxicology of inorganic borates, see Patty's Industrial Hygiene and Toxicology, 4th Ed. Vol. II, (1994), Chap. 42, Boron; ECETOC Tech. Report No. 63 (1995).

**Product label text hazard information*:**

- May be harmful if swallowed.
- May cause reproductive harm or birth defects based on animal data.
- Avoid contamination of food or feed.
- Not for food, drug or pesticidal use⁺.
- Refer to MSDS.
- KEEP OUT OF REACH OF CHILDREN.

*The WHMIS panel format is used for Canadian product.
⁺Except for NF (pharmaceutical grade) products.

**National Fire Protection Assoc. (NFPA) Classification:**

| | |
|---|---|
| Health | 0 |
| Flammability | 0 |
| Reactivity | 0 |

**Hazardous Materials Information Systems (HMIS):**

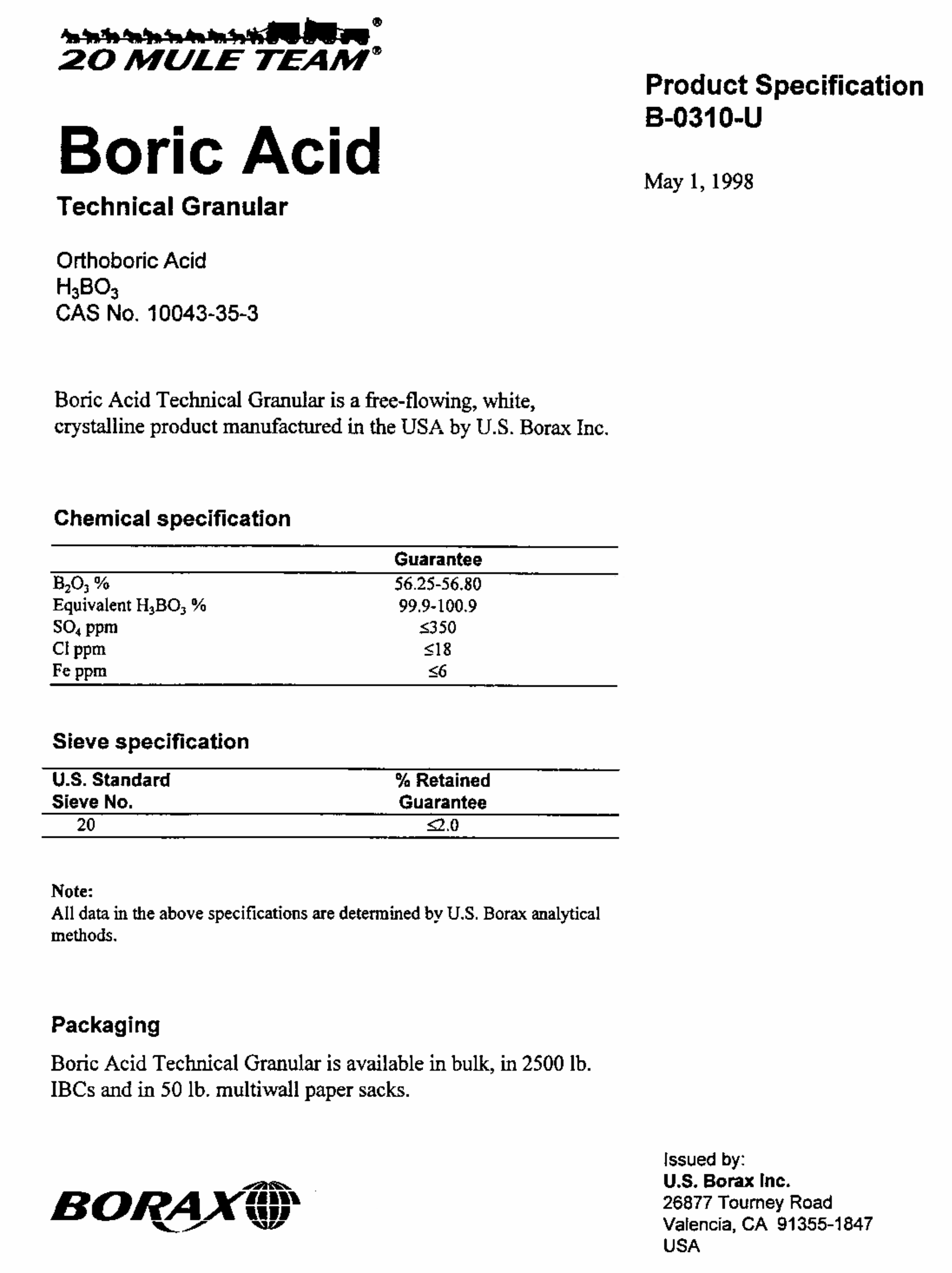
| | |
|---|---|
| Red: (Flammability) | 0 |
| Yellow: (Reactivity) | 0 |
| Blue: (Acute Health) | 1* |

*Chronic Effects

**For further information contact:**

**U.S. Borax Inc.**
**Occupational Health & Product Safety Department**
**(805) 287-6050**

Figure B.2: Boric Acid – Vendor Technical Data



20 MULE TEAM®

# Boric Acid

## Technical Granular

Orthoboric Acid
$H_3BO_3$
CAS No. 10043-35-3

**Product Specification**
**B-0310-U**

May 1, 1998

Boric Acid Technical Granular is a free-flowing, white, crystalline product manufactured in the USA by U.S. Borax Inc.

### Chemical specification

| | Guarantee |
|---|---|
| $B_2O_3$ % | 56.25-56.80 |
| Equivalent $H_3BO_3$ % | 99.9-100.9 |
| $SO_4$ ppm | ≤350 |
| Cl ppm | ≤18 |
| Fe ppm | ≤6 |

### Sieve specification

| U.S. Standard Sieve No. | % Retained Guarantee |
|---|---|
| 20 | ≤2.0 |

**Note:**
All data in the above specifications are determined by U.S. Borax analytical methods.

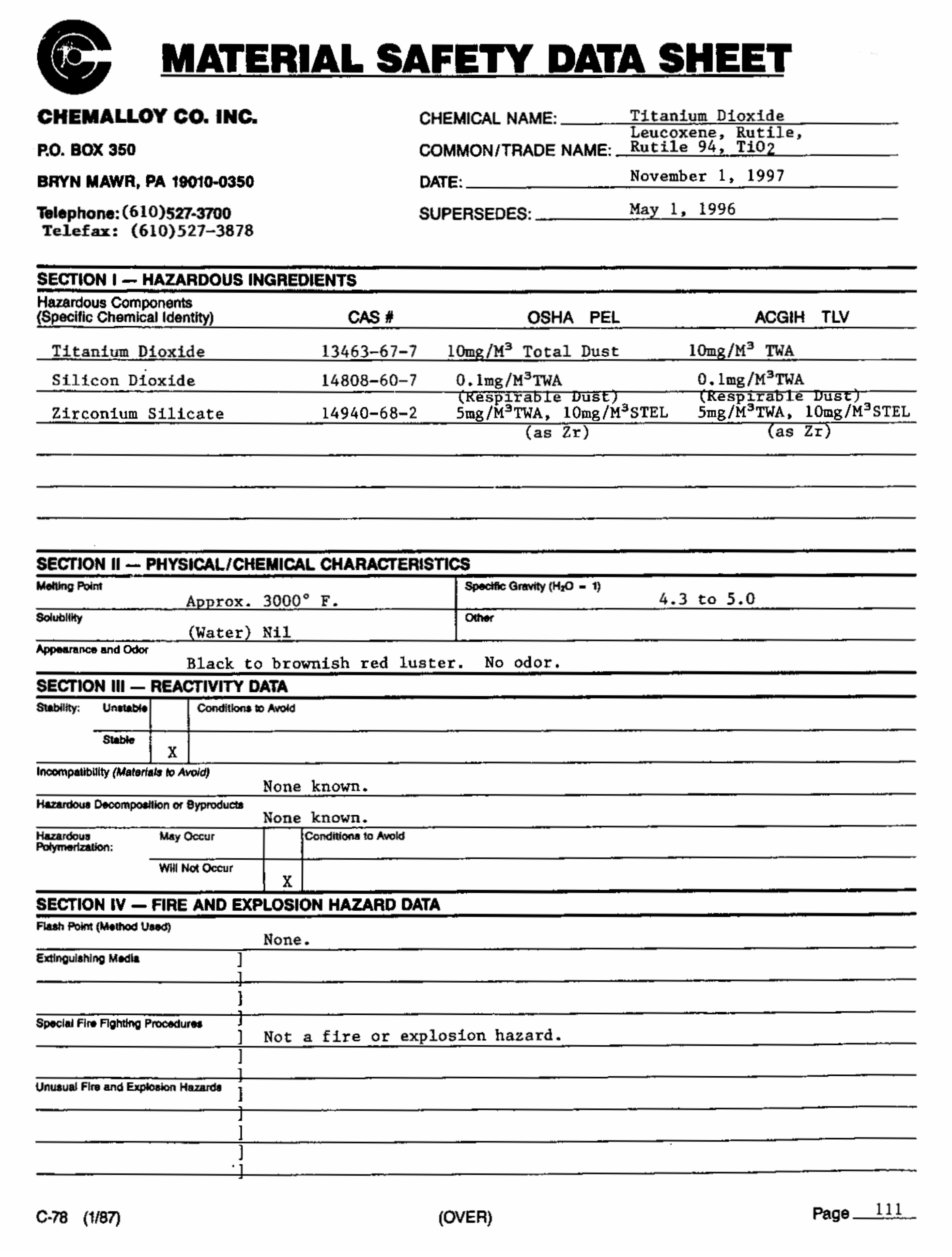
### Packaging

Boric Acid Technical Granular is available in bulk, in 2500 lb. IBCs and in 50 lb. multiwall paper sacks.

BORAX

Issued by:
**U.S. Borax Inc.**
26877 Tourney Road
Valencia, CA 91355-1847
USA

Figure B.3: Titanium Dioxide - MSDS



# MATERIAL SAFETY DATA SHEET

**CHEMALLOY CO. INC.**
P.O. BOX 350
BRYN MAWR, PA 19010-0350
Telephone: (610)527-3700
Telefax: (610)527-3878

CHEMICAL NAME: Titanium Dioxide
COMMON/TRADE NAME: Leucoxene, Rutile, Rutile 94, $TiO_2$
DATE: November 1, 1997
SUPERSEDES: May 1, 1996

## SECTION I — HAZARDOUS INGREDIENTS

| Hazardous Components (Specific Chemical Identity) | CAS # | OSHA PEL | ACGIH TLV |
|---|---|---|---|
| Titanium Dioxide | 13463-67-7 | 10mg/M$^3$ Total Dust | 10mg/M$^3$ TWA |
| Silicon Dioxide | 14808-60-7 | 0.1mg/M$^3$TWA (Respirable Dust) | 0.1mg/M$^3$TWA (Respirable Dust) |
| Zirconium Silicate | 14940-68-2 | 5mg/M$^3$TWA, 10mg/M$^3$STEL (as Zr) | 5mg/M$^3$TWA, 10mg/M$^3$STEL (as Zr) |

## SECTION II — PHYSICAL/CHEMICAL CHARACTERISTICS

| | |
|---|---|
| Melting Point: Approx. 3000° F. | Specific Gravity ($H_2O$ = 1): 4.3 to 5.0 |
| Solubility: (Water) Nil | Other |

Appearance and Odor: Black to brownish red luster. No odor.

## SECTION III — REACTIVITY DATA

| Stability: | | | Conditions to Avoid |
|---|---|---|---|
| | Unstable | ☐ | |
| | Stable | ☒ | |

Incompatibility (*Materials to Avoid*): None known.

Hazardous Decomposition or Byproducts: None known.

| Hazardous Polymerization: | | | Conditions to Avoid |
|---|---|---|---|
| | May Occur | ☐ | |
| | Will Not Occur | ☒ | |

## SECTION IV — FIRE AND EXPLOSION HAZARD DATA

Flash Point (Method Used): None.

Extinguishing Media
Special Fire Fighting Procedures: Not a fire or explosion hazard.
Unusual Fire and Explosion Hazards

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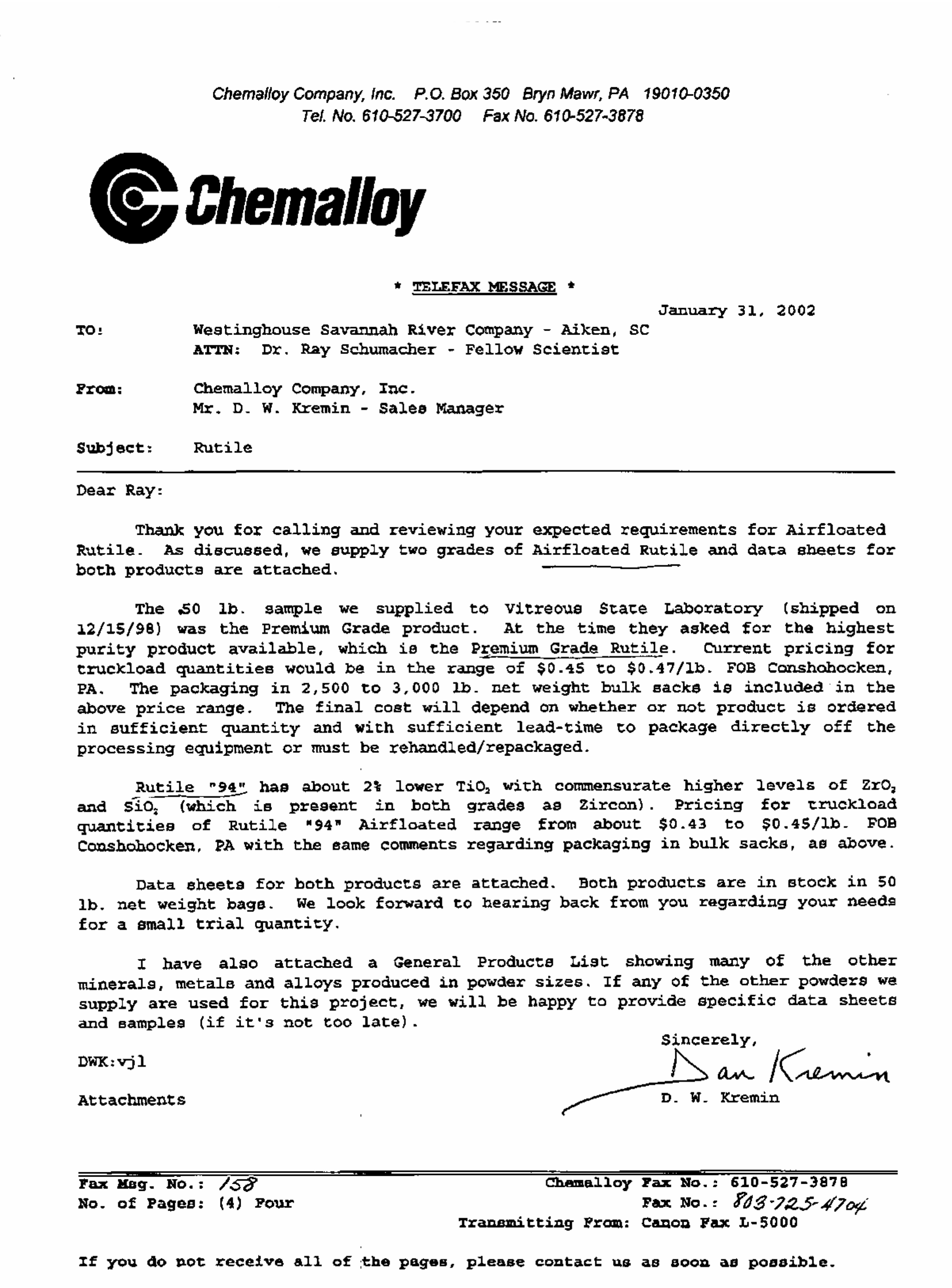
Figure B.4: Titanium Dioxide – Vendor Technical Data



*Chemalloy Company, Inc.   P.O. Box 350   Bryn Mawr, PA   19010-0350*
*Tel. No. 610-527-3700   Fax No. 610-527-3878*

Chemalloy

* **TELEFAX MESSAGE** *

January 31, 2002

TO: Westinghouse Savannah River Company - Aiken, SC
ATTN: Dr. Ray Schumacher - Fellow Scientist

From: Chemalloy Company, Inc.
Mr. D. W. Kremin - Sales Manager

Subject: Rutile

Dear Ray:

Thank you for calling and reviewing your expected requirements for Airfloated Rutile. As discussed, we supply two grades of Airfloated Rutile and data sheets for both products are attached.

The 50 lb. sample we supplied to Vitreous State Laboratory (shipped on 12/15/98) was the Premium Grade product. At the time they asked for the highest purity product available, which is the Premium Grade Rutile. Current pricing for truckload quantities would be in the range of $0.45 to $0.47/lb. FOB Conshohocken, PA. The packaging in 2,500 to 3,000 lb. net weight bulk sacks is included in the above price range. The final cost will depend on whether or not product is ordered in sufficient quantity and with sufficient lead-time to package directly off the processing equipment or must be rehandled/repackaged.

Rutile "94" has about 2% lower $TiO_2$ with commensurate higher levels of $ZrO_2$ and $SiO_2$ (which is present in both grades as Zircon). Pricing for truckload quantities of Rutile "94" Airfloated range from about $0.43 to $0.45/lb. FOB Conshohocken, PA with the same comments regarding packaging in bulk sacks, as above.

Data sheets for both products are attached. Both products are in stock in 50 lb. net weight bags. We look forward to hearing back from you regarding your needs for a small trial quantity.

I have also attached a General Products List showing many of the other minerals, metals and alloys produced in powder sizes. If any of the other powders we supply are used for this project, we will be happy to provide specific data sheets and samples (if it's not too late).

Sincerely,

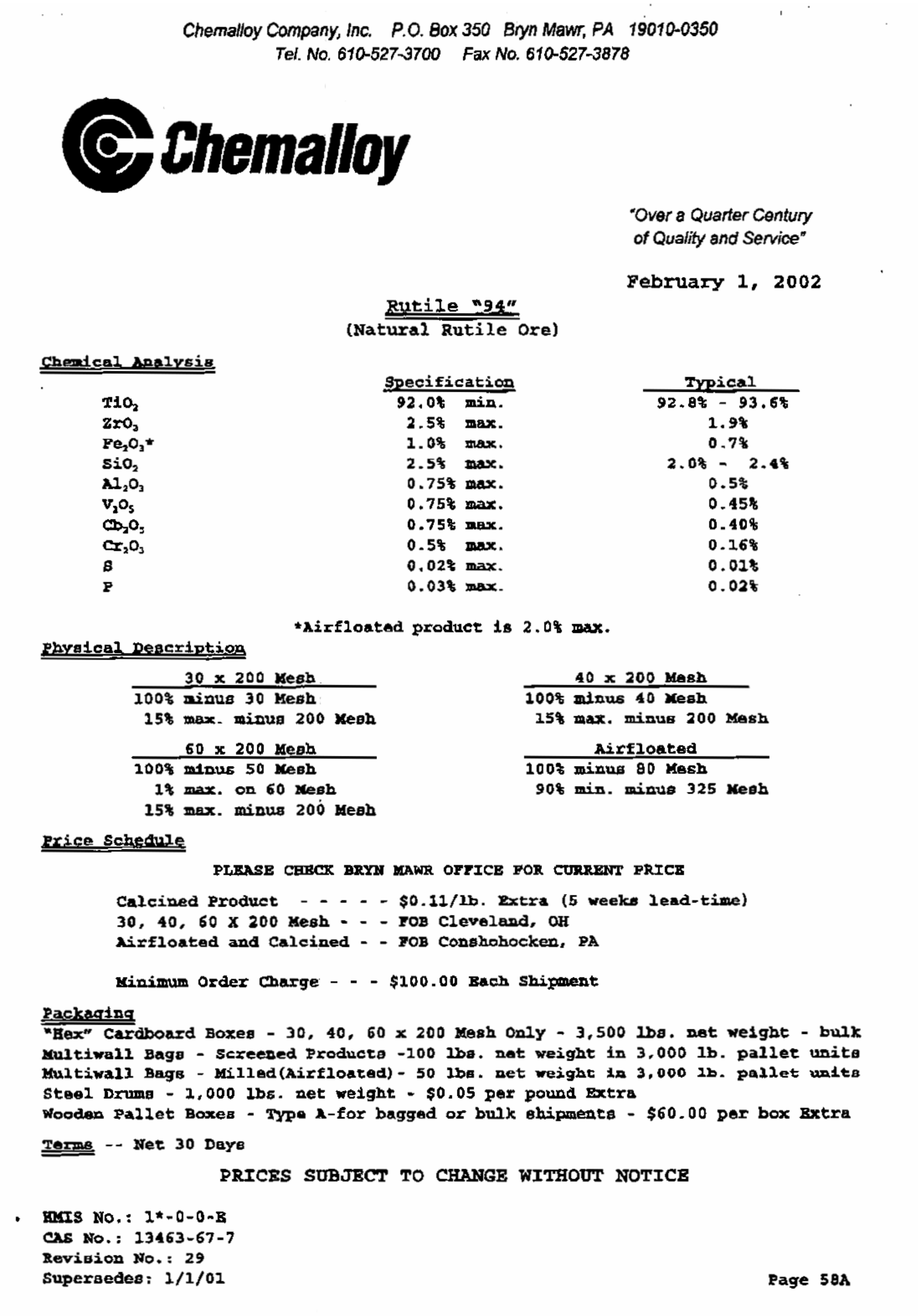
Dan Kremin
D. W. Kremin

DWK:vjl

Attachments

Fax Msg. No.: 158
No. of Pages: (4) Four
Chemalloy Fax No.: 610-527-3878
Fax No.: 803-725-4704
Transmitting From: Canon Fax L-5000

If you do not receive all of the pages, please contact us as soon as possible.



*Chemalloy Company, Inc.  P.O. Box 350  Bryn Mawr, PA  19010-0350*
*Tel. No. 610-527-3700  Fax No. 610-527-3878*

Chemalloy

*"Over a Quarter Century
of Quality and Service"*

February 1, 2002

## Rutile "94"
(Natural Rutile Ore)

### Chemical Analysis

| | Specification | Typical |
|---|---|---|
| $TiO_2$ | 92.0% min. | 92.8% - 93.6% |
| $ZrO_3$ | 2.5% max. | 1.9% |
| $Fe_2O_3$* | 1.0% max. | 0.7% |
| $SiO_2$ | 2.5% max. | 2.0% - 2.4% |
| $Al_2O_3$ | 0.75% max. | 0.5% |
| $V_2O_5$ | 0.75% max. | 0.45% |
| $Cb_2O_5$ | 0.75% max. | 0.40% |
| $Cr_2O_3$ | 0.5% max. | 0.16% |
| S | 0.02% max. | 0.01% |
| P | 0.03% max. | 0.02% |

*Airfloated product is 2.0% max.

### Physical Description

| 30 x 200 Mesh | 40 x 200 Mesh |
|---|---|
| 100% minus 30 Mesh | 100% minus 40 Mesh |
| 15% max. minus 200 Mesh | 15% max. minus 200 Mesh |

| 60 x 200 Mesh | Airfloated |
|---|---|
| 100% minus 50 Mesh | 100% minus 80 Mesh |
| 1% max. on 60 Mesh | 90% min. minus 325 Mesh |
| 15% max. minus 200 Mesh | |

### Price Schedule

PLEASE CHECK BRYN MAWR OFFICE FOR CURRENT PRICE

Calcined Product - - - - - $0.11/lb. Extra (5 weeks lead-time)
30, 40, 60 X 200 Mesh - - - FOB Cleveland, OH
Airfloated and Calcined - - FOB Conshohocken, PA

Minimum Order Charge - - - $100.00 Each Shipment

### Packaging

"Hex" Cardboard Boxes - 30, 40, 60 x 200 Mesh Only - 3,500 lbs. net weight - bulk
Multiwall Bags - Screened Products -100 lbs. net weight in 3,000 lb. pallet units
Multiwall Bags - Milled(Airfloated)- 50 lbs. net weight in 3,000 lb. pallet units
Steel Drums - 1,000 lbs. net weight - $0.05 per pound Extra
Wooden Pallet Boxes - Type A-for bagged or bulk shipments - $60.00 per box Extra

Terms -- Net 30 Days

PRICES SUBJECT TO CHANGE WITHOUT NOTICE

HMIS No.: 1*-0-0-E
CAS No.: 13463-67-7
Revision No.: 29
Supersedes: 1/1/01

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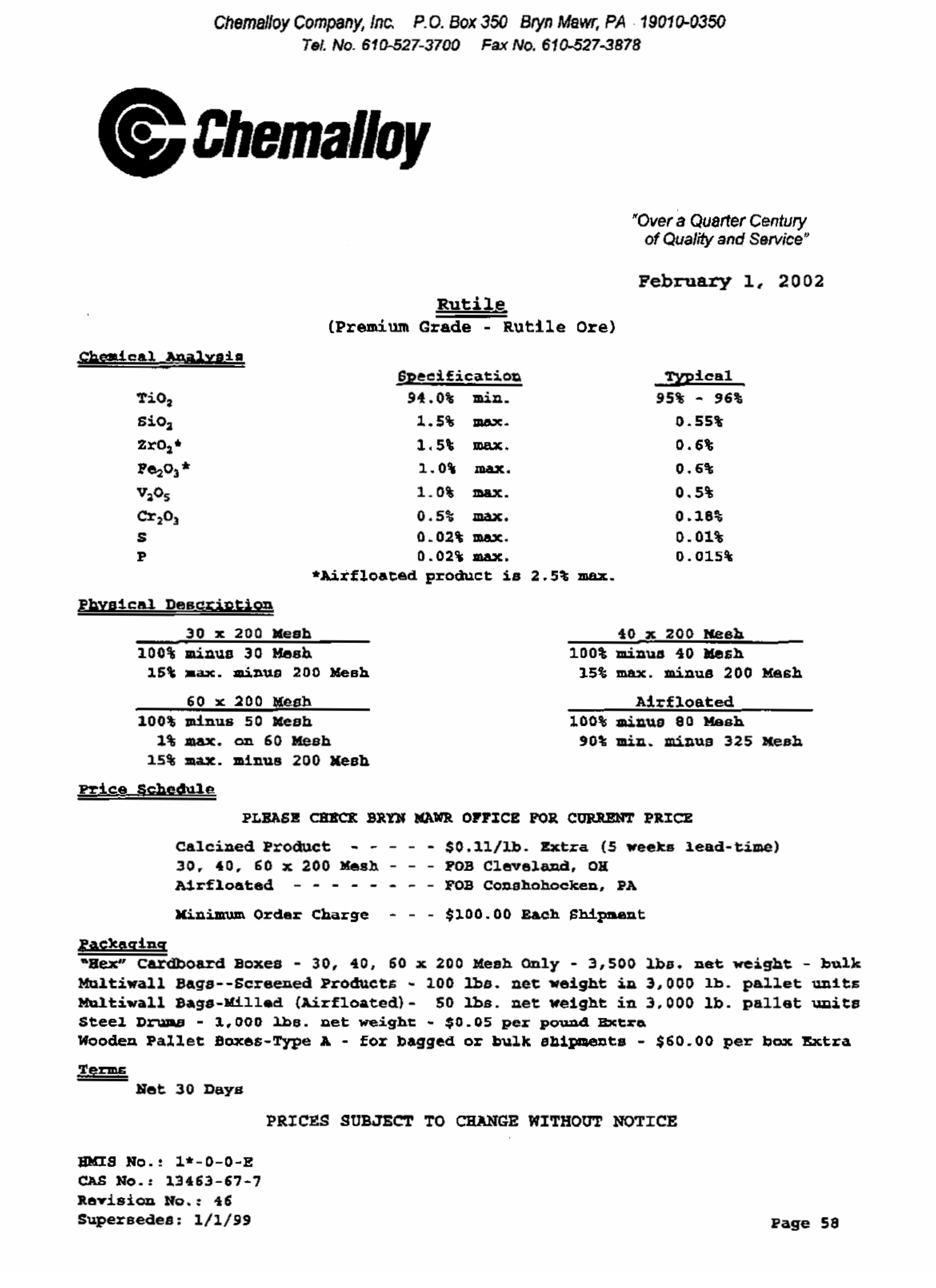

Chemalloy Company, Inc. P.O. Box 350 Bryn Mawr, PA 19010-0350
Tel. No. 610-527-3700 Fax No. 610-527-3878

Chemalloy

"Over a Quarter Century
of Quality and Service"

February 1, 2002

## Rutile

(Premium Grade - Rutile Ore)

**Chemical Analysis**

| | Specification | Typical |
|---|---|---|
| $TiO_2$ | 94.0% min. | 95% - 96% |
| $SiO_2$ | 1.5% max. | 0.55% |
| $ZrO_2$* | 1.5% max. | 0.6% |
| $Fe_2O_3$* | 1.0% max. | 0.6% |
| $V_2O_5$ | 1.0% max. | 0.5% |
| $Cr_2O_3$ | 0.5% max. | 0.18% |
| S | 0.02% max. | 0.01% |
| P | 0.02% max. | 0.015% |

*Airfloated product is 2.5% max.

**Physical Description**

| 30 x 200 Mesh | 40 x 200 Mesh |
|---|---|
| 100% minus 30 Mesh<br>15% max. minus 200 Mesh | 100% minus 40 Mesh<br>15% max. minus 200 Mesh |

| 60 x 200 Mesh | Airfloated |
|---|---|
| 100% minus 50 Mesh<br>1% max. on 60 Mesh<br>15% max. minus 200 Mesh | 100% minus 80 Mesh<br>90% min. minus 325 Mesh |

**Price Schedule**

PLEASE CHECK BRYN MAWR OFFICE FOR CURRENT PRICE

Calcined Product - - - - - $0.11/lb. Extra (5 weeks lead-time)
30, 40, 60 x 200 Mesh - - - FOB Cleveland, OH
Airfloated - - - - - - - - FOB Conshohocken, PA

Minimum Order Charge - - - $100.00 Each Shipment

**Packaging**

"Hex" Cardboard Boxes - 30, 40, 60 x 200 Mesh Only - 3,500 lbs. net weight - bulk
Multiwall Bags--Screened Products - 100 lbs. net weight in 3,000 lb. pallet units
Multiwall Bags-Milled (Airfloated)- 50 lbs. net weight in 3,000 lb. pallet units
Steel Drums - 1,000 lbs. net weight - $0.05 per pound Extra
Wooden Pallet Boxes-Type A - for bagged or bulk shipments - $60.00 per box Extra

**Terms**

Net 30 Days

PRICES SUBJECT TO CHANGE WITHOUT NOTICE

HMIS No.: 1*-0-0-E
CAS No.: 13463-67-7
Revision No.: 46
Supersedes: 1/1/99

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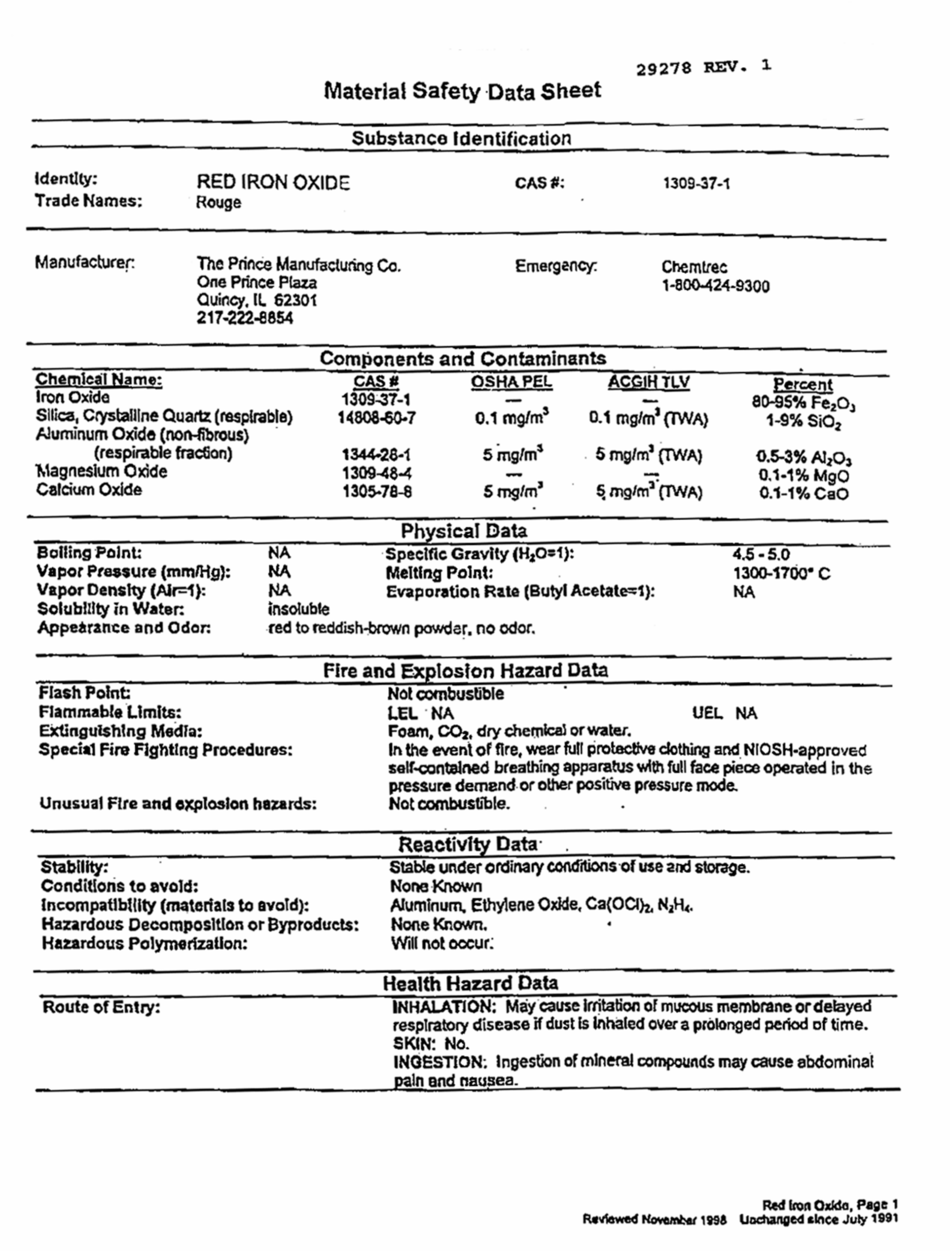
Figure B.5: Iron Oxide - MSDS



29278 REV. 1

## Material Safety Data Sheet

### Substance Identification

| | | | |
|---|---|---|---|
| **Identity:** | RED IRON OXIDE | **CAS #:** | 1309-37-1 |
| **Trade Names:** | Rouge | | |

Manufacturer:

The Prince Manufacturing Co.
One Prince Plaza
Quincy, IL 62301
217-222-8854

Emergency:

Chemtrec
1-800-424-9300

### Components and Contaminants

| Chemical Name: | CAS # | OSHA PEL | ACGIH TLV | Percent |
|---|---|---|---|---|
| Iron Oxide | 1309-37-1 | — | — | 80-95% $Fe_2O_3$ |
| Silica, Crystalline Quartz (respirable) | 14808-60-7 | 0.1 mg/$m^3$ | 0.1 mg/$m^3$ (TWA) | 1-9% $SiO_2$ |
| Aluminum Oxide (non-fibrous) (respirable fraction) | 1344-28-1 | 5 mg/$m^3$ | 5 mg/$m^3$ (TWA) | 0.5-3% $Al_2O_3$ |
| Magnesium Oxide | 1309-48-4 | — | — | 0.1-1% MgO |
| Calcium Oxide | 1305-78-8 | 5 mg/$m^3$ | 5 mg/$m^3$ (TWA) | 0.1-1% CaO |

### Physical Data

| | | | |
|---|---|---|---|
| **Boiling Point:** | NA | **Specific Gravity ($H_2O$=1):** | 4.5 - 5.0 |
| **Vapor Pressure (mm/Hg):** | NA | **Melting Point:** | 1300-1700° C |
| **Vapor Density (Air=1):** | NA | **Evaporation Rate (Butyl Acetate=1):** | NA |
| **Solubility in Water:** | insoluble | | |
| **Appearance and Odor:** | red to reddish-brown powder, no odor. | | |

### Fire and Explosion Hazard Data

| | |
|---|---|
| **Flash Point:** | Not combustible |
| **Flammable Limits:** | LEL NA UEL NA |
| **Extinguishing Media:** | Foam, $CO_2$, dry chemical or water. |
| **Special Fire Fighting Procedures:** | In the event of fire, wear full protective clothing and NIOSH-approved self-contained breathing apparatus with full face piece operated in the pressure demand or other positive pressure mode. |
| **Unusual Fire and explosion hazards:** | Not combustible. |

### Reactivity Data

| | |
|---|---|
| **Stability:** | Stable under ordinary conditions of use and storage. |
| **Conditions to avoid:** | None Known |
| **Incompatibility (materials to avoid):** | Aluminum, Ethylene Oxide, $Ca(OCl)_2$, $N_2H_4$. |
| **Hazardous Decomposition or Byproducts:** | None Known. |
| **Hazardous Polymerization:** | Will not occur. |

### Health Hazard Data

| | |
|---|---|
| **Route of Entry:** | INHALATION: May cause irritation of mucous membrane or delayed respiratory disease if dust is inhaled over a prolonged period of time.<br>SKIN: No.<br>INGESTION: Ingestion of mineral compounds may cause abdominal pain and nausea. |

Red Iron Oxide, Page 1
Reviewed November 1998 Unchanged since July 1991

## Health Hazard Data (cont.)

| | |
|---|---|
| **Health Hazards (Acute and Chronic):** | Respiratory disease may result from prolonged overexposure. Can cause eye irritation. |
| **Carcinogenicity:** | NTP: No IARC Monographs: Yes (Silica) |
| **Signs and Symptoms of Exposure:** | Excessive inhalation of dust may result in shortness of breath and reduced pulmonary function. Symptoms of silicosis include impaired pulmonary function and wheezing. |
| **Aggravation of Pre-existing Conditions:** | Persons with impaired respiratory function may be more susceptible to the effect of this substance. |
| **Emergency and First Aid Procedures:** | **IF INHALED**, remove to fresh air and seek medical attention for any breathing difficulty.<br>**IN CASE OF SKIN CONTACT**, wash with soap & water. Seek medical attention if red & irritated.<br>**IN CASE OF EYE CONTACT**, flush eyes immediately with water for at least 15 minutes. Seek medical attention if irritation persists.<br>**IF INGESTED**, induce vomiting immediately by giving two glasses of water and sticking finger down throat. Never give anything by mouth to an unconscious person. Call a physician immediately. |

## Precautions for Safe Handling and Use

| | |
|---|---|
| **Material Release or Spill Precautions:** | Should a spill occur, ventilate area. Clean-up personnel require respiratory protection. Recover uncontaminated material for use. Vacuum or sweep remaining material, keeping dust to a minimum. |
| **Waste Disposal Method:** | Dispose of unreclaimable material in a RCRA-approved waste facility. |
| **Handling and Storing Precautions:** | Protect containers from damage and keep closed when not in use. |
| **Other Precautions:** | Observe good personal hygiene. Wash after handling. |

## Control Measures

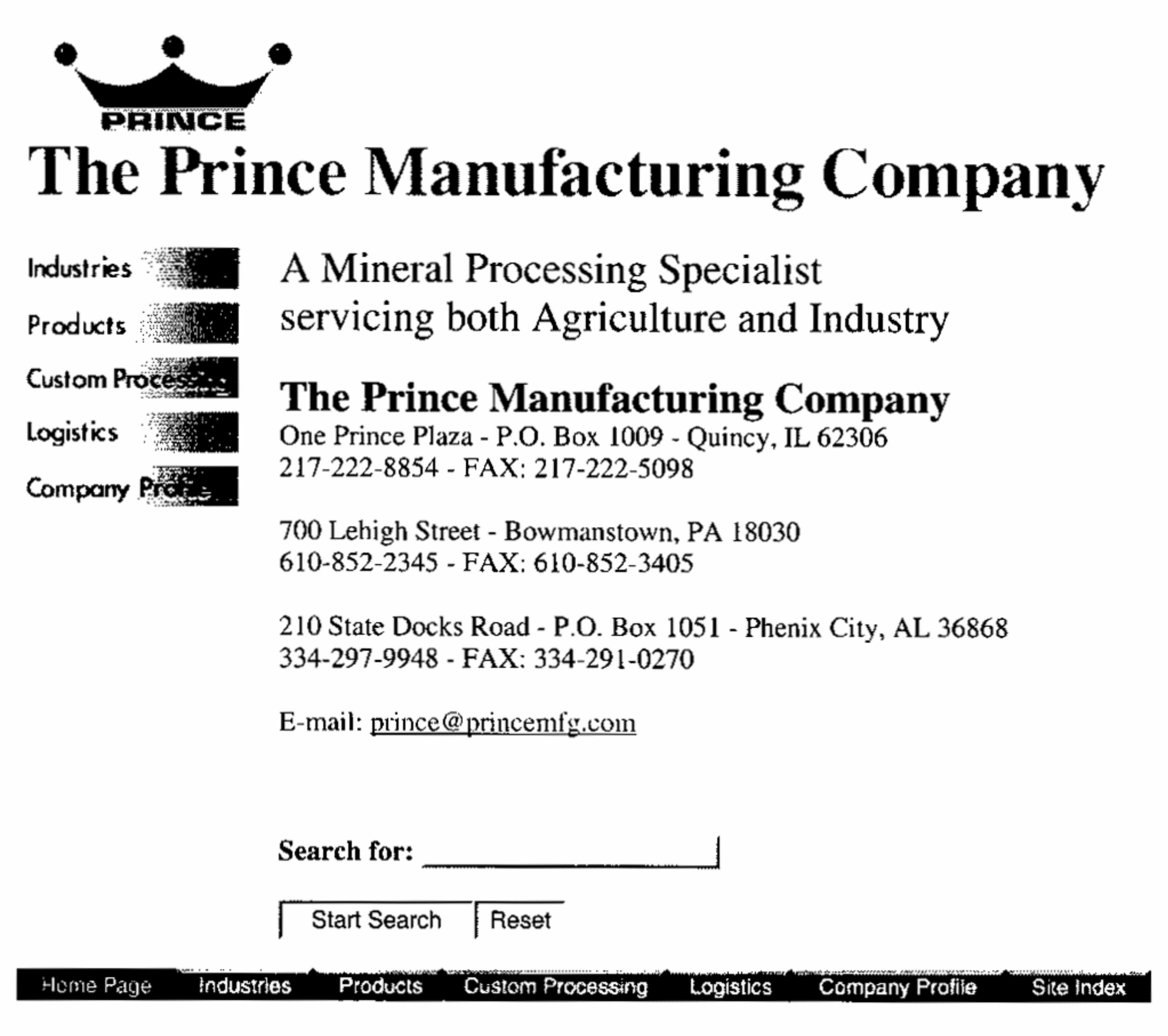
| | |
|---|---|
| **Respiratory Protection:** | Use NIOSH approved particulate respirator if dust generation occurs or is anticipated. OSHA standard 1910.134 or ANSI Z88.2-1980 specifications are recommended. |
| **Ventilation:** | A system of local and/or general exhaust is recommended to keep employee exposures below the Airborne Exposure Limits. Local exhaust is generally preferred because it can control the emissions of the contaminant at its source, preventing dispersion of it into the general work area. Please refer to the ACGIH document, "Industrial Ventilation, A Manual of Recommended Practices", most recent edition, for details. |
| **Protective Gloves:** | Yes |
| **Eye Protection:** | Safety goggles are recommended. |
| **Other Protective Clothing or Equipment:** | Use other protective equipment when necessary in order to avoid prolonged exposure to skin. |
| **Work and Hygienic Practices:** | Observe good personal hygiene. Wash after handling. |

## SARA Title III Section 313 Supplier Notification

This product does not contain chemicals subject to the reporting requirements of section 313 of the Emergency Planning and Community Right-to-Know Act of 1986 and of 40 CFR 372.45:

This information must be included in all MSDS's that are copied and distributed for this material.

**Figure B.6: Iron Oxide – Vendor Technical Data**



The Prince Manufacturing Company

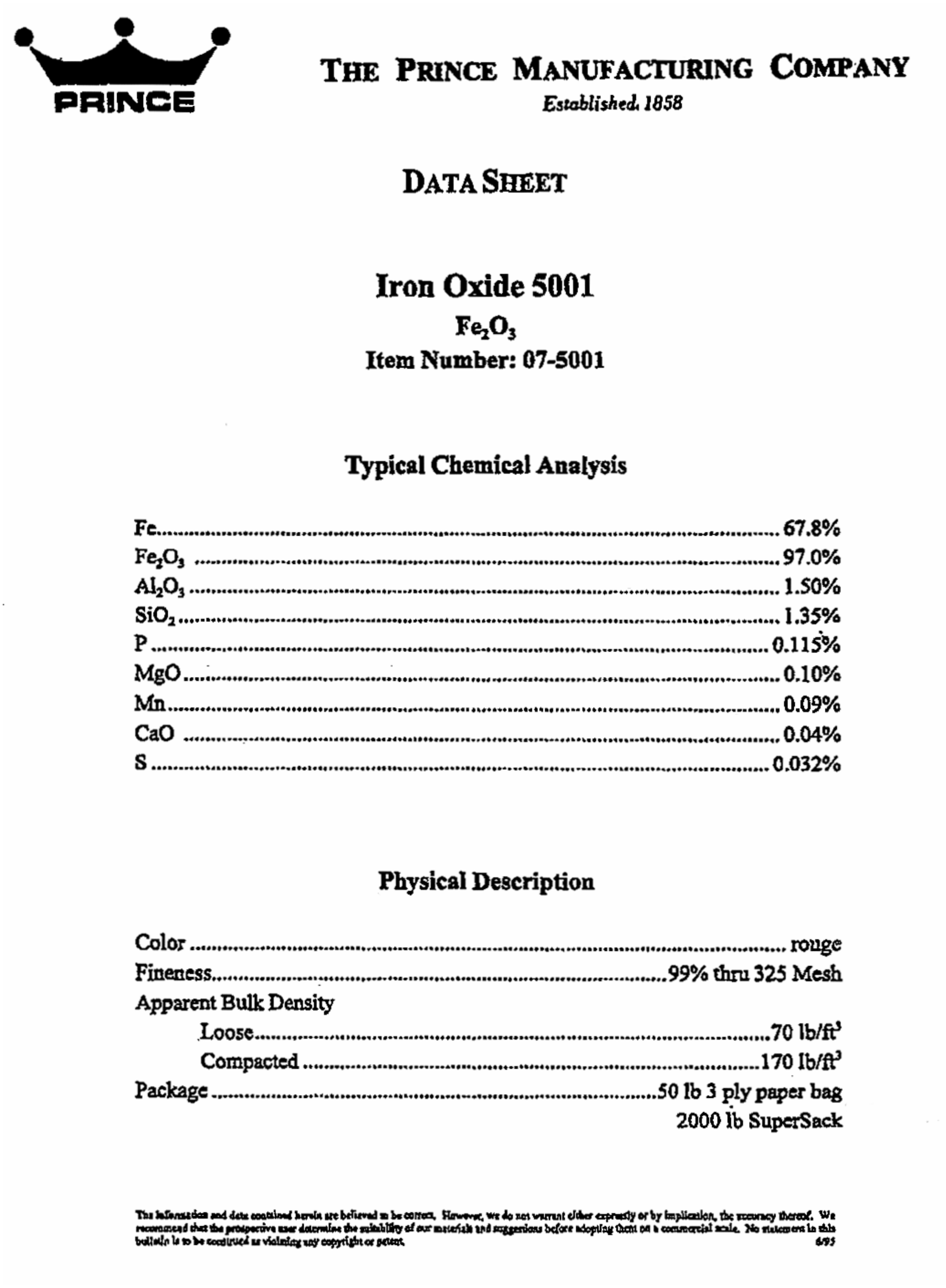
A Mineral Processing Specialist
servicing both Agriculture and Industry

**The Prince Manufacturing Company**
One Prince Plaza - P.O. Box 1009 - Quincy, IL 62306
217-222-8854 - FAX: 217-222-5098

700 Lehigh Street - Bowmanstown, PA 18030
610-852-2345 - FAX: 610-852-3405

210 State Docks Road - P.O. Box 1051 - Phenix City, AL 36868
334-297-9948 - FAX: 334-291-0270

E-mail: prince@princemfg.com



**PRINCE**

# THE PRINCE MANUFACTURING COMPANY

*Established 1858*

## DATA SHEET

## Iron Oxide 5001

**$Fe_2O_3$**

**Item Number: 07-5001**

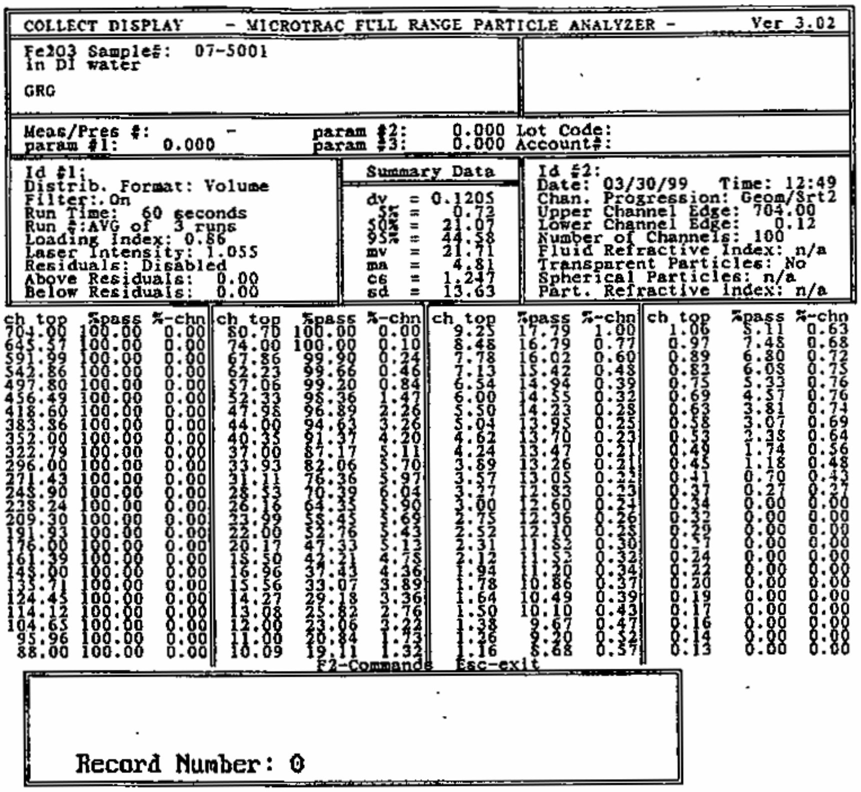
### Typical Chemical Analysis

| | |
|---|---|
| Fe | 67.8% |
| $Fe_2O_3$ | 97.0% |
| $Al_2O_3$ | 1.50% |
| $SiO_2$ | 1.35% |
| P | 0.115% |
| MgO | 0.10% |
| Mn | 0.09% |
| CaO | 0.04% |
| S | 0.032% |

### Physical Description

| | |
|---|---|
| Color | rouge |
| Fineness | 99% thru 325 Mesh |
| Apparent Bulk Density | |
| Loose | 70 lb/ft$^3$ |
| Compacted | 170 lb/ft$^3$ |
| Package | 50 lb 3 ply paper bag<br>2000 lb SuperSack |

6/95



```
COLLECT DISPLAY     - MICROTRAC FULL RANGE PARTICLE ANALYZER -       Ver 3.02
Fe2O3 Sample#:  07-5001
in DI water

GRG

Meas/Pres #:          -        param #2:     0.000 Lot Code:
param #1:     0.000            param #3:     0.000 Account#:

Id #1:                          Summary Data     Id #2:
Distrib. Format: Volume        dv  = 0.1205     Date: 03/30/99   Time: 12:49
Filter:.On                      5% =   0.72     Chan. Progression: Geom/Srt2
Run Time:  60 seconds          50% =  21.07     Upper Channel Edge: 704.00
Run #:AVG of  3 runs           95% =  44.58     Lower Channel Edge:   0.12
Loading Index: 0.86            mv  =  21.71     Number of Channels: 100
Laser Intensity: 1.055         ma  =   4.81     Fluid Refractive Index: n/a
Residuals: Disabled            cs  =  1.247     Transparent Particles: No
Above Residuals:  0.00         sd  =  13.63     Spherical Particles: n/a
Below Residuals:  0.00                          Part. Refractive Index: n/a

ch top  %pass  %-chn  ch top  %pass  %-chn  ch top  %pass  %-chn  ch top  %pass  %-chn
704.00 100.00   0.00   80.70 100.00   0.00    9.25  17.79   1.00    1.06   8.11   0.63
645.57 100.00   0.00   74.00 100.00   0.10    8.48  16.79   0.77    0.97   7.48   0.68
591.99 100.00   0.00   67.86  99.90   0.24    7.78  16.02   0.60    0.89   6.80   0.72
542.86 100.00   0.00   62.23  99.66   0.46    7.13  15.42   0.48    0.82   6.08   0.75
497.80 100.00   0.00   57.06  99.20   0.84    6.54  14.94   0.39    0.75   5.33   0.76
456.49 100.00   0.00   52.33  98.36   1.47    6.00  14.55   0.32    0.69   4.57   0.76
418.60 100.00   0.00   47.98  96.89   2.26    5.50  14.23   0.28    0.63   3.81   0.74
383.86 100.00   0.00   44.00  94.63   3.26    5.04  13.95   0.25    0.58   3.07   0.69
352.00 100.00   0.00   40.35  91.37   4.20    4.62  13.70   0.23    0.53   2.38   0.64
322.79 100.00   0.00   37.00  87.17   5.11    4.24  13.47   0.21    0.49   1.74   0.56
296.00 100.00   0.00   33.93  82.06   5.70    3.89  13.26   0.21    0.45   1.18   0.48
271.43 100.00   0.00   31.11  76.36   5.97    3.57  13.05   0.22    0.41   0.70   0.43
248.90 100.00   0.00   28.53  70.39   6.04    3.27  12.83   0.23    0.37   0.27   0.27
228.24 100.00   0.00   26.16  64.35   5.90    3.00  12.60   0.24    0.34   0.00   0.00
209.30 100.00   0.00   23.99  58.45   5.69    2.75  12.36   0.26    0.32   0.00   0.00
191.93 100.00   0.00   22.00  52.76   5.43    2.52  12.10   0.28    0.29   0.00   0.00
176.00 100.00   0.00   20.17  47.33   5.13    2.31  11.82   0.30    0.27   0.00   0.00
161.39 100.00   0.00   18.50  42.21   4.78    2.12  11.52   0.32    0.24   0.00   0.00
148.00 100.00   0.00   16.96  37.43   4.36    1.94  11.20   0.34    0.22   0.00   0.00
135.71 100.00   0.00   15.56  33.07   3.89    1.78  10.86   0.37    0.20   0.00   0.00
124.45 100.00   0.00   14.27  29.18   3.36    1.64  10.49   0.39    0.19   0.00   0.00
114.12 100.00   0.00   13.08  25.82   2.76    1.50  10.10   0.43    0.17   0.00   0.00
104.65 100.00   0.00   12.00  23.06   2.22    1.38   9.67   0.47    0.16   0.00   0.00
 95.96 100.00   0.00   11.00  20.84   1.73    1.26   9.20   0.52    0.14   0.00   0.00
 88.00 100.00   0.00   10.09  19.11   1.32    1.16   8.68   0.57    0.13   0.00   0.00
                                  F2-Commands   Esc-exit

     Record Number: 0
```

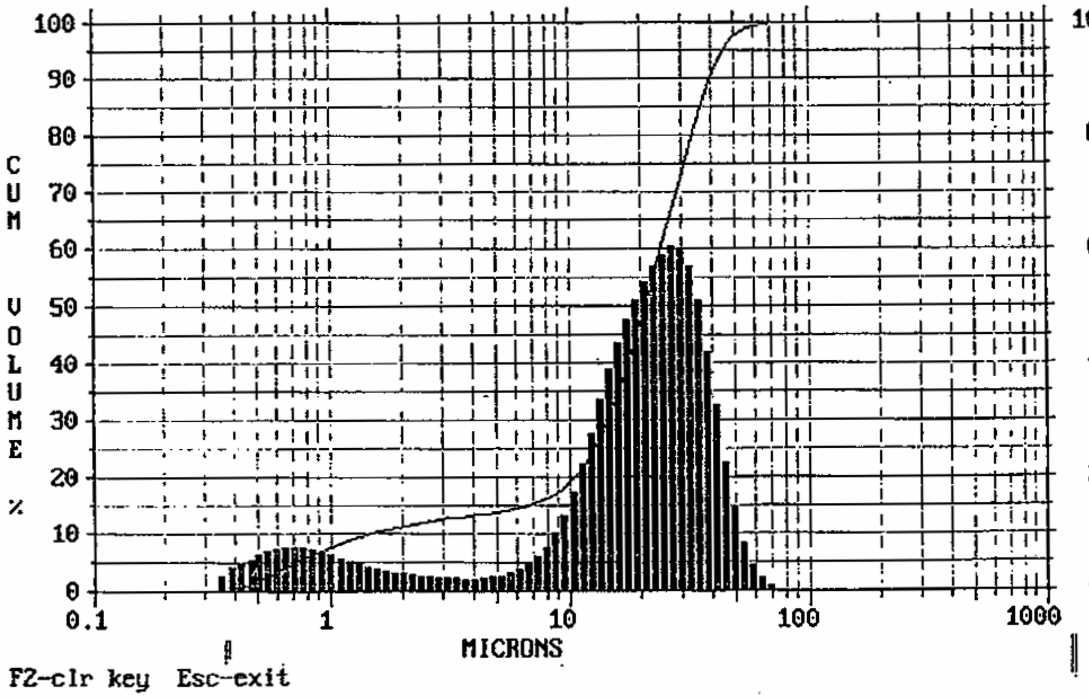
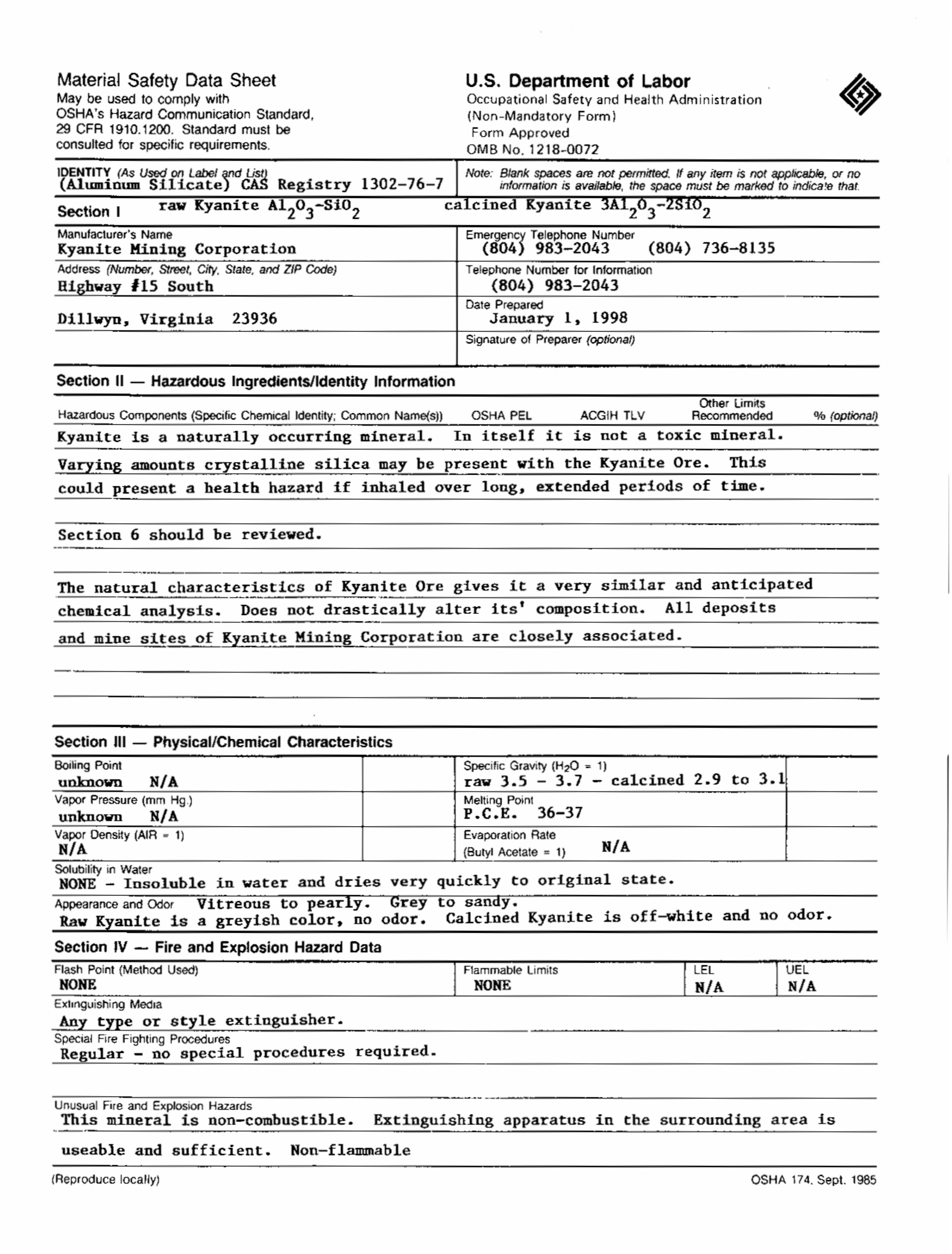


**Figure B.7: Kyanite - MSDS**



**Material Safety Data Sheet**
May be used to comply with
OSHA's Hazard Communication Standard,
29 CFR 1910.1200. Standard must be
consulted for specific requirements.

**U.S. Department of Labor**
Occupational Safety and Health Administration
(Non-Mandatory Form)
Form Approved
OMB No. 1218-0072

**IDENTITY** *(As Used on Label and List)*
(Aluminum Silicate) CAS Registry 1302-76-7

*Note: Blank spaces are not permitted. If any item is not applicable, or no information is available, the space must be marked to indicate that.*

**Section I** raw Kyanite $Al_2O_3$-$SiO_2$ calcined Kyanite $3Al_2O_3$-$2SiO_2$

| | |
|---|---|
| Manufacturer's Name<br>Kyanite Mining Corporation | Emergency Telephone Number<br>(804) 983-2043 (804) 736-8135 |
| Address *(Number, Street, City, State, and ZIP Code)*<br>Highway #15 South | Telephone Number for Information<br>(804) 983-2043 |
| Dillwyn, Virginia 23936 | Date Prepared<br>January 1, 1998 |
| | Signature of Preparer *(optional)* |

**Section II — Hazardous Ingredients/Identity Information**

| Hazardous Components (Specific Chemical Identity; Common Name(s)) | OSHA PEL | ACGIH TLV | Other Limits Recommended | % *(optional)* |
|---|---|---|---|---|

Kyanite is a naturally occurring mineral. In itself it is not a toxic mineral.
Varying amounts crystalline silica may be present with the Kyanite Ore. This
could present a health hazard if inhaled over long, extended periods of time.

Section 6 should be reviewed.

The natural characteristics of Kyanite Ore gives it a very similar and anticipated
chemical analysis. Does not drastically alter its' composition. All deposits
and mine sites of Kyanite Mining Corporation are closely associated.

**Section III — Physical/Chemical Characteristics**

| | | | |
|---|---|---|---|
| Boiling Point<br>unknown N/A | | Specific Gravity ($H_2O$ = 1)<br>raw 3.5 - 3.7 - calcined 2.9 to 3.1 | |
| Vapor Pressure (mm Hg.)<br>unknown N/A | | Melting Point<br>P.C.E. 36-37 | |
| Vapor Density (AIR = 1)<br>N/A | | Evaporation Rate<br>(Butyl Acetate = 1) N/A | |

Solubility in Water
NONE - Insoluble in water and dries very quickly to original state.

Appearance and Odor Vitreous to pearly. Grey to sandy.
Raw Kyanite is a greyish color, no odor. Calcined Kyanite is off-white and no odor.

**Section IV — Fire and Explosion Hazard Data**

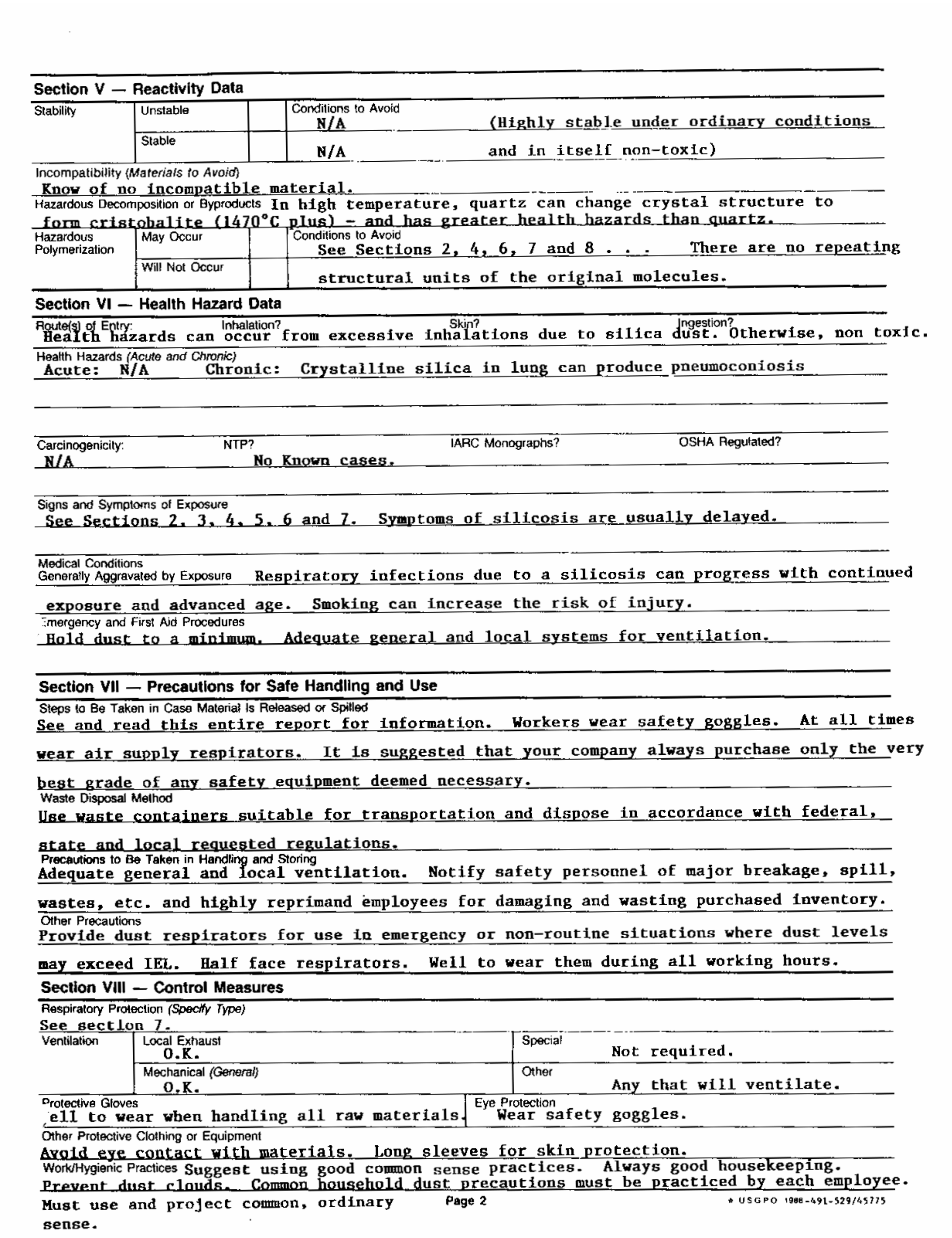
| | | | |
|---|---|---|---|
| Flash Point (Method Used)<br>NONE | Flammable Limits<br>NONE | LEL<br>N/A | UEL<br>N/A |

Extinguishing Media
Any type or style extinguisher.

Special Fire Fighting Procedures
Regular - no special procedures required.

Unusual Fire and Explosion Hazards
This mineral is non-combustible. Extinguishing apparatus in the surrounding area is
useable and sufficient. Non-flammable

(Reproduce locally) OSHA 174, Sept. 1985



## Section V — Reactivity Data

| | | | |
|---|---|---|---|
| Stability | Unstable | | Conditions to Avoid<br>N/A (Highly stable under ordinary conditions |
| | Stable | | N/A and in itself non-toxic) |

Incompatibility (*Materials to Avoid*)
Know of no incompatible material.

Hazardous Decomposition or Byproducts In high temperature, quartz can change crystal structure to form cristobalite (1470°C plus) - and has greater health hazards than quartz.

| | | | |
|---|---|---|---|
| Hazardous Polymerization | May Occur | | Conditions to Avoid<br>See Sections 2, 4, 6, 7 and 8 . . . There are no repeating |
| | Will Not Occur | | structural units of the original molecules. |

## Section VI — Health Hazard Data

Route(s) of Entry: Inhalation? Skin? Ingestion?
Health hazards can occur from excessive inhalations due to silica dust. Otherwise, non toxic.

Health Hazards (*Acute and Chronic*)
Acute: N/A Chronic: Crystalline silica in lung can produce pneumoconiosis

Carcinogenicity: NTP? IARC Monographs? OSHA Regulated?
N/A No Known cases.

Signs and Symptoms of Exposure
See Sections 2, 3, 4, 5, 6 and 7. Symptoms of silicosis are usually delayed.

Medical Conditions Generally Aggravated by Exposure Respiratory infections due to a silicosis can progress with continued exposure and advanced age. Smoking can increase the risk of injury.

Emergency and First Aid Procedures
Hold dust to a minimum. Adequate general and local systems for ventilation.

## Section VII — Precautions for Safe Handling and Use

Steps to Be Taken in Case Material Is Released or Spilled
See and read this entire report for information. Workers wear safety goggles. At all times wear air supply respirators. It is suggested that your company always purchase only the very best grade of any safety equipment deemed necessary.

Waste Disposal Method
Use waste containers suitable for transportation and dispose in accordance with federal, state and local requested regulations.

Precautions to Be Taken in Handling and Storing
Adequate general and local ventilation. Notify safety personnel of major breakage, spill, wastes, etc. and highly reprimand employees for damaging and wasting purchased inventory.

Other Precautions
Provide dust respirators for use in emergency or non-routine situations where dust levels may exceed IEL. Half face respirators. Well to wear them during all working hours.

## Section VIII — Control Measures

Respiratory Protection (*Specify Type*)
See section 7.

| | | |
|---|---|---|
| Ventilation | Local Exhaust<br>O.K. | Special<br>Not required. |
| | Mechanical (*General*)<br>O.K. | Other<br>Any that will ventilate. |

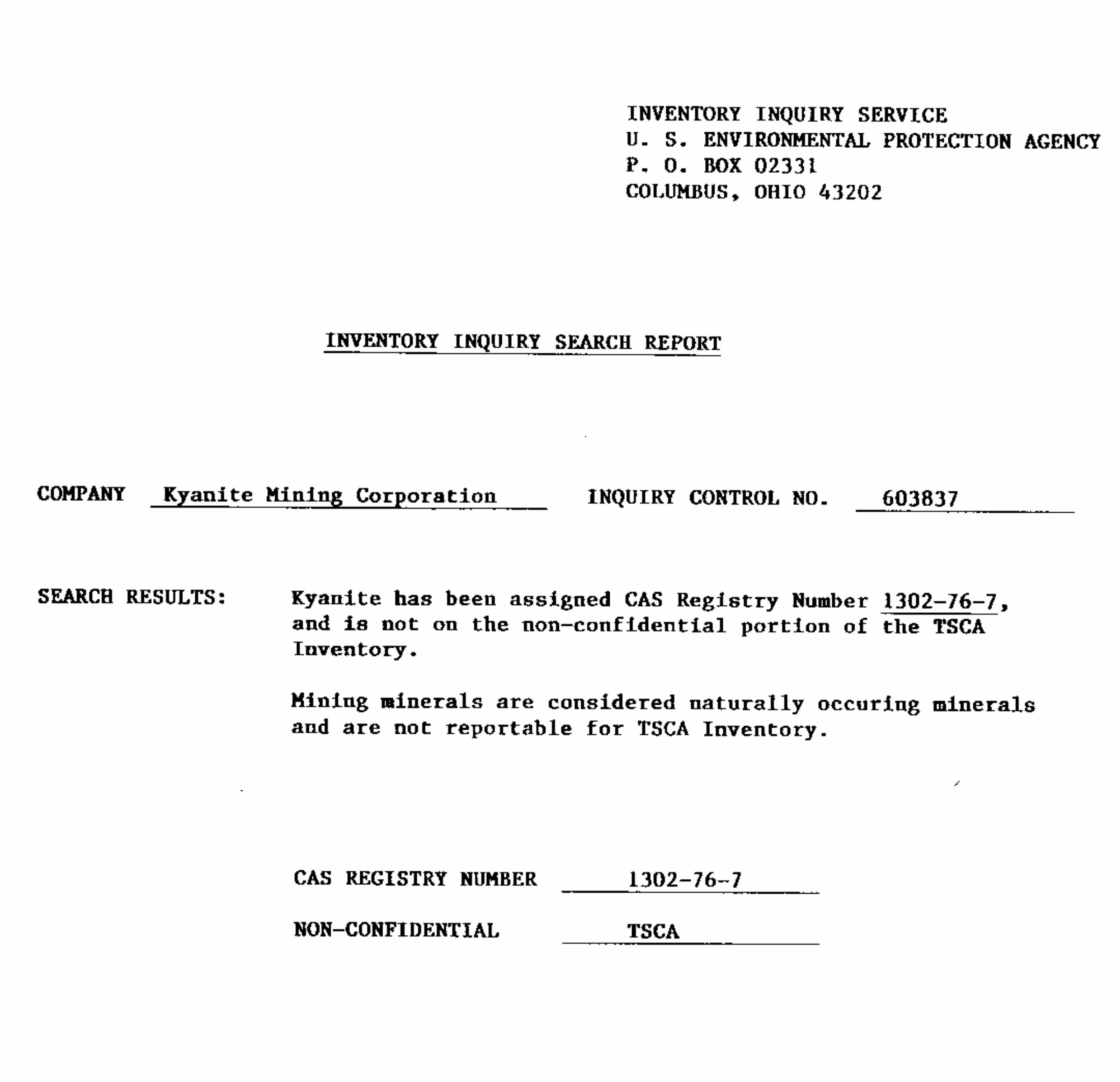
| | |
|---|---|
| Protective Gloves<br>ell to wear when handling all raw materials. | Eye Protection<br>Wear safety goggles. |

Other Protective Clothing or Equipment
Avoid eye contact with materials. Long sleeves for skin protection.

Work/Hygienic Practices Suggest using good common sense practices. Always good housekeeping. Prevent dust clouds. Common household dust precautions must be practiced by each employee. Must use and project common, ordinary sense.

Page 2

* USGPO 1986-491-529/45775



INVENTORY INQUIRY SERVICE
U. S. ENVIRONMENTAL PROTECTION AGENCY
P. O. BOX 02331
COLUMBUS, OHIO 43202

## INVENTORY INQUIRY SEARCH REPORT

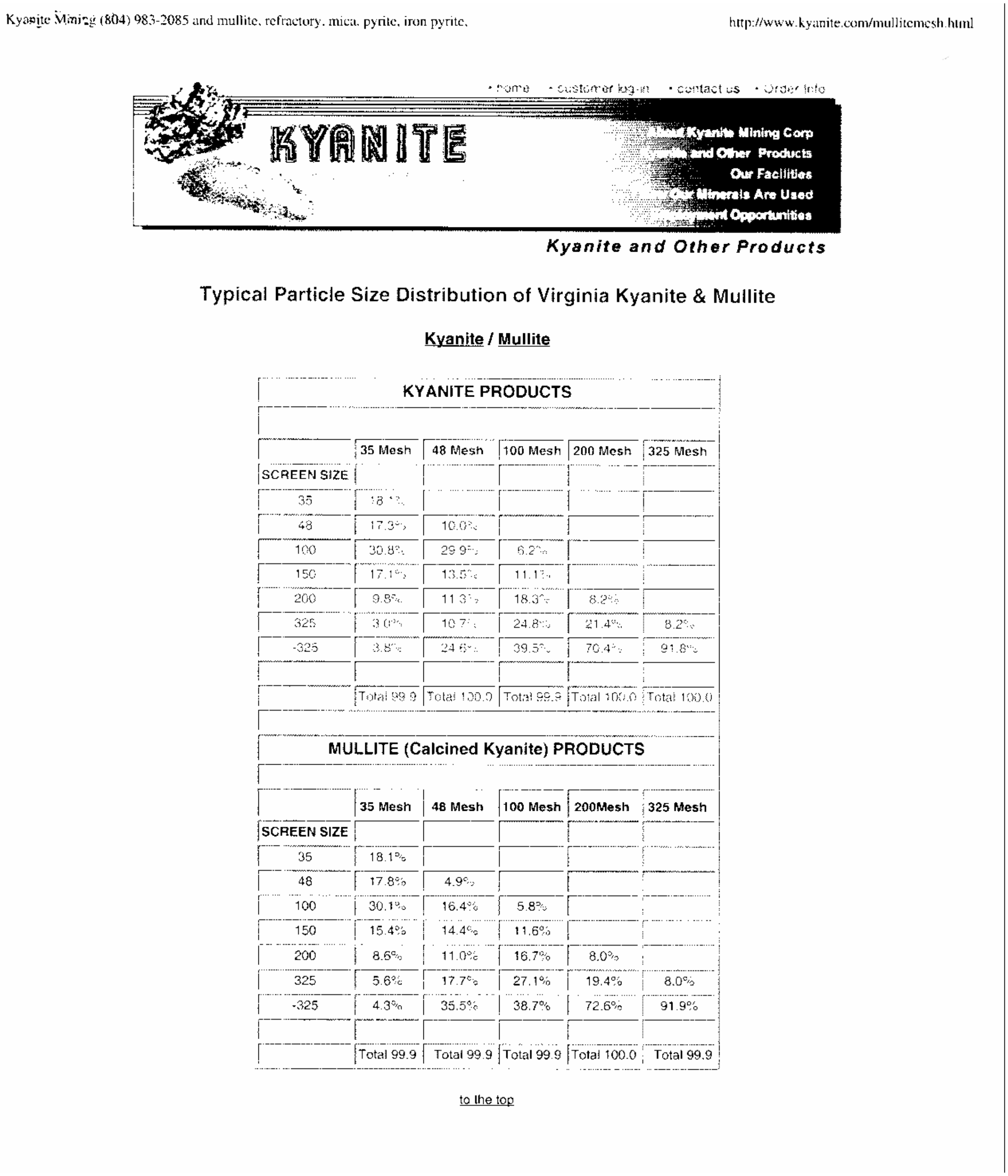
COMPANY Kyanite Mining Corporation INQUIRY CONTROL NO. 603837

SEARCH RESULTS: Kyanite has been assigned CAS Registry Number 1302-76-7, and is not on the non-confidential portion of the TSCA Inventory.

Mining minerals are considered naturally occuring minerals and are not reportable for TSCA Inventory.

CAS REGISTRY NUMBER 1302-76-7

NON-CONFIDENTIAL TSCA



Kyanite Mining (804) 983-2085 and mullite, refractory, mica, pyrite, iron pyrite, http://www.kyanite.com/mullitemesh.html

• home • customer log-in • contact us • Order Info

Kyanite Mining Corp
and Other Products
Our Facilities
Our Minerals Are Used
Opportunities

*Kyanite and Other Products*

## Typical Particle Size Distribution of Virginia Kyanite & Mullite

**Kyanite / Mullite**

### KYANITE PRODUCTS

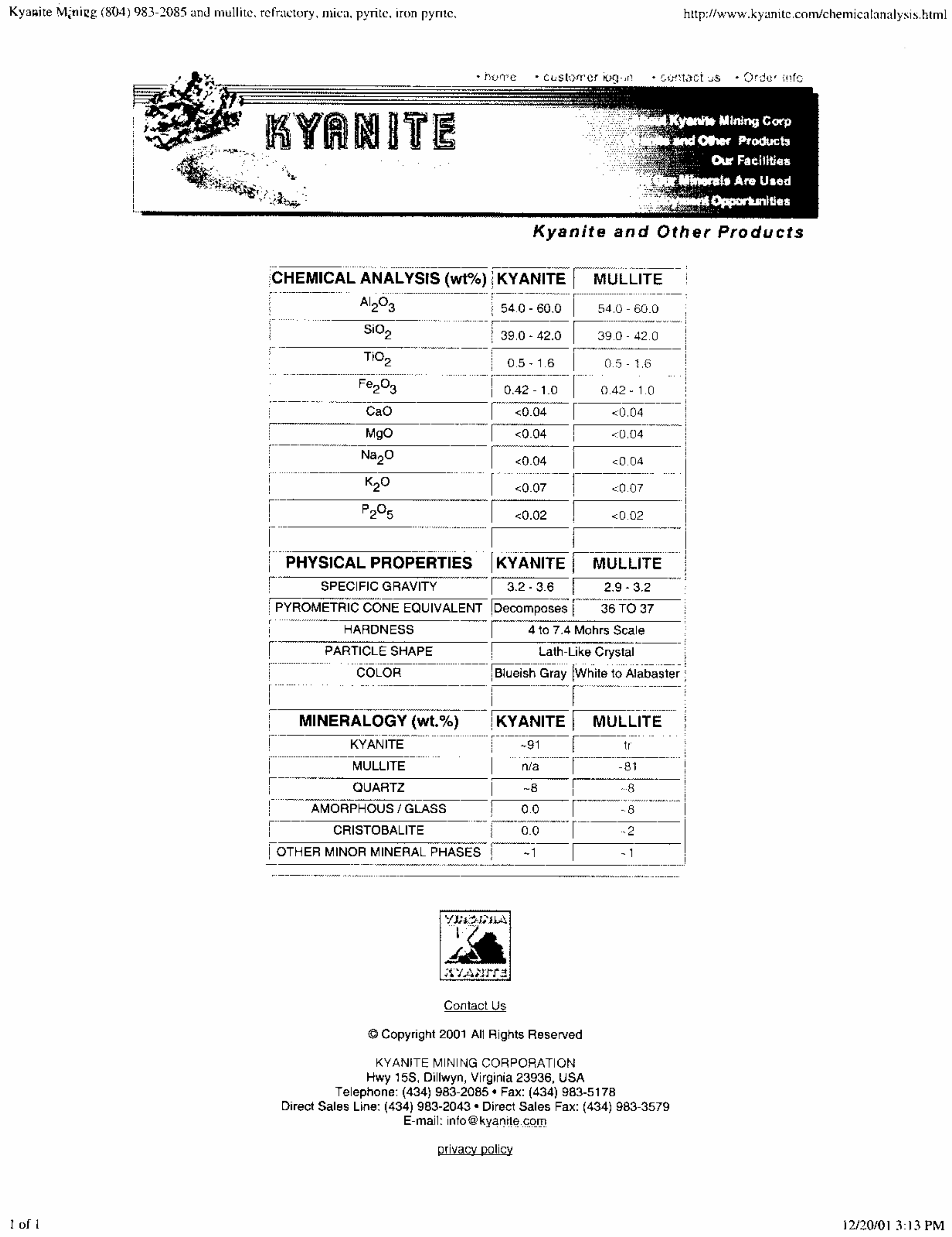
| | 35 Mesh | 48 Mesh | 100 Mesh | 200 Mesh | 325 Mesh |
|---|---|---|---|---|---|
| SCREEN SIZE | | | | | |
| 35 | 18.1% | | | | |
| 48 | 17.3% | 10.0% | | | |
| 100 | 30.8% | 29.9% | 6.2% | | |
| 150 | 17.1% | 13.5% | 11.1% | | |
| 200 | 9.8% | 11.3% | 18.3% | 8.2% | |
| 325 | 3.0% | 10.7% | 24.8% | 21.4% | 8.2% |
| -325 | 3.8% | 24.6% | 39.5% | 70.4% | 91.8% |
| | | | | | |
| | Total 99.9 | Total 100.0 | Total 99.9 | Total 100.0 | Total 100.0 |

### MULLITE (Calcined Kyanite) PRODUCTS

| | 35 Mesh | 48 Mesh | 100 Mesh | 200Mesh | 325 Mesh |
|---|---|---|---|---|---|
| SCREEN SIZE | | | | | |
| 35 | 18.1% | | | | |
| 48 | 17.8% | 4.9% | | | |
| 100 | 30.1% | 16.4% | 5.8% | | |
| 150 | 15.4% | 14.4% | 11.6% | | |
| 200 | 8.6% | 11.0% | 16.7% | 8.0% | |
| 325 | 5.6% | 17.7% | 27.1% | 19.4% | 8.0% |
| -325 | 4.3% | 35.5% | 38.7% | 72.6% | 91.9% |
| | | | | | |
| | Total 99.9 | Total 99.9 | Total 99.9 | Total 100.0 | Total 99.9 |

to the top

## Figure B.8: Kyanite – Vendor Technical Data



Kyanite Mining (804) 983-2085 and mullite, refractory, mica, pyrite, iron pyrite, http://www.kyanite.com/chemicalanalysis.html

• home • customer log-in • contact us • Order info
KYANITE
Kyanite Mining Corp
Kyanite and Other Products
Our Facilities
Our Minerals Are Used
Opportunities

**Kyanite and Other Products**

| CHEMICAL ANALYSIS (wt%) | KYANITE | MULLITE |
|---|---|---|
| $Al_2O_3$ | 54.0 - 60.0 | 54.0 - 60.0 |
| $SiO_2$ | 39.0 - 42.0 | 39.0 - 42.0 |
| $TiO_2$ | 0.5 - 1.6 | 0.5 - 1.6 |
| $Fe_2O_3$ | 0.42 - 1.0 | 0.42 - 1.0 |
| CaO | <0.04 | <0.04 |
| MgO | <0.04 | <0.04 |
| $Na_2O$ | <0.04 | <0.04 |
| $K_2O$ | <0.07 | <0.07 |
| $P_2O_5$ | <0.02 | <0.02 |
| | | |
| **PHYSICAL PROPERTIES** | **KYANITE** | **MULLITE** |
| SPECIFIC GRAVITY | 3.2 - 3.6 | 2.9 - 3.2 |
| PYROMETRIC CONE EQUIVALENT | Decomposes | 36 TO 37 |
| HARDNESS | 4 to 7.4 Mohrs Scale | |
| PARTICLE SHAPE | Lath-Like Crystal | |
| COLOR | Blueish Gray | White to Alabaster |
| | | |
| **MINERALOGY (wt.%)** | **KYANITE** | **MULLITE** |
| KYANITE | ~91 | tr |
| MULLITE | n/a | ~81 |
| QUARTZ | ~8 | ~8 |
| AMORPHOUS / GLASS | 0.0 | ~8 |
| CRISTOBALITE | 0.0 | ~2 |
| OTHER MINOR MINERAL PHASES | ~1 | ~1 |

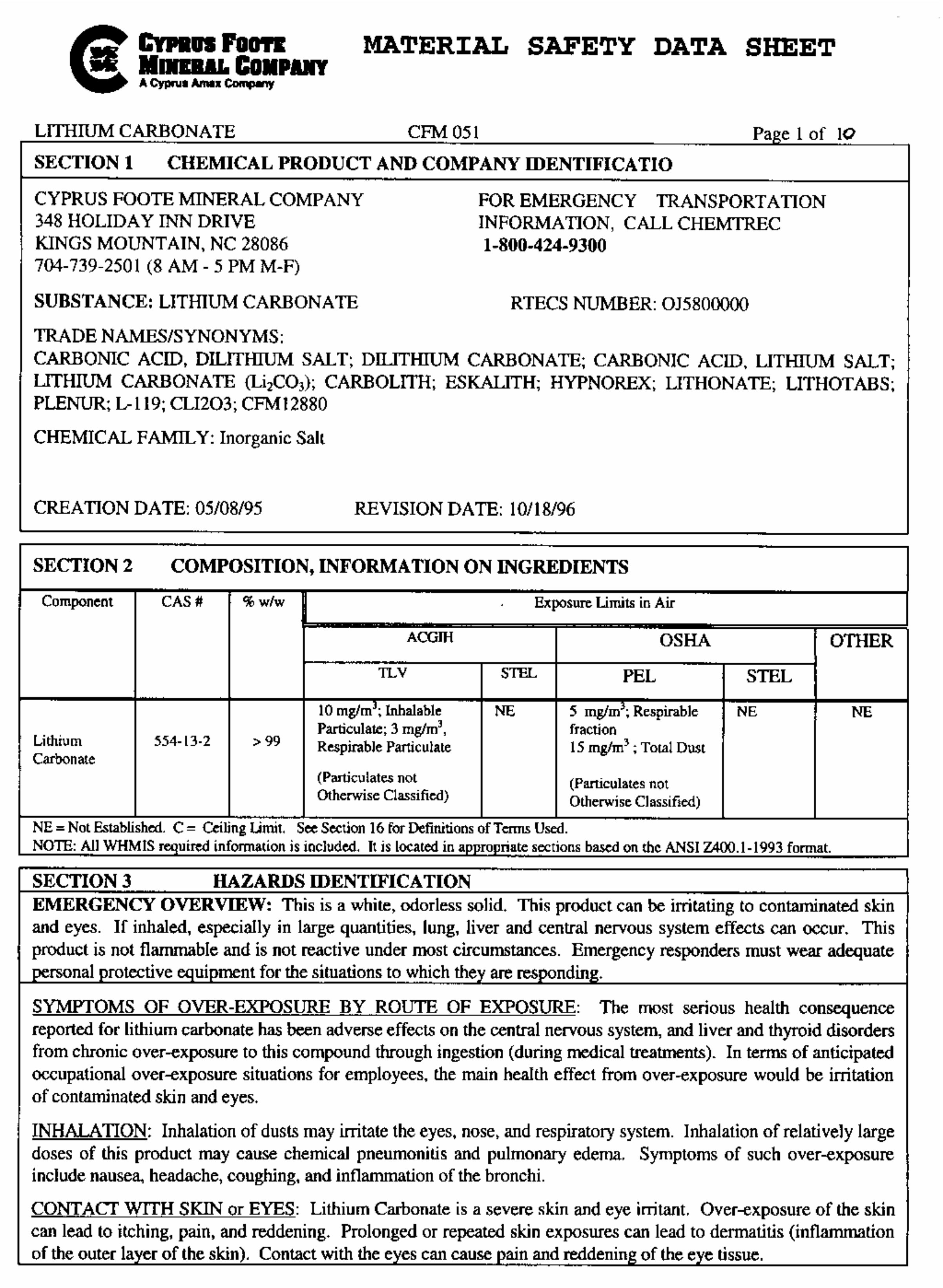
Contact Us

KYANITE MINING CORPORATION
Hwy 15S, Dillwyn, Virginia 23936, USA
Telephone: (434) 983-2085 • Fax: (434) 983-5178
Direct Sales Line: (434) 983-2043 • Direct Sales Fax: (434) 983-3579
E-mail: info@kyanite.com

privacy policy

1 of 1 12/20/01 3:13 PM

Figure B.9: Lithium Carbonate - MSDS



**CYPRUS FOOTE MINERAL COMPANY**
A Cyprus Amax Company

# MATERIAL SAFETY DATA SHEET

LITHIUM CARBONATE CFM 051 Page 1 of 10

## SECTION 1 CHEMICAL PRODUCT AND COMPANY IDENTIFICATIO

CYPRUS FOOTE MINERAL COMPANY
348 HOLIDAY INN DRIVE
KINGS MOUNTAIN, NC 28086
704-739-2501 (8 AM - 5 PM M-F)

FOR EMERGENCY TRANSPORTATION INFORMATION, CALL CHEMTREC
**1-800-424-9300**

**SUBSTANCE:** LITHIUM CARBONATE

RTECS NUMBER: OJ5800000

TRADE NAMES/SYNONYMS:
CARBONIC ACID, DILITHIUM SALT; DILITHIUM CARBONATE; CARBONIC ACID, LITHIUM SALT; LITHIUM CARBONATE ($Li_2CO_3$); CARBOLITH; ESKALITH; HYPNOREX; LITHONATE; LITHOTABS; PLENUR; L-119; CLI2O3; CFM12880

CHEMICAL FAMILY: Inorganic Salt

CREATION DATE: 05/08/95 REVISION DATE: 10/18/96

## SECTION 2 COMPOSITION, INFORMATION ON INGREDIENTS

| Component | CAS # | % w/w | Exposure Limits in Air | | | | |
|---|---|---|---|---|---|---|---|
| | | | ACGIH | | OSHA | | OTHER |
| | | | TLV | STEL | PEL | STEL | |
| Lithium Carbonate | 554-13-2 | > 99 | 10 mg/m$^3$; Inhalable Particulate; 3 mg/m$^3$, Respirable Particulate<br>(Particulates not Otherwise Classified) | NE | 5 mg/m$^3$; Respirable fraction<br>15 mg/m$^3$ ; Total Dust<br>(Particulates not Otherwise Classified) | NE | NE |

NE = Not Established. C = Ceiling Limit. See Section 16 for Definitions of Terms Used.
NOTE: All WHMIS required information is included. It is located in appropriate sections based on the ANSI Z400.1-1993 format.

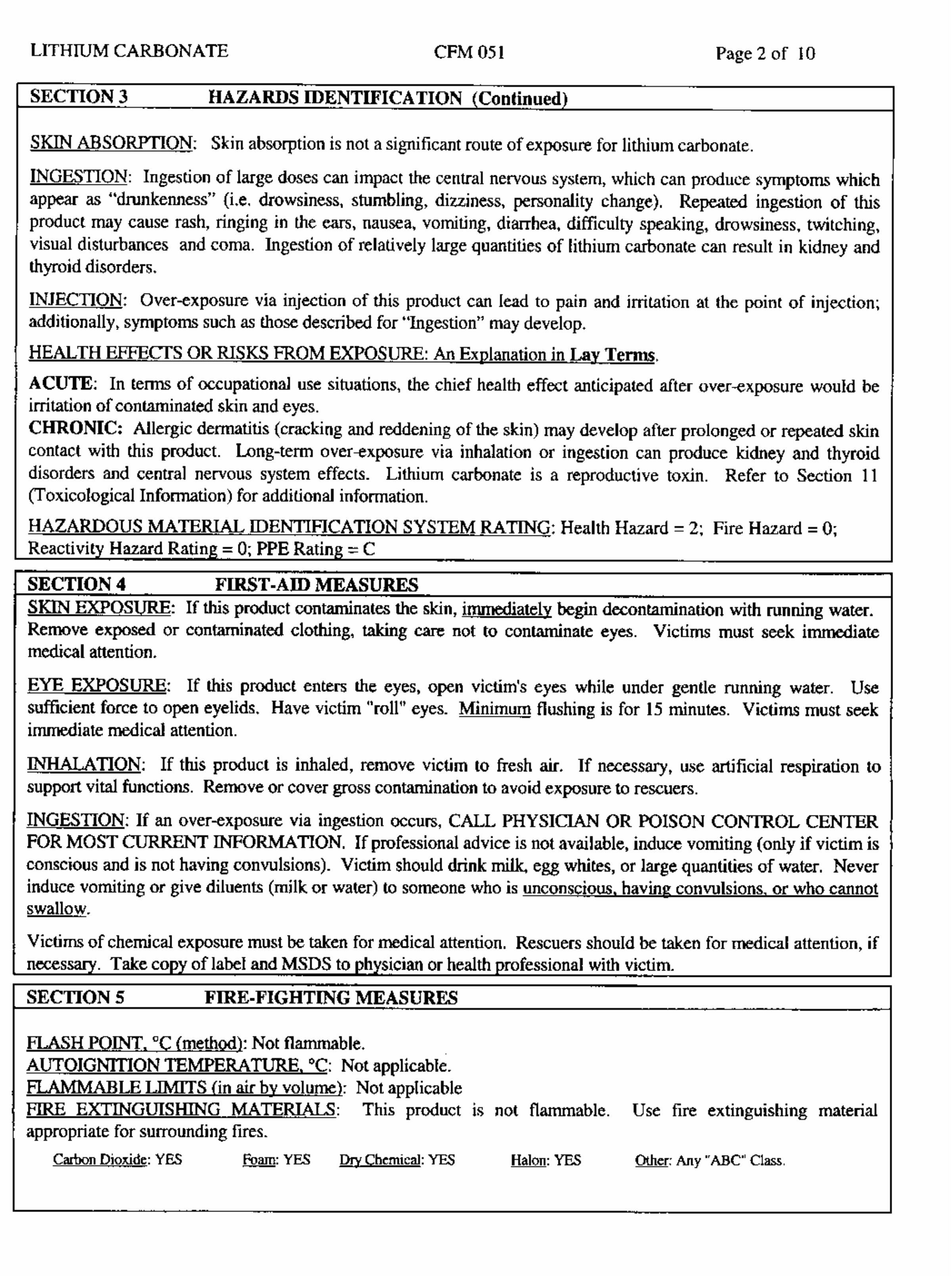
## SECTION 3 HAZARDS IDENTIFICATION

**EMERGENCY OVERVIEW:** This is a white, odorless solid. This product can be irritating to contaminated skin and eyes. If inhaled, especially in large quantities, lung, liver and central nervous system effects can occur. This product is not flammable and is not reactive under most circumstances. Emergency responders must wear adequate personal protective equipment for the situations to which they are responding.

SYMPTOMS OF OVER-EXPOSURE BY ROUTE OF EXPOSURE: The most serious health consequence reported for lithium carbonate has been adverse effects on the central nervous system, and liver and thyroid disorders from chronic over-exposure to this compound through ingestion (during medical treatments). In terms of anticipated occupational over-exposure situations for employees, the main health effect from over-exposure would be irritation of contaminated skin and eyes.

INHALATION: Inhalation of dusts may irritate the eyes, nose, and respiratory system. Inhalation of relatively large doses of this product may cause chemical pneumonitis and pulmonary edema. Symptoms of such over-exposure include nausea, headache, coughing, and inflammation of the bronchi.

CONTACT WITH SKIN or EYES: Lithium Carbonate is a severe skin and eye irritant. Over-exposure of the skin can lead to itching, pain, and reddening. Prolonged or repeated skin exposures can lead to dermatitis (inflammation of the outer layer of the skin). Contact with the eyes can cause pain and reddening of the eye tissue.



## SECTION 3 HAZARDS IDENTIFICATION (Continued)

SKIN ABSORPTION: Skin absorption is not a significant route of exposure for lithium carbonate.

INGESTION: Ingestion of large doses can impact the central nervous system, which can produce symptoms which appear as "drunkenness" (i.e. drowsiness, stumbling, dizziness, personality change). Repeated ingestion of this product may cause rash, ringing in the ears, nausea, vomiting, diarrhea, difficulty speaking, drowsiness, twitching, visual disturbances and coma. Ingestion of relatively large quantities of lithium carbonate can result in kidney and thyroid disorders.

INJECTION: Over-exposure via injection of this product can lead to pain and irritation at the point of injection; additionally, symptoms such as those described for "Ingestion" may develop.

HEALTH EFFECTS OR RISKS FROM EXPOSURE: An Explanation in **Lay Terms**.

**ACUTE**: In terms of occupational use situations, the chief health effect anticipated after over-exposure would be irritation of contaminated skin and eyes.
**CHRONIC:** Allergic dermatitis (cracking and reddening of the skin) may develop after prolonged or repeated skin contact with this product. Long-term over-exposure via inhalation or ingestion can produce kidney and thyroid disorders and central nervous system effects. Lithium carbonate is a reproductive toxin. Refer to Section 11 (Toxicological Information) for additional information.

HAZARDOUS MATERIAL IDENTIFICATION SYSTEM RATING: Health Hazard = 2; Fire Hazard = 0; Reactivity Hazard Rating = 0; PPE Rating = C

## SECTION 4 FIRST-AID MEASURES

SKIN EXPOSURE: If this product contaminates the skin, immediately begin decontamination with running water. Remove exposed or contaminated clothing, taking care not to contaminate eyes. Victims must seek immediate medical attention.

EYE EXPOSURE: If this product enters the eyes, open victim's eyes while under gentle running water. Use sufficient force to open eyelids. Have victim "roll" eyes. Minimum flushing is for 15 minutes. Victims must seek immediate medical attention.

INHALATION: If this product is inhaled, remove victim to fresh air. If necessary, use artificial respiration to support vital functions. Remove or cover gross contamination to avoid exposure to rescuers.

INGESTION: If an over-exposure via ingestion occurs, CALL PHYSICIAN OR POISON CONTROL CENTER FOR MOST CURRENT INFORMATION. If professional advice is not available, induce vomiting (only if victim is conscious and is not having convulsions). Victim should drink milk, egg whites, or large quantities of water. Never induce vomiting or give diluents (milk or water) to someone who is unconscious, having convulsions, or who cannot swallow.

Victims of chemical exposure must be taken for medical attention. Rescuers should be taken for medical attention, if necessary. Take copy of label and MSDS to physician or health professional with victim.

## SECTION 5 FIRE-FIGHTING MEASURES

FLASH POINT, °C (method): Not flammable.
AUTOIGNITION TEMPERATURE, °C: Not applicable.
FLAMMABLE LIMITS (in air by volume): Not applicable
FIRE EXTINGUISHING MATERIALS: This product is not flammable. Use fire extinguishing material appropriate for surrounding fires.

Carbon Dioxide: YES Foam: YES Dry Chemical: YES Halon: YES Other: Any "ABC" Class.

## SECTION 5 FIRE-FIGHTING MEASURES (Continued)

UNUSUAL FIRE AND EXPLOSION HAZARDS: When involved in a fire, this material may decompose and produce irritating fumes and toxic gases (lithium compounds, carbon oxides).

Explosion Sensitivity to Mechanical Impact: Not sensitive.
Explosion Sensitivity to Static Discharge: Not sensitive.

SPECIAL FIRE-FIGHTING PROCEDURES: Incipient fire responders should wear eye protection. Structural fire fighters must wear Self-Contained Breathing Apparatus and full protective equipment

NFPA RATING: Health Hazard = 2; Fire Hazard = 0; Reactivity Hazard Rating = 0.

## SECTION 6 ACCIDENTAL RELEASE MEASURES

Uncontrolled releases should be responded to by trained personnel using pre-planned procedures. Proper protective equipment should be used. In case of a spill, clear the affected area, protect people, and respond with trained personnel.

The minimum Personal Protective Equipment recommended for response to non-incidental releases should be **Level C: triple-gloves (rubber gloves and nitrile gloves, over latex gloves), chemically resistant suit and boots, hard-hat, and air-purifying respirator with high-efficiency particulate filter. Level B with a Self-Contained Breathing Apparatus should be worn in situations where the oxygen level is below 19.5 % or is unknown.**

Sweep-up or vacuum spilled material carefully, avoiding the generation of dusts. Decontaminate the area thoroughly. Place all spill residue in an appropriate container. Dispose of in accordance with Federal, State, and local solid waste disposal regulations (see Section 13, Disposal Considerations).

## SECTION 7 HANDLING AND STORAGE

WORK PRACTICES AND HYGIENE PRACTICES: As with all chemicals, avoid getting this product ON YOU or IN YOU. Do not eat or drink while handling this product. Wash hands after handling this material. Avoid creating dusts of this product.

STORAGE AND HANDLING PRACTICES: All employees who handle this material should be trained to handle it safely. Avoid breathing dusts or particles generated by this product. Wash thoroughly after using this material. Read instructions provided with the product prior to use.

PROTECTIVE PRACTICES DURING MAINTENANCE OF CONTAMINATED EQUIPMENT: Follow practices indicated in Section 6 (Accidental Release Measures). Make certain application equipment is locked and tagged-out safely, as applicable. Always use this product in areas where adequate ventilation is provided. Decontaminate equipment using soapy water before maintenance begins. Collect all rinsates and dispose of according to applicable Federal, State, or local procedures.

## SECTION 8 EXPOSURE CONTROLS, PERSONAL PROTECTION

VENTILATION AND ENGINEERING CONTROLS: Use with adequate ventilation. Mechanical exhaust may be needed. Ensure eyewash/safety shower stations are available near areas where this product is used.

RESPIRATORY PROTECTION: Maintain airborne contaminant concentrations below exposure limits listed in Section 2 (Composition and Information on Ingredients). If respiratory protection is needed, use only protection authorized in 29 CFR 1910.134, or applicable State regulations. Use supplied air respiration protection if oxygen levels are below 19.5% or are unknown.

## SECTION 8 EXPOSURE CONTROLS, PERSONAL PROTECTION (Continued)

EYE PROTECTION: Splash goggles or safety glasses.

HAND PROTECTION: Wear neoprene gloves for routine industrial use.

BODY PROTECTION: Use body protection appropriate for task (i.e. Apron or Tyvek suit).

## SECTION 9 PHYSICAL AND CHEMICAL PROPERTIES

RELATIVE VAPOR DENSITY (air = 1): Not applicable.
SPECIFIC GRAVITY: 2.1
SOLUBILITY IN WATER: 1.54% @ 20 °C
VAPOR PRESSURE, mm Hg @ 20 °C: 0
EVAPORATION RATE : Not applicable.
MELTING/FREEZING POINT: 723 °C, (1333 °F)
BOILING POINT: 1310 °C, (2390 °F)
pH: 11.2 @ 1% solution
ODOR THRESHOLD: Not available.
COEFFICIENT WATER/OIL DISTRIBUTION: Not available.
APPEARANCE AND COLOR: White, odorless solid.
HOW TO DETECT THIS SUBSTANCE (warning properties): This product does not have any unique warning properties.

## SECTION 10 STABILITY AND REACTIVITY

STABILITY: Stable.
DECOMPOSITION PRODUCTS: Thermal decomposition of the components of this product include toxic oxides of carbon.
MATERIALS WITH WHICH SUBSTANCE IS INCOMPATIBLE: This product is not compatible with strong acids and strong oxidizers.
HAZARDOUS POLYMERIZATION: Will not occur.
CONDITIONS TO AVOID: Avoid mixing this product with incompatible chemicals.

## SECTION 11 TOXICOLOGICAL INFORMATION

TOXICITY DATA: Additional toxicology information for Lithium Carbonate is provided below:

DNA Damage System (human, fibroblast) = 500 mg/L
Mammalian Somatic Cell (hamster, ingestion) = 2 g/L
TDLo (oral, woman) = 4256 mg/kg/1-38 weeks pregnant/reproductive effects.
TDLo (oral, woman) = 4900 mg/kg/1-35 weeks pregnant/teratogenic effects
TDLo (oral, woman) = 3600 mg/kg/21 weeks continuous/carcinogenic effects/blood effects
TD (oral, woman) = 21 g/kg/3.5 years continuous/carcinogenic effects
TD (oral, woman) = 5940 mg/kg/47 weeks continuous/carcinogenic effects/blood effects
TD (oral, man) = 6132 mg/kg/2 years continuous/carcinogenic effects/blood effects
TDLo (oral, human) = 4111 mg/kg/central nervous system effects/gastrointestinal effects.
TDLo (oral, man) = 8 mg/kg/gastrointestinal effects/skin effects.
TDLo (oral, man) = 54 mg/kg
TDLo (oral, woman) = 120 mg/kg/10 days intermittent
TDLo (oral, man) = 1080 mg/kg/13 weeks intermittent/skin effects.
TDLo (unreported, woman) = 556 mg/kg/32 days.
$LD_{50}$(oral, rat) = 525 mg/kg
$LD_{50}$(intraperitoneal, rat) = 156 mg/kg
$LD_{50}$(subcutaneous, rat) = 434 mg/kg
$LD_{50}$(intravenous, rat) = 241 mg/kg
$LD_{50}$(oral, mouse) = 531 mg/kg
$LD_{50}$(intraperitoneal, mouse) = 236 mg/kg
$LD_{50}$(subcutaneous, mouse) = 413 mg/kg
$LD_{50}$(intravenous, mouse) = 497 mg/kg
$LD_{50}$(oral, dog) = 500 mg/kg

SUSPECTED CANCER AGENT: Lithium Carbonate is not found on the following lists: FEDERAL OSHA Z LIST, NTP, IARC, CAL-OSHA and is therefore not considered to be, or suspected to be, a cancer-causing agent by these agencies.

IRRITANCY OF PRODUCT: This product is expected to cause irritancy to the skin and eyes.

## SECTION 11 TOXICOLOGICAL INFORMATION (Continued)

SENSITIZATION TO THE PRODUCT: Lithium Carbonate can cause allergic dermatitis (cracking and reddening of the skin) upon repeated or prolonged over-exposures

REPRODUCTIVE TOXICITY INFORMATION: Lithium Carbonate is used as a medication for manic-depression. Overexposures to Lithium Carbonate may cause reproductive disorders, based on clinical tests with laboratory animals. Lithium Carbonate may cause fetal harm when administered to a pregnant woman. Children of mothers who received Lithium Carbonate during the first three months of pregnancy have reported in some, but not all, studies to have a slightly increased frequency of malformations of the heart and blood vessels. Even though this risk is low and uncertain, it is strongly recommended that women discontinue lithium therapy during the first three months of pregnancy. Additionally, Lithium is excreted in human milk. Nursing should not be undertaken during lithium therapy except in rare and unusual circumstances.

**NOTE!** It is important for pregnant women not to be exposed above the exposure limits defined in Section 2 (Composition and Information on Ingredients) during the first trimester, due to the reported teratogenicity of lithium carbonate at high doses.

Mutagenicity: Human mutation data is reported for lithium carbonate, during clinical studies of specific human tissue exposed to relatively high doses.
Embryotoxicity: This product is not reported to produce embryotoxic effects in humans.
Teratogenicity: Clinical studies involving test animals exposed to high doses of Lithium Carbonate indicate teratogenic effects.
Reproductive Toxicity: Clinical studies involving test animals exposed to high doses of Lithium Carbonate indicate adverse reproductive effects.

*A mutagen is a chemical which causes permanent changes to genetic material (DNA) such that the changes will propagate through generational lines. An embryotoxin is a chemical which causes damage to a developing embryo (i.e. within the first eight weeks of pregnancy in humans), but the damage does not propagate across generational lines. A teratogen is a chemical which causes damage to a developing fetus, but the damage does not propagate across generational lines. A reproductive toxin is any substance which interferes in any way with the reproductive process..*

MEDICAL CONDITIONS AGGRAVATED BY EXPOSURE: Pre-existing respiratory, skin, central nervous system, and kidney conditions can be aggravated by over-exposure to this product.

RECOMMENDATIONS TO PHYSICIANS: Respiratory problems, dermatitis and skin disorders can be aggravated by exposure to this product

BIOLOGICAL EXPOSURE INDICES: Currently there are no Biological Exposure Indices (BEIs) associated with Lithium Carbonate.

Additional detailed toxicology information is presented in the sections below.

**LITHIUM SALTS:**

ACUTE EXPOSURE: Ingestion of a large dose of lithium salts may cause severe gastroenteritis and effects on the central nervous system, renal function and fluid and electrolyte balance. Symptoms, possibly delayed, may include nausea, vomiting, thirst, anorexia, diarrhea, blurred vision, drowsiness, weakness, tremor, staggering, bradycardia and coma. More unusual reactions may include delirium with EEG changes, action myoclonus, rhabdomyolysis, ECG changes, glycosuria, and allergic erythema. A painful discoloration of the fingers and toes and coldness of the extremities within 1 day of therapeutic use has been reported. In severe cases, death may occur due to renal failure or cardiac or pulmonary complications. Some survivors may have long-lasting or permanent sequelae, mostly of cerebellar nature but, sometimes with peripheral neuropathy or parkinsonism

## SECTION 11 TOXICOLOGICAL INFORMATION (Continued)

CHRONIC EXPOSURE: Repeated or prolonged ingestion of lithium salts may cause symptoms as detailed in acute ingestion. In addition, a metallic taste, dry mouth, excessive thirst, abdominal pain and incontinence of urine and feces may occur. Nervous system effects may include a dazed feeling, confusion, giddiness, mental lapses, dyspraxia, drowsiness, vertigo, headache, apathy, restlessness, anxiety, some suppression of the rem phases of sleep, positive Romberg sign, blackout spells, stupor, tinnitus, unconsciousness and coma. Neurologic asymmetry, psychomotor retardation, slurred speech, nystagmus, changes in the EEG and epileptiform seizures may occur. Pseudotumor cerebri (increased intracranial pressure and papilledema) has been reported and may possibly result in enlargement of the blind spot, constriction of visual fields and eventual blindness due to optic atrophy. Photophobia has been reported. Muscular effects may include tremors, ataxia, muscular and reflex hyperirritability with fasiculations, twitching and spastic or choreo-athetotic movements, cogwheel rigidity, parkinsonism and dystonia. Two cases involving severe generalized sensorimotor peripheral neuropathy have been reported. ECG changes, cardiac arrhythmias, hypotension, peripheral circulatory collapse, and interstitial myocarditis are possible. Leukocytosis is fairly common. Endocrine effects may include disturbed iodine metabolism, stimulation of antithyroidal auto-antibodies, hypothyroidism with myxedema, or rarely hyperthyroidism. Osteoporosis, an increase in serum total calcium, ionized calcium and parathyroid hormone and independently functioning parathyroid adenomas have been reported. Transitory nephrotic syndrome and acquired nephrogenic diabetes insipidus may occur. Transient hyperglycemia, lowered urinary concentrating ability leading to hypernatremia and hyperosmolality, sodium depletion, polyuria, glycosuria, oliguria, anuria, and azotemia are possible. Morphologic changes with glomerular and interstitial fibrosis and nephron atrophy have been reported. However, a causal relationship has not been established. Dermatologic effects may include cutaneous hyperalgesia or anesthesia, xerosis cutis, chronic folliculitis, generalized pruritus with or without rash, development or exacerbation of acne or psoriasis, cutaneous ulcers and alopecia. Hyper- or hypothermia, weight gain, edema of the ankles and wrists and sexual dysfunction have been reported. Death may occur due to renal failure, brain damage or pulmonary complications. Lithium readily crosses the placental barrier and is excreted in breast milk. The use of lithium during pregnancy has been associated with neonatal goiter, cardiac anomalies, especially ebstein's, central nervous system depression and hypotonia. Marked functional and structural changes in the kidneys of newborn rats exposed to lithium via their mother's milk have been reported. Adverse effects on nidation in rats and embryo viability in mice have been attributed to lithium, as have teratogenicity in submammalian species and cleft palates in mice. However, studies in rats, rabbits and monkeys have shown no evidence of lithium-induced developmental defects. Leukemia has been reported during lithium treatment. However, an epidemiologic study involving a population of 173,000 persons yielded negative results

### NOTE TO PHYSICIAN

ANTIDOTE: The following antidote has been recommended. However, the decision as to whether the severity of poisoning requires administration of any antidote and actual dose required should be made by qualified medical personnel.

LITHIUM/LITHIUM SALT POISONING:

1) In single ingestion episodes, give syrup of ipecac and/or perform gastric lavage if productive vomiting has not already occurred. 2) Fluid and electrolyte replacement for the correction of dehydration and acid-base imbalances. Overhydration may precipitate pulmonary edema. 3) Infusion of urea or mannitol, alkalinization of the urine and, and aminophylline increase lithium excretion in patients with good renal function. 4) Extracorporeal or peritoneal hemodialysis to decrease lithium levels and control uremia in severe intoxications. If a massive overdose is known with certainty to have been ingested, it may be prudent to institute these measures even in the absence of positive clinical findings because of severe delayed toxicity. 5) Diazepam for the suppression of abnormal motor activity. 6) Support treatment for central nervous system depression. 7) Frequent electrocardiograms to assess cardiac status. (Gosselin, Smith, Hodge - Clinical Toxicology of Commercial Products, Fifth Edition).

Activated charcoal does not bind lithium effectively and is not useful in isolated lithium toxicity. (Groleau, Lithium Toxicity, Emergency Medicine Clinics of North America, Volume 12, Number 2, May, 1994).Raising the sodium intake does not increase lithium clearance (Thomsen, K. Renal lithium elimination in man and active treatment of lithium poisoning. Acta Psychiatr. Scand., Suppl. No. 207:83-84,1969).

## SECTION 12 ECOLOGICAL INFORMATION

ENVIRONMENTAL STABILITY: Lithium Carbonate is stable in the environment.
EFFECT OF MATERIAL ON PLANTS or ANIMALS: The effects on exposed animals would be primarily irritation of contaminated tissue (see Section 11, Toxicological Information). The main effect on plants would be the increase in salinity of contaminated soils if large volumes of this product are released. As with all chemicals, work practices should be aimed at minimizing environmental releases.
EFFECT OF CHEMICAL ON AQUATIC LIFE: Releases of large quantities of this product can be detrimental to an aquatic environment, by altering the salinity of a body of water. As with all chemicals, work practices should be aimed at minimizing environmental releases.
ACUTE AQUATIC TOXICITY: No data available.
DEGRADABILITY: No data available.
LOG BIOCONCENTRATION FACTOR (BCF): No data available.
LOG OCTANOL/WATER PARTITION COEFFICIENT: No data available.

## SECTION 13 DISPOSAL CONSIDERATIONS

PREPARING WASTES FOR DISPOSAL: Waste disposal must be in accordance with appropriate Federal, State, and local regulations. This chemical, if unaltered by use, may be disposed of by treatment at a permitted facility or as advised by your local solid waste regulatory authority.
EPA WASTE NUMBER: Not applicable to the product.

## SECTION 14 TRANSPORT INFORMATION

THIS MATERIAL IS NOT HAZARDOUS AS DEFINED BY 49 CFR 172.101 BY THE U.S. DEPARTMENT OF TRANSPORTATION.

| | |
|---|---|
| PROPER SHIPPING NAME: | Not applicable. |
| HAZARD CLASS NUMBER and DESCRIPTION: | Not applicable. |
| UN IDENTIFICATION NUMBER: | Not applicable. |
| PACKING GROUP: | Not applicable. |
| DOT LABEL(S) REQUIRED: | Not applicable. |

NORTH AMERICAN EMERGENCY RESPONSE GUIDEBOOK NUMBER, 1996: Not applicable.
MARINE POLLUTANT: No component of this product is designated as a DOT Marine Pollutant (49 CFR 172.101, Appendix B).
TRANSPORT CANADA TRANSPORTATION OF DANGEROUS GOODS REGULATIONS: THIS MATERIAL IS NOT CONSIDERED AS DANGEROUS GOODS.

EMERGENCY RESPONSE CONTACT FOR AN INCIDENT DURING TRANSPORTATION:
CHEMTREC 1-800-424-9300 or 1-703-527-3887

## SECTION 15 REGULATORY INFORMATION

SARA REPORTING REQUIREMENTS: Lithium Carbonate is subject to the reporting requirements of the Comprehensive Environmental Response, Compensation, and Liability Act and Sections 302, 304 and 313 of Title III of the Superfund Amendments and Reauthorization Act., as follows:

| | |
|---|---|
| CERCLA SECTION 103 (40 CFR 302.4): | No |
| SARA SECTION 302 (40 CFR 355.30): | No |
| SARA SECTION 304 (40 CFR 355.40): | No |
| SARA SECTION 313 (40 CFR 372.65): | Yes |

## SECTION 15 REGULATORY INFORMATION (Continued)

SARA Threshold Planning Quantity: Not applicable.
TSCA INVENTORY STATUS: Lithium Carbonate is listed on the TSCA Inventory.
CERCLA REPORTABLE QUANTITY (RQ): Not applicable.
OTHER FEDERAL REGULATIONS: Not applicable.
STATE REGULATORY INFORMATION: Lithium Carbonate is covered under specific State regulations, as denoted below:

Alaska - Designated Toxic and Hazardous Substances: No.
Florida - Substance List: No.
Kansas - Section 302/313 List: No.
Minnesota - List of Hazardous Substances: No.
New Jersey - Right to Know Hazardous Substance List: No.
Pennsylvania - Hazardous Substance List: No.
Texas - Hazardous Substance List: No.
Wisconsin - Toxic and Hazardous Substances: No.
California - Permissible Exposure Limits for Chemical Contaminants: No.
Illinois - Toxic Substance List: No.
Massachusetts - Substance List: No.
Missouri - Employer Information/Toxic Substance List: No.
North Dakota - List of Hazardous Chemicals, Reportable Quantities: No.
Rhode Island - Hazardous Substance List: No.
West Virginia - Hazardous Substance List: No.

CALIFORNIA PROPOSITION 65: Lithium Carbonate is on the California Proposition 65 lists as a compound known to the State of California to cause birth defects or other reproductive harm.

LABELING (Precautionary Statements): **WARNING!** CAUSES SKIN AND EYE IRRITATION. MAY BE HARMFUL IF SWALLOWED. CAN CAUSE CENTRAL NERVOUS SYSTEM EFFECTS AND KIDNEY DAMAGE. SUSPECTED REPRODUCTIVE TOXIN. Avoid contact with skin, eyes, and clothing. Wash thoroughly after handling. Use in well-ventilated area. Wear gloves, goggles and appropriate body protection. FIRST-AID: In case of skin or eye contact, flush skin with water for 15 minutes. Remove contaminated clothing and shoes. If inhaled, remove to fresh air. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. if ingested, do not induces vomiting. Seek medical attention. IN CASE OF FIRE: Use water fog, dry chemical, $CO_2$, or "alcohol" foam. IN CASE OF SPILL: Sweep-up or vacuum spilled material. Place in a suitable container. Consult Material Safety Data Sheet before use.

WARNING! This product contains a chemical known to the State of California to cause birth defects or other reproductive harm.

TARGET ORGANS: Eyes, skin,. (via inhalation or ingestion: central nervous system, kidneys).
WHMIS SYMBOLS: Not applicable.

## SECTION 16 OTHER INFORMATION

The information in this Material Safety Data Sheet is based on data that Cyprus Foote Mineral believes to be reliable as of the MSDS's date of revision. Cyprus Foote Mineral makes no warranty or representation of any kind that the MSDS does not contain errors. The data in this MSDS relates only to the specific material designated herein and does not relate to use in combination with any other material or in any process. It is intended for use by persons having technical skill and at their own discretion and risk. Since conditions of use are outside the control of Cyprus Foote Mineral, there are no warranties, expressed or implied, and Cyprus Foote Mineral assumes no liability in connection with the use of this information. Nothing herein is to be taken as a license to operate under or a recommendation to infringe on any patents. Any use of these data and information must be determined by the user to be in accordance with Federal, State and local laws and regulations.

**PREPARED BY:**

CHEMICAL SAFETY ASSOCIATES, Inc.
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619/565-0302

### DEFINITIONS OF TERMS

A large number of abbreviations and acronyms appear on a MSDS. Some of these which are commonly used include the following:

**CAS #:** This is the Chemical Abstract Service Number which uniquely identifies each constituent. It is used for computer-related searching.
**EXPOSURE LIMITS IN AIR:**
**ACGIH** - American Conference of Governmental Industrial Hygienists, a professional association which establishes exposure limits.

## SECTION 16 OTHER INFORMATION (Continued)

**TLV - Threshold Limit Value** - an airborne concentration of a substance which represents conditions under which it is generally believed that nearly all workers may be repeatedly exposed without adverse effect. The duration must be considered, including the 8-hour **Time Weighted Average (TWA)**, the 15-minute **Short Term Exposure Limit**, and the instantaneous **Ceiling Level**. Skin adsorption effects must also be considered.
**OSHA** - U.S. Occupational Safety and Health Administration.
**PEL - Permissible Exposure Limit** - this exposure value means exactly the same as a TLV, except that it is enforceable by OSHA. The **IDLH - Immediately Dangerous to Life and Health** level represents a concentration from which one can escape within 30-minutes without suffering escape-preventing or permanent injury. **The DFG - MAK** is the Republic of Germany's Maximum Exposure Level, similar to the U.S. PEL. **NIOSH** is the National Institute of Occupational Safety and Health, which is the research arm of the U.S. Occupational Safety and Health Administration (**OSHA**). NIOSH issues exposure guidelines called Recommended Exposure Levels (**RELs**). When no exposure guidelines are established, an entry of **NE** is made for reference.

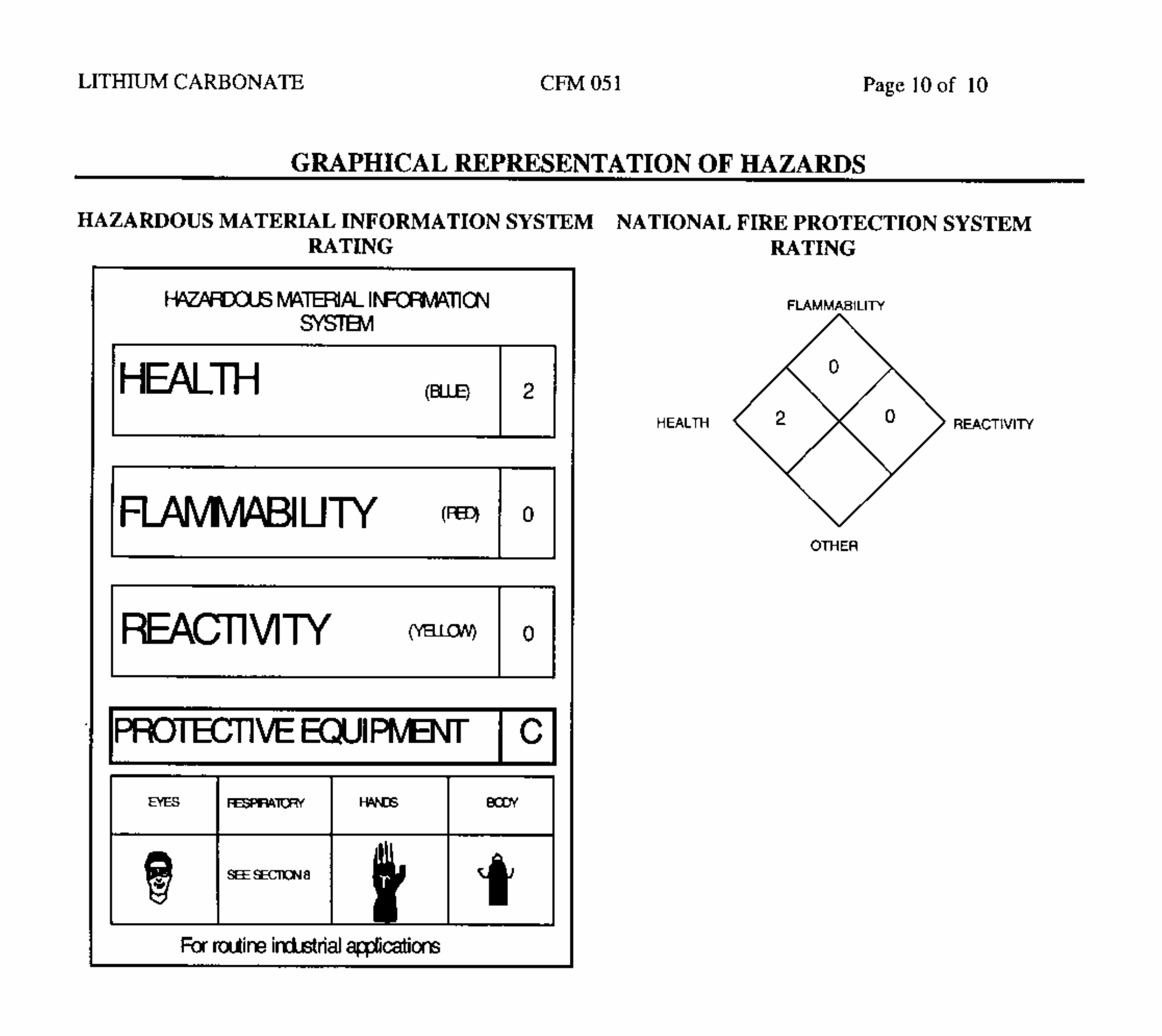
**FLAMMABILITY LIMITS IN AIR**: Much of the information related to fire and explosion is derived from the National Fire Protection Association (**NFPA**). LEL - the lowest percent of vapor in air, by volume, that will explode or ignite in the presence of an ignition source. UEL - the highest percent of vapor in air, by volume, that will explode or ignite in the presence of an ignition source.

### TOXICOLOGICAL INFORMATION

Possible health hazards as derived from human data, animal studies, or from the results of studies with similar compounds are presented. Definitions of some terms used in this section are: **$LD_{50}$** - Lethal Dose (solids & liquids) which kills 50% of the exposed animals; **$LC_{50}$** - Lethal Concentration (gases) which kills 50% of the exposed animals; **ppm** concentration expressed in parts of material per million parts of air or water; **mg/m$^3$** concentration expressed in weight of substance per volume of air; **mg/kg** quantity of material, by weight, administered to a test subject, based on their body weight in kg. Data from several sources are used to evaluate the cancer-causing potential of the material. The sources are: **IARC** - the International Agency for Research on Cancer; **NTP** - the National Toxicology Program, **RTECS** - the Registry of Toxic Effects of Chemical Substances, **OSHA** and **CAL/OSHA**. IARC and NTP rate chemicals on a scale of decreasing potential to cause human cancer with rankings from 1 to 4. Subrankings (2A, 2B, etc.) are also used. Other measures of toxicity include **TDLo**, the lowest dose to cause a symptom and **TCLo** the lowest concentration to cause a symptom; **TDo, LDLo**, and **LDo**, or **TC, TCo, LCLo**, and **LCo**, the lowest dose (or concentration) to cause death. **BEI** - Biological Exposure Indices, represent the levels of determinants which are most likely to be observed in specimens collected from a healthy worker who has been exposed to chemicals to the same extent as a worker with inhalation exposure to the TLV.

### REGULATORY INFORMATION

This section explains the impact of various laws and regulations on the material. **EPA** is the U.S. Environmental Protection Agency. **WHMIS** is the Canadian Workplace Hazard information System. **DOT** and **CTC** are the U.S. Department of Transportation and the Canadian Transportation Commission, respectively. These are: **Superfund Amendments and Reauthorization Act** (SARA); the **Toxic Substance Control Act** (TSCA); Marine Pollutant status according to the **DOT**; California's Safe Drinking Water Act (**Proposition 65**); the **Comprehensive Environmental Response, Compensation, and Liability Act** (**CERCLA or Superfund**); and various state regulations. This section also includes information on the precautionary warnings which appear on the materials package label.



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## GRAPHICAL REPRESENTATION OF HAZARDS

**HAZARDOUS MATERIAL INFORMATION SYSTEM RATING**

HAZARDOUS MATERIAL INFORMATION SYSTEM

| | |
|---|---|
| HEALTH (BLUE) | 2 |
| FLAMMABILITY (RED) | 0 |
| REACTIVITY (YELLOW) | 0 |
| PROTECTIVE EQUIPMENT | C |

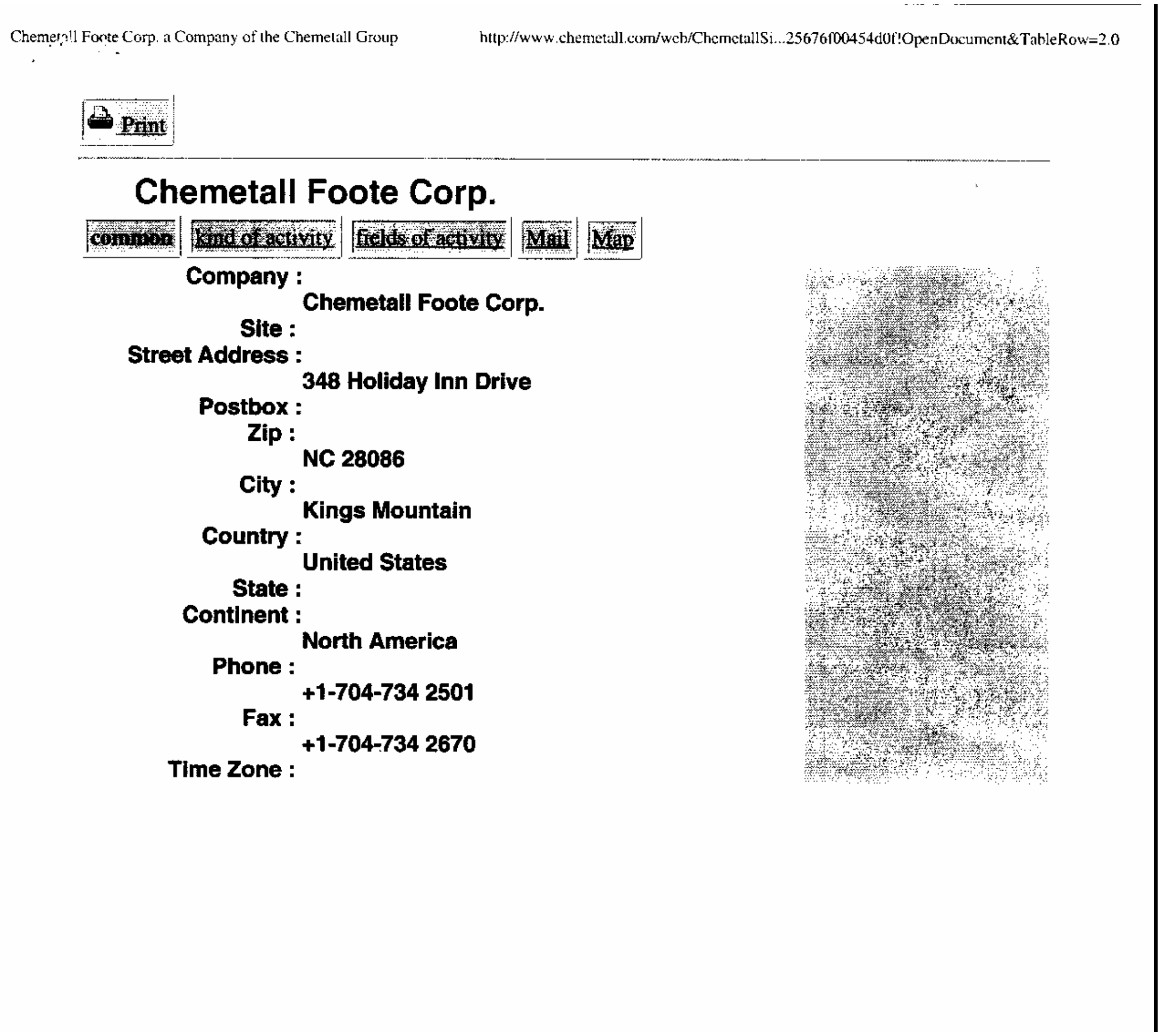
| EYES | RESPIRATORY | HANDS | BODY |
|---|---|---|---|
| | SEE SECTION 8 | | |

For routine industrial applications

**NATIONAL FIRE PROTECTION SYSTEM RATING**

FLAMMABILITY 0
HEALTH 2
REACTIVITY 0
OTHER

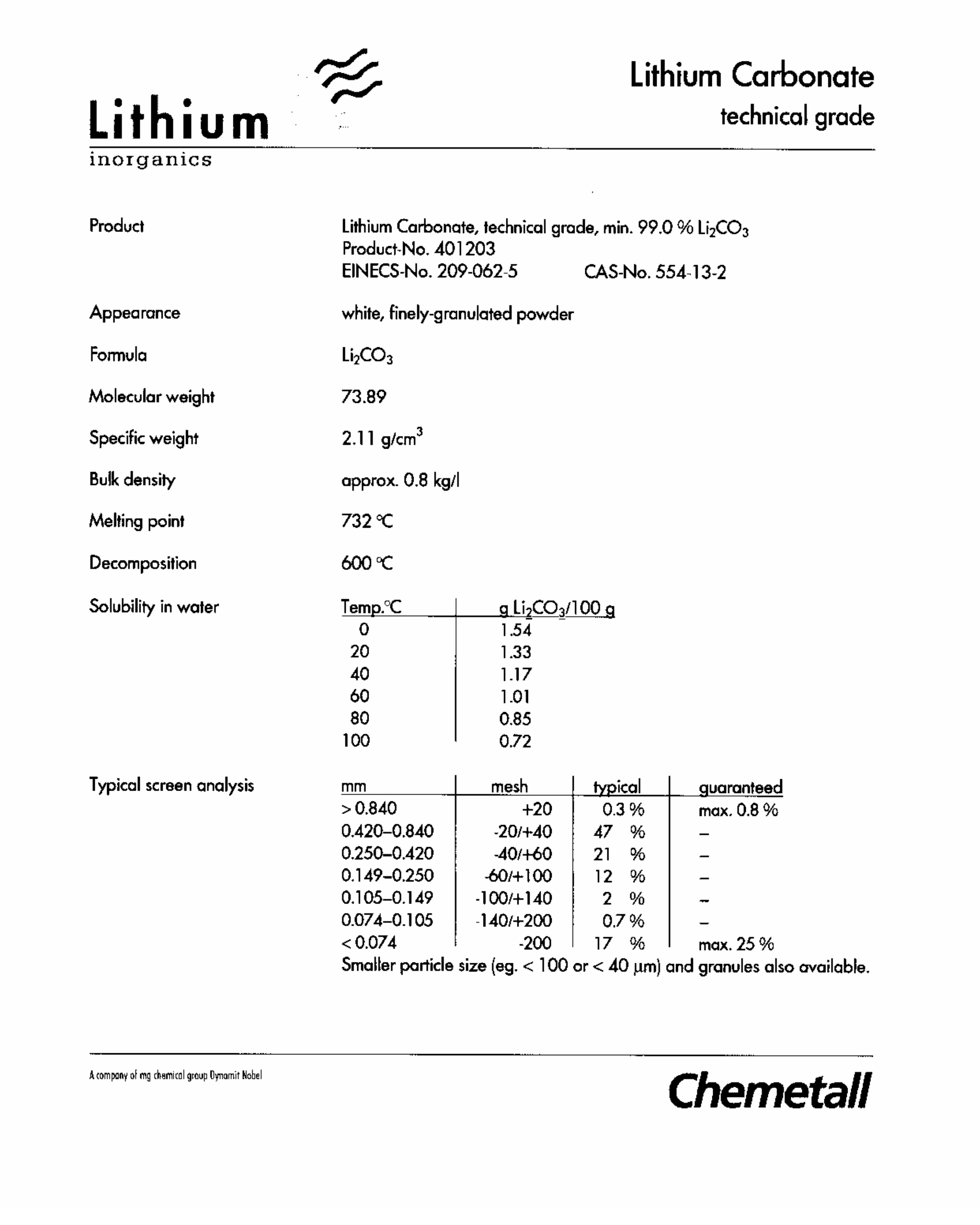
**Figure B.10: Lithium Carbonate – Vendor Technical Data**



Chemetall Foote Corp. a Company of the Chemetall Group http://www.chemetall.com/web/ChemetallSi...25676f00454d0f!OpenDocument&TableRow=2.0

## Chemetall Foote Corp.

**Company :**
**Chemetall Foote Corp.**
**Site :**
**Street Address :**
**348 Holiday Inn Drive**
**Postbox :**
**Zip :**
**NC 28086**
**City :**
**Kings Mountain**
**Country :**
**United States**
**State :**
**Continent :**
**North America**
**Phone :**
**+1-704-734 2501**
**Fax :**
**+1-704-734 2670**
**Time Zone :**



**Lithium**
inorganics

# Lithium Carbonate
technical grade

| | |
|---|---|
| Product | Lithium Carbonate, technical grade, min. 99.0 % $Li_2CO_3$<br>Product-No. 401203<br>EINECS-No. 209-062-5 CAS-No. 554-13-2 |
| Appearance | white, finely-granulated powder |
| Formula | $Li_2CO_3$ |
| Molecular weight | 73.89 |
| Specific weight | 2.11 g/cm$^3$ |
| Bulk density | approx. 0.8 kg/l |
| Melting point | 732 °C |
| Decomposition | 600 °C |

Solubility in water

| Temp.°C | g $Li_2CO_3$/100 g |
|---|---|
| 0 | 1.54 |
| 20 | 1.33 |
| 40 | 1.17 |
| 60 | 1.01 |
| 80 | 0.85 |
| 100 | 0.72 |

Typical screen analysis

| mm | mesh | typical | guaranteed |
|---|---|---|---|
| > 0.840 | +20 | 0.3 % | max. 0.8 % |
| 0.420–0.840 | -20/+40 | 47 % | – |
| 0.250–0.420 | -40/+60 | 21 % | – |
| 0.149–0.250 | -60/+100 | 12 % | – |
| 0.105–0.149 | -100/+140 | 2 % | – |
| 0.074–0.105 | -140/+200 | 0.7 % | – |
| < 0.074 | -200 | 17 % | max. 25 % |

Smaller particle size (eg. < 100 or < 40 µm) and granules also available.

A company of mg chemical group Dynamit Nobel

**Chemetall**

Chemical analysis

| | typical | guaranteed |
|---|---|---|
| $Li_2CO_3$*) | 99.4 % | min. 99.0 % |
| Cl | 0.01 % | max. 0.015 % |
| K | 0.0003 % | max. 0.001 % |
| Na | 0.06 % | max. 0.08 % |
| Mg | 0.004 % | max. 0.01 % |
| $SO_4$ | 0.04 % | max. 0.05 % |
| $Fe_2O_3$ | 0.001 % | max. 0.003 % |
| Ca | 0.01 % | max. 0.016 % |
| Loss at 550 °C | 0.6 % | max. 0.75 % |
| $H_2O$ (110 °C) | 0.014 % | – |

*) Determination by titration with potentiometric endpoint indication

Method of analysis/ titroprocess

| | |
|---|---|
| $Li_2CO_3$ | acidimetrically with $H_2SO_4$ |
| Cl | argentom. titrating apparatus |
| K | FES/AAS |
| Na | FES/AAS |
| Mg | ICP-Method |
| $SO_4$ | IC |
| $Fe_2O_3$ | ICP-Method |
| Ca | FES/AAS |

| | |
|---|---|
| Application | Raw material for the glass, ceramics and enamel industries; basis material for the manufacture of other lithium compounds; catalyst for esterification; additive and flux for welding rods; additive in aluminium electrolysis melts; additive for quick-setting cement |
| Handling and storage | No special precautions necessary |
| Transport regulations | None<br>No regulations according to RID, ADR, IMDG and IATA-DGR |
| Marking | $X_n$ Harmful<br>R+S-phrases see Material Safety Data Sheet |
| Packing | 25 kg-bags on pallets of 1.000 kg, 100 kg reinforced cardboard drums with polyethylene lining or 1000 kg big bags. |
| Time of delivery | In general prompt after receipt of order |

09/01

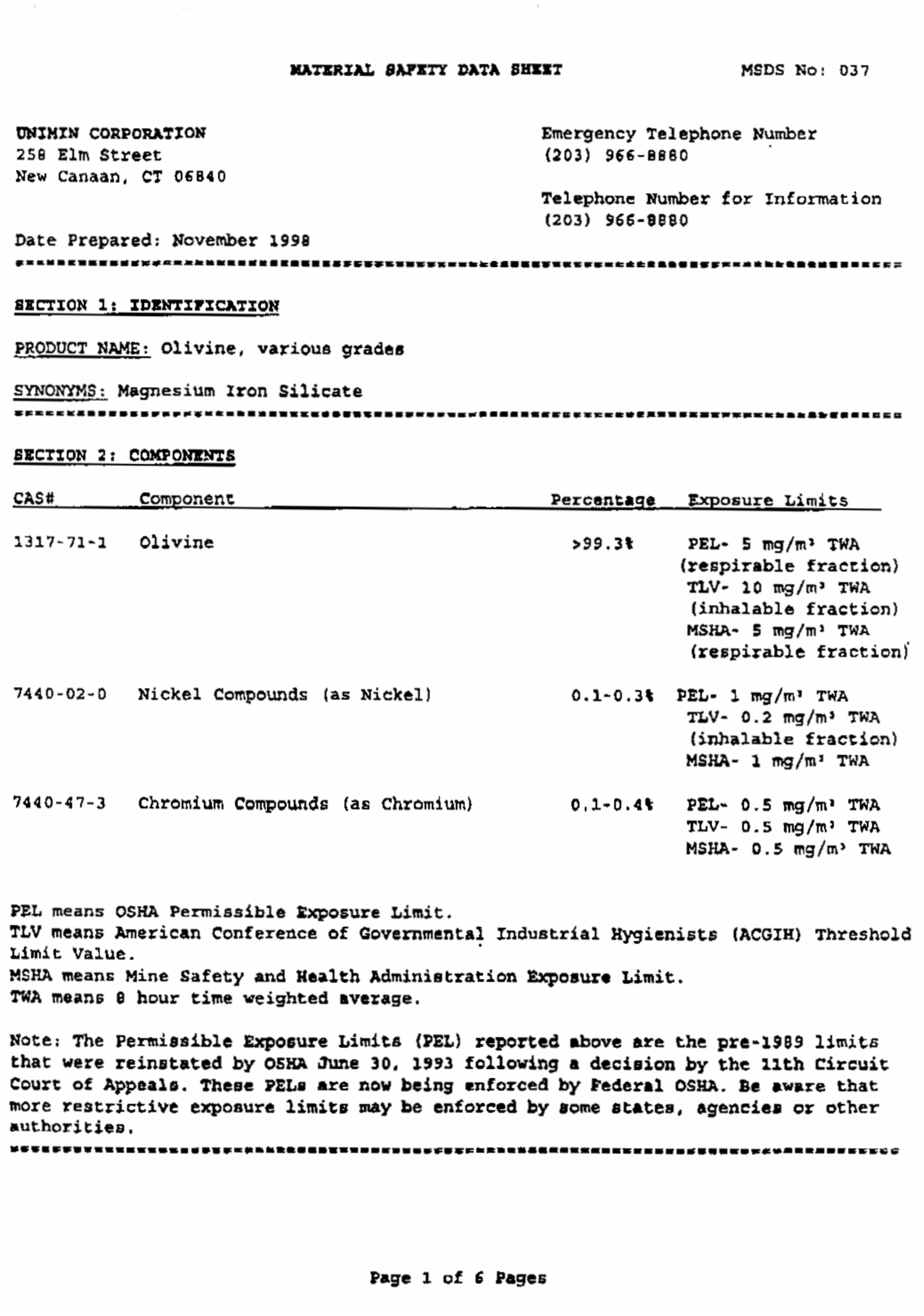
Europe:
Chemetall GmbH
Fax +49 69 7165-2053

Americas:
Chemetall Foote Corp.
Fax +1 704 734-2718

Asia:
Chemetall Taiwan Co., Ltd
Fax +886 4 758-6415

**e-mail: lithium@chemetall.com**
**www.chemetalllithium.com**

**Figure B.11: Olivine - MSDS**



**MATERIAL SAFETY DATA SHEET** MSDS No: 037

**UNIMIN CORPORATION**
258 Elm Street
New Canaan, CT 06840

Emergency Telephone Number
(203) 966-8880

Telephone Number for Information
(203) 966-8880

Date Prepared: November 1998

## SECTION 1: IDENTIFICATION

PRODUCT NAME: **Olivine, various grades**

SYNONYMS: Magnesium Iron Silicate

## SECTION 2: COMPONENTS

| CAS# | Component | Percentage | Exposure Limits |
|---|---|---|---|
| 1317-71-1 | Olivine | >99.3% | PEL- 5 mg/m³ TWA (respirable fraction)<br>TLV- 10 mg/m³ TWA (inhalable fraction)<br>MSHA- 5 mg/m³ TWA (respirable fraction) |
| 7440-02-0 | Nickel Compounds (as Nickel) | 0.1-0.3% | PEL- 1 mg/m³ TWA<br>TLV- 0.2 mg/m³ TWA (inhalable fraction)<br>MSHA- 1 mg/m³ TWA |
| 7440-47-3 | Chromium Compounds (as Chromium) | 0.1-0.4% | PEL- 0.5 mg/m³ TWA<br>TLV- 0.5 mg/m³ TWA<br>MSHA- 0.5 mg/m³ TWA |

PEL means OSHA Permissible Exposure Limit.
TLV means American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value.
MSHA means Mine Safety and Health Administration Exposure Limit.
TWA means 8 hour time weighted average.

Note: The Permissible Exposure Limits (PEL) reported above are the pre-1989 limits that were reinstated by OSHA June 30, 1993 following a decision by the 11th Circuit Court of Appeals. These PELs are now being enforced by Federal OSHA. Be aware that more restrictive exposure limits may be enforced by some states, agencies or other authorities.

**Page 1 of 6 Pages**

## SECTION 3: HAZARDS IDENTIFICATION

### EMERGENCY OVERVIEW

This product is a chemically inert, non-combustible mineral. Excessive inhalation of dust may cause lung injury with symptoms of shortness of breath and reduced pulmonary function. See "Cancer Status" in this Section 3.

================================================================================

### HEALTH HAZARDS:

Inhalation: Inhalation of dust may cause irritation of the nose, throat and respiratory passages.

Skin Contact: No adverse effects expected.

Eye Contact: Contact may cause mechanical irritation and possible injury.

Ingestion: No adverse effects expected for normal, incidental ingestion.

Chronic Health Effects: Prolonged overexposure to any nuisance dust may cause lung injury. Symptoms include cough, shortness of breath, and reduced pulmonary function. This product contains small amounts of nickel and chromium compounds. Hexavalent chromium has not been detected in this product (detection limit 0.1%). Overexposure to nickel and chromium compounds may cause respiratory and skin sensitization.

Cancer Status: Nickel compounds are classified by IARC as "carcinogenic to humans" (Group 1) and by NTP as "reasonably anticipated to be a carcinogen". Olivine is not listed as a carcinogen or suspected carcinogen by IARC, NTP or OSHA.

Medical Conditions Aggravated by Exposure: Individuals with respiratory disease, including but not limited to, asthma and bronchitis, or subject to eye irritation should be excluded from exposure.

Signs and Symptoms of Exposure: Overexposure to nuisance dusts may cause mucous membrane and respiratory irritation, cough, sore throat, nasal congestion, sneezing and shortness of breath.

================================================================================

## SECTION 4: FIRST AID

Gross Inhalation: Remove victim to fresh air. If breathing has stopped, perform artificial respiration. If breathing is difficult have qualified personnel administer oxygen. Get prompt medical attention.

Skin Contact: No first aid should be needed since this product does not affect the skin. Wash exposed skin with soap and water before breaks and at the end of the shift.

Eye Contact: Flush the eyes immediately with large amounts of running water, lifting the upper and lower lids occasionally. If irritation persists or for imbedded foreign body, get immediate medical attention.

Ingestion: If large amounts are swallowed, get immediate medical attention.

## SECTION 5: FIRE AND EXPLOSION DATA

Flash Point (Method Used): Fully oxidized, will not burn.
Autoignition Temp: Will not burn.

Flammable Limits: LEL: Not applicable UEL: Not applicable

Extinguishing Media: This product will not burn but is compatible with all extinguishing media. Use any media that is appropriate for the surrounding fire.

Special Fire Fighting Procedures: None required with respect to this product. Firefighters should always wear self-contained breathing apparatus for fires indoors or in confined areas.

Unusual Fire and Explosion Hazards: None.

Hazardous Combustion Products: None.

## SECTION 6: ACCIDENTAL RELEASE MEASURES

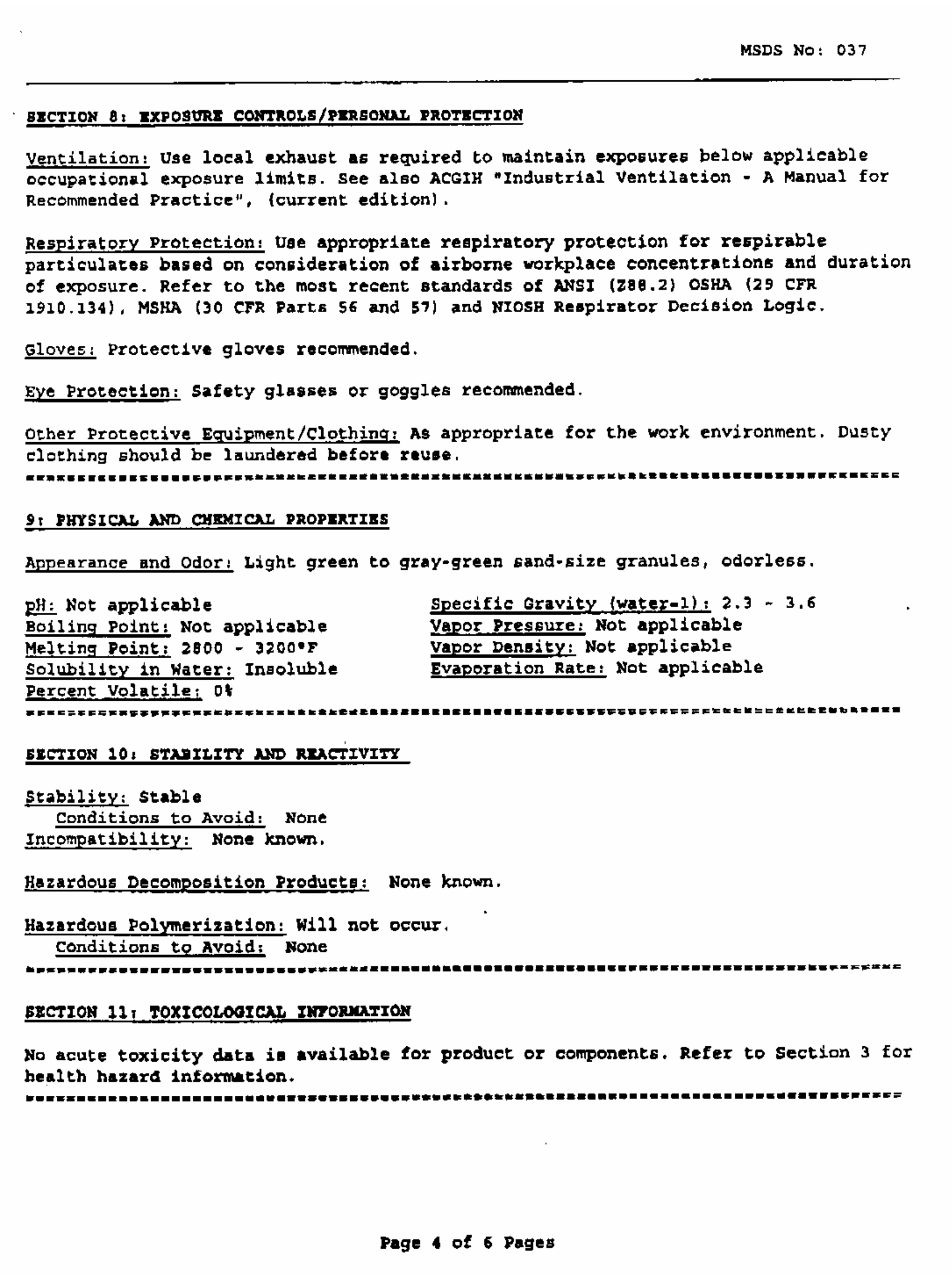
Wear appropriate protective equipment. If uncontaminated, collect using dustless method (HEPA vacuum or wet method) and place in appropriate container for use. If contaminated: a) use appropriate method for the nature of contamination, b) consider possible toxic or fire hazards associated with the contaminating substance. Collect for disposal.

## SECTION 7: HANDLING AND STORAGE

Avoid breathing dust. Use normal precautions against bag breakage or spills of bulk material. Avoid creation of respirable dust. Use good housekeeping in storage and use areas to prevent accumulation of dust in work area.

Use adequate ventilation and dust collection. Maintain and use proper, clean respiratory equipment (See Section 8). Launder clothing that has become dusty. WARN and TRAIN employees in accordance with state and federal regulations.

WARN YOUR EMPLOYEES (AND YOUR CUSTOMERS - USERS IN CASE OF RESALE) BY POSTING AND OTHER MEANS OF THE HAZARDS AND OSHA PRECAUTIONS TO BE USED. PROVIDE TRAINING FOR YOUR EMPLOYEES ABOUT OSHA PRECAUTIONS.



## SECTION 8: EXPOSURE CONTROLS/PERSONAL PROTECTION

Ventilation: Use local exhaust as required to maintain exposures below applicable occupational exposure limits. See also ACGIH "Industrial Ventilation - A Manual for Recommended Practice", (current edition).

Respiratory Protection: Use appropriate respiratory protection for respirable particulates based on consideration of airborne workplace concentrations and duration of exposure. Refer to the most recent standards of ANSI (Z88.2) OSHA (29 CFR 1910.134), MSHA (30 CFR Parts 56 and 57) and NIOSH Respirator Decision Logic.

Gloves: Protective gloves recommended.

Eye Protection: Safety glasses or goggles recommended.

Other Protective Equipment/Clothing: As appropriate for the work environment. Dusty clothing should be laundered before reuse.

## 9: PHYSICAL AND CHEMICAL PROPERTIES

Appearance and Odor: Light green to gray-green sand-size granules, odorless.

pH: Not applicable
Boiling Point: Not applicable
Melting Point: 2800 - 3200°F
Solubility in Water: Insoluble
Percent Volatile: 0%

Specific Gravity (water=1): 2.3 - 3.6
Vapor Pressure: Not applicable
Vapor Density: Not applicable
Evaporation Rate: Not applicable

## SECTION 10: STABILITY AND REACTIVITY

Stability: Stable
Conditions to Avoid: None
Incompatibility: None known.

Hazardous Decomposition Products: None known.

Hazardous Polymerization: Will not occur.
Conditions to Avoid: None

## SECTION 11: TOXICOLOGICAL INFORMATION

No acute toxicity data is available for product or components. Refer to Section 3 for health hazard information.

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## SECTION 12: ECOLOGICAL INFORMATION

No ecotoxicity data is available. This product is not expected to present an environmental hazard.

## SECTION 13: DISPOSAL

Waste Disposal Method: If uncontaminated, dispose as an inert, non-metallic mineral. If contaminated, dispose in accordance with all applicable local, state/provincial and federal regulations.

## SECTION 14: TRANSPORTATION DATA

U.S. DOT HAZARD CLASSIFICATION
- Proper Shipping Name: Not Regulated
- Technical Name: N/A
- UN Number: N/A
- Hazard Class/Packing Group: N/A
- Labels Required: None
- DOT Packaging Requirements: N/A
- Exceptions: N/A

## SECTION 15: OTHER REGULATORY INFORMATION

SARA 311/312: Hazard Categories for SARA Section 311/312 Reporting:
Chronic health

SARA 313 This Product Contains the Following Chemicals Subject to Annual Release Reporting Requirements Under the SARA Section 313 (40 CFR 372):
- Nickel Compounds 0.1 - 0.3%
- Chromium Compounds 0.1 - 0.4%

CERCLA Section 103 Reportable Quantity: None

California Proposition 65: This product contains nickel compounds which are known to the State of California to cause cancer.

Toxic Substances Control Act: All of the components of this product are listed on the EPA TSCA Inventory or exempt from notification requirements.

European Inventory of Commercial Chemical Substances: All of the components of this product are listed on the EINECS Inventory or exempt from notification requirements.

Canadian Environmental Protection Act: All the components of this product are listed on the Canadian Domestic Substances List or exempt from notification requirements.

Japan MITI: All of the components of this product are existing chemical substances as defined in the Chemical Substance Control Law.

Australian Inventory of Chemical Substances: All of the components of this product are listed on the AICS inventory or exempt from notification requirements.

Canadian WHMIS Classification: Class D, Division 2, Subdivision A (Very Toxic Material causing other Toxic Effect)

## 16: OTHER INFORMATION

European Community Labeling Classification: N/A

European Community Risk and Safety Phrases: None

| | | | |
|---|---|---|---|
| NFPA Hazard Rating: | Health: 1 | Fire: 0 | Reactivity: 0 |
| HMIS Hazard Rating: | Health: 1 | Fire: 0 | Reactivity: 0 |

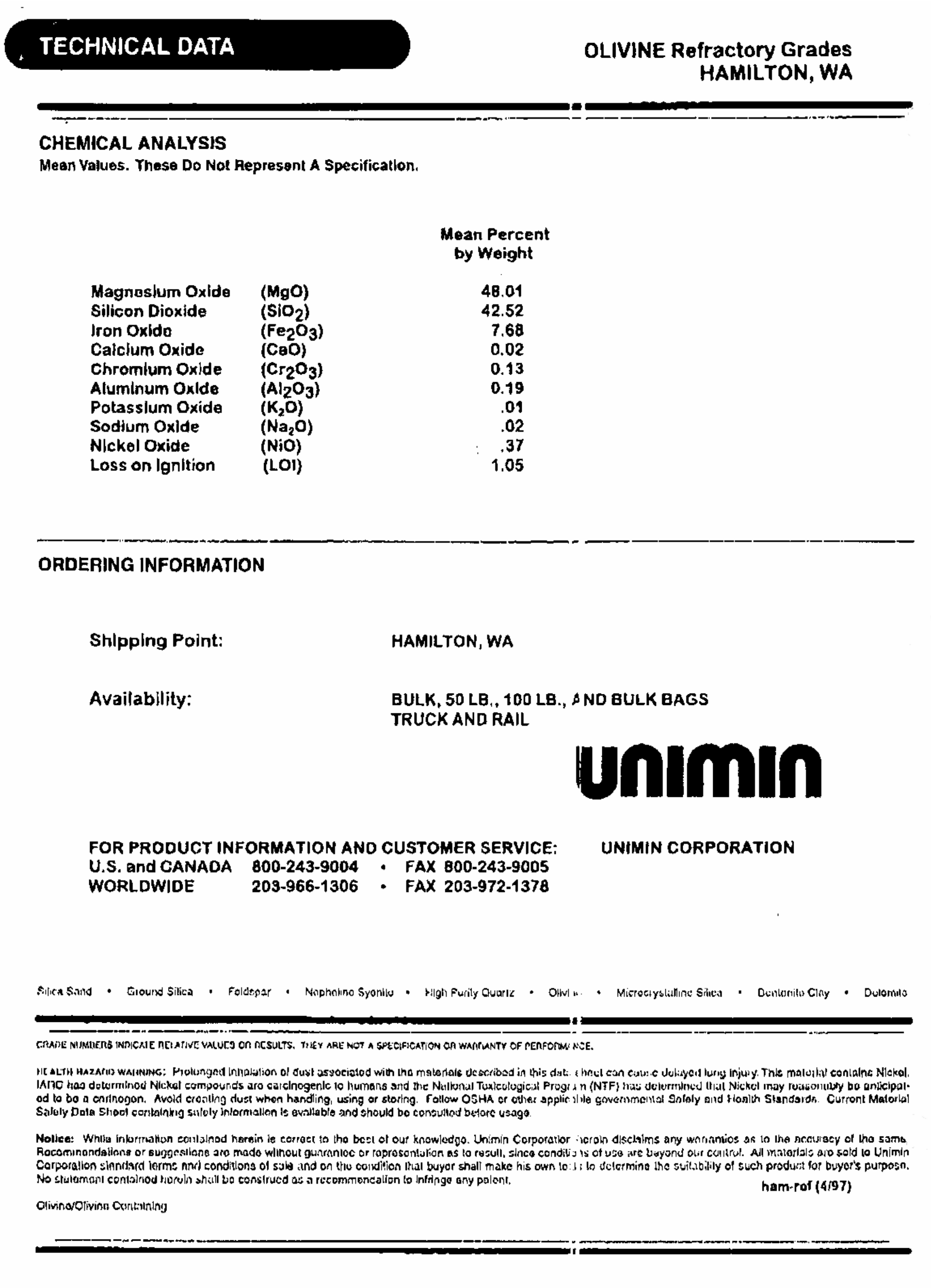
References:

Registry for Toxic Effects of Chemical Substances (RTECS), 1998
Hawley's Condensed Chemical Dictionary, twelfth edition
NTP Seventh Annual Report on Carcinogens, 1994
Patty's Industrial Hygiene and Toxicology

Revision Summary: Revise exposure limits (Section 2) and California Proposition 65 statement (Section 15)

The data in this Material Safety Data Sheet relates only to the specific material designated herein and does not relate to use in combination with any other material or in any process. The information set forth herein is based on technical data the Unimin Corporation believes reliable. It is intended for use by persons having technical skill and at their own discretion and risk. Since conditions of use are outside the control of Unimin Corporation, no warranties, expressed or implied, are made and no liability is assumed in connection with any use of this information. Any use of these data and information must be determined by the user to be in accordance with federal, state and local laws and regulations.

# Figure B.12: Olivine – Vendor Technical Data



**TECHNICAL DATA**

**OLIVINE Refractory Grades**
**HAMILTON, WA**

## CHEMICAL ANALYSIS

**Mean Values. These Do Not Represent A Specification.**

| | | Mean Percent by Weight |
|---|---|---|
| Magnesium Oxide | ($MgO$) | 48.01 |
| Silicon Dioxide | ($SiO_2$) | 42.52 |
| Iron Oxide | ($Fe_2O_3$) | 7.68 |
| Calcium Oxide | ($CaO$) | 0.02 |
| Chromium Oxide | ($Cr_2O_3$) | 0.13 |
| Aluminum Oxide | ($Al_2O_3$) | 0.19 |
| Potassium Oxide | ($K_2O$) | .01 |
| Sodium Oxide | ($Na_2O$) | .02 |
| Nickel Oxide | ($NiO$) | .37 |
| Loss on Ignition | (LOI) | 1.05 |

## ORDERING INFORMATION

| | |
|---|---|
| Shipping Point: | HAMILTON, WA |
| Availability: | BULK, 50 LB., 100 LB., AND BULK BAGS<br>TRUCK AND RAIL |

**unimin**

FOR PRODUCT INFORMATION AND CUSTOMER SERVICE: **UNIMIN CORPORATION**
U.S. and CANADA 800-243-9004 • FAX 800-243-9005
WORLDWIDE 203-966-1306 • FAX 203-972-1378

Silica Sand • Ground Silica • Feldspar • Nepheline Syenite • High Purity Quartz • Olivine • Microcrystalline Silica • Bentonite Clay • Dolomite

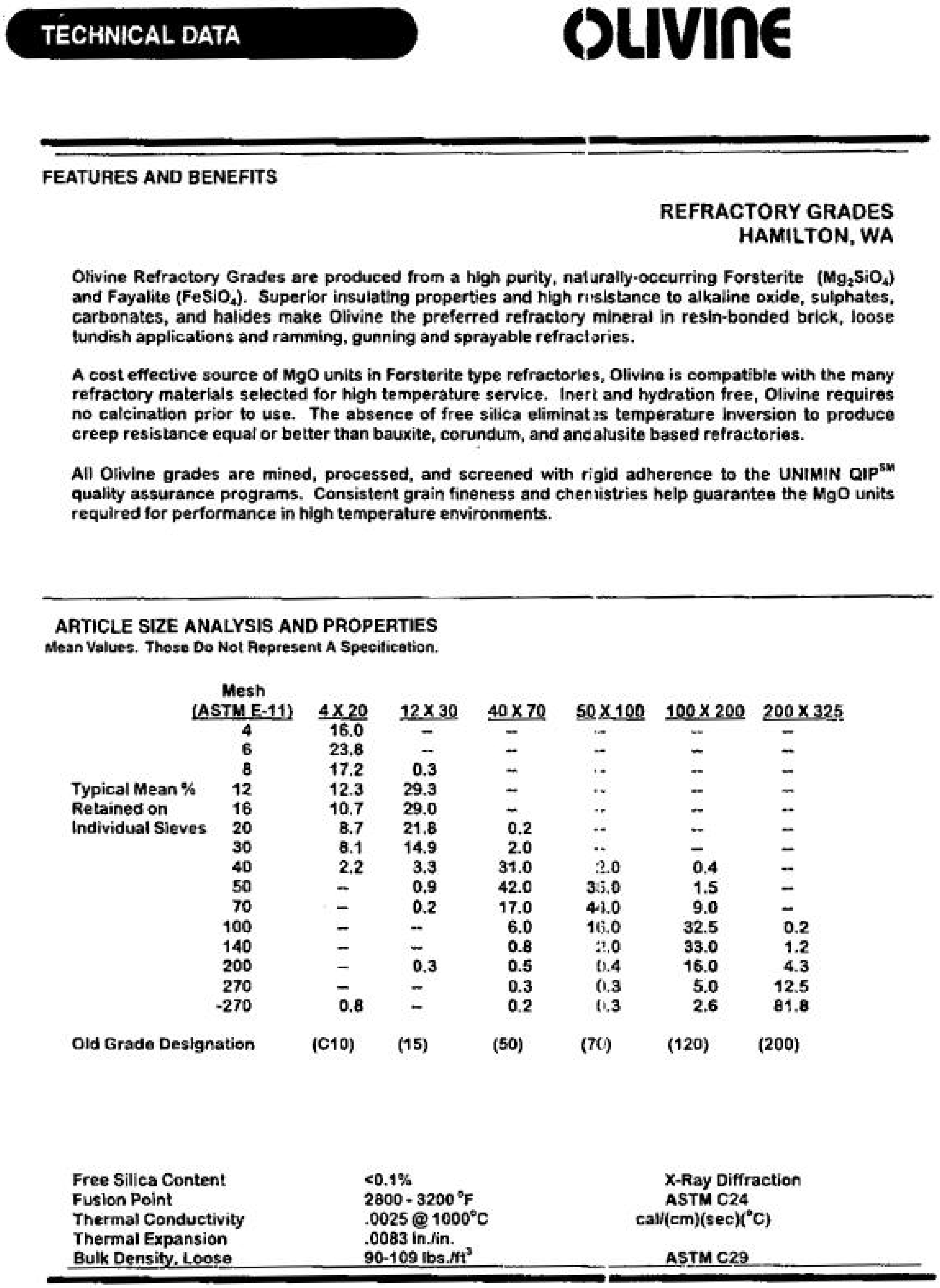
GRADE NUMBERS INDICATE RELATIVE VALUES OR RESULTS. THEY ARE NOT A SPECIFICATION OR WARRANTY OF PERFORMANCE.

HEALTH HAZARD WARNING: Prolonged inhalation of dust associated with the materials described in this data sheet can cause delayed lung injury. This material contains Nickel. IARC has determined Nickel compounds are carcinogenic to humans and the National Toxicological Program (NTP) has determined that Nickel may reasonably be anticipated to be a carcinogen. Avoid creating dust when handling, using or storing. Follow OSHA or other applicable governmental Safety and Health Standards. Current Material Safety Data Sheet containing safety information is available and should be consulted before usage.

**Notice:** While information contained herein is correct to the best of our knowledge, Unimin Corporation herein disclaims any warranties as to the accuracy of the same. Recommendations or suggestions are made without guarantee or representation as to result, since conditions of use are beyond our control. All materials are sold to Unimin Corporation standard terms and conditions of sale and on the condition that buyer shall make his own tests to determine the suitability of such product for buyer's purpose. No statement contained herein shall be construed as a recommendation to infringe any patent.

**ham-ref (4/97)**

Olivine/Olivine Containing



**TECHNICAL DATA**

# OLIVINE

## FEATURES AND BENEFITS

### REFRACTORY GRADES
### HAMILTON, WA

Olivine Refractory Grades are produced from a high purity, naturally-occurring Forsterite ($Mg_2SiO_4$) and Fayalite ($FeSiO_4$). Superior insulating properties and high resistance to alkaline oxide, sulphates, carbonates, and halides make Olivine the preferred refractory mineral in resin-bonded brick, loose tundish applications and ramming, gunning and sprayable refractories.

A cost effective source of MgO units in Forsterite type refractories, Olivine is compatible with the many refractory materials selected for high temperature service. Inert and hydration free, Olivine requires no calcination prior to use. The absence of free silica eliminates temperature inversion to produce creep resistance equal or better than bauxite, corundum, and andalusite based refractories.

All Olivine grades are mined, processed, and screened with rigid adherence to the UNIMIN QIP$^{SM}$ quality assurance programs. Consistent grain fineness and chemistries help guarantee the MgO units required for performance in high temperature environments.

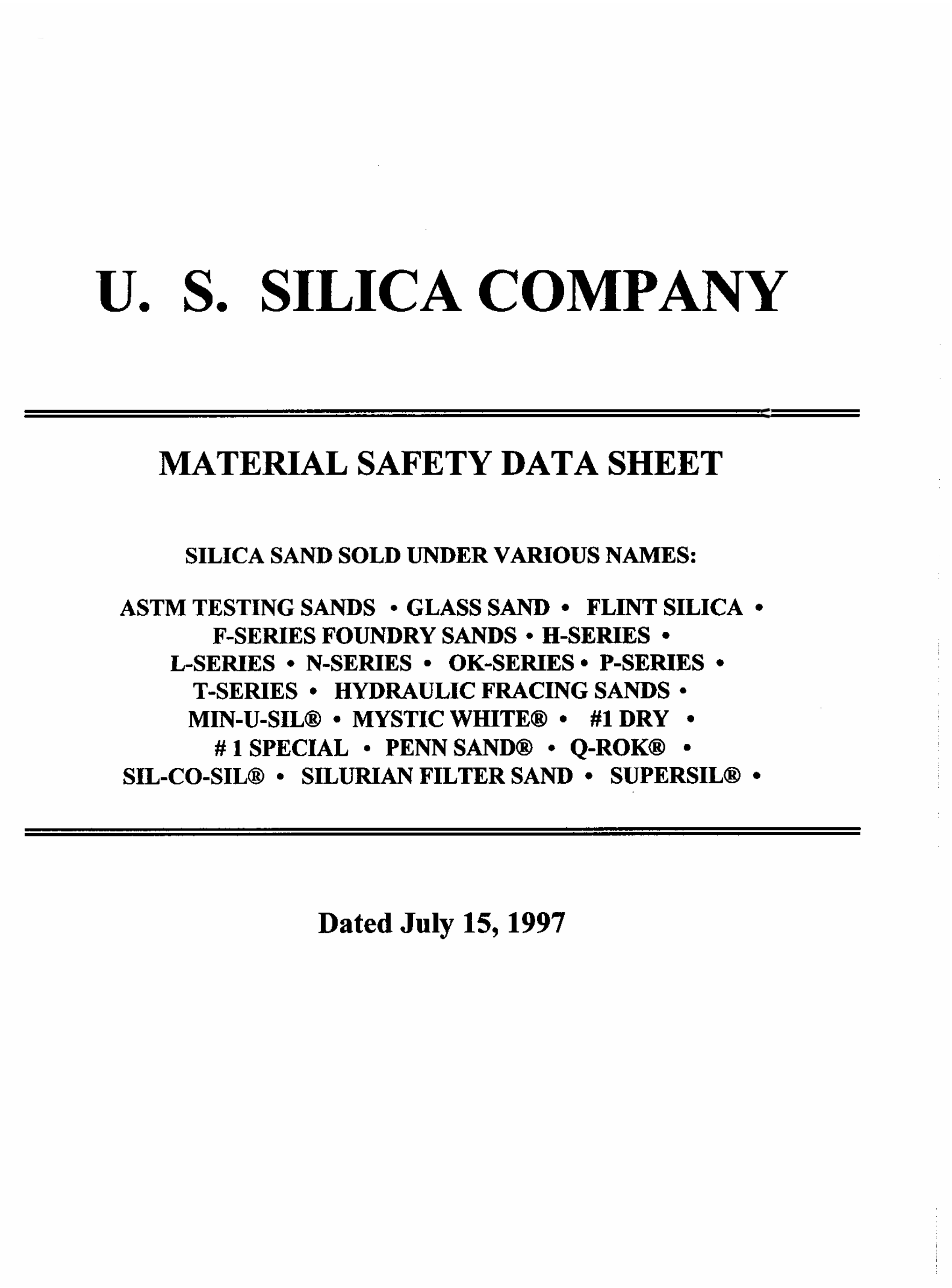
## ARTICLE SIZE ANALYSIS AND PROPERTIES

Mean Values. Those Do Not Represent A Specification.

|  | Mesh (ASTM E-11) | 4 X 20 | 12 X 30 | 40 X 70 | 50 X 100 | 100 X 200 | 200 X 325 |
|---|---|---|---|---|---|---|---|
|  | 4 | 16.0 | — | — | — | — | — |
|  | 6 | 23.8 | — | — | — | — | — |
|  | 8 | 17.2 | 0.3 | — | — | — | — |
| Typical Mean % Retained on Individual Sieves | 12 | 12.3 | 29.3 | — | — | — | — |
|  | 16 | 10.7 | 29.0 | — | — | — | — |
|  | 20 | 8.7 | 21.8 | 0.2 | — | — | — |
|  | 30 | 8.1 | 14.9 | 2.0 | — | — | — |
|  | 40 | 2.2 | 3.3 | 31.0 | 2.0 | 0.4 | — |
|  | 50 | — | 0.9 | 42.0 | 35.0 | 1.5 | — |
|  | 70 | — | 0.2 | 17.0 | 44.0 | 9.0 | — |
|  | 100 | — | — | 6.0 | 16.0 | 32.5 | 0.2 |
|  | 140 | — | — | 0.8 | 2.0 | 33.0 | 1.2 |
|  | 200 | — | 0.3 | 0.5 | 0.4 | 16.0 | 4.3 |
|  | 270 | — | — | 0.3 | 0.3 | 5.0 | 12.5 |
|  | -270 | 0.8 | — | 0.2 | 0.3 | 2.6 | 81.8 |
| Old Grade Designation |  | (C10) | (15) | (50) | (70) | (120) | (200) |

|  |  |  |
|---|---|---|
| Free Silica Content | <0.1% | X-Ray Diffraction |
| Fusion Point | 2800 - 3200 °F | ASTM C24 |
| Thermal Conductivity | .0025 @ 1000°C | cal/(cm)(sec)(°C) |
| Thermal Expansion | .0083 in./in. |  |
| Bulk Density, Loose | 90-109 lbs./ft$^3$ | ASTM C29 |

Figure B.13: Silica - MSDS



# U. S. SILICA COMPANY

## MATERIAL SAFETY DATA SHEET

**SILICA SAND SOLD UNDER VARIOUS NAMES:**

**ASTM TESTING SANDS • GLASS SAND • FLINT SILICA •
F-SERIES FOUNDRY SANDS • H-SERIES •
L-SERIES • N-SERIES • OK-SERIES • P-SERIES •
T-SERIES • HYDRAULIC FRACING SANDS •
MIN-U-SIL® • MYSTIC WHITE® • #1 DRY •
# 1 SPECIAL • PENN SAND® • Q-ROK® •
SIL-CO-SIL® • SILURIAN FILTER SAND • SUPERSIL® •**

**Dated July 15, 1997**

# MATERIAL SAFETY DATA SHEET

## SECTION 1 - CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

**Product Names/Trade Names**: Silica Sand sold under various names: ASTM TESTING SANDS, GLASS SAND, FLINT SILICA, F-SERIES FOUNDRY SANDS, H-SERIES, L-SERIES, N-SERIES, OK-SERIES, P-SERIES, T-SERIES, HYDRAULIC FRACING SANDS, MIN-U-SIL®, MYSTIC WHITE®, #1 DRY, #1 SPECIAL, PENN SAND®, Q-ROK®, SIL-CO-SIL®, SILURIAN FILTER SAND, SUPERSIL®.

**Synonyms/Common Names**: Sand, Silica Sand, Quartz, Crystalline Silica, Flint, Ground Silica.

**Manufacturer's Name:**
U. S. Silica Company
P. O. Box 187
Berkeley Springs, WV 25411

**Emergency Telephone Number**:
304-258-2500
304-258-8295 (fax)

**Date Prepared**: July 15, 1997

## SECTION 2 - COMPOSITION/INFORMATION ON INGREDIENTS

**Hazardous Ingredient:** Crystalline silica (quartz), typically 99.2% to 99.9%

**Chemical Formula:** $SiO_2$ **CAS#:** 14808-60-7

**OSHA PEL**: Exposure to airborne crystalline silica shall not exceed an 8-hour time-weighted average limit as stated in 29 CFR §1910.1000 Table Z-1-A, Air Contaminants, specifically:

$$\frac{10\ \text{mg/m}^3}{\text{SiO}_2+2}$$

**ACGIH TLV**: Crystalline Silica (quartz)
TLV-TWA = 0.1 $mg/m^3$ Respirable Crystalline Silica (quartz)
See Threshold Limit Value and Biological Exposure Indices for American Conference of Governmental Industrial Hygienists (latest edition).

**Other Recommended Limits:** National Institute for Occupational Safety and Health (NIOSH). Recommended standard maximum permissible concentration=0.05 $mg/m^3$ (respirable free silica) as determined by a full-shift sample up to 10-hour working day, 40-hour work week. See NIOSH Criteria for a Recommended Standard Occupational Exposure to Crystalline Silica.

**CAUTION:** Crystalline silica exists in several forms, the most common of which is quartz. If crystalline silica (quartz) is heated to more than 870°C it can change to a form of crystalline silica known as trydimite, and if crystalline silica (quartz) is heated to more than 1470°C, it can change to a form of crystalline silica known as cristobalite. Crystalline silica as trydimite and cristobalite are more fibrogenic than crystalline silica as quartz. The OSHA PEL for crystalline silica as trydimite and cristobalite is one-half the PEL for crystalline silica (quartz); the ACGIH TLV for crystalline silica as trydimite and cristobalite is one-half the TLV for crystalline silica as quartz.

## SECTION 3 - HAZARD IDENTIFICATION

**EMERGENCY OVERVIEW:**

The U. S. Silica Company material is a white or tan sand, or ground sand. It is not flammable, combustible or explosive. It does not cause burns or severe skin or eye irritation. A single exposure will not result in serious adverse health effects. Crystalline silica (quartz) is not known to be an environmental hazard.

Crystalline silica (quartz) is incompatible with hydrofluoric acid, fluorine, chlorine trifluoride or oxygen difluoride.

**POTENTIAL HEALTH EFFECTS:**

**Inhalation:**

a. Silicosis — Respirable crystalline silica (quartz) can cause silicosis, a fibrosis (scarring) of the lungs. Silicosis may be progressive; it may lead to disability and death.

| | |
|---|---|
| b. Cancer | Crystalline silica (quartz) inhaled from occupational sources is classified as carcinogenic to humans. |
| c. Scleroderma | There is evidence that exposure to respirable crystalline silica or that the disease silicosis is associated with the increased incidence of scleroderma, an autoimmune disorder manifested by a fibrosis (scarring) of the skin and internal organs. |
| d. Tuberculosis | Silicosis increases the risk of tuberculosis. |
| e. Nephrotoxicity | There are several studies suggesting that exposure to respirable crystalline silica or that the disease silicosis is associated with the increased incidence of kidney disorders. |

**Eye Contact**: Crystalline silica (quartz) may cause abrasion of the cornea.

**Skin Contact**: Not applicable.

**Ingestion**: Not applicable.

**Chronic Effects**: The adverse health effects -- silicosis, cancer, scleroderma, tuberculosis, and nephrotoxicity -- are chronic effects.

**Signs and Symptoms of Exposure**: There are generally no signs or symptoms of exposure to crystalline silica (quartz). Often, chronic silicosis has no symptoms. The symptoms of chronic silicosis, if present, are shortness of breath, wheezing, cough and sputum production. The symptoms of acute silicosis are the same; additionally, weight loss and fever are associated with acute silicosis. The symptoms of scleroderma include thickening and stiffness of the skin, particularly in the fingers, shortness of breath, difficulty swallowing and joint problems.

**Medical Conditions Generally Aggravated by Exposure**: The condition of individuals with lung disease (e.g., bronchitis, emphysema, chronic obstructive pulmonary disease) can be aggravated by exposure.

See Section 11, Toxicological Information, for additional detail on potential adverse health effects.

## SECTION 4 - FIRST-AID MEASURES

**Inhalation**: No specific first-aid is necessary since the adverse health effects associated with exposure to crystalline silica (quartz) result from chronic exposures. If there is a gross inhalation of crystalline silica (quartz), remove the person immediately to fresh air, give artificial respiration as needed, seek medical attention as needed.

**Eye Contact**: Wash immediately with water. If irritation persists, seek medical attention.

**Skin Contact**: Not applicable.

**Ingestion**: Not applicable.

## SECTION 5 - FIRE FIGHTING MEASURES

| | | | |
|---|---|---|---|
| **Flammability:** | Crystalline silica (quartz) is non-flammable and non-explosive | **Extinguishing Media**: | None required |
| **Flash Point:** | None | **Special Fire Fighting Procedures:** | N/A |
| **Flammable Limits**: | None | **Unusual Fire and Explosion Hazards**: | None |

## SECTION 6 - ACCIDENTAL RELEASE MEASURES

**Spills**: Use dustless methods (vacuum) and place into closable container for disposal, or flush with water. Do not dry sweep. Wear protective equipment specified below.

**Waste Disposal Method**: See Section 13.

## SECTION 7 - HANDLING AND STORAGE

**Precautions During Handling and Use**: Do not breath dust. Use adequate ventilation and dust collection. Keep airborne dust concentrations below PEL. Practice good housekeeping. Do not permit dust to collect on walls, floors, sills, ledges, machinery, or equipment. Maintain, clean, and fit test respirators in accordance with OSHA regulations. Maintain and test ventilation and dust collection equipment. Wash or vacuum clothing which has become dusty. See also control measures in Section 8.

**Precautions During Storage**: Avoid breakage of bagged material or spills of bulk material. See control measures in Section 8.

**Do not use U. S. Silica Company materials for sandblasting.**

The OSHA Hazard Communication Standard, 29 CFR Sections 1910.1200, 1915.99, 1917.28, 1918.90, 1926.59, and 1928.21, and state and local worker or community "right to know" laws and regulations should be strictly followed. WARN YOUR EMPLOYEES (AND YOUR CUSTOMERS IN CASE OF RESALE) BY POSTING AND OTHER MEANS OF THE HAZARDS AND THE REQUIRED OSHA PRECAUTIONS. PROVIDE TRAINING FOR YOUR EMPLOYEES ABOUT THE OSHA PRECAUTIONS.

See also American Society for Testing and Materials (ASTM) standard practice E 1132-86, "Standard Practice for Health Requirements Relating to Occupational Exposure to Quartz Dust."

## SECTION 8 - EXPOSURE CONTROLS/PERSONAL PROTECTION

**Local Exhaust**: Use sufficient local exhaust to reduce the level of respirable crystalline silica to below the PEL. See ACGIH "Industrial Ventilation, A Manual of Recommended Practice" (latest edition).

**Respiratory Protection**: The following chart specifies the types of respirators which may provide respiratory protection for crystalline silica.

| CONDITION Particulate Concentration | MINIMUM RESPIRATORY PROTECTION* |
|---|---|
| 5 x PEL or less | Any particulate respirator. |
| 10 x PEL or less | Any particulate respirator, except single-use or quarter-mask respirator.<br>Any fume respirator or high efficiency particulate filter respirator.<br>Any supplied-air respirator.<br>Any self-contained breathing apparatus. |
| 50 x PEL or less | A high efficiency particulate filter respirator with a full facepiece.<br>Any supplied-air respirator with a full facepiece, helmet, or hood.<br>Any self-contained breathing apparatus with a full facepiece. |
| 500 x PEL or less | A powered air-purifying respirator with a high efficiency particulate filter.<br>A Type C supplied-air respirator operated in pressure-demand or other positive pressure or continuous-flow mode. |
| Greater than 500 x PEL or entry and escape from unknown concentrations | Self-contained breathing apparatus with a full facepiece operated in pressure-demand or other positive pressure mode.<br>A combination respirator which includes a Type C supplied-air respirator with a full facepiece operated in pressure-demand or other positive pressure continuous-flow mode and an auxiliary self-contained breathing apparatus operated in pressure-demand or other positive pressure mode. |
| ***Use only NIOSH-approved or MSHA-approved equipment. See 29 CFR §1910.134 and 42 CFR §84.** | |

See also ANSI standard Z88.2 (latest revision) "American National Standard for Respiratory Protection"

**Permissible Exposure Levels**:

| | | | Exposure Guidelines | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Component | CAS No. | Percentage (by wt.) | OSHA | | ACGIH | | NIOSH | | |
| | | | TWA | STEL | TWA | STEL | TWA | STEL | Unit |
| Crystalline Silica (quartz) | 14808-60-7 | 99.2-99.9 | $\frac{10}{\% SiO_2+2}$ | None | .1 | None | .05 | None | mg/m³ |

## SECTION 9 - PHYSICAL AND CHEMICAL PROPERTIES

| | | | |
|---|---|---|---|
| **Appearance:** | White or tan sand; granular, crushed, or ground | | |
| **Boiling Point**: | 4046°F | **Odor:** | None |
| **Vapor Pressure (mm Hg.):** | None | **Specific Gravity (Water = 1):** | 2.65 |
| **Vapor Density (Air = 1):** | None | **Melting Point:** | 3110°F |
| **Solubility in Water:** | Insoluble in water | **Evaporation Rate (Butyl Acetate = 1):** | None |

## SECTION 10 - STABILITY AND REACTIVITY

**Stability**: Crystalline silica (quartz) is stable.

**Incompatibility (Materials to Avoid)**: Contact with powerful oxidizing agents such as fluorine, chlorine trifluoride, oxygen difluoride, may cause fires.

**Hazardous Decomposition or Byproducts**: Silica will dissolve in hydrofluoric acid and produce a corrosive gas - silicon tetrafluoride.

**Hazardous Polymerization**: Will not occur.

## SECTION 11 - TOXICOLOGICAL INFORMATION

### A. SILICOSIS

The major concern is silicosis, caused by the inhalation and retention of respirable crystalline silica dust. Silicosis can exist in several forms, chronic (or ordinary), accelerated, or acute.

Chronic or Ordinary Silicosis is the most common form of silicosis, and can occur after many years of exposure to relatively low levels of airborne respirable crystalline silica dust. It is further defined as either simple or complicated silicosis.

Simple silicosis is characterized by lung lesions (shown as radiographic opacities) less than 1 centimeter in diameter, primarily in the upper lung zones. Often, simple silicosis is not associated with symptoms, detectable changes in lung function or disability.

Simple silicosis may be progressive and may develop into complicated silicosis or progressive massive fibrosis (PMF). Complicated silicosis or PMF is characterized by lung lesions (shown as radiographic opacities) greater than 1 centimeter in diameter. Although there may be no symptoms associated with complicated silicosis or PMF, the symptoms, if present, are shortness of breath, wheezing, cough and sputum production. Complicated silicosis or PMF may be associated with decreased lung function and may be disabling. Advanced complicated silicosis or PMF may lead to death. Advanced complicated silicosis or PMF can result in heart disease secondary to the lung disease (cor pumonale).

Accelerated Silicosis can occur with exposure to high concentrations of respirable crystalline silica over a relatively short period; the lung lesions can appear within five (5) years of the initial exposure. The progression can be rapid. Accelerated silicosis is similar to chronic or ordinary silicosis, except that the lung lesions appear earlier and the progression is more rapid.

Acute Silicosis can occur with exposures to very high concentrations of respirable crystalline silica over a very short time period, sometimes as short as a few months. The symptoms of acute silicosis include progressive shortness of breath, fever, cough and weight loss. Acute silicosis is fatal.

### B. CANCER

IARC - The International Agency for Research on Cancer ("IARC") concluded that there was "*sufficient evidence* in humans for the carcinogenicity of crystalline silica in the forms of quartz or cristobalite from occupational sources", and that there is "*sufficient evidence* in experimental animals for the carcinogenicity of quartz and cristobalite." The overall IARC evaluation was that "crystalline silica inhaled in the form of quartz or cristobalite from occupational sources is *carcinogenic to humans* (*Group 1*)." The IARC evaluation noted that "carcinogenicity was not detected in all industrial circumstances studies. Carcinogenicity may be dependent on inherent characteristics of the crystalline silica or on external factors affecting its biological activity or distribution of its polymorphs." For further information on the IARC evaluation, see IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, Volume 68, "Silica, Some Silicates..." (1997).

NTP - The National Toxicology Program, in its Sixth Annual Report on Carcinogens, concluded that "silica, crystalline (respirable)" may reasonably be anticipated to be a carcinogen, based on sufficient evidence in experimental animals and limited evidence in humans.

OSHA - Crystalline silica (quartz) is not regulated by the U. S. Occupational Safety and Health Administration as a carcinogen.

There is substantial literature on the issues of the carcinogenicity of crystalline silica, which the reader should consult for additional information. A summary of the literature is set forth in "Exposure to crystalline silica and risk of lung cancer; the epidemiological evidence", Thorax, Volume 51, pp. 97-102 (1996). The official statement of the American Thoracic Society on the issue of silica carcinogenicity was published in "Adverse Effects of Crystalline Silica Exposure", American Journal of Respiratory and Critical Care Medicine, Volume 155, pp. 761-765 (1997). The official statement concluded that "The available data support the conclusion that silicosis produces increased risk for bronchogenic carcinoma. The cancer risk may also be increased by smoking and other carcinogens in the workplace. Epidemiologic studies provide convincing evidence for increased cancer risk among tobacco smokers with silicosis. Less information is available for never-smokers and for workers exposed to silica but who do not have silicosis. For workers with silicosis, the risks for lung cancer are relatively high and consistent among various countries and investigators. Silicosis should be considered a condition that predisposes workers to an increased risk of lung cancer." Id. at 763.

### C. SCLERODERMA

There is evidence that exposure to respirable crystalline silica or that the disease silicosis is associated with the increased incidence of scleroderma, an immune system disorder manifested by a fibrosis (scarring) of the lungs, skin and other internal organs. Recently, the American Thoracic Society noted that "there is persuasive evidence relating scleroderma to occupational silica exposures in setting where there is appreciable silicosis risk." The following may be consulted for additional information on silica, silicosis and scleroderma (also known as progressive systemic sclerosis): Occupational Lung Disorders, Third Edition, Chapter 12, entitled "Silicosis and Related Diseases", Parkes, W. Raymond (1994). "Adverse Effects of Crystalline Silica Exposure", American Journal of Respiratory and Critical Care Medicine, Volume 155, pp. 761-765 (1997).

### D. TUBERCULOSIS

Individuals with silicosis are at increased risk to develop tuberculosis, if exposed to persons with tuberculosis. The following may be consulted for further information: Occupational Lung Disorders, Third Edition, Chapter 12, entitled "Silicosis and Related Diseases", Parkes, W. Raymond (1994). "Adverse Effects of Crystalline Silica Exposure", American Journal of Respiratory and Critical Care Medicine, Volume 155, pp. 761-765 (1997).

### E. NEPHROTOXICITY

There are several recent studies suggesting that exposure to respirable crystalline silica or that the disease silicosis is associated with the increased incidence of kidney disorders. The following may be consulted for additional information on silica, silicosis and nephrotoxicity: Occupational Lung Disorders, Third Edition, Chapter 12, entitled "Silicosis and Related Diseases", Parkes, W. Raymond (1994). "Further evidence of human silica nephrotoxicity in occupationally exposed workers", British Journal of Industrial Medicine, Vol. 50, No. 10, pp. 907-912 (1993). "Adverse Effects of Crystalline Silica Exposure", American Journal of Respiratory and Critical Care Medicine, Volume 155, pp. 761-765 (1997).

## SECTION 12 - ECOLOGICAL INFORMATION

Crystalline silica (quartz) is not known to be ecotoxic; i.e., there is no data which suggests that crystalline silica (quartz) is toxic to birds, fish, invertebrates, microorganisms or plants. For additional information on crystalline silica (quartz), see Sections 9 (physical and chemical properties) and 10 (stability and reactivity) of this MSDS.

## SECTION 13 - DISPOSAL CONSIDERATIONS

**General**: The packaging and material may be landfilled; however, material should be covered to minimize generation of airborne dust.

**RCRA**: Crystalline silica (quartz) is not classified as a hazardous waste under the Resource Conservation and Recovery Act, or its regulations, 40 CFR §261 et seq.

The above applies to materials as sold by U.S. Silica Company. The material may be contaminated during use, and it is the responsibility of the user to assess the appropriate disposal of the used material.

## SECTION 14 - TRANSPORT INFORMATION

Crystalline silica (quartz) is not a hazardous material for purposes of transportation under the U. S. Department of Transportation Table of Hazardous Materials, 49 CFR §172.101.

## SECTION 15 - REGULATORY INFORMATION

UNITED STATES (FEDERAL AND STATE)

TSCA No.: Crystalline silica (quartz) appears on the EPA TSCA inventory under the CAS No. 14808-60-7.

RCRA: Crystalline silica (quartz) is not classified as a hazardous waste under the Resource Conservation and Recovery Act, or its regulations, 40 CFR §261 et seq.

CERCLA: Crystalline silica (quartz) is not classified as a hazardous substance under regulations of the Comprehensive Environmental Response Compensation and Liability Act (CERCLA), 40 CFR §302.

Emergency Planning and Community Right to Know Act: Crystalline silica (quartz) is not an extremely hazardous substance under Section 302 and is not a toxic chemical subject to the requirements of Section 313.

Clean Air Act: Crystalline silica (quartz) mined and processed by U.S. Silica Company was not processed with or does not contain any Class I or Class II ozone depleting substances.

FDA: Silica is included in the list of substances that may be included in coatings used in food contact surfaces, 21 CFR §175.300(b)(3)(xxvi).

NTP: Respirable crystalline silica (quartz) is classified as a probable carcinogen.

OSHA Carcinogen: Crystalline silica (quartz) is not listed.

California Proposition 65: Crystalline silica (quartz) is classified as a substance known to the state of California to be a carcinogen.

**CANADA**

Domestic Substances List: U. S. Silica Company products, as naturally occurring substances, are on the Canadian DSL.

WHMIS Classification: D-2A

**OTHER**

EINECS No.: 231-545-4

EEC Label (Risk/Safety Phrases): R 48/20, R 40/20, S22, S38

IARC: Crystalline silica (quartz) is classified in IARC Group 1.

**National, state, provincial or local emergency planning, community right to know or other laws, regulations or ordinances may be applicable--consult applicable national, state, provincial or local laws.**

## SECTION 16 - OTHER INFORMATION

**Hazardous Material Information System (HMIS):**

| | |
|---|---|
| Health | * |
| Flammability | 0 |
| Reactivity | 0 |
| Protective Equipment | E |

* For further information on health effects, see Sections 3 and 11 of this MSDS.

**National Fire Protection Association (NFPA):**

| | |
|---|---|
| Health | 0 |
| Flammability | 0 |
| Reactivity | 0 |

**Warning Label Text:**

WARNING
Contains Silica Dust
Can Cause Silicosis and Cancer

Avoid Breathing Dust

HAZARDS

Silica dust can cause severe and permanent lung damage and other diseases.

- Breathing silica dust can cause silicosis, a lung disease that can lead to serious breathing difficulties and death. Silicosis also increases the risk of tuberculosis.
- Breathing silica dust can cause cancer.
- Breathing silica dust may cause scleroderma, a scarring of the skin and internal organs.

Breathing silica dust may not cause noticeable injury or illness, even though permanent lung damage may be occurring.

PRECAUTIONS

Avoid breathing dust. Use with adequate and properly maintained dust collection systems to keep silica dust below permissible limits.

Avoid creating dust when using, handling, storing, or disposing of this product or bag.

- Do not dry sweep product. Wet product with water or use a dustless method (vacuum) to clean spills.
- Do not allow dust to collect on floors, sills, ledges, machinery, or equipment.

Do not rely on your sight to determine if dust is in the air. Silica may be in the air without a visible dust cloud. If dust cannot be kept below permissible limits, wear a respirator approved for silica dust when using, handling, storing or disposing of this product or bag.

DO NOT USE FOR SANDBLASTING!

See U. S. Silica Company Material Safety Data Sheet in Your Employer's Possession for More

Information on Hazards and Precautions

CAS#14808-60-7

**Web Sites With Information About Effects of Crystalline Silica Exposure:**

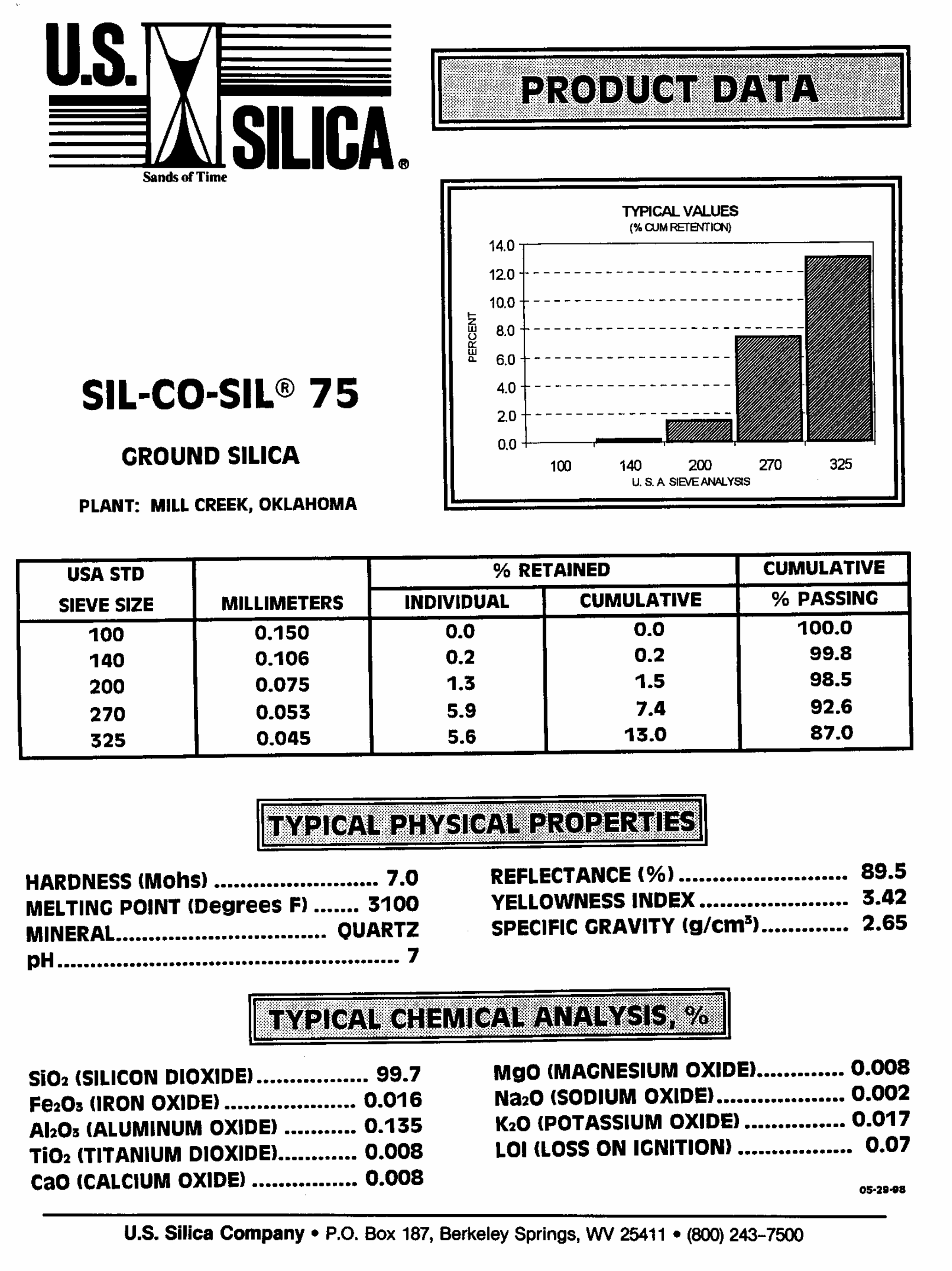
http://www.msha.gov - The Mine Safety Health Administration Home Page, which contains general (not mining specific) information on silicosis. Click on "Silicosis Prevention".

http://www.cdc.gov/niosh/silicpag.html - NIOSH Hotlinks to Silicosis Prevention.

## U. S. SILICA COMPANY DISCLAIMER

**The information and recommendations contained herein are based upon data believed to be correct. However, no guarantee or warranty of any kind, express or implied, is made with respect to the information contained herein. We accept no responsibility and disclaim all liability for any harmful effects which may be caused by purchase, resale, use or exposure to our silica. Customers-users of silica must comply with all applicable health and safety laws, regulations, and orders, including the OSHA Hazardous Communication Standard.**

Figure B.14: Silica – Vendor Technical Data


TYPICAL VALUES
(% CUM RETENTION)
PERCENT
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
100
140
200
270
325
U. S. A. SIEVE ANALYSIS

U.S. SILICA®
Sands of Time

## PRODUCT DATA

## SIL-CO-SIL® 75

### GROUND SILICA

**PLANT: MILL CREEK, OKLAHOMA**

| USA STD SIEVE SIZE | MILLIMETERS | % RETAINED | | CUMULATIVE |
|---|---|---|---|---|
| | | INDIVIDUAL | CUMULATIVE | % PASSING |
| 100 | 0.150 | 0.0 | 0.0 | 100.0 |
| 140 | 0.106 | 0.2 | 0.2 | 99.8 |
| 200 | 0.075 | 1.3 | 1.5 | 98.5 |
| 270 | 0.053 | 5.9 | 7.4 | 92.6 |
| 325 | 0.045 | 5.6 | 13.0 | 87.0 |

## TYPICAL PHYSICAL PROPERTIES

| | |
|---|---|
| HARDNESS (Mohs) | 7.0 |
| MELTING POINT (Degrees F) | 3100 |
| MINERAL | QUARTZ |
| pH | 7 |
| REFLECTANCE (%) | 89.5 |
| YELLOWNESS INDEX | 3.42 |
| SPECIFIC GRAVITY (g/cm³) | 2.65 |

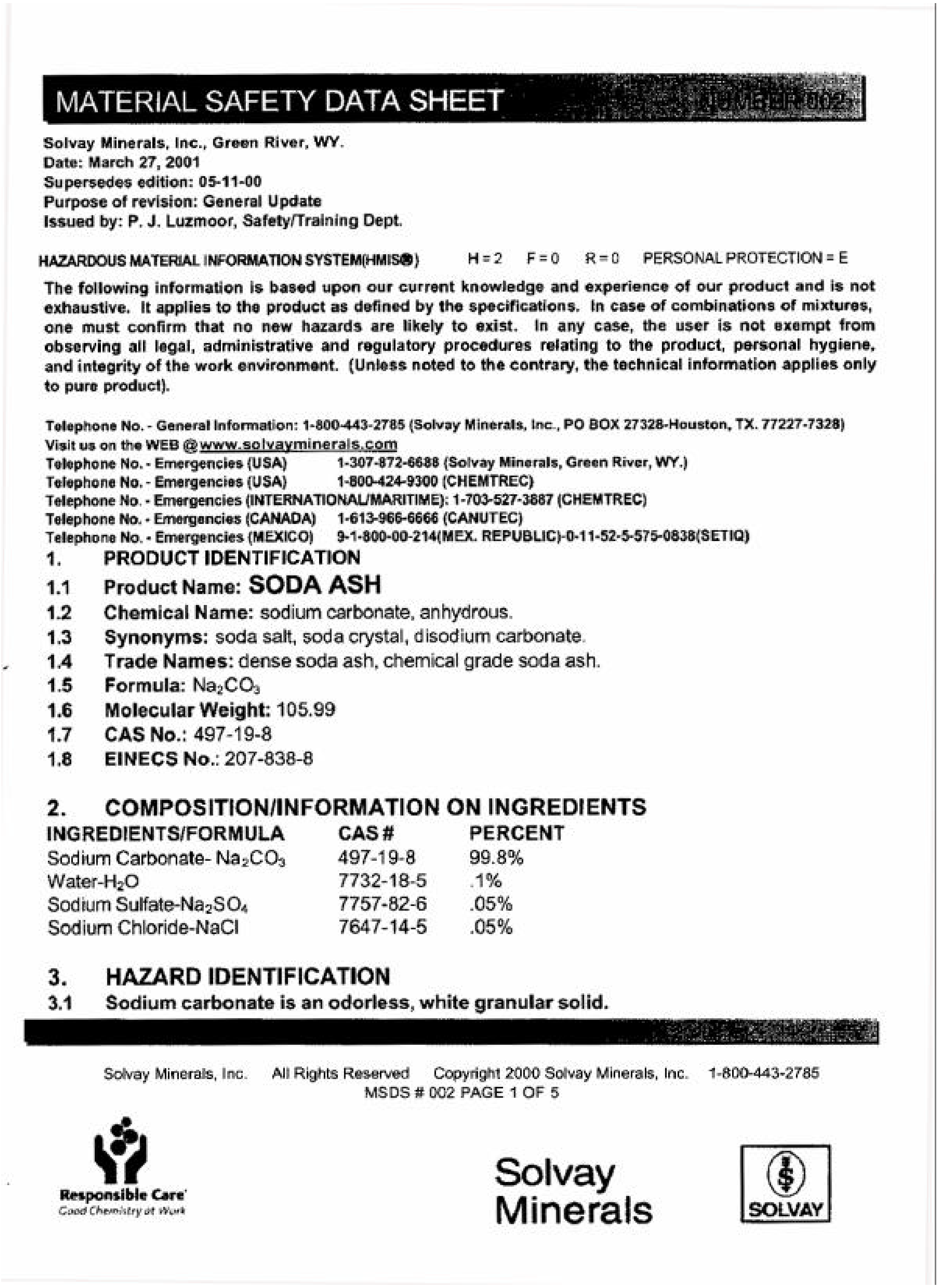
## TYPICAL CHEMICAL ANALYSIS, %

| | |
|---|---|
| $SiO_2$ (SILICON DIOXIDE) | 99.7 |
| $Fe_2O_3$ (IRON OXIDE) | 0.016 |
| $Al_2O_3$ (ALUMINUM OXIDE) | 0.135 |
| $TiO_2$ (TITANIUM DIOXIDE) | 0.008 |
| CaO (CALCIUM OXIDE) | 0.008 |
| MgO (MAGNESIUM OXIDE) | 0.008 |
| $Na_2O$ (SODIUM OXIDE) | 0.002 |
| $K_2O$ (POTASSIUM OXIDE) | 0.017 |
| LOI (LOSS ON IGNITION) | 0.07 |

05-29-98

**U.S. Silica Company** • P.O. Box 187, Berkeley Springs, WV 25411 • (800) 243-7500

**Figure B.15: Sodium Carbonate - MSDS**



# MATERIAL SAFETY DATA SHEET NUMBER 002

**Solvay Minerals, Inc., Green River, WY.**
**Date: March 27, 2001**
**Supersedes edition: 05-11-00**
**Purpose of revision: General Update**
**Issued by: P. J. Luzmoor, Safety/Training Dept.**

**HAZARDOUS MATERIAL INFORMATION SYSTEM(HMIS®)** H = 2 F = 0 R = 0 PERSONAL PROTECTION = E

**The following information is based upon our current knowledge and experience of our product and is not exhaustive. It applies to the product as defined by the specifications. In case of combinations of mixtures, one must confirm that no new hazards are likely to exist. In any case, the user is not exempt from observing all legal, administrative and regulatory procedures relating to the product, personal hygiene, and integrity of the work environment. (Unless noted to the contrary, the technical information applies only to pure product).**

**Telephone No. - General Information: 1-800-443-2785 (Solvay Minerals, Inc., PO BOX 27328-Houston, TX. 77227-7328)**
**Visit us on the WEB @ www.solvayminerals.com**
**Telephone No. - Emergencies (USA) 1-307-872-6688 (Solvay Minerals, Green River, WY.)**
**Telephone No. - Emergencies (USA) 1-800-424-9300 (CHEMTREC)**
**Telephone No. - Emergencies (INTERNATIONAL/MARITIME): 1-703-527-3887 (CHEMTREC)**
**Telephone No. - Emergencies (CANADA) 1-613-966-6666 (CANUTEC)**
**Telephone No. - Emergencies (MEXICO) 9-1-800-00-214(MEX. REPUBLIC)-0-11-52-5-575-0838(SETIQ)**

## 1. PRODUCT IDENTIFICATION

1.1 **Product Name: SODA ASH**
1.2 **Chemical Name:** sodium carbonate, anhydrous.
1.3 **Synonyms:** soda salt, soda crystal, disodium carbonate.
1.4 **Trade Names:** dense soda ash, chemical grade soda ash.
1.5 **Formula:** $Na_2CO_3$
1.6 **Molecular Weight:** 105.99
1.7 **CAS No.:** 497-19-8
1.8 **EINECS No.:** 207-838-8

## 2. COMPOSITION/INFORMATION ON INGREDIENTS

| INGREDIENTS/FORMULA | CAS # | PERCENT |
|---|---|---|
| Sodium Carbonate- $Na_2CO_3$ | 497-19-8 | 99.8% |
| Water-$H_2O$ | 7732-18-5 | .1% |
| Sodium Sulfate-$Na_2SO_4$ | 7757-82-6 | .05% |
| Sodium Chloride-NaCl | 7647-14-5 | .05% |

## 3. HAZARD IDENTIFICATION

3.1 **Sodium carbonate is an odorless, white granular solid.**

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Minerals

SOLVAY

3.2 **Route(s) of Entry:** Inhalation? Yes Skin? Yes Ingestion? Yes

3.3 **Effects of exposure:** Irritating to mucous membranes and eyes.

**Inhalation (dust):** May be irritating to the nose, throat, and respiratory tract. Repeated exposure may cause nosebleeds.

**Eyes (dust):** Severe eye irritation, watering, redness and swelling of the eyelids. Risk of serious or permanent eye lesions.

**Skin:** May cause skin irritation, seen as redness and swelling. In the presence of moisture or sweat, irritation may become more severe leading to rash. May cause dry and chapped skin.

**Ingestion:** May cause severe irritation and risk of burns to the mouth, throat, esophagus and stomach. Ingestion of large quantities can cause nausea and vomiting (bloody) abdominal cramps and diarrhea (bloody).

## 4. FIRST AID MEASURES

4.1 **Inhalation:** Remove subject to a dust free environment and blow nose. If breathing is difficult or has stopped, administer artificial respiration. If any irritation is present, seek medical attention.

**Eyes: Recommendation:** In cases of splashing of concentrated solution in the eyes and face, treat the eyes first, then continue first aid as defined under "contact with the skin." **WITHOUT LOSS OF TIME:** Rinse the eyes with running water for 15 minutes, maintaining the eyelids wide open to eliminate the product. Protect the eyes from strong light. Consult a physician or ophthalmologist in all cases. Transport subject to a medical facility.

**Skin:** Remove shoes and contaminated clothing, under a shower if necessary. Wash the affected area with luke-warm water. Dry carefully. In case of persistent pain or reddening, consult a physician. Provide clean clothes.

**Ingestion:** DO NOT ATTEMPT TO GIVE ANYTHING BY MOUTH TO AN UNCONSCIOUS PERSON. Do not induce vomiting. Remove any evidence of the product from the person's mouth. If the person is conscious and alert, give 8-12 ounces of water. SEEK MEDICAL ATTENTION.

4.2 **Medical Conditions Aggravated by Exposure:**

Skin irritation may be aggravated in persons with existing skin lesions. Breathing of dust may aggravate asthma or other chronic pulmonary diseases.

## 5. FIRE FIGHTING MEASURES

5.1 **Flash Point:** Non combustible. Method: Not applicable.

5.2 **Auto-ignition Temperature:** Not applicable.

5.3 **Flammability Limits: Upper & Lower Limit:** Non flammable.

5.4 **Fire Fighting Procedures:** Not applicable.

5.5 **Common Extinguishing Methods**: In case of fire in close proximity, all means of extinguishing are acceptable.

## 6. ACCIDENTAL RELEASE MEASURES

6.1 **Spills**: Shovel back into the original dry, uncontaminated container or waste receptacle. Flush area with water; contain runoff, dispose of waste in accordance with applicable federal, state, and local environmental laws and regulations.

## 7. HANDLING AND STORAGE

7.1 **Handling:** Avoid prolonged or repeated contact with the skin or eyes. Do not wear contact lenses without proper eye protection when using this product. Avoid prolonged or repeated breathing of dusts. Use vacuum or wet mop to clean up dust.

7.2 **Storage:** Keep in a closed, properly labeled container in a dry area away from acids. Protect from physical damage.

7.3 **For all operations:** DO NOT TAKE INTERNALLY.

## 8. EXPOSURE CONTROLS/PERSONAL PROTECTION

8.1 **Exposure Limits:** OSHA Permissible Exposure Limit (PEL) Nuisance Dust-5 $mg/m^3$ (Respirable Fraction), 15 $mg/m^3$ (Total Dust).

8.2 **Ventilation:** In places with the possibility for creating excessive dust in excess of exposure limits, ventilation should be provided.

8.3 **Respiratory Protection:** In case of significant or accidental dust emissions, a NIOSH/MSHA approved dust respirator should be worn.

8.4 **Protective Gloves:** Chemical resistant gloves.

8.5 **Eye Protection: Wear** In cases of significant dust, dust proof goggles are recommended.

8.6 **Other Protective Clothing or Equipment**: Chemical protective clothing in dusty areas. An eyewash and safety shower should be nearby and ready for use. Use good hygiene practices when handling this product including changing work clothes after use. Do not eat, drink or smoke in areas where this material is handled.

## 9. PHYSICAL AND CHEMICAL PROPERTIES

9.1 **Melting Point** 851°C (1564°F).

9.2 **Boiling Point** Not applicable.

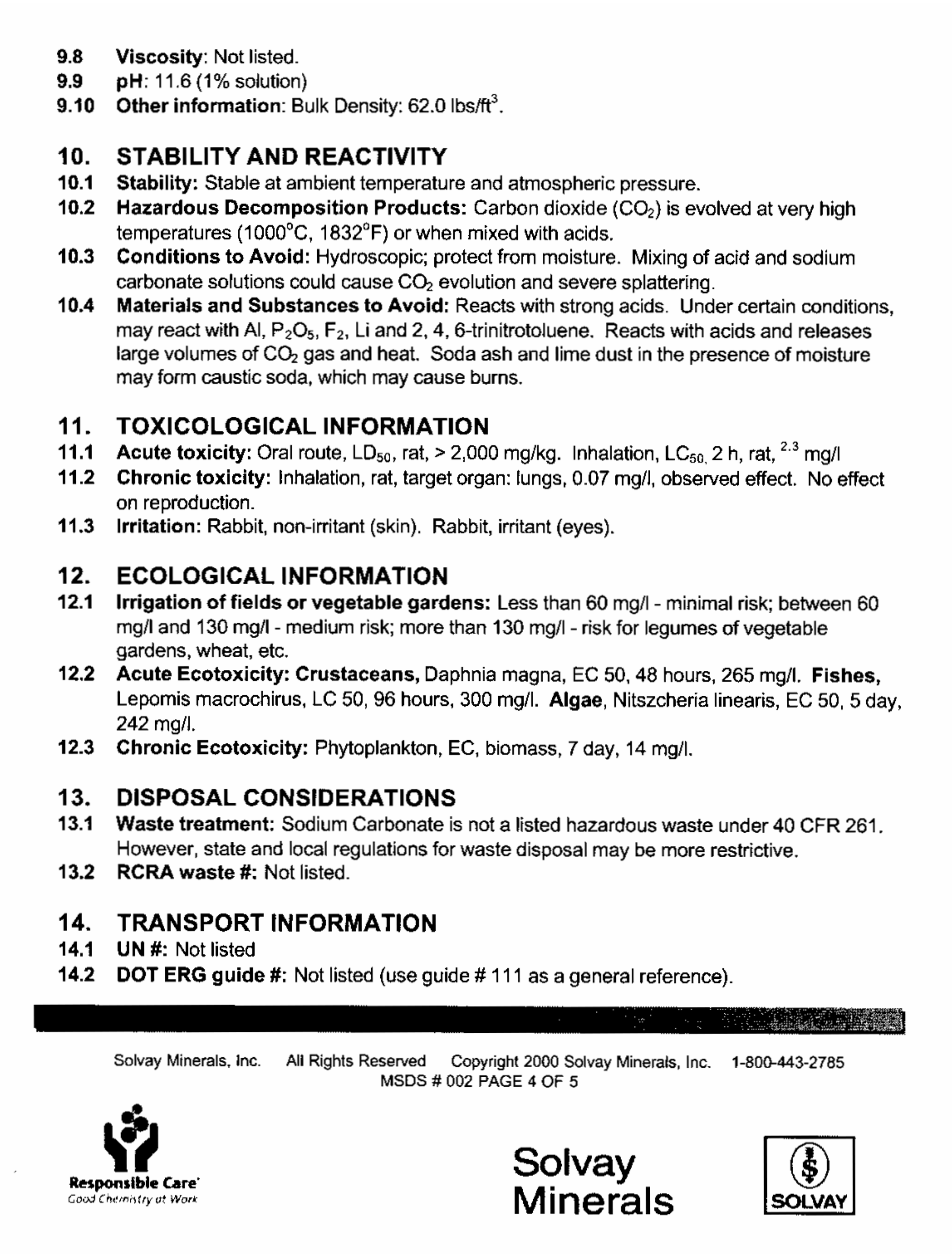
9.3 **Specific Gravity** ($H_2O$=1): 2.533 @ 25°C (77°F).

9.4 **Vapor Density** (air=1): Not applicable.

9.5 **Vapor Pressure**: Not listed.

9.6 **Solubility**: 33% maximum by weight in water.

9.7 **Decomposition Temperature**: Beginning at 400°C (752°F).



**9.8 Viscosity**: Not listed.

**9.9 pH**: 11.6 (1% solution)

**9.10 Other information**: Bulk Density: 62.0 lbs/ft$^3$.

## 10. STABILITY AND REACTIVITY

**10.1 Stability:** Stable at ambient temperature and atmospheric pressure.

**10.2 Hazardous Decomposition Products:** Carbon dioxide ($CO_2$) is evolved at very high temperatures (1000°C, 1832°F) or when mixed with acids.

**10.3 Conditions to Avoid:** Hydroscopic; protect from moisture. Mixing of acid and sodium carbonate solutions could cause $CO_2$ evolution and severe splattering.

**10.4 Materials and Substances to Avoid:** Reacts with strong acids. Under certain conditions, may react with Al, $P_2O_5$, $F_2$, Li and 2, 4, 6-trinitrotoluene. Reacts with acids and releases large volumes of $CO_2$ gas and heat. Soda ash and lime dust in the presence of moisture may form caustic soda, which may cause burns.

## 11. TOXICOLOGICAL INFORMATION

**11.1 Acute toxicity:** Oral route, $LD_{50}$, rat, > 2,000 mg/kg. Inhalation, $LC_{50}$, 2 h, rat, $^{2.3}$ mg/l

**11.2 Chronic toxicity:** Inhalation, rat, target organ: lungs, 0.07 mg/l, observed effect. No effect on reproduction.

**11.3 Irritation:** Rabbit, non-irritant (skin). Rabbit, irritant (eyes).

## 12. ECOLOGICAL INFORMATION

**12.1 Irrigation of fields or vegetable gardens:** Less than 60 mg/l - minimal risk; between 60 mg/l and 130 mg/l - medium risk; more than 130 mg/l - risk for legumes of vegetable gardens, wheat, etc.

**12.2 Acute Ecotoxicity: Crustaceans,** Daphnia magna, EC 50, 48 hours, 265 mg/l. **Fishes,** Lepomis macrochirus, LC 50, 96 hours, 300 mg/l. **Algae**, Nitszcheria linearis, EC 50, 5 day, 242 mg/l.

**12.3 Chronic Ecotoxicity:** Phytoplankton, EC, biomass, 7 day, 14 mg/l.

## 13. DISPOSAL CONSIDERATIONS

**13.1 Waste treatment:** Sodium Carbonate is not a listed hazardous waste under 40 CFR 261. However, state and local regulations for waste disposal may be more restrictive.

**13.2 RCRA waste #:** Not listed.

## 14. TRANSPORT INFORMATION

**14.1 UN #:** Not listed

**14.2 DOT ERG guide #:** Not listed (use guide # 111 as a general reference).

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**14.3 STCC #:** 28-123-22

## 15. REGULATORY INFORMATION

**15.1 NFPA®:** Health-**2** **HMIS®:** Health–**2** **WHMIS: D-2**
Flammability-**0** Fire-**0**
Reactivity–**0** Reactivity-**0**
Special-**NA** Personal Protection-**E**

**15.2 Regulatory/Carcinogenicity Status: NTP, IARC, OSHA:** None (2001)

**15.3 CERCLA RQ (**40 CFR 302)**:** Not listed.

**15.4 SARA TITLE III 302 & 303**(40 CFR 355) Extremely hazardous substance listing**:** Not listed.

**15.5 SARA TITLE III 311 & 312**(40 CFR 370)
Hazardous Categories (product): Fire: N Sudden release of pressure: N Reactive: N
Acute health: N Chronic health: Y

**15.6 SARA TITLE III 313** (40 CFR 372): **LISTED TOXIC CHEMICAL:** NO
**REPORTING THRESHOLD:** NA.

**15.7 US TSCA STATUS** (CFR 40 710-712.3): **YES**

## 16. OTHER INFORMATION

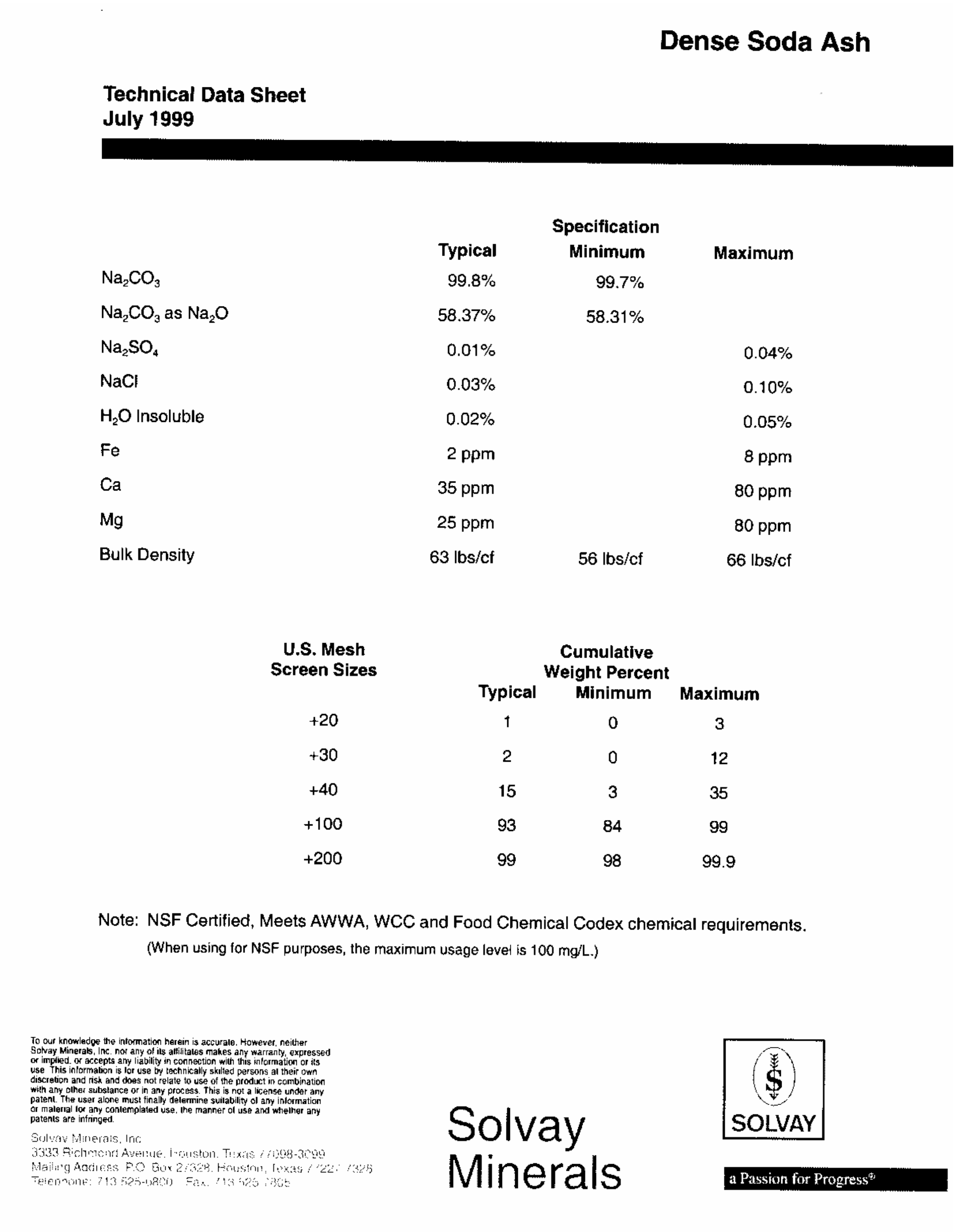
**16.1** The National Sanitation Foundation (NSF) recommends that the maximum usage level is 100 mg/l for potable water treatment.

Responsible Care®
Good Chemistry at Work

Solvay
Minerals

SOLVAY

**Figure B.16: Sodium Carbonate – Vendor Technical Data**



## Dense Soda Ash

**Technical Data Sheet**
**July 1999**

| | Typical | Specification Minimum | Maximum |
|---|---|---|---|
| $Na_2CO_3$ | 99.8% | 99.7% | |
| $Na_2CO_3$ as $Na_2O$ | 58.37% | 58.31% | |
| $Na_2SO_4$ | 0.01% | | 0.04% |
| NaCl | 0.03% | | 0.10% |
| $H_2O$ Insoluble | 0.02% | | 0.05% |
| Fe | 2 ppm | | 8 ppm |
| Ca | 35 ppm | | 80 ppm |
| Mg | 25 ppm | | 80 ppm |
| Bulk Density | 63 lbs/cf | 56 lbs/cf | 66 lbs/cf |

| U.S. Mesh Screen Sizes | | Cumulative Weight Percent | |
|---|---|---|---|
| | Typical | Minimum | Maximum |
| +20 | 1 | 0 | 3 |
| +30 | 2 | 0 | 12 |
| +40 | 15 | 3 | 35 |
| +100 | 93 | 84 | 99 |
| +200 | 99 | 98 | 99.9 |

Note: NSF Certified, Meets AWWA, WCC and Food Chemical Codex chemical requirements.
(When using for NSF purposes, the maximum usage level is 100 mg/L.)

Solvay Minerals, Inc.
3333 Richmond Avenue, Houston, Texas 77098-3099
Mailing Address: P.O. Box 27328, Houston, Texas 77227-7328
Telephone: 713 525-6800 Fax: 713 525 7805

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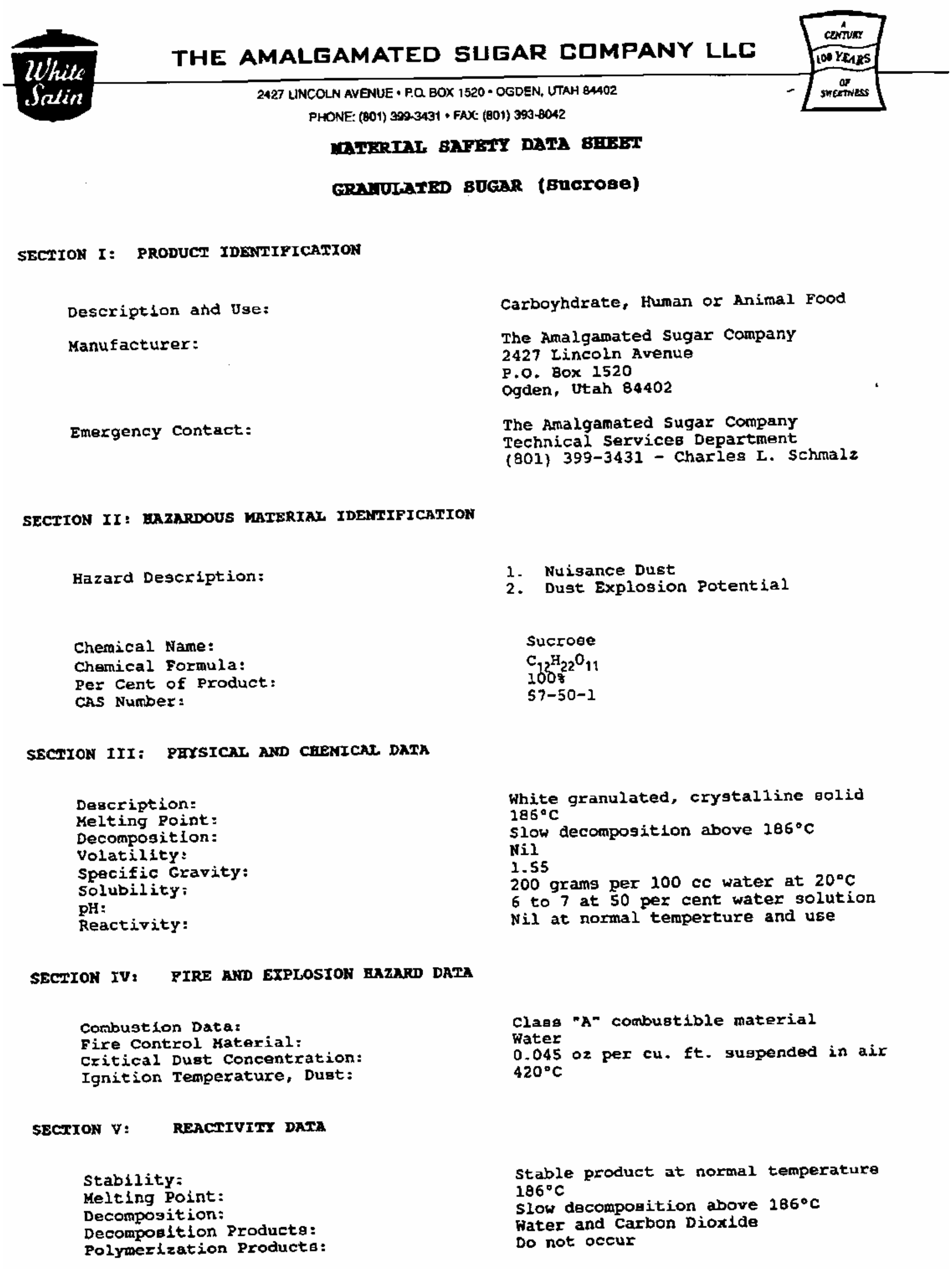
Figure B.17: Sugar - MSDS



THE AMALGAMATED SUGAR COMPANY LLC
2427 LINCOLN AVENUE • P.O. BOX 1520 • OGDEN, UTAH 84402
PHONE: (801) 399-3431 • FAX: (801) 393-8042

## MATERIAL SAFETY DATA SHEET

## GRANULATED SUGAR (Sucrose)

### SECTION I: PRODUCT IDENTIFICATION

| | |
|---|---|
| Description and Use: | Carboyhdrate, Human or Animal Food |
| Manufacturer: | The Amalgamated Sugar Company<br>2427 Lincoln Avenue<br>P.O. Box 1520<br>Ogden, Utah 84402 |
| Emergency Contact: | The Amalgamated Sugar Company<br>Technical Services Department<br>(801) 399-3431 - Charles L. Schmalz |

### SECTION II: HAZARDOUS MATERIAL IDENTIFICATION

| | |
|---|---|
| Hazard Description: | 1. Nuisance Dust<br>2. Dust Explosion Potential |
| Chemical Name: | Sucrose |
| Chemical Formula: | $C_{12}H_{22}O_{11}$ |
| Per Cent of Product: | 100% |
| CAS Number: | 57-50-1 |

### SECTION III: PHYSICAL AND CHEMICAL DATA

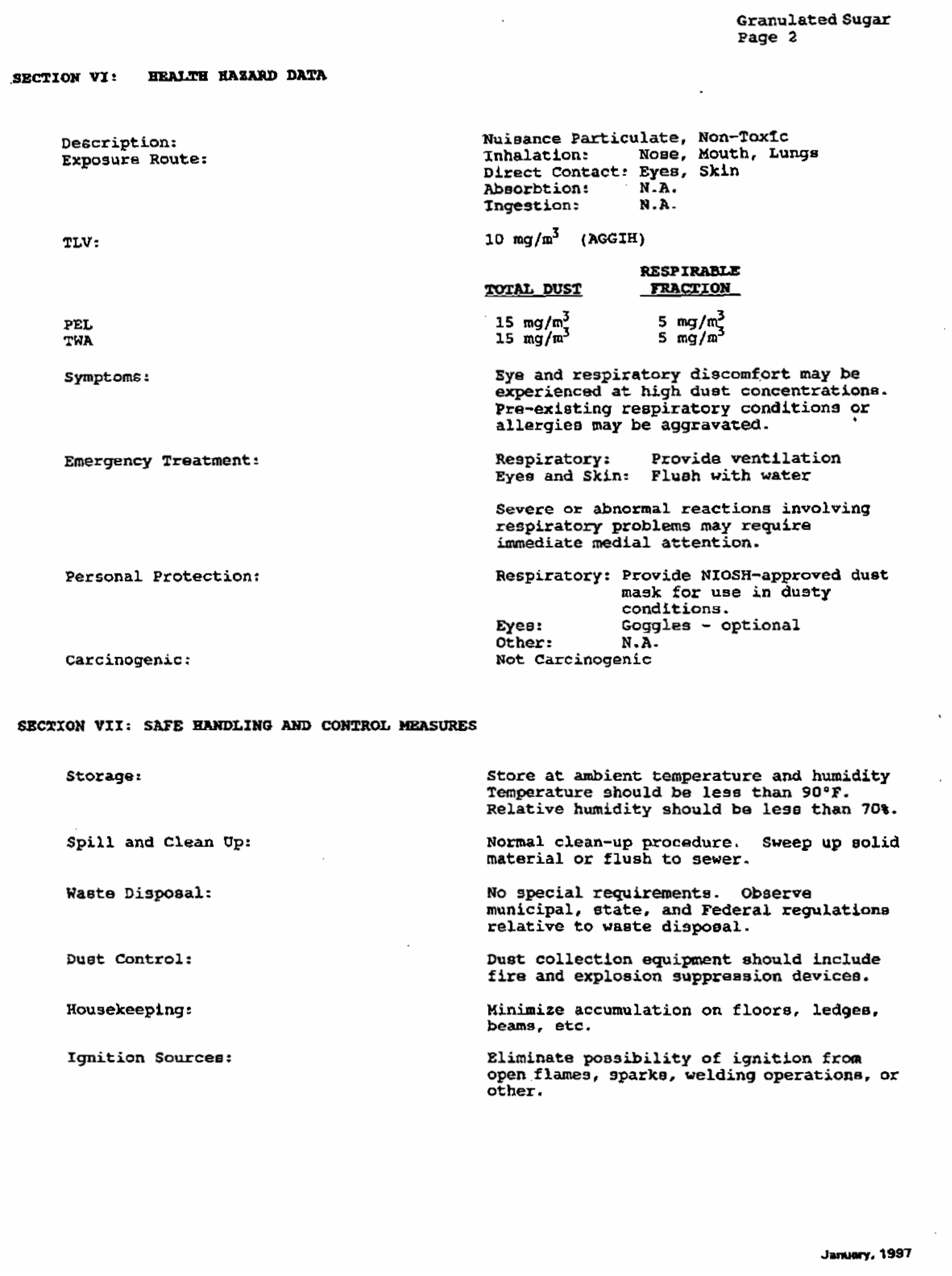
| | |
|---|---|
| Description: | White granulated, crystalline solid |
| Melting Point: | 186°C |
| Decomposition: | Slow decomposition above 186°C |
| Volatility: | Nil |
| Specific Gravity: | 1.55 |
| Solubility: | 200 grams per 100 cc water at 20°C |
| pH: | 6 to 7 at 50 per cent water solution |
| Reactivity: | Nil at normal temperture and use |

### SECTION IV: FIRE AND EXPLOSION HAZARD DATA

| | |
|---|---|
| Combustion Data: | Class "A" combustible material |
| Fire Control Material: | Water |
| Critical Dust Concentration: | 0.045 oz per cu. ft. suspended in air |
| Ignition Temperature, Dust: | 420°C |

### SECTION V: REACTIVITY DATA

| | |
|---|---|
| Stability: | Stable product at normal temperature |
| Melting Point: | 186°C |
| Decomposition: | Slow decomposition above 186°C |
| Decomposition Products: | Water and Carbon Dioxide |
| Polymerization Products: | Do not occur |



Granulated Sugar
Page 2

## SECTION VI: HEALTH HAZARD DATA

| | |
|---|---|
| Description: | Nuisance Particulate, Non-Toxic |
| Exposure Route: | Inhalation: Nose, Mouth, Lungs<br>Direct Contact: Eyes, Skin<br>Absorbtion: N.A.<br>Ingestion: N.A. |
| TLV: | 10 mg/m$^3$ (AGGIH) |

| | TOTAL DUST | RESPIRABLE FRACTION |
|---|---|---|
| PEL | 15 mg/m$^3$ | 5 mg/m$^3$ |
| TWA | 15 mg/m$^3$ | 5 mg/m$^3$ |

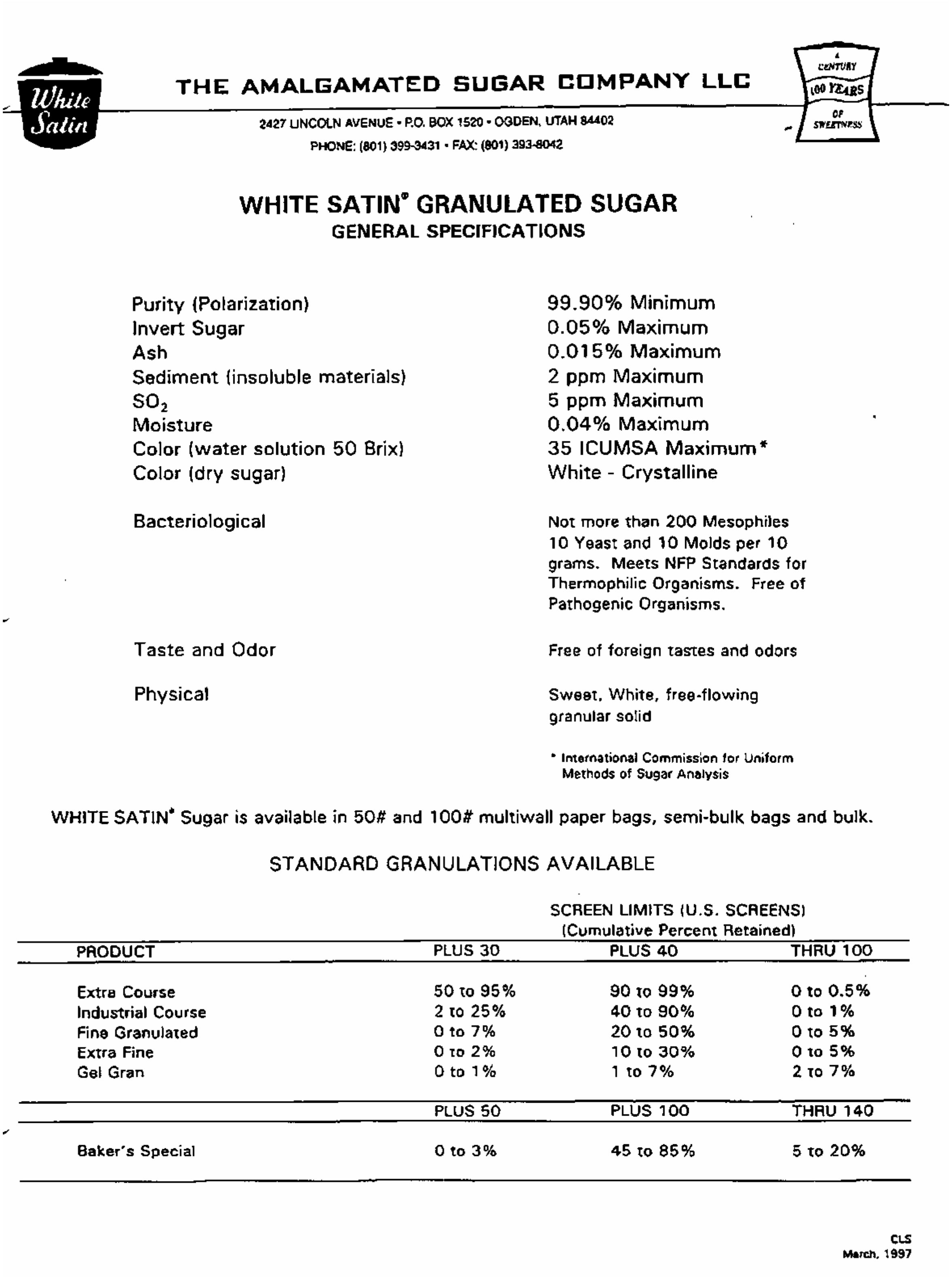
| | |
|---|---|
| Symptoms: | Eye and respiratory discomfort may be experienced at high dust concentrations. Pre-existing respiratory conditions or allergies may be aggravated. |
| Emergency Treatment: | Respiratory: Provide ventilation<br>Eyes and Skin: Flush with water<br>Severe or abnormal reactions involving respiratory problems may require immediate medial attention. |
| Personal Protection: | Respiratory: Provide NIOSH-approved dust mask for use in dusty conditions.<br>Eyes: Goggles - optional<br>Other: N.A. |
| Carcinogenic: | Not Carcinogenic |

## SECTION VII: SAFE HANDLING AND CONTROL MEASURES

| | |
|---|---|
| Storage: | Store at ambient temperature and humidity Temperature should be less than 90°F. Relative humidity should be less than 70%. |
| Spill and Clean Up: | Normal clean-up procedure. Sweep up solid material or flush to sewer. |
| Waste Disposal: | No special requirements. Observe municipal, state, and Federal regulations relative to waste disposal. |
| Dust Control: | Dust collection equipment should include fire and explosion suppression devices. |
| Housekeeping: | Minimize accumulation on floors, ledges, beams, etc. |
| Ignition Sources: | Eliminate possibility of ignition from open flames, sparks, welding operations, or other. |

January, 1997

## Figure B.18: Sugar – Vendor Technical Data



**THE AMALGAMATED SUGAR COMPANY LLC**

2427 LINCOLN AVENUE • P.O. BOX 1520 • OGDEN, UTAH 84402
PHONE: (801) 399-3431 • FAX: (801) 393-8042

### WHITE SATIN® GRANULATED SUGAR
### GENERAL SPECIFICATIONS

| | |
|---|---|
| Purity (Polarization) | 99.90% Minimum |
| Invert Sugar | 0.05% Maximum |
| Ash | 0.015% Maximum |
| Sediment (insoluble materials) | 2 ppm Maximum |
| $SO_2$ | 5 ppm Maximum |
| Moisture | 0.04% Maximum |
| Color (water solution 50 Brix) | 35 ICUMSA Maximum* |
| Color (dry sugar) | White - Crystalline |
| Bacteriological | Not more than 200 Mesophiles 10 Yeast and 10 Molds per 10 grams. Meets NFP Standards for Thermophilic Organisms. Free of Pathogenic Organisms. |
| Taste and Odor | Free of foreign tastes and odors |
| Physical | Sweet, White, free-flowing granular solid |

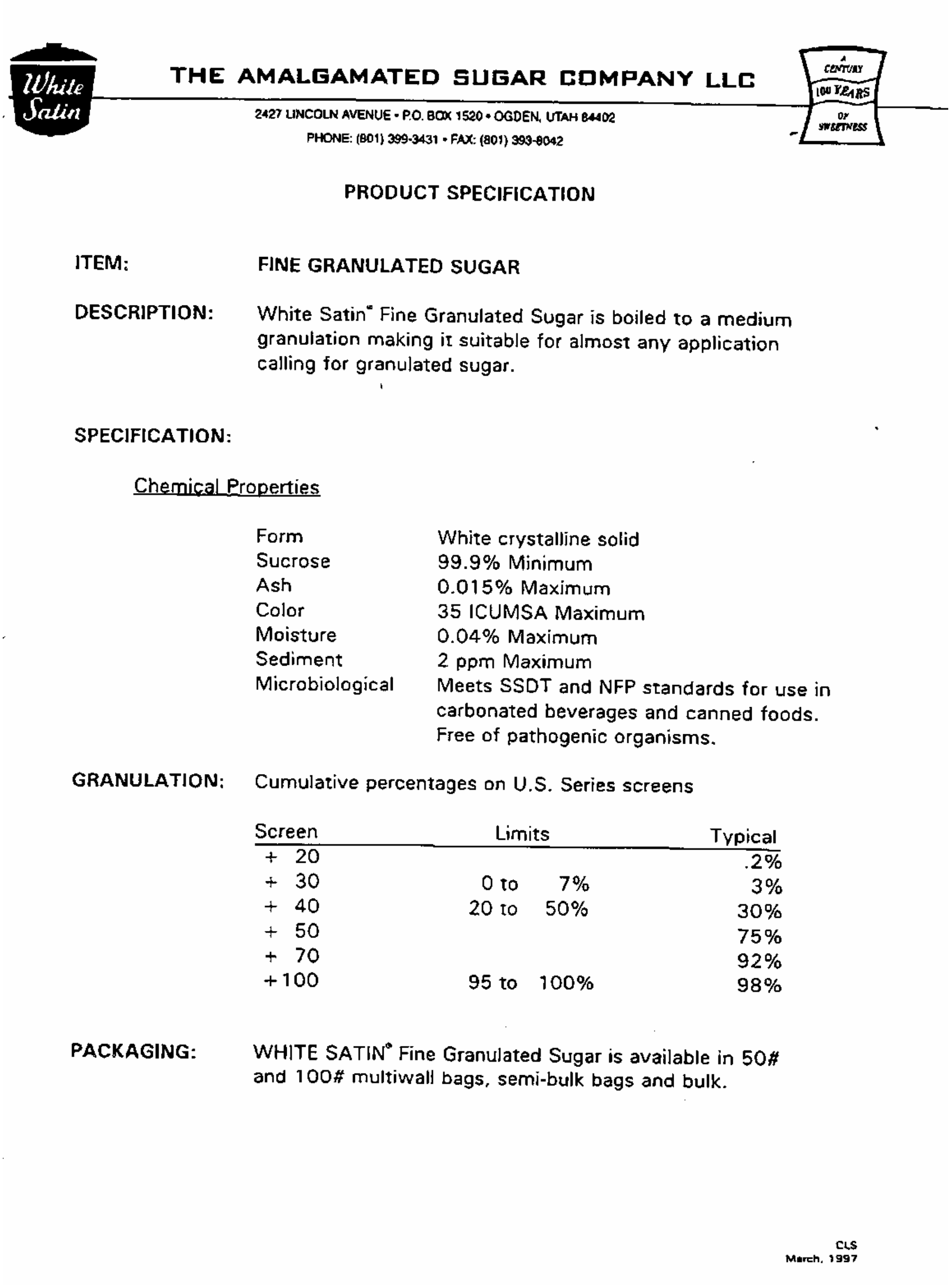
* International Commission for Uniform Methods of Sugar Analysis

WHITE SATIN® Sugar is available in 50# and 100# multiwall paper bags, semi-bulk bags and bulk.

STANDARD GRANULATIONS AVAILABLE

| | SCREEN LIMITS (U.S. SCREENS) (Cumulative Percent Retained) | | |
|---|---|---|---|
| PRODUCT | PLUS 30 | PLUS 40 | THRU 100 |
| Extra Course | 50 to 95% | 90 to 99% | 0 to 0.5% |
| Industrial Course | 2 to 25% | 40 to 90% | 0 to 1% |
| Fine Granulated | 0 to 7% | 20 to 50% | 0 to 5% |
| Extra Fine | 0 to 2% | 10 to 30% | 0 to 5% |
| Gel Gran | 0 to 1% | 1 to 7% | 2 to 7% |
| | PLUS 50 | PLUS 100 | THRU 140 |
| Baker's Special | 0 to 3% | 45 to 85% | 5 to 20% |

CLS
March, 1997



**THE AMALGAMATED SUGAR COMPANY LLC**

2427 LINCOLN AVENUE • P.O. BOX 1520 • OGDEN, UTAH 84402
PHONE: (801) 399-3431 • FAX: (801) 393-8042

## PRODUCT SPECIFICATION

**ITEM:** FINE GRANULATED SUGAR

**DESCRIPTION:** White Satin® Fine Granulated Sugar is boiled to a medium granulation making it suitable for almost any application calling for granulated sugar.

**SPECIFICATION:**

Chemical Properties

| | |
|---|---|
| Form | White crystalline solid |
| Sucrose | 99.9% Minimum |
| Ash | 0.015% Maximum |
| Color | 35 ICUMSA Maximum |
| Moisture | 0.04% Maximum |
| Sediment | 2 ppm Maximum |
| Microbiological | Meets SSDT and NFP standards for use in carbonated beverages and canned foods. Free of pathogenic organisms. |

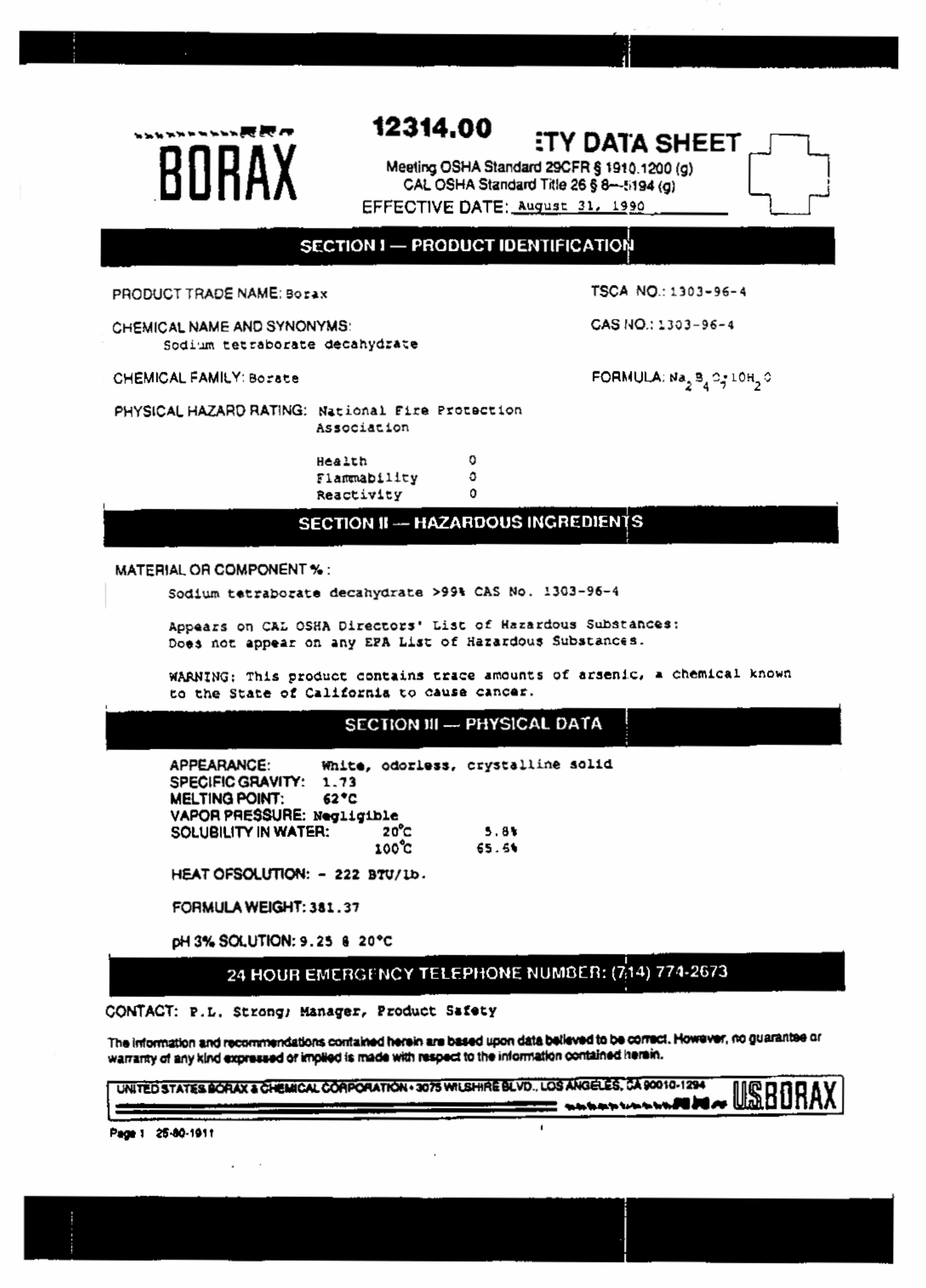
**GRANULATION:** Cumulative percentages on U.S. Series screens

| Screen | Limits | Typical |
|---|---|---|
| + 20 | | .2% |
| + 30 | 0 to 7% | 3% |
| + 40 | 20 to 50% | 30% |
| + 50 | | 75% |
| + 70 | | 92% |
| +100 | 95 to 100% | 98% |

**PACKAGING:** WHITE SATIN® Fine Granulated Sugar is available in 50# and 100# multiwall bags, semi-bulk bags and bulk.

CLS
March, 1997

## Figure B.19: Borax - MSDS



BORAX

12314.00

TY DATA SHEET

Meeting OSHA Standard 29CFR § 1910.1200 (g)
CAL OSHA Standard Title 26 § 8—5194 (g)

EFFECTIVE DATE: August 31, 1990

### SECTION I — PRODUCT IDENTIFICATION

PRODUCT TRADE NAME: Borax

TSCA NO.: 1303-96-4

CHEMICAL NAME AND SYNONYMS:
Sodium tetraborate decahydrate

CAS NO.: 1303-96-4

CHEMICAL FAMILY: Borate

FORMULA: $Na_2B_4O_7 \cdot 10H_2O$

PHYSICAL HAZARD RATING: National Fire Protection Association

| | |
|---|---|
| Health | 0 |
| Flammability | 0 |
| Reactivity | 0 |

### SECTION II — HAZARDOUS INGREDIENTS

MATERIAL OR COMPONENT % :

Sodium tetraborate decahydrate >99% CAS No. 1303-96-4

Appears on CAL OSHA Directors' List of Hazardous Substances:
Does not appear on any EPA List of Hazardous Substances.

WARNING: This product contains trace amounts of arsenic, a chemical known to the State of California to cause cancer.

### SECTION III — PHYSICAL DATA

APPEARANCE: White, odorless, crystalline solid
SPECIFIC GRAVITY: 1.73
MELTING POINT: 62°C
VAPOR PRESSURE: Negligible
SOLUBILITY IN WATER: 20°C 5.8%
100°C 65.5%

HEAT OFSOLUTION: - 222 BTU/lb.

FORMULA WEIGHT: 381.37

pH 3% SOLUTION: 9.25 @ 20°C

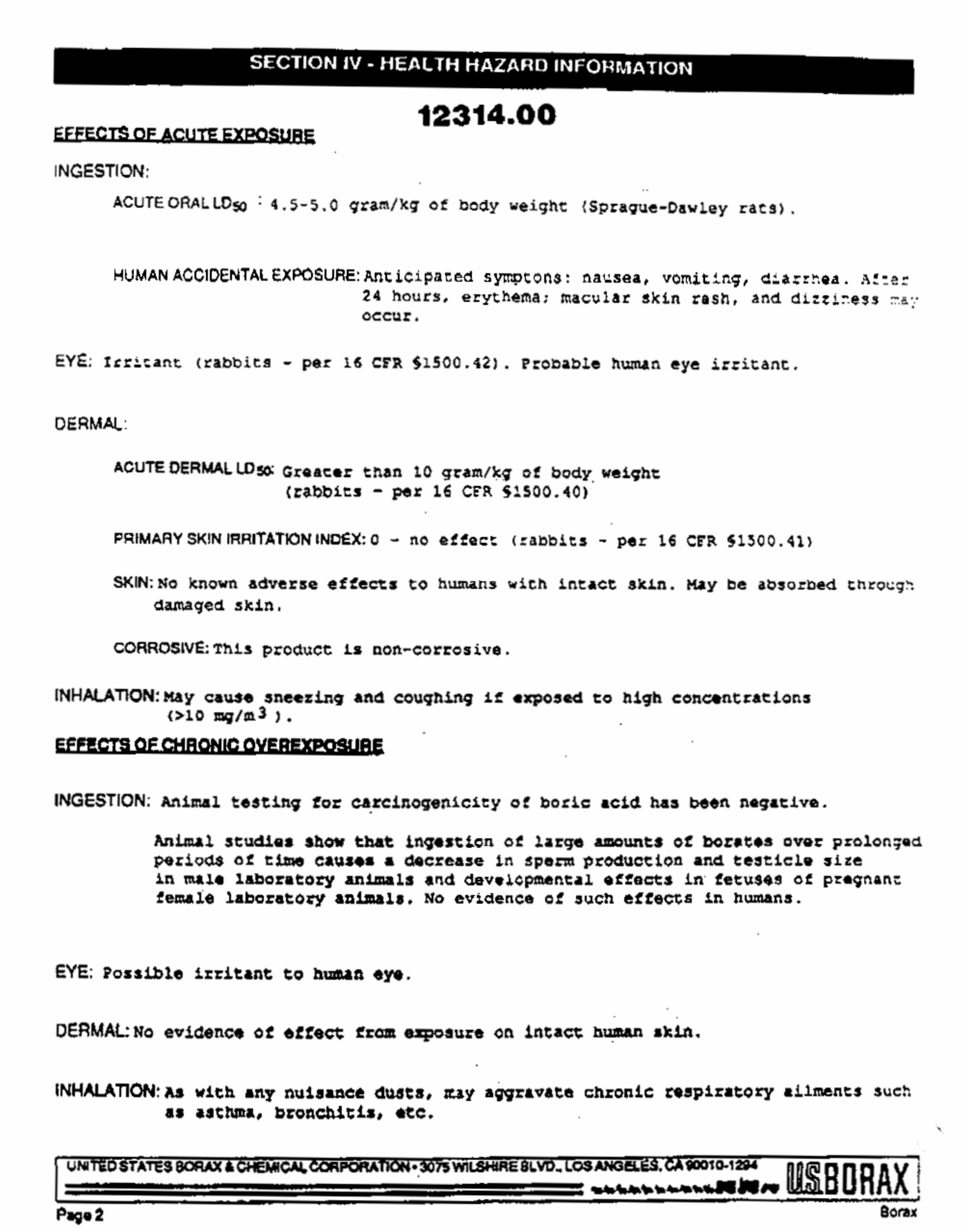
**24 HOUR EMERGENCY TELEPHONE NUMBER: (714) 774-2673**

CONTACT: P.L. Strong, Manager, Product Safety

The information and recommendations contained herein are based upon data believed to be correct. However, no guarantee or warranty of any kind expressed or implied is made with respect to the information contained herein.

UNITED STATES BORAX & CHEMICAL CORPORATION • 3075 WILSHIRE BLVD., LOS ANGELES, CA 90010-1294 US BORAX

Page 1 25-80-1911



## SECTION IV - HEALTH HAZARD INFORMATION

**12314.00**

### EFFECTS OF ACUTE EXPOSURE

INGESTION:

ACUTE ORAL $LD_{50}$ : 4.5-5.0 gram/kg of body weight (Sprague-Dawley rats).

HUMAN ACCIDENTAL EXPOSURE: Anticipated symptons: nausea, vomiting, diarrhea. After 24 hours, erythema; macular skin rash, and dizziness may occur.

EYE: Irritant (rabbits - per 16 CFR $1500.42). Probable human eye irritant.

DERMAL:

ACUTE DERMAL $LD_{50}$: Greater than 10 gram/kg of body weight (rabbits - per 16 CFR $1500.40)

PRIMARY SKIN IRRITATION INDEX: 0 - no effect (rabbits - per 16 CFR $1500.41)

SKIN: No known adverse effects to humans with intact skin. May be absorbed through damaged skin.

CORROSIVE: This product is non-corrosive.

INHALATION: May cause sneezing and coughing if exposed to high concentrations ($>10$ mg/m$^3$ ).

### EFFECTS OF CHRONIC OVEREXPOSURE

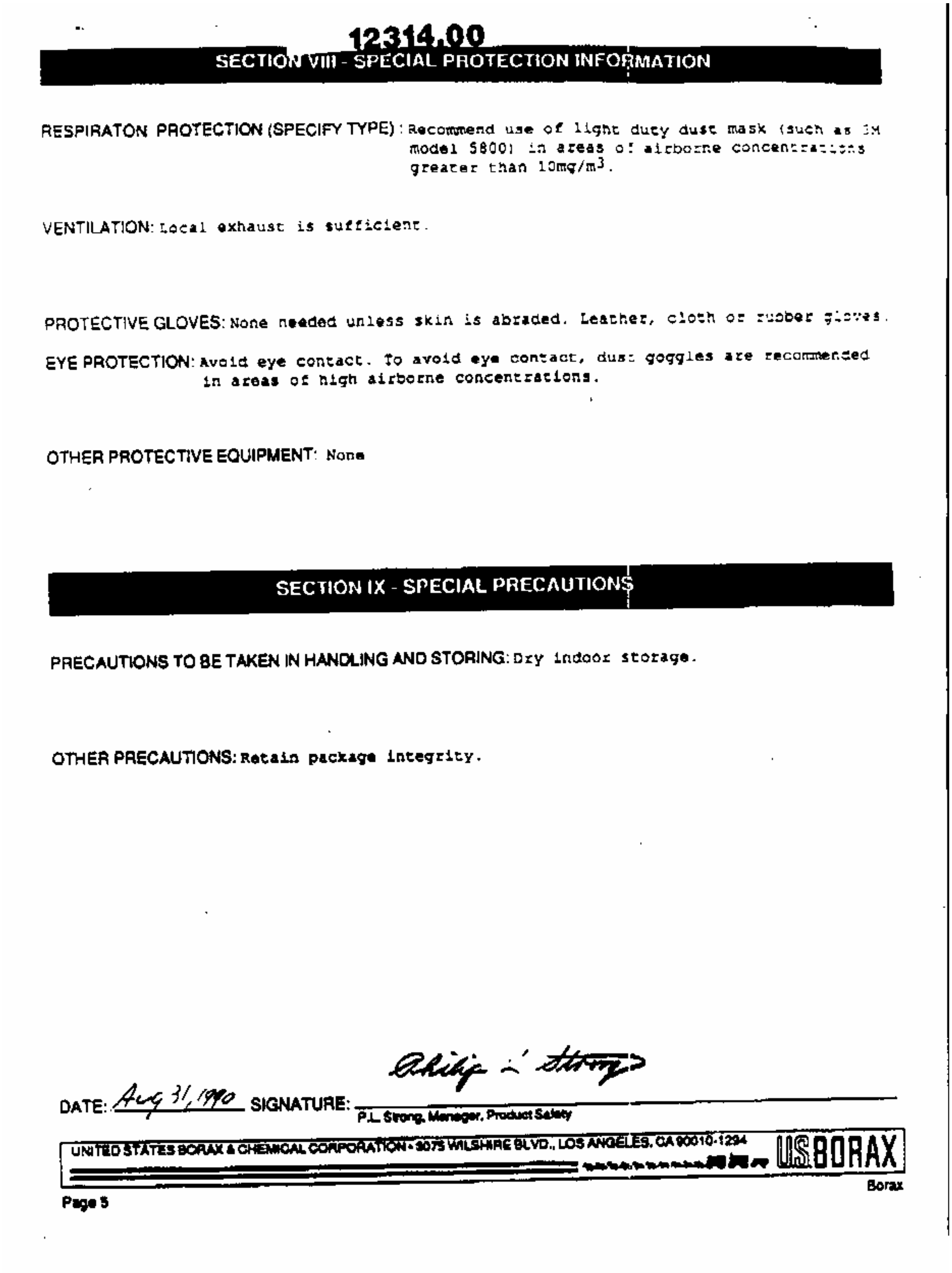
INGESTION: Animal testing for carcinogenicity of boric acid has been negative.

Animal studies show that ingestion of large amounts of borates over prolonged periods of time causes a decrease in sperm production and testicle size in male laboratory animals and developmental effects in fetuses of pregnant female laboratory animals. No evidence of such effects in humans.

EYE: Possible irritant to human eye.

DERMAL: No evidence of effect from exposure on intact human skin.

INHALATION: As with any nuisance dusts, may aggravate chronic respiratory ailments such as asthma, bronchitis, etc.



12314.00

## SECTION VIII - SPECIAL PROTECTION INFORMATION

RESPIRATON PROTECTION (SPECIFY TYPE): Recommend use of light duty dust mask (such as 3M model 8800) in areas of airborne concentrations greater than 10mg/m$^3$.

VENTILATION: Local exhaust is sufficient.

PROTECTIVE GLOVES: None needed unless skin is abraded. Leather, cloth or rubber gloves.

EYE PROTECTION: Avoid eye contact. To avoid eye contact, dust goggles are recommended in areas of high airborne concentrations.

OTHER PROTECTIVE EQUIPMENT: None

## SECTION IX - SPECIAL PRECAUTIONS

PRECAUTIONS TO BE TAKEN IN HANDLING AND STORING: Dry indoor storage.

OTHER PRECAUTIONS: Retain package integrity.

DATE: Aug 31, 1990 SIGNATURE: Philip L. Strong

P.L. Strong, Manager, Product Safety

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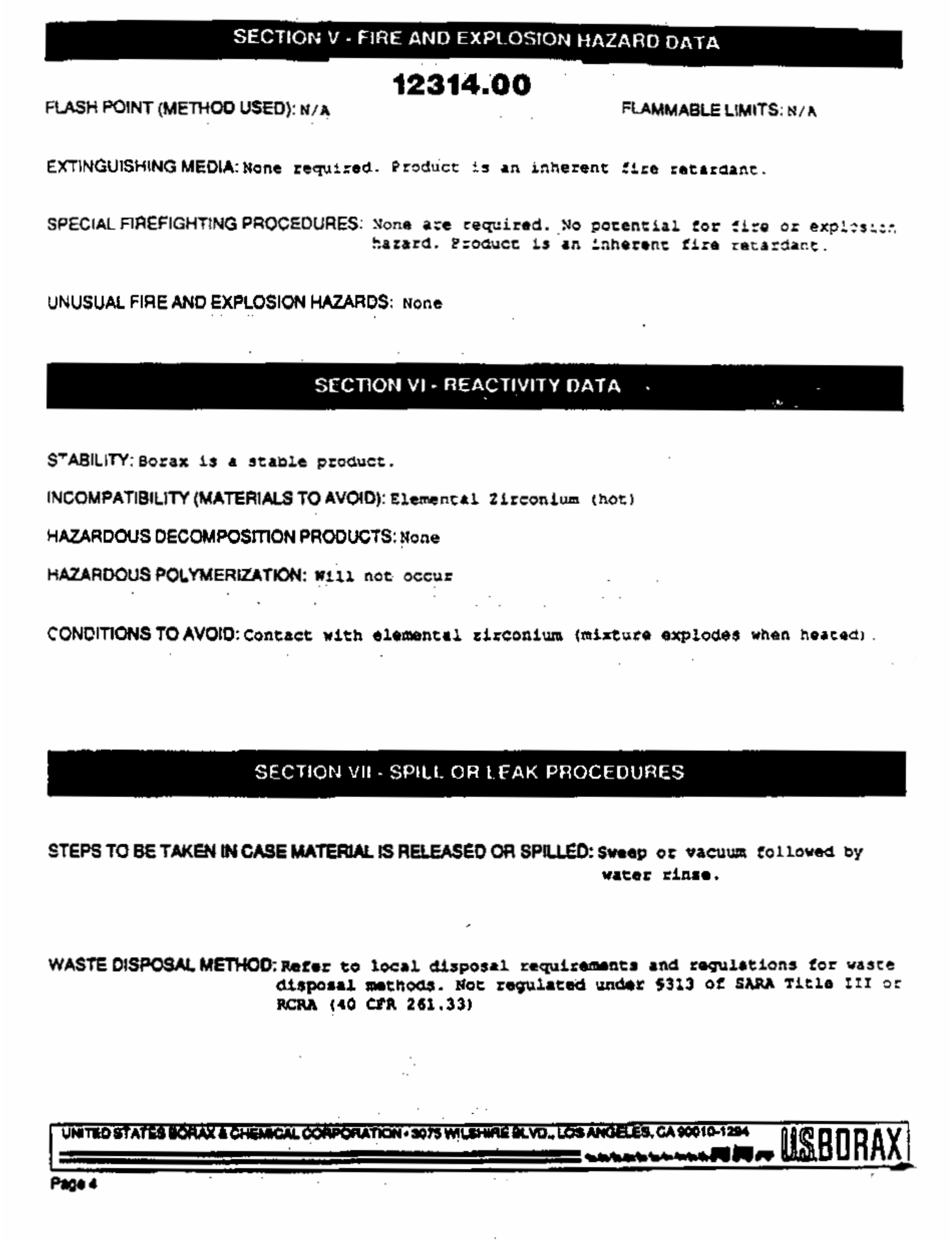
US BORAX

Borax

Page 5



## SECTION V - FIRE AND EXPLOSION HAZARD DATA

**12314.00**

**FLASH POINT (METHOD USED):** N/A

**FLAMMABLE LIMITS:** N/A

**EXTINGUISHING MEDIA:** None required. Product is an inherent fire retardant.

**SPECIAL FIREFIGHTING PROCEDURES:** None are required. No potential for fire or explosion hazard. Product is an inherent fire retardant.

**UNUSUAL FIRE AND EXPLOSION HAZARDS:** None

## SECTION VI - REACTIVITY DATA

**STABILITY:** Borax is a stable product.

**INCOMPATIBILITY (MATERIALS TO AVOID):** Elemental Zirconium (hot)

**HAZARDOUS DECOMPOSITION PRODUCTS:** None

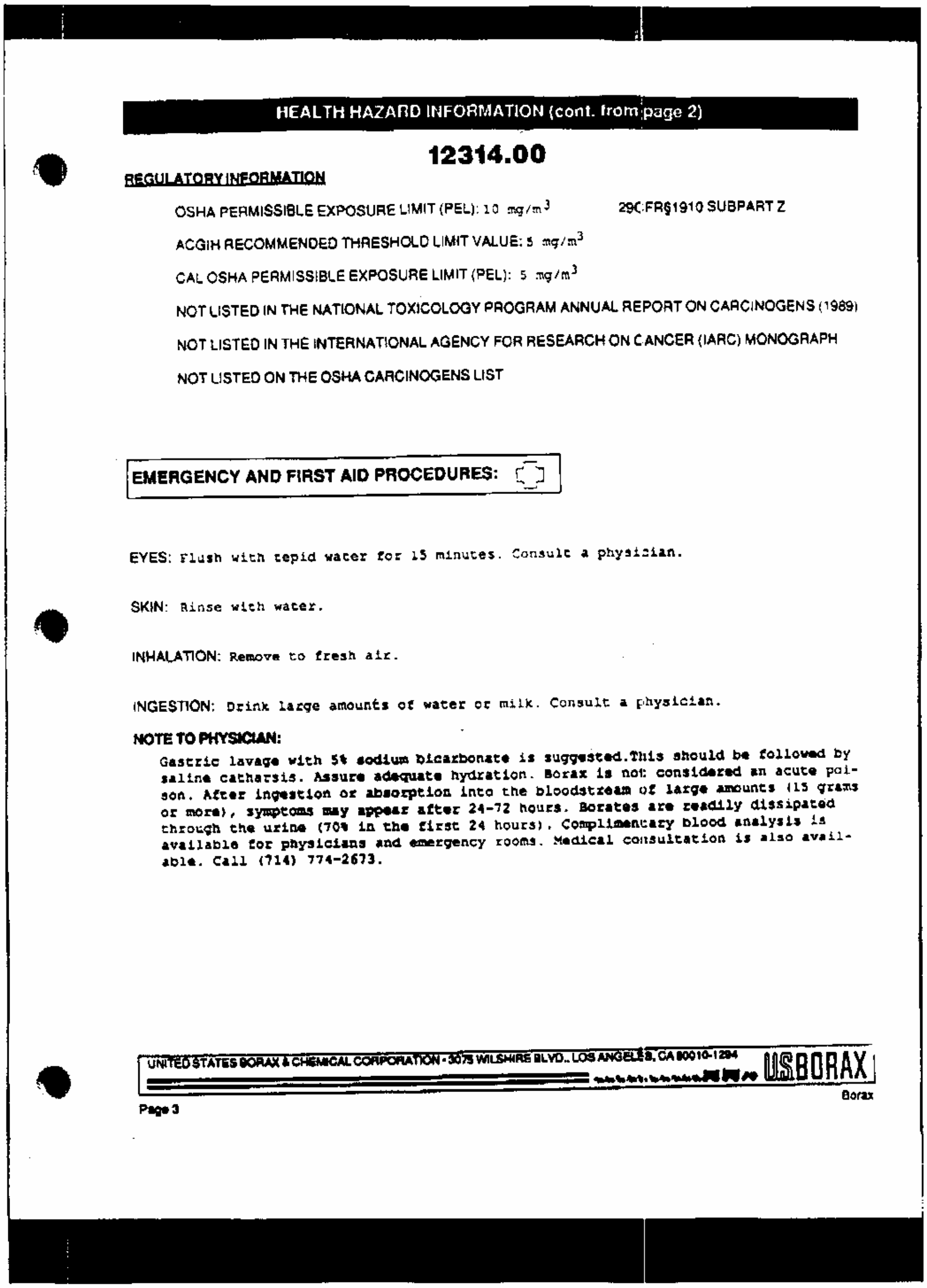
**HAZARDOUS POLYMERIZATION:** Will not occur

**CONDITIONS TO AVOID:** Contact with elemental zirconium (mixture explodes when heated).

## SECTION VII - SPILL OR LEAK PROCEDURES

**STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED:** Sweep or vacuum followed by water rinse.

**WASTE DISPOSAL METHOD:** Refer to local disposal requirements and regulations for waste disposal methods. Not regulated under §313 of SARA Title III or RCRA (40 CFR 261.33)



## HEALTH HAZARD INFORMATION (cont. from page 2)

**12314.00**

**REGULATORY INFORMATION**

OSHA PERMISSIBLE EXPOSURE LIMIT (PEL): 10 $mg/m^3$ 29CFR§1910 SUBPART Z

ACGIH RECOMMENDED THRESHOLD LIMIT VALUE: 5 $mg/m^3$

CAL OSHA PERMISSIBLE EXPOSURE LIMIT (PEL): 5 $mg/m^3$

NOT LISTED IN THE NATIONAL TOXICOLOGY PROGRAM ANNUAL REPORT ON CARCINOGENS (1989)

NOT LISTED IN THE INTERNATIONAL AGENCY FOR RESEARCH ON CANCER (IARC) MONOGRAPH

NOT LISTED ON THE OSHA CARCINOGENS LIST

## EMERGENCY AND FIRST AID PROCEDURES:

EYES: Flush with tepid water for 15 minutes. Consult a physician.

SKIN: Rinse with water.

INHALATION: Remove to fresh air.

INGESTION: Drink large amounts of water or milk. Consult a physician.

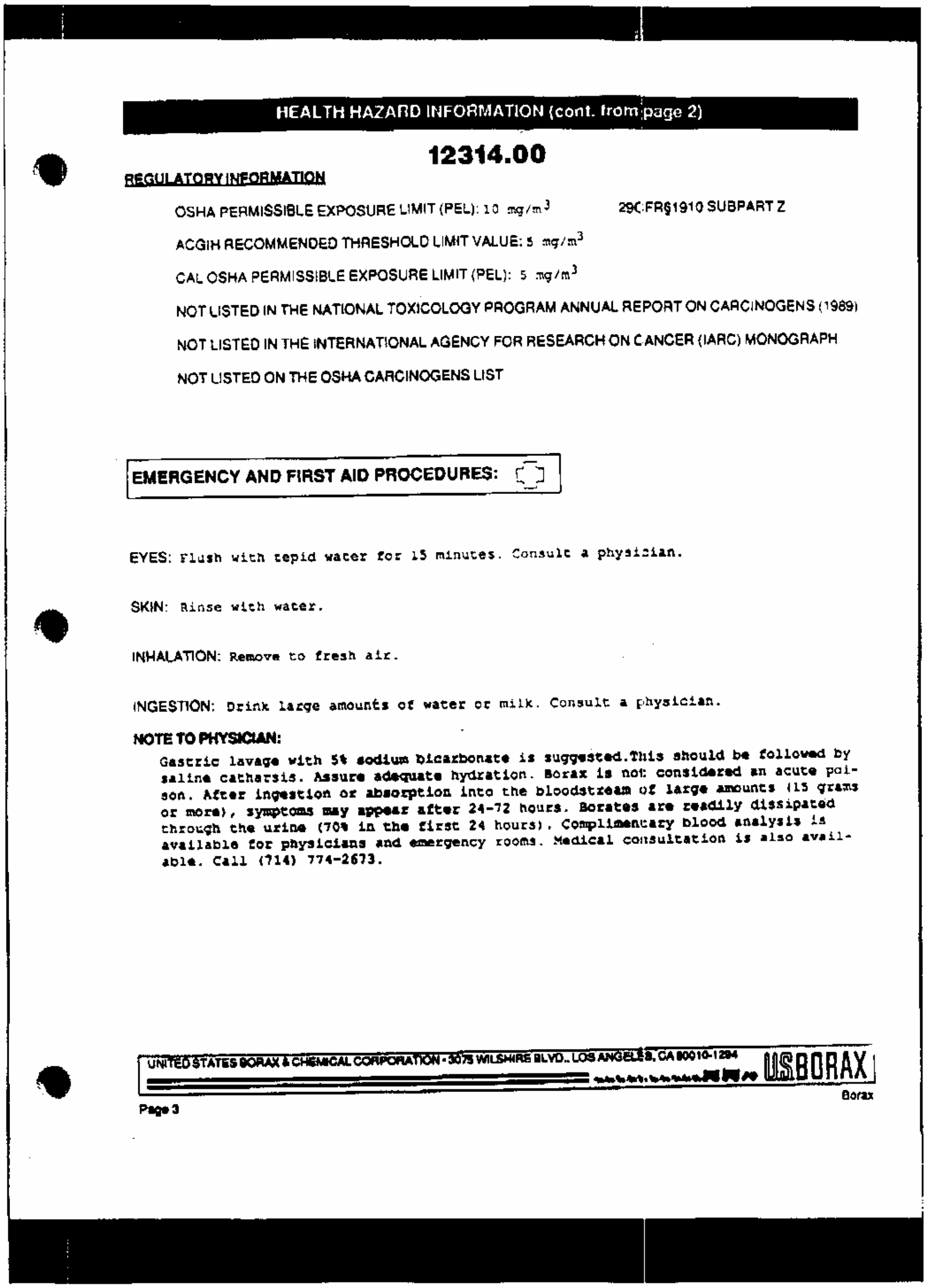
**NOTE TO PHYSICIAN:**

Gastric lavage with 5% sodium bicarbonate is suggested.This should be followed by saline catharsis. Assure adequate hydration. Borax is not considered an acute poison. After ingestion or absorption into the bloodstream of large amounts (15 grams or more), symptoms may appear after 24-72 hours. Borates are readily dissipated through the urine (70% in the first 24 hours). Complimentary blood analysis is available for physicians and emergency rooms. Medical consultation is also available. Call (714) 774-2673.

UNITED STATES BORAX & CHEMICAL CORPORATION · 3075 WILSHIRE BLVD., LOS ANGELES, CA 90010-1294 USBORAX

Borax

Page 3



## HEALTH HAZARD INFORMATION (cont. from page 2)

**12314.00**

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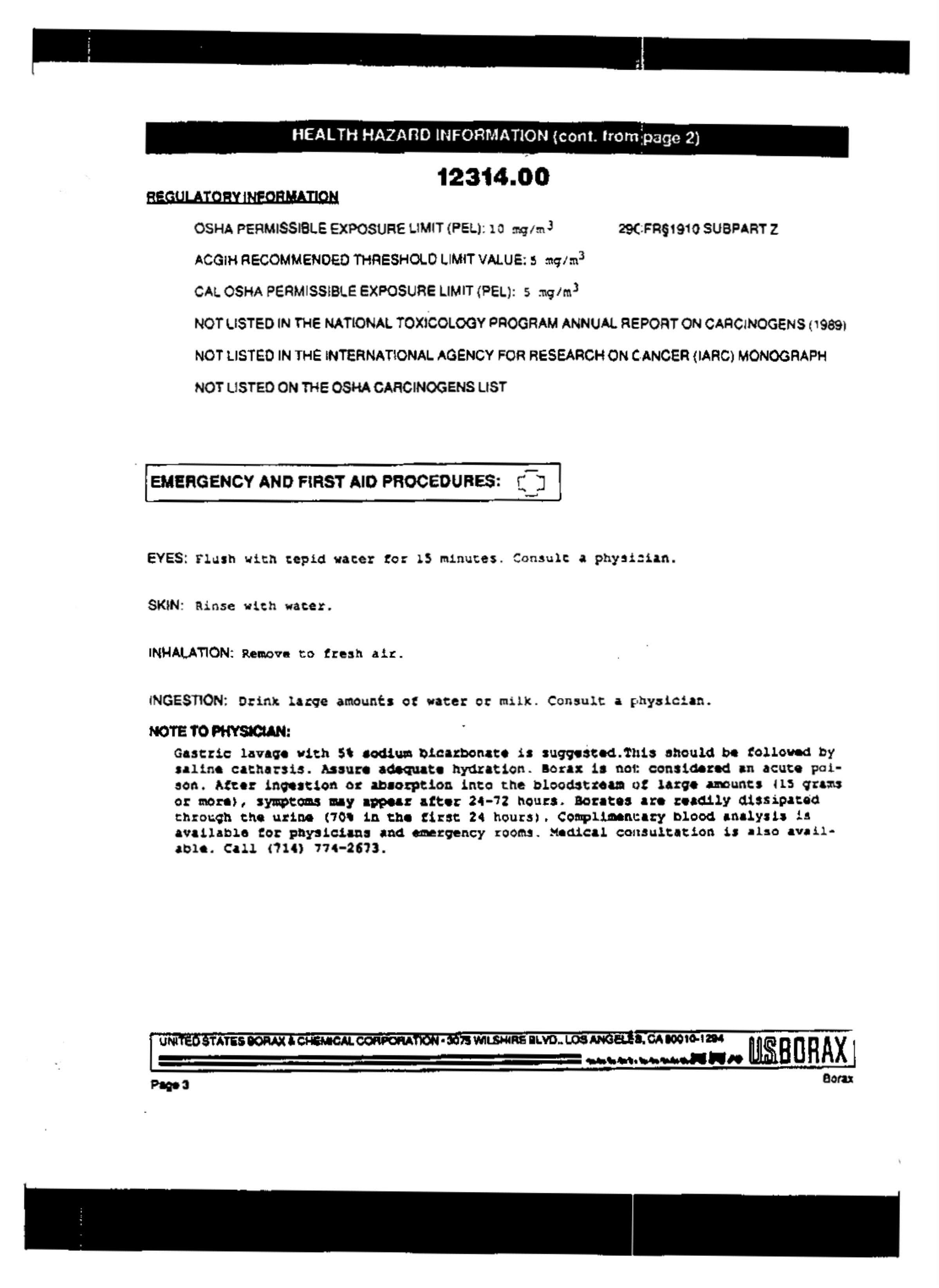
Borax

Page 3



## HEALTH HAZARD INFORMATION (cont. from page 2)

**12314.00**

**REGULATORY INFORMATION**

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ACGIH RECOMMENDED THRESHOLD LIMIT VALUE: 5 mg/m$^3$

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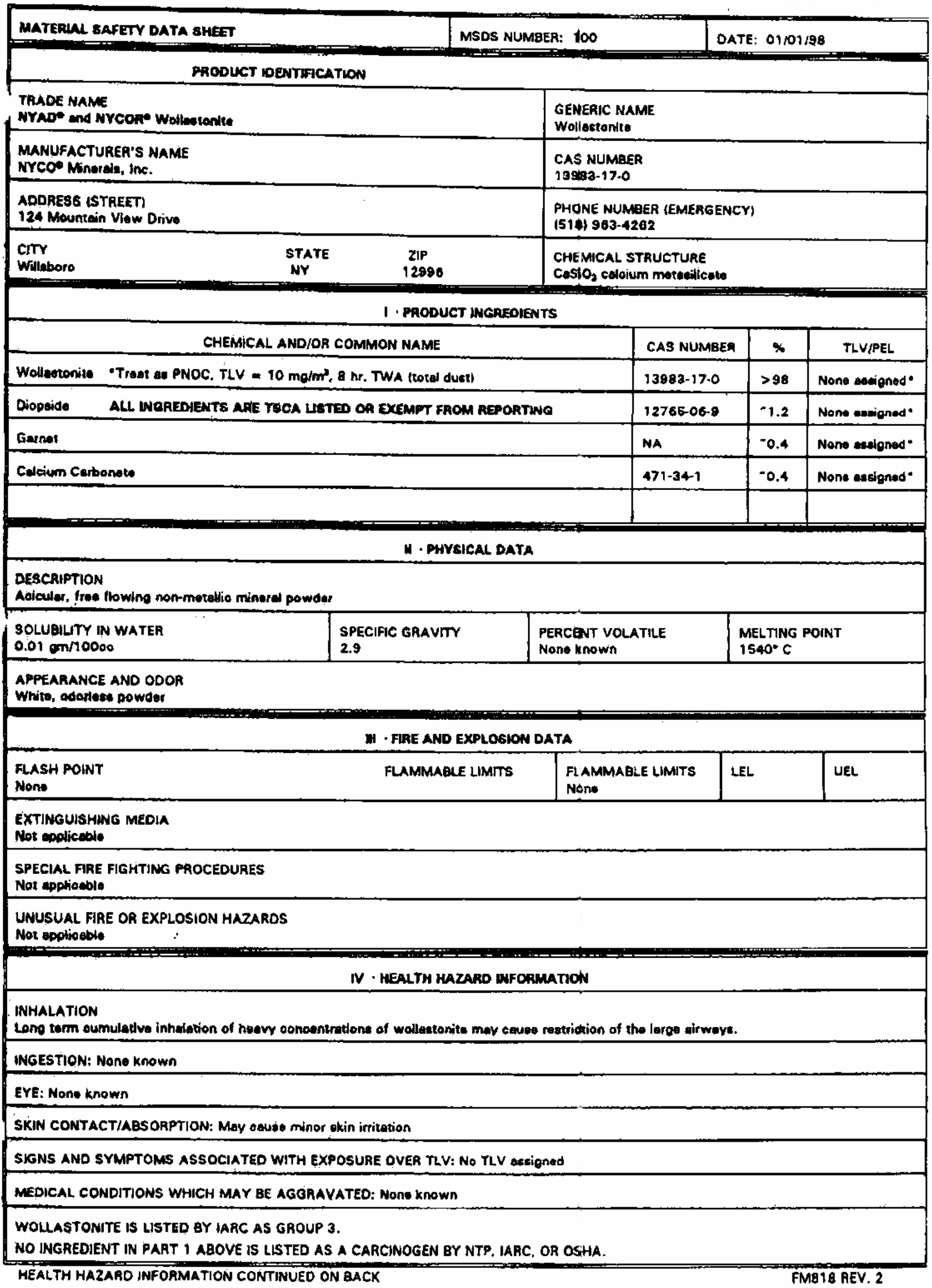
Figure B.20: Wollastonite - MSDS



| | | |
|---|---|---|
| **MATERIAL SAFETY DATA SHEET** | MSDS NUMBER: 100 | DATE: 01/01/98 |

**PRODUCT IDENTIFICATION**

| | |
|---|---|
| TRADE NAME<br>NYAD® and NYCOR® Wollastonite | GENERIC NAME<br>Wollastonite |
| MANUFACTURER'S NAME<br>NYCO® Minerals, Inc. | CAS NUMBER<br>13983-17-0 |
| ADDRESS (STREET)<br>124 Mountain View Drive | PHONE NUMBER (EMERGENCY)<br>(518) 963-4262 |
| CITY Willsboro STATE NY ZIP 12996 | CHEMICAL STRUCTURE<br>$CaSiO_3$ calcium metasilicate |

**I - PRODUCT INGREDIENTS**

| CHEMICAL AND/OR COMMON NAME | CAS NUMBER | % | TLV/PEL |
|---|---|---|---|
| Wollastonite *Treat as PNOC, TLV = 10 mg/m³, 8 hr. TWA (total dust) | 13983-17-0 | >98 | None assigned* |
| Diopside ALL INGREDIENTS ARE TSCA LISTED OR EXEMPT FROM REPORTING | 12765-06-9 | ~1.2 | None assigned* |
| Garnet | NA | ~0.4 | None assigned* |
| Calcium Carbonate | 471-34-1 | ~0.4 | None assigned* |
| | | | |

**II - PHYSICAL DATA**

DESCRIPTION
Acicular, free flowing non-metallic mineral powder

| | | | |
|---|---|---|---|
| SOLUBILITY IN WATER<br>0.01 gm/100cc | SPECIFIC GRAVITY<br>2.9 | PERCENT VOLATILE<br>None known | MELTING POINT<br>1540° C |

APPEARANCE AND ODOR
White, odorless powder

**III - FIRE AND EXPLOSION DATA**

| | | | | |
|---|---|---|---|---|
| FLASH POINT<br>None | FLAMMABLE LIMITS | FLAMMABLE LIMITS<br>None | LEL | UEL |

EXTINGUISHING MEDIA
Not applicable

SPECIAL FIRE FIGHTING PROCEDURES
Not applicable

UNUSUAL FIRE OR EXPLOSION HAZARDS
Not applicable

**IV - HEALTH HAZARD INFORMATION**

INHALATION
Long term cumulative inhalation of heavy concentrations of wollastonite may cause restriction of the large airways.

INGESTION: None known

EYE: None known

SKIN CONTACT/ABSORPTION: May cause minor skin irritation

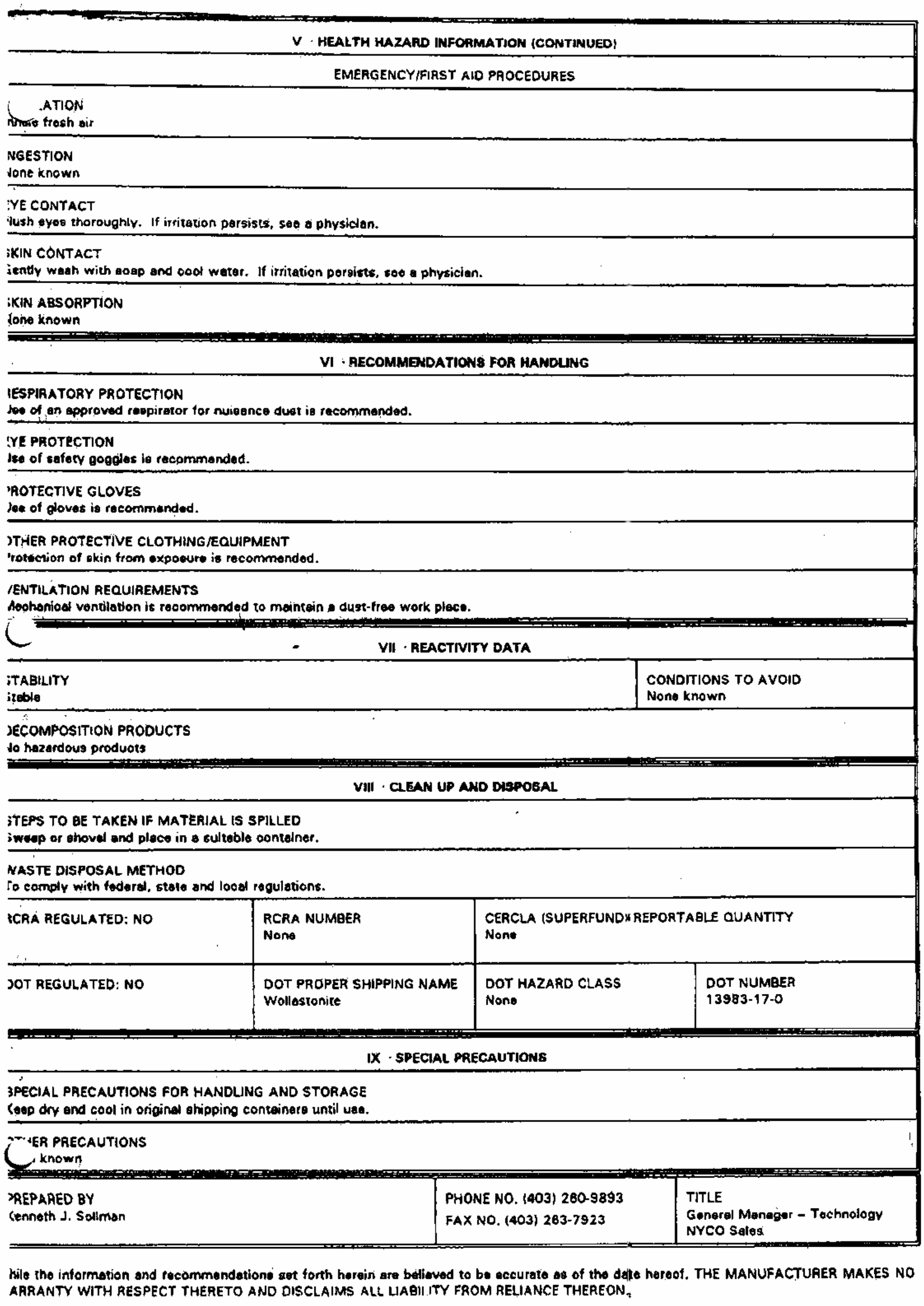
SIGNS AND SYMPTOMS ASSOCIATED WITH EXPOSURE OVER TLV: No TLV assigned

MEDICAL CONDITIONS WHICH MAY BE AGGRAVATED: None known

WOLLASTONITE IS LISTED BY IARC AS GROUP 3.
NO INGREDIENT IN PART 1 ABOVE IS LISTED AS A CARCINOGEN BY NTP, IARC, OR OSHA.

HEALTH HAZARD INFORMATION CONTINUED ON BACK

FM818 REV. 2



V · HEALTH HAZARD INFORMATION (CONTINUED)

EMERGENCY/FIRST AID PROCEDURES

.ATION
nhale fresh air

NGESTION
one known

YE CONTACT
lush eyes thoroughly. If irritation persists, see a physician.

KIN CONTACT
ently wash with soap and cool water. If irritation persists, see a physician.

KIN ABSORPTION
one known

VI · RECOMMENDATIONS FOR HANDLING

ESPIRATORY PROTECTION
se of an approved respirator for nuisance dust is recommended.

YE PROTECTION
se of safety goggles is recommended.

ROTECTIVE GLOVES
se of gloves is recommended.

THER PROTECTIVE CLOTHING/EQUIPMENT
rotection of skin from exposure is recommended.

ENTILATION REQUIREMENTS
echanical ventilation is recommended to maintain a dust-free work place.

VII · REACTIVITY DATA

| | |
|---|---|
| TABILITY<br>table | CONDITIONS TO AVOID<br>None known |

ECOMPOSITION PRODUCTS
o hazardous products

VIII · CLEAN UP AND DISPOSAL

TEPS TO BE TAKEN IF MATERIAL IS SPILLED
weep or shovel and place in a suitable container.

VASTE DISPOSAL METHOD
o comply with federal, state and local regulations.

| | | | |
|---|---|---|---|
| CRA REGULATED: NO | RCRA NUMBER<br>None | CERCLA (SUPERFUND) REPORTABLE QUANTITY<br>None | |
| OT REGULATED: NO | DOT PROPER SHIPPING NAME<br>Wollastonite | DOT HAZARD CLASS<br>None | DOT NUMBER<br>13983-17-0 |

IX · SPECIAL PRECAUTIONS

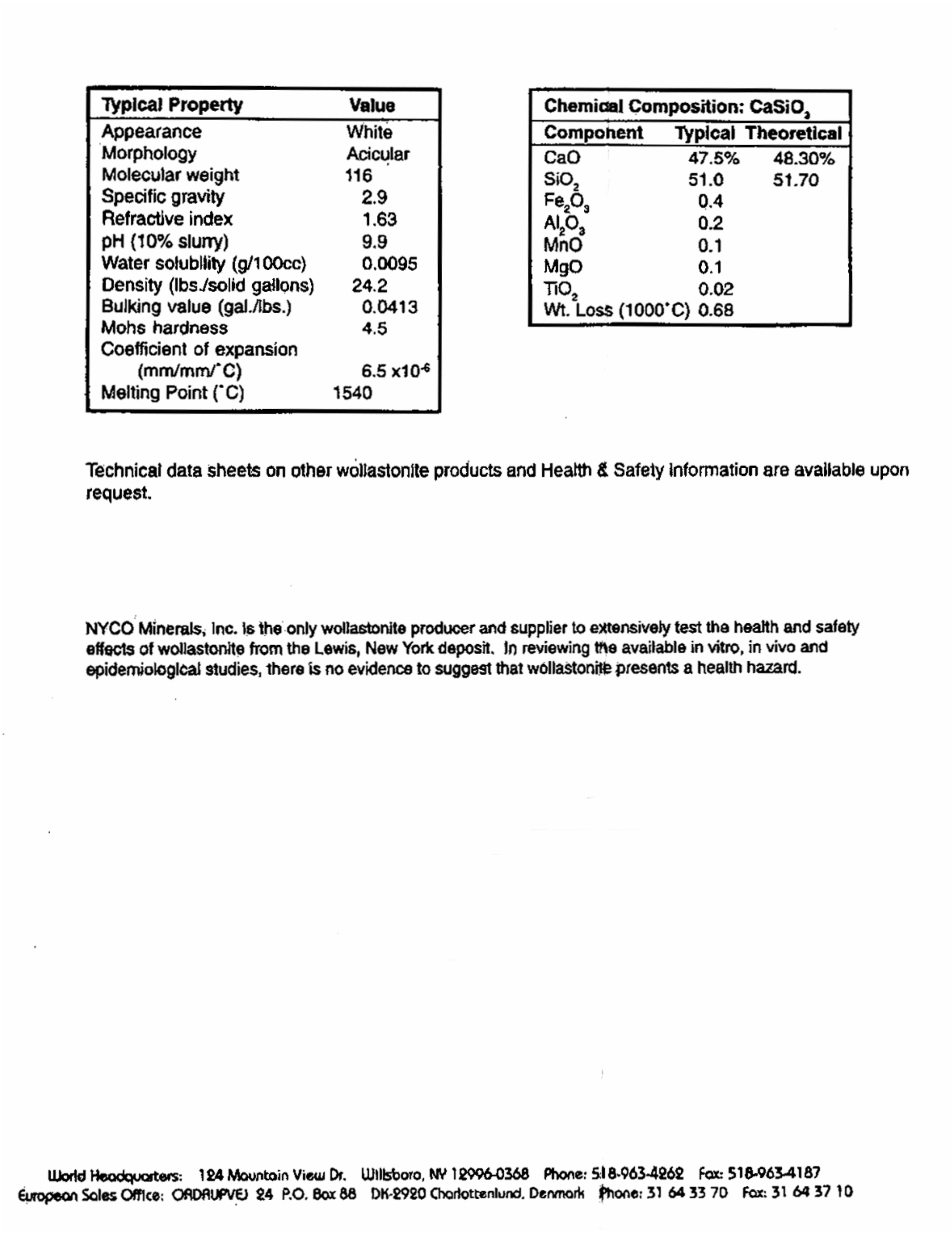
PECIAL PRECAUTIONS FOR HANDLING AND STORAGE
eep dry and cool in original shipping containers until use.

ER PRECAUTIONS
known

| | | |
|---|---|---|
| REPARED BY<br>enneth J. Soliman | PHONE NO. (403) 260-9893<br>FAX NO. (403) 263-7923 | TITLE<br>General Manager – Technology<br>NYCO Sales |

hile the information and recommendations set forth herein are believed to be accurate as of the date hereof, THE MANUFACTURER MAKES NO ARRANTY WITH RESPECT THERETO AND DISCLAIMS ALL LIABILITY FROM RELIANCE THEREON.

Figure B.21: Wollastonite – Vendor Technical Data



| Typical Property | Value |
|---|---|
| Appearance | White |
| Morphology | Acicular |
| Molecular weight | 116 |
| Specific gravity | 2.9 |
| Refractive index | 1.63 |
| pH (10% slurry) | 9.9 |
| Water solubility (g/100cc) | 0.0095 |
| Density (lbs./solid gallons) | 24.2 |
| Bulking value (gal./lbs.) | 0.0413 |
| Mohs hardness | 4.5 |
| Coefficient of expansion (mm/mm/°C) | $6.5 \times 10^{-6}$ |
| Melting Point (°C) | 1540 |

**Chemical Composition: $CaSiO_3$**

| Component | Typical | Theoretical |
|---|---|---|
| CaO | 47.5% | 48.30% |
| $SiO_2$ | 51.0 | 51.70 |
| $Fe_2O_3$ | 0.4 | |
| $Al_2O_3$ | 0.2 | |
| MnO | 0.1 | |
| MgO | 0.1 | |
| $TiO_2$ | 0.02 | |
| Wt. Loss (1000°C) | 0.68 | |

Technical data sheets on other wollastonite products and Health & Safety information are available upon request.

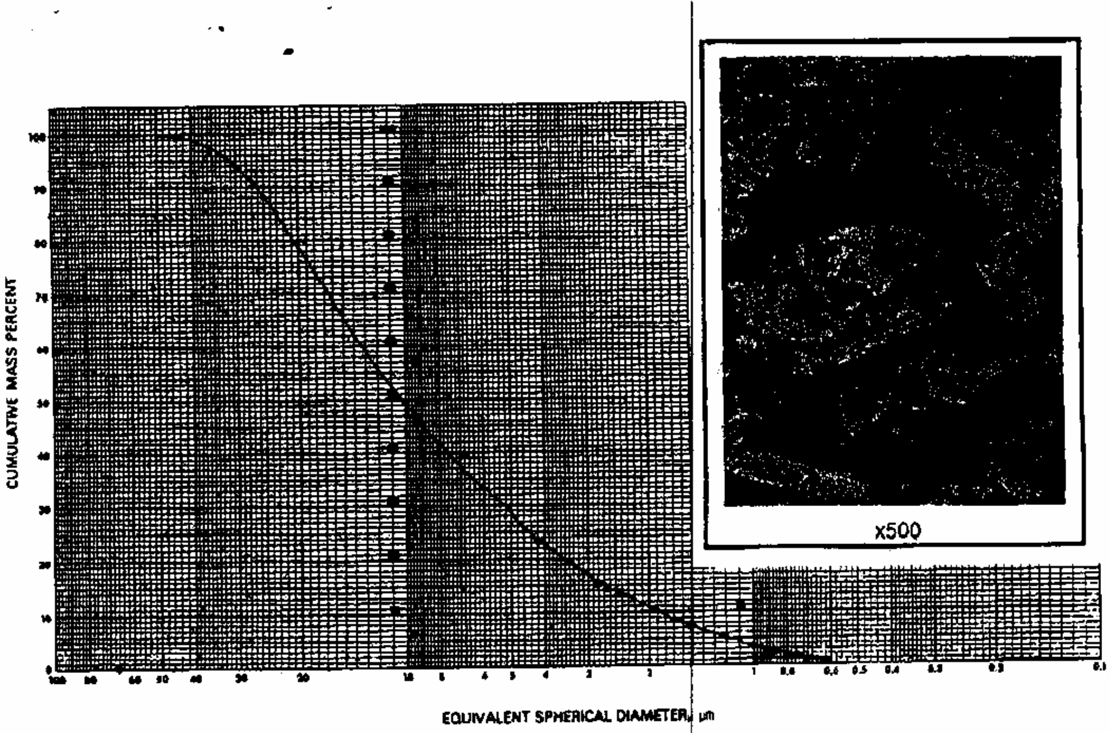
NYCO Minerals, Inc. is the only wollastonite producer and supplier to extensively test the health and safety effects of wollastonite from the Lewis, New York deposit. In reviewing the available in vitro, in vivo and epidemiological studies, there is no evidence to suggest that wollastonite presents a health hazard.

World Headquarters: 124 Mountain View Dr. Willsboro, NY 12996-0368 Phone: 518-963-4262 Fax: 518-963-4187
European Sales Office: ORDRUPVEJ 24 P.O. Box 88 DK-2920 Charlottenlund, Denmark Phone: 31 64 33 70 Fax: 31 64 37 10

NYCO
MINERALS, INC.

# NYAD® 325
## 325 Mesh Grade Wollastonite
## Technical Data Sheet

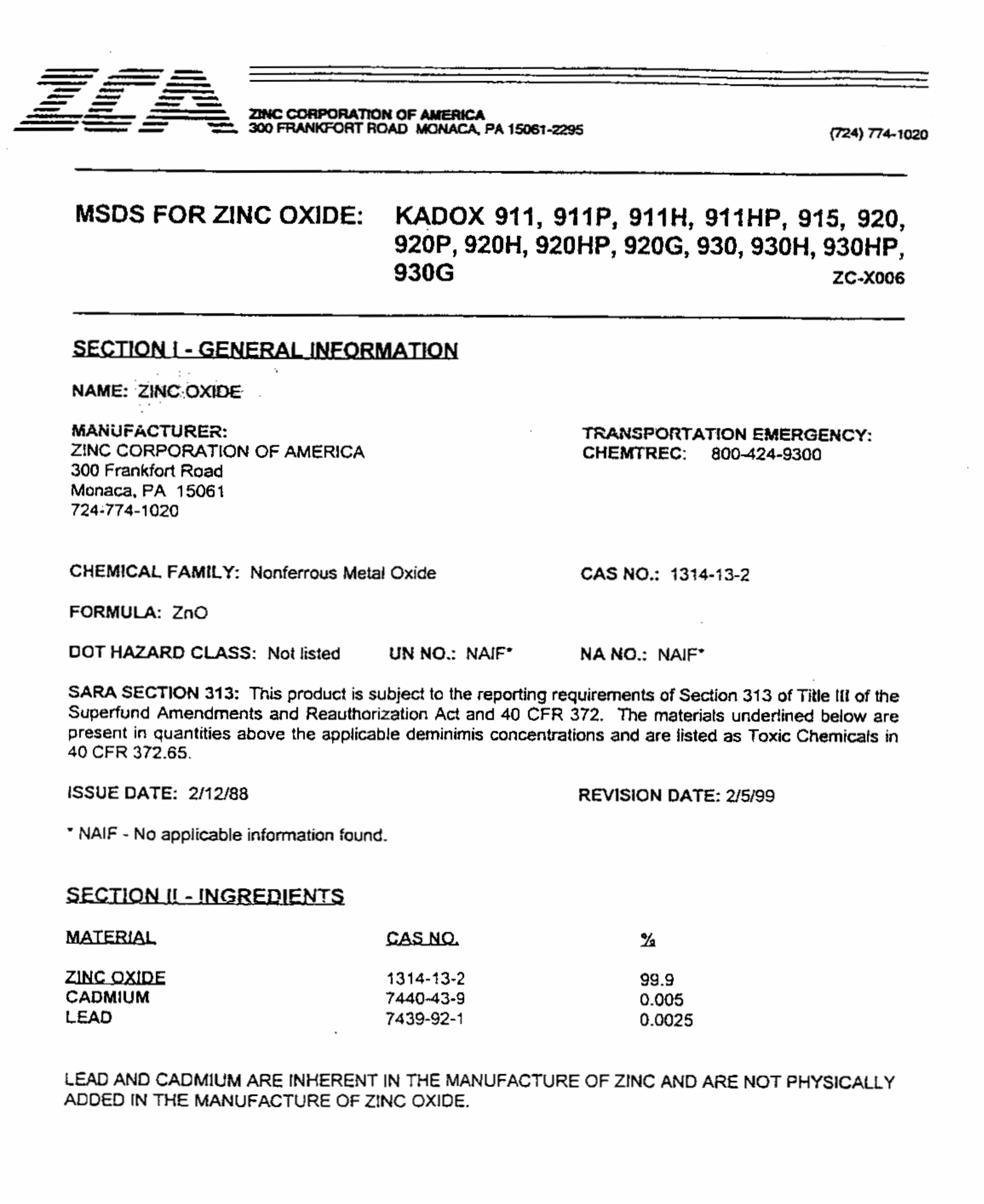
| Typical Property | Typical Value | Method |
|---|---|---|
| G.E. Brightness | 94 | ASTM E97 |
| Oil Absorption (lbs./100 lbs.) | 20 | ASTM D281 |
| Fineness of Grind (Hegman) | 2.8 | ASTM D1210 |
| Bulk Density | | |
| Loose (lbs./cu.ft.) | 45 | ASTM C87 |
| (g/cc) | 0.72 | ASTM C87 |
| Tapped (lbs./cu.ft.) | 70 | ASTM C87 |
| (g/cc) | 1.12 | ASTM C87 |
| Aspect Ratio (L/D) | 5:1 | NYCO I-10 |
| Surface Area (m²/g) (BET) | 1.5 | ASAP 2000 (Micromeritics) |
| Minus 325 U.S. Mesh Screen (%) | 99 | ASTM C115 |
| Moisture (%) | 0.20 | Karl Fischer |
| Loss on Ignition (1000°C) (%) | 0.30 | ASTM D1208 |
| Median Particle Size (microns) | 10 | Sedigraph 5100 |



This data contains general information and describes typical properties only. It is offered for use by persons qualified to determine for themselves the suitability of our products for particular purposes. No guarantee is made or liability assumed, the application of this data and the products described herein being at the sole risk of the user.

IN-82-88-3®

Figure B.22: Zinc Oxide - MSDS



ZINC CORPORATION OF AMERICA
300 FRANKFORT ROAD MONACA, PA 15061-2295
(724) 774-1020

## MSDS FOR ZINC OXIDE: KADOX 911, 911P, 911H, 911HP, 915, 920, 920P, 920H, 920HP, 920G, 930, 930H, 930HP, 930G

ZC-X006

### SECTION I - GENERAL INFORMATION

**NAME:** ZINC OXIDE

**MANUFACTURER:**
ZINC CORPORATION OF AMERICA
300 Frankfort Road
Monaca, PA 15061
724-774-1020

**TRANSPORTATION EMERGENCY:**
**CHEMTREC:** 800-424-9300

**CHEMICAL FAMILY:** Nonferrous Metal Oxide

**CAS NO.:** 1314-13-2

**FORMULA:** ZnO

**DOT HAZARD CLASS:** Not listed **UN NO.:** NAIF* **NA NO.:** NAIF*

**SARA SECTION 313:** This product is subject to the reporting requirements of Section 313 of Title III of the Superfund Amendments and Reauthorization Act and 40 CFR 372. The materials underlined below are present in quantities above the applicable deminimis concentrations and are listed as Toxic Chemicals in 40 CFR 372.65.

**ISSUE DATE:** 2/12/88

**REVISION DATE:** 2/5/99

* NAIF - No applicable information found.

### SECTION II - INGREDIENTS

| MATERIAL | CAS NO. | % |
|---|---|---|
| ZINC OXIDE | 1314-13-2 | 99.9 |
| CADMIUM | 7440-43-9 | 0.005 |
| LEAD | 7439-92-1 | 0.0025 |

LEAD AND CADMIUM ARE INHERENT IN THE MANUFACTURE OF ZINC AND ARE NOT PHYSICALLY ADDED IN THE MANUFACTURE OF ZINC OXIDE.

EFFECTS OF SHORT TERM OVEREXPOSURE:

**ZINC OXIDE:** Inhalation of high levels of zinc oxide may result in tightness of chest, metallic taste, cough, dizziness, fever, chills, headache, nausea, and dry throat. Overexposure may produce symptoms known as metal fume fever or "zinc shakes"; an acute, self-limiting condition without recognized complications. Symptoms of metal fume fever include: chills, fever, muscular pain, nausea and vomiting. Like any finely divided particulate matter, zinc oxide may cause mechanical irritation to skin and eyes.

**MEDICAL CONDITIONS GENERALLY AGGRAVATED BY EXPOSURE:** Inhalation of dust may be an irritant to pre-existing respiratory conditions.

**EMERGENCY AND FIRST AID PROCEDURES:** Symptoms resulting from inhalation overexposure usually disappear within 24 hours. Symptomatic treatment, such as bed rest and possibly aspirin is recommended to provide relief from fever and chills. Skin contact - flush areas with large amounts of water. Eye contact - flush eyes with copious amounts of water. In all cases, consult physician for medical attention.

EFFECTS OF LONG TERM OVEREXPOSURE:

**ZINC OXIDE:** Chronic exposure to zinc oxide may cause respiratory tract irritation with nasopharyngitis and laryngitis.

**CARCINOGENIC ASSESSMENT:**

**NTP?** No **IARC MONOGRAPH?** No **OSHA?** No

## SECTION VI - REACTIVITY DATA

**STABILITY:** ( ) Unstable
(X) Stable

**CONDITIONS TO AVOID:** None

**INCOMPATIBILITY (MATERIALS TO AVOID):** None known.

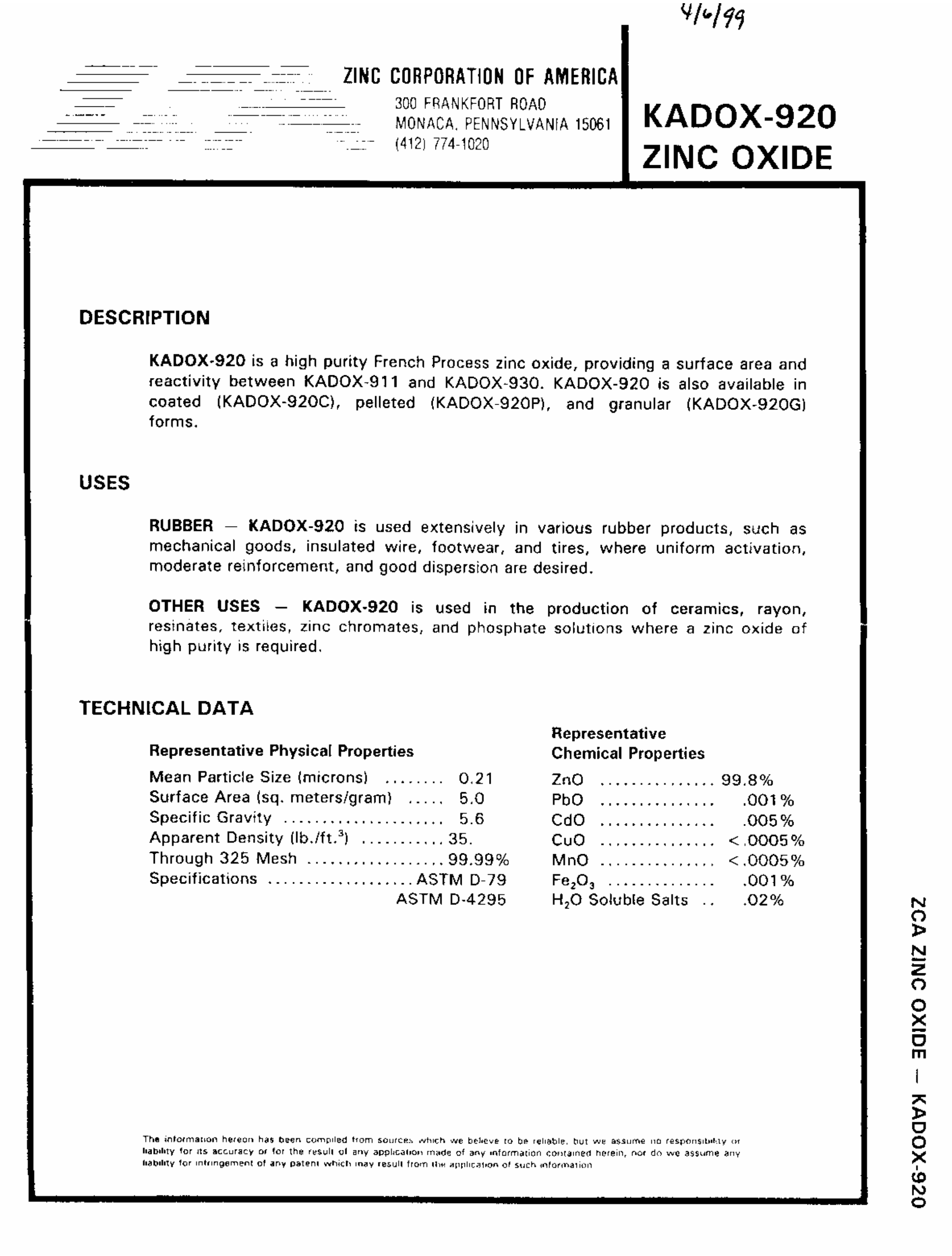
**HAZARDOUS DECOMPOSITION PRODUCTS:** None

**HAZARDOUS POLYMERIZATION:** ( ) May occur
(X) Will not occur

## SECTION VII - SPILL OR LEAK PROCEDURES

**STEPS TO BE TAKEN IN CASE MATERIAL IS RELEASED OR SPILLED:** As with any nuisance dust, avoid excessive dusting. Material should be contained for recycling.

Figure B.23: Zinc Oxide – Vendor Technical Data



4/6/99

**ZINC CORPORATION OF AMERICA**
300 FRANKFORT ROAD
MONACA, PENNSYLVANIA 15061
(412) 774-1020

# KADOX-920
# ZINC OXIDE

## DESCRIPTION

**KADOX-920** is a high purity French Process zinc oxide, providing a surface area and reactivity between KADOX-911 and KADOX-930. KADOX-920 is also available in coated (KADOX-920C), pelleted (KADOX-920P), and granular (KADOX-920G) forms.

## USES

**RUBBER** — **KADOX-920** is used extensively in various rubber products, such as mechanical goods, insulated wire, footwear, and tires, where uniform activation, moderate reinforcement, and good dispersion are desired.

**OTHER USES** — **KADOX-920** is used in the production of ceramics, rayon, resinates, textiles, zinc chromates, and phosphate solutions where a zinc oxide of high purity is required.

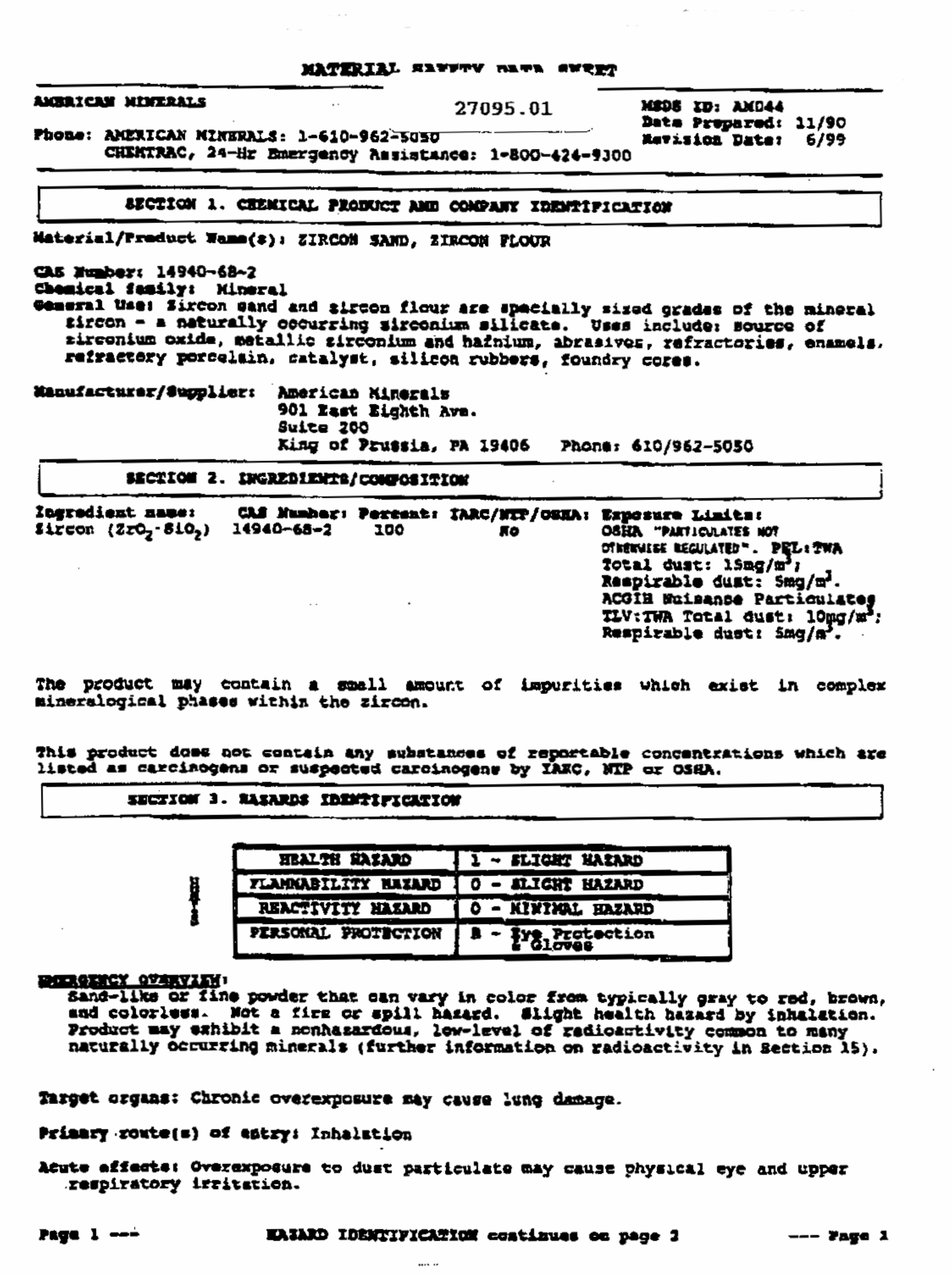
## TECHNICAL DATA

| Representative Physical Properties | |
|---|---|
| Mean Particle Size (microns) | 0.21 |
| Surface Area (sq. meters/gram) | 5.0 |
| Specific Gravity | 5.6 |
| Apparent Density (lb./ft.$^3$) | 35. |
| Through 325 Mesh | 99.99% |
| Specifications | ASTM D-79<br>ASTM D-4295 |

| Representative Chemical Properties | |
|---|---|
| ZnO | 99.8% |
| PbO | .001% |
| CdO | .005% |
| CuO | <.0005% |
| MnO | <.0005% |
| $Fe_2O_3$ | .001% |
| $H_2O$ Soluble Salts | .02% |

ZCA ZINC OXIDE — KADOX-920

Figure B.24: Zircon - MSDS



## MATERIAL SAFETY DATA SHEET

**AMERICAN MINERALS**

27095.01

**MSDS ID:** AM044
**Date Prepared:** 11/90
**Revision Date:** 6/99

**Phone:** AMERICAN MINERALS: 1-610-962-5050
CHEMTRAC, 24-Hr Emergency Assistance: 1-800-424-9300

### SECTION 1. CHEMICAL PRODUCT AND COMPANY IDENTIFICATION

**Material/Product Name(s):** ZIRCON SAND, ZIRCON FLOUR

**CAS Number:** 14940-68-2
**Chemical family:** Mineral
**General Use:** Zircon sand and zircon flour are specially sized grades of the mineral zircon - a naturally occurring zirconium silicate. Uses include: source of zirconium oxide, metallic zirconium and hafnium, abrasives, refractories, enamels, refractory porcelain, catalyst, silicon rubbers, foundry cores.

**Manufacturer/Supplier:** American Minerals
901 East Eighth Ave.
Suite 200
King of Prussia, PA 19406 Phone: 610/962-5050

### SECTION 2. INGREDIENTS/COMPOSITION

| Ingredient name: | CAS Number: | Percent: | IARC/NTP/OSHA: | Exposure Limits: |
|---|---|---|---|---|
| Zircon ($ZrO_2 \cdot SiO_2$) | 14940-68-2 | 100 | No | OSHA "PARTICULATES NOT OTHERWISE REGULATED". PEL:TWA Total dust: 15mg/m$^3$; Respirable dust: 5mg/m$^3$. ACGIH Nuisance Particulates TLV:TWA Total dust: 10mg/m$^3$; Respirable dust: 5mg/m$^3$. |

The product may contain a small amount of impurities which exist in complex mineralogical phases within the zircon.

This product does not contain any substances of reportable concentrations which are listed as carcinogens or suspected carcinogens by IARC, NTP or OSHA.

### SECTION 3. HAZARDS IDENTIFICATION

| | |
|---|---|
| HEALTH HAZARD | 1 - SLIGHT HAZARD |
| FLAMMABILITY HAZARD | 0 - SLIGHT HAZARD |
| REACTIVITY HAZARD | 0 - MINIMAL HAZARD |
| PERSONAL PROTECTION | B - Eye Protection & Gloves |

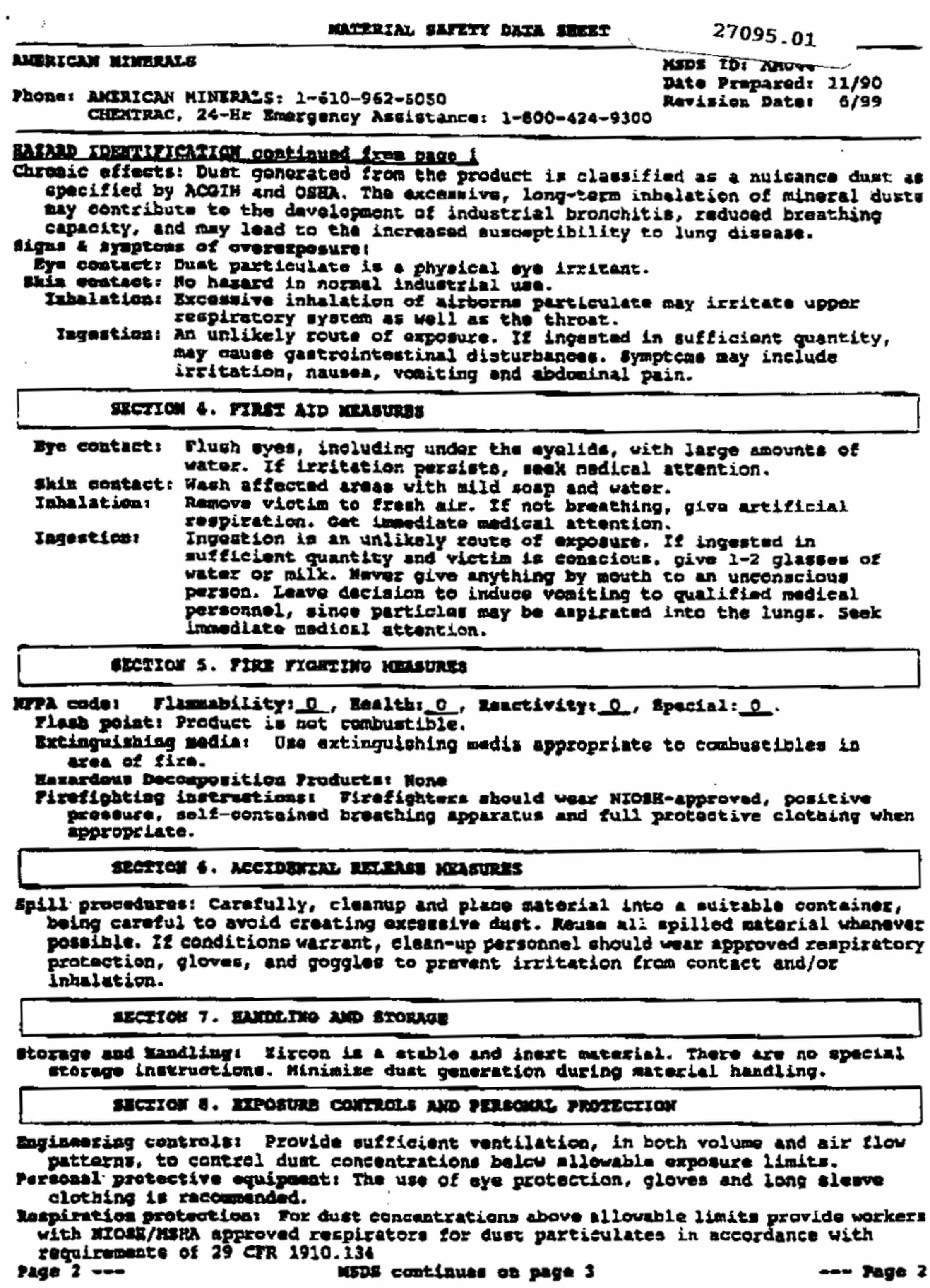
**EMERGENCY OVERVIEW:**
Sand-like or fine powder that can vary in color from typically gray to red, brown, and colorless. Not a fire or spill hazard. Slight health hazard by inhalation. Product may exhibit a nonhazardous, low-level of radioactivity common to many naturally occurring minerals (further information on radioactivity in Section 15).

**Target organs:** Chronic overexposure may cause lung damage.

**Primary route(s) of entry:** Inhalation

**Acute effects:** Overexposure to dust particulate may cause physical eye and upper respiratory irritation.

Page 1 --- HAZARD IDENTIFICATION continues on page 2 --- Page 1



MATERIAL SAFETY DATA SHEET 27095.01

**AMERICAN MINERALS**

**MSDS ID:** AMO
**Date Prepared:** 11/90
**Revision Date:** 6/99

**Phone:** AMERICAN MINERALS: 1-610-962-5050
CHEMTRAC, 24-Hr Emergency Assistance: 1-800-424-9300

**HAZARD IDENTIFICATION continued from page 1**

**Chronic effects:** Dust generated from the product is classified as a nuisance dust as specified by ACGIH and OSHA. The excessive, long-term inhalation of mineral dusts may contribute to the development of industrial bronchitis, reduced breathing capacity, and may lead to the increased susceptibility to lung disease.

**Signs & symptoms of overexposure:**

**Eye contact:** Dust particulate is a physical eye irritant.

**Skin contact:** No hazard in normal industrial use.

**Inhalation:** Excessive inhalation of airborne particulate may irritate upper respiratory system as well as the throat.

**Ingestion:** An unlikely route of exposure. If ingested in sufficient quantity, may cause gastrointestinal disturbances. Symptoms may include irritation, nausea, vomiting and abdominal pain.

## SECTION 4. FIRST AID MEASURES

**Eye contact:** Flush eyes, including under the eyelids, with large amounts of water. If irritation persists, seek medical attention.

**Skin contact:** Wash affected areas with mild soap and water.

**Inhalation:** Remove victim to fresh air. If not breathing, give artificial respiration. Get immediate medical attention.

**Ingestion:** Ingestion is an unlikely route of exposure. If ingested in sufficient quantity and victim is conscious, give 1-2 glasses of water or milk. Never give anything by mouth to an unconscious person. Leave decision to induce vomiting to qualified medical personnel, since particles may be aspirated into the lungs. Seek immediate medical attention.

## SECTION 5. FIRE FIGHTING MEASURES

**NFPA code:** **Flammability:** 0 , **Health:** 0 , **Reactivity:** 0 , **Special:** 0 .

**Flash point:** Product is not combustible.

**Extinguishing media:** Use extinguishing media appropriate to combustibles in area of fire.

**Hazardous Decomposition Products:** None

**Firefighting instructions:** Firefighters should wear NIOSH-approved, positive pressure, self-contained breathing apparatus and full protective clothing when appropriate.

## SECTION 6. ACCIDENTAL RELEASE MEASURES

**Spill procedures:** Carefully, cleanup and place material into a suitable container, being careful to avoid creating excessive dust. Reuse all spilled material whenever possible. If conditions warrant, clean-up personnel should wear approved respiratory protection, gloves, and goggles to prevent irritation from contact and/or inhalation.

## SECTION 7. HANDLING AND STORAGE

**Storage and Handling:** Zircon is a stable and inert material. There are no special storage instructions. Minimize dust generation during material handling.

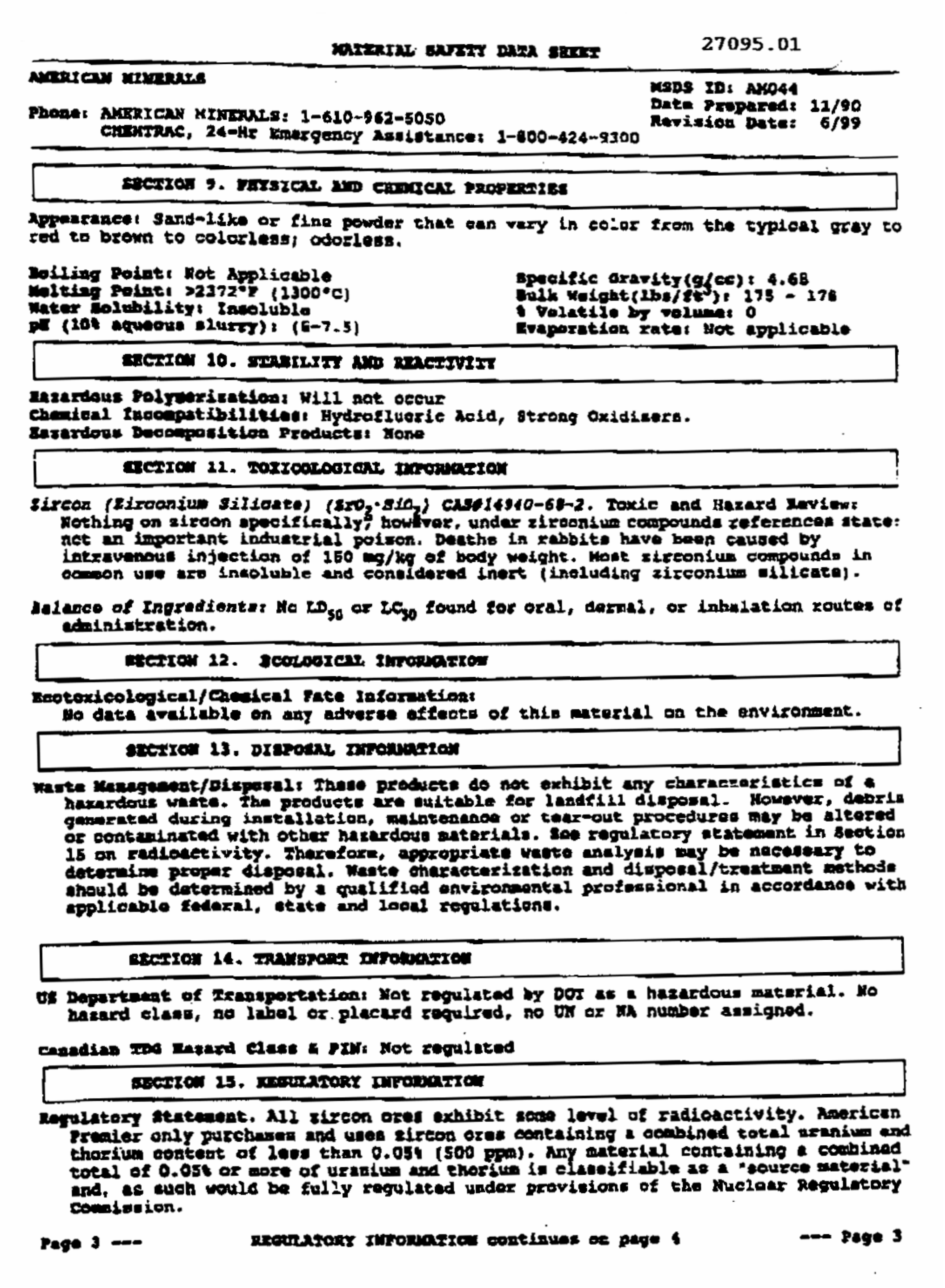
## SECTION 8. EXPOSURE CONTROLS AND PERSONAL PROTECTION

**Engineering controls:** Provide sufficient ventilation, in both volume and air flow patterns, to control dust concentrations below allowable exposure limits.

**Personal protective equipment:** The use of eye protection, gloves and long sleeve clothing is recommended.

**Respiration protection:** For dust concentrations above allowable limits provide workers with NIOSH/MSHA approved respirators for dust particulates in accordance with requirements of 29 CFR 1910.134

Page 2 --- MSDS continues on page 3 --- Page 2



## MATERIAL SAFETY DATA SHEET

27095.01

**AMERICAN MINERALS**

**MSDS ID:** AM044
**Date Prepared:** 11/90
**Revision Date:** 6/99

**Phone:** AMERICAN MINERALS: 1-610-962-5050
CHEMTRAC, 24-Hr Emergency Assistance: 1-800-424-9300

### SECTION 9. PHYSICAL AND CHEMICAL PROPERTIES

**Appearance:** Sand-like or fine powder that can vary in color from the typical gray to red to brown to colorless; odorless.

**Boiling Point:** Not Applicable
**Melting Point:** >2372°F (1300°C)
**Water Solubility:** Insoluble
**pH (10% aqueous slurry):** (6-7.5)
**Specific Gravity(g/cc):** 4.68
**Bulk Weight(lbs/ft$^3$):** 175 - 178
**% Volatile by volume:** 0
**Evaporation rate:** Not applicable

### SECTION 10. STABILITY AND REACTIVITY

**Hazardous Polymerization:** Will not occur
**Chemical Incompatibilities:** Hydrofluoric Acid, Strong Oxidizers.
**Hazardous Decomposition Products:** None

### SECTION 11. TOXICOLOGICAL INFORMATION

*Zircon (Zirconium Silicate) ($ZrO_2 \cdot SiO_2$) CAS#14940-68-2.* Toxic and Hazard Review: Nothing on zircon specifically; however, under zirconium compounds references state: not an important industrial poison. Deaths in rabbits have been caused by intravenous injection of 150 mg/kg of body weight. Most zirconium compounds in common use are insoluble and considered inert (including zirconium silicate).

***Balance of Ingredients:*** No $LD_{50}$ or $LC_{50}$ found for oral, dermal, or inhalation routes of administration.

### SECTION 12. ECOLOGICAL INFORMATION

**Ecotoxicological/Chemical Fate Information:**
No data available on any adverse effects of this material on the environment.

### SECTION 13. DISPOSAL INFORMATION

**Waste Management/Disposal:** These products do not exhibit any characteristics of a hazardous waste. The products are suitable for landfill disposal. However, debris generated during installation, maintenance or tear-out procedures may be altered or contaminated with other hazardous materials. See regulatory statement in Section 15 on radioactivity. Therefore, appropriate waste analysis may be necessary to determine proper disposal. Waste characterization and disposal/treatment methods should be determined by a qualified environmental professional in accordance with applicable federal, state and local regulations.

### SECTION 14. TRANSPORT INFORMATION

**US Department of Transportation:** Not regulated by DOT as a hazardous material. No hazard class, no label or placard required, no UN or NA number assigned.

**Canadian TDG Hazard Class & PIN:** Not regulated

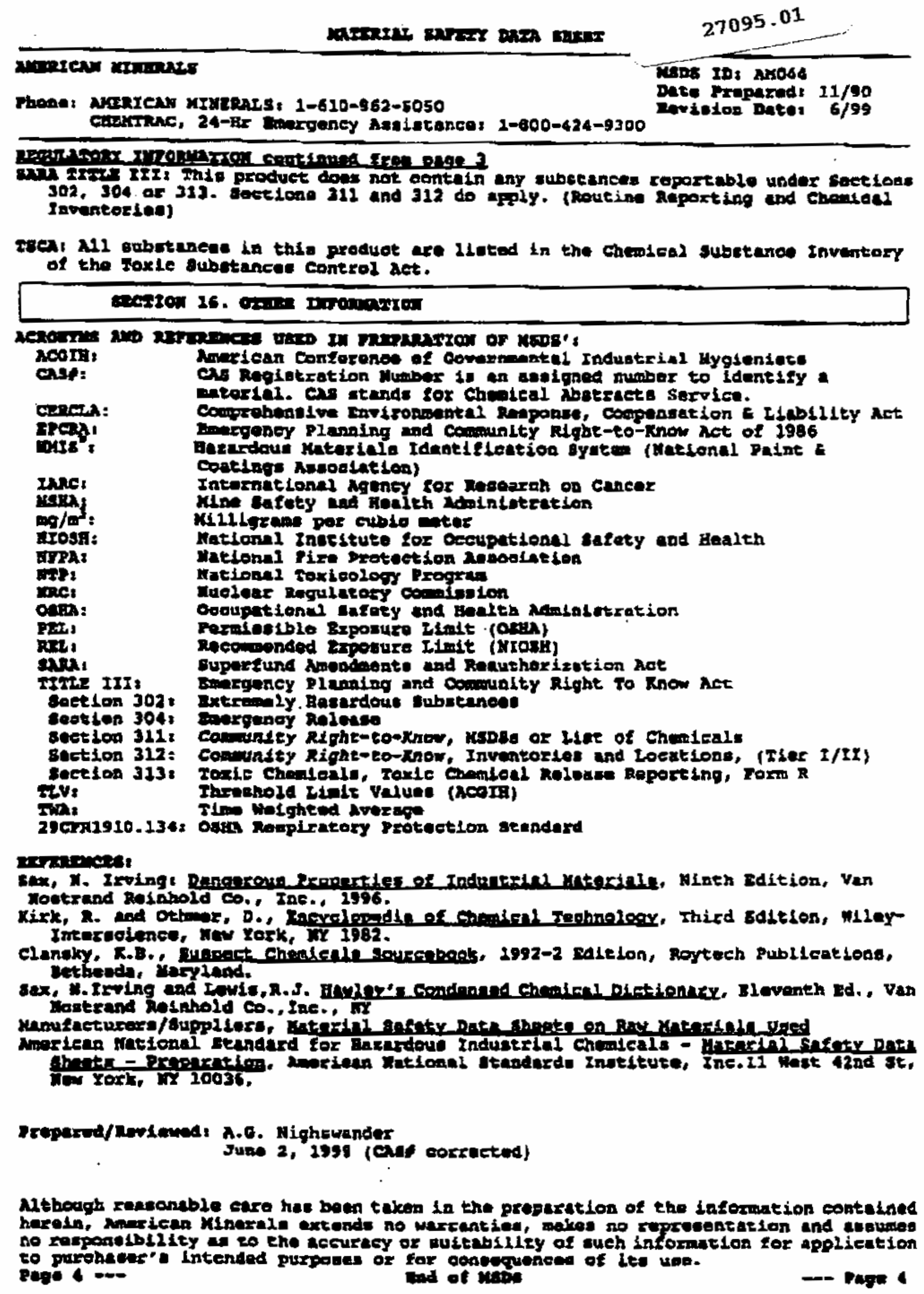
### SECTION 15. REGULATORY INFORMATION

**Regulatory Statement.** All zircon ores exhibit some level of radioactivity. American Premier only purchases and uses zircon ores containing a combined total uranium and thorium content of less than 0.05% (500 ppm). Any material containing a combined total of 0.05% or more of uranium and thorium is classifiable as a "source material" and, as such would be fully regulated under provisions of the Nuclear Regulatory Commission.

**Page 3 ---**

REGULATORY INFORMATION continues on page 4

**--- Page 3**



## MATERIAL SAFETY DATA SHEET

27095.01

AMERICAN MINERALS

MSDS ID: AM066
Date Prepared: 11/90
Revision Date: 6/99

Phone: AMERICAN MINERALS: 1-610-862-5050
CHEMTRAC, 24-Hr Emergency Assistance: 1-800-424-9300

**REGULATORY INFORMATION continued from page 3**

**SARA TITLE III:** This product does not contain any substances reportable under Sections 302, 304 or 313. Sections 311 and 312 do apply. (Routine Reporting and Chemical Inventories)

**TSCA:** All substances in this product are listed in the Chemical Substance Inventory of the Toxic Substances Control Act.

### SECTION 16. OTHER INFORMATION

**ACRONYMS AND REFERENCES USED IN PREPARATION OF MSDS':**

| | |
|---|---|
| ACGIH: | American Conference of Governmental Industrial Hygienists |
| CAS#: | CAS Registration Number is an assigned number to identify a material. CAS stands for Chemical Abstracts Service. |
| CERCLA: | Comprehensive Environmental Response, Compensation & Liability Act |
| EPCRA: | Emergency Planning and Community Right-to-Know Act of 1986 |
| HMIS®: | Hazardous Materials Identification System (National Paint & Coatings Association) |
| IARC: | International Agency for Research on Cancer |
| MSHA: | Mine Safety and Health Administration |
| $mg/m^3$: | Milligrams per cubic meter |
| NIOSH: | National Institute for Occupational Safety and Health |
| NFPA: | National Fire Protection Association |
| NTP: | National Toxicology Program |
| NRC: | Nuclear Regulatory Commission |
| OSHA: | Occupational Safety and Health Administration |
| PEL: | Permissible Exposure Limit (OSHA) |
| REL: | Recommended Exposure Limit (NIOSH) |
| SARA: | Superfund Amendments and Reauthorization Act |
| TITLE III: | Emergency Planning and Community Right To Know Act |
| Section 302: | Extremely Hazardous Substances |
| Section 304: | Emergency Release |
| Section 311: | *Community Right-to-Know*, MSDSs or List of Chemicals |
| Section 312: | *Community Right-to-Know*, Inventories and Locations, (Tier I/II) |
| Section 313: | Toxic Chemicals, Toxic Chemical Release Reporting, Form R |
| TLV: | Threshold Limit Values (ACGIH) |
| TWA: | Time Weighted Average |
| 29CFR1910.134: | OSHA Respiratory Protection Standard |

**REFERENCES:**

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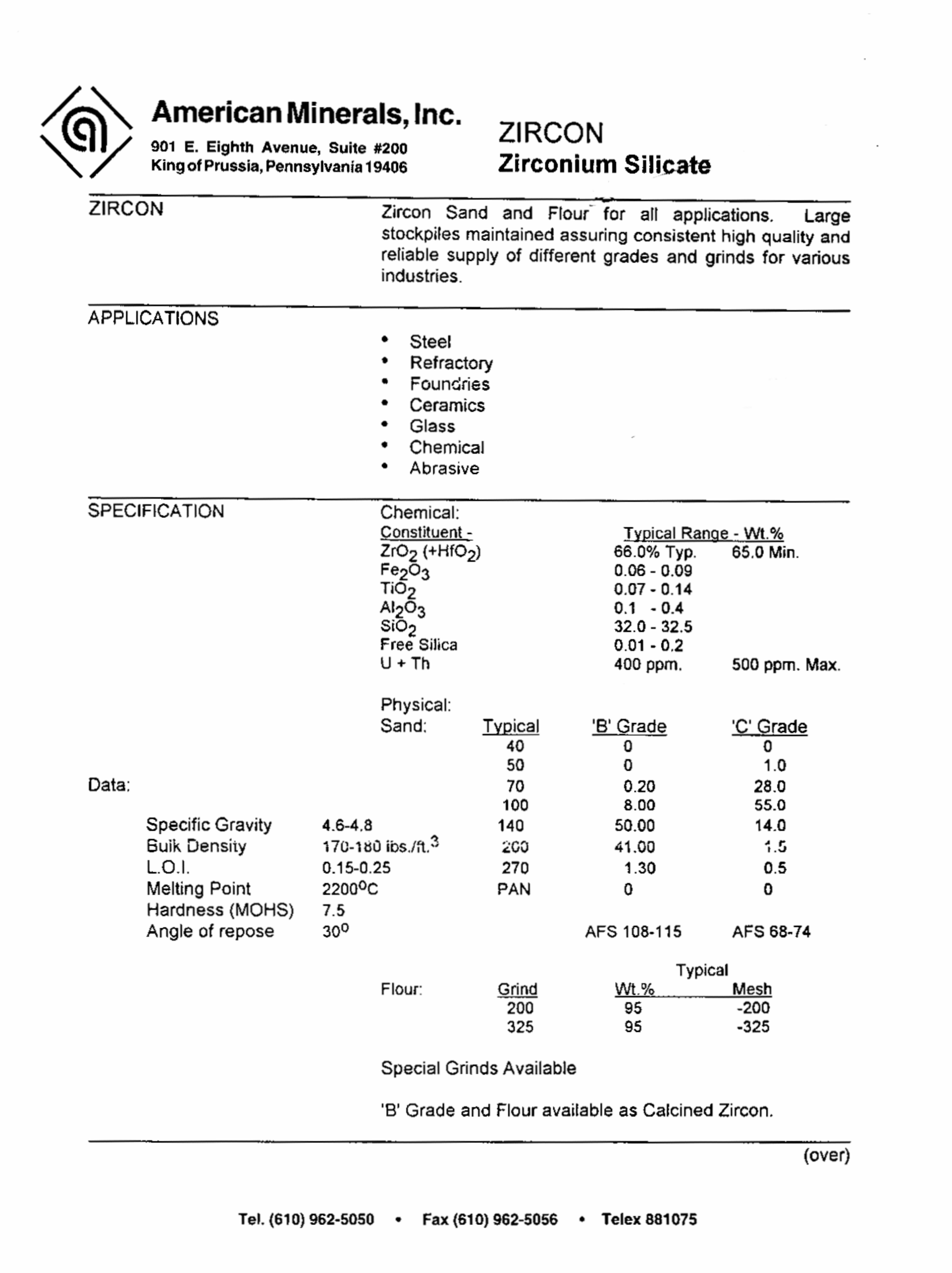
Kirk, R. and Othmer, D., Encyclopedia of Chemical Technology, Third Edition, Wiley-Interscience, New York, NY 1982.
Clansky, K.B., Suspect Chemicals Sourcebook, 1992-2 Edition, Roytech Publications, Bethesda, Maryland.
Sax, N.Irving and Lewis,R.J. Hawley's Condensed Chemical Dictionary, Eleventh Ed., Van Nostrand Reinhold Co.,Inc., NY
Manufacturers/Suppliers, Material Safety Data Sheets on Raw Materials Used
American National Standard for Hazardous Industrial Chemicals - Material Safety Data Sheets - Preparation, American National Standards Institute, Inc.11 West 42nd St, New York, NY 10036.

**Prepared/Reviewed:** A.G. Nighswander
June 2, 1999 (CAS# corrected)

Although reasonable care has been taken in the preparation of the information contained herein, American Minerals extends no warranties, makes no representation and assumes no responsibility as to the accuracy or suitability of such information for application to purchaser's intended purposes or for consequences of its use.

Page 4 --- End of MSDS --- Page 4

Figure B.25: Zircon – Vendor Technical Data



**American Minerals, Inc.**
**901 E. Eighth Avenue, Suite #200**
**King of Prussia, Pennsylvania 19406**

## ZIRCON
## Zirconium Silicate

ZIRCON

Zircon Sand and Flour for all applications. Large stockpiles maintained assuring consistent high quality and reliable supply of different grades and grinds for various industries.

APPLICATIONS

- Steel
- Refractory
- Foundries
- Ceramics
- Glass
- Chemical
- Abrasive

SPECIFICATION

Chemical:

| Constituent - | Typical Range - Wt.% | |
|---|---|---|
| $ZrO_2$ (+$HfO_2$) | 66.0% Typ. | 65.0 Min. |
| $Fe_2O_3$ | 0.06 - 0.09 | |
| $TiO_2$ | 0.07 - 0.14 | |
| $Al_2O_3$ | 0.1 - 0.4 | |
| $SiO_2$ | 32.0 - 32.5 | |
| Free Silica | 0.01 - 0.2 | |
| U + Th | 400 ppm. | 500 ppm. Max. |

Physical:

Sand:

| Typical | 'B' Grade | 'C' Grade |
|---|---|---|
| 40 | 0 | 0 |
| 50 | 0 | 1.0 |
| 70 | 0.20 | 28.0 |
| 100 | 8.00 | 55.0 |
| 140 | 50.00 | 14.0 |
| 200 | 41.00 | 1.5 |
| 270 | 1.30 | 0.5 |
| PAN | 0 | 0 |
| | AFS 108-115 | AFS 68-74 |

Data:

| | |
|---|---|
| Specific Gravity | 4.6-4.8 |
| Bulk Density | 170-180 lbs./ft.$^3$ |
| L.O.I. | 0.15-0.25 |
| Melting Point | 2200°C |
| Hardness (MOHS) | 7.5 |
| Angle of repose | 30° |

Flour:

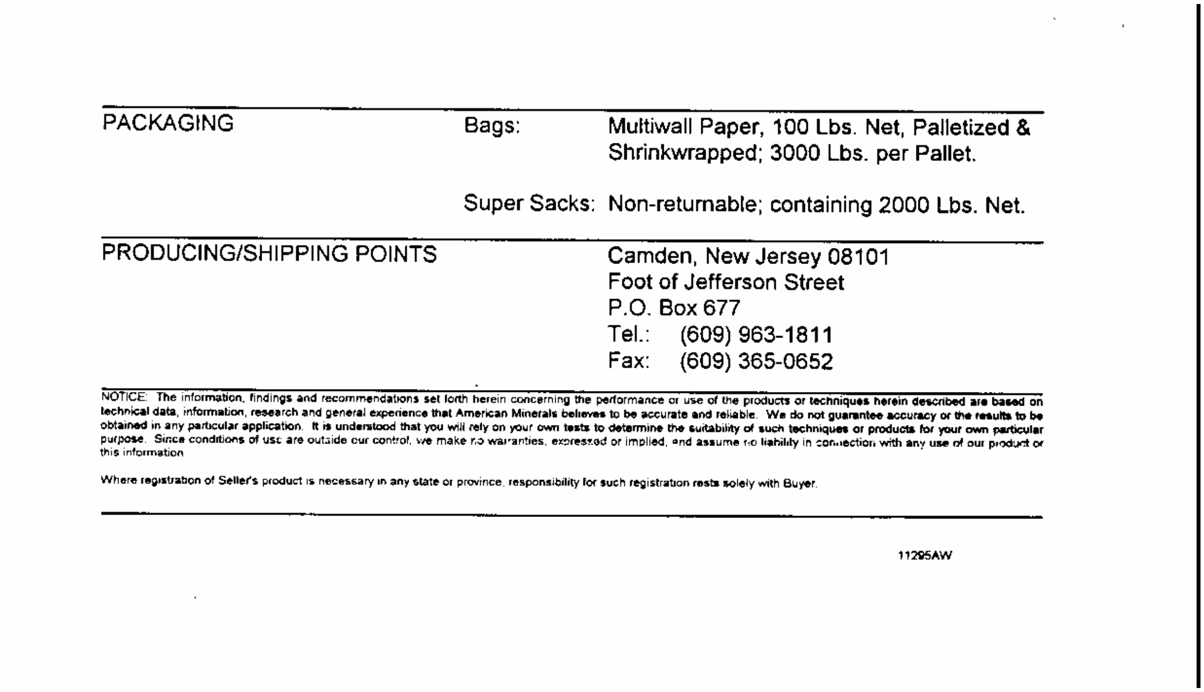
| Grind | Typical Wt.% | Mesh |
|---|---|---|
| 200 | 95 | -200 |
| 325 | 95 | -325 |

Special Grinds Available

'B' Grade and Flour available as Calcined Zircon.

(over)

Tel. (610) 962-5050 • Fax (610) 962-5056 • Telex 881075



| | | |
|---|---|---|
| PACKAGING | Bags: | Multiwall Paper, 100 Lbs. Net, Palletized & Shrinkwrapped; 3000 Lbs. per Pallet. |
| | Super Sacks: | Non-returnable; containing 2000 Lbs. Net. |
| PRODUCING/SHIPPING POINTS | | Camden, New Jersey 08101<br>Foot of Jefferson Street<br>P.O. Box 677<br>Tel.: (609) 963-1811<br>Fax: (609) 365-0652 |

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11295AW

# APPENDIX C. CALCULATIONS FOR GFC BLENDS

## Table C. 1: LAW Blend Formulations Provided By VSL

| **Glass Former Chemicals** | **Test Blend A** | **Test Blend B** | **Test Blend C** |
|---|---|---|---|
| | **LAW A LAWA44 for AN105** | **LAW B LAWB45 AZ101** | **LAW C LAWC22 AN107** |
| Kyanite -325 Mesh Raw, Kyanite Min. | 37.586 | 93.822 | 98.060 |
| Boric Acid -U.S. Borax | 162.051 | 222.108 | 181.335 |
| Wollastonite, NYAD 325 | 42.086 | 140.382 | 107.597 |
| Iron Oxide, Fe2O3 | 67.938 | 47.861 | 51.942 |
| Lithium Carb. Chemetall, Tech Grade | **N/A** | 115.654 | 62.894 |
| Olivine Unimin #180 | 41.923 | 62.450 | 31.768 |
| Silica, SilCoSil 75 U.S. Silica | 376.643 | 328.613 | 343.156 |
| Rutile Sand, Air Floated, | 21.380 | **N/A** | 12.241 |
| Zinc Oxide, ZCA, Kadox 910 | 29.718 | 31.604 | 30.710 |
| Zircon flour, -325 mesh | 45.759 | 48.223 | 46.218 |
| Sugar, Granulated. | 58.038 | 23.618 | 6.151 |
| Glass Target Wt. | 1000.000 | 1000.000 | 1000.000 |
| Sum of GFCs | 825.084 | 1090.717 | 965.921 |
| Sum of GFCs+Sugar | 883.122 | 1114.335 | 972.072 |

## Table C.2: HLW Blend Formulation

| **Glass Former Chemicals** | **HLW AZ 102** | | **HLW C-106/AY-104** | |
|---|---|---|---|---|
| | **No Borax** | **Test Blend With Borax** | **No Borax** | **Test Blend With Borax** |
| Boric Acid -U.S. Borax | 10.651 | **N/A** | 25.283 | 17.157 |
| Ten Mole Borax - U.S. Borax | **N/A** | 16.011 | **N/A** | 12.216 |
| Sodium Carbonate – Solvay | 24.567 | 19.987 | 3.495 | **N/A** |
| Lithium Carb. Chemetall, Tech Grade | 18.682 | 18.682 | 20.059 | 20.059 |
| Silica, SilCoSil 75 U.S. Silica | 72.247 | 72.247 | 71.645 | 71.645 |
| Zinc Oxide, ZCA, Kadox 910 | 0.000 | 0.000 | 4.088 | 4.088 |
| Sum of GFCs | 126.148 | 126.926 | 124.570 | 125.164 |

* Oxide basis provide by VSL – SRTC Calculated GFC Required

## Table C.3: HLW Blend Determinations Using Borax or Boric Acid

| | Glass Former Chemicals | Oxides Weight Factors | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Oxide Factors for Given GFC** | | **$SiO_2$** | **$B_2O_3$** | **$Na_2O$** | **$Li_2O$** | **no** | **$Fe_2O_3$** | **$Al_2O_3$** |
| | $Na_2B_4O_7.10H_2O$ | **N/A** | 0.3760 | 0.1670 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $H_3BO_3$ | **N/A** | 0.5652 | **N/A** | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Na_2CO_3$ | **N/A** | **N/A** | 0.5837 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Li_2CO_3$ | **N/A** | **N/A** | **N/A** | 0.4068 | **N/A** | **N/A** | **N/A** |
| | $SiO_2$ | 0.9970 | **N/A** | **N/A** | **N/A** | **N/A** | 0.0002 | 0.0009 |
| | **ZnO** | **N/A** | **N/A** | **N/A** | **N/A** | 0.9980 | **N/A** | **N/A** |

| | Glass Former Chemicals | | Oxide Required For AZ-102 Blend | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **AZ 102 Calculation for GFC Blends** | Chemical | Mass Required | **$SiO_2$** | **$B_2O_3$** | **$Na_2O$** | **$Li_2O$** | **no** | **$Fe_2O_3$** | **$Al_2O_3$** |
| | $Na_2B_4O_7.10H_2O$ | 16.011 | **N/A** | 6.020 | 2.674 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $H_3BO_3$ | 10.651 | **N/A** | 6.020 | **N/A** | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Na_2CO_3$ w/ten mole | 19.987 | **N/A** | **N/A** | 11.666 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Na_2CO_3$ w/boric acid | 24.567 | **N/A** | **N/A** | 14.340 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Li_2CO_3$ | 18.682 | **N/A** | **N/A** | **N/A** | 7.600 | **N/A** | **N/A** | **N/A** |
| | $SiO_2$ | 72.247 | 72.030 | **N/A** | **N/A** | **N/A** | **N/A** | 0.014 | 0.065 |
| | Zno | 0.000 | **N/A** | **N/A** | **N/A** | **N/A** | **N/A** | **N/A** | **N/A** |
| | Mass of Oxide Required → | | **72.030** | **6.020** | **14.340** | **7.600** | 0.000 | 0.014 | 0.065 |

| | Glass Former Chemicals | | Oxide Required For C-106/AY-104 Blend | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **C-106/AY-104 Calculation for GFC Blends** | Chemical | Mass Required | **$SiO_2$** | **$B_2O_3$** | **$Na_2O$** | **$Li_2O$** | **no** | **$Fe_2O_3$** | **$Al_2O_3$** |
| | $Na_2B_4O_7.10H_2O$ | 12.216 | **N/A** | 4.593 | 2.040 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $H_3BO_3$ | 25.283 | **N/A** | 14.290 | **N/A** | **N/A** | **N/A** | **N/A** | **N/A** |
| | $H_3BO_3$ w/ten mole | 17.157 | **N/A** | 9.697 | **N/A** | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Na_2CO_3$ w/ten mole | 0.000 | **N/A** | **N/A** | 0.000 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Na_2CO_3$ w/boric acid | 3.495 | **N/A** | **N/A** | 2.040 | **N/A** | **N/A** | **N/A** | **N/A** |
| | $Li_2CO_3$ | 20.059 | **N/A** | **N/A** | **N/A** | 8.160 | **N/A** | **N/A** | **N/A** |
| | $SiO_2$ | 71.645 | 71.430 | **N/A** | **N/A** | **N/A** | **N/A** | 0.014 | 0.064 |
| | no | 4.088 | **N/A** | **N/A** | **N/A** | **N/A** | 4.080 | **N/A** | **N/A** |
| | Mass of Oxide Required → | | **71.430** | **14.290** | **2.040** | **8.160** | **4.080** | 0.014 | 0.064 |

## Table C.4: VSL – LAWA44, LAW A - AN105 J&J Blend Recipe

| GFCs | Minimum Density (lbm/$ft^3$) | Moisture Content wt. % | VSL Recipe | | J&J Batch | Actual |
|---|---|---|---|---|---|---|
| | | | Batch | wt. % | grams | grams |
| Kyanite, -325Mesh, Raw | 56 | 0.14% | 37.586 | 4.26% | 425 | 425 |
| Boric Acid, Tech. Grade, Gran. | 55 | 0.00% | 162.051 | 18.35% | 1833 | 1833 |
| Wollastonite, NYAD325,Mexico | 46 | 0.18% | 42.086 | 4.77% | 476 | 476 |
| Iron Oxide, 5001 | 89 | 0.30% | 67.938 | 7.69% | 768 | 768 |
| Olivine, #180 Grade, WA | 89 | 0.20% | 41.923 | 4.75% | 474 | 474 |
| Silica, SilCoSil 75, Mill Creek | 50 | 0.10% | 376.643 | 42.65% | 4260 | 4260 |
| Air Floated Rutile Ore, "94" | 91 | 0.00% | 21.380 | 2.42% | 242 | 242 |
| Zinc Oxide, Kadox 920 | 31 | 0.15% | 29.718 | 3.37% | 336 | 336 |
| Zircon Flour 325 Mesh | 106 | 0.00% | 45.759 | 5.18% | 518 | 518 |
| Sugar, Granular | 52 | 0.00% | 58.038 | 6.57% | 656 | 656 |
| | | **Total:** | 883.122 | 100.0% | 9989 | **9989** |
| Average Density | 55.1 | lbm/$ft^3$ | **N/A** | Water | **0** | Grams |
| Total Volume | 0.4 | $ft^3$ | **N/A** | **N/A** | **N/A** | **N/A** |
| Total Mass | 22.02 | Lbm | 9989 | Grams | **N/A** | **N/A** |

## Table C.5: VSL – LAWB45, LAW B -AZ101 J&J Blend Recipe

| GFCs | Minimum Density (lbm/$ft^3$) | Moisture Content wt. % | VSL Recipe | | J&J Batch | Actual |
|---|---|---|---|---|---|---|
| | | | Batch | wt. % | grams | grams |
| Kyanite, -325Mesh, Raw | 56 | 0.14% | 93.822 | 8.42% | 823 | 823 |
| Boric Acid, Tech. Grade, Gran. | 55 | 0.00% | 222.108 | 19.93% | 1948 | 1948 |
| Wollastonite, NYAD325,Mexico | 46 | 0.18% | 140.382 | 12.60% | 1231 | 1231 |
| Iron Oxide, 5001 | 89 | 0.30% | 47.861 | 4.30% | 420 | 420 |
| Lithium Carbonate, Tech.Grade | 53 | 0.07% | 115.654 | 10.38% | 1014 | 1014 |
| Olivine, #180 Grade, WA | 89 | 0.20% | 62.450 | 5.60% | 548 | 548 |
| Silica, SilCoSil 75, Mill Creek | 50 | 0.10% | 328.613 | 29.49% | 2882 | 2882 |
| Zinc Oxide, Kadox 920 | 31 | 0.15% | 31.604 | 2.84% | 277 | 277 |
| Zircon Flour 325 Mesh | 106 | 0.00% | 48.223 | 4.33% | 423 | 423 |
| Sugar, Granular | 52 | 0.00% | 23.618 | 2.12% | 207 | 207 |
| | | **Total:** | 1114.335 | 100.0% | 9773 | **9773** |
| Average Density | 53.9 | lbm/$ft^3$ | **N/A** | Water | **0** | Grams |
| Total Volume | 0.4 | $ft^3$ | **N/A** | **N/A** | **N/A** | **N/A** |
| Total Mass | 21.55 | lbm | 9773 | Grams | **N/A** | **N/A** |

## Table C.6: VSL – LAWC22, LAW C – AN107 J&J Blend Recipe

| GFCs | Minimum Density (lbm/ft$^3$) | Moisture Content wt. % | VSL Recipe | | J&J Batch | Actual |
|---|---|---|---|---|---|---|
| | | | Batch | wt. % | grams | grams |
| Kyanite, -325Mesh, Raw | 56 | 0.14% | 98.060 | 10.09% | 985 | 985 |
| Boric Acid, Tech. Grade, Gran. | 55 | 0.00% | 181.335 | 18.65% | 2169 | 2169 |
| Wollastonite, NYAD325,Mexico | 46 | 0.18% | 107.597 | 11.07% | 1081 | 1081 |
| Iron Oxide, 5001 | 89 | 0.30% | 51.942 | 5.34% | 522 | 522 |
| Lithium Carbonate, Tech.Grade | 53 | 0.07% | 62.894 | 6.47% | 632 | 632 |
| Olivine, #180 Grade, WA | 89 | 0.20% | 31.768 | 3.27% | 319 | 319 |
| Silica, SilCoSil 75, Mill Creek | 50 | 0.10% | 343.156 | 35.30% | 3448 | 3448 |
| Air Floated Rutile Ore, "94" | 91 | 0.00% | 12.241 | 1.26% | 123 | 123 |
| Zinc Oxide, Kadox 920 | 31 | 0.15% | 30.710 | 3.16% | 309 | 309 |
| Zircon Flour 325 Mesh | 106 | 0.00% | 46.218 | 4.75% | 464 | 464 |
| Sugar, Granular | 52 | 0.00% | 6.151 | 0.63% | 62 | 62 |
| | | total | 972.072 | 100% | 10115 | **10115** |
| Average Density | 53.8 | lbm/ft$^3$ | **N/A** | Water | **347** | Grams |
| Total Volume | 0.4 | ft$^3$ | **N/A** | **N/A** | **N/A** | **N/A** |
| Total Mass | 21.53 | lbm | 9768 | Grams | **N/A** | **N/A** |

## Table C.7: HLW D - AZ-101 J&J Blend Recipe

| GFCs | Minimum Density (lbm/ft$^3$) | Moisture Content Wt. % | VSL Recipe | | J&J Batch | Actual |
|---|---|---|---|---|---|---|
| | | | Batch | wt. % | grams | grams |
| Ten Mole Borax, Tech Grade | 48 | 0.00% | 16.011 | 12.61% | 1189 | 1189 |
| Sodium Carbonate, Dense | 64 | 0.20% | 19.987 | 15.75% | 1484 | 1484 |
| Lithium Carbonate, Tech.Grade | 53 | 0.07% | 18.682 | 14.72% | 1387 | 1387 |
| Silica, SilCoSil 75, Mill Creek | 50 | 0.10% | 72.247 | 56.92% | 5365 | 5365 |
| | | total | 126.927 | 100.0% | 9426 | **9426** |
| Average Density | 51.9 | Lbm/ft$^3$ | **N/A** | Water | **0** | Grams |
| Total Volume | 0.4 | ft$^3$ | **N/A** | **N/A** | **N/A** | **N/A** |
| Total Mass | 20.78 | lbm | 9426 | grams | **N/A** | **N/A** |

## Table C.8: HLW D – C106/AY104 J&J Blend Recipe

| **GFCs** | **Minimum Density (lbm/ft$^3$)** | **Moisture Content Wt. %** | **VSL Recipe** | | **J&J Batch** | **Actual** |
|---|---|---|---|---|---|---|
| | | | **Batch** | **wt. %** | **grams** | **grams** |
| Boric Acid, Tech. Grade, Gran. | 55 | *0.00%* | 17.157 | 13.71% | ***1240*** | 1240 |
| Ten Mole Borax, Tech Grade | 48 | *0.00%* | 12.216 | 9.76% | ***883*** | 883 |
| Lithium Carbonate, Tech.Grade | *53* | *0.07%* | *20.059* | 16.03% | ***1450*** | 1450 |
| Silica, SilCoSil 75, Mill Creek | *50* | *0.10%* | *71.645* | 57.24% | ***5180*** | 5180 |
| Zinc Oxide, Kadox 920 | *31* | *0.15%* | *4.088* | 3.27% | ***296*** | 296 |
| | | total | 125.165 | 100.0% | *9049* | **9049** |
| Average Density | 49.9 | lbm/ft$^3$ | **N/A** | water | **0** | Grams |
| Total Volume | 0.4 | ft$^3$ | **N/A** | **N/A** | **N/A** | **N/A** |
| Total Mass | 19.95 | lbm | 9049 | grams | **N/A** | **N/A** |

# APPENDIX D. J&J FLOW PROPERTIES TEST REPORT FOR GLASS FORMING CHEMICALS (GFCS) AND GFC BLENDS

JENIKE & JOHANSON
INCORPORATED

June 26, 2002

Ray Schumacher
Senior Fellow Ceramist
Westinghouse Savannah River Company
SRTC-773-43A
Aiken, SC 29808

Dear Ray,

Attached is our Flow Properties Test Report on the thirteen glass forming chemicals and five blends. After you have reviewed the report, please contact me so we can discuss any questions you may have.

As you know, I will be starting the design of the thirteen storage silos for each of the raw glass forming chemicals. These designs will be based upon the material flow properties contained in this report, as well as the design requirements provided by Bechtel personnel.

I look forward to continuing to work with you and your colleagues on this project.

Sincerely,

*Eric P. Maynard*

Eric P. Maynard

Project Engineer

Attachments

cc: John W. Carson, Ph.D., President

cc: Thomas Miniard, WSRC Procurement Specialist

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JENIKE & JOHANSON
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Bulk Solids: Science/Engineering/Design

# Flow Properties Test Report for Glass Forming Chemicals (GFCs) and GFC Blends

Westinghouse Savannah River Company
4537-1

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JENIKE&
JOHANSON

June 26, 2002

# Flow Properties Test Report for Glass Forming Chemicals (GFCs) and GFC Blends

Westinghouse Savannah River Company (4537-1)

## 1 INTRODUCTION

Westinghouse Savannah River Company (WSRC) continues to develop the design of a nuclear waste treatment facility to be implemented at the Department of Energy (DOE) Hanford, Washington site. A liquid vitrification system will be utilized at this facility to treat both high and low activity waste (LAW) streams, and materials utilized in this process will consist partly of glass forming chemicals. The glass forming chemicals (GFCs) to be used in the processes are “bulk solids” and as such, can be susceptible to flow difficulties. Poor handling characteristics of bulk solids can negatively impact processing efficiency and possibly create dangerous operating conditions.

To this end, WSRC has requested that Jenike & Johanson, Inc. (J&J) provide bulk solids consulting services to ensure reliable handling of the glass forming chemicals in the proposed process. This report contains flow properties test results from material characterization studies for the GFCs and custom GFC blends. A *second* report will contain silo designs to ensure reliable flow of the GFCs.

## 2 TEST CONDITIONS

Samples listed in Table 1 below were received from WSRC for flow properties characterization. Tests were run on the samples at their *as received* moisture contents[1] (see Table 1).

**Table 1: Glass forming chemicals (GFCs)**

| GFCs | Moisture content |
|---|---|
| Borax (dried at 40°C for 4 hrs.) | 8.0% |
| Boric acid (dried at 60°C for 4 hrs.) | 0.1% |
| Iron oxide | 0.3% |
| Kyanite | 0.1% |
| Lithium carbonate | 0.1% |
| Olivine | 0.2% |
| Silica | 0.1% |
| Soda ash | 0.2% |
| Sugar | 0.1% |
| Titanium dioxide | 0.2% |
| Wollastonite | 0.2% |
| Zinc oxide | 0.2% |
| Zircon flour | 0.1% |

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[1] Moisture values were determined by drying small samples at 107°C for two hours in a forced convection oven. The loss in weight of each sample, divided by its original weight before drying, is denoted as the *moisture*.

These tests were run to determine the cohesive strength of the material (used for critical arching and ratholing dimensions), wall friction angles (used for calculating mass flow hopper angles), permeability (used to determine critical steady-state discharge rates), the bulk density/consolidating pressure relationship, and minimum chute angles required to maintain flow after impact (blends only). Cohesive strength and wall friction tests for the GFC's were run for continuous flow conditions and for flow after seven days storage at rest. Cohesive strength and wall friction tests for the GFC blends were run for continuous flow conditions and for flow after one (LAW blend) or three (HLW blend) days storage at rest.

All flow properties tests were performed at room temperature (72° F).

GFC blends were prepared at J&J's laboratory by mixing specific quantities of the chemicals in a high-intensity mechanical mixer. The chemical proportions were provided by WSRC personnel and are indicated in Table 2 below.

**Table 2: Glass forming chemical blend compositions**

| | **LAW A** | **LAW B** | **LAW C** | **HLW D** | **HLW D** |
|---|---|---|---|---|---|
| | AN105 | AZ101 | AN107 | AZ102 | C106/AY10 |
| **GFCs** | **Weight %** | **Weight %** | **Weight %** | **Weight %** | **Weight %** |
| Borax (ten mole) | -- | -- | -- | 12.61% | 9.76% |
| Boric acid | 18.35% | 19.93% | 18.65% | -- | 13.71% |
| Iron oxide | 7.69% | 4.30% | 5.34% | -- | -- |
| Kyanite | 4.26% | 8.42% | 10.09% | -- | -- |
| Lithium carbonate | -- | 10.38% | 6.47% | 14.72% | 16.03% |
| Olivine | 4.75% | 5.60% | 3.27% | -- | -- |
| Silica | 42.65% | 29.49% | 35.30% | 56.92% | 57.24% |
| Soda ash | -- | -- | -- | 15.75% | -- |
| Sugar | 6.57% | 2.12% | 0.63% | -- | -- |
| Titanium dioxide | 2.42% | -- | 1.26% | -- | -- |
| Wollastonite | 4.77% | 12.60% | 11.07% | -- | -- |
| Zinc oxide | 3.37% | 2.84% | 3.16% | -- | 3.27% |
| Zircon flour | 5.18% | 4.33% | 4.75% | -- | -- |

## 3 SILO FLOW PATTERNS AND FLOW PROBLEMS

Before presentation of the results from the flow properties tests, one must first understand how bulk solids flow through silos. There are two primary flow patterns that can develop in a bin: *funnel flow* and *mass flow*. Both patterns are shown below in Fig. 1.

In *funnel flow*, an active flow channel forms above the outlet, with non-flowing material at the periphery. As the level of material in the bin decreases, layers of the non-flowing material may or may not slide into the flowing channel, which can result in the formation of stable ratholes. In addition, funnel flow can cause product caking, provide a first-in-last-out flow sequence, and increase the extent to which sifting segregation impacts the discharging material.

*Ratholing* occurs when a stable, empty channel (typically vertical) forms within material in a funnel flow bin. Ratholing can occur with *cohesive* materials handled in funnel flow bins; however, ratholing will not occur with *free-flowing* materials discharging in funnel flow.

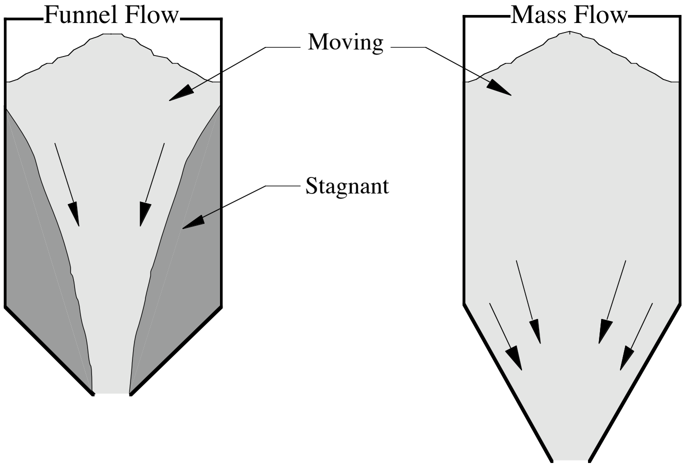

**Fig. 1: Two flow patterns that can occur in a bin; funnel flow and mass flow**

In *mass flow*, all of the material is in motion whenever any is withdrawn from the hopper. Material from the center as well as the periphery moves toward the outlet. Mass flow hoppers provide a first-in-first-out flow sequence, eliminate stagnant material, reduce sifting segregation, and provide a steady discharge with a consistent bulk density and a flow which is uniform and well-controlled. Requirements for achieving mass flow include sizing the outlet large enough to prevent arching and ensuring the hopper walls are sufficiently smooth and steep enough to promote flow at the walls.

A third type of flow pattern, called *expanded flow*, can develop when a mass flow hopper (or hoppers) is placed beneath a funnel flow hopper. As shown in Fig. 2, the mass flow hopper is designed to activate a flow channel in the conical funnel flow hopper, which is sized to prevent the formation of a stable rathole. The major advantage of an expanded flow discharge pattern is the savings in headroom. The wall angles of the funnel flow hopper are more shallow than the angles necessary for a mass flow hopper; therefore, the height of the funnel flow hopper section is decreased. The mass flow hopper beneath the funnel flow hopper still has the benefits of discharging material with a consistent bulk density while preventing flooding[2].

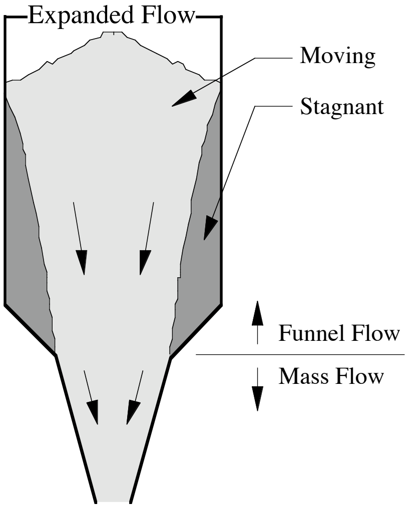

**Fig. 2: Example of expanded flow silo**

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[2] Flooding is still a possibility in mass flow if the discharge rates are too high to allow material sufficient time to deaerate.

## 4 SUMMARY OF FLOW PROPERTIES

Highlights of the test results are discussed below. The complete test results should be used for design purposes.

### Cohesive strength tests (arching and ratholing dimensions)

Jenike Direct Shear tests were performed on each GFC and GFC blend to determine cohesive strength as a function of consolidating pressure. The tests were performed according to ASTM (American Society for Testing and Materials) standard D 6128-97.

Table 3 below provides the critical rathole diameter for all of the samples and GFC blends as a function of storage at rest and effective consolidating head. The critical rathole diameter (DF) describes the size of the outlet required to prevent a stable rathole from forming in a funnel flow silo.

Bulk solids can be handled in a funnel flow or an expanded flow silo if:

- the opening is large enough to overcome ratholing,
- a first-in-last-out flow pattern is acceptable,
- the material does not degrade with time, and
- particle segregation is not a concern

**Table 3: Cohesive strength results – dimensions to prevent ratholing**

| | Critical rathole diameter (DF) at a 10 ft. effective head | |
|---|---|---|
| **GFCs** | **Continuous flow** | **Seven days storage at rest** |
| Borax (ten mole) | 2 ft. | 12 ft. |
| Boric acid | 1 ft. | 5 ft. |
| Iron oxide | 8 ft. | 8 ft. |
| Kyanite | 6 ft. | 6 ft. |
| Lithium carbonate | 5 ft. | 5 ft. |
| Olivine | 2 ft. | 2 ft. |
| Silica | 6 ft. | 6 ft. |
| Soda ash | 1 ft. | 3 ft. |
| Sugar | 2 ft. | 3 ft. |
| Titanium dioxide | 7 ft. | 7 ft. |
| Wollastonite | 7 ft. | 11 ft. |
| Zinc oxide | 18 ft. | 22 ft. |
| Zircon flour | 6 ft. | 6 ft. |
| **GFC blends** | **Continuous flow** | **One day storage at rest** |
| LAW A: AN105 | 8 ft. | 8 ft. |
| LAW B: AZ101 | 15 ft. | 19 ft. |
| LAW C: AN107 | 15 ft. | 19 ft. |
| | **Continuous flow** | **Three days storage at rest** |
| HLW D: AZ102 | 8 ft. | 13 ft. |
| HLW D: C106/AY104 | 12 ft. | 22 ft. |

As shown by the data in Table 3, the majority of the GFCs are highly cohesive and require prohibitively large outlet sizes in order to prevent ratholing from occurring. All of the GFC blends are cohesive and should not be handled in funnel flow bins because they are highly likely to form stable ratholes.

A technique for eliminating ratholing is by using a mass flow silo, which provides a first-in-first-out flow sequence, stagnant material, and minimizes segregation effects. One of the requirements for achieving mass flow is to size the outlet large enough to prevent arching.

(Additional requirements, such as ensuring that the hopper walls are steep enough and sufficiently low in friction, are discussed later.)

Arching (also known as bridging and doming) occurs when individual particles bond together and collectively form a flow obstruction over the outlet of a hopper. Table 4 provides the minimum outlet diameter (BC) required to prevent arching in a mass flow conical hopper as a function of storage at rest conditions.

**Table 4: Cohesive strength results – dimensions to prevent arching**

| | Minimum outlet diameter (BC) required to prevent arching | |
|---|---|---|
| **GFCs** | **Continuous flow** | **Seven days storage at rest** |
| Borax | 0.0 ft. | 3.0 ft. |
| Boric acid | 0.0 ft. | 0.0 ft. |
| Iron oxide* | 0.5 ft. | 0.5 ft. |
| Kyanite | 0.6 ft. | 1.1 ft. |
| Lithium carbonate | 0.5 ft. | 0.5 ft. |
| Olivine | 0.0 ft. | 0.0 ft. |
| Silica | 0.6 ft. | 1.1 ft. |
| Soda ash | 0.0 ft. | 0.3 ft. |
| Sugar | 0.1 ft. | 1.0 ft. |
| Titanium dioxide | 0.1 ft. | 0.2 ft. |
| Wollastonite* | 0.8 ft. | 3.9 ft. |
| Zinc oxide* | > 27 ft. | > 33 ft. |
| Zircon flour* | 0.6 ft. | 0.6 ft. |
| **GFC blends** | **Continuous flow** | **One day storage at rest** |
| LAW A: AN105* | 0.4 ft. | 1.0 ft. |
| LAW B: AZ101* | 0.2 ft. | 0.6 ft. |
| LAW C: AN107* | 0.9 ft. | 1.8 ft. |
| | **Continuous flow** | **Three days storage at rest** |
| HLW D: AZ102 | 0.2 ft. | 4.0 ft. |
| HLW D: C106/AY104* | 0.6 ft. | 6.0 ft. |

(* = pressure sensitive material)

Note that for materials that show a minimum dimension of “0.0 ft.” required to prevent cohesive arching in a mass flow silo, the outlet sizes should be based on other considerations such as particle interlocking, flow rate requirements, or feeder configurations.

Also, some of the GFCs (iron oxide, wollastonite, zinc oxide, zircon flour) and four of the five blends are highly pressure sensitive (as indicated by the asterisk).

Thus, if these materials are subjected to an overpressure, due, for example, to vibration or impact upon loading, the minimum outlet diameter required to prevent a stable arch from forming in a mass flow silo can become quite large. Hence, these materials should be handled gently to avoid any overpressure.

### Compressibility test (bulk density as a function of consolidating pressure)

The bulk density of most bulk solids varies with consolidating pressure. Consideration must be given to using the proper value for such calculations as silo loads, silo capacities, and feed density.

The ranges of densities measured in our lab are given in Table 5 below. The bulk density was measured at an unconsolidated (i.e., loose fill) state to a level with a consolidating pressure of approximately 2,360 psf. Densities for specific consolidating pressures are given later in this report. The tests were performed according to ASTM standard D 6683.

**Table 5: Glass forming chemicals (GFCs)**

| GFCs | Measured range of bulk density, pcf |
|---|---|
| Borax | 48 - 54 |
| Boric acid | 55 - 59 |
| Iron oxide | 89 - 141 |
| Kyanite | 56 - 101 |
| Lithium carbonate | 53 - 72 |
| Olivine | 89 - 98 |
| Silica | 50 - 89 |
| Soda ash | 64 - 68 |
| Sugar | 53 - 56 |
| Titanium dioxide | 91 - 135 |
| Wollastonite | 46 - 77 |
| Zinc oxide | 34 - 66 |
| Zircon flour | 96 - 155 |
| **GFC blends** | |
| LAW A: AN105 | 56 - 90 |
| LAW B: AZ101 | 50 - 74 |
| LAW C: AN107 | 47 - 72 |
| HLW D: AZ102 | 52 - 84 |
| HLW D: C106/AY104 | 47 -77 |

Note that density values can vary significantly if the particle size of the actual material to be handled is different than tested. Also note that lower densities are possible if fine materials are fluidized or aerated.

### Wall friction tests (mass flow hopper angles)

In addition to a properly sized outlet, the design of a mass flow silo must consider the hopper wall angles, materials of construction, and surface finish. The hopper walls must be steep enough and have sufficiently low friction to allow the material to flow along them.

Wall friction angles were determined on the wall materials listed in Table 6. As an example of the test results, if a conical hopper with a 1 ft. diameter opening were lined or fabricated using the listed wall materials, the corresponding wall angles would be the maximum recommended for mass flow to occur.[3] The wall friction tests were performed according to ASTM standard D 6128-97.

**Table 6: Wall friction results – mass flow conical hopper angles**

| | Maximum recommended mass flow wall angles[4] (from vertical) | |
|---|---|---|
| **GFCs and wall materials** | **Continuous flow** | **Seven days storage at rest** |
| *Borax* | | |
| 304 #2B finish stainless steel sheet[5] | None[6] | None |
| Mild carbon steel plate, mill finish[7] | 9° | 5° |
| TIVAR®-88[8] | 14° | 9° |
| *Boric acid* | | |
| 304 #2B finish stainless steel sheet | 33° | 19° |
| Mild carbon steel plate, mill finish | 28° | 24° |
| TIVAR®-88 | 29° | 29° |
| *Iron oxide* | | |
| 304 #2B finish stainless steel sheet | 8° | 7° |
| Mild carbon steel plate, mill finish | 10° | 7° |
| TIVAR®-88 | 11° | 8° |
| *Kyanite* | | |
| 304 #2B finish stainless steel sheet | 9° | 9° |
| Mild carbon steel plate, mill finish | None | None |
| TIVAR®-88 | 3° | 3° |
| *Lithium carbonate* | | |
| 304 #2B finish stainless steel sheet | 16° | 16° |
| Mild carbon steel plate, mill finish | 17° | 15° |
| TIVAR®-88 | 16° | 15° |

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[3] Hoppers with elongated outlets require significantly less steep angles than conical hoppers (typically 10° to 12° less steep). Critical angles for such hoppers are given later in this report.

[4] The maximum recommended wall angle may vary, depending on outlet size. The angles specified here apply only for the given outlet size, which may not be applicable due to arching dimensions of the material. The maximum recommended wall angles should be selected from the appropriate table in this report, based on the actual outlet size for a given design.

[5] This surface is a cold rolled mill finish that cannot be achieved by polishing. It is also important to note that sheet thickness material was tested. Plate thickness, less commonly available, should not be substituted unless tests are conducted to confirm that it is suitable.

[6] Flow along the walls is questionable at any angle.

[7] Mill finish carbon steel. Smooth, free of corrosion. Plate thickness.

[8] Ultra high molecular weight (UHMW) polyethylene manufactured by Poly-Hi Solidur of Fort Wayne, Indiana.

| Table 6 (continued): Wall friction results – mass flow conical hopper angles | | |
|---|---|---|
| | Maximum recommended mass flow wall angles (from vertical) | |
| **GFCs and wall materials** | **Continuous flow** | **Seven days storage at rest** |
| *Olivine* | | |
| 304 #2B finish stainless steel sheet | 17° | 17° |
| Mild carbon steel plate, mill finish | 6° | None |
| TIVAR®-88 | 22° | 20° |
| *Silica* | | |
| 304 #2B finish stainless steel sheet | 10° | 10° |
| Mild carbon steel plate, mill finish | None | None |
| TIVAR®-88 | 7° | 6° |
| *Soda ash* | | |
| 304 #2B finish stainless steel sheet | 14° | 14° |
| Mild carbon steel plate, mill finish | 10° | 10° |
| TIVAR®-88 | 13° | 13° |
| *Sugar* | | |
| 304 #2B finish stainless steel sheet | None | None |
| Mild carbon steel plate, mill finish | None | None |
| TIVAR®-88 | 10° | 10° |
| *Titanium dioxide* | | |
| 304 #2B finish stainless steel sheet | 5° | 5° |
| Mild carbon steel plate, mill finish | None | None |
| TIVAR®-88 | None | None |
| *Wollastonite* | | |
| 304 #2B finish stainless steel sheet | 6° | 6° |
| Mild carbon steel plate, mill finish | None | None |
| TIVAR®-88 | 5° | 5° |
| *Zinc oxide* | | |
| 304 #2B finish stainless steel sheet | 2° | 2° |
| Mild carbon steel plate, mill finish | None | None |
| TIVAR®-88 | 15° | 13° |
| *Zircon flour* | | |
| 304 #2B finish stainless steel sheet | 8° | 8° |
| Mild carbon steel plate, mill finish | 4° | 4° |
| TIVAR®-88 | 6° | 6° |
| **GFC blends** | **Continuous flow** | **One day storage at rest** |
| *LAW A: AN105* | | |
| 304 #2B finish stainless steel sheet | 10° | 10° |
| Mild carbon steel plate, mill finish | 3° | 3° |
| TIVAR®-88 | 5° | 5° |

| **Table 6 (continued): Wall friction results – mass flow conical hopper angles** | | |
|---|---|---|
| | Maximum recommended mass flow wall angles (from vertical) | |
| **GFCs and wall materials** | **Continuous flow** | **One day storage at rest** |
| *LAW B: AZ101* | | |
| 304 #2B finish stainless steel sheet | 7° | 5° |
| Mild carbon steel plate, mill finish | 5° | 5° |
| TIVAR®-88 | 9° | 9° |
| *LAW C: AN107* | | |
| 304 #2B finish stainless steel sheet | 6° | None |
| Mild carbon steel plate, mill finish | 3° | None |
| TIVAR®-88 | 17° | 12° |
| | **Continuous flow** | **Three days storage at rest** |
| *HLW D: AZ102* | | |
| 304 #2B finish stainless steel sheet | 15° | 14° |
| Mild carbon steel plate, mill finish | 13° | 7° |
| TIVAR®-88 | 16° | 10° |
| *HLW D: C106/AY104* | | |
| 304 #2B finish stainless steel sheet | 12° | None |
| Mild carbon steel plate, mill finish | 8° | None |
| TIVAR®-88 | 13° | 13° |

### Permeability test (limiting flow rates)

An outlet must be sized not only to prevent arching, but also to achieve the required discharge rate. Fine powders often exhibit a rate limitation not experienced with coarse materials that readily allow air to pass through them. A permeability test was run to determine critical steady-state discharge rates for the materials listed in Table 7.

**Table 7: Permeability results – critical flow rates**

| **GFCs** | **Critical flow rate, lb./hr.** |
|---|---|
| Iron oxide | 820 |
| Kyanite | 220 |
| Lithium carbonate | 1,260 |
| Silica | 240 |
| Titanium dioxide | 860 |
| Wollastonite | 180 |
| Zinc oxide | 13,600 |
| Zircon flour | 620 |
| **GFC blends** | |
| LAW A: AN105 | 400 |
| LAW B: AZ101 | 4,800 |
| LAW C: AN107 | 4,000 |
| HLW D: AZ102 | 800 |
| HLW D: C106/AY104 | 1,160 |

The results above assume discharge from a mass flow cone with a 1 ft. diameter outlet and a cylinder containing a 10 ft. effective head of fully deaerated material. The permeability test results illustrate that the majority of the GFCs and their blends are highly susceptible to discharge rate limitations, based upon the desired flow rates provided by WSRC.

### Chute tests (critical chute angles)

Tests were run to determine the minimum chute angles required for non-converging flat chutes in order to maintain flow after impact. The results of the chute tests (shown in Table 8 below) indicate that the GFC blends are not highly impact pressure sensitive; however, they are sensitive to the surface they flow against.

**Table 8: Chute test results – critical chute angles**

| | Minimum recommended chute angles[9] (from horizontal) | |
|---|---|---|
| **GFCs and wall materials** | **Impact pressure = 43 psf** | **Impact pressure = 160 psf** |
| *LAW A: AN105* | | |
| 304 #2B finish stainless steel sheet | 37° | 37° |
| Mild carbon steel plate, mill finish | 38° | 45° |
| TIVAR®-88 | 39° | 39° |
| *LAW B: AZ101* | | |
| 304 #2B finish stainless steel sheet | 39° | 40° |
| Mild carbon steel plate, mill finish | 40° | 60° |
| TIVAR®-88 | 44° | 52° |
| *LAW C: AN107* | | |
| 304 #2B finish stainless steel sheet | 46° | 57° |
| Mild carbon steel plate, mill finish | 44° | 70° |
| TIVAR®-88 | 40° | 44° |
| *HLW D: AZ102* | | |
| 304 #2B finish stainless steel sheet | 50° | 50° |
| Mild carbon steel plate, mill finish | 53° | 67° |
| TIVAR®-88 | 39° | 39° |
| *HLW D: C106/AY104* | | |
| 304 #2B finish stainless steel sheet | 63° | 77° |
| Mild carbon steel plate, mill finish | 62° | 79° |
| TIVAR®-88 | 47° | 40° |

For these materials, a low drop height is recommended to minimize the impact of material falling onto the chute.

### Angle of repose

An angle of repose test was performed for each GFC and GFC blend to determine the static angle (from horizontal) of a slowly formed pile. This information is utilized in estimating storage capacities for silos.

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[9] For design purposes, a 5° safety margin has been added to the maximum values determined from the laboratory tests. Also note that increases in impact pressure typically result in steeper required chute angles.

The angle of repose was measured via a technique similar to that described in ASTM D 6393-99. After formation of the pile, the angle of repose was measured in four locations around the pile and the range and average results are noted in Table 9:

**Table 9: Angle of repose results** (from horizontal)

| GFCs | Angle of repose (range) | Angle of repose (average) |
|---|---|---|
| Borax | 29° - 33° | 31° |
| Boric acid | 27° - 36° | 32° |
| Iron oxide | 36° - 41° | 38° |
| Kyanite | 40° - 43° | 41° |
| Lithium carbonate | 34° - 42° | 38° |
| Olivine | 28° - 30° | 29° |
| Silica | 36° - 45° | 40° |
| Soda ash | 30° - 35° | 33° |
| Sugar | 29° - 31° | 30° |
| Titanium dioxide | 40° - 43° | 41° |
| Wollastonite | 35° - 38° | 36° |
| Zinc oxide | 31° - 34° | 33° |
| Zircon flour | 40° - 47° | 43° |
| **GFC blends** | | |
| LAW A: AN105 | 41° - 45° | 43° |
| LAW B: AZ101 | 41° - 45° | 43° |
| LAW C: AN107 | 33° - 34° | 33° |
| HLW D: AZ102 | 28° - 43° | 37° |
| HLW D: C106/AY104 | 26° - 51° | 37° |

## Particle size distribution

The GFC samples' *as received* particle size distributions were determined via a Malvern Mastersizer 2000 with the Scirocco dry dispersion unit. Tests were conducted using 0.0 bar and 3.0 bar additional conveying pressure (higher conveying pressure may result in breaking up agglomerates, removing fine particles loosely bound to coarse particles, or attriting weak particles).

The average of three results is shown in the accompanying plots. The calculated d(0.1), d(0.5), and d(0.9)[10] are shown in the Table 10 for each sample, at 0.0 and 3.0 bar pressure.

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[10] The term *d(0.1)* refers to the particle size in microns below which 10% of the sample lies, *d(0.5)* refers to the size in microns at which 50% of the sample is smaller (this value is also referred to as the *mass median diameter*), and *d(0.9)* gives the particle size below which 90% of the sample lies.

**Table 10: Particle size distribution results**

| GFCs | Pressure (bar) | d(0.1), μm | d(0.5), μm | d(0.9), μm |
|---|---|---|---|---|
| Borax | 0.0 | 231 | 389 | 624 |
| | 3.0 | 60 | 276 | 548 |
| Boric acid | 0.0 | 131 | 336 | 750 |
| | 3.0 | 49 | 183 | 484 |
| Iron oxide | 0.0 | 5 | 24 | 69 |
| | 3.0 | 2 | 21 | 57 |
| Kyanite | 0.0 | 2 | 14 | 53 |
| | 3.0 | 1 | 11 | 54 |
| Lithium carbonate | 0.0 | 16 | 197 | 469 |
| | 3.0 | 6 | 59 | 306 |
| Olivine | 0.0 | 62 | 104 | 170 |
| | 3.0 | 47 | 93 | 162 |
| Silica | 0.0 | 3 | 21 | 71 |
| | 3.0 | 2 | 19 | 66 |
| Soda ash | 0.0 | 165 | 287 | 455 |
| | 3.0 | 20 | 148 | 378 |
| Sugar | 0.0 | 246 | 400 | 637 |
| | 3.0 | 90 | 336 | 604 |
| Titanium dioxide | 0.0 | 5 | 20 | 49 |
| | 3.0 | 2 | 20 | 52 |
| Wollastonite | 0.0 | 3 | 15 | 45 |
| | 3.0 | 2 | 11 | 41 |
| Zinc oxide | 0.0 | 34 | 110 | 685 |
| | 3.0 | 1 | 3 | 110 |
| Zircon flour | 0.0 | 3 | 18 | 50 |
| | 3.0 | 2 | 19 | 51 |

## 5 GENERAL COMMENTS

All dimensions tabulated in this report represent limiting conditions for flow; therefore, larger outlets, steeper hoppers and chutes, and flow rates below critical are acceptable.

In case you are unfamiliar with the use of this type of data, an Appendix follows the main body of the report. Most of the symbols used in the report are shown in the figures on pages A17 to A19. A Glossary of Terms and Symbols is provided on pages A12 to A14.

## SUMMARY OF TESTS PERFORMED

This report presents various flow property test results as indicated for the following material(s) :

| BULK MATERIAL | MATERIAL ID # | DESCRIPTION | PARTICLE SIZE | MOISTURE CONTENT |
|---|---|---|---|---|
| 1 | 22615 | Borax (ten mole) | As Rec'd | 8.0% |
| 2 | 22609 | Boric acid | As Rec'd | 0.1% |
| 3 | 22617 | Iron oxide | As Rec'd | 0.3% |
| 4 | 22606 | Kyanite | As Rec'd | 0.1% |
| 5 | 22613 | Lithium carbonate | As Rec'd | 0.1% |
| 6 | 22605 | Olivine | As Rec'd | 0.2% |
| 7 | 22604 | Silica | As Rec'd | 0.1% |
| 8 | 22616 | Soda Ash | As Rec'd | 0.2% |
| 9 | 22639 | Sugar | As Rec'd | 0.1% |
| 10 | 22647 | Titanium dioxide | As Rec'd | 0.2% |
| 11 | 22614 | Wollastonite | As Rec'd | 0.2% |
| 12 | 22612 | Zinc oxide | As Rec'd | 0.2% |
| 13 | 22645 | Zircon flour | As Rec'd | 0.1% |
| 14 | 22644 | LAW A: AN105 | As Rec'd | As Rec'd |
| 15 | 22648 | LAW B: AZ101 | As Rec'd | As Rec'd |
| 16 | 22650 | LAW C: AN107 | As Rec'd | As Rec'd |
| 17 | 22632 | HLW D: AZ102 | As Rec'd | As Rec'd |
| 18 | 22636 | HLW D: C106/AY104 | As Rec'd | As Rec'd |

| BULK MATERIAL | TIME hr | TEMPERATURE deg F | SIEVE ANALYSIS | BIN DIM | BULK DENSITY | HOPPER ANGLES | CHUTE ANGLES | FLOW RATE | OTHER |
|---|---|---|---|---|---|---|---|---|---|
| 1 | .0 | 72 |  | X | X | X |  |  |  |
|  | 168.0 | 72 |  | X |  | X |  |  |  |
| 2 | .0 | 72 |  | X | X | X |  |  |  |
|  | 168.0 | 72 |  | X |  | X |  |  |  |
| 3 | .0 | 72 |  | X | X | X |  | X | X |
|  | 168.0 | 72 |  | X |  | X |  |  |  |
| 4 | .0 | 72 |  | X | X | X |  | X | X |
|  | 168.0 | 72 |  | X |  | X |  |  |  |
| 5 | .0 | 72 |  | X | X | X |  | X | X |
|  | 168.0 | 72 |  | X |  | X |  |  |  |
| 6 | .0 | 72 |  | X | X | X |  |  |  |
|  | 168.0 | 72 |  | X |  | X |  |  |  |
| 7 | .0 | 72 |  | X | X | X |  | X | X |
|  | 168.0 | 72 |  | X |  | X |  |  |  |

| BULK MATERIAL | TIME hr | TEMPERATURE deg F | SIEVE ANALYSIS | BIN DIM | BULK DENSITY | HOPPER ANGLES | CHUTE ANGLES | FLOW RATE | OTHER |
|---|---|---|---|---|---|---|---|---|---|
| 8 | .0 | 72 | | X | X | X | | | |
| | 168.0 | 72 | | X | | X | | | |
| 9 | .0 | 72 | | X | X | X | | | |
| | 168.0 | 72 | | X | | X | | | |
| 10 | .0 | 72 | | X | X | X | | X | X |
| | 168.0 | 72 | | X | | X | | | |
| 11 | .0 | 72 | | X | X | X | | X | X |
| | 168.0 | 72 | | X | | X | | | |
| 12 | .0 | 72 | | X | X | X | | X | X |
| | 168.0 | 72 | | X | | X | | | |
| 13 | .0 | 72 | | X | X | X | | X | X |
| | 168.0 | 72 | | X | | X | | | |
| 14 | .0 | 72 | | X | X | X | X | X | X |
| | 24.0 | 72 | | X | | X | | | |
| 15 | .0 | 72 | | X | X | X | X | X | X |
| | 24.0 | 72 | | X | | X | | | |
| 16 | .0 | 72 | | X | X | X | X | X | X |
| | 24.0 | 72 | | X | | X | | | |
| 17 | .0 | 72 | | X | X | X | X | X | X |
| | 72.0 | 72 | | X | | X | | | |
| 18 | .0 | 72 | | X | X | X | X | X | X |
| | 72.0 | 72 | | X | | X | | | |

BULK MATERIAL 1:  Borax (ten mole)

PARTICLE SIZE As Rec’d

MOISTURE CONTENT 8.0%

## SECTION I.  BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest     .0 hrs
Temperature   72 deg F

### PART A.  BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 0.* | 0.* |
| 1.25 | 0.* | 0.* |
| 1.50 | 0.* | 0.* |
| 2.00 | 0.* | 0.* |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | 1.0 | 2.5 | 5 | 10 | 20 | 21 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 0.* | | 0.0 | .4 | 1.0 | 2.3 | 4.9 | 5 |
| 1.25 | 0.* | | .1 | .6 | 1.4 | 3.0 | 6 | 6 |
| 1.50 | 0.* | | .1 | .7 | 1.7 | 3.6 | 7 | 8 |
| 2.00 | 0.* | | .3 | 1.0 | 2.3 | 4.8 | 10 | 10 |

0.* Indicates that no minimum dimensions are given by the tests.  Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 1: Borax (ten mole)

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 8.0%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 3.0 | 1.4 |
| 1.25 | 4.1 | 2.0 |
| 1.50 | 5.4 | 2.6 |
| 2.00 | 7.9 | 3.8 |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= 1.0 | 2.5 | 5 | 10 | 20 | 21 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 1.8 | 3.3 | 5 | 8 | 12 | 16 | 17 |
| 1.25 | 2.5 | 3.6 | 6 | 9 | 13 | 18 | 18 |
| 1.50 | 3.3 | 4.0 | 7 | 10 | 14 | 19 | 19 |
| 2.00 | 4.5 | 4.6 | 8 | 12 | 16 | 20 | 21 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 1:  Borax (ten mole)

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 8.0%

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 26. | 52. | 130. | 261. | 525. | 1059. | 2137. | 4317. |
| GAMMA (pcf) | 51.1 | 51.7 | 52.0 | 52.3 | 52.5 | 53.0 | 53.4 | 54.0 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\left[\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}},\mathrm{GAMMAM}\right]$$

Minimum bulk density GAMMAM =  48.2 pcf

| I | SIGMA1(I)<br>psf | GAMMA(I)<br>pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 51.7 | .02049 |
| 2 | 102.7 | 51.9 | .00609 |
| 3 | 308.0 | 52.3 | .00682 |
| 4 | 601.4 | 52.6 | .00694 |
| 5 | 1188.1 | 53.0 | .01244 |
| 6 | 1774.8 | 53.3 | .01135 |
| 7 | 2361.5 | 53.5 | .01447 |

BULK MATERIAL 1: Borax (ten mole)

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 8.0%

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .28 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 16.00 | 16.61 |
| Width of Oval (feet) | .14 | .26 | .52 | 1.03 | 2.06 | 4.09 | 8.12 | 8.43 |
| SIGMA (psf) | 6.0 | 10.7 | 22. | 44. | 90. | 186. | 394. | 410. |
| SIGMA1 (psf) | 9.8 | 17.6 | 35. | 71. | 141. | 281. | 552. | 572. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 33. | 33. | 32. | 32. | 31. | 30. | 28. | 28. |
| Hopper Angles<br>THETA-P (deg) | 16.* | 16.* | 17. | 17. | 18. | 20. | 23. | 24. |
| THETA-C (deg) | 4.* | 4.* | 4.* | 5. | 6. | 8. | 12. | 12. |

* Flow along walls is questionable.

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                     BULK MATERIAL 1:  Borax (ten mole)

                     PARTICLE SIZE As Rec'd

                     MOISTURE CONTENT 8.0%



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .25    .25    .50   1.00   2.00   4.00   8.00  15.55
Width of Oval (feet)      .13    .13    .25    .51   1.01   2.02   4.04   7.83

SIGMA (psf)              6.0    6.1   12.    25.    50.   101.   205.   410.
SIGMA1 (psf)             8.2    8.2   17.    33.    67.   134.   268.   517.

Wall Friction Angle
PHI-PRIME (deg)         27.    27.    27.    27.    26.    26.    25.    23.

Hopper Angles
THETA-P (deg)           25.    25.    25.    25.    26.    26.    28.    30.
THETA-C (deg)           14.    14.    14.    14.    14.    15.    16.    18.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .83   1.00   2.00   4.00   8.00  11.04
Width of Oval (feet)      .42    .51   1.02   2.03   4.05   5.58

SIGMA (psf)             19.0   23.1   47.    96.   198.   280.
SIGMA1 (psf)            28.3   34.3   69.   137.   272.   372.

Wall Friction Angle
PHI-PRIME (deg)         30.    30.    29.    29.    27.    26.

Hopper Angles
THETA-P (deg)           20.    21.    21.    22.    25.    26.
THETA-C (deg)            8.     9.     9.    11.    13.    15.
```

```
                     BULK MATERIAL 1:  Borax (ten mole)

                     PARTICLE SIZE As Rec'd

                     MOISTURE CONTENT 8.0%



WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .26    .50   1.00   2.00   4.00   8.00  16.00  16.77
Width of Oval (feet)      .13    .25    .51   1.02   2.04   4.07   8.12   8.52

SIGMA (psf)              5.9   11.4   23.    47.    95.   192.   391.   410.
SIGMA1 (psf)             8.7   16.9   34.    69.   138.   276.   551.   578.

Wall Friction Angle
PHI-PRIME (deg)         30.    30.    29.    29.    29.    29.    28.    28.

Hopper Angles
THETA-P (deg)           21.    21.    21.    21.    22.    22.    23.    23.
THETA-C (deg)            9.     9.     9.     9.    10.    10.    11.    11.


WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .87   1.00   2.00   4.00   8.00  11.67
Width of Oval (feet)      .45    .51   1.02   2.04   4.07   5.94

SIGMA (psf)             19.0   22.1   46.    94.   190.   280.
SIGMA1 (psf)            30.6   35.0   69.   139.   277.   404.

Wall Friction Angle
PHI-PRIME (deg)         32.    32.    30.    30.    29.    29.

Hopper Angles
THETA-P (deg)           17.    18.    20.    21.    22.    22.
THETA-C (deg)            5.     5.     8.     9.    10.    10.
```

## BULK MATERIAL 2: Boric acid

PARTICLE SIZE As Rec’d

MOISTURE CONTENT 0.1%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 0.* | 0.* |
| 1.25 | 0.* | 0.* |
| 1.50 | 0.* | 0.* |
| 2.00 | 0.* | 0.* |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 feet |
|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | 0.* | .0 | .1 | .5 | .9 | 1.2 |
| 1.25 | 0.* | .0 | .2 | .7 | 1.0 | 1.3 |
| 1.50 | 0.* | .0 | .3 | .8 | 1.1 | 1.3 |
| 2.00 | 0.* | .1 | .4 | .9 | 1.2 | 1.4 |

0.* Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 2: Boric acid

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 0.* | 0.* |
| 1.25 | 0.* | 0.* |
| 1.50 | 0.* | 0.* |
| 2.00 | 0.* | 0.* |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 feet |
|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | 0.* | | .2 | .7 | 1.8 | 3.2 | 4.6 |
| 1.25 | 0.* | | .3 | .9 | 2.2 | 3.6 | 5 |
| 1.50 | 0.* | | .4 | 1.1 | 2.6 | 4.0 | 5 |
| 2.00 | 0.* | | .7 | 1.5 | 3.2 | 4.6 | 6 |

0.* Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 2:  Boric acid

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 28. | 57. | 143. | 287. | 580. | 1169. | 2362. | 4788. |
| GAMMA (pcf) | 56.5 | 56.9 | 57.2 | 57.4 | 58.0 | 58.5 | 59.0 | 59.8 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\ [\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}}, \mathrm{GAMMAM}]$$

Minimum bulk density GAMMAM =  54.6 pcf

| I | SIGMA1(I)<br>psf | GAMMA(I)<br>pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 56.8 | .01214 |
| 2 | 102.7 | 57.1 | .00476 |
| 3 | 308.0 | 57.4 | .00547 |
| 4 | 601.4 | 58.1 | .01663 |
| 5 | 1188.1 | 58.5 | .01023 |
| 6 | 1774.8 | 58.7 | .01104 |
| 7 | 2361.5 | 59.0 | .01912 |

```
                   BULK MATERIAL 2:  Boric acid

                   PARTICLE SIZE As Rec'd

                   MOISTURE CONTENT 0.1%


SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW



WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .24    .25    .50   1.00   2.00   4.00   8.00  12.75
Width of Oval (feet)       .13    .13    .25    .50    .98   1.95   3.88   6.17

SIGMA (psf)               6.1    6.5   14.    30.    61.   126.   255.   410.
SIGMA1 (psf)              6.6    7.0   15.    31.    65.   133.   269.   433.

Wall Friction Angle
PHI-PRIME (deg)          15.    15.    13.    12.    12.    12.    12.    11.

Hopper Angles
THETA-P (deg)            39.    39.    43.    46.    47.    47.    47.    47.
THETA-C (deg)            27.    28.    31.    33.    34.    35.    35.    36.



WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .70   1.00   2.00   4.00   8.00   8.81
Width of Oval (feet)       .36    .51   1.00   1.98   3.91   4.30

SIGMA (psf)              18.9   28.0   59.   123.   254.   280.
SIGMA1 (psf)             24.1   34.9   71.   141.   277.   303.

Wall Friction Angle
PHI-PRIME (deg)          24.    23.    21.    18.    15.    14.

Hopper Angles
THETA-P (deg)            28.    30.    33.    38.    43.    44.
THETA-C (deg)            17.    19.    22.    26.    31.    32.
```

```
                        BULK MATERIAL 2:  Boric acid

                        PARTICLE SIZE As Rec’d

                        MOISTURE CONTENT 0.1%



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .24    .25    .50   1.00   2.00   4.00   8.00  12.76
Width of Oval (feet)      .13    .13    .26    .50    .99   1.95   3.87   6.16

SIGMA (psf)              6.1    6.4   14.    30.    61.   126.   255.   410.
SIGMA1 (psf)             6.9    7.2   16.    32.    66.   133.   268.   429.

Wall Friction Angle
PHI-PRIME (deg)         19.    19.    17.    15.    13.    12.    11.    11.

Hopper Angles
THETA-P (deg)           34.    34.    38.    41.    45.    47.    48.    49.
THETA-C (deg)           23.    23.    26.    29.    32.    35.    36.    37.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .67   1.00   2.00   4.00   8.00   8.75
Width of Oval (feet)      .34    .50    .99   1.96   3.89   4.25

SIGMA (psf)             19.2   29.6   61.   126.   255.   280.
SIGMA1 (psf)            21.3   32.5   66.   135.   272.   297.

Wall Friction Angle
PHI-PRIME (deg)         17.    15.    14.    13.    12.    12.

Hopper Angles
THETA-P (deg)           39.    41.    43.    45.    46.    46.
THETA-C (deg)           27.    29.    31.    33.    34.    34.
```

BULK MATERIAL 2: Boric acid

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .24 | .25 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 12.75 |
| Width of Oval (feet) | .13 | .13 | .26 | .50 | .99 | 1.96 | 3.90 | 6.21 |
| SIGMA (psf) | 6.1 | 6.4 | 14. | 30. | 61. | 126. | 255. | 410. |
| SIGMA1 (psf) | 6.9 | 7.2 | 16. | 33. | 67. | 137. | 276. | 441. |
| Wall Friction Angle | | | | | | | | |
| PHI-PRIME (deg) | 18. | 18. | 17. | 16. | 15. | 14. | 14. | 13. |
| Hopper Angles | | | | | | | | |
| THETA-P (deg) | 35. | 35. | 37. | 40. | 42. | 43. | 44. | 45. |
| THETA-C (deg) | 23. | 24. | 26. | 28. | 30. | 31. | 32. | 33. |

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | |
|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .69 | 1.00 | 2.00 | 4.00 | 8.00 | 8.82 |
| Width of Oval (feet) | .35 | .51 | 1.00 | 1.97 | 3.92 | 4.32 |
| SIGMA (psf) | 19.2 | 29.1 | 61. | 125. | 253. | 280. |
| SIGMA1 (psf) | 22.9 | 33.9 | 69. | 139. | 278. | 306. |
| Wall Friction Angle | | | | | | |
| PHI-PRIME (deg) | 21. | 20. | 18. | 16. | 15. | 15. |
| Hopper Angles | | | | | | |
| THETA-P (deg) | 32. | 35. | 38. | 40. | 42. | 43. |
| THETA-C (deg) | 21. | 24. | 27. | 29. | 31. | 31. |

## BULK MATERIAL 3: Iron oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.3%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .5 | .2 |
| 1.25 | .5 | .2 |
| 1.50 | .6 | .3 |
| 2.00 | 1.1 | .5 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 7 feet |
|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | .3 | | .9 | 1.3 | 2.5 | 4.1 | 5 |
| 1.25 | .3 | | 1.0 | 1.5 | 2.9 | 4.7 | 6 |
| 1.50 | .4 | | 1.1 | 1.7 | 3.3 | 5 | 7 |
| 2.00 | 1.3 | | 1.3 | 2.0 | 4.0 | 6 | 9 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 3:  Iron oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.3%

Storage Time at Rest  168.0 hrs
Temperature   72 deg F

## PART A.  BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .5 | .2 |
| 1.25 | .5 | .2 |
| 1.50 | .6 | .3 |
| 2.00 | 1.1 | .5 |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 7 feet |
|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | .3 | | .9 | 1.3 | 2.5 | 4.1 | 5 |
| 1.25 | .3 | | 1.0 | 1.5 | 2.9 | 4.7 | 6 |
| 1.50 | .4 | | 1.1 | 1.7 | 3.3 | 5 | 7 |
| 2.00 | 1.3 | | 1.3 | 2.0 | 4.0 | 6 | 9 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 3:  Iron oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.3%

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 57. | 119. | 315. | 660. | 1379. | 2885. | 6034. | 12621. |
| GAMMA (pcf) | 113.7 | 118.9 | 126.1 | 131.9 | 137.9 | 144.3 | 150.9 | 157.8 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

GAMMA is the greater of $\text{GAMMA0 (SIGMA1/SIGMA0)}^{\text{BETA}}$ and GAMMAM.

For GAMMA between  110.6 and  140.9 pcf

GAMMA0 =  103.96 pcf

SIGMA0 =   13.00 psf

BETA =  .06065

Minimum bulk density  GAMMAM =  88.9 pcf

```
                        BULK MATERIAL 3:  Iron oxide

                        PARTICLE SIZE As Rec'd

                        MOISTURE CONTENT 0.3%


SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW



WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .30    .50   1.00   2.00   4.00   6.83
Width of Oval (feet)      .17    .28    .53   1.04   2.05   3.48

SIGMA (psf)             11.1   19.9   45.   105.   230.   415.
SIGMA1 (psf)            16.3   28.9   66.   149.   322.   574.

Wall Friction Angle
PHI-PRIME (deg)         34.    33.    32.    30.    28.    28.

Hopper Angles
THETA-P (deg)           18.    19.    18.    21.    23.    24.
THETA-C (deg)            6.     7.     8.    10.    11.    12.


WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .62   1.00   2.00   4.00   4.86
Width of Oval (feet)      .34    .53   1.04   2.05   2.49

SIGMA (psf)             24.1   44.5  105.   230.   285.
SIGMA1 (psf)            37.7   66.2  151.   328.   406.

Wall Friction Angle
PHI-PRIME (deg)         36.    32.    30.    29.    29.

Hopper Angles
THETA-P (deg)           15.    17.    20.    22.    22.
THETA-C (deg)            4.     7.     9.    10.    10.
```

```
                        BULK MATERIAL 3:  Iron oxide

                        PARTICLE SIZE As Rec'd

                        MOISTURE CONTENT 0.3%



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .28    .50   1.00   2.00   4.00   6.90
Width of Oval (feet)      .15    .27    .53   1.03   2.05   3.51

SIGMA (psf)             11.1   21.2   47.   106.   229.   415.
SIGMA1 (psf)            14.6   28.1   65.   148.   323.   583.

Wall Friction Angle
PHI-PRIME (deg)         29.    29.    29.    29.    29.    28.

Hopper Angles
THETA-P (deg)           21.    21.    21.    22.    22.    23.
THETA-C (deg)           11.    11.    11.    11.    11.    12.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .57   1.00   2.00   4.00   5.07
Width of Oval (feet)      .31    .53   1.04   2.06   2.60

SIGMA (psf)             24.1   46.4  103.   221.   285.
SIGMA1 (psf)            32.9   65.5  150.   329.   426.

Wall Friction Angle
PHI-PRIME (deg)         30.    30.    30.    30.    30.

Hopper Angles
THETA-P (deg)           20.    20.    20.    20.    20.
THETA-C (deg)            8.     8.     8.     8.     8.
```

```
                    BULK MATERIAL 3:  Iron oxide

                    PARTICLE SIZE As Rec'd

                    MOISTURE CONTENT 0.3%




WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .29    .50   1.00   2.00   4.00   6.83
Width of Oval (feet)      .16    .28    .53   1.03   2.05   3.47

SIGMA (psf)             11.1   20.7   47.   106.   231.   415.
SIGMA1 (psf)            15.2   28.4   65.   148.   321.   573.

Wall Friction Angle
PHI-PRIME (deg)         31.    31.    30.    29.    28.    27.

Hopper Angles
THETA-P (deg)           20.    20.    20.    22.    23.    24.
THETA-C (deg)            9.    10.    10.    11.    12.    12.



WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .58   1.00   2.00   4.00   5.10
Width of Oval (feet)      .32    .53   1.04   2.06   2.62

SIGMA (psf)             24.1   45.8  102.   219.   285.
SIGMA1 (psf)            33.9   65.9  151.   330.   430.

Wall Friction Angle
PHI-PRIME (deg)         32.    31.    31.    31.    31.

Hopper Angles
THETA-P (deg)           19.    19.    19.    19.    19.
THETA-C (deg)            7.     7.     7.     7.     7.
```

BULK MATERIAL 3: Iron oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.3%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .04 | .03 | .03 | .02 | .02 |
| .75 feet | .27 | .22 | .18 | .15 | .14 |
| 1.00 feet | .63 | .50 | .41 | .36 | .32 |
| 2.00 feet | 3.4 | 2.7 | 2.3 | 2.0 | 1.7 |
| 4.00 feet | 15. | 12. | 10. | 9.1 | 8.1 |
| 8.00 feet | 66. | 52. | 45. | 39. | 34. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .00 | .00 | .00 | .00 | .00 |
| .50 feet | .34 | .27 | .23 | .20 | .18 |
| .75 feet | .68 | .56 | .47 | .40 | .36 |
| 1.00 feet | 1.0 | .83 | .70 | .61 | .54 |
| 2.00 feet | 2.4 | 1.9 | 1.6 | 1.4 | 1.2 |
| 4.00 feet | 5.1 | 4.1 | 3.5 | 3.0 | 2.7 |
| 8.00 feet | 10. | 8.6 | 7.2 | 6.3 | 5.6 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 3: Iron oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.3%

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\,(GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\,(GAMMA / GAMMA0)^{-a}$$

At room temperature, for GAMMA between 101.8 and 149.6 pcf:

K0 = .001532 ft/s

GAMMA0 = 100.4 pcf

a = 5.35

## BULK MATERIAL 4: Kyanite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .6 | .3 |
| 1.25 | .6 | .3 |
| 1.50 | .7 | .3 |
| 2.00 | .9 | .4 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 11 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .3 | .8 | 1.0 | 1.8 | 3.2 | 6 | 7 |
| 1.25 | .3 | .8 | 1.1 | 2.1 | 3.9 | 7 | 8 |
| 1.50 | .4 | .9 | 1.3 | 2.5 | 4.5 | 9 | 9 |
| 2.00 | .6 | 1.0 | 1.5 | 3.1 | 6 | 11 | 12 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 4: Kyanite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 1.1 | .6 |
| 1.25 | 1.2 | .6 |
| 1.50 | 1.3 | .7 |
| 2.00 | 1.6 | .8 |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 11 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .6 | | 1.3 | 1.5 | 2.2 | 3.5 | 6 | 7 |
| 1.25 | .7 | | 1.4 | 1.6 | 2.5 | 4.1 | 7 | 8 |
| 1.50 | .7 | | 1.4 | 1.7 | 2.8 | 4.7 | 9 | 9 |
| 2.00 | 1.0 | | 1.5 | 1.9 | 3.4 | 6 | 11 | 12 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 4: Kyanite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 38. | 81. | 220. | 464. | 967. | 2012. | 4121. | 8443. |
| GAMMA (pcf) | 75.1 | 80.7 | 87.9 | 92.7 | 96.7 | 100.6 | 103.0 | 105.5 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\ [\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}}\ ,\mathrm{GAMMAM}]$$

Minimum bulk density GAMMAM = 56.1 pcf

| I | SIGMA1(I)<br>psf | GAMMA(I)<br>pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 76.2 | .09511 |
| 2 | 102.7 | 82.5 | .09340 |
| 3 | 308.0 | 90.4 | .08310 |
| 4 | 601.4 | 94.2 | .06229 |
| 5 | 1188.1 | 97.8 | .05530 |
| 6 | 1774.8 | 100.2 | .05863 |
| 7 | 2361.5 | 101.1 | .03350 |

BULK MATERIAL 4:  Kyanite

PARTICLE SIZE As Rec’d

MOISTURE CONTENT 0.1%

## SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW

```
WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .35    .50   1.00   2.00   4.00   8.00   9.39
Width of Oval (feet)      .20    .28    .52   1.02   2.04   4.06   4.77

SIGMA (psf)              8.8   13.3   33.    74.   162.   347.   413.
SIGMA1 (psf)            12.0   18.2   48.   106.   228.   480.   570.

Wall Friction Angle
PHI-PRIME (deg)         31.    31.    30.    29.    28.    27.    27.

Hopper Angles
THETA-P (deg)           20.    20.    20.    22.    23.    24.    24.
THETA-C (deg)            9.     9.     9.    10.    12.    12.    13.


WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F


No time effect! Use results from test having storage time at rest of 0.0 hrs.
```

```
                        BULK MATERIAL 4:  Kyanite

                        PARTICLE SIZE As Rec'd

                        MOISTURE CONTENT 0.1%



WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .39    .50   1.00   2.00   4.00   8.00   9.76
Width of Oval (feet)       .22    .28    .53   1.04   2.06   4.09   4.98

SIGMA (psf)               8.8   12.1   30.    68.   150.   331.   413.
SIGMA1 (psf)             14.1   19.9   51.   113.   238.   492.   605.

Wall Friction Angle
PHI-PRIME (deg)          38.    38.    36.    34.    32.    30.    29.

Hopper Angles
THETA-P (deg)            13.*   13.*   13.*   15.*   17.    20.    21.
THETA-C (deg)             2.*    2.*    2.*    3.*    5.     9.     9.

*  Flow along walls is questionable.


WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .78   1.00   2.00   4.00   7.04
Width of Oval (feet)       .41    .53   1.04   2.08   3.61

SIGMA (psf)              21.8   30.1    68.   146.   283.
SIGMA1 (psf)             37.7   51.1  113.   242.   433.

Wall Friction Angle
PHI-PRIME (deg)          38.    37.    36.    34.    31.

Hopper Angles
THETA-P (deg)            12.*   13.*   15.*   16.*   19.
THETA-C (deg)             2.*    2.*    3.*    3.*    7.

*  Flow along walls is questionable.
```

## BULK MATERIAL 4:  Kyanite

PARTICLE SIZE As Rec’d

MOISTURE CONTENT 0.1%

```
WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .38    .50   1.00   2.00   4.00   8.00   9.66
Width of Oval (feet)      .21    .28    .53   1.04   2.05   4.09   4.93

SIGMA (psf)              8.8   12.6   31.    69.   155.   336.   413.
SIGMA1 (psf)            13.4   19.5   50.   109.   230.   480.   586.

Wall Friction Angle
PHI-PRIME (deg)         36.    36.    34.    32.    30.    29.    29.

Hopper Angles
THETA-P (deg)           14.    14.    14.    17.    20.    22.    22.
THETA-C (deg)            3.     3.     3.     5.     8.    10.    11.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .76   1.00   2.00   4.00   6.92
Width of Oval (feet)      .41    .53   1.04   2.06   3.55

SIGMA (psf)             21.8   30.5   69.   151.   283.
SIGMA1 (psf)            36.5   50.4  110.   232.   415.

Wall Friction Angle
PHI-PRIME (deg)         35.    34.    33.    31.    30.

Hopper Angles
THETA-P (deg)           13.    14.    16.    18.    21.
THETA-C (deg)            2.     3.     5.     7.     9.
```

## BULK MATERIAL 4: Kyanite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN Air

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .75 feet | .05 | .04 | .04 | .03 | .03 |
| 1.00 feet | .15 | .12 | .11 | .10 | .10 |
| 2.00 feet | .94 | .77 | .68 | .63 | .59 |
| 4.00 feet | 4.4 | 3.6 | 3.2 | 2.9 | 2.8 |
| 8.00 feet | 19. | 15. | 14. | 12. | 12. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .07 | .06 | .05 | .05 | .05 |
| .75 feet | .17 | .15 | .13 | .12 | .11 |
| 1.00 feet | .27 | .23 | .20 | .18 | .18 |
| 2.00 feet | .68 | .58 | .50 | .47 | .43 |
| 4.00 feet | 1.4 | 1.2 | 1.1 | 1.0 | .95 |
| 8.00 feet | 3.1 | 2.5 | 2.3 | 2.1 | 2.0 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 4: Kyanite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION V. Air PERMEABILITY TEST RESULTS

Temperature 72 deg F

K, the Air permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA)\ /\ (dp/dx)$$

where:

u = superficial Air velocity through the bed of solids

dp/dx = Air pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

For GAMMA(I-1) < GAMMA < GAMMA(I) :

$$K = K(I)\ (GAMMA\ /\ GAMMA(I))^{-A(I)}$$

At room temperature, for GAMMA between 63.4 and 94.9 pcf:

| I | GAMMA(I)<br>pcf | K(I)<br>ft/s | A(I)<br>dimless |
|---|---|---|---|
| 1 | 63.37 | .001736 | 20.94493 |
| 2 | 64.76 | .001102 | 20.94493 |
| 3 | 67.53 | .000771 | 8.50648 |
| 4 | 70.54 | .000634 | 4.51559 |
| 5 | 73.75 | .000579 | 2.04483 |
| 6 | 77.41 | .000441 | 5.60026 |
| 7 | 81.70 | .000386 | 2.47992 |
| 8 | 85.57 | .000303 | 5.20904 |
| 9 | 90.29 | .000248 | 3.73601 |
| 10 | 94.91 | .000220 | 2.35893 |

BULK MATERIAL 5: Lithium carbonate

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .5 | .2 |
| 1.25 | .5 | .2 |
| 1.50 | .5 | .3 |
| 2.00 | .6 | .3 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 18 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .2 | .8 | 1.0 | 1.6 | 2.6 | 4.8 | 8 |
| 1.25 | .3 | .8 | 1.1 | 1.8 | 3.1 | 6 | 10 |
| 1.50 | .3 | .9 | 1.2 | 2.1 | 3.7 | 7 | 12 |
| 2.00 | .3 | 1.0 | 1.3 | 2.6 | 4.7 | 9 | 16 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 5: Lithium carbonate

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

**Optimum Mass Flow Dimensions**

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .5 | .2 |
| 1.25 | .5 | .2 |
| 1.50 | .5 | .3 |
| 2.00 | .6 | .3 |

**Funnel Flow Dimensions**

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 18 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .2 | | .8 | 1.0 | 1.6 | 2.6 | 4.8 | 8 |
| 1.25 | .3 | | .8 | 1.1 | 1.8 | 3.1 | 6 | 10 |
| 1.50 | .3 | | .9 | 1.2 | 2.1 | 3.7 | 7 | 12 |
| 2.00 | .3 | | 1.0 | 1.3 | 2.6 | 4.7 | 9 | 16 |

**TERMS**

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 5: Lithium carbonate

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 30. | 63. | 165. | 340. | 696. | 1423. | 2902. | 5914. |
| GAMMA (pcf) | 60.8 | 63.1 | 66.0 | 67.9 | 69.6 | 71.2 | 72.5 | 73.9 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\text{GAMMA} = \text{MAX}\ [\text{GAMMA(I)}\ (\text{SIGMA1}/\text{SIGMA1(I)})^{\text{BETA(I)}}\ ,\text{GAMMAM}]$$

Minimum bulk density GAMMAM = 53.1 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 61.8 | .04644 |
| 2 | 102.7 | 64.8 | .05552 |
| 3 | 308.0 | 67.7 | .04013 |
| 4 | 601.4 | 69.3 | .03342 |
| 5 | 1188.1 | 70.8 | .03280 |
| 6 | 1774.8 | 71.6 | .02763 |
| 7 | 2361.5 | 72.2 | .02654 |

BULK MATERIAL 5: Lithium carbonate

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .26 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 12.53 |
| Width of Oval (feet) | .13 | .26 | .51 | 1.02 | 2.04 | 4.09 | 6.40 |
| SIGMA (psf) | 7.0 | 14.1 | 29. | 61. | 126. | 259. | 411. |
| SIGMA1 (psf) | 9.0 | 18.2 | 38. | 78. | 162. | 332. | 529. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 25. | 25. | 25. | 25. | 25. | 25. | 25. |
| Hopper Angles<br>THETA-P (deg) | 27. | 27. | 27. | 27. | 27. | 27. | 27. |
| THETA-C (deg) | 16. | 16. | 16. | 16. | 16. | 16. | 16. |

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                          BULK MATERIAL 5:  Lithium carbonate

                          PARTICLE SIZE As Rec'd

                          MOISTURE CONTENT 0.1%



WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .25    .50   1.00   2.00   4.00   8.00  12.41
Width of Oval (feet)      .13    .26    .51   1.02   2.04   4.08   6.33

SIGMA (psf)              7.0   14.3   30.    61.   127.   261.   411.
SIGMA1 (psf)             8.9   18.1   37.    78.   161.   331.   521.

Wall Friction Angle
PHI-PRIME (deg)         24.    24.    24.    24.    24.    24.    24.

Hopper Angles
THETA-P (deg)           28.    28.    28.    28.    28.    28.    28.
THETA-C (deg)           17.    17.    17.    17.    17.    17.    17.


WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .71   1.00   2.00   4.00   8.00   8.57
Width of Oval (feet)      .36    .51   1.02   2.04   4.08   4.37

SIGMA (psf)             20.0   29.0   61.   126.   261.   281.
SIGMA1 (psf)            26.3   37.7   78.   161.   331.   355.

Wall Friction Angle
PHI-PRIME (deg)         26.    26.    25.    25.    24.    24.

Hopper Angles
THETA-P (deg)           26.    26.    27.    28.    28.    29.
THETA-C (deg)           15.    15.    16.    17.    17.    18.
```

```
                     BULK MATERIAL 5:  Lithium carbonate

                     PARTICLE SIZE As Rec'd

                     MOISTURE CONTENT 0.1%



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .26    .50   1.00   2.00   4.00   8.00  12.08
Width of Oval (feet)      .13    .26    .51   1.02   2.04   4.08   6.16

SIGMA (psf)              7.0   14.0   29.    61.   126.   264.   411.
SIGMA1 (psf)             9.2   18.3   38.    78.   161.   329.   499.

Wall Friction Angle
PHI-PRIME (deg)         26.    26.    26.    25.    25.    23.    22.

Hopper Angles
THETA-P (deg)           26.    26.    27.    27.    28.    30.    31.
THETA-C (deg)           15.    15.    16.    16.    17.    19.    20.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .71   1.00   2.00   4.00   8.00   8.80
Width of Oval (feet)      .36    .51   1.02   2.05   4.09   4.50

SIGMA (psf)             20.0   28.7   60.   124.   254.   281.
SIGMA1 (psf)            26.4   37.9   79.   163.   335.   370.

Wall Friction Angle
PHI-PRIME (deg)         26.    26.    26.    26.    26.    26.

Hopper Angles
THETA-P (deg)           26.    26.    26.    26.    26.    26.
THETA-C (deg)           15.    15.    15.    15.    15.    15.
```

BULK MATERIAL 5: Lithium carbonate

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .05 | .04 | .04 | .03 | .03 |
| .75 feet | .36 | .31 | .27 | .23 | .22 |
| 1.00 feet | .86 | .72 | .63 | .58 | .52 |
| 2.00 feet | 4.8 | 4.0 | 3.5 | 3.1 | 2.9 |
| 4.00 feet | 21. | 18. | 16. | 14. | 13. |
| 8.00 feet | 93. | 77. | 68. | 61. | 55. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .01 | .01 | .01 | .01 | .01 |
| .50 feet | .47 | .40 | .34 | .31 | .29 |
| .75 feet | .95 | .79 | .70 | .63 | .58 |
| 1.00 feet | 1.4 | 1.2 | 1.0 | .95 | .88 |
| 2.00 feet | 3.4 | 2.8 | 2.5 | 2.2 | 2.0 |
| 4.00 feet | 7.3 | 6.1 | 5.3 | 4.8 | 4.4 |
| 8.00 feet | 15. | 12. | 11. | 9.9 | 9.2 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 5: Lithium carbonate

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (\mathrm{GAMMA}) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (\mathrm{GAMMA} / \mathrm{GAMMA0})^{-a}$$

At room temperature, for GAMMA between 53.5 and 69.6 pcf:

K0 = .002209 ft/s

GAMMA0 = 58.4 pcf

a = 4.60

## BULK MATERIAL 6: Olivine

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 0.* | 0.* |
| 1.25 | 0.* | 0.* |
| 1.50 | 0.* | 0.* |
| 2.00 | 0.* | 0.* |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 12 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 0.* | | .0 | 0.0 | .4 | .8 | 1.7 | 2.0 |
| 1.25 | 0.* | | .0 | .1 | .5 | 1.1 | 2.0 | 2.4 |
| 1.50 | 0.* | | .0 | .1 | .6 | 1.3 | 2.3 | 2.7 |
| 2.00 | 0.* | | 0.0 | .2 | .8 | 1.7 | 2.8 | 3.3 |

0.* Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 6: Olivine

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 0.* | 0.* |
| 1.25 | 0.* | 0.* |
| 1.50 | 0.* | 0.* |
| 2.00 | 0.* | 0.* |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 12 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 0.* | | .0 | .1 | .4 | .9 | 1.7 | 2.0 |
| 1.25 | 0.* | | 0.0 | .1 | .5 | 1.1 | 2.0 | 2.4 |
| 1.50 | 0.* | | 0.0 | .2 | .6 | 1.3 | 2.4 | 2.7 |
| 2.00 | 0.* | | .1 | .3 | .9 | 1.7 | 2.8 | 3.3 |

0.* Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 6:  Olivine

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 47. | 95. | 238. | 480. | 969. | 1955. | 3938. | 7932. |
| GAMMA (pcf) | 94.5 | 94.6 | 95.1 | 96.0 | 96.9 | 97.7 | 98.4 | 99.2 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\left[\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1}/\mathrm{SIGMA1(I)})^{\mathrm{BETA(I)}},\mathrm{GAMMAM}\right]$$

Minimum bulk density GAMMAM =  89.3 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 94.5 | .02038 |
| 2 | 102.7 | 94.6 | .00167 |
| 3 | 308.0 | 95.3 | .00645 |
| 4 | 601.4 | 96.4 | .01711 |
| 5 | 1188.1 | 97.1 | .01060 |
| 6 | 1774.8 | 97.6 | .01449 |
| 7 | 2361.5 | 97.9 | .01022 |

BULK MATERIAL 6: Olivine

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .21 | .25 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 8.05 |
| Width of Oval (feet) | .11 | .13 | .25 | .50 | 1.00 | 2.00 | 3.97 | 4.00 |
| SIGMA (psf) | 8.7 | 10.5 | 22. | 47. | 97. | 199. | 410. | 413. |
| SIGMA1 (psf) | 13.1 | 15.5 | 31. | 61. | 121. | 243. | 495. | 498. |
| Wall Friction Angle | | | | | | | | |
| PHI-PRIME (deg) | 30. | 29. | 27. | 25. | 23. | 22. | 21. | 21. |
| Hopper Angles | | | | | | | | |
| THETA-P (deg) | 20. | 21. | 25. | 28. | 31. | 33. | 33. | 33. |
| THETA-C (deg) | 8. | 9. | 13. | 17. | 19. | 21. | 22. | 22. |

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

BULK MATERIAL 6: Olivine

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .21 | .25 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 8.69 |
| Width of Oval (feet) | .11 | .13 | .26 | .51 | 1.02 | 2.02 | 4.01 | 4.36 |
| SIGMA (psf) | 8.4 | 9.9 | 20. | 42. | 86. | 179. | 378. | 413. |
| SIGMA1 (psf) | 13.7 | 16.0 | 32. | 65. | 129. | 257. | 520. | 566. |
| Wall Friction Angle | | | | | | | | |
| PHI-PRIME (deg) | 32. | 32. | 32. | 31. | 30. | 28. | 27. | 27. |
| Hopper Angles | | | | | | | | |
| THETA-P (deg) | 17. | 17. | 18. | 19. | 21. | 23. | 25. | 25. |
| THETA-C (deg) | 4. | 5. | 5. | 6. | 8. | 11. | 13. | 13. |

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | |
|---|---|---|---|---|---|
| Dia of Cone (feet) | .54 | 1.00 | 2.00 | 4.00 | 6.16 |
| Width of Oval (feet) | .28 | .52 | 1.03 | 2.05 | 3.11 |
| SIGMA (psf) | 21.8 | 40.3 | 81. | 173. | 283. |
| SIGMA1 (psf) | 35.5 | 65.8 | 132. | 263. | 399. |
| Wall Friction Angle | | | | | |
| PHI-PRIME (deg) | 34. | 34. | 32. | 30. | 28. |
| Hopper Angles | | | | | |
| THETA-P (deg) | 17.* | 17.* | 17.* | 20. | 24. |
| THETA-C (deg) | 4.* | 4.* | 4.* | 7. | 11. |

* Flow along walls is questionable.

```
                                    BULK MATERIAL 6:  Olivine

                                    PARTICLE SIZE As Rec'd

                                    MOISTURE CONTENT 0.2%



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .20    .25    .50   1.00   2.00   4.00   7.88
Width of Oval (feet)      .10    .13    .25    .50   1.00   1.99   3.89

SIGMA (psf)              8.7   11.3   24.    49.   100.   204.   413.
SIGMA1 (psf)            11.7   14.9   30.    59.   118.   237.   475.

Wall Friction Angle
PHI-PRIME (deg)         26.    25.    23.    21.    20.    19.    18.

Hopper Angles
THETA-P (deg)           26.    27.    30.    33.    35.    37.    37.
THETA-C (deg)           14.    15.    19.    22.    24.    25.    26.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .47    .50   1.00   2.00   4.00   5.55
Width of Oval (feet)      .24    .25    .50   1.00   1.99   2.76

SIGMA (psf)             21.8   23.2   49.    99.   202.   283.
SIGMA1 (psf)            28.5   30.2   60.   119.   240.   335.

Wall Friction Angle
PHI-PRIME (deg)         25.    25.    22.    21.    20.    20.

Hopper Angles
THETA-P (deg)           27.    28.    32.    33.    34.    35.
THETA-C (deg)           16.    16.    20.    22.    23.    23.
```

BULK MATERIAL 7: Silica

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .6 | .3 |
| 1.25 | .6 | .3 |
| 1.50 | .8 | .4 |
| 2.00 | 1.3 | .6 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 12 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .3 | | .7 | 1.0 | 1.8 | 3.2 | 6 | 7 |
| 1.25 | .4 | | .8 | 1.1 | 2.1 | 3.9 | 7 | 9 |
| 1.50 | .5 | | .8 | 1.2 | 2.5 | 4.6 | 9 | 10 |
| 2.00 | 1.0 | | .9 | 1.5 | 3.1 | 6 | 11 | 14 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 7: Silica

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 1.1 | .5 |
| 1.25 | 1.3 | .6 |
| 1.50 | 1.5 | .7 |
| 2.00 | 2.4 | 1.2 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 12 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .6 | | 1.1 | 1.3 | 2.1 | 3.4 | 6 | 7 |
| 1.25 | .7 | | 1.1 | 1.4 | 2.4 | 4.1 | 7 | 9 |
| 1.50 | .9 | | 1.2 | 1.6 | 2.7 | 4.7 | 9 | 10 |
| 2.00 | 1.5 | | 1.3 | 1.8 | 3.3 | 6 | 11 | 14 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 7:  Silica

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 34. | 72. | 195. | 410. | 852. | 1762. | 3609. | 7392. |
| GAMMA (pcf) | 67.3 | 72.0 | 77.9 | 82.0 | 85.2 | 88.1 | 90.2 | 92.4 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$GAMMA = MAX\left[GAMMA(I)\,(SIGMA1/SIGMA1(I))^{BETA(I)}, GAMMAM\right]$$

Minimum bulk density GAMMAM =  49.6 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 69.1 | .09927 |
| 2 | 102.7 | 74.1 | .08292 |
| 3 | 308.0 | 80.7 | .07665 |
| 4 | 601.4 | 83.8 | .05784 |
| 5 | 1188.1 | 86.6 | .04711 |
| 6 | 1774.8 | 88.1 | .04389 |
| 7 | 2361.5 | 88.9 | .03335 |

BULK MATERIAL 7:  Silica

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .37 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 9.64 |
| Width of Oval (feet) | .21 | .28 | .52 | 1.02 | 2.00 | 3.98 | 4.79 |
| SIGMA (psf) | 8.1 | 11.4 | 29. | 68. | 155. | 336. | 412. |
| SIGMA1 (psf) | 11.6 | 16.1 | 42. | 96. | 212. | 453. | 554. |
| Wall Friction Angle PHI-PRIME (deg) | 34. | 33. | 30. | 28. | 26. | 26. | 25. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 19. | 20. | 20. | 23. | 26. | 27. | 27. |
| THETA-C (deg) | 7. | 8. | 10. | 12. | 13. | 15. | 15. |

WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                                BULK MATERIAL 7:  Silica

                                PARTICLE SIZE As Rec'd

                                MOISTURE CONTENT 0.1%



WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .45    .50   1.00   2.00   4.00   8.00  10.11
Width of Oval (feet)       .26    .29    .53   1.03   2.03   4.03   5.08

SIGMA (psf)               8.1    9.4   26.     63.   147.   319.   412.
SIGMA1 (psf)             16.1   18.4   45.    101.   221.   468.   601.

Wall Friction Angle
PHI-PRIME (deg)          47.    46.    37.    32.    30.    28.    28.

Hopper Angles
THETA-P (deg)             7.*    8.*   12.*   17.    21.    22.    23.
THETA-C (deg)             0.*    0.*    2.*    5.     7.     9.     9.

*  Flow along walls is questionable.


WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .86   1.00   2.00   4.00   7.26
Width of Oval (feet)       .46    .53   1.03   2.05   3.70

SIGMA (psf)              21.1   26.3   63.    146.   282.
SIGMA1 (psf)             36.9   45.2  101.    224.   431.

Wall Friction Angle
PHI-PRIME (deg)          40.    38.    32.    30.    30.

Hopper Angles
THETA-P (deg)            11.*   12.*   17.    20.    21.
THETA-C (deg)             1.*    2.*    4.     6.     6.

*  Flow along walls is questionable.
```

## BULK MATERIAL 7:  Silica

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

### WALL MATERIAL:  Tivar-88

```
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                     HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .37    .50   1.00   2.00   4.00   8.00  10.07
Width of Oval (feet)       .21    .28    .52   1.02   2.01   4.00   5.03

SIGMA (psf)               8.1   11.7   29.    67.   149.   321.   412.
SIGMA1 (psf)             12.6   17.6   43.    97.   213.   454.   582.

Wall Friction Angle
PHI-PRIME (deg)          37.    35.    31.    29.    28.    27.    27.

Hopper Angles
THETA-P (deg)            16.    17.    18.    21.    23.    24.    24.
THETA-C (deg)             3.     5.     7.    10.    11.    11.    12.
```

### WALL MATERIAL:  Tivar-88

```
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                     HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)         .80   1.00   2.00   4.00   7.20
Width of Oval (feet)       .43    .52   1.02   2.02   3.62

SIGMA (psf)              21.1   28.6   66.   147.   282.
SIGMA1 (psf)             32.8   43.7   98.   215.   409.

Wall Friction Angle
PHI-PRIME (deg)          34.    32.    30.    29.    28.

Hopper Angles
THETA-P (deg)            15.    17.    21.    22.    23.
THETA-C (deg)             5.     6.     9.     9.    10.
```

BULK MATERIAL 7: Silica

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .75 feet | .06 | .05 | .04 | .04 | .03 |
| 1.00 feet | .18 | .14 | .12 | .10 | .09 |
| 2.00 feet | 1.1 | .88 | .74 | .63 | .56 |
| 4.00 feet | 5.2 | 4.1 | 3.4 | 2.9 | 2.6 |
| 8.00 feet | 23. | 17. | 14. | 12. | 11. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .09 | .07 | .06 | .05 | .04 |
| .75 feet | .22 | .17 | .14 | .12 | .10 |
| 1.00 feet | .32 | .25 | .22 | .18 | .17 |
| 2.00 feet | .81 | .65 | .54 | .47 | .41 |
| 4.00 feet | 1.7 | 1.4 | 1.1 | 1.0 | .90 |
| 8.00 feet | 3.7 | 2.9 | 2.4 | 2.1 | 1.8 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 7: Silica

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (\mathrm{GAMMA})\ /\ (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (\mathrm{GAMMA}\ /\ \mathrm{GAMMA0})^{-a}$$

At room temperature, for GAMMA between 60.6 and 91.5 pcf:

K0 = .000630 ft/s

GAMMA0 = 64.9 pcf

a = 4.52

## BULK MATERIAL 8: Soda Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 0.* | 0.* |
| 1.25 | 0.* | 0.* |
| 1.50 | 0.* | 0.* |
| 2.00 | 0.* | 0.* |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 17 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 0.* | .0 | 0.0 | .1 | .3 | .7 | 1.3 |
| 1.25 | 0.* | .0 | 0.0 | .2 | .4 | .9 | 1.7 |
| 1.50 | 0.* | .0 | 0.0 | .2 | .5 | 1.1 | 2.0 |
| 2.00 | 0.* | 0.0 | .1 | .3 | .7 | 1.5 | 2.7 |

0.* Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 8: Soda Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .3 | .2 |
| 1.25 | .3 | .2 |
| 1.50 | .3 | .2 |
| 2.00 | .4 | .2 |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 17 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .2 | | .5 | .6 | 1.0 | 1.5 | 2.6 | 4.1 |
| 1.25 | .2 | | .6 | .7 | 1.1 | 1.8 | 3.2 | 5 |
| 1.50 | .2 | | .6 | .8 | 1.2 | 2.1 | 3.7 | 6 |
| 2.00 | .2 | | .6 | .9 | 1.5 | 2.6 | 4.8 | 8 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 8:  Soda Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 33. | 66. | 166. | 333. | 669. | 1344. | 2704. | 5446. |
| GAMMA (pcf) | 66.1 | 66.4 | 66.5 | 66.7 | 66.9 | 67.2 | 67.6 | 68.1 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\,[\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}}\ ,\mathrm{GAMMAM}]$$

Minimum bulk density GAMMAM =  64.2 pcf

| I | SIGMA1(I) | GAMMA(I) | BETA(I) |
|---|---|---|---|
| | psf | pcf | |
| 1 | 44.0 | 66.3 | .01053 |
| 2 | 102.7 | 66.4 | .00244 |
| 3 | 308.0 | 66.7 | .00327 |
| 4 | 601.4 | 66.9 | .00415 |
| 5 | 1188.1 | 67.1 | .00613 |
| 6 | 1774.8 | 67.3 | .00731 |
| 7 | 2361.5 | 67.5 | .00981 |

## BULK MATERIAL 8: Soda Ash

PARTICLE SIZE As Rec’d

MOISTURE CONTENT 0.2%

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

### WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet

STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .21 | .25 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 12.53 |
| Width of Oval (feet) | .11 | .13 | .25 | .50 | 1.01 | 2.01 | 4.02 | 6.30 |
| SIGMA (psf) | 6.7 | 8.1 | 16. | 32. | 65. | 130. | 262. | 411. |
| SIGMA1 (psf) | 9.1 | 10.8 | 22. | 44. | 88. | 176. | 353. | 553. |
| Wall Friction Angle | | | | | | | | |
| PHI-PRIME (deg) | 26. | 26. | 26. | 26. | 26. | 26. | 26. | 26. |
| Hopper Angles | | | | | | | | |
| THETA-P (deg) | 26. | 26. | 26. | 26. | 26. | 26. | 26. | 26. |
| THETA-C (deg) | 14. | 14. | 14. | 14. | 14. | 14. | 14. | 14. |

### WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet

STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                         BULK MATERIAL 8:  Soda Ash

                         PARTICLE SIZE As Rec'd

                         MOISTURE CONTENT 0.2%



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .21    .25    .50   1.00   2.00   4.00   8.00  12.44
Width of Oval (feet)      .11    .13    .25    .50   1.01   2.01   4.02   6.25

SIGMA (psf)              6.7    7.9   16.    32.    65.   130.   263.   411.
SIGMA1 (psf)             9.3   10.9   22.    44.    88.   176.   352.   547.

Wall Friction Angle
PHI-PRIME (deg)         27.    27.    27.    27.    26.    26.    26.    26.

Hopper Angles
THETA-P (deg)           24.    25.    25.    25.    25.    26.    26.    27.
THETA-C (deg)           13.    13.    13.    13.    14.    14.    15.    15.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F


No time effect! Use results from test having storage time at rest of 0.0 hrs.
```

BULK MATERIAL 8: Soda Ash

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .22 | .25 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 13.18 |
| Width of Oval (feet) | .11 | .13 | .25 | .51 | 1.01 | 2.03 | 4.06 | 6.68 |
| SIGMA (psf) | 6.7 | 7.7 | 15. | 31. | 62. | 124. | 249. | 411. |
| SIGMA1 (psf) | 9.7 | 11.1 | 22. | 45. | 90. | 180. | 362. | 598. |
| Wall Friction Angle | | | | | | | | |
| PHI-PRIME (deg) | 29. | 29. | 29. | 29. | 29. | 29. | 29. | 29. |
| Hopper Angles | | | | | | | | |
| THETA-P (deg) | 22. | 22. | 22. | 22. | 22. | 22. | 22. | 22. |
| THETA-C (deg) | 10. | 10. | 10. | 10. | 10. | 10. | 10. | 10. |

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

BULK MATERIAL 9:  Sugar

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION I.  BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest     .0 hrs
Temperature   72 deg F

### PART A.  BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .1 | 0.0 |
| 1.25 | .1 | 0.0 |
| 1.50 | .1 | 0.0 |
| 2.00 | .1 | 0.0 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 18 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 0.0 | | .2 | .3 | .6 | 1.1 | 2.0 | 3.5 |
| 1.25 | 0.0 | | .2 | .4 | .7 | 1.3 | 2.5 | 4.4 |
| 1.50 | .1 | | .3 | .4 | .8 | 1.5 | 2.9 | 5 |
| 2.00 | .1 | | .3 | .5 | 1.1 | 2.0 | 3.9 | 7 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 9: Sugar

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 1.0 | .5 |
| 1.25 | 1.0 | .5 |
| 1.50 | 1.0 | .5 |
| 2.00 | 1.1 | .5 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 18 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .5 | | 1.4 | 1.4 | 1.6 | 1.9 | 2.5 | 3.5 |
| 1.25 | .5 | | 1.4 | 1.4 | 1.7 | 2.0 | 2.8 | 4.4 |
| 1.50 | .5 | | 1.4 | 1.5 | 1.7 | 2.2 | 3.1 | 5 |
| 2.00 | .5 | | 1.4 | 1.5 | 1.9 | 2.5 | 3.9 | 7 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 9: Sugar

PARTICLE SIZE As Rec’d

MOISTURE CONTENT 0.1%

### SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 27. | 54. | 137. | 274. | 552. | 1110. | 2231. | 4485. |
| GAMMA (pcf) | 53.9 | 54.2 | 54.6 | 54.9 | 55.2 | 55.5 | 55.8 | 56.1 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

GAMMA is the greater of $\text{GAMMA0}\ (\text{SIGMA1}/\text{SIGMA0})^{\text{BETA}}$ and GAMMAM.

For GAMMA between 54.2 and 55.9 pcf

GAMMA0 = 53.65 pcf

SIGMA0 = 13.00 psf

BETA = .00753

Minimum bulk density GAMMAM = 52.6 pcf

BULK MATERIAL 9:  Sugar

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .19 | .25 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 14.79 |
| Width of Oval (feet) | .11 | .14 | .27 | .52 | 1.03 | 2.06 | 4.06 | 7.38 |
| SIGMA (psf) | 3.3 | 4.5 | 10. | 22. | 47. | 99. | 208. | 407. |
| SIGMA1 (psf) | 6.0 | 7.9 | 17. | 37. | 76. | 159. | 316. | 572. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 41. | 39. | 36. | 34. | 33. | 31. | 30. | 27. |
| Hopper Angles<br>THETA-P (deg) | 9.* | 9.* | 12.* | 15.* | 17.* | 18.* | 21. | 25. |
| THETA-C (deg) | 0.* | 0.* | 2.* | 3.* | 4.* | 5.* | 7. | 12. |

*  Flow along walls is questionable.

WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                           BULK MATERIAL 9:  Sugar

                           PARTICLE SIZE As Rec'd

                           MOISTURE CONTENT 0.1%



WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .19    .25    .50   1.00   2.00   4.00   8.00  14.79
Width of Oval (feet)      .11    .14    .27    .52   1.03   2.06   4.06   7.38

SIGMA (psf)              3.3    4.5   10.    22.    47.    99.   208.   407.
SIGMA1 (psf)             6.0    7.9   17.    37.    76.   159.   316.   572.

Wall Friction Angle
PHI-PRIME (deg)         41.    39.    36.    34.    33.    31.    30.    27.

Hopper Angles
THETA-P (deg)            9.*    9.*   12.*   15.*   17.*   18.*   21.    25.
THETA-C (deg)            0.*    0.*    2.*    3.*    4.*    5.*    7.    12.

*  Flow along walls is questionable.
```

```
WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .76   1.00   2.00   4.00   8.00  10.43
Width of Oval (feet)      .40    .52   1.03   2.06   4.11   5.25

SIGMA (psf)             16.3   22.0   47.    99.   208.   277.
SIGMA1 (psf)            27.5   36.6   76.   159.   321.   409.

Wall Friction Angle
PHI-PRIME (deg)         40.    38.    35.    33.    30.    29.

Hopper Angles
THETA-P (deg)           14.*   15.*   17.*   18.*   20.    22.
THETA-C (deg)            2.*    3.*    4.*    5.*    6.     9.

*  Flow along walls is questionable.
```

BULK MATERIAL 9: Sugar

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

WALL MATERIAL: Tivar-88
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .19 | .25 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 14.13 |
| Width of Oval (feet) | .11 | .14 | .26 | .51 | 1.01 | 2.00 | 3.98 | 7.01 |
| SIGMA (psf) | 3.3 | 4.5 | 11. | 24. | 52. | 110. | 227. | 407. |
| SIGMA1 (psf) | 6.2 | 7.9 | 16. | 35. | 72. | 148. | 300. | 533. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 42. | 39. | 33. | 29. | 27. | 26. | 25. | 24. |
| Hopper Angles<br>THETA-P (deg) | 8.* | 10.* | 17. | 21. | 24. | 26. | 28. | 28. |
| THETA-C (deg) | 0.* | 0.* | 6. | 10. | 12. | 14. | 16. | 16. |

* Flow along walls is questionable.

WALL MATERIAL: Tivar-88
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

BULK MATERIAL 10: Titanium dioxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .1 | .1 |
| 1.25 | .1 | .1 |
| 1.50 | .1 | .1 |
| 2.00 | .2 | .1 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 9 feet |
|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | .1 | | .4 | .7 | 1.7 | 3.2 | 6 |
| 1.25 | .1 | | .5 | .9 | 2.0 | 4.0 | 7 |
| 1.50 | .1 | | .5 | 1.0 | 2.4 | 4.7 | 8 |
| 2.00 | .1 | | .7 | 1.3 | 3.1 | 6 | 11 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 10: Titanium dioxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .2 | .1 |
| 1.25 | .2 | .1 |
| 1.50 | .2 | .1 |
| 2.00 | .3 | .1 |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 9 feet |
|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | .1 | | .5 | .8 | 1.7 | 3.3 | 6 |
| 1.25 | .1 | | .6 | .9 | 2.1 | 4.0 | 7 |
| 1.50 | .1 | | .6 | 1.1 | 2.4 | 4.7 | 8 |
| 2.00 | .2 | | .8 | 1.4 | 3.1 | 6 | 11 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 10:  Titanium dioxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
| SIGMA1 (psf) | 56. | 117. | 310. | 643. | 1325. | 2718. | 5584. | 11471. |
| GAMMA (pcf) | 111.9 | 117.2 | 123.9 | 128.6 | 132.5 | 135.9 | 139.6 | 143.4 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\left[\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}},\mathrm{GAMMAM}\right]$$

Minimum bulk density GAMMAM =  91.2 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 110.3 | .06943 |
| 2 | 102.7 | 116.3 | .06272 |
| 3 | 308.0 | 123.9 | .05783 |
| 4 | 601.4 | 128.3 | .05152 |
| 5 | 1188.1 | 132.0 | .04219 |
| 6 | 1774.8 | 133.8 | .03341 |
| 7 | 2361.5 | 135.2 | .03718 |

## BULK MATERIAL 10:  Titanium dioxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW

### WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet

```
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .26    .50   1.00   2.00   4.00   6.88
Width of Oval (feet)      .14    .26    .52   1.02   2.03   3.48

SIGMA (psf)             10.0   21.6   48.   106.   229.   415.
SIGMA1 (psf)            16.5   35.5   75.   156.   323.   571.

Wall Friction Angle
PHI-PRIME (deg)         36.    34.    32.    30.    28.    27.

Hopper Angles
THETA-P (deg)           12.    14.    17.    21.    23.    25.
THETA-C (deg)            3.     3.     5.     9.    11.    13.
```

### WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet

```
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F
```

No time effect! Use results from test having storage time at rest of 0.0 hrs.

BULK MATERIAL 10:  Titanium dioxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

```
WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .29    .50   1.00   2.00   4.00   7.13
Width of Oval (feet)      .15    .27    .52   1.03   2.04   3.62

SIGMA (psf)             10.6   21.0   46.   101.   220.   415.
SIGMA1 (psf)            18.9   36.0   77.   160.   329.   605.

Wall Friction Angle
PHI-PRIME (deg)         42.    39.    35.    32.    30.    29.

Hopper Angles
THETA-P (deg)           10.*   12.*   15.*   17.    20.    22.
THETA-C (deg)            0.*    2.*    3.*    5.     8.     9.

*  Flow along walls is questionable.
```

```
WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .56   1.00   2.00   4.00   5.12
Width of Oval (feet)      .30    .52   1.04   2.05   2.62

SIGMA (psf)             23.7   45.9  100.   216.   284.
SIGMA1 (psf)            40.3   76.8  161.   331.   427.

Wall Friction Angle
PHI-PRIME (deg)         39.    35.    33.    31.    30.

Hopper Angles
THETA-P (deg)           12.*   14.*   16.    19.    20.
THETA-C (deg)            2.*    2.*    4.     7.     8.

*  Flow along walls is questionable.
```

```
                     BULK MATERIAL 10:  Titanium dioxide

                     PARTICLE SIZE As Rec'd

                     MOISTURE CONTENT 0.2%



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .29    .50   1.00   2.00   4.00   7.05
Width of Oval (feet)      .15    .27    .52   1.03   2.04   3.58

SIGMA (psf)             10.6   21.0   46.   102.   222.   415.
SIGMA1 (psf)            18.9   36.0   77.   159.   328.   594.

Wall Friction Angle
PHI-PRIME (deg)         38.    37.    34.    32.    30.    28.

Hopper Angles
THETA-P (deg)           10.*   12.*   15.*   18.    21.    22.
THETA-C (deg)            0.*    2.*    3.*    6.     9.    11.

*  Flow along walls is questionable.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .55   1.00   2.00   4.00   5.22
Width of Oval (feet)      .29    .52   1.03   2.06   2.68

SIGMA (psf)             23.7   46.2  100.   213.   284.
SIGMA1 (psf)            40.4   77.2  161.   335.   445.

Wall Friction Angle
PHI-PRIME (deg)         37.    34.    32.    31.    31.

Hopper Angles
THETA-P (deg)           12.*   15.*   17.    18.    18.
THETA-C (deg)            2.*    3.*    5.     6.     6.

*  Flow along walls is questionable.
```

BULK MATERIAL 10: Titanium dioxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .02 | .02 | .02 | .02 | .02 |
| .50 feet | .12 | .10 | .10 | .09 | .09 |
| .75 feet | .29 | .25 | .23 | .22 | .22 |
| 1.00 feet | .52 | .47 | .43 | .41 | .38 |
| 2.00 feet | 2.1 | 1.9 | 1.8 | 1.7 | 1.6 |
| 4.00 feet | 8.9 | 8.0 | 7.4 | 7.0 | 6.6 |
| 8.00 feet | 36. | 32. | 30. | 28. | 27. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .14 | .13 | .12 | .11 | .10 |
| .50 feet | .32 | .29 | .27 | .25 | .23 |
| .75 feet | .50 | .45 | .41 | .40 | .38 |
| 1.00 feet | .68 | .61 | .58 | .54 | .50 |
| 2.00 feet | 1.4 | 1.2 | 1.1 | 1.1 | 1.0 |
| 4.00 feet | 2.8 | 2.5 | 2.3 | 2.2 | 2.1 |
| 8.00 feet | 5.7 | 5.2 | 4.8 | 4.5 | 4.3 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 10: Titanium dioxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA / GAMMA0)^{-a}$$

At room temperature, for GAMMA between 92.7 and 139.2 pcf:

K0 = .000696 ft/s

GAMMA0 = 104.5 pcf

a = 3.79

## BULK MATERIAL 11: Wollastonite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .8 | .4 |
| 1.25 | .9 | .4 |
| 1.50 | 1.0 | .5 |
| 2.00 | 1.5 | .7 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 15 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .4 | | .9 | 1.2 | 2.1 | 3.8 | 7 | 11 |
| 1.25 | .5 | | 1.0 | 1.3 | 2.5 | 4.6 | 9 | 13 |
| 1.50 | .6 | | 1.0 | 1.5 | 2.9 | 5 | 10 | 16 |
| 2.00 | 1.1 | | 1.2 | 1.7 | 3.6 | 7 | 14 | 21 |

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 11: Wollastonite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 3.9 | 1.9 |
| 1.25 | 5.2 | 2.5 |
| 1.50 | 6.4 | 3.1 |
| 2.00 | 8.3 | 4.1 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 15 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 2.4 | | 2.3 | 2.9 | 4.7 | 7 | 11 | 14 |
| 1.25 | 3.2 | | 2.4 | 3.2 | 5 | 8 | 13 | 16 |
| 1.50 | 3.8 | | 2.6 | 3.4 | 6 | 9 | 14 | 18 |
| 2.00 | 4.7 | | 2.8 | 3.9 | 7 | 11 | 17 | 22 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 11: Wollastonite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 28. | 60. | 164. | 346. | 723. | 1503. | 3118. | 6470. |
| GAMMA (pcf) | 56.8 | 60.2 | 65.4 | 69.2 | 72.3 | 75.1 | 77.9 | 80.9 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\text{GAMMA} = \text{MAX}\left[\text{GAMMA(I)}\,(\text{SIGMA1}/\text{SIGMA1(I)})^{\text{BETA(I)}},\text{GAMMAM}\right]$$

Minimum bulk density GAMMAM = 46.4 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 58.5 | .06832 |
| 2 | 102.7 | 63.1 | .08912 |
| 3 | 308.0 | 68.7 | .07668 |
| 4 | 601.4 | 71.5 | .06024 |
| 5 | 1188.1 | 74.3 | .05634 |
| 6 | 1774.8 | 75.7 | .04784 |
| 7 | 2361.5 | 76.8 | .05070 |

BULK MATERIAL 11: Wollastonite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .39 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 12.48 |
| Width of Oval (feet) | .22 | .28 | .53 | 1.04 | 2.06 | 4.10 | 6.38 |
| SIGMA (psf) | 7.4 | 9.7 | 23. | 52. | 113. | 248. | 412. |
| SIGMA1 (psf) | 10.8 | 13.9 | 34. | 79. | 169. | 353. | 559. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 34. | 34. | 33. | 32. | 31. | 29. | 27. |
| Hopper Angles<br>THETA-P (deg) | 17. | 17. | 17. | 18. | 19. | 22. | 24. |
| THETA-C (deg) | 6. | 6. | 6. | 6. | 8. | 10. | 13. |

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

BULK MATERIAL 11: Wollastonite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .43 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 13.24 |
| Width of Oval (feet) | .25 | .28 | .54 | 1.06 | 2.10 | 4.14 | 6.81 |
| SIGMA (psf) | 7.4 | 8.7 | 21. | 48. | 105. | 234. | 412. |
| SIGMA1 (psf) | 12.6 | 14.7 | 37. | 82. | 176. | 363. | 614. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 40. | 40. | 38. | 37. | 34. | 32. | 31. |
| Hopper Angles<br>THETA-P (deg) | 11.* | 11.* | 11.* | 13.* | 14. | 18. | 19. |
| THETA-C (deg) | 0.* | 0.* | 1.* | 2.* | 2.* | 6. | 8. |

* Flow along walls is questionable.

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                    BULK MATERIAL 11:  Wollastonite

                    PARTICLE SIZE As Rec'd

                    MOISTURE CONTENT 0.2%




WALL MATERIAL:  Tivar- 88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .39    .50   1.00   2.00   4.00   8.00  12.87
Width of Oval (feet)      .22    .28    .53   1.04   2.07   4.11   6.60

SIGMA (psf)              7.4    9.6   22.    51.   111.   243.   412.
SIGMA1 (psf)            10.7   13.9   35.    80.   170.   356.   587.

Wall Friction Angle
PHI-PRIME (deg)         34.    34.    33.    33.    31.    30.    29.

Hopper Angles
THETA-P (deg)           16.    16.    16.    16.    18.    20.    22.
THETA-C (deg)            5.     5.     5.     5.     7.     9.    10.


WALL MATERIAL:  Tivar- 88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F


No time effect! Use results from test having storage time at rest of 0.0 hrs.
```

BULK MATERIAL 11: Wollastonite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| 1.00 feet | .13 | .10 | .09 | .08 | .07 |
| 2.00 feet | 1.1 | .88 | .76 | .67 | .61 |
| 4.00 feet | 5.6 | 4.4 | 3.8 | 3.4 | 3.1 |
| 8.00 feet | 25. | 19. | 16. | 15. | 13. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .04 | .03 | .03 | .03 | .03 |
| .75 feet | .18 | .14 | .12 | .11 | .10 |
| 1.00 feet | .32 | .25 | .22 | .20 | .17 |
| 2.00 feet | .86 | .68 | .58 | .52 | .47 |
| 4.00 feet | 1.9 | 1.5 | 1.3 | 1.1 | 1.0 |
| 8.00 feet | 4.1 | 3.2 | 2.7 | 2.4 | 2.2 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 11: Wollastonite

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\,(GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

For GAMMA(I-1) < GAMMA < GAMMA(I) :

$$K = K(I)\,(GAMMA / GAMMA(I))^{-A(I)}$$

At room temperature, for GAMMA between 50.6 and 77.2 pcf:

| I | GAMMA(I)<br>pcf | K(I)<br>ft/s | A(I)<br>dimless |
|---|---|---|---|
| 1 | 50.55 | .002077 | 15.00958 |
| 2 | 51.49 | .001577 | 15.00958 |
| 3 | 52.17 | .001346 | 12.12650 |
| 4 | 52.96 | .001173 | 9.10007 |
| 5 | 53.78 | .000962 | 12.94985 |
| 6 | 55.39 | .000866 | 3.57848 |
| 7 | 56.84 | .000712 | 7.57858 |
| 8 | 58.40 | .000596 | 6.51833 |
| 9 | 59.87 | .000519 | 5.55230 |
| 10 | 62.30 | .000404 | 6.32159 |
| 11 | 63.89 | .000365 | 3.97384 |
| 12 | 65.89 | .000327 | 3.61117 |
| 13 | 71.59 | .000269 | 2.34009 |
| 14 | 74.08 | .000250 | 2.15995 |
| 15 | 75.93 | .000231 | 3.26091 |
| 16 | 77.23 | .000212 | 5.09567 |

## BULK MATERIAL 12: Zinc oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | +++ | *** |
| 1.25 | +++ | *** |
| 1.50 | +++ | *** |
| 2.00 | +++ | *** |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 17 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | *** | | 1.3 | 2.6 | 6 | 11 | 18 | 28 |
| 1.25 | *** | | 1.6 | 3.1 | 7 | 13 | 20 | 34 |
| 1.50 | *** | | 1.9 | 3.7 | 9 | 15 | 24 | 40 |
| 2.00 | *** | | 2.5 | 4.8 | 11 | 18 | 30 | 51 |

0.* Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 13.7 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to 27.5 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 12: Zinc oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

#### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | +++ | *** |
| 1.25 | +++ | *** |
| 1.50 | +++ | *** |
| 2.00 | +++ | *** |

#### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 17 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | *** | 1.6 | 3.1 | 7 | 14 | 22 | 34 |
| 1.25 | *** | 1.9 | 3.8 | 9 | 16 | 25 | 42 |
| 1.50 | *** | 2.3 | 4.5 | 10 | 18 | 29 | 48 |
| 2.00 | *** | 3.0 | 6 | 13 | 21 | 37 | 62 |

0.* Indicates that no minimum dimensions are given by the tests. Instead, the outlet size should be selected by consideration of particle interlocking, flow rate, etc.

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 16.7 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to 33.4 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

#### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 12: Zinc oxide

PARTICLE SIZE As Rec’d

MOISTURE CONTENT 0.2%

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 20. | 42. | 113. | 245. | 531. | 1177. | 2701. | 6162. |
| GAMMA (pcf) | 40.6 | 42.5 | 45.1 | 49.0 | 53.1 | 58.8 | 67.5 | 77.0 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\left[\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}}, \mathrm{GAMMAM}\right]$$

Minimum bulk density GAMMAM = 33.8 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 42.5 | .06138 |
| 2 | 102.7 | 44.7 | .05819 |
| 3 | 308.0 | 50.2 | .10487 |
| 4 | 601.4 | 53.8 | .10584 |
| 5 | 1188.1 | 58.9 | .13225 |
| 6 | 1774.8 | 63.2 | .17360 |
| 7 | 2361.5 | 66.1 | .15952 |

## BULK MATERIAL 12: Zinc oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

### WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet

STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 16.00 | 20.48 |
| Width of Oval (feet) | .28 | .55 | 1.10 | 2.18 | 4.33 | 8.62 | 11.01 |
| SIGMA (psf) | 6.3 | 13.3 | 29. | 62. | 138. | 308. | 410. |
| SIGMA1 (psf) | 10.5 | 21.8 | 45. | 95. | 204. | 445. | 590. |
| Wall Friction Angle | | | | | | | |
| PHI-PRIME (deg) | 37. | 37. | 36. | 34. | 33. | 32. | 32. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 12. | 12. | 14. | 15. | 17. | 18. | 18. |
| THETA-C (deg) | 1. | 2. | 3. | 5. | 7. | 8. | 8. |

### WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet

STORAGE TIME AT REST 168.0 hr
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

BULK MATERIAL 12:  Zinc oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

```
                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .53   1.00   2.00   4.00   8.00  16.00  22.64
Width of Oval (feet)      .30    .56   1.12   2.24   4.48   8.90  12.44

SIGMA (psf)               6.3   12.3   26.     55.   120.   265.   410.
SIGMA1 (psf)             11.7   22.9   48.    103.   223.   488.   717.

Wall Friction Angle
PHI-PRIME (deg)          46.    46.    45.    44.    43.    40.    38.

Hopper Angles
THETA-P (deg)             8.*    8.*    8.*    8.*    8.*    8.*   10.*
THETA-C (deg)             0.*    0.*    0.*    0.*    0.*    0.*    0.*

*  Flow along walls is questionable.
```

WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                        BULK MATERIAL 12:  Zinc oxide

                        PARTICLE SIZE As Rec'd

                        MOISTURE CONTENT 0.2%




WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .43    .50   1.00   2.00   4.00   8.00  16.00  18.58
Width of Oval (feet)      .23    .27    .54   1.08   2.15   4.30   8.57   9.94

SIGMA (psf)              6.3    7.5    16.    34.    73.   158.   346.   410.
SIGMA1 (psf)             8.2    9.6    20.    42.    88.   191.   419.   497.

Wall Friction Angle
PHI-PRIME (deg)         28.    27.    25.    24.    24.    24.    23.    23.

Hopper Angles
THETA-P (deg)           23.    24.    26.    28.    28.    28.    29.    29.
THETA-C (deg)           13.    13.    15.    16.    17.    17.    18.    18.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)       1.14   2.00   4.00   8.00  12.68
Width of Oval (feet)      .62   1.08   2.15   4.30   6.80

SIGMA (psf)             19.3   36.0    76.   166.   280.
SIGMA1 (psf)            25.1   45.1    94.   202.   340.

Wall Friction Angle
PHI-PRIME (deg)         27.    26.    24.    24.    24.

Hopper Angles
THETA-P (deg)           24.    26.    27.    28.    28.
THETA-C (deg)           13.    15.    16.    17.    17.
```

BULK MATERIAL 12: Zinc oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .61 | .50 | .43 | .36 | .31 |
| .50 feet | 2.4 | 2.0 | 1.7 | 1.4 | 1.2 |
| .75 feet | 5.5 | 4.5 | 3.8 | 3.2 | 2.8 |
| 1.00 feet | 9.9 | 8.0 | 6.8 | 5.8 | 4.9 |
| 2.00 feet | 39. | 32. | 27. | 23. | 19. |
| 4.00 feet | 158. | 129. | 109. | 93. | 79. |
| 8.00 feet | 630. | 522. | 432. | 378. | 324. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | 3.1 | 2.5 | 2.1 | 1.8 | 1.5 |
| .50 feet | 6.3 | 5.1 | 4.3 | 3.7 | 3.1 |
| .75 feet | 9.4 | 7.6 | 6.5 | 5.5 | 4.7 |
| 1.00 feet | 12. | 10. | 8.7 | 7.4 | 6.3 |
| 2.00 feet | 25. | 19. | 17. | 14. | 12. |
| 4.00 feet | 50. | 41. | 34. | 30. | 25. |
| 8.00 feet | 100. | 82. | 70. | 59. | 50. |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 12: Zinc oxide

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.2%

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA / GAMMA0)^{-a}$$

At room temperature, for GAMMA between 36.4 and 47.1 pcf:

K0 = .055973 ft/s

GAMMA0 = 33.6 pcf

a = 8.87

## BULK MATERIAL 13:  Zircon flour

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION I.  BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest     .0 hrs
Temperature   72 deg F

### PART A.  BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .6 | .3 |
| 1.25 | .6 | .3 |
| 1.50 | .7 | .3 |
| 2.00 | .9 | .4 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 11 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .3 | .8 | 1.1 | 1.9 | 3.3 | 6 | 7 |
| 1.25 | .3 | .8 | 1.2 | 2.2 | 4.0 | 8 | 8 |
| 1.50 | .4 | .9 | 1.3 | 2.5 | 4.7 | 9 | 10 |
| 2.00 | .6 | 1.0 | 1.6 | 3.2 | 6 | 12 | 13 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 13: Zircon flour

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

Storage Time at Rest 168.0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

#### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .6 | .3 |
| 1.25 | .6 | .3 |
| 1.50 | .7 | .3 |
| 2.00 | .9 | .4 |

#### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 11 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .3 | | .8 | 1.1 | 1.9 | 3.3 | 6 | 7 |
| 1.25 | .3 | | .8 | 1.2 | 2.2 | 4.0 | 8 | 8 |
| 1.50 | .4 | | .9 | 1.3 | 2.5 | 4.7 | 9 | 10 |
| 2.00 | .6 | | 1.0 | 1.6 | 3.2 | 6 | 12 | 13 |

#### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 13: Zircon flour

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 63. | 133. | 355. | 739. | 1526. | 3126. | 6390. | 13065. |
| GAMMA (pcf) | 125.5 | 133.1 | 142.1 | 147.8 | 152.6 | 156.3 | 159.8 | 163.3 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\text{GAMMA} = \text{MAX}\left[\text{GAMMA(I)}\,(\text{SIGMA1}/\text{SIGMA1(I)})^{\text{BETA(I)}}, \text{GAMMAM}\right]$$

Minimum bulk density GAMMAM = 96.0 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 121.9 | .08873 |
| 2 | 102.7 | 130.7 | .08271 |
| 3 | 308.0 | 141.0 | .06860 |
| 4 | 601.4 | 146.4 | .05663 |
| 5 | 1188.1 | 151.0 | .04547 |
| 6 | 1774.8 | 153.6 | .04214 |
| 7 | 2361.5 | 154.9 | .03074 |

## BULK MATERIAL 13:  Zircon flour

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW

### WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet

STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .29 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 9.46 |
| Width of Oval (feet) | .16 | .28 | .53 | 1.03 | 2.03 | 4.04 | 4.77 |
| SIGMA (psf) | 11.9 | 22.1 | 52. | 119. | 261. | 563. | 677. |
| SIGMA1 (psf) | 17.5 | 31.9 | 77. | 171. | 363. | 766. | 917. |
| Wall Friction Angle | | | | | | | |
| PHI-PRIME (deg) | 34. | 33. | 31. | 29. | 28. | 27. | 26. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 18. | 18. | 18. | 21. | 24. | 25. | 25. |
| THETA-C (deg) | 6. | 7. | 8. | 10. | 12. | 14. | 14. |

### WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet

STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

## BULK MATERIAL 13:  Zircon flour

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

### HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .30 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 9.70 |
| Width of Oval (feet) | .17 | .28 | .53 | 1.03 | 2.04 | 4.06 | 4.92 |
| SIGMA (psf) | 11.9 | 21.1 | 50. | 114. | 252. | 547. | 677. |
| SIGMA1 (psf) | 18.9 | 32.8 | 79. | 175. | 369. | 778. | 957. |
| Wall Friction Angle | | | | | | | |
| PHI-PRIME (deg) | 37. | 36. | 34. | 31. | 29. | 28. | 28. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 15. | 15. | 15. | 18. | 21. | 23. | 23. |
| THETA-C (deg) | 3. | 4. | 4. | 6. | 9. | 11. | 11. |

WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

```
                       BULK MATERIAL 13:  Zircon flour

                       PARTICLE SIZE As Rec'd

                       MOISTURE CONTENT 0.1%




WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .30    .50   1.00   2.00   4.00   8.00   9.74
Width of Oval (feet)      .17    .28    .53   1.03   2.04   4.06   4.94

SIGMA (psf)             11.9   21.5   51.   116.   254.   546.   677.
SIGMA1 (psf)            18.5   32.5   78.   174.   368.   779.   964.

Wall Friction Angle
PHI-PRIME (deg)         37.    35.    33.    31.    29.    28.    28.

Hopper Angles
THETA-P (deg)           16.    17.    16.    19.    21.    23.    23.
THETA-C (deg)            4.     5.     6.     8.    10.    11.    11.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  168.0 hr
TEMPERATURE   72 deg F


No time effect! Use results from test having storage time at rest of 0.0 hrs.
```

BULK MATERIAL 13: Zircon flour

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .75 feet | .14 | .12 | .11 | .10 | .09 |
| 1.00 feet | .40 | .34 | .31 | .29 | .27 |
| 2.00 feet | 2.5 | 2.1 | 1.9 | 1.7 | 1.6 |
| 4.00 feet | 11. | 10. | 8.9 | 8.3 | 7.8 |
| 8.00 feet | 50. | 43. | 37. | 36. | 34. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .20 | .17 | .15 | .14 | .13 |
| .75 feet | .47 | .40 | .36 | .32 | .31 |
| 1.00 feet | .74 | .63 | .56 | .52 | .49 |
| 2.00 feet | 1.8 | 1.5 | 1.3 | 1.2 | 1.2 |
| 4.00 feet | 4.0 | 3.4 | 3.0 | 2.8 | 2.6 |
| 8.00 feet | 8.3 | 7.0 | 6.3 | 5.8 | 5.5 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 13: Zircon flour

PARTICLE SIZE As Rec'd

MOISTURE CONTENT 0.1%

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\,(GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\,(GAMMA / GAMMA0)^{-a}$$

At room temperature, for GAMMA between 112.6 and 161.5 pcf:

K0 = .000993 ft/s

GAMMA0 = 115.0 pcf

a = 5.09

## BULK MATERIAL 14: LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .4 | .2 |
| 1.25 | .4 | .2 |
| 1.50 | .5 | .2 |
| 2.00 | .8 | .3 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 feet |
|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | .2 | | .7 | 1.1 | 2.2 | 4.1 | 8 |
| 1.25 | .3 | | .8 | 1.3 | 2.7 | 5 | 10 |
| 1.50 | .4 | | .9 | 1.4 | 3.1 | 6 | 12 |
| 2.00 | .9 | | 1.0 | 1.8 | 4.0 | 8 | 15 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 14: LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

| | |
|---|---|
| Storage Time at Rest | 24.0 hrs |
| Temperature | 72 deg F |

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 1.0 | .5 |
| 1.25 | 1.1 | .5 |
| 1.50 | 1.3 | .6 |
| 2.00 | 2.0 | .9 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 feet |
|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | |
| 1.00 | .6 | 1.3 | 1.6 | 2.6 | 4.4 | 8 |
| 1.25 | .7 | 1.3 | 1.7 | 3.0 | 5 | 10 |
| 1.50 | .8 | 1.4 | 1.9 | 3.4 | 6 | 12 |
| 2.00 | 1.7 | 1.6 | 2.2 | 4.2 | 8 | 15 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 14:  LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
| SIGMA1 (psf) | 34. | 73. | 196. | 412. | 857. | 1767. | 3652. | 7548. |
| GAMMA (pcf) | 68.9 | 72.8 | 78.4 | 82.4 | 85.7 | 88.4 | 91.3 | 94.4 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\,[\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}},\mathrm{GAMMAM}]$$

Minimum bulk density GAMMAM =  56.1 pcf

| I | SIGMA1(I)<br>psf | GAMMA(I)<br>pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 70.1 | .06924 |
| 2 | 102.7 | 74.7 | .07512 |
| 3 | 308.0 | 81.0 | .07372 |
| 4 | 601.4 | 84.1 | .05632 |
| 5 | 1188.1 | 87.2 | .05324 |
| 6 | 1774.8 | 88.4 | .03224 |
| 7 | 2361.5 | 89.5 | .04516 |

BULK MATERIAL 14: LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .35 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 10.40 |
| Width of Oval (feet) | .20 | .27 | .53 | 1.03 | 2.04 | 4.07 | 5.28 |
| SIGMA (psf) | 7.7 | 12.0 | 28. | 66. | 146. | 311. | 412. |
| SIGMA1 (psf) | 12.1 | 18.1 | 40. | 91. | 197. | 419. | 554. |
| Wall Friction Angle | | | | | | | |
| PHI-PRIME (deg) | 37. | 34. | 30. | 28. | 27. | 27. | 26. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 16. | 17. | 19. | 23. | 24. | 25. | 25. |
| THETA-C (deg) | 3. | 6. | 10. | 12. | 13. | 14. | 14. |

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST 24.0 hrs
TEMPERATURE 72 deg F

No time effect! Use results from test having storage time at rest of 0.0 hrs.

## BULK MATERIAL 14: LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

### WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish

STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .36 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 10.55 |
| Width of Oval (feet) | .21 | .28 | .53 | 1.04 | 2.05 | 4.08 | 5.37 |
| SIGMA (psf) | 7.4 | 11.0 | 26. | 62. | 141. | 305. | 412. |
| SIGMA1 (psf) | 13.2 | 19.2 | 43. | 94. | 201. | 423. | 567. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 41. | 39. | 35. | 31. | 29. | 28. | 27. |
| Hopper Angles<br>THETA-P (deg) | 10.* | 10.* | 13. | 18. | 22. | 24. | 24. |
| THETA-C (deg) | 0.* | 0.* | 3. | 7. | 10. | 12. | 13. |

### WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish

STORAGE TIME AT REST 24.0 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | |
|---|---|---|---|---|---|
| Dia of Cone (feet) | .84 | 1.00 | 2.00 | 4.00 | 7.47 |
| Width of Oval (feet) | .45 | .53 | 1.04 | 2.05 | 3.81 |
| SIGMA (psf) | 21.0 | 26.1 | 62. | 139. | 282. |
| SIGMA1 (psf) | 35.0 | 42.4 | 94. | 202. | 395. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 36. | 35. | 32. | 30. | 28. |
| Hopper Angles<br>THETA-P (deg) | 12. | 13. | 18. | 21. | 23. |
| THETA-C (deg) | 2. | 3. | 7. | 9. | 12. |

```
                   BULK MATERIAL 14:  LAW A: AN105

                   PARTICLE SIZE As Rec'd

                   MOISTURE CONTENT As Rec'd




WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .35    .50   1.00   2.00   4.00   8.00  10.41
Width of Oval (feet)      .20    .28    .53   1.03   2.05   4.07   5.29

SIGMA (psf)              7.2   11.2   27.    64.   144.   310.   412.
SIGMA1 (psf)            12.5   18.9   42.    93.   199.   419.   555.

Wall Friction Angle
PHI-PRIME (deg)         41.    38.    34.    30.    28.    27.    27.

Hopper Angles
THETA-P (deg)           12.*   12.*   15.    20.    23.    25.    25.
THETA-C (deg)            0.*    1.*    5.     9.    12.    14.    14.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  24.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .83   1.00   2.00   4.00   7.36
Width of Oval (feet)      .45    .53   1.04   2.05   3.75

SIGMA (psf)             21.0   26.6   63.   141.   282.
SIGMA1 (psf)            34.2   42.0   93.   200.   385.

Wall Friction Angle
PHI-PRIME (deg)         36.    34.    31.    29.    27.

Hopper Angles
THETA-P (deg)           13.    15.    19.    22.    24.
THETA-C (deg)            3.     5.     8.    11.    13.
```

## BULK MATERIAL 14: LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .03 | .03 | .02 | .02 | .02 |
| .75 feet | .12 | .10 | .09 | .08 | .08 |
| 1.00 feet | .27 | .22 | .20 | .18 | .17 |
| 2.00 feet | 1.3 | 1.1 | .99 | .92 | .85 |
| 4.00 feet | 6.0 | 4.9 | 4.4 | 4.0 | 3.7 |
| 8.00 feet | 25. | 21. | 18. | 17. | 15. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .02 | .02 | .01 | .01 | .01 |
| .50 feet | .15 | .12 | .11 | .10 | .09 |
| .75 feet | .29 | .23 | .20 | .20 | .18 |
| 1.00 feet | .41 | .34 | .31 | .29 | .25 |
| 2.00 feet | .94 | .77 | .68 | .63 | .59 |
| 4.00 feet | 2.0 | 1.6 | 1.4 | 1.3 | 1.2 |
| 8.00 feet | 4.0 | 3.4 | 3.0 | 2.7 | 2.5 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 14:  LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION V.  AIR PERMEABILITY TEST RESULTS

Temperature  68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\,(GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\,(GAMMA / GAMMA0)^{-a}$$

At room temperature, for GAMMA between  61.3 and  84.3 pcf:

K0 =  .000719 ft/s

GAMMA0 =  65.8 pcf

a =  5.40

BULK MATERIAL 14: LAW A: AN105

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION VI. CHUTE ANGLES

Tests were conducted at the indicated impact pressures, temperatures, and time(s) at rest to determine the angles required for nonconverging chutes in order to maintain flow after material impact. The angle given is the minimum angle from the horizontal that will cause a bed of material to slide on the chute. In general, chutes should be designed with at least a 5 degree safety margin on this angle; if the chute converges, a significantly steeper chute may be required.

| Chute Material | Temperature(deg F) Material | Chute | Time at Rest (hours) | Impact Pressure (psf) | Chute Angles (deg) Range | Min. Rec. |
|---|---|---|---|---|---|---|
| 304 #2B Finish Stainless Steel Sheet | 72 | 72 | .0 | 3.5 | 29 to 31 | 36. |
| | | | | 42.6 | 31 to 32 | 37. |
| | | | | 81.7 | 29 to 32 | 37. |
| | | | | 159.9 | 29 to 32 | 37. |
| Mild Carbon Steel Plate, Mill Finish | 72 | 72 | .0 | 3.5 | 29 to 31 | 36. |
| | | | | 42.6 | 30 to 33 | 38. |
| | | | | 81.7 | 37 to 41 | 46. |
| | | | | 159.9 | 36 to 40 | 45. |
| Tivar-88 | 72 | 72 | .0 | 3.5 | 32 to 36 | 41. |
| | | | | 42.6 | 31 to 34 | 39. |
| | | | | 81.7 | 29 to 33 | 38. |
| | | | | 159.9 | 31 to 34 | 39. |

## BULK MATERIAL 15:  LAW B: AZ101

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION I.  BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest     .0 hrs
Temperature   72 deg F

### PART A.  BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .2 | .1 |
| 1.25 | .2 | .1 |
| 1.50 | .3 | .1 |
| 2.00 | +++ | *** |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 16 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .1 | 1.1 | 2.0 | 4.6 | 9 | 15 | 20 |
| 1.25 | .3 | 1.3 | 2.4 | 6 | 10 | 17 | 21 |
| 1.50 | *** | 1.5 | 2.8 | 7 | 12 | 19 | 23 |
| 2.00 | *** | 1.9 | 3.6 | 8 | 14 | 21 | 30 |

*** Denotes unassisted gravity flow is impossible. However, widths of only up to   7.5 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to  15.1 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 15: LAW B: AZ101

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

Storage Time at Rest 24.0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .6 | .3 |
| 1.25 | 1.0 | .4 |
| 1.50 | +++ | .9 |
| 2.00 | +++ | *** |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 16 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .8 | 1.6 | 2.8 | 6 | 11 | 19 | 25 |
| 1.25 | *** | 1.9 | 3.3 | 7 | 13 | 22 | 27 |
| 1.50 | *** | 2.2 | 3.8 | 8 | 15 | 24 | 29 |
| 2.00 | *** | 2.7 | 4.8 | 11 | 18 | 27 | 38 |

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 9.6 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to 19.2 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 15: LAW B: AZ101

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 28. | 59. | 156. | 327. | 686. | 1437. | 3012. | 6313. |
| GAMMA (pcf) | 56.0 | 58.7 | 62.5 | 65.5 | 68.6 | 71.9 | 75.3 | 78.9 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

GAMMA is the greater of $\text{GAMMA0}\,(\text{SIGMA1}/\text{SIGMA0})^{\text{BETA}}$ and GAMMAM.

For GAMMA between 58.1 and 74.4 pcf

GAMMA0 = 53.39 pcf

SIGMA0 = 13.00 psf

BETA = .06318

Minimum bulk density GAMMAM = 49.6 pcf

## BULK MATERIAL 15: LAW B: AZ101

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION III. MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .38 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 14.02 |
| Width of Oval (feet) | .21 | .28 | .55 | 1.08 | 2.12 | 4.22 | 7.37 |
| SIGMA (psf) | 6.7 | 9.3 | 21. | 47. | 104. | 224. | 411. |
| SIGMA1 (psf) | 10.8 | 14.6 | 31. | 65. | 139. | 294. | 537. |
| Wall Friction Angle | | | | | | | |
| PHI-PRIME (deg) | 38. | 36. | 33. | 30. | 28. | 27. | 27. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 15. | 16. | 18. | 21. | 23. | 24. | 24. |
| THETA-C (deg) | 2. | 4. | 7. | 10. | 12. | 14. | 14. |

WALL MATERIAL: 304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST 24.0 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | |
|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .98 | 1.00 | 2.00 | 4.00 | 8.00 | 9.94 |
| Width of Oval (feet) | .54 | .55 | 1.08 | 2.13 | 4.23 | 5.24 |
| SIGMA (psf) | 20.1 | 20.4 | 45. | 98. | 218. | 281. |
| SIGMA1 (psf) | 30.7 | 31.3 | 67. | 143. | 298. | 373. |
| Wall Friction Angle | | | | | | |
| PHI-PRIME (deg) | 35. | 35. | 33. | 32. | 29. | 28. |
| Hopper Angles | | | | | | |
| THETA-P (deg) | 16. | 16. | 16. | 18. | 22. | 23. |
| THETA-C (deg) | 5. | 5. | 6. | 8. | 12. | 13. |

```
                    BULK MATERIAL 15:  LAW B: AZ101

                    PARTICLE SIZE As Rec'd

                    MOISTURE CONTENT As Rec'd




WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .39    .50   1.00   2.00   4.00   8.00  14.18
Width of Oval (feet)      .22    .28    .55   1.08   2.13   4.22   7.46

SIGMA (psf)              7.0    9.3    21.    46.   101.   220.   411.
SIGMA1 (psf)            11.1   14.5    31.    66.   141.   297.   548.

Wall Friction Angle
PHI-PRIME (deg)         37.    36.    34.    32.    30.    28.    28.

Hopper Angles
THETA-P (deg)           16.    16.    17.    18.    20.    22.    23.
THETA-C (deg)            3.     4.     5.     8.    10.    12.    13.


WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  24.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .98   1.00   2.00   4.00   8.00  10.35
Width of Oval (feet)      .54    .55   1.08   2.13   4.23   5.47

SIGMA (psf)             20.1   20.5    46.    99.   212.   281.
SIGMA1 (psf)            30.6   31.2    66.   142.   301.   398.

Wall Friction Angle
PHI-PRIME (deg)         35.    35.    32.    31.    30.    30.

Hopper Angles
THETA-P (deg)           16.    16.    18.    19.    20.    20.
THETA-C (deg)            5.     5.     8.     9.    10.    10.
```

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                       BULK MATERIAL 15:  LAW B: AZ101

                       PARTICLE SIZE As Rec'd

                       MOISTURE CONTENT As Rec'd




WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .36    .50   1.00   2.00   4.00   8.00  13.92
Width of Oval (feet)      .20    .28    .55   1.08   2.12   4.22   7.32

SIGMA (psf)              7.0   10.1   22.    48.   104.   225.   411.
SIGMA1 (psf)             9.9   14.0   30.    65.   139.   293.   531.

Wall Friction Angle
PHI-PRIME (deg)         32.    32.    31.    29.    28.    27.    26.

Hopper Angles
THETA-P (deg)           21.    21.    21.    21.    23.    24.    25.
THETA-C (deg)            8.     9.     9.    11.    13.    14.    15.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  24.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .93   1.00   2.00   4.00   8.00  10.21
Width of Oval (feet)      .51    .55   1.08   2.13   4.23   5.39

SIGMA (psf)             20.1   21.8   47.   102.   216.   281.
SIGMA1 (psf)            27.9   30.3   65.   141.   299.   389.

Wall Friction Angle
PHI-PRIME (deg)         31.    31.    30.    30.    29.    29.

Hopper Angles
THETA-P (deg)           21.    20.    20.    21.    21.    21.
THETA-C (deg)            9.     9.    10.    11.    11.    11.
```

BULK MATERIAL 15: LAW B: AZ101

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .09 | .08 | .07 | .06 | .06 |
| .50 feet | .68 | .58 | .50 | .45 | .41 |
| .75 feet | 1.7 | 1.4 | 1.3 | 1.1 | 1.0 |
| 1.00 feet | 3.3 | 2.8 | 2.4 | 2.2 | 2.0 |
| 2.00 feet | 14. | 12. | 10. | 9.7 | 8.8 |
| 4.00 feet | 61. | 52. | 45. | 39. | 36. |
| 8.00 feet | 252. | 216. | 180. | 165. | 149. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .79 | .67 | .59 | .52 | .49 |
| .50 feet | 2.0 | 1.7 | 1.5 | 1.3 | 1.2 |
| .75 feet | 3.3 | 2.8 | 2.4 | 2.2 | 2.0 |
| 1.00 feet | 4.5 | 3.8 | 3.4 | 3.0 | 2.7 |
| 2.00 feet | 9.6 | 8.1 | 7.1 | 6.3 | 5.8 |
| 4.00 feet | 19. | 16. | 14. | 13. | 11. |
| 8.00 feet | 39. | 34. | 28. | 27. | 23. |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 15: LAW B: AZ101

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION V. AIR PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (\mathrm{GAMMA}) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (\mathrm{GAMMA} / \mathrm{GAMMA0})^{-a}$$

At room temperature, for GAMMA between 50.6 and 65.2 pcf:

K0 = .007376 ft/s

GAMMA0 = 53.4 pcf

a = 6.15

BULK MATERIAL 15:  LAW B: AZ101

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION VI.  CHUTE ANGLES

Tests were conducted at the indicated impact pressures, temperatures, and time(s) at rest to determine the angles required for nonconverging chutes in order to maintain flow after material impact.  The angle given is the minimum angle from the horizontal that will cause a bed of material to slide on the chute.  In general, chutes should be designed with at least a 5 degree safety margin on this angle; if the chute converges, a significantly steeper chute may be required.

| Chute Material | Temperature(deg F) Material | Chute | Time at Rest (hours) | Impact Pressure (psf) | Chute Angles (deg) Range | Min. Rec. |
|---|---|---|---|---|---|---|
| 304 #2B Finish Stainless Steel Sheet | 72 | 72 | .0 | 3.1 | 27 to 29 | 34. |
| | | | | 42.2 | 32 to 34 | 39. |
| | | | | 81.3 | 32 to 34 | 39. |
| | | | | 159.6 | 34 to 35 | 40. |
| Mild Carbon Steel Plate, Mill Finish | 72 | 72 | .0 | 3.1 | 29 to 32 | 37. |
| | | | | 42.2 | 33 to 35 | 40. |
| | | | | 81.3 | 36 to 40 | 45. |
| | | | | 159.6 | 50 to 55 | 60. |
| Tivar-88 | 72 | 72 | .0 | 3.1 | 27 to 30 | 35. |
| | | | | 42.2 | 37 to 39 | 44. |
| | | | | 81.3 | 40 to 43 | 48. |
| | | | | 159.6 | 45 to 47 | 52. |

## BULK MATERIAL 16: LAW C: AN107

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .9 | .4 |
| 1.25 | 1.2 | .5 |
| 1.50 | 2.1 | .8 |
| 2.00 | +++ | *** |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 15 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .7 | 1.1 | 1.7 | 3.6 | 7 | 15 | 24 |
| 1.25 | 2.0 | 1.2 | 1.9 | 4.3 | 9 | 19 | 31 |
| 1.50 | *** | 1.3 | 2.2 | 5 | 10 | 23 | 38 |
| 2.00 | *** | 1.6 | 2.8 | 7 | 14 | 32 | 55 |

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 7.8 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to 15.6 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 16: LAW C: AN107

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

Storage Time at Rest 24.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 1.8 | .8 |
| 1.25 | 4.3 | 1.4 |
| 1.50 | +++ | *** |
| 2.00 | +++ | *** |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 15 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 3.2 | | 1.5 | 2.2 | 4.6 | 9 | 19 | 30 |
| 1.25 | *** | | 1.6 | 2.6 | 6 | 11 | 24 | 39 |
| 1.50 | *** | | 1.8 | 2.9 | 6 | 13 | 29 | 48 |
| 2.00 | *** | | 2.1 | 3.6 | 8 | 18 | 40 | 70 |

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 9.9 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to 19.8 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 16: LAW C: AN107

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
| SIGMA1 (psf) | 25. | 53. | 144. | 305. | 645. | 1365. | 2890. | 6118. |
| GAMMA (pcf) | 50.5 | 53.4 | 57.6 | 60.9 | 64.5 | 68.3 | 72.3 | 76.5 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

GAMMA is the greater of $\text{GAMMA0}\,(\text{SIGMA1}/\text{SIGMA0})^{\text{BETA}}$ and GAMMAM.

For GAMMA between 53.1 and 71.5 pcf

GAMMA0 = 48.01 pcf

SIGMA0 = 13.00 psf

BETA = .07566

Minimum bulk density GAMMAM = 47.0 pcf

```
                       BULK MATERIAL 16:  LAW C: AN107

                       PARTICLE SIZE As Rec'd

                       MOISTURE CONTENT As Rec'd


SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW



WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .43     .50    1.00    2.00    4.00    8.00   15.46
Width of Oval (feet)      .24     .28     .53    1.06    2.11    4.22    8.16

SIGMA (psf)              6.8     8.2    20.     43.     94.    201.    411.
SIGMA1 (psf)            10.7    12.6    30.     63.    133.    280.    570.

Wall Friction Angle
PHI-PRIME (deg)         37.     36.     33.     31.     30.     30.     29.

Hopper Angles
THETA-P (deg)           15.     16.     16.     18.     20.     20.     21.
THETA-C (deg)            3.      4.      6.      9.     10.     11.     11.



WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  24.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)       1.10    2.00    4.00    8.00   11.21
Width of Oval (feet)      .60    1.08    2.13    4.23    5.93

SIGMA (psf)             19.8    38.0    87.    192.    281.
SIGMA1 (psf)            35.4    67.5   138.    285.    409.

Wall Friction Angle
PHI-PRIME (deg)         46.     39.     34.     32.     31.

Hopper Angles
THETA-P (deg)            9.*    10.*    14.     17.     18.
THETA-C (deg)            0.*     0.*     5.      8.      8.

*  Flow along walls is questionable.
```

## BULK MATERIAL 16: LAW C: AN107

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST .00 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .42 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 15.34 |
| Width of Oval (feet) | .24 | .28 | .54 | 1.07 | 2.12 | 4.23 | 8.09 |
| SIGMA (psf) | 6.8 | 8.2 | 19. | 41. | 90. | 198. | 411. |
| SIGMA1 (psf) | 10.5 | 12.6 | 31. | 65. | 135. | 282. | 563. |
| Wall Friction Angle | | | | | | | |
| PHI-PRIME (deg) | 37. | 36. | 36. | 34. | 32. | 30. | 29. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 13. | 13. | 13. | 14. | 17. | 20. | 22. |
| THETA-C (deg) | 3. | 3. | 3. | 5. | 7. | 10. | 12. |

WALL MATERIAL: Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST 24.0 hrs
TEMPERATURE 72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | |
|---|---|---|---|---|---|
| Dia of Cone (feet) | 1.10 | 2.00 | 4.00 | 8.00 | 11.16 |
| Width of Oval (feet) | .60 | 1.08 | 2.14 | 4.24 | 5.90 |
| SIGMA (psf) | 19.8 | 38.9 | 86. | 190. | 281. |
| SIGMA1 (psf) | 35.4 | 66.6 | 138. | 287. | 406. |
| Wall Friction Angle | | | | | |
| PHI-PRIME (deg) | 39. | 37. | 35. | 33. | 31. |
| Hopper Angles | | | | | |
| THETA-P (deg) | 9.* | 11. | 14. | 17. | 19. |
| THETA-C (deg) | 0.* | 2. | 4. | 7. | 9. |

* Flow along walls is questionable.

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                       BULK MATERIAL 16:  LAW C: AN107

                       PARTICLE SIZE As Rec’d

                       MOISTURE CONTENT As Rec’d




WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .38    .50   1.00   2.00   4.00   8.00  14.22
Width of Oval (feet)      .21    .28    .53   1.05   2.10   4.21   7.47

SIGMA (psf)              6.8    9.3   22.    49.   104.   220.   411.
SIGMA1 (psf)             8.8   11.8   28.    60.   126.   267.   497.

Wall Friction Angle
PHI-PRIME (deg)         29.    27.    25.    24.    23.    23.    23.

Hopper Angles
THETA-P (deg)           24.    26.    27.    29.    29.    29.    30.
THETA-C (deg)           12.    13.    17.    18.    19.    19.    19.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  24.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .93   1.00   2.00   4.00   8.00  10.10
Width of Oval (feet)      .50    .53   1.05   2.11   4.21   5.31

SIGMA (psf)             19.8   21.4   46.   100.   216.   281.
SIGMA1 (psf)            26.6   28.8   61.   129.   270.   346.

Wall Friction Angle
PHI-PRIME (deg)         28.    28.    27.    26.    25.    24.

Hopper Angles
THETA-P (deg)           22.    22.    24.    25.    27.    28.
THETA-C (deg)           12.    12.    14.    15.    17.    18.
```

BULK MATERIAL 16: LAW C: AN107

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| 1.00 feet | 3.1 | 2.4 | 2.0 | 1.7 | 1.5 |
| 2.00 feet | 27. | 19. | 16. | 14. | 12. |
| 4.00 feet | 133. | 102. | 84. | 72. | 63. |
| 8.00 feet | 594. | 450. | 378. | 324. | 288. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | 1.1 | .90 | .74 | .63 | .56 |
| .75 feet | 4.3 | 3.3 | 2.7 | 2.3 | 2.0 |
| 1.00 feet | 7.5 | 5.8 | 4.7 | 4.1 | 3.6 |
| 2.00 feet | 19. | 15. | 12. | 11. | 9.7 |
| 4.00 feet | 45. | 36. | 28. | 25. | 21. |
| 8.00 feet | 97. | 75. | 61. | 52. | 46. |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 16:  LAW C: AN107

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION V.  AIR PERMEABILITY TEST RESULTS

Temperature  68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA / GAMMA0)^{-a}$$

At room temperature, for GAMMA between   43.3 and   71.4 pcf:

K0 =  .024481 ft/s

GAMMA0 =   48.0 pcf

a =   5.89

BULK MATERIAL 16:  LAW C: AN107

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION VI.  CHUTE ANGLES

Tests were conducted at the indicated impact pressures, temperatures, and time(s) at rest to determine the angles required for nonconverging chutes in order to maintain flow after material impact.  The angle given is the minimum angle from the horizontal that will cause a bed of material to slide on the chute.  In general, chutes should be designed with at least a 5 degree safety margin on this angle; if the chute converges, a significantly steeper chute may be required.

| Chute Material | Temperature(deg F) Material | Chute | Time at Rest (hours) | Impact Pressure (psf) | Chute Angles (deg) Range | Min. Rec. |
|---|---|---|---|---|---|---|
| 304 #2B Finish Stainless Steel Sheet | 72 | 72 | .0 | 2.8 | 32 to 33 | 38. |
| | | | | 41.9 | 38 to 41 | 46. |
| | | | | 81.0 | 40 to 44 | 49. |
| | | | | 159.2 | 49 to 52 | 57. |
| Mild Carbon Steel Plate, Mill Finish | 72 | 72 | .0 | 2.8 | 30 to 32 | 37. |
| | | | | 41.9 | 36 to 39 | 44. |
| | | | | 81.0 | 52 to 58 | 63. |
| | | | | 159.2 | 60 to 65 | 70. |
| Tivar-88 | 72 | 72 | .0 | 2.8 | 28 to 30 | 35. |
| | | | | 41.9 | 33 to 35 | 40. |
| | | | | 81.0 | 35 to 36 | 41. |
| | | | | 159.2 | 37 to 39 | 44. |

BULK MATERIAL 17: HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .2 | .1 |
| 1.25 | .2 | .1 |
| 1.50 | .2 | .1 |
| 2.00 | .3 | .1 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 12 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .1 | .6 | 1.0 | 2.2 | 4.2 | 8 | 10 |
| 1.25 | .1 | .7 | 1.1 | 2.6 | 5 | 10 | 12 |
| 1.50 | .2 | .8 | 1.3 | 3.1 | 6 | 12 | 14 |
| 2.00 | .3 | .9 | 1.7 | 4.0 | 8 | 16 | 19 |

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 17: HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

Storage Time at Rest 72.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 4.0 | 2.0 |
| 1.25 | 4.8 | 2.3 |
| 1.50 | 6.0 | 2.8 |
| 2.00 | +++ | *** |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= | .5 | 1.0 | 2.5 | 5 | 10 | 12 feet |
|---|---|---|---|---|---|---|---|---|
| | | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | 2.3 | | 4.6 | 4.8 | 6 | 8 | 13 | 15 |
| 1.25 | 3.0 | | 4.7 | 5.0 | 7 | 9 | 16 | 18 |
| 1.50 | 4.4 | | 4.7 | 5 | 7 | 11 | 18 | 21 |
| 2.00 | *** | | 4.8 | 5 | 8 | 13 | 23 | 27 |

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 5.4 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to 10.7 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 17: HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION II. SOLIDS DENSITY

TEMPERATURE 72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 32. | 68. | 185. | 389. | 804. | 1656. | 3394. | 6952. |
| GAMMA (pcf) | 63.4 | 67.9 | 74.1 | 77.8 | 80.4 | 82.8 | 84.8 | 86.9 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$GAMMA = MAX\ [GAMMA(I)\ (SIGMA1/SIGMA1(I))^{BETA(I)}\ ,GAMMAM]$$

Minimum bulk density GAMMAM = 52.4 pcf

| I | SIGMA1(I) psf | GAMMA(I) pcf | BETA(I) |
|---|---|---|---|
| 1 | 44.0 | 64.8 | .06472 |
| 2 | 102.7 | 71.0 | .10842 |
| 3 | 308.0 | 76.8 | .07156 |
| 4 | 601.4 | 79.5 | .05117 |
| 5 | 1188.1 | 81.7 | .03948 |
| 6 | 1774.8 | 83.0 | .04023 |
| 7 | 2361.5 | 83.8 | .03346 |

BULK MATERIAL 17:  HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW

WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .32 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 10.79 |
| Width of Oval (feet) | .17 | .27 | .53 | 1.03 | 2.04 | 4.07 | 5.48 |
| SIGMA (psf) | 7.6 | 12.6 | 28. | 63. | 140. | 299. | 412. |
| SIGMA1 (psf) | 9.5 | 16.0 | 36. | 82. | 182. | 387. | 532. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 27. | 26. | 26. | 26. | 26. | 25. | 25. |
| Hopper Angles<br>THETA-P (deg) | 25. | 25. | 25. | 26. | 27. | 27. | 28. |
| THETA-C (deg) | 14. | 14. | 15. | 15. | 16. | 16. | 16. |

WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  72.0 hrs
TEMPERATURE   72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | |
|---|---|---|---|---|---|
| Dia of Cone (feet) | .77 | 1.00 | 2.00 | 4.00 | 7.63 |
| Width of Oval (feet) | .41 | .53 | 1.03 | 2.05 | 3.88 |
| SIGMA (psf) | 20.6 | 27.6 | 63. | 138. | 281. |
| SIGMA1 (psf) | 26.5 | 35.7 | 83. | 183. | 370. |
| Wall Friction Angle<br>PHI-PRIME (deg) | 27. | 27. | 26. | 26. | 26. |
| Hopper Angles<br>THETA-P (deg) | 25. | 25. | 25. | 26. | 26. |
| THETA-C (deg) | 14. | 14. | 14. | 15. | 15. |

```
                       BULK MATERIAL 17:  HLW D: AZ102

                       PARTICLE SIZE As Rec'd

                       MOISTURE CONTENT As Rec'd




WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .31    .50   1.00   2.00   4.00   8.00  10.85
Width of Oval (feet)      .17    .27    .53   1.03   2.04   4.07   5.51

SIGMA (psf)              7.6   12.8   28.    64.   140.   298.   412.
SIGMA1 (psf)             9.3   15.9   35.    82.   182.   388.   537.

Wall Friction Angle
PHI-PRIME (deg)         25.    25.    25.    25.    25.    25.    25.

Hopper Angles
THETA-P (deg)           26.    26.    26.    27.    27.    27.    27.
THETA-C (deg)           15.    15.    16.    16.    16.    16.    16.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  72.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .80   1.00   2.00   4.00   8.00   8.17
Width of Oval (feet)      .43    .53   1.04   2.06   4.11   4.20

SIGMA (psf)             20.6   26.5   60.   130.   275.   281.
SIGMA1 (psf)            28.3   36.6   85.   186.   396.   405.

Wall Friction Angle
PHI-PRIME (deg)         29.    29.    29.    29.    29.    29.

Hopper Angles
THETA-P (deg)           21.    21.    21.    21.    21.    21.
THETA-C (deg)           10.    10.    10.    10.    10.    10.
```

## BULK MATERIAL 17:  HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

```
WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .32     .50    1.00    2.00    4.00    8.00   10.89
Width of Oval (feet)      .18     .27     .53    1.04    2.05    4.07    5.54

SIGMA (psf)              7.6    12.4    27.     62.    138.    296.    412.
SIGMA1 (psf)             9.8    16.1    36.     83.    183.    390.    541.

Wall Friction Angle
PHI-PRIME (deg)         28.     28.     28.     27.     26.     26.     26.

Hopper Angles
THETA-P (deg)           23.     23.     23.     24.     25.     26.     27.
THETA-C (deg)           13.     13.     13.     14.     14.     15.     15.
```

```
WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  72.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .85    1.00    2.00    4.00    8.00    8.06
Width of Oval (feet)      .45     .53    1.04    2.06    4.10    4.13

SIGMA (psf)             20.6    25.1    59.    131.    279.    281.
SIGMA1 (psf)            31.1    37.4    86.    189.    401.    405.

Wall Friction Angle
PHI-PRIME (deg)         33.     32.     30.     30.     29.     29.

Hopper Angles
THETA-P (deg)           16.     17.     20.     21.     21.     21.
THETA-C (deg)            6.      7.      9.     10.     10.     10.
```

## BULK MATERIAL 17: HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION IV. CRITICAL STEADY SOLIDS FLOW RATES IN AIR

TEMPERATURE 72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .01 | .01 | .01 | .01 | .01 |
| .50 feet | .10 | .08 | .08 | .07 | .07 |
| .75 feet | .25 | .22 | .20 | .20 | .18 |
| 1.00 feet | .49 | .41 | .40 | .36 | .34 |
| 2.00 feet | 2.1 | 1.8 | 1.7 | 1.6 | 1.5 |
| 4.00 feet | 8.9 | 7.8 | 7.2 | 6.7 | 6.4 |
| 8.00 feet | 36. | 32. | 28. | 27. | 27. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .25 feet | .11 | .10 | .09 | .08 | .08 |
| .50 feet | .29 | .25 | .23 | .22 | .22 |
| .75 feet | .49 | .41 | .40 | .36 | .34 |
| 1.00 feet | .67 | .58 | .54 | .50 | .49 |
| 2.00 feet | 1.4 | 1.2 | 1.1 | 1.0 | 1.0 |
| 4.00 feet | 2.9 | 2.5 | 2.3 | 2.2 | 2.0 |
| 8.00 feet | 5.8 | 5.1 | 4.7 | 4.4 | 4.2 |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 17:  HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION V.  AIR PERMEABILITY TEST RESULTS

Temperature  68 deg F

K, the AIR permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\,(GAMMA) / (dp/dx)$$

where:

u = superficial AIR velocity through the bed of solids

dp/dx = AIR pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\,(GAMMA / GAMMA0)^{-a}$$

At room temperature, for GAMMA between   57.0 and   83.9 pcf:

K0 =  .001295 ft/s

GAMMA0 =   59.9 pcf

a =   4.88

BULK MATERIAL 17:  HLW D: AZ102

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION VI.  CHUTE ANGLES

Tests were conducted at the indicated impact pressures, temperatures, and time(s) at rest to determine the angles required for nonconverging chutes in order to maintain flow after material impact.  The angle given is the minimum angle from the horizontal that will cause a bed of material to slide on the chute.  In general, chutes should be designed with at least a 5 degree safety margin on this angle; if the chute converges, a significantly steeper chute may be required.

| Chute Material | Temperature(deg F) Material | Temperature(deg F) Chute | Time at Rest (hours) | Impact Pressure (psf) | Chute Angles (deg) Range | Chute Angles (deg) Min. Rec. |
|---|---|---|---|---|---|---|
| 304 #2B Finish Stainless Steel Sheet | 72 | 72 | .0 | 3.4 | 29 to 30 | 35. |
| | | | | 42.5 | 37 to 44 | 50. |
| | | | | 81.7 | 39 to 46 | 51. |
| | | | | 159.9 | 37 to 44 | 50. |
| Tivar-88 | 72 | 72 | .0 | 3.4 | 30 to 32 | 38. |
| | | | | 42.5 | 33 to 34 | 39. |
| | | | | 81.7 | 31 to 34 | 40. |
| | | | | 159.9 | 31 to 34 | 39. |
| Mild Carbon Steel Plate, Mill Finish | 72 | 72 | .0 | 3.4 | 32 to 33 | 39. |
| | | | | 42.5 | 43 to 47 | 53. |
| | | | | 81.7 | 54 to 59 | 64. |
| | | | | 159.9 | 55 to 61 | 67. |

## BULK MATERIAL 18: HLW D: C106/AY104

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION I. BIN DIMENSIONS FOR DEPENDABLE FLOW

Storage Time at Rest .0 hrs
Temperature 72 deg F

### PART A. BINS WITH UNLIMITED MAXIMUM SIZE

Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | .6 | .3 |
| 1.25 | .7 | .3 |
| 1.50 | 1.0 | .4 |
| 2.00 | 5.5 | 1.2 |

Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 13 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | .4 | 1.1 | 1.6 | 3.3 | 6 | 12 | 16 |
| 1.25 | .6 | 1.2 | 1.9 | 4.0 | 8 | 15 | 19 |
| 1.50 | 1.3 | 1.4 | 2.1 | 4.6 | 9 | 17 | 23 |
| 2.00 | *** | 1.6 | 2.5 | 6 | 12 | 23 | 30 |

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 5.5 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

BULK MATERIAL 18: HLW D: C106/AY104

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

Storage Time at Rest 72.0 hrs
Temperature 72 deg F

## PART A. BINS WITH UNLIMITED MAXIMUM SIZE

### Optimum Mass Flow Dimensions

| P-Factor | BC feet | BP feet |
|---|---|---|
| 1.00 | 6.0 | 2.2 |
| 1.25 | +++ | *** |
| 1.50 | +++ | *** |
| 2.00 | +++ | *** |

### Funnel Flow Dimensions

| P-Factor | BF (feet) | EH= .5 | 1.0 | 2.5 | 5 | 10 | 13 feet |
|---|---|---|---|---|---|---|---|
| | | Critical Rathole Diameters, DF (feet) | | | | | |
| 1.00 | *** | 2.7 | 3.6 | 7 | 12 | 22 | 29 |
| 1.25 | *** | 2.9 | 4.0 | 8 | 14 | 27 | 35 |
| 1.50 | *** | 3.1 | 4.4 | 9 | 17 | 32 | 41 |
| 2.00 | *** | 3.5 | 5 | 11 | 21 | 42 | 54 |

*** Denotes unassisted gravity flow is impossible. However, widths of only up to 10.1 feet were simulated by our tests. If larger widths are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

+++ Denotes unassisted gravity flow is impossible. However, diameters of only up to 20.1 feet were simulated by our tests. If larger diameters are practical for your application, further testing at higher pressures might reveal conditions under which unassisted gravity flow is possible.

### TERMS

P-FACTOR = overpressure factor
BC = recommended minimum outlet diameter, conical hopper
BP = recommended minimum outlet width, slotted or oval outlet
BF = minimum width of rectanglar outlet in a funnel flow bin
EH = effective consolidating head

For detailed explanations of terms see appendix pages A5, A6, and A7.

## BULK MATERIAL 18:  HLW D: C106/AY104

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION II.  SOLIDS DENSITY

TEMPERATURE   72 deg F

### BULK DENSITY

The bulk density, GAMMA, is a function of the major consolidating pressure, SIGMA1, expressed in terms of effective head, EH.

| EH (feet) | .5 | 1.0 | 2.5 | 5.0 | 10.0 | 20.0 | 40.0 | 80.0 |
|---|---|---|---|---|---|---|---|---|
| SIGMA1 (psf) | 27. | 57. | 163. | 347. | 724. | 1511. | 3082. | 6257. |
| GAMMA (pcf) | 53.8 | 57.2 | 65.2 | 69.4 | 72.4 | 75.5 | 77.0 | 78.2 |

### COMPRESSIBILITY PARAMETERS

Bulk density, GAMMA, is a function of the major consolidating pressure SIGMA1, as follows:

For SIGMA1(I-1) < SIGMA1 < SIGMA1(I) :

$$\mathrm{GAMMA} = \mathrm{MAX}\left[\mathrm{GAMMA(I)}\ (\mathrm{SIGMA1/SIGMA1(I)})^{\mathrm{BETA(I)}}, \mathrm{GAMMAM}\right]$$

Minimum bulk density GAMMAM =  47.2 pcf

| I | SIGMA1(I) | GAMMA(I) | BETA(I) |
|---|---|---|---|
| | psf | pcf | |
| 1 | 44.0 | 55.0 | .04492 |
| 2 | 102.7 | 62.6 | .15428 |
| 3 | 308.0 | 68.9 | .08647 |
| 4 | 601.4 | 71.6 | .05723 |
| 5 | 1188.1 | 74.6 | .06156 |
| 6 | 1774.8 | 76.2 | .04989 |
| 7 | 2361.5 | 76.6 | .02116 |

BULK MATERIAL 18:  HLW D: C106/AY104

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION III.  MAXIMUM HOPPER ANGLES FOR MASS FLOW

```
WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .35    .50   1.00   2.00   4.00   8.00  12.68
Width of Oval (feet)      .19    .28    .54   1.06   2.09   4.15   6.56

SIGMA (psf)              7.0   10.2   22.    50.   113.   248.   411.
SIGMA1 (psf)             8.9   13.0   29.    66.   151.   328.   535.

Wall Friction Angle
PHI-PRIME (deg)         28.    28.    28.    28.    27.    27.    26.

Hopper Angles
THETA-P (deg)           23.    23.    23.    23.    24.    25.    26.
THETA-C (deg)           12.    12.    12.    13.    13.    14.    15.
```

```
WALL MATERIAL:  304 #2B Finish Stainless Steel Sheet
STORAGE TIME AT REST  72.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)       1.12   2.00   4.00   8.00   9.61
Width of Oval (feet)      .62   1.09   2.14   4.19   5.01

SIGMA (psf)             20.0   41.4    96.   225.   281.
SIGMA1 (psf)            36.9   73.7   167.   344.   414.

Wall Friction Angle
PHI-PRIME (deg)         48.    42.    37.    32.    31.

Hopper Angles
THETA-P (deg)            8.*   10.*   11.*   17.    19.
THETA-C (deg)            0.*    0.*    1.*    6.     8.

*  Flow along walls is questionable.
```

```
                     BULK MATERIAL 18:  HLW D: C106/AY104

                     PARTICLE SIZE As Rec'd

                     MOISTURE CONTENT As Rec'd



WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .36    .50   1.00   2.00   4.00   8.00  12.67
Width of Oval (feet)      .20    .28    .54   1.06   2.09   4.15   6.55

SIGMA (psf)              7.0   10.1   22.    51.   116.   251.   411.
SIGMA1 (psf)             9.3   13.1   29.    65.   150.   326.   534.

Wall Friction Angle
PHI-PRIME (deg)         30.    29.    27.    26.    26.    26.    26.

Hopper Angles
THETA-P (deg)           23.    23.    24.    25.    25.    26.    26.
THETA-C (deg)           11.    12.    13.    15.    15.    15.    15.


WALL MATERIAL:  Tivar-88
STORAGE TIME AT REST  72.0 hrs
TEMPERATURE   72 deg F

                  HOPPER ANGLES FOR VARIOUS HOPPER SPANS

Dia of Cone (feet)        .91   1.00   2.00   4.00   8.00   8.92
Width of Oval (feet)      .49    .54   1.06   2.09   4.15   4.62

SIGMA (psf)             20.0   22.2   50.   115.   250.   281.
SIGMA1 (psf)            25.9   28.7   65.   150.   327.   368.

Wall Friction Angle
PHI-PRIME (deg)         28.    27.    27.    26.    26.    26.

Hopper Angles
THETA-P (deg)           24.    24.    24.    25.    25.    25.
THETA-C (deg)           13.    13.    14.    15.    15.    15.
```

BULK MATERIAL 18:  HLW D: C106/AY104

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  .00 hrs
TEMPERATURE   72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dia of Cone (feet) | .38 | .50 | 1.00 | 2.00 | 4.00 | 8.00 | 12.79 |
| Width of Oval (feet) | .21 | .28 | .54 | 1.06 | 2.09 | 4.15 | 6.62 |
| SIGMA (psf) | 6.7 | 9.2 | 21. | 49. | 113. | 248. | 411. |
| SIGMA1 (psf) | 10.2 | 13.7 | 30. | 67. | 152. | 329. | 543. |
| Wall Friction Angle | | | | | | | |
| PHI-PRIME (deg) | 36. | 35. | 32. | 29. | 28. | 27. | 27. |
| Hopper Angles | | | | | | | |
| THETA-P (deg) | 17. | 18. | 19. | 21. | 23. | 24. | 25. |
| THETA-C (deg) | 4. | 6. | 8. | 11. | 13. | 14. | 14. |

WALL MATERIAL:  Mild Carbon Steel Plate, Mill Finish
STORAGE TIME AT REST  72.0 hrs
TEMPERATURE   72 deg F

HOPPER ANGLES FOR VARIOUS HOPPER SPANS

| | | | | | |
|---|---|---|---|---|---|
| Dia of Cone (feet) | 1.12 | 2.00 | 4.00 | 8.00 | 9.38 |
| Width of Oval (feet) | .62 | 1.09 | 2.14 | 4.19 | 4.88 |
| SIGMA (psf) | 20.0 | 41.4 | 96. | 226. | 281. |
| SIGMA1 (psf) | 36.9 | 73.7 | 167. | 344. | 399. |
| Wall Friction Angle | | | | | |
| PHI-PRIME (deg) | 46. | 44. | 40. | 32. | 30. |
| Hopper Angles | | | | | |
| THETA-P (deg) | 8.* | 10.* | 11.* | 17. | 20. |
| THETA-C (deg) | 0.* | 0.* | 1.* | 6. | 10. |

*  Flow along walls is questionable.

BULK MATERIAL 18:  HLW D: C106/AY104

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION IV.  CRITICAL STEADY SOLIDS FLOW RATES IN Air

TEMPERATURE  72.0 deg F

### CONICAL MASS FLOW HOPPER

Flow rate expressed in units of tons/hr.

| BC | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .75 feet | .29 | .23 | .20 | .18 | .18 |
| 1.00 feet | .79 | .65 | .58 | .52 | .50 |
| 2.00 feet | 4.9 | 4.0 | 3.6 | 3.2 | 3.1 |
| 4.00 feet | 23. | 19. | 16. | 15. | 14. |
| 8.00 feet | 100. | 82. | 73. | 66. | 63. |

### TRANSITION MASS FLOW HOPPER

Flow rate expressed in units of tons/hr per feet length of outlet.

| BP | EH = 2.5 feet | 5.0 feet | 10.0 feet | 20.0 feet | 40.0 feet |
|---|---|---|---|---|---|
| .50 feet | .40 | .32 | .29 | .25 | .25 |
| .75 feet | .94 | .76 | .67 | .61 | .58 |
| 1.00 feet | 1.4 | 1.1 | 1.0 | .95 | .92 |
| 2.00 feet | 3.6 | 2.9 | 2.6 | 2.3 | 2.2 |
| 4.00 feet | 7.9 | 6.4 | 5.7 | 5.1 | 4.9 |
| 8.00 feet | 16. | 13. | 11. | 10. | 10. |

### TERMS

BC = diameter of circular outlet
BP = width of slotted outlet
EH = effective consolidating head

BULK MATERIAL 18: HLW D: C106/AY104

PARTICLE SIZE As Rec'd

MOISTURE CONTENT As Rec'd

## SECTION V. Air PERMEABILITY TEST RESULTS

Temperature 68 deg F

K, the Air permeability factor of the solid is defined from Darcy's law in the following form:

$$K = -u\ (GAMMA)\ /\ (dp/dx)$$

where:

u = superficial Air velocity through the bed of solids

dp/dx = Air pressure gradient across the bed

GAMMA = bulk density of the solid in the bed

K is a function of the bulk density of the solid

$$K = K0\ (GAMMA\ /\ GAMMA0)^{-a}$$

At room temperature, for GAMMA between 44.0 and 65.8 pcf:

K0 = .004634 ft/s

GAMMA0 = 52.0 pcf

a = 6.03

BULK MATERIAL 18: HLW D: C106/AY104

PARTICLE SIZE As Rec’d

MOISTURE CONTENT As Rec’d

## SECTION VI. CHUTE ANGLES

Tests were conducted at the indicated impact pressures, temperatures, and time(s) at rest to determine the angles required for nonconverging chutes in order to maintain flow after material impact. The angle given is the minimum angle from the horizontal that will cause a bed of material to slide on the chute. In general, chutes should be designed with at least a 5 degree safety margin on this angle; if the chute converges, a significantly steeper chute may be required.

| | Temperature(deg F) | | Time | Impact | Chute Angles (deg) | |
|---|---|---|---|---|---|---|
| Chute Material | Material | Chute | at Rest (hours) | Pressure (psf) | Range | Min. Rec. |
| 304 #2B Finish Stainless Steel Sheet | 72 | 72 | .0 | 3.0 | 29 to 33 | 39. |
| | | | | 42.1 | 55 to 58 | 63. |
| | | | | 81.2 | 58 to 72 | 77. |
| | | | | 159.5 | 49 to 72 | 77. |
| Tivar-88 | 72 | 72 | .0 | 3.0 | 30 to 31 | 36. |
| | | | | 42.1 | 32 to 42 | 47. |
| | | | | 81.2 | 29 to 32 | 38. |
| | | | | 159.5 | 30 to 35 | 40. |
| Mild Carbon Steel Plate, Mill Finish | 72 | 72 | .0 | 3.0 | 30 to 34 | 39. |
| | | | | 42.1 | 47 to 57 | 62. |
| | | | | 81.2 | 53 to 59 | 64. |
| | | | | 159.5 | 59 to 74 | 79. |

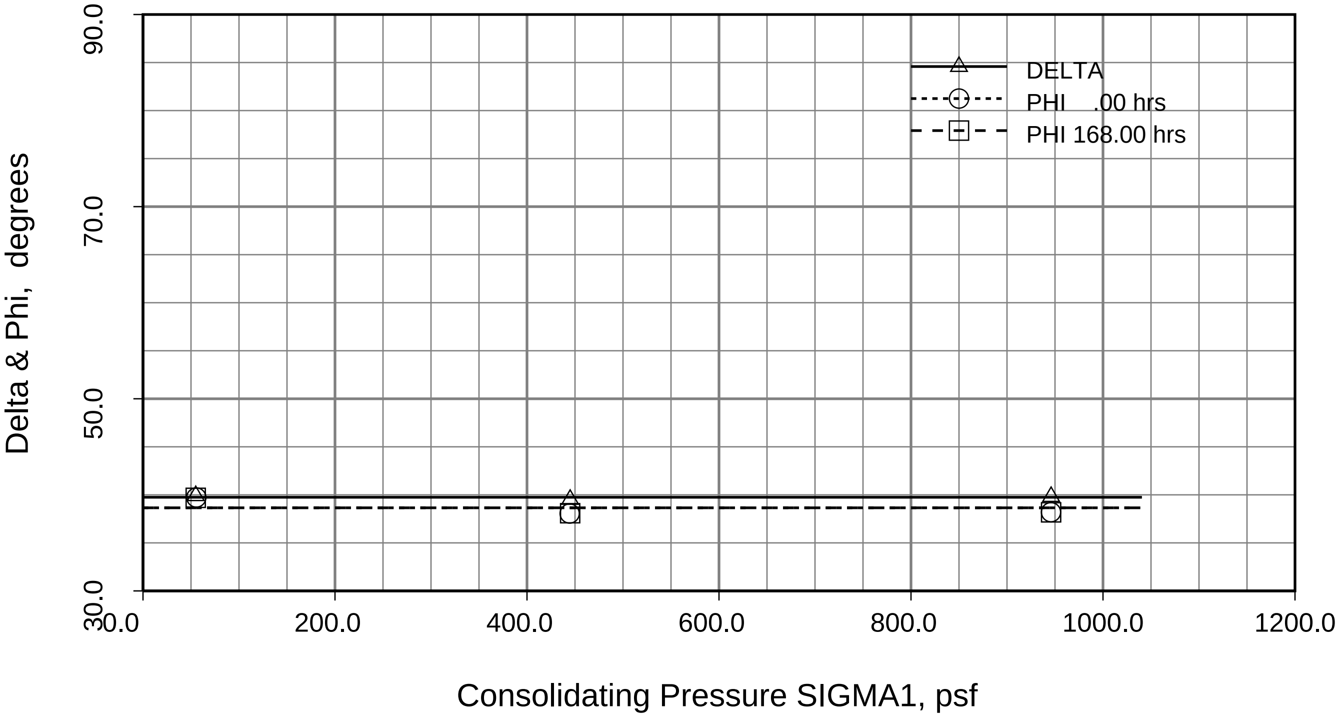
generic EM

BULK MATERIAL: Borax (ten mole)
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 8.0%

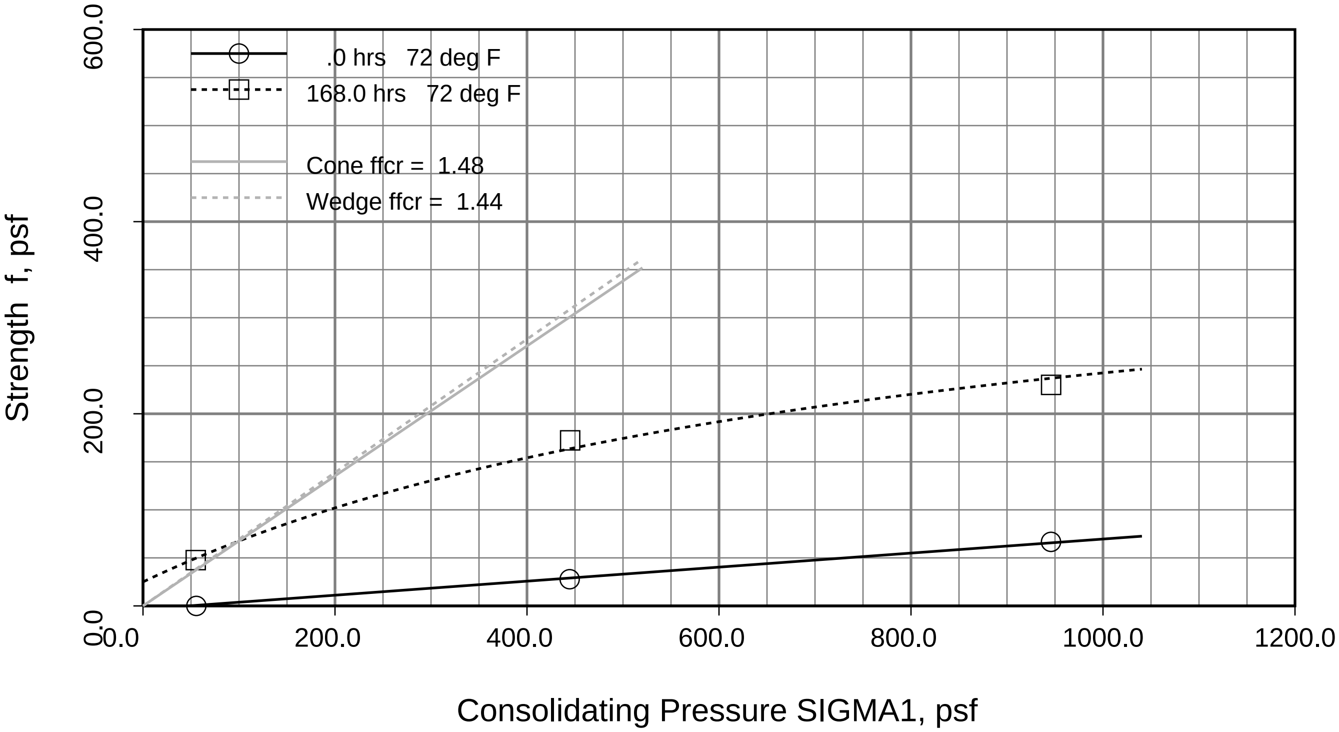
CREATE: 2/04/31
RUN: 2/06/26

JOB#: 994537
ID#: 22615

DELTA & PHI RELATIONS



FLOW FUNCTION(S)



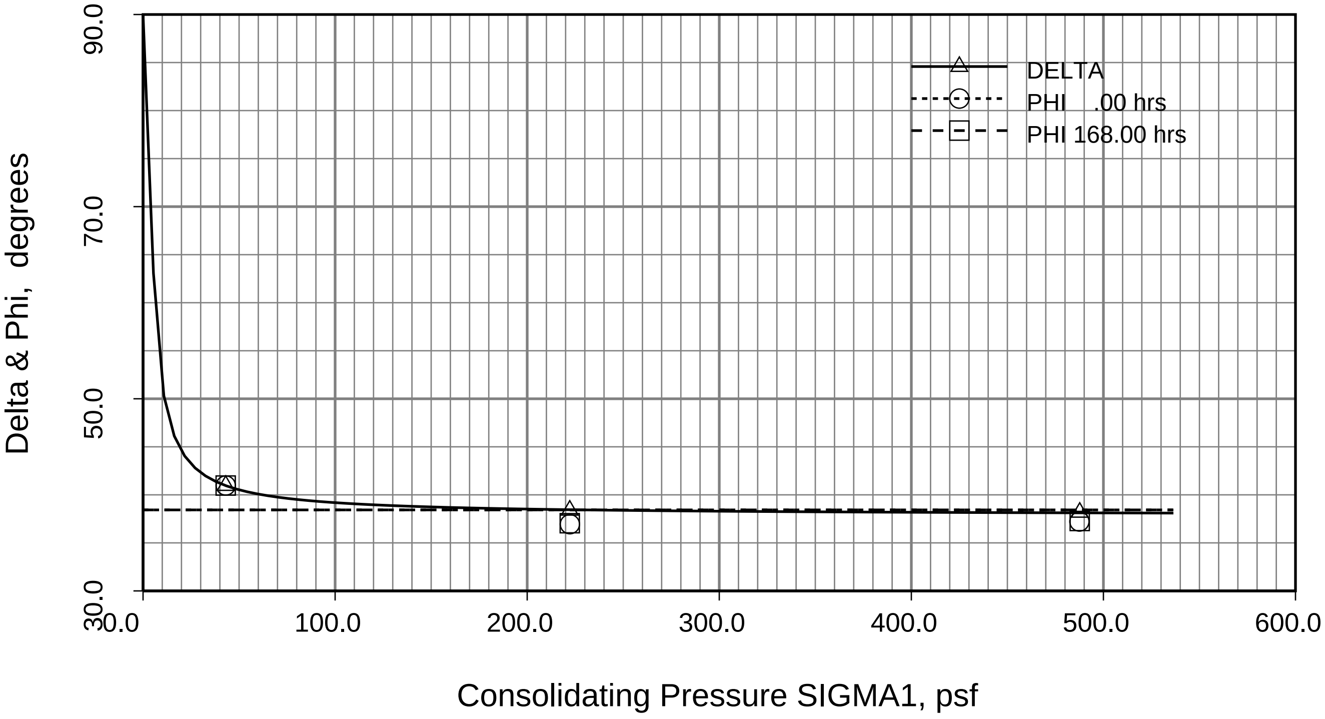
JENIKE & JOHANSON INCORPORATED

generic EM

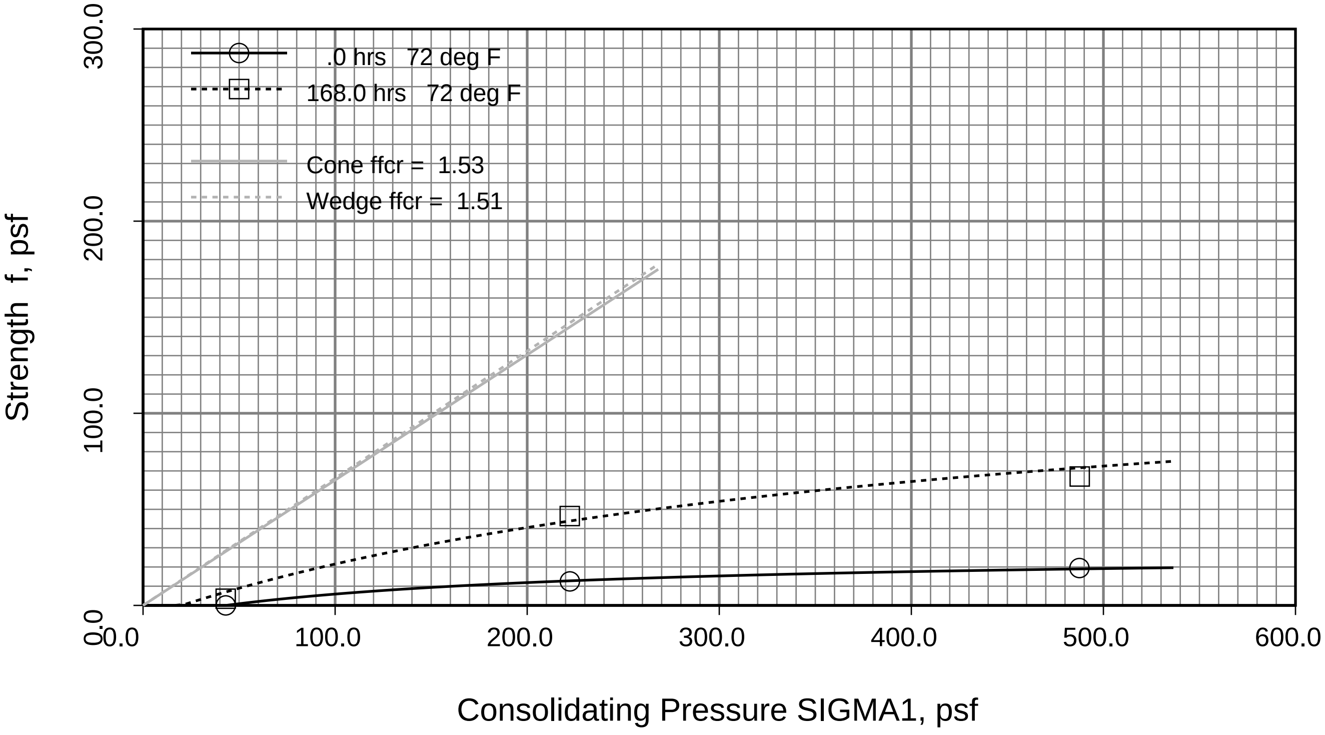
BULK MATERIAL: Boric acid
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.1%

CREATE: 2/04/29 JOB#: 994537
RUN: 2/06/26 ID#: 22609

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

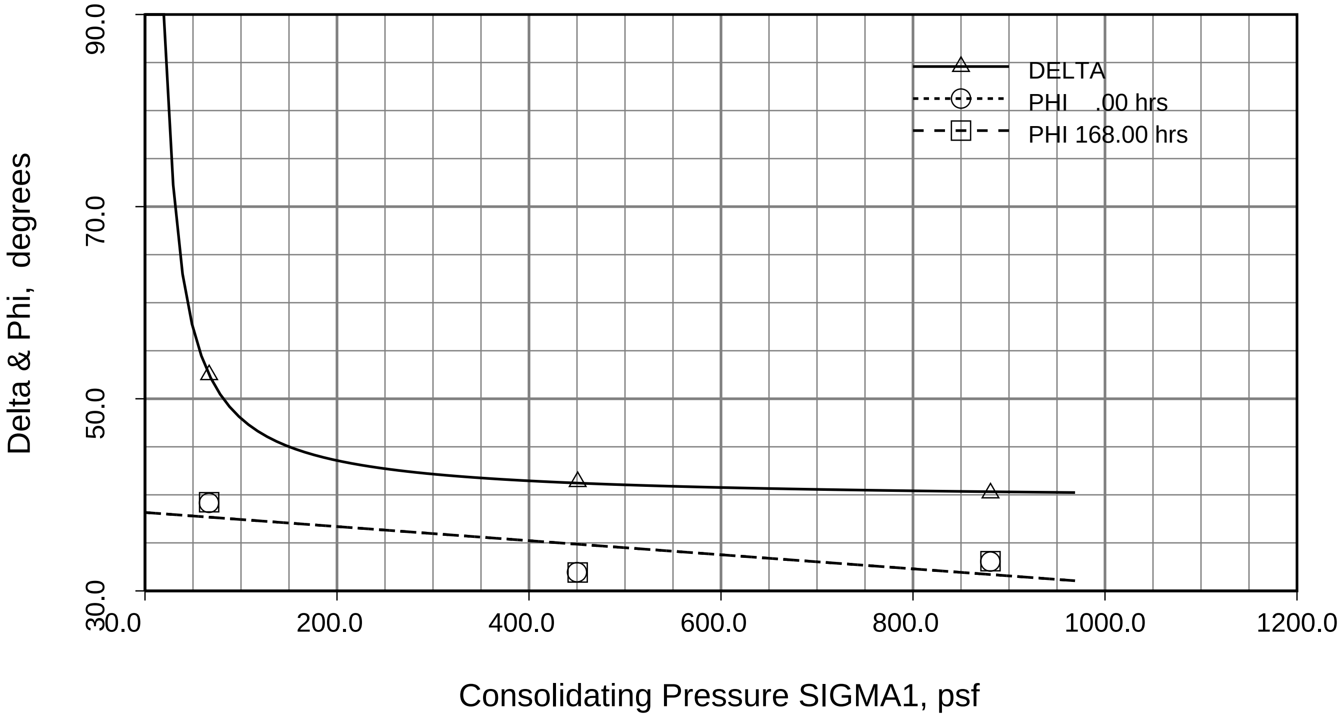
generic EM

BULK MATERIAL: Iron oxide
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.3%

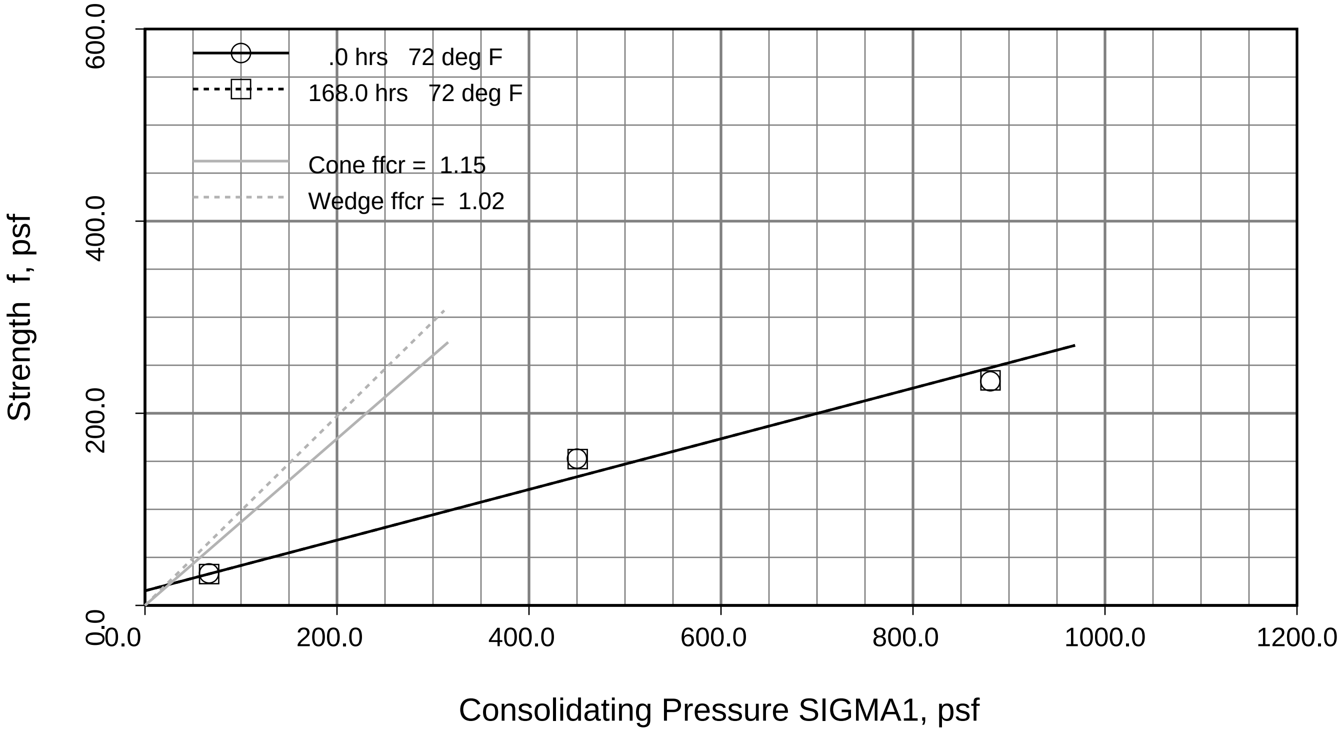
CREATE: 2/04/31
RUN: 2/06/26

JOB#: 994537
ID#: 22617

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

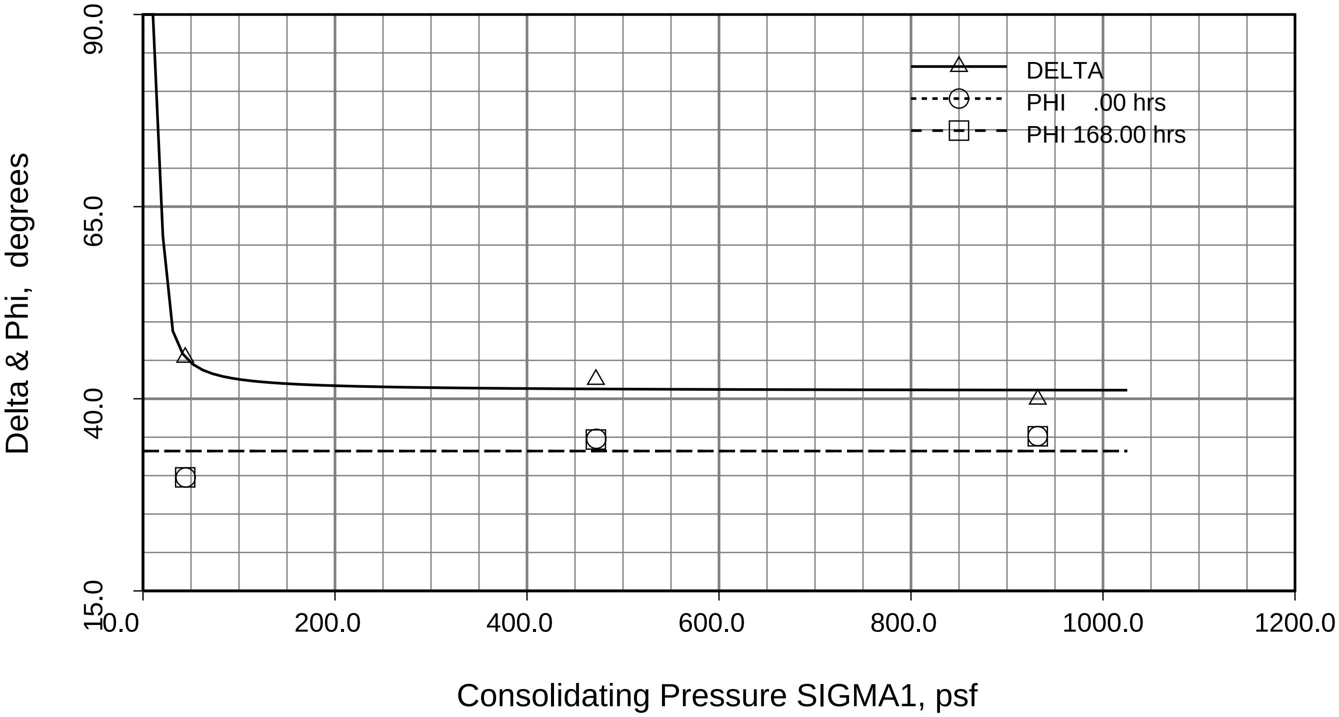
generic EM

BULK MATERIAL: Kyanite
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.1%

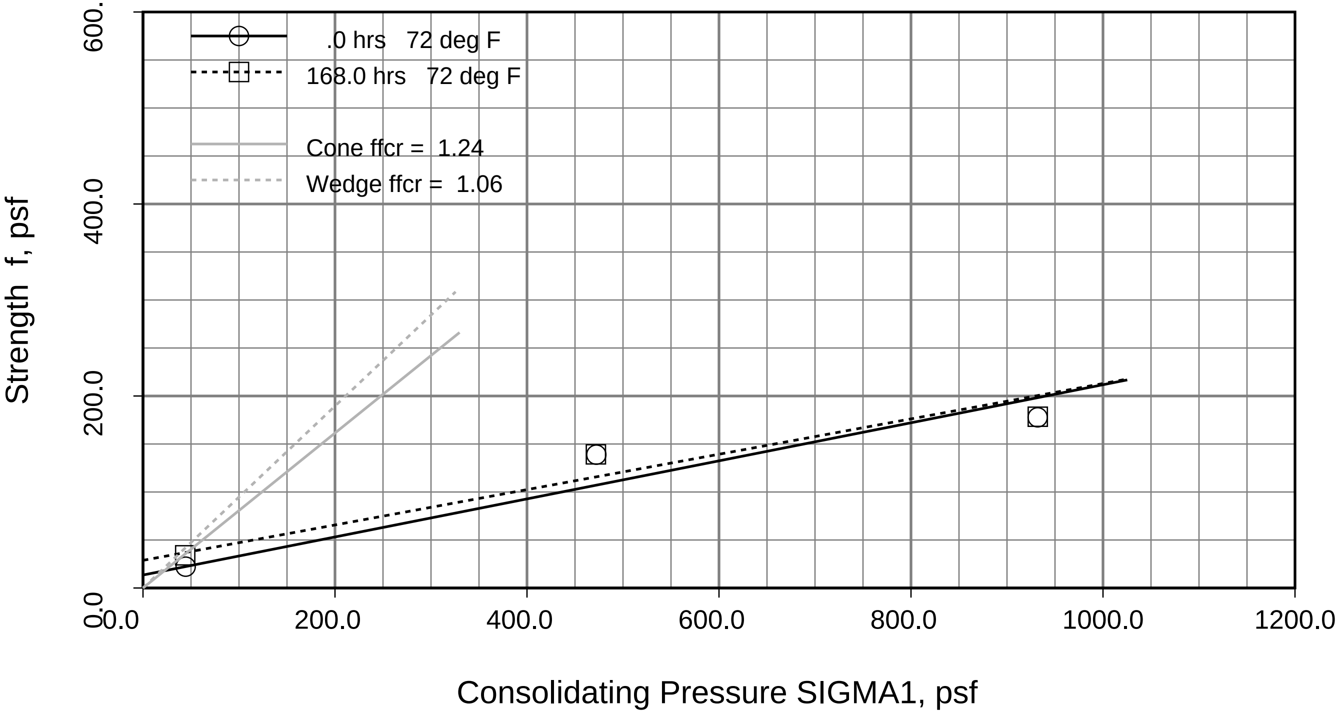
CREATE: 2/04/26
RUN: 2/06/26

JOB#: 994537
ID#: 22606

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

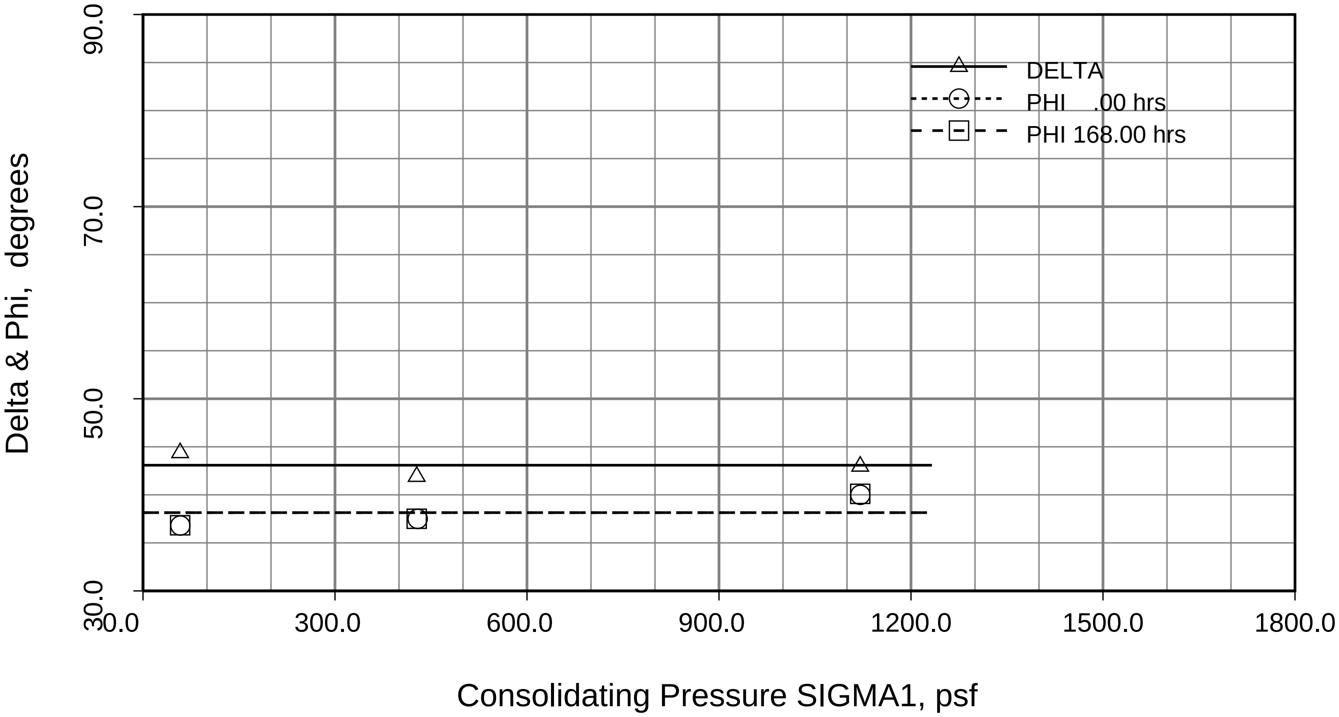
generic EM

BULK MATERIAL: Lithium carbonate
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.1%

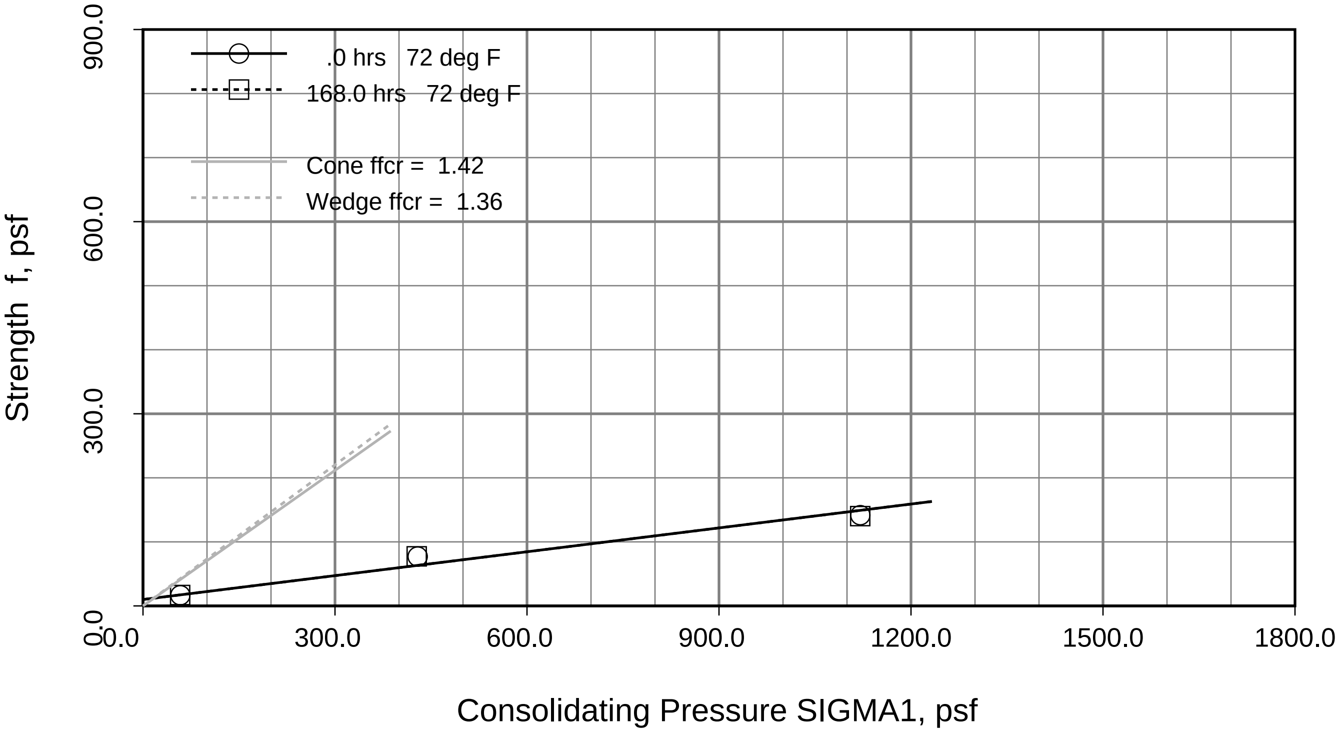
CREATE: 2/04/31
RUN: 2/06/26

JOB#: 994537
ID#: 22613

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

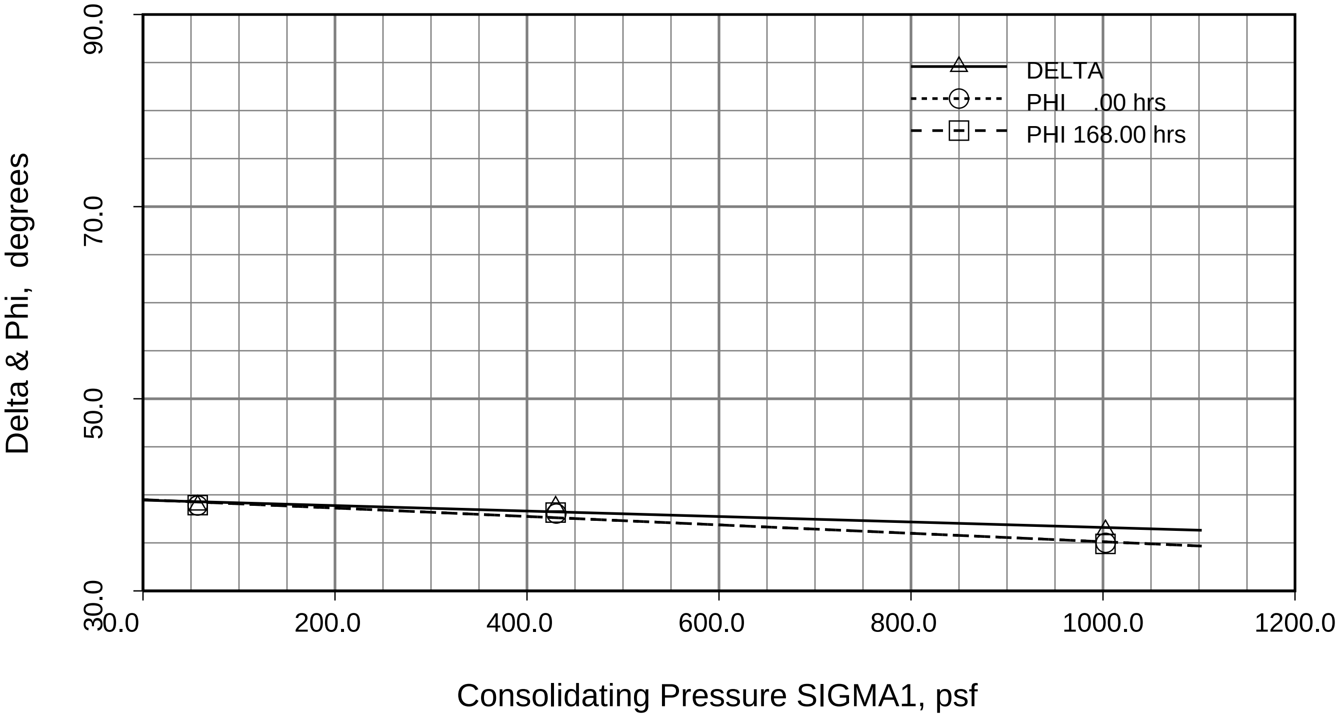
generic EM

BULK MATERIAL: Olivine
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.2%

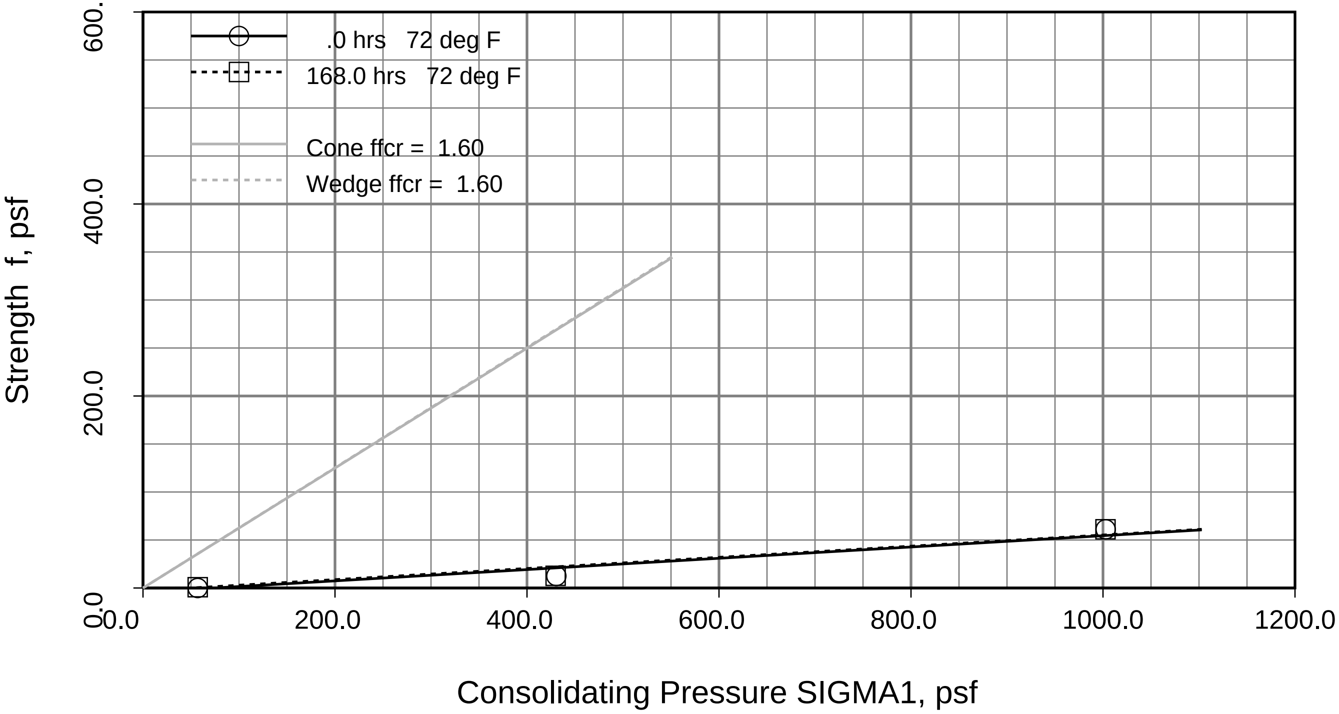
CREATE: 2/04/26
RUN: 2/06/26

JOB#: 994537
ID#: 22605

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

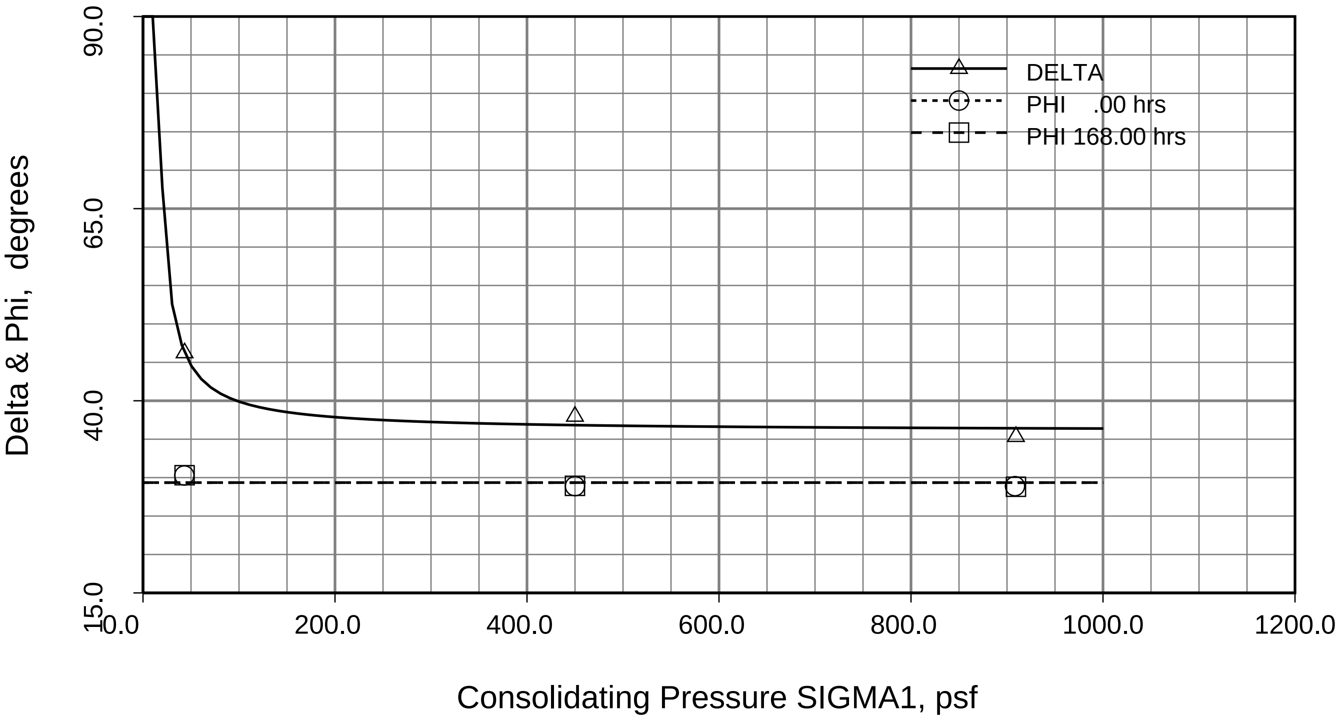
generic EM

BULK MATERIAL: Silica
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.1%

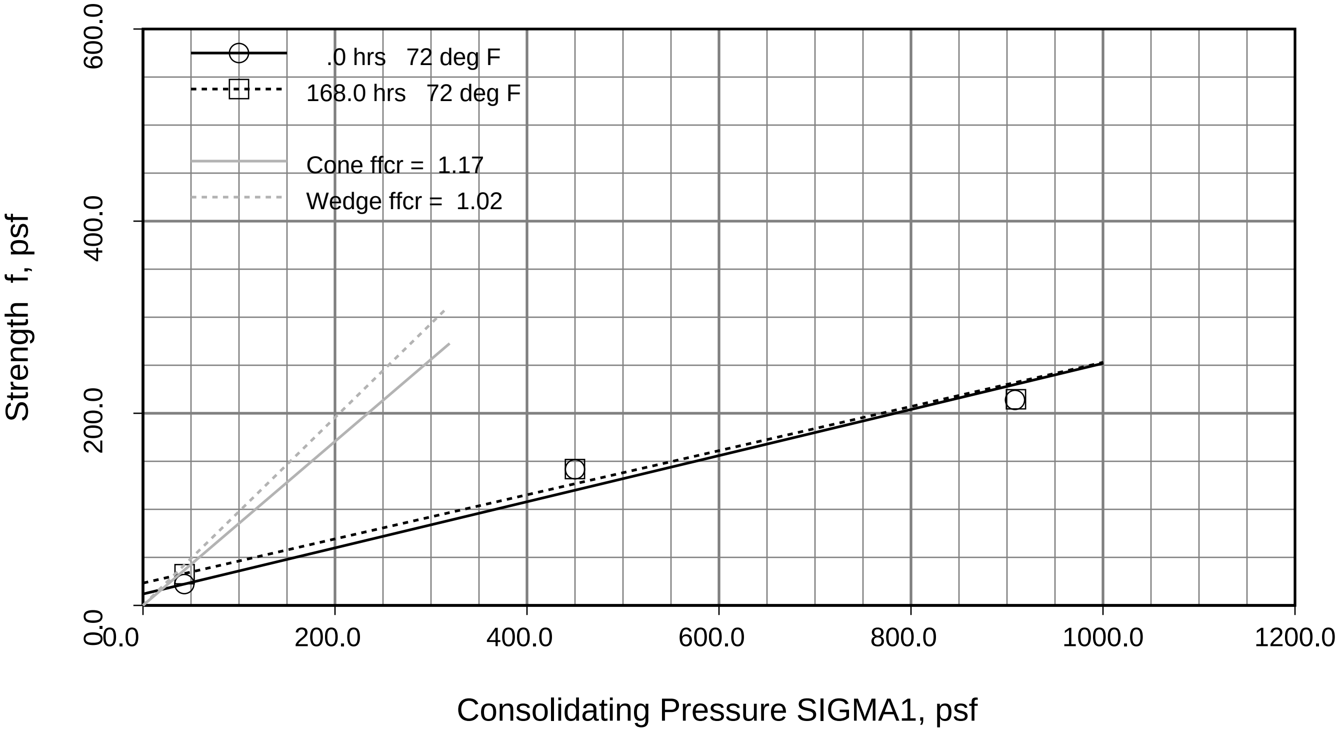
CREATE: 2/04/26
RUN: 2/06/26

JOB#: 994537
ID#: 22604

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

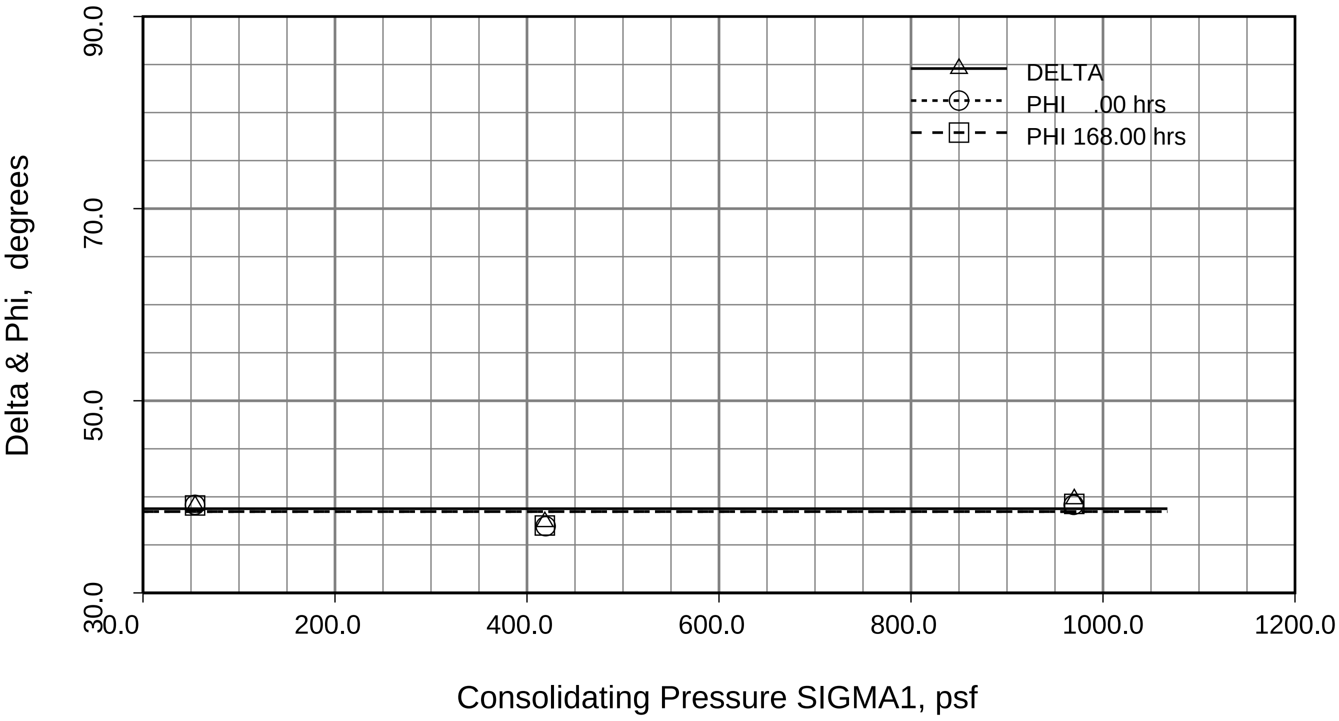
generic EM

BULK MATERIAL: Soda Ash
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.2%

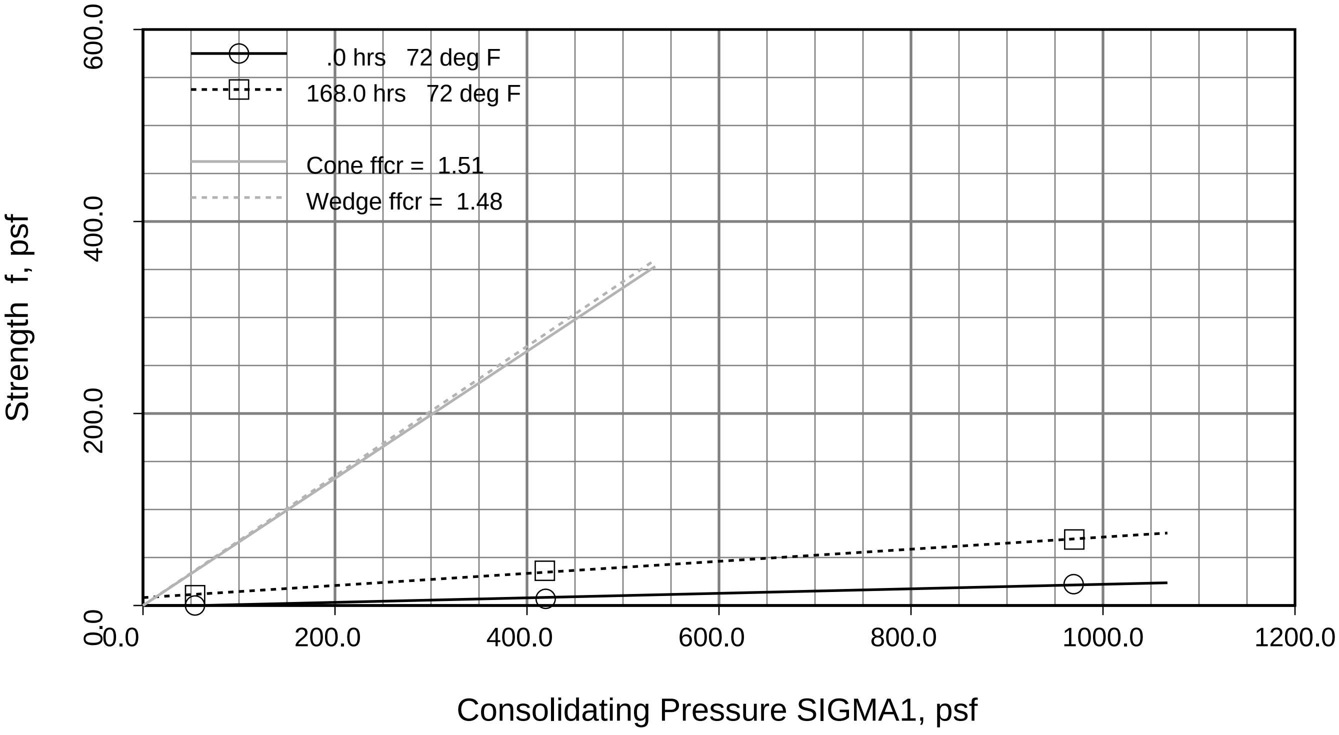
CREATE: 2/04/31
RUN: 2/06/26

JOB#: 994537
ID#: 22616

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

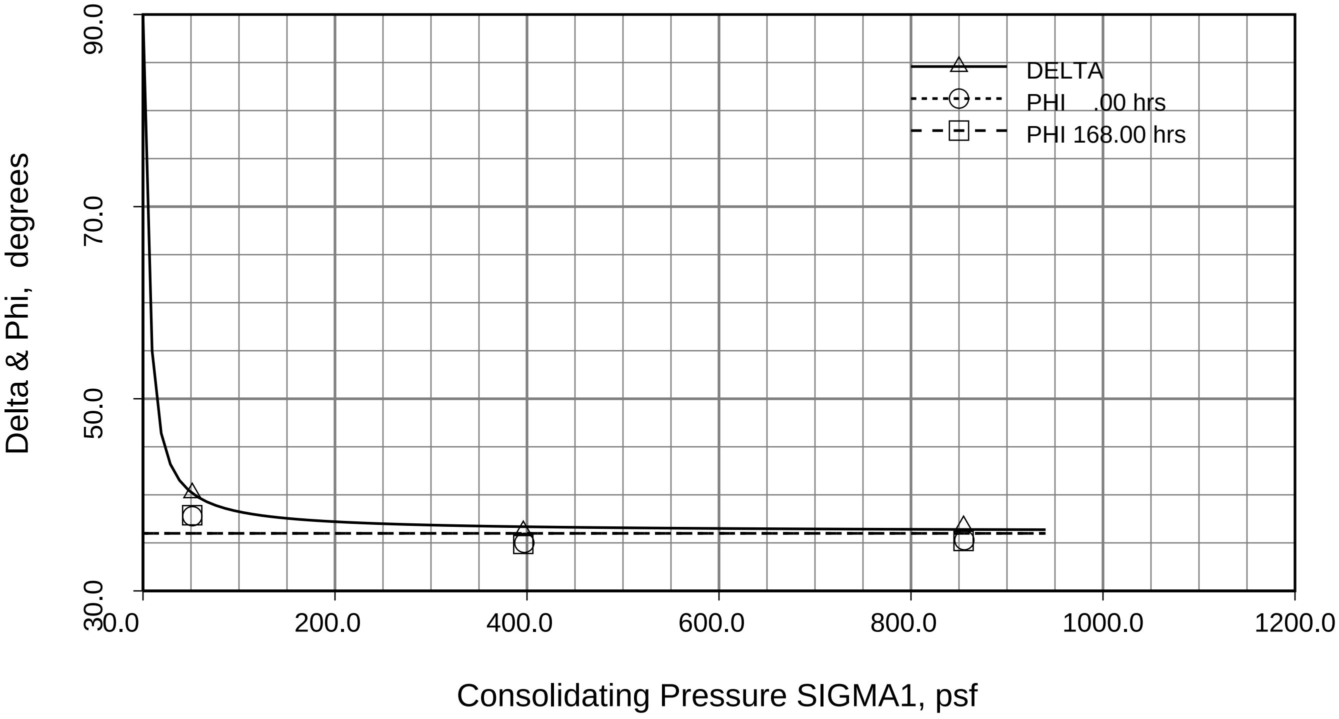
generic EM

BULK MATERIAL: Sugar
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.1%

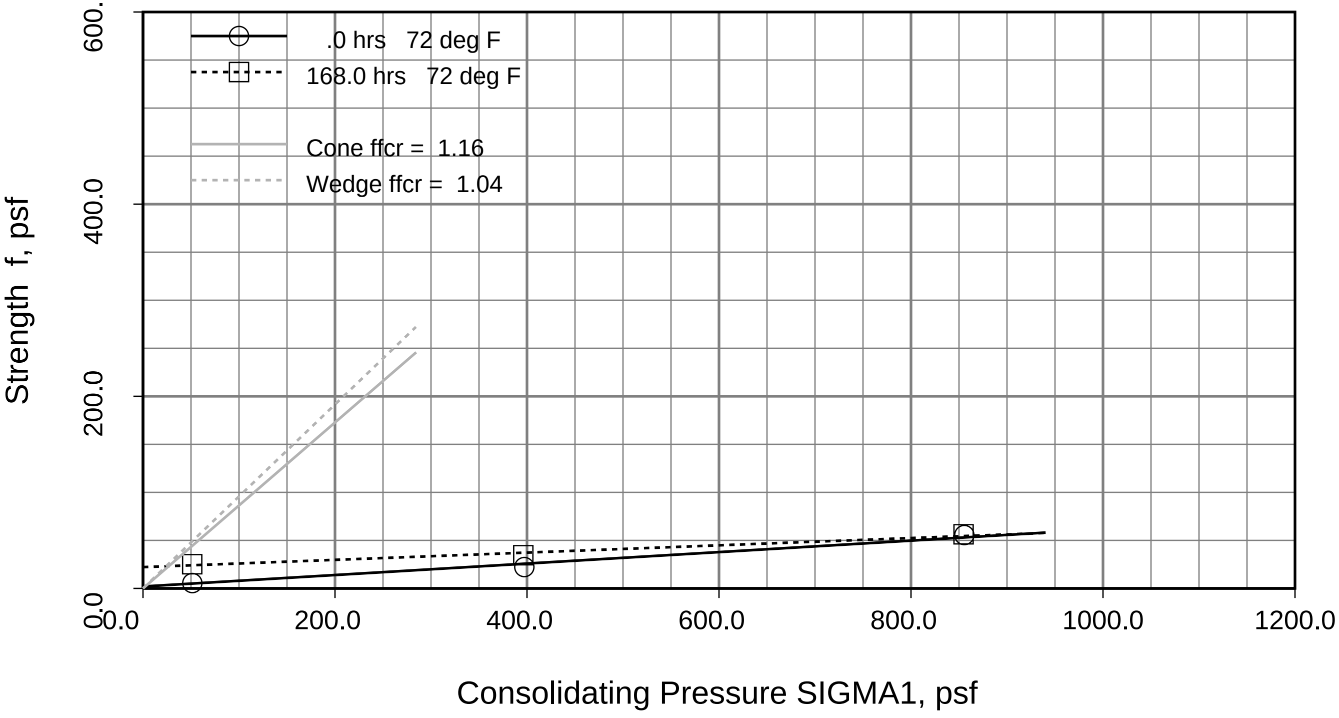
CREATE: 2/05/29
RUN: 2/06/26

JOB#: 994537
ID#: 22639

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON
INCORPORATED

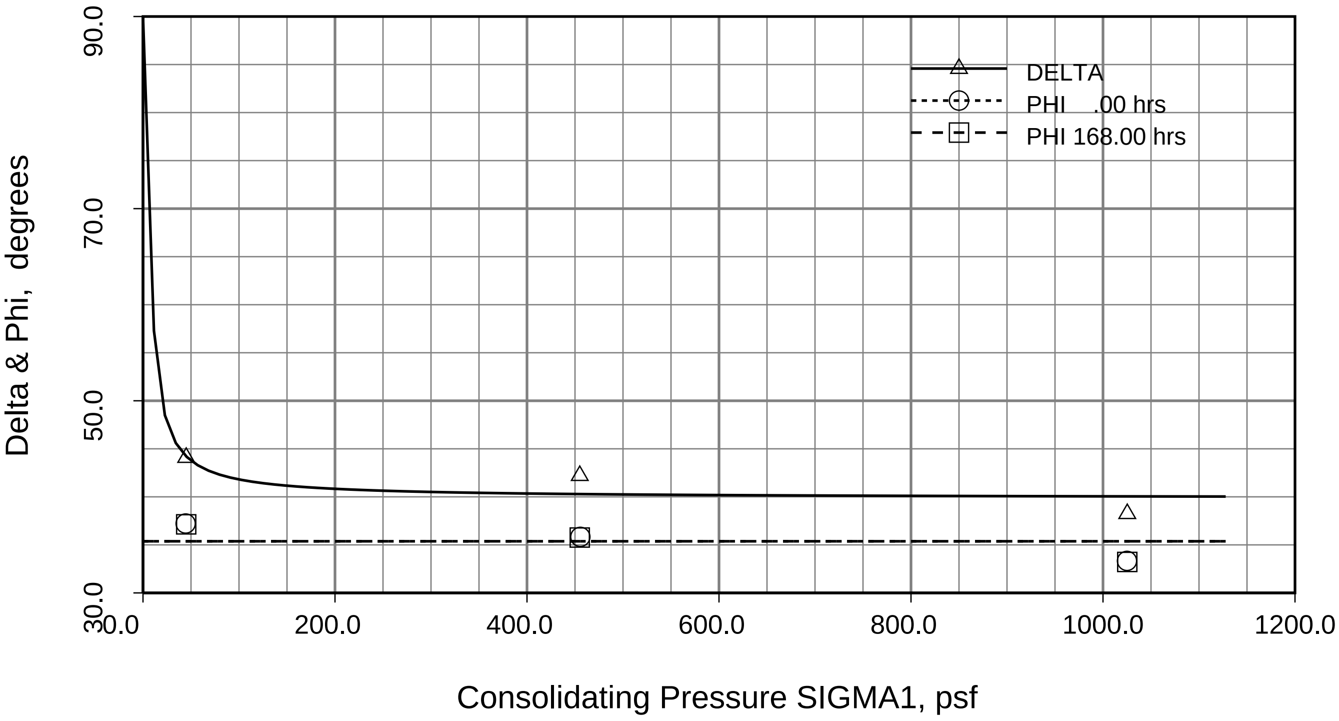
generic EM

BULK MATERIAL: Titanium dioxide
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.2%

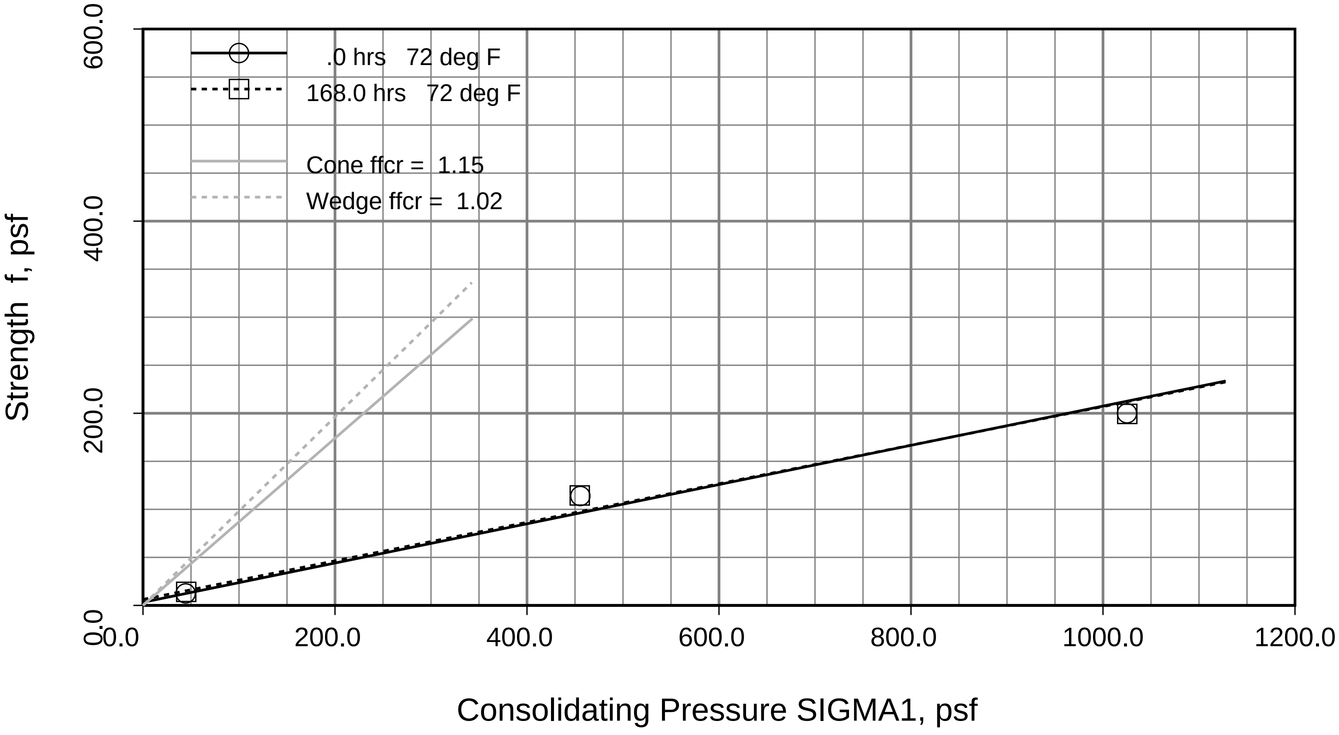
CREATE: 2/06/09
RUN: 2/06/26

JOB#: 4537
ID#: 22647

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



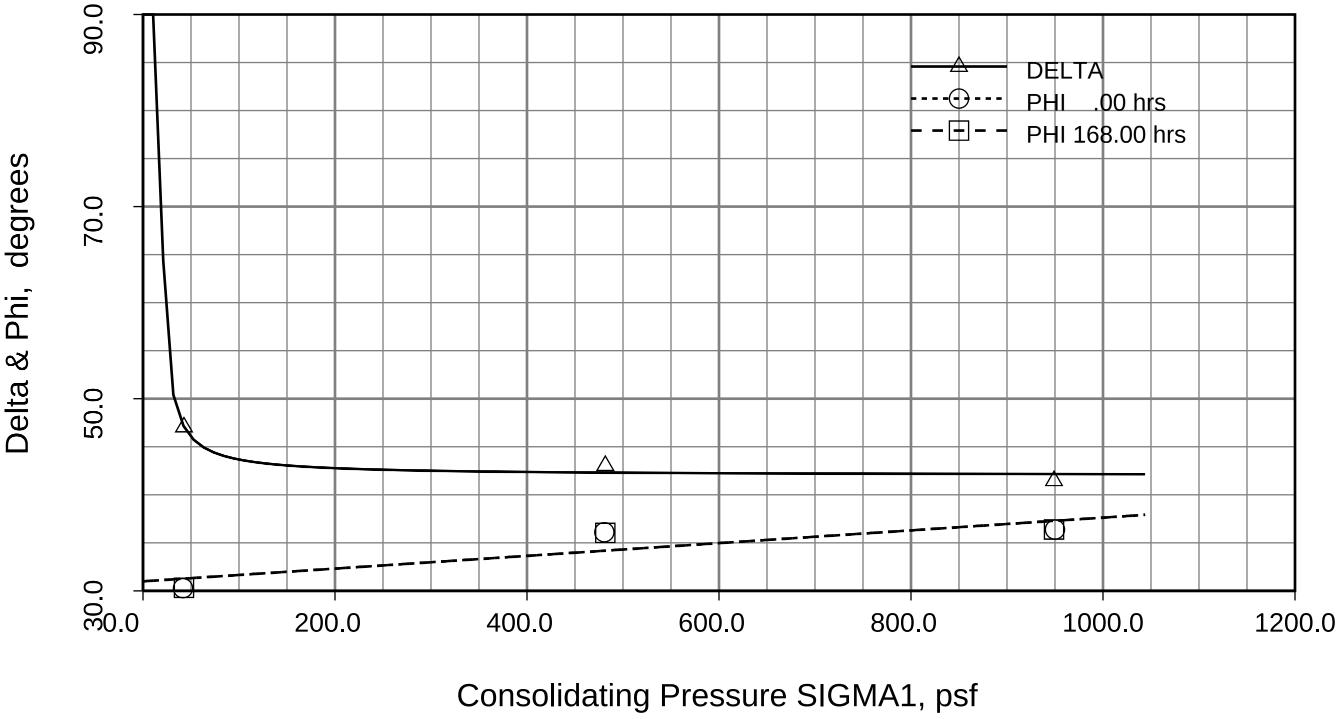
generic EM

BULK MATERIAL: Wollastonite
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.2%

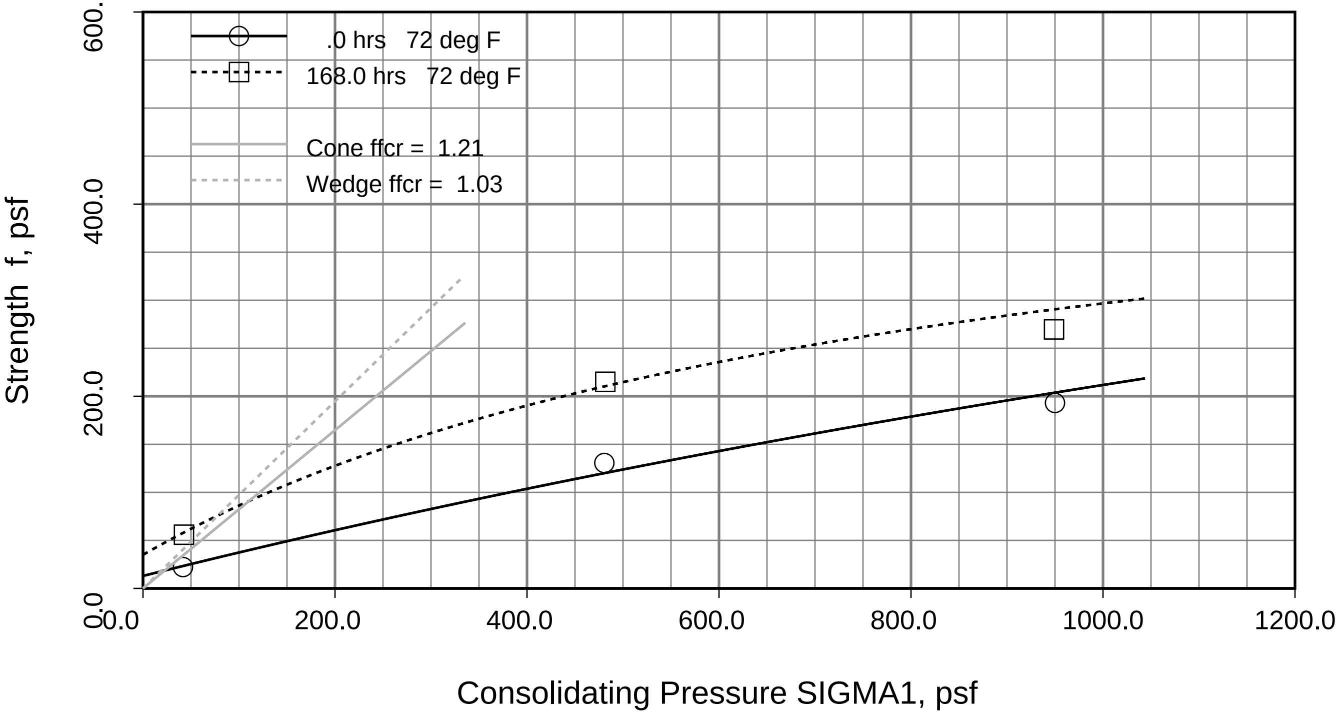
CREATE: 2/04/31
RUN: 2/06/26

JOB#: 994537
ID#: 22614

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

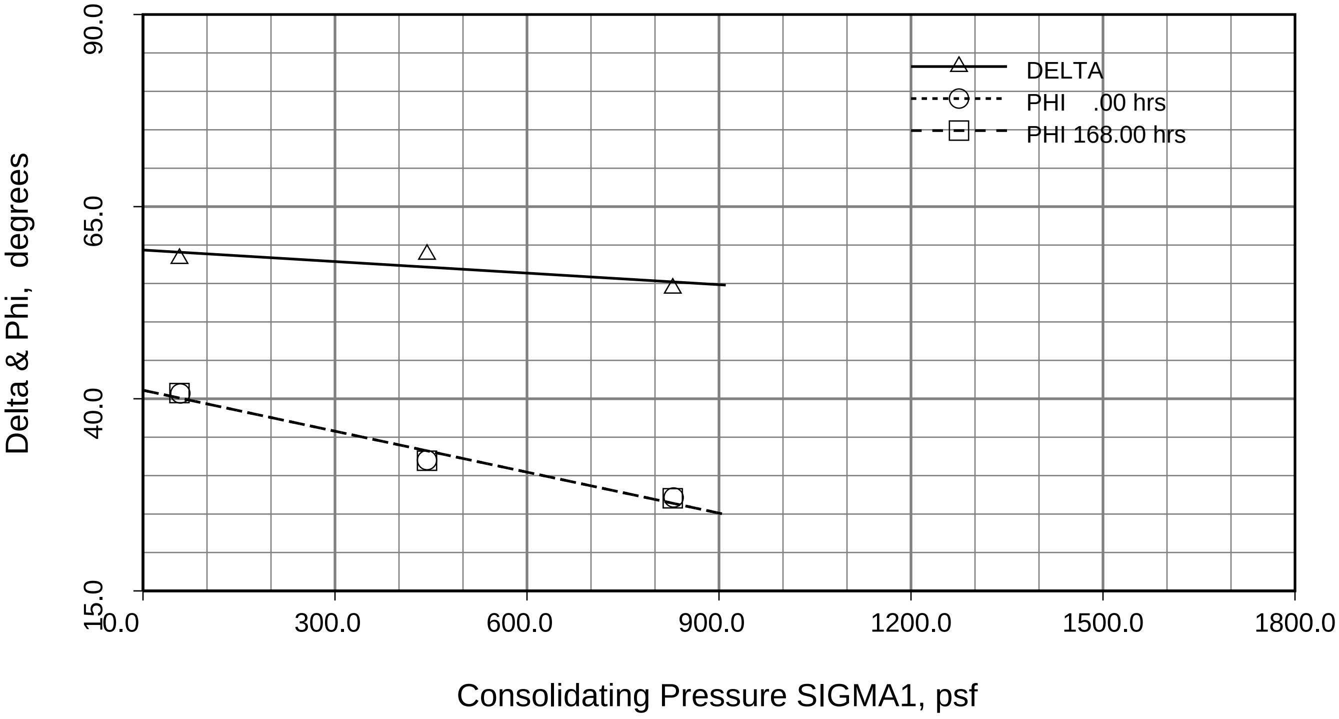
generic EM

BULK MATERIAL: Zinc oxide
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.2%

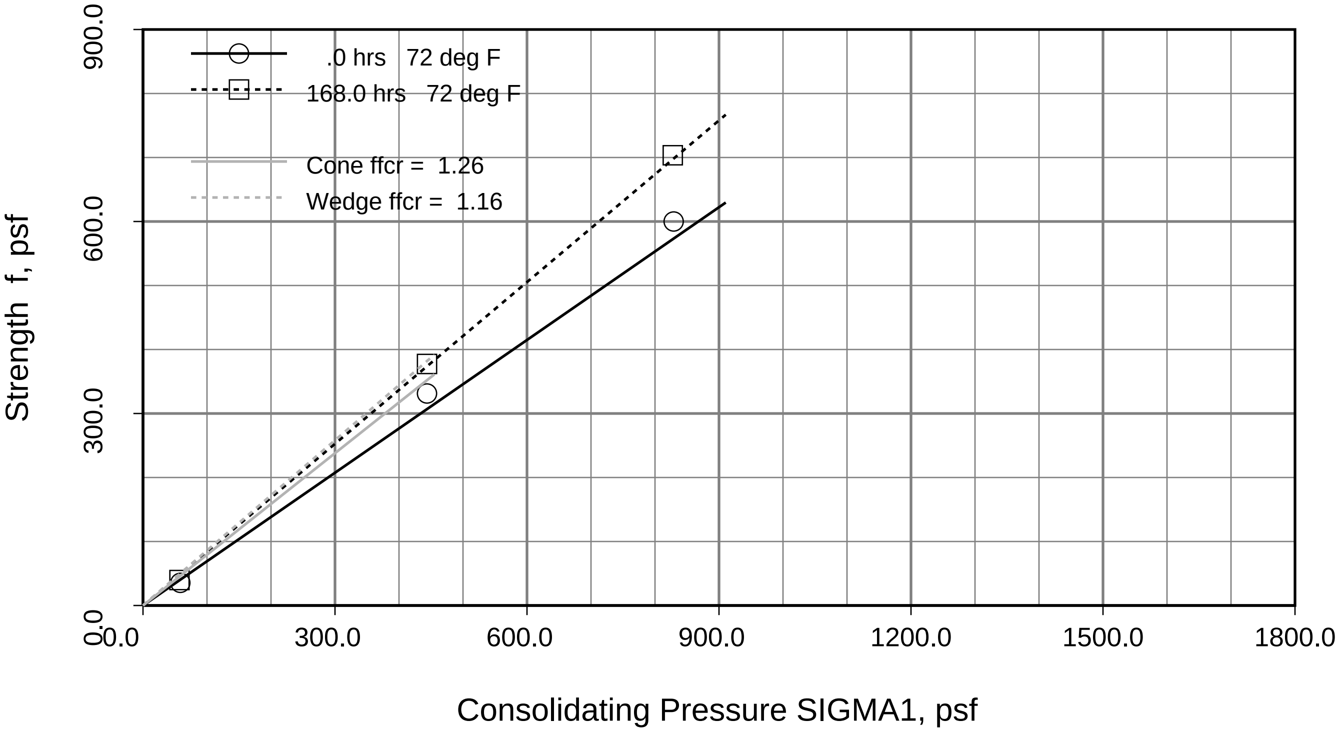
CREATE: 2/04/31
RUN: 2/06/26

JOB#: 994537
ID#: 22612

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



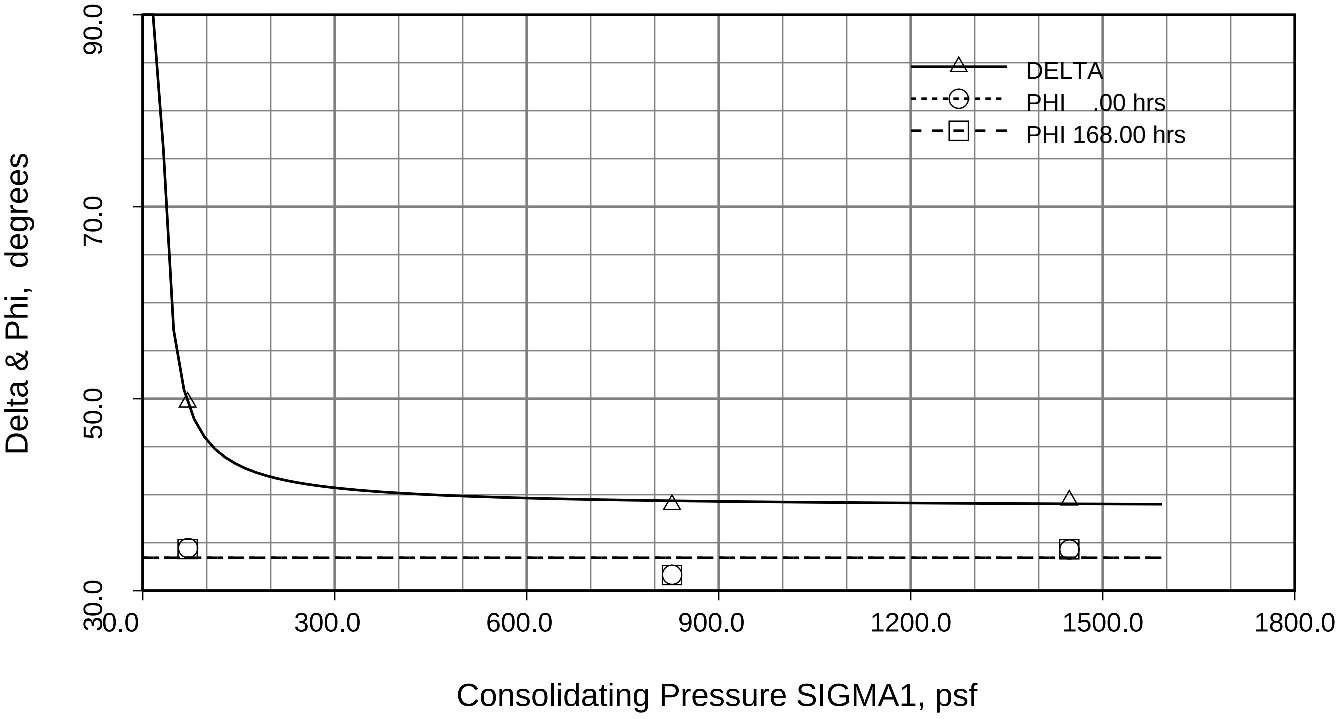
generic EM

BULK MATERIAL: Zircon flour
PARTICLE SIZE: As Rec'd
MOISTURE % WT: 0.1%

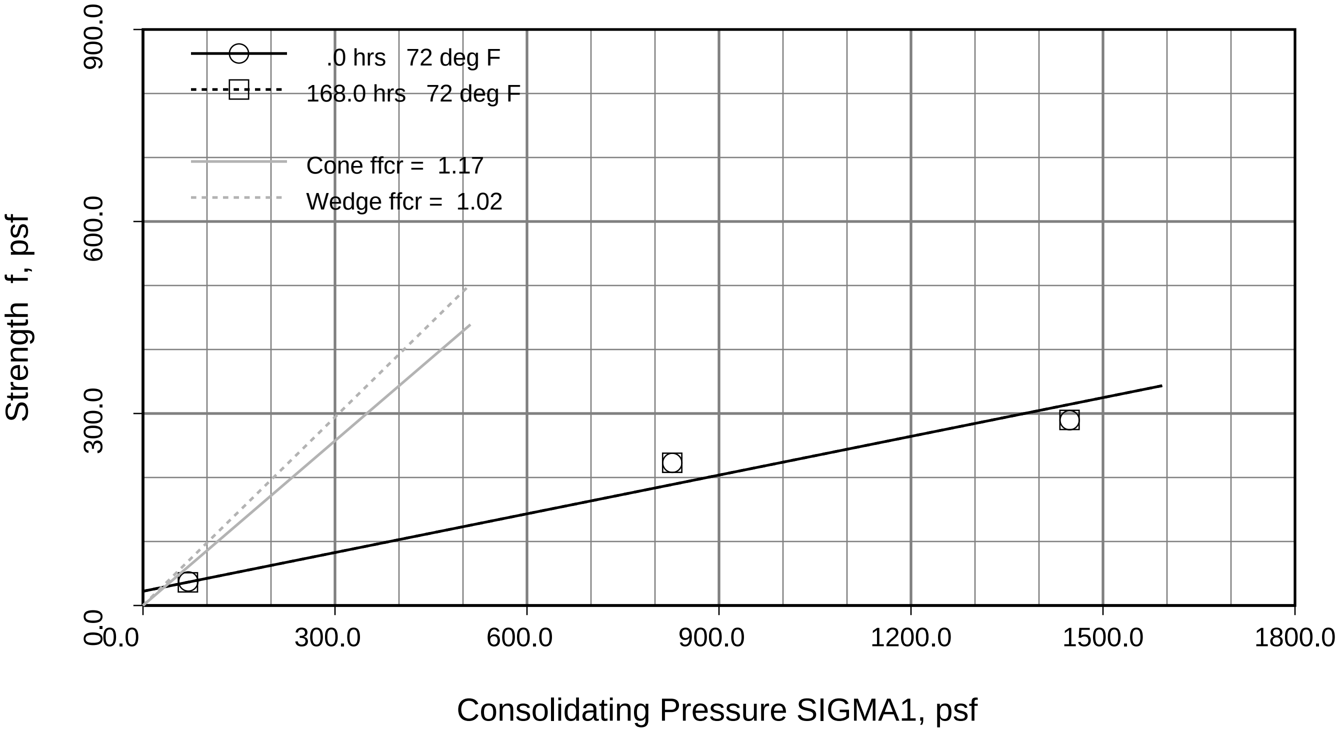
CREATE: 2/06/04
RUN: 2/06/26

JOB#: 994537
ID#: 22645

DELTA & PHI RELATIONS



FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

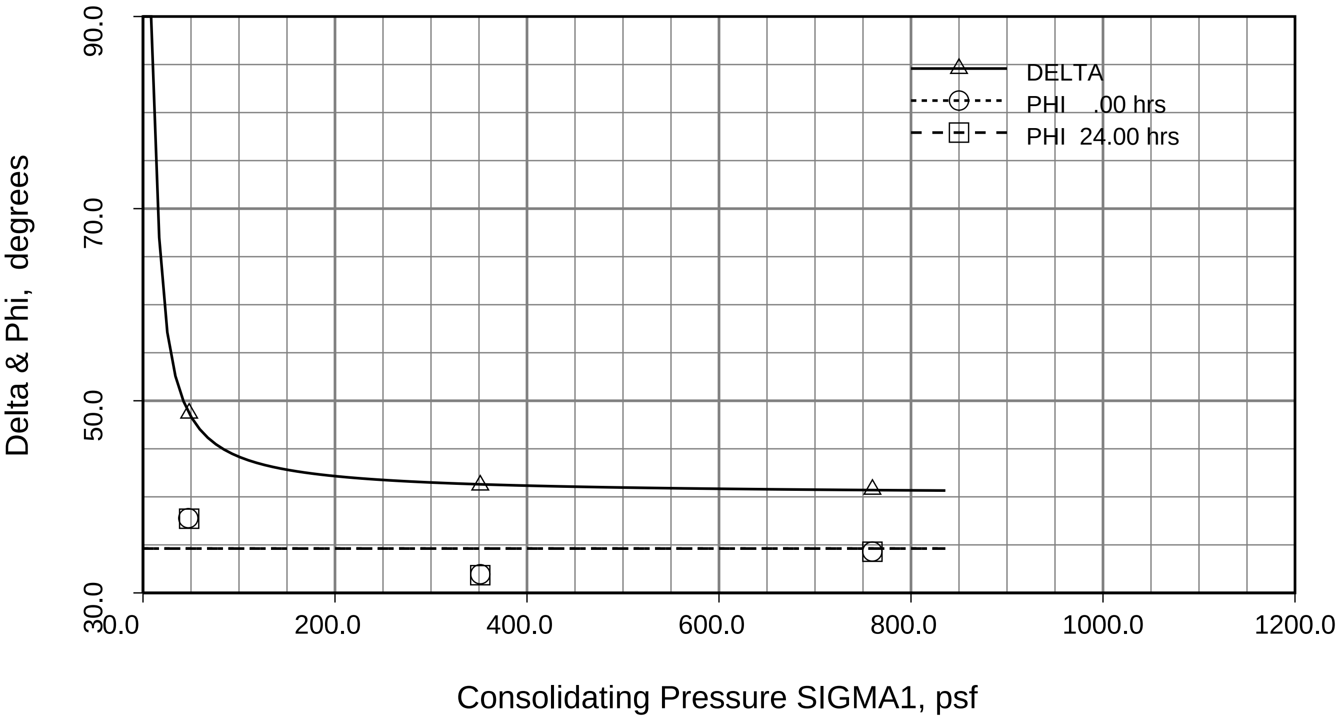
generic EM

BULK MATERIAL: LAW A: AN105
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd

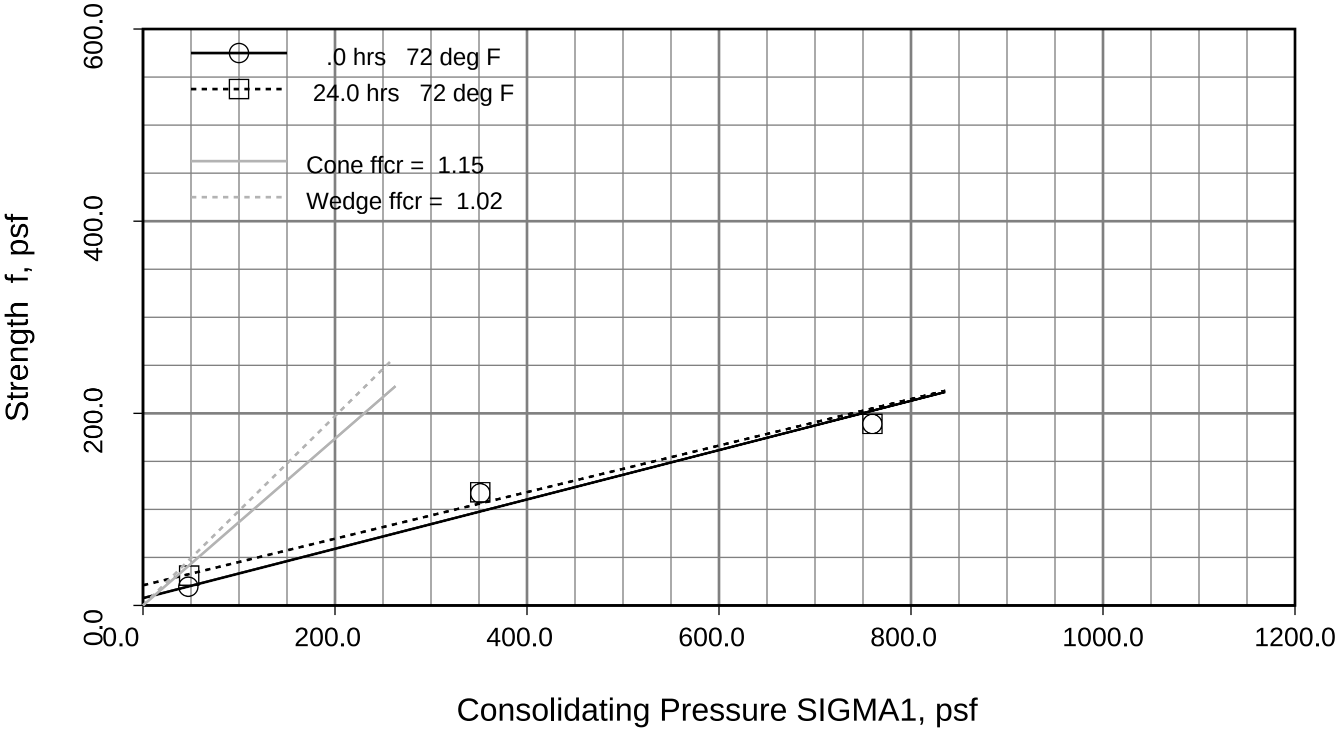
CREATE: 2/05/31
RUN: 2/06/26

JOB#: 994537
ID#: 22644

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)



JENIKE & JOHANSON INCORPORATED

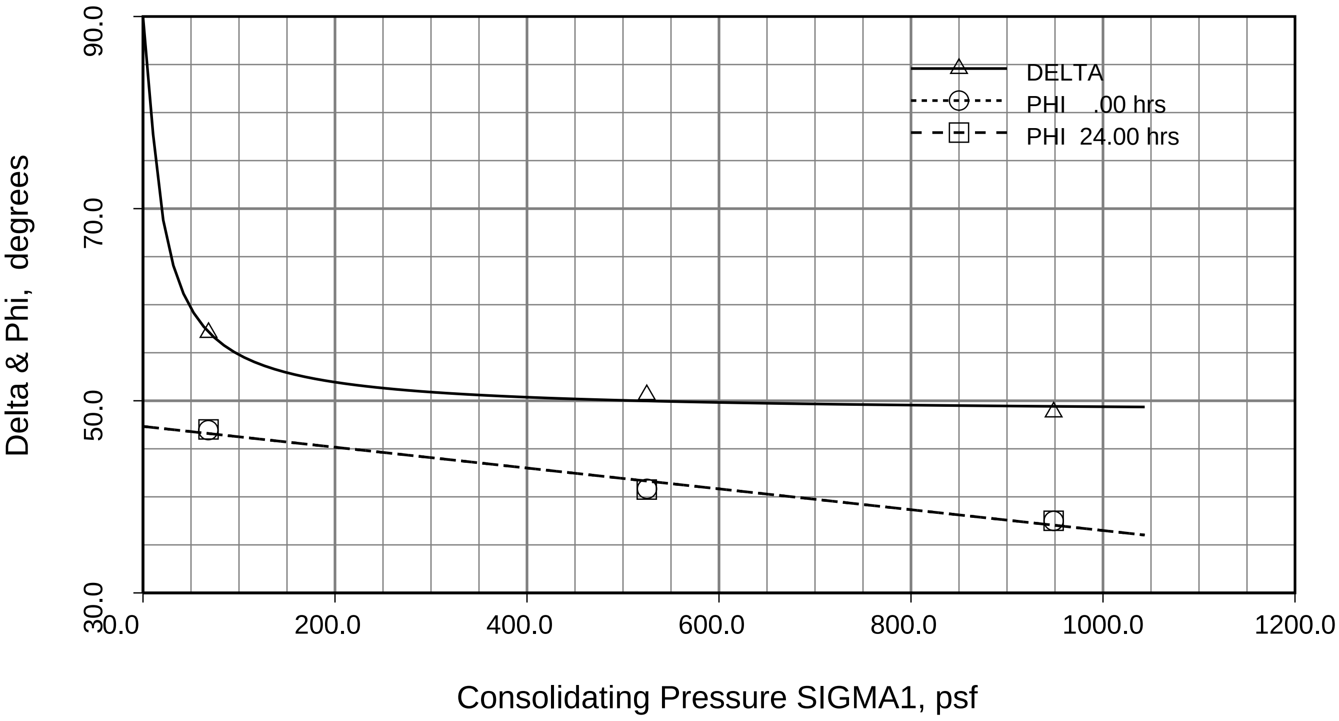
generic EM

BULK MATERIAL: LAW B: AZ101
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd

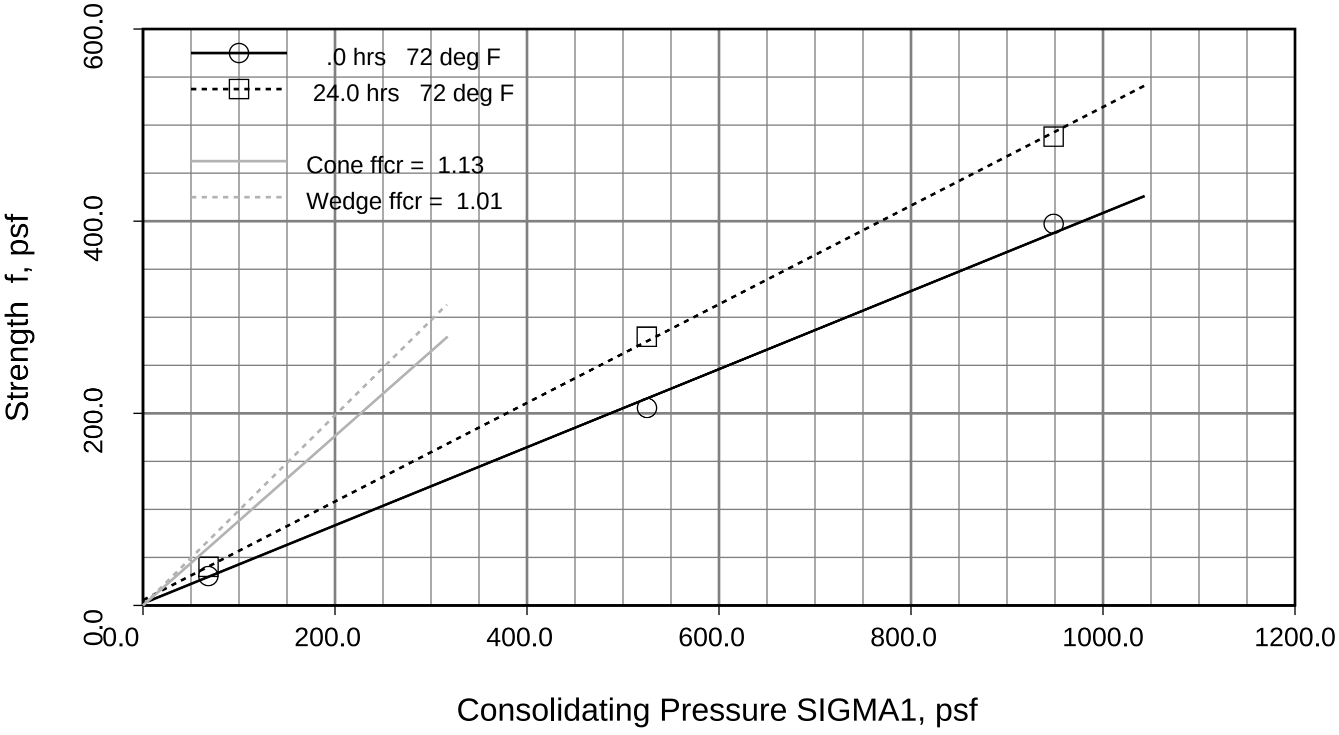
CREATE: 2/06/09
RUN: 2/06/26

JOB#: 994537
ID#: 22648

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)

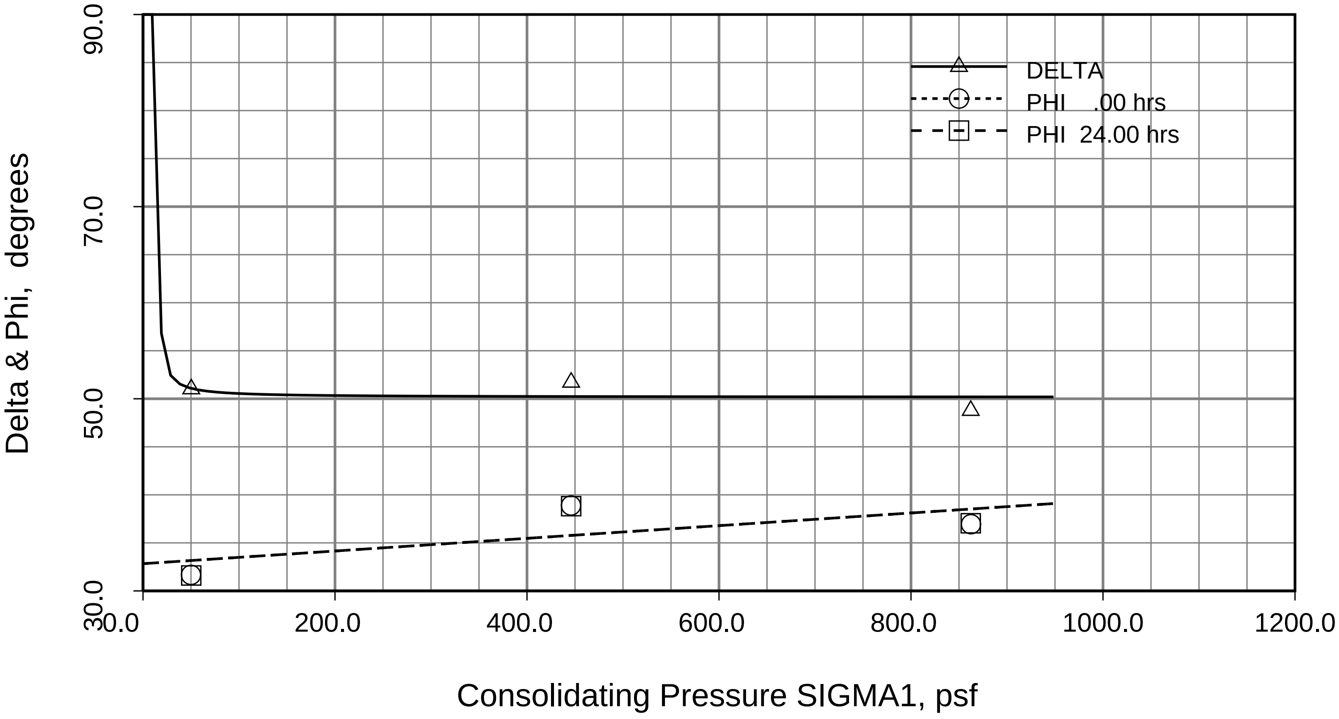


generic EM

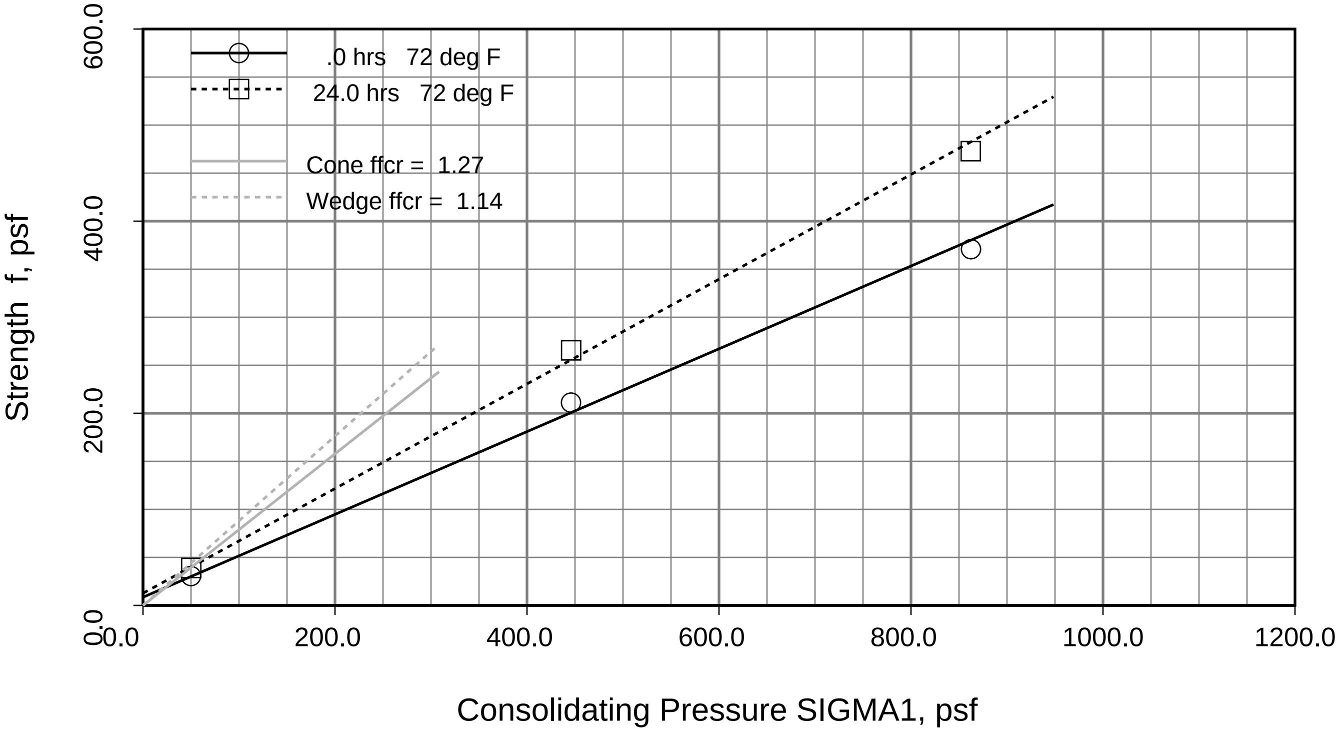
BULK MATERIAL: LAW C: AN107
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd

CREATE: 2/06/09 JOB#: 994537
RUN: 2/06/26 ID#: 22650

DELTA & PHI RELATIONS



FLOW FUNCTION(S)



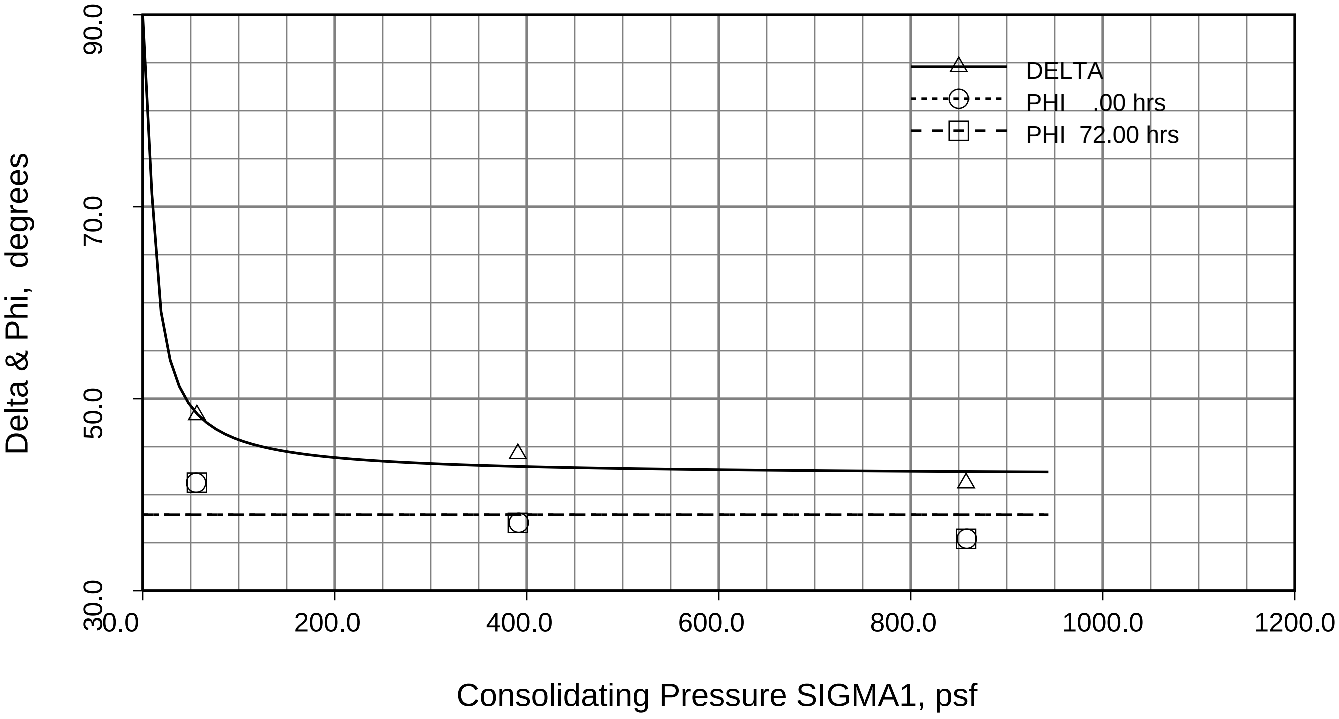
generic EM

BULK MATERIAL: HLW D: AZ102
PARTICLE SIZE: As Rec'd
MOISTURE % WT: As Rec'd

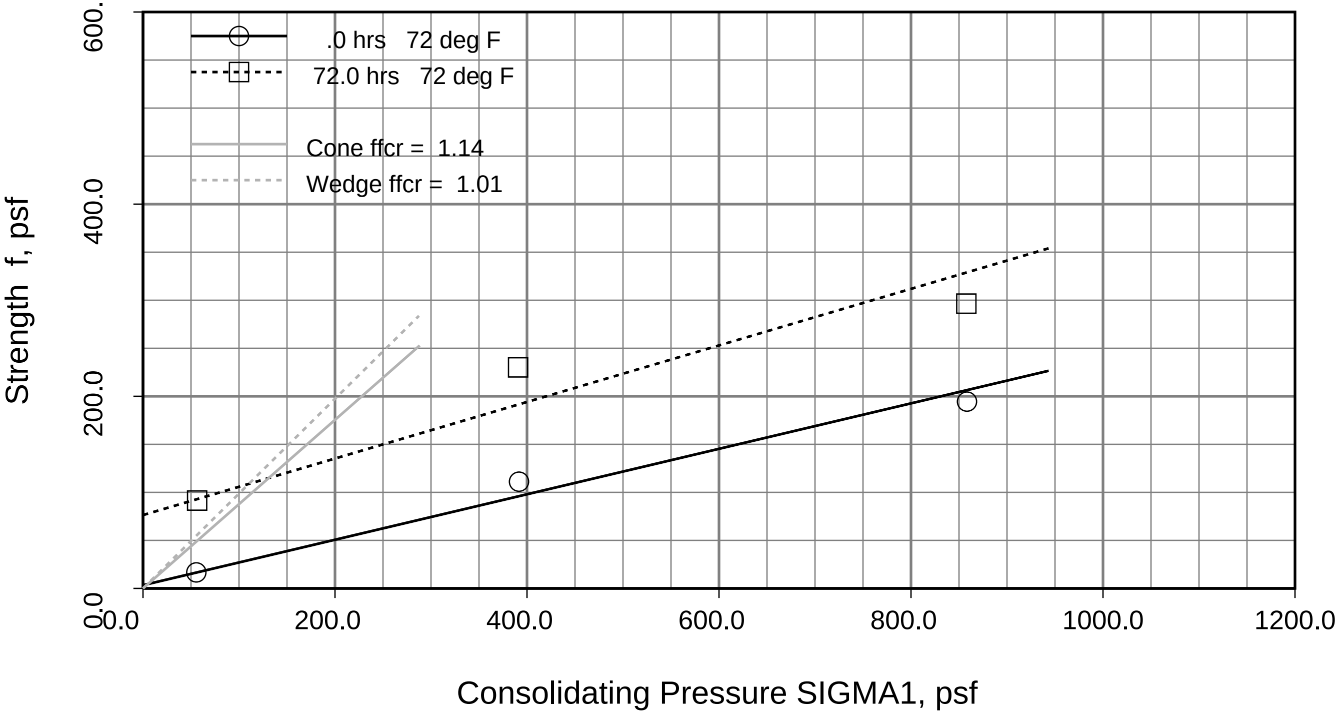
CREATE: 2/05/21
RUN: 2/06/26

JOB#: 994537
ID#: 22632

## DELTA & PHI RELATIONS



## FLOW FUNCTION(S)

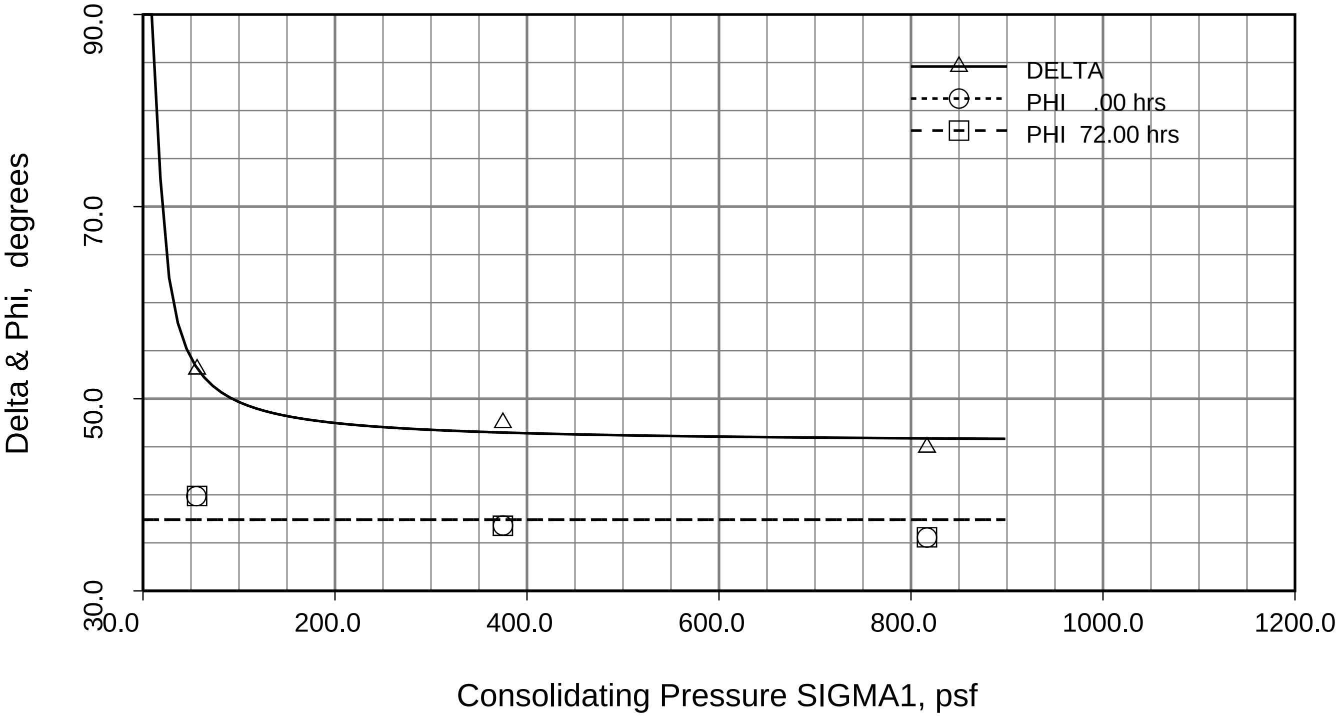


JENIKE & JOHANSON INCORPORATED

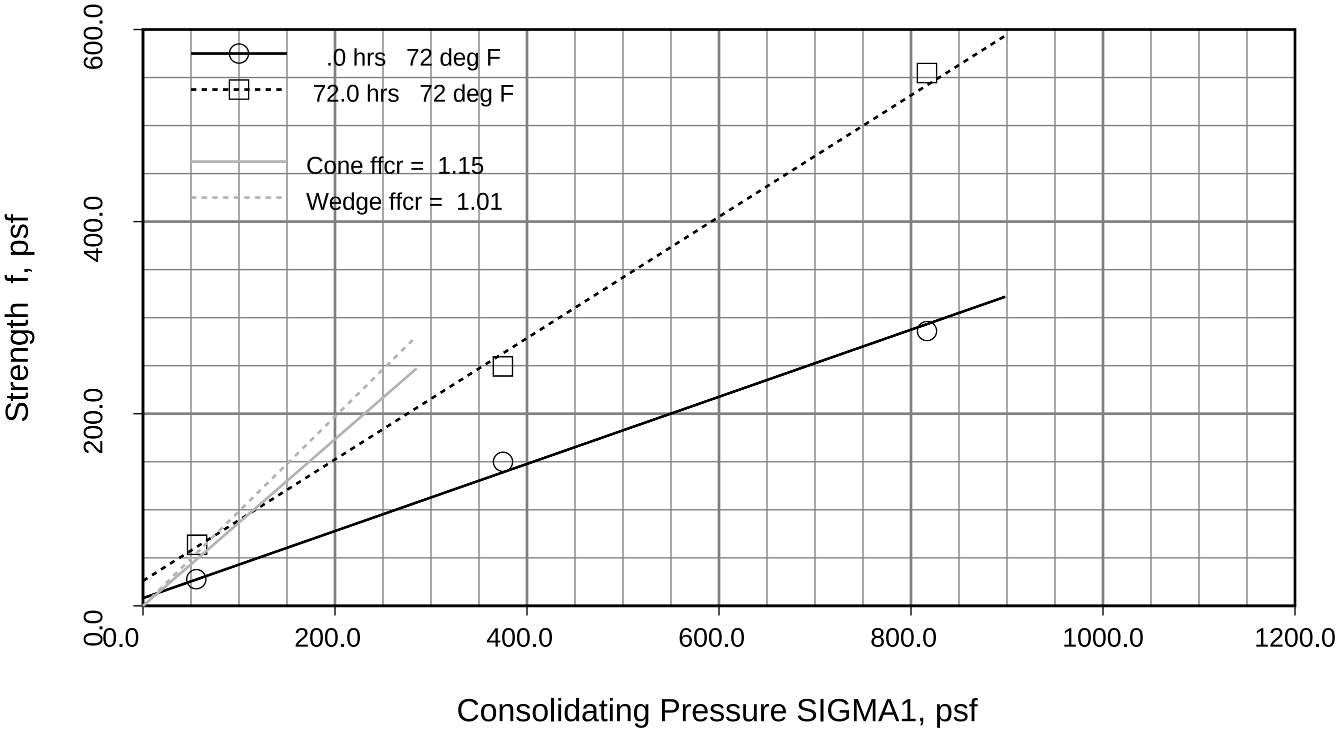
generic EM

BULK MATERIAL: HLW D: C106/AY104
PARTICLE SIZE: As Rec'd CREATE: 2/05/24 JOB#: 994537
MOISTURE % WT: As Rec'd RUN: 2/06/26 ID#: 22636

## DELTA & PHI RELATIONS



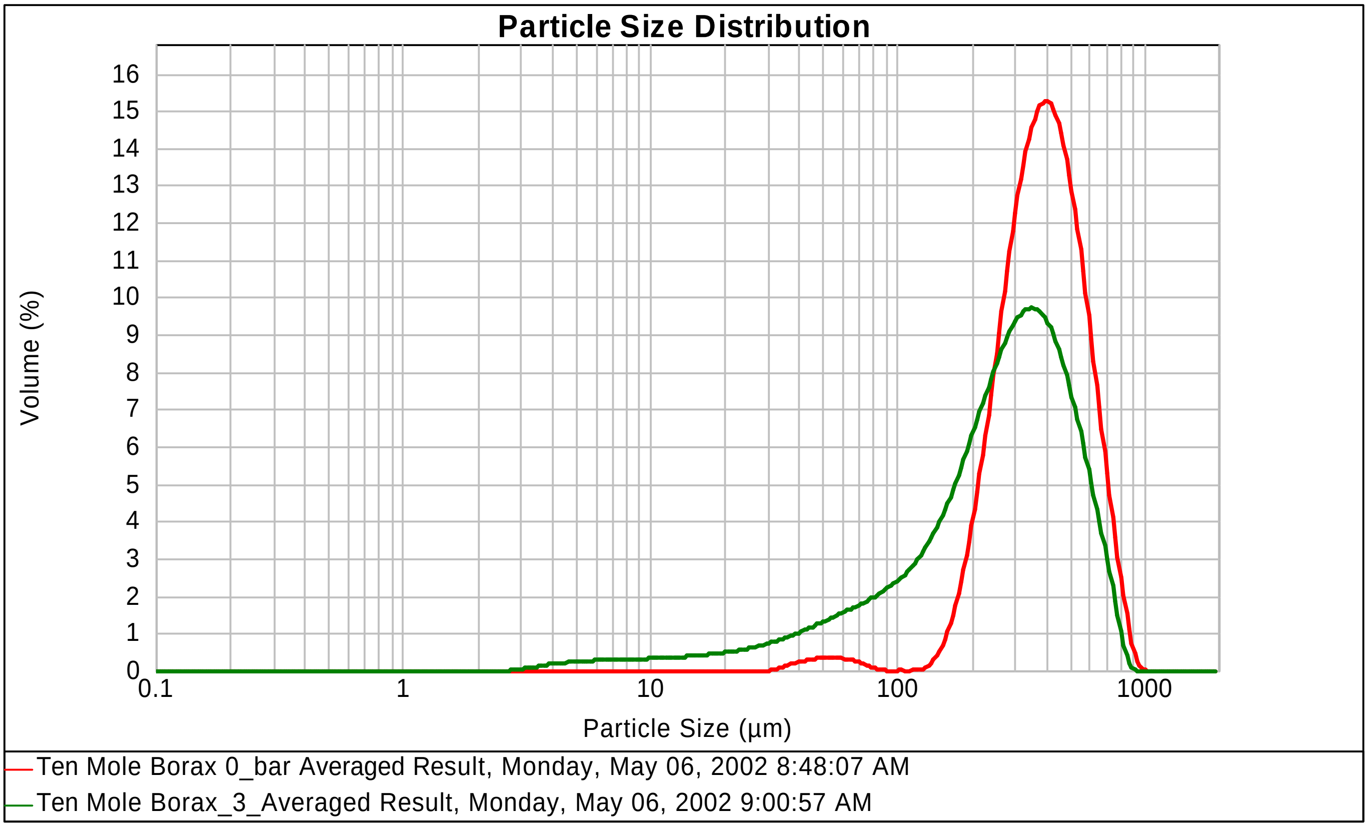
## FLOW FUNCTION(S)

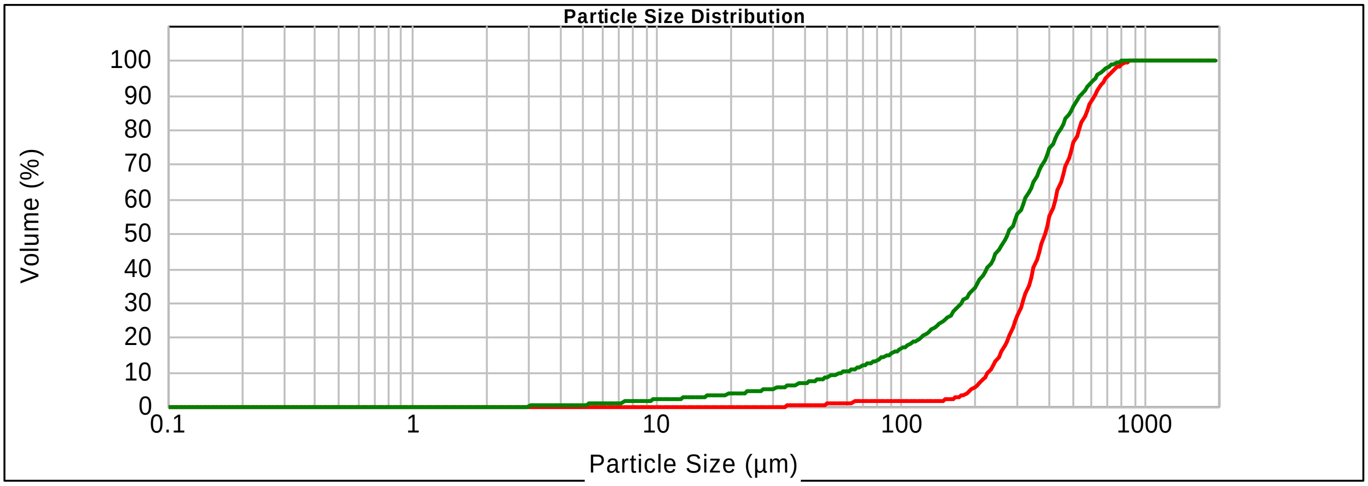


JENIKE & JOHANSON

# Particle Size Distribution Comparison - Borax

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
|  | 0.300 |  |  |
| 1 | 0.353 | 0.00 | 0.00 |
| 2 | 0.416 | 0.00 | 0.00 |
| 3 | 0.489 | 0.00 | 0.00 |
| 4 | 0.576 | 0.00 | 0.00 |
| 5 | 0.678 | 0.00 | 0.00 |
| 6 | 0.798 | 0.00 | 0.00 |
| 7 | 0.939 | 0.00 | 0.00 |
| 8 | 1.106 | 0.00 | 0.00 |
| 9 | 1.301 | 0.00 | 0.00 |
| 10 | 1.532 | 0.00 | 0.00 |
| 11 | 1.803 | 0.00 | 0.00 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
|  | 1.803 |  |  |
| 12 | 2.123 | 0.00 | 0.00 |
| 13 | 2.499 | 0.00 | 0.00 |
| 14 | 2.941 | 0.00 | 0.00 |
| 15 | 3.462 | 0.00 | 0.07 |
| 16 | 4.075 | 0.00 | 0.15 |
| 17 | 4.797 | 0.00 | 0.21 |
| 18 | 5.646 | 0.00 | 0.26 |
| 19 | 6.646 | 0.00 | 0.29 |
| 20 | 7.823 | 0.00 | 0.31 |
| 21 | 9.209 | 0.00 | 0.33 |
| 22 | 10.840 | 0.00 | 0.34 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
|  | 10.840 |  |  |
| 23 | 12.759 | 0.00 | 0.37 |
| 24 | 15.019 | 0.00 | 0.40 |
| 25 | 17.679 | 0.00 | 0.44 |
| 26 | 20.810 | 0.00 | 0.50 |
| 27 | 24.495 | 0.00 | 0.57 |
| 28 | 28.833 | 0.00 | 0.67 |
| 29 | 33.939 | 0.01 | 0.81 |
| 30 | 39.950 | 0.17 | 0.98 |
| 31 | 47.025 | 0.29 | 1.18 |
| 32 | 55.353 | 0.36 | 1.41 |
| 33 | 65.156 | 0.35 | 1.64 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
|  | 65.156 |  |  |
| 34 | 76.695 | 0.23 | 1.88 |
| 35 | 90.278 | 0.05 | 2.14 |
| 36 | 106.266 | 0.00 | 2.48 |
| 37 | 125.085 | 0.00 | 2.98 |
| 38 | 147.238 | 0.18 | 3.71 |
| 39 | 173.314 | 1.07 | 4.74 |
| 40 | 204.008 | 3.01 | 6.07 |
| 41 | 240.137 | 6.01 | 7.56 |
| 42 | 282.665 | 9.00 | 9.77 |
| 43 | 332.725 | 10.02 | 13.36 |
| 44 | 391.651 | 10.31 | 15.76 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
|  | 391.651 |  |  |
| 45 | 461.012 | 9.66 | 16.07 |
| 46 | 542.656 | 8.10 | 14.09 |
| 47 | 638.761 | 5.90 | 10.42 |
| 48 | 751.885 | 3.55 | 6.23 |
| 49 | 885.043 | 0.95 | 2.41 |
| 50 | 1041.784 | 0.00 | 0.15 |
| 51 | 1226.283 | 0.00 | 0.00 |
| 52 | 1443.457 | 0.00 | 0.00 |
| 53 | 1699.092 | 0.00 | 0.00 |
| 54 | 2000.000 | 0.00 | 0.00 |

Malvern Instruments Ltd.
Malvern, UK
Tel := +[44] (0) 1684-892456 Fax +[44] (0) 1684-892789

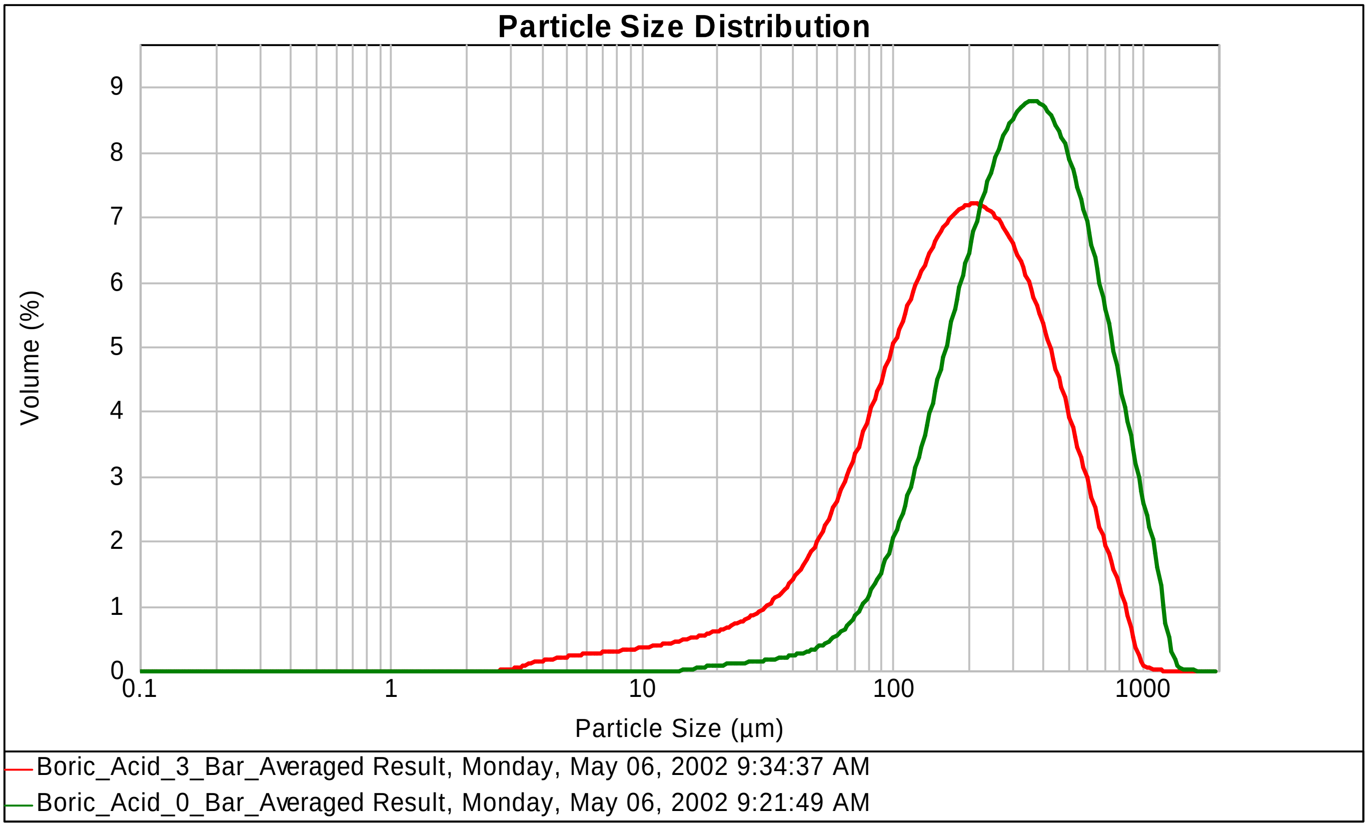
Mastersizer 2000 Ver. Version 4.00
Serial Number : 34403-27

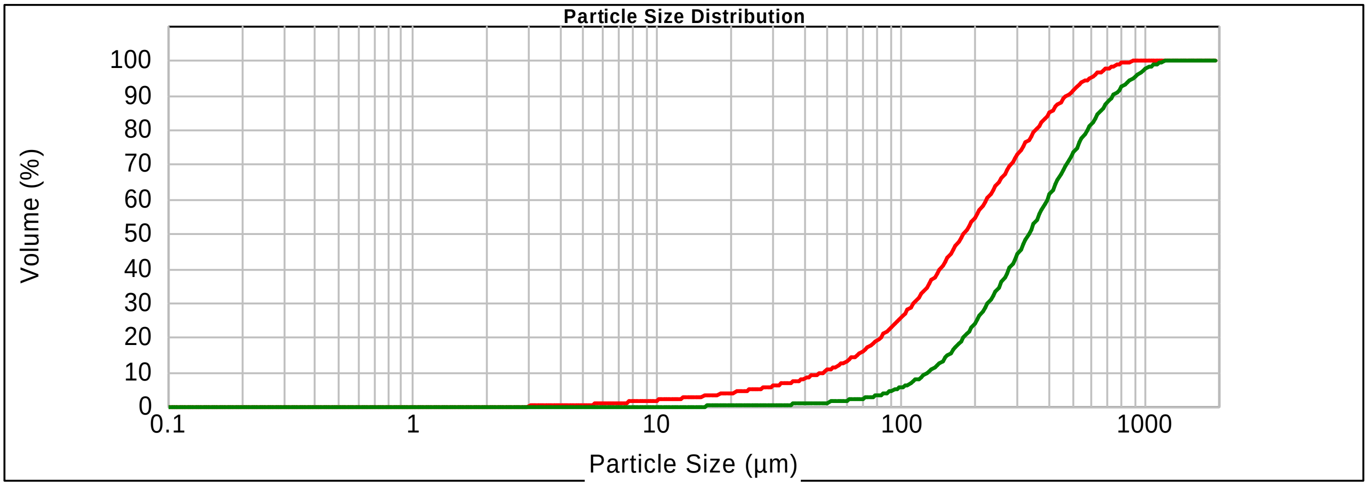
File name: 4537_Ten  Mole Borax.mea
Record Number: 10
25 Jun 2002 02:48:32 PM

JENIKE & JOHANSON

# Particle Size Distribution Comparison - Boric acid

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | | 0.00 | 0.00 |
| | 0.353 | | |
| 2 | | 0.00 | 0.00 |
| | 0.416 | | |
| 3 | | 0.00 | 0.00 |
| | 0.489 | | |
| 4 | | 0.00 | 0.00 |
| | 0.576 | | |
| 5 | | 0.00 | 0.00 |
| | 0.678 | | |
| 6 | | 0.00 | 0.00 |
| | 0.798 | | |
| 7 | | 0.00 | 0.00 |
| | 0.939 | | |
| 8 | | 0.00 | 0.00 |
| | 1.106 | | |
| 9 | | 0.00 | 0.00 |
| | 1.301 | | |
| 10 | | 0.00 | 0.00 |
| | 1.532 | | |
| 11 | | 0.00 | 0.00 |
| | 1.803 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | | 0.00 | 0.00 |
| | 2.123 | | |
| 13 | | 0.00 | 0.00 |
| | 2.499 | | |
| 14 | | 0.00 | 0.00 |
| | 2.941 | | |
| 15 | | 0.00 | 0.04 |
| | 3.462 | | |
| 16 | | 0.00 | 0.13 |
| | 4.075 | | |
| 17 | | 0.00 | 0.19 |
| | 4.797 | | |
| 18 | | 0.00 | 0.24 |
| | 5.646 | | |
| 19 | | 0.00 | 0.27 |
| | 6.646 | | |
| 20 | | 0.00 | 0.30 |
| | 7.823 | | |
| 21 | | 0.00 | 0.34 |
| | 9.209 | | |
| 22 | | 0.00 | 0.37 |
| | 10.840 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | | 0.00 | 0.42 |
| | 12.759 | | |
| 24 | | 0.00 | 0.48 |
| | 15.019 | | |
| 25 | | 0.03 | 0.54 |
| | 17.679 | | |
| 26 | | 0.08 | 0.63 |
| | 20.810 | | |
| 27 | | 0.10 | 0.73 |
| | 24.495 | | |
| 28 | | 0.13 | 0.86 |
| | 28.833 | | |
| 29 | | 0.17 | 1.05 |
| | 33.939 | | |
| 30 | | 0.21 | 1.31 |
| | 39.950 | | |
| 31 | | 0.28 | 1.68 |
| | 47.025 | | |
| 32 | | 0.39 | 2.17 |
| | 55.353 | | |
| 33 | | 0.57 | 2.78 |
| | 65.156 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | | 0.87 | 3.50 |
| | 76.695 | | |
| 35 | | 1.33 | 4.31 |
| | 90.278 | | |
| 36 | | 1.99 | 5.15 |
| | 106.266 | | |
| 37 | | 2.85 | 5.98 |
| | 125.085 | | |
| 38 | | 3.92 | 6.70 |
| | 147.238 | | |
| 39 | | 5.11 | 7.26 |
| | 173.314 | | |
| 40 | | 6.36 | 7.59 |
| | 204.008 | | |
| 41 | | 7.51 | 7.65 |
| | 240.137 | | |
| 42 | | 7.44 | 8.47 |
| | 282.665 | | |
| 43 | | 6.96 | 9.11 |
| | 332.725 | | |
| 44 | | 6.24 | 9.35 |
| | 391.651 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | | 5.33 | 9.15 |
| | 461.012 | | |
| 46 | | 4.30 | 8.51 |
| | 542.656 | | |
| 47 | | 3.24 | 7.48 |
| | 638.761 | | |
| 48 | | 2.21 | 6.15 |
| | 751.885 | | |
| 49 | | 1.33 | 4.68 |
| | 885.043 | | |
| 50 | | 0.27 | 3.19 |
| | 1041.784 | | |
| 51 | | 0.01 | 1.83 |
| | 1226.283 | | |
| 52 | | 0.00 | 0.21 |
| | 1443.457 | | |
| 53 | | 0.00 | 0.00 |
| | 1699.092 | | |
| 54 | | 0.00 | 0.00 |
| | 2000.000 | | |

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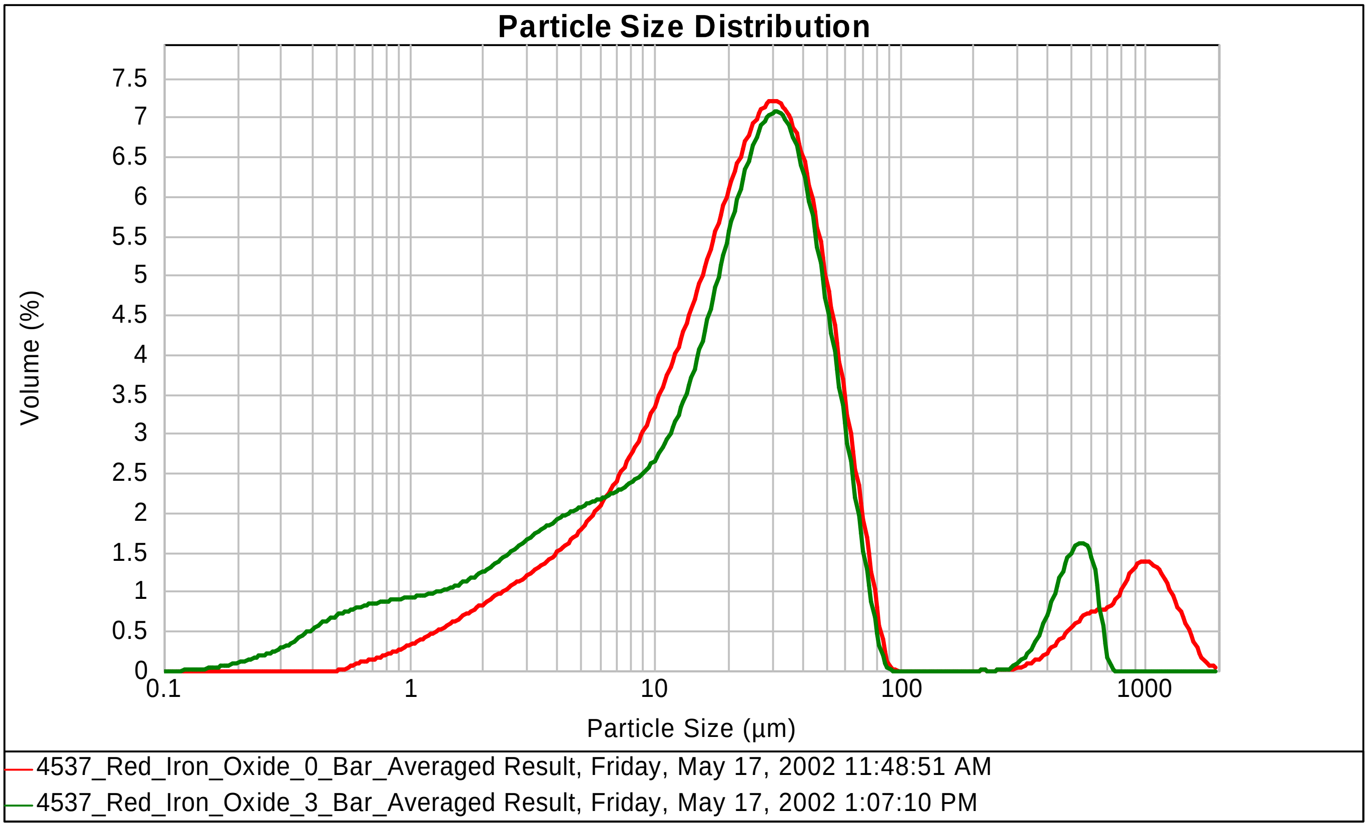
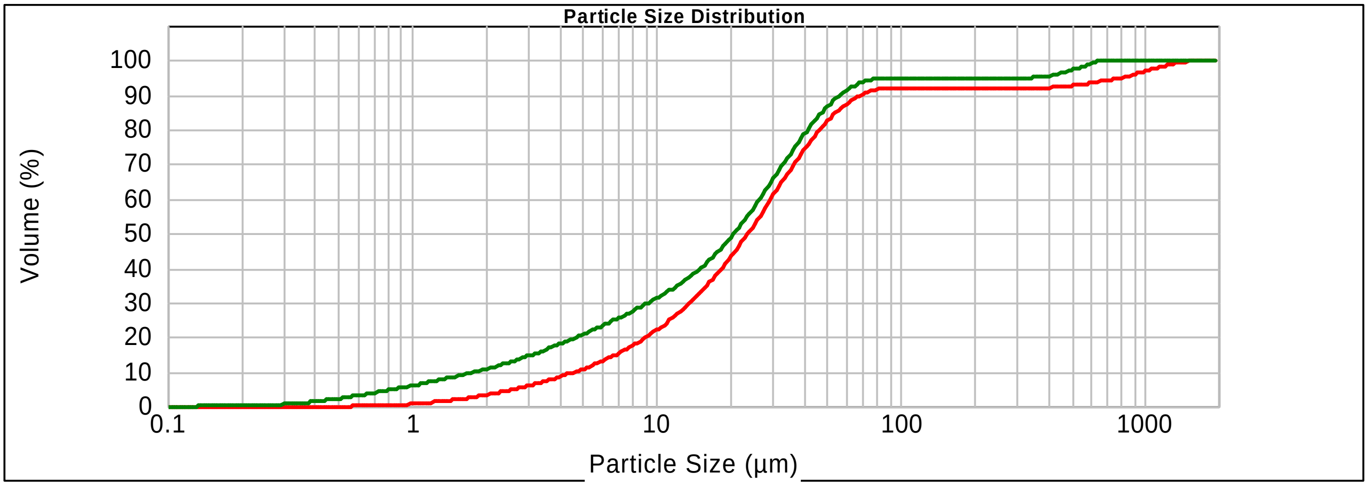
# Particle Size Distribution Comparison - Iron oxide

See individual plots for complete analysis





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | 0.353 | 0.00 | 0.36 |
| 2 | 0.416 | 0.00 | 0.51 |
| 3 | 0.489 | 0.00 | 0.65 |
| 4 | 0.576 | 0.01 | 0.77 |
| 5 | 0.678 | 0.10 | 0.85 |
| 6 | 0.798 | 0.17 | 0.91 |
| 7 | 0.939 | 0.25 | 0.95 |
| 8 | 1.106 | 0.35 | 0.99 |
| 9 | 1.301 | 0.47 | 1.03 |
| 10 | 1.532 | 0.59 | 1.09 |
| 11 | 1.803 | 0.73 | 1.19 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | 2.123 | 0.87 | 1.31 |
| 13 | 2.499 | 1.02 | 1.46 |
| 14 | 2.941 | 1.17 | 1.63 |
| 15 | 3.462 | 1.33 | 1.81 |
| 16 | 4.075 | 1.51 | 1.97 |
| 17 | 4.797 | 1.71 | 2.11 |
| 18 | 5.646 | 1.96 | 2.23 |
| 19 | 6.646 | 2.26 | 2.32 |
| 20 | 7.823 | 2.43 | 2.62 |
| 21 | 9.209 | 2.58 | 3.05 |
| 22 | 10.840 | 2.83 | 3.55 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | 12.759 | 3.23 | 4.12 |
| 24 | 15.019 | 3.83 | 4.76 |
| 25 | 17.679 | 4.63 | 5.48 |
| 26 | 20.810 | 5.57 | 6.23 |
| 27 | 24.495 | 6.52 | 6.95 |
| 28 | 28.833 | 7.24 | 7.48 |
| 29 | 33.939 | 7.52 | 7.66 |
| 30 | 39.950 | 7.21 | 7.36 |
| 31 | 47.025 | 6.28 | 6.51 |
| 32 | 55.353 | 4.89 | 5.21 |
| 33 | 65.156 | 3.30 | 3.66 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | 76.695 | 1.72 | 2.14 |
| 35 | 90.278 | 0.35 | 0.63 |
| 36 | 106.266 | 0.00 | 0.00 |
| 37 | 125.085 | 0.00 | 0.00 |
| 38 | 147.238 | 0.00 | 0.00 |
| 39 | 173.314 | 0.00 | 0.00 |
| 40 | 204.008 | 0.00 | 0.00 |
| 41 | 240.137 | 0.00 | 0.00 |
| 42 | 282.665 | 0.00 | 0.00 |
| 43 | 332.725 | 0.04 | 0.10 |
| 44 | 391.651 | 0.14 | 0.41 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | 461.012 | 0.33 | 1.00 |
| 46 | 542.656 | 0.57 | 1.58 |
| 47 | 638.761 | 0.77 | 1.66 |
| 48 | 751.885 | 0.39 | 0.84 |
| 49 | 885.043 | 0.00 | 1.13 |
| 50 | 1041.784 | 0.00 | 1.45 |
| 51 | 1226.283 | 0.00 | 1.37 |
| 52 | 1443.457 | 0.00 | 0.95 |
| 53 | 1699.092 | 0.00 | 0.44 |
| 54 | 2000.000 | 0.00 | 0.08 |

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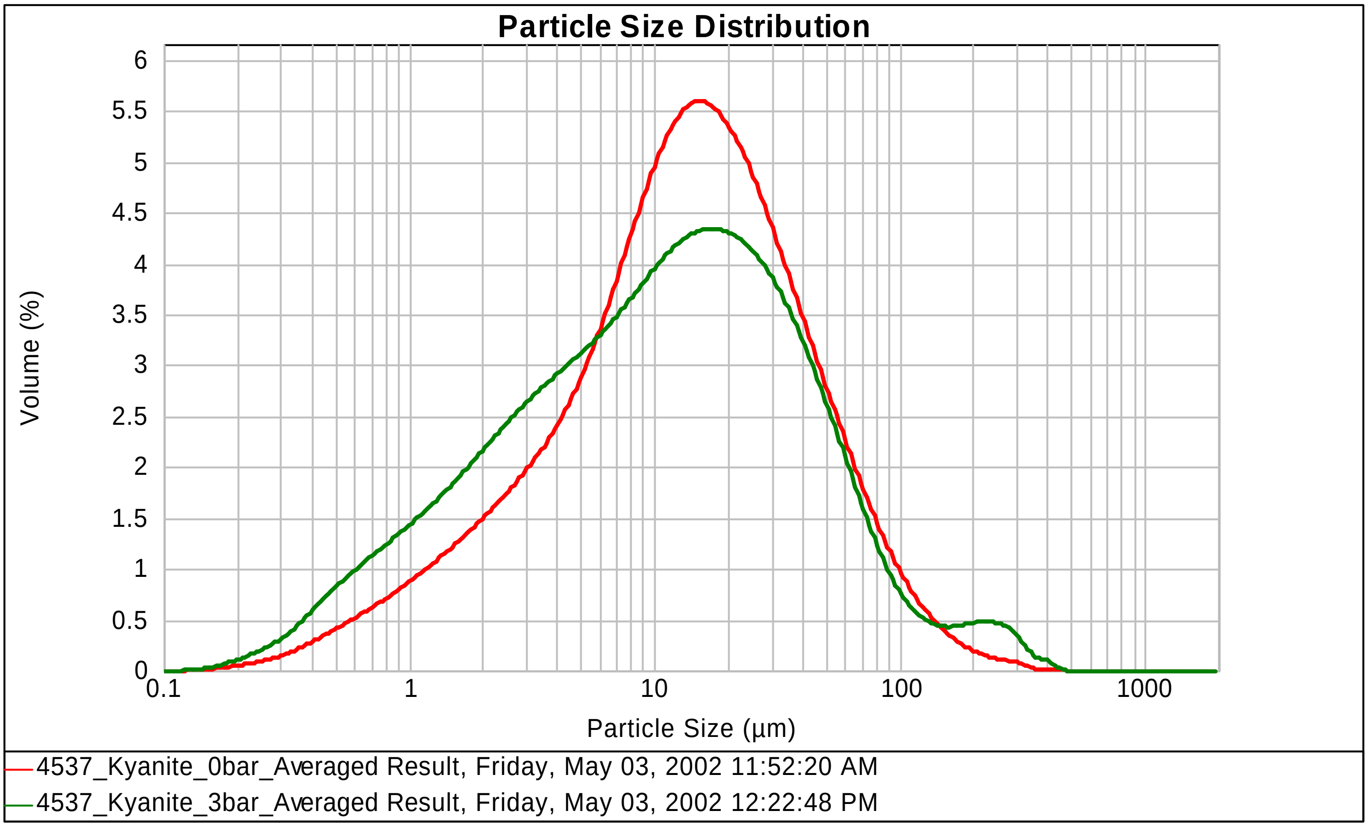
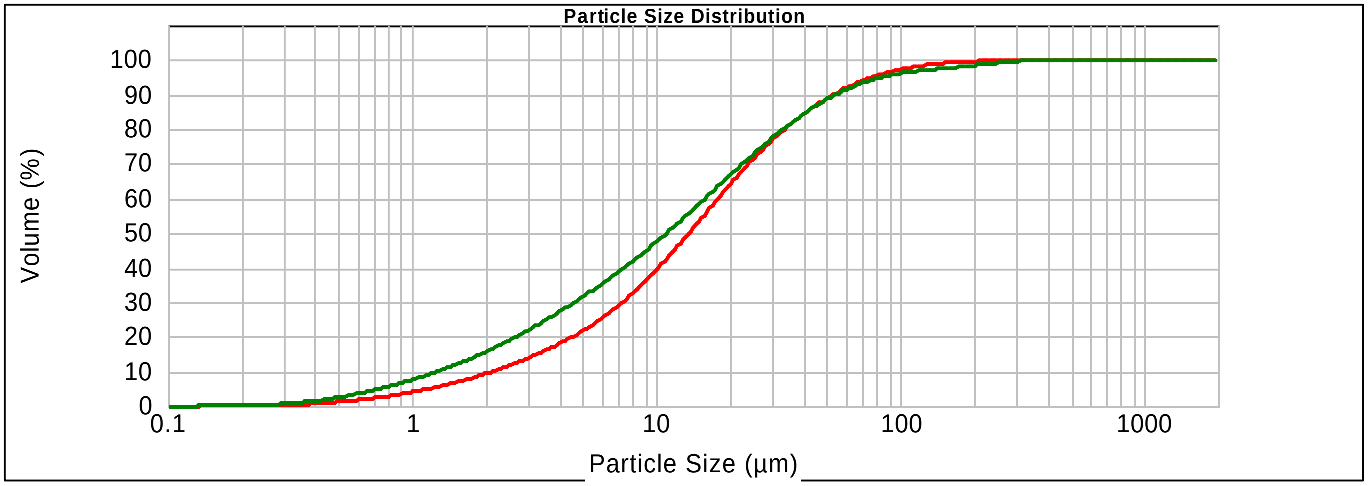
# Particle Size Distribution Comparison - Kyanite

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | 0.353 | 0.18 | 0.39 |
| 2 | 0.416 | 0.27 | 0.57 |
| 3 | 0.489 | 0.37 | 0.76 |
| 4 | 0.576 | 0.47 | 0.93 |
| 5 | 0.678 | 0.58 | 1.09 |
| 6 | 0.798 | 0.69 | 1.24 |
| 7 | 0.939 | 0.81 | 1.38 |
| 8 | 1.106 | 0.94 | 1.54 |
| 9 | 1.301 | 1.08 | 1.70 |
| 10 | 1.532 | 1.23 | 1.88 |
| 11 | 1.803 | 1.40 | 2.07 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | 2.123 | 1.57 | 2.27 |
| 13 | 2.499 | 1.76 | 2.48 |
| 14 | 2.941 | 1.96 | 2.68 |
| 15 | 3.462 | 2.18 | 2.87 |
| 16 | 4.075 | 2.44 | 3.04 |
| 17 | 4.797 | 2.76 | 3.20 |
| 18 | 5.646 | 3.15 | 3.36 |
| 19 | 6.646 | 3.53 | 3.63 |
| 20 | 7.823 | 3.74 | 4.17 |
| 21 | 9.209 | 3.97 | 4.74 |
| 22 | 10.840 | 4.20 | 5.27 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | 12.759 | 4.41 | 5.68 |
| 24 | 15.019 | 4.55 | 5.91 |
| 25 | 17.679 | 4.62 | 5.95 |
| 26 | 20.810 | 4.60 | 5.78 |
| 27 | 24.495 | 4.50 | 5.47 |
| 28 | 28.833 | 4.32 | 5.04 |
| 29 | 33.939 | 4.05 | 4.54 |
| 30 | 39.950 | 3.69 | 4.01 |
| 31 | 47.025 | 3.26 | 3.47 |
| 32 | 55.353 | 2.77 | 2.94 |
| 33 | 65.156 | 2.24 | 2.42 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | 76.695 | 1.72 | 1.93 |
| 35 | 90.278 | 1.25 | 1.48 |
| 36 | 106.266 | 0.88 | 1.10 |
| 37 | 125.085 | 0.63 | 0.79 |
| 38 | 147.238 | 0.50 | 0.55 |
| 39 | 173.314 | 0.37 | 0.46 |
| 40 | 204.008 | 0.25 | 0.48 |
| 41 | 240.137 | 0.17 | 0.51 |
| 42 | 282.665 | 0.12 | 0.48 |
| 43 | 332.725 | 0.08 | 0.35 |
| 44 | 391.651 | 0.02 | 0.15 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | 461.012 | 0.01 | 0.07 |
| 46 | 542.656 | 0.00 | 0.00 |
| 47 | 638.761 | 0.00 | 0.00 |
| 48 | 751.885 | 0.00 | 0.00 |
| 49 | 885.043 | 0.00 | 0.00 |
| 50 | 1041.784 | 0.00 | 0.00 |
| 51 | 1226.283 | 0.00 | 0.00 |
| 52 | 1443.457 | 0.00 | 0.00 |
| 53 | 1699.092 | 0.00 | 0.00 |
| 54 | 2000.000 | 0.00 | 0.00 |

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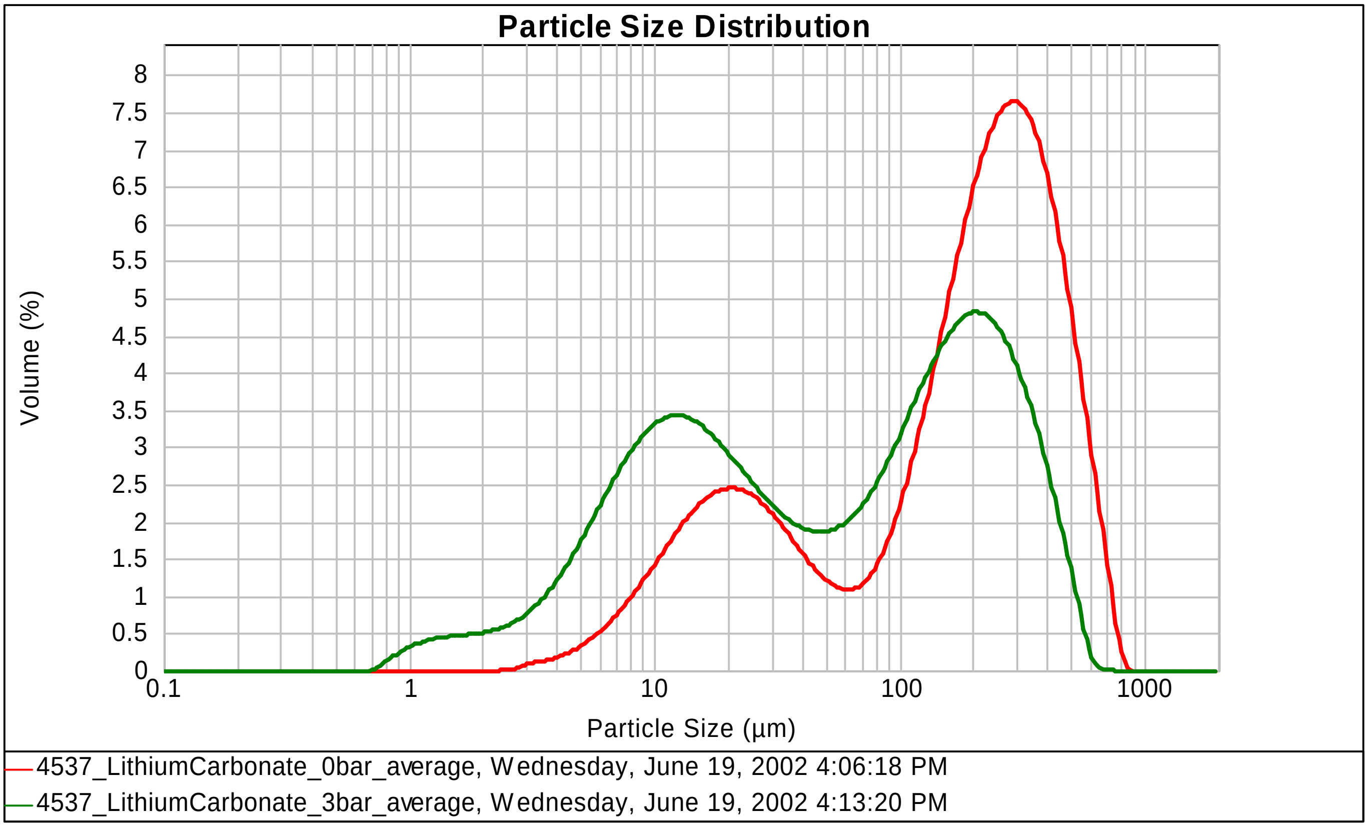
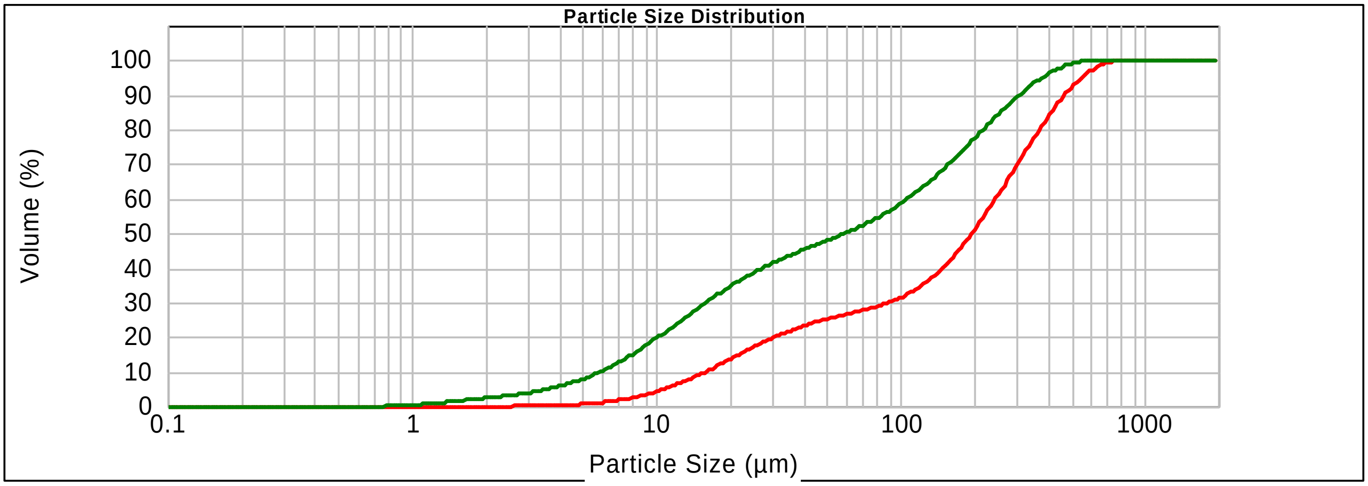
# Particle Size Distribution Comparison - Lithium carbonate

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | | 0.00 | 0.00 |
| | 0.353 | | |
| 2 | | 0.00 | 0.00 |
| | 0.416 | | |
| 3 | | 0.00 | 0.00 |
| | 0.489 | | |
| 4 | | 0.00 | 0.00 |
| | 0.576 | | |
| 5 | | 0.00 | 0.00 |
| | 0.678 | | |
| 6 | | 0.00 | 0.03 |
| | 0.798 | | |
| 7 | | 0.00 | 0.20 |
| | 0.939 | | |
| 8 | | 0.00 | 0.35 |
| | 1.106 | | |
| 9 | | 0.00 | 0.43 |
| | 1.301 | | |
| 10 | | 0.00 | 0.48 |
| | 1.532 | | |
| 11 | | 0.00 | 0.51 |
| | 1.803 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | | 0.00 | 0.54 |
| | 2.123 | | |
| 13 | | 0.00 | 0.59 |
| | 2.499 | | |
| 14 | | 0.03 | 0.70 |
| | 2.941 | | |
| 15 | | 0.10 | 0.89 |
| | 3.462 | | |
| 16 | | 0.16 | 1.16 |
| | 4.075 | | |
| 17 | | 0.24 | 1.52 |
| | 4.797 | | |
| 18 | | 0.38 | 1.95 |
| | 5.646 | | |
| 19 | | 0.58 | 2.41 |
| | 6.646 | | |
| 20 | | 0.84 | 2.86 |
| | 7.823 | | |
| 21 | | 1.16 | 3.25 |
| | 9.209 | | |
| 22 | | 1.51 | 3.52 |
| | 10.840 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | | 1.88 | 3.65 |
| | 12.759 | | |
| 24 | | 2.21 | 3.62 |
| | 15.019 | | |
| 25 | | 2.46 | 3.45 |
| | 17.679 | | |
| 26 | | 2.59 | 3.19 |
| | 20.810 | | |
| 27 | | 2.59 | 2.89 |
| | 24.495 | | |
| 28 | | 2.45 | 2.59 |
| | 28.833 | | |
| 29 | | 2.19 | 2.32 |
| | 33.939 | | |
| 30 | | 1.87 | 2.12 |
| | 39.950 | | |
| 31 | | 1.54 | 2.00 |
| | 47.025 | | |
| 32 | | 1.28 | 2.00 |
| | 55.353 | | |
| 33 | | 1.16 | 2.12 |
| | 65.156 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | | 1.24 | 2.37 |
| | 76.695 | | |
| 35 | | 1.59 | 2.77 |
| | 90.278 | | |
| 36 | | 2.23 | 3.27 |
| | 106.266 | | |
| 37 | | 3.12 | 3.84 |
| | 125.085 | | |
| 38 | | 4.21 | 4.38 |
| | 147.238 | | |
| 39 | | 4.82 | 5.38 |
| | 173.314 | | |
| 40 | | 5.08 | 6.51 |
| | 204.008 | | |
| 41 | | 5.10 | 7.43 |
| | 240.137 | | |
| 42 | | 4.84 | 8.02 |
| | 282.665 | | |
| 43 | | 4.30 | 8.12 |
| | 332.725 | | |
| 44 | | 3.51 | 7.66 |
| | 391.651 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | | 2.53 | 6.65 |
| | 461.012 | | |
| 46 | | 1.47 | 5.18 |
| | 542.656 | | |
| 47 | | 0.37 | 3.48 |
| | 638.761 | | |
| 48 | | 0.02 | 1.76 |
| | 751.885 | | |
| 49 | | 0.00 | 0.21 |
| | 885.043 | | |
| 50 | | 0.00 | 0.00 |
| | 1041.784 | | |
| 51 | | 0.00 | 0.00 |
| | 1226.283 | | |
| 52 | | 0.00 | 0.00 |
| | 1443.457 | | |
| 53 | | 0.00 | 0.00 |
| | 1699.092 | | |
| 54 | | 0.00 | 0.00 |
| | 2000.000 | | |

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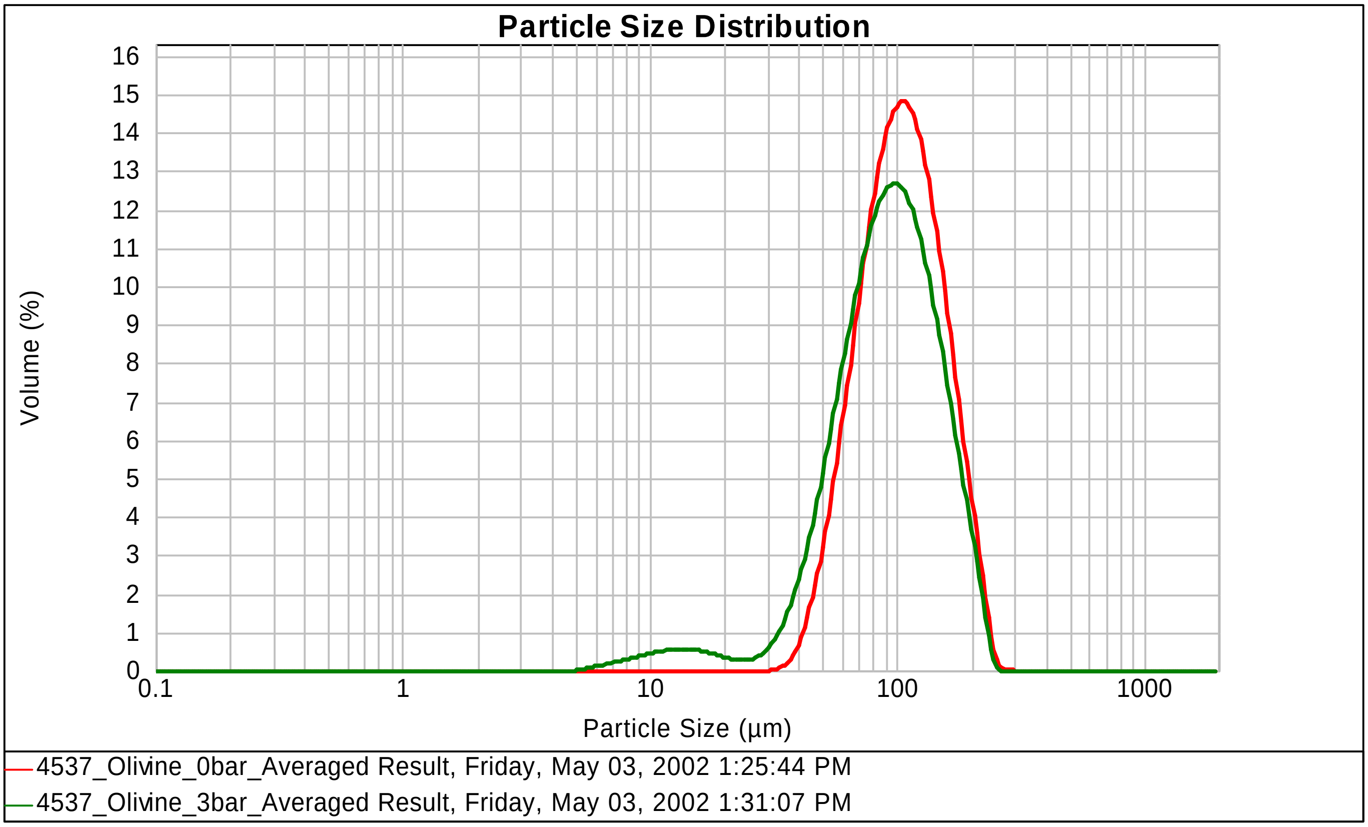
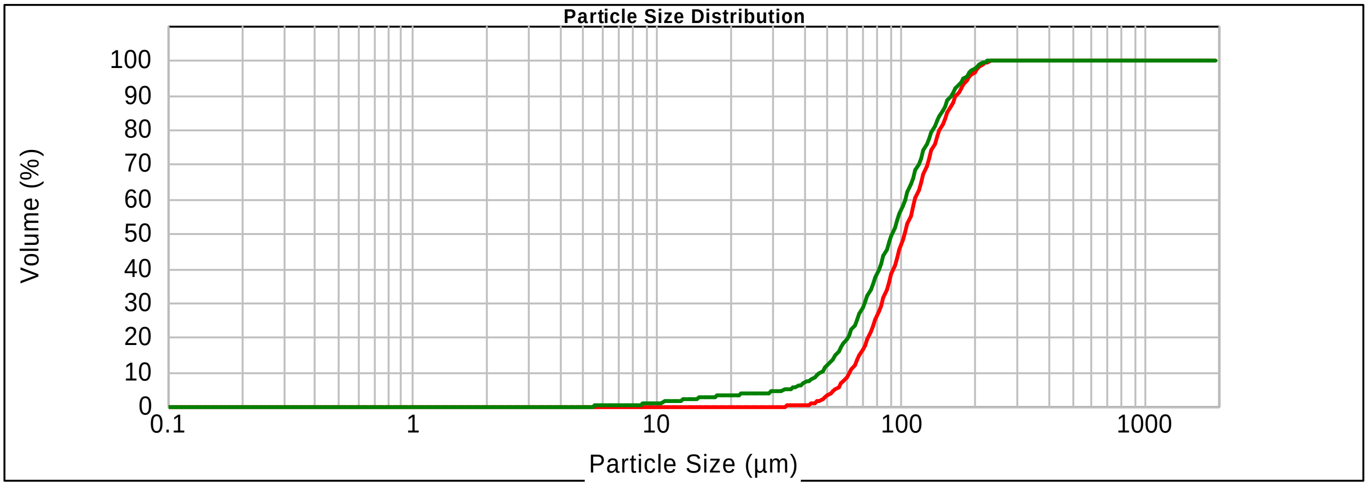
# Particle Size Distribution Comparison - Olivine

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 1 | 0.300 | 0.00 | 0.00 |
| 2 | 0.353 | 0.00 | 0.00 |
| 3 | 0.416 | 0.00 | 0.00 |
| 4 | 0.489 | 0.00 | 0.00 |
| 5 | 0.576 | 0.00 | 0.00 |
| 6 | 0.678 | 0.00 | 0.00 |
| 7 | 0.798 | 0.00 | 0.00 |
| 8 | 0.939 | 0.00 | 0.00 |
| 9 | 1.106 | 0.00 | 0.00 |
| 10 | 1.301 | 0.00 | 0.00 |
| 11 | 1.532 | 0.00 | 0.00 |
|  | 1.803 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 12 | 1.803 | 0.00 | 0.00 |
| 13 | 2.123 | 0.00 | 0.00 |
| 14 | 2.499 | 0.00 | 0.00 |
| 15 | 2.941 | 0.00 | 0.00 |
| 16 | 3.462 | 0.00 | 0.00 |
| 17 | 4.075 | 0.00 | 0.00 |
| 18 | 4.797 | 0.00 | 0.02 |
| 19 | 5.646 | 0.00 | 0.13 |
| 20 | 6.646 | 0.00 | 0.23 |
| 21 | 7.823 | 0.00 | 0.35 |
| 22 | 9.209 | 0.00 | 0.48 |
|  | 10.840 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 23 | 10.840 | 0.00 | 0.57 |
| 24 | 12.759 | 0.00 | 0.59 |
| 25 | 15.019 | 0.00 | 0.54 |
| 26 | 17.679 | 0.00 | 0.41 |
| 27 | 20.810 | 0.00 | 0.30 |
| 28 | 24.495 | 0.00 | 0.35 |
| 29 | 28.833 | 0.01 | 0.77 |
| 30 | 33.939 | 0.26 | 1.74 |
| 31 | 39.950 | 1.50 | 3.42 |
| 32 | 47.025 | 3.67 | 5.72 |
| 33 | 55.353 | 6.85 | 8.39 |
|  | 65.156 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 34 | 65.156 | 10.45 | 10.94 |
| 35 | 76.695 | 12.81 | 13.67 |
| 36 | 90.278 | 13.50 | 15.55 |
| 37 | 106.266 | 12.78 | 15.48 |
| 38 | 125.085 | 10.79 | 13.42 |
| 39 | 147.238 | 7.99 | 10.03 |
| 40 | 173.314 | 5.03 | 6.20 |
| 41 | 204.008 | 2.15 | 2.80 |
| 42 | 240.137 | 0.00 | 0.11 |
| 43 | 282.665 | 0.00 | 0.00 |
| 44 | 332.725 | 0.00 | 0.00 |
|  | 391.651 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 45 | 391.651 | 0.00 | 0.00 |
| 46 | 461.012 | 0.00 | 0.00 |
| 47 | 542.656 | 0.00 | 0.00 |
| 48 | 638.761 | 0.00 | 0.00 |
| 49 | 751.885 | 0.00 | 0.00 |
| 50 | 885.043 | 0.00 | 0.00 |
| 51 | 1041.784 | 0.00 | 0.00 |
| 52 | 1226.283 | 0.00 | 0.00 |
| 53 | 1443.457 | 0.00 | 0.00 |
| 54 | 1699.092 | 0.00 | 0.00 |
|  | 2000.000 |  |  |

File name: 4537_Olivine.mea
Record Number: 10
25 Jun 2002 03:37:49 PM

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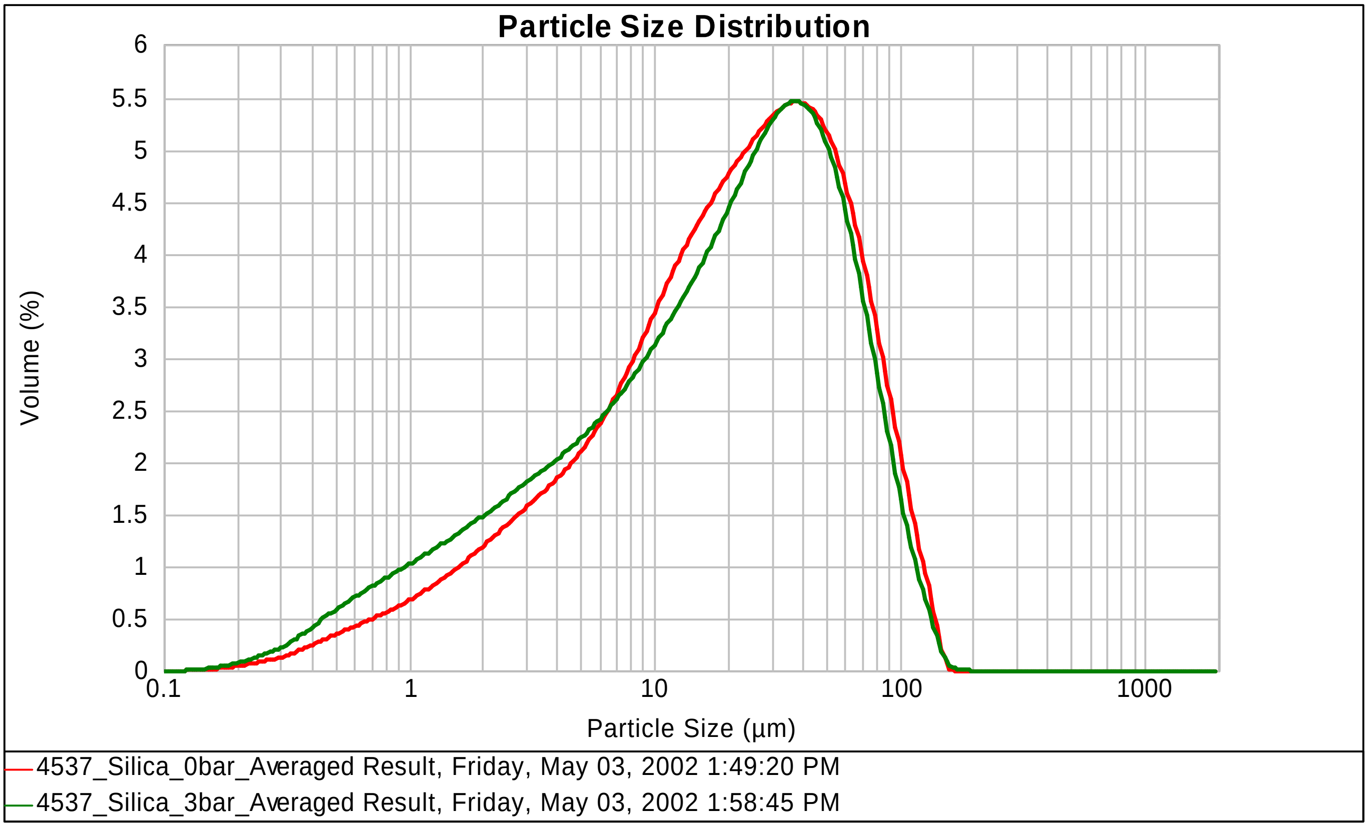
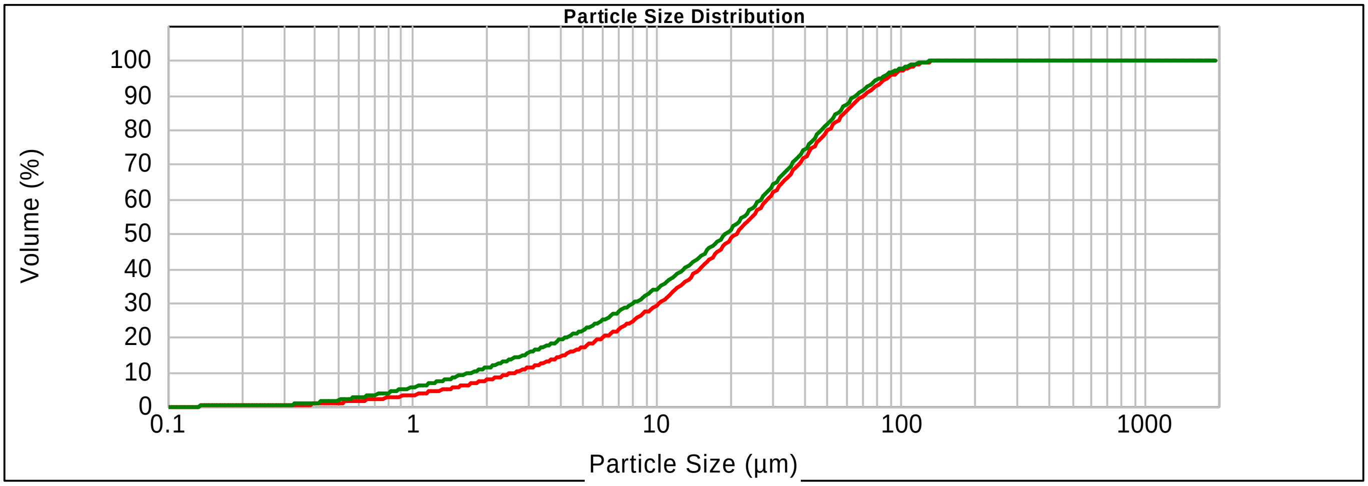
# Particle Size Distribution Comparison - Silica

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | | 0.16 | 0.28 |
| | 0.353 | | |
| 2 | | 0.24 | 0.40 |
| | 0.416 | | |
| 3 | | 0.32 | 0.54 |
| | 0.489 | | |
| 4 | | 0.39 | 0.66 |
| | 0.576 | | |
| 5 | | 0.47 | 0.78 |
| | 0.678 | | |
| 6 | | 0.55 | 0.89 |
| | 0.798 | | |
| 7 | | 0.63 | 0.99 |
| | 0.939 | | |
| 8 | | 0.73 | 1.10 |
| | 1.106 | | |
| 9 | | 0.83 | 1.20 |
| | 1.301 | | |
| 10 | | 0.96 | 1.32 |
| | 1.532 | | |
| 11 | | 1.10 | 1.43 |
| | 1.803 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | | 1.25 | 1.56 |
| | 2.123 | | |
| 13 | | 1.40 | 1.69 |
| | 2.499 | | |
| 14 | | 1.56 | 1.83 |
| | 2.941 | | |
| 15 | | 1.72 | 1.96 |
| | 3.462 | | |
| 16 | | 1.89 | 2.10 |
| | 4.075 | | |
| 17 | | 2.07 | 2.25 |
| | 4.797 | | |
| 18 | | 2.28 | 2.41 |
| | 5.646 | | |
| 19 | | 2.55 | 2.59 |
| | 6.646 | | |
| 20 | | 2.81 | 2.88 |
| | 7.823 | | |
| 21 | | 3.05 | 3.25 |
| | 9.209 | | |
| 22 | | 3.32 | 3.65 |
| | 10.840 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | | 3.61 | 4.05 |
| | 12.759 | | |
| 24 | | 3.91 | 4.40 |
| | 15.019 | | |
| 25 | | 4.24 | 4.71 |
| | 17.679 | | |
| 26 | | 4.60 | 4.98 |
| | 20.810 | | |
| 27 | | 4.99 | 5.25 |
| | 24.495 | | |
| 28 | | 5.37 | 5.49 |
| | 28.833 | | |
| 29 | | 5.67 | 5.70 |
| | 33.939 | | |
| 30 | | 5.80 | 5.81 |
| | 39.950 | | |
| 31 | | 5.72 | 5.76 |
| | 47.025 | | |
| 32 | | 5.36 | 5.49 |
| | 55.353 | | |
| 33 | | 4.71 | 4.97 |
| | 65.156 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | | 3.85 | 4.24 |
| | 76.695 | | |
| 35 | | 2.89 | 3.35 |
| | 90.278 | | |
| 36 | | 1.95 | 2.43 |
| | 106.266 | | |
| 37 | | 1.15 | 1.52 |
| | 125.085 | | |
| 38 | | 0.51 | 0.68 |
| | 147.238 | | |
| 39 | | 0.03 | 0.06 |
| | 173.314 | | |
| 40 | | 0.00 | 0.00 |
| | 204.008 | | |
| 41 | | 0.00 | 0.00 |
| | 240.137 | | |
| 42 | | 0.00 | 0.00 |
| | 282.665 | | |
| 43 | | 0.00 | 0.00 |
| | 332.725 | | |
| 44 | | 0.00 | 0.00 |
| | 391.651 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | | 0.00 | 0.00 |
| | 461.012 | | |
| 46 | | 0.00 | 0.00 |
| | 542.656 | | |
| 47 | | 0.00 | 0.00 |
| | 638.761 | | |
| 48 | | 0.00 | 0.00 |
| | 751.885 | | |
| 49 | | 0.00 | 0.00 |
| | 885.043 | | |
| 50 | | 0.00 | 0.00 |
| | 1041.784 | | |
| 51 | | 0.00 | 0.00 |
| | 1226.283 | | |
| 52 | | 0.00 | 0.00 |
| | 1443.457 | | |
| 53 | | 0.00 | 0.00 |
| | 1699.092 | | |
| 54 | | 0.00 | 0.00 |
| | 2000.000 | | |

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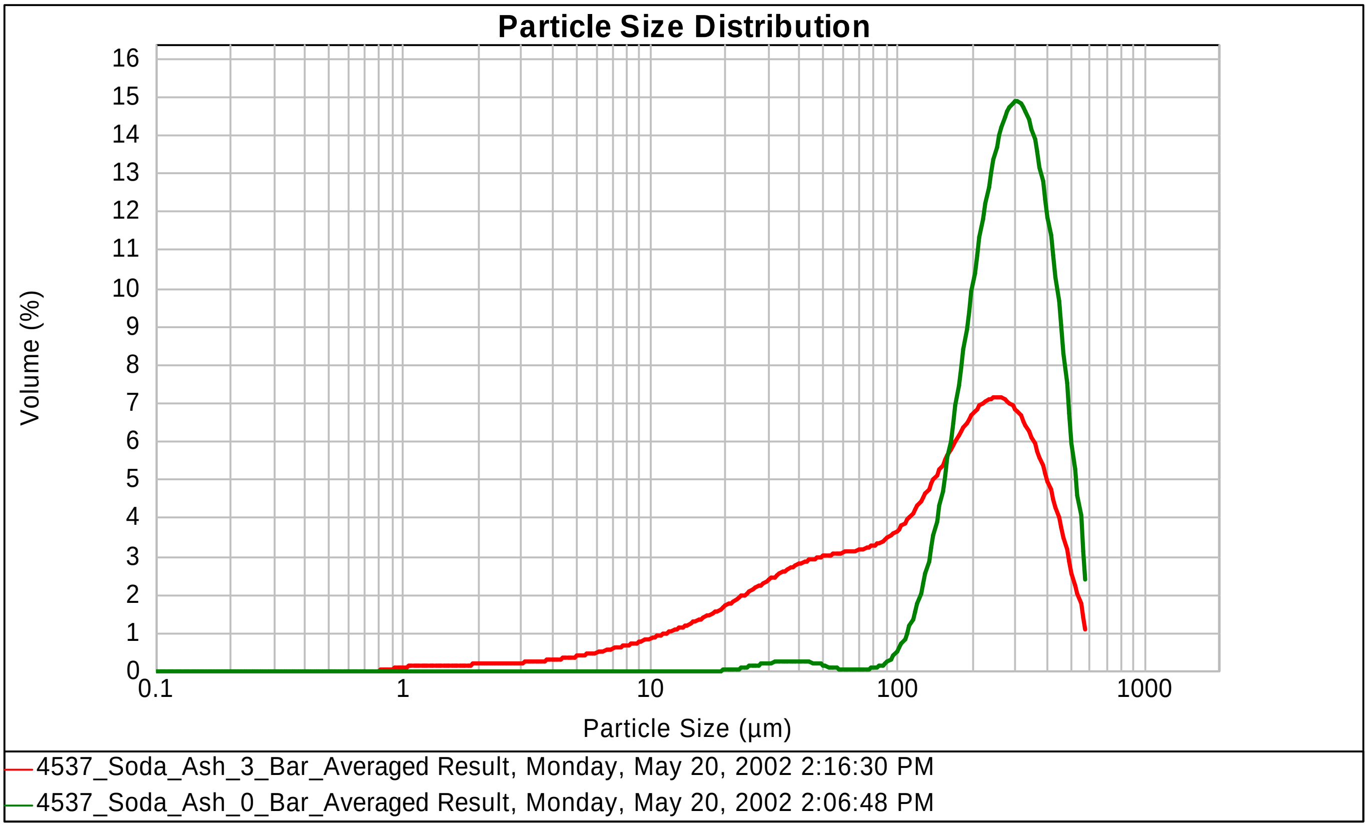
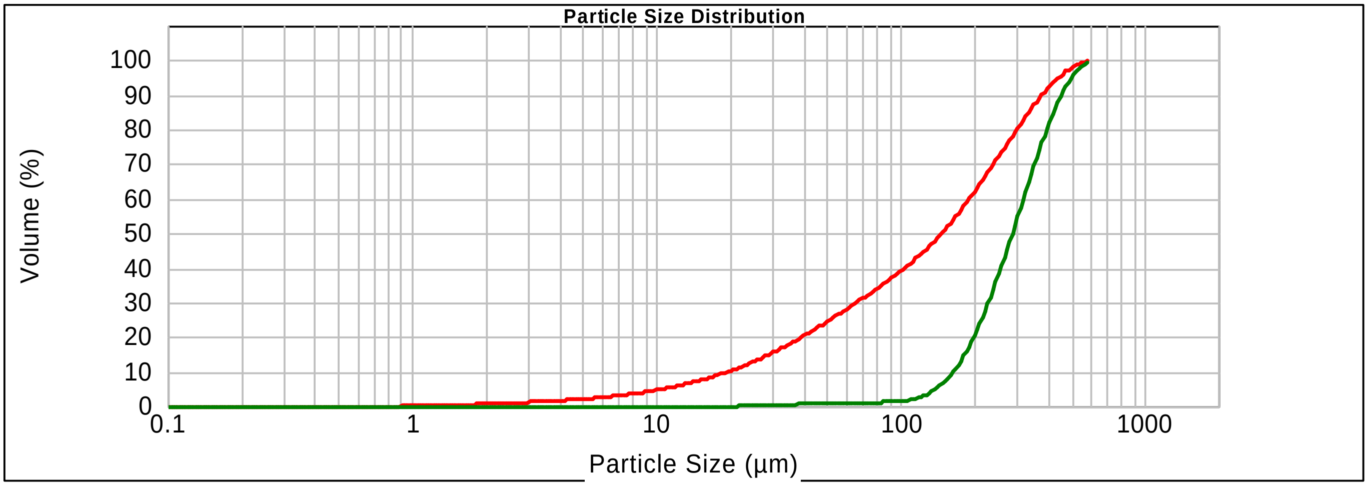
# Particle Size Distribution Comparison - Soda ash

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | 0.353 | 0.00 | 0.00 |
| 2 | 0.416 | 0.00 | 0.00 |
| 3 | 0.489 | 0.00 | 0.00 |
| 4 | 0.576 | 0.00 | 0.00 |
| 5 | 0.678 | 0.00 | 0.00 |
| 6 | 0.798 | 0.00 | 0.00 |
| 7 | 0.939 | 0.00 | 0.02 |
| 8 | 1.106 | 0.00 | 0.11 |
| 9 | 1.301 | 0.00 | 0.13 |
| 10 | 1.532 | 0.00 | 0.15 |
| 11 | 1.803 | 0.00 | 0.16 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | 2.123 | 0.00 | 0.17 |
| 13 | 2.499 | 0.00 | 0.18 |
| 14 | 2.941 | 0.00 | 0.20 |
| 15 | 3.462 | 0.00 | 0.23 |
| 16 | 4.075 | 0.00 | 0.28 |
| 17 | 4.797 | 0.00 | 0.34 |
| 18 | 5.646 | 0.00 | 0.42 |
| 19 | 6.646 | 0.00 | 0.51 |
| 20 | 7.823 | 0.00 | 0.62 |
| 21 | 9.209 | 0.00 | 0.74 |
| 22 | 10.840 | 0.00 | 0.89 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | 12.759 | 0.00 | 1.05 |
| 24 | 15.019 | 0.00 | 1.24 |
| 25 | 17.679 | 0.00 | 1.45 |
| 26 | 20.810 | 0.00 | 1.70 |
| 27 | 24.495 | 0.04 | 1.98 |
| 28 | 28.833 | 0.14 | 2.28 |
| 29 | 33.939 | 0.22 | 2.57 |
| 30 | 39.950 | 0.26 | 2.84 |
| 31 | 47.025 | 0.24 | 3.04 |
| 32 | 55.353 | 0.14 | 3.18 |
| 33 | 65.156 | 0.04 | 3.27 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | 76.695 | 0.03 | 3.36 |
| 35 | 90.278 | 0.10 | 3.52 |
| 36 | 106.266 | 0.45 | 3.84 |
| 37 | 125.085 | 1.41 | 4.37 |
| 38 | 147.238 | 3.18 | 5.11 |
| 39 | 173.314 | 5.82 | 5.96 |
| 40 | 204.008 | 6.80 | 9.12 |
| 41 | 240.137 | 7.40 | 12.40 |
| 42 | 282.665 | 7.58 | 14.92 |
| 43 | 332.725 | 7.22 | 15.82 |
| 44 | 391.651 | 6.28 | 14.70 |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | 461.012 | 4.88 | 11.74 |
| 46 | 542.656 | 3.00 | 7.11 |
| 47 | 638.761 | 0.95 | 2.12 |
| 48 | 751.885 | 0.00 | 0.00 |
| 49 | 885.043 | 0.00 | 0.00 |
| 50 | 1041.784 | 0.00 | 0.00 |
| 51 | 1226.283 | 0.00 | 0.00 |
| 52 | 1443.457 | 0.00 | 0.00 |
| 53 | 1699.092 | 0.00 | 0.00 |
| 54 | 2000.000 | 0.00 | 0.00 |

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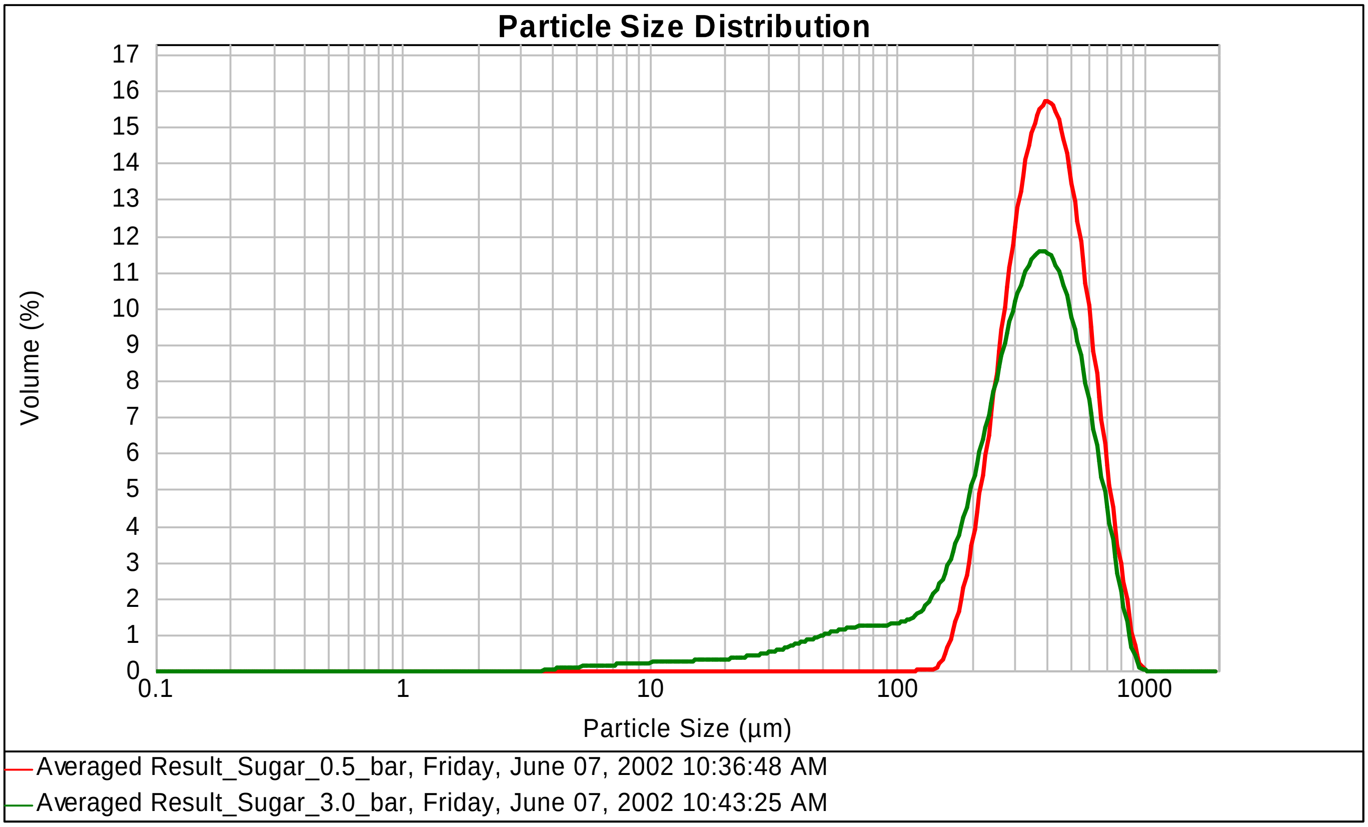
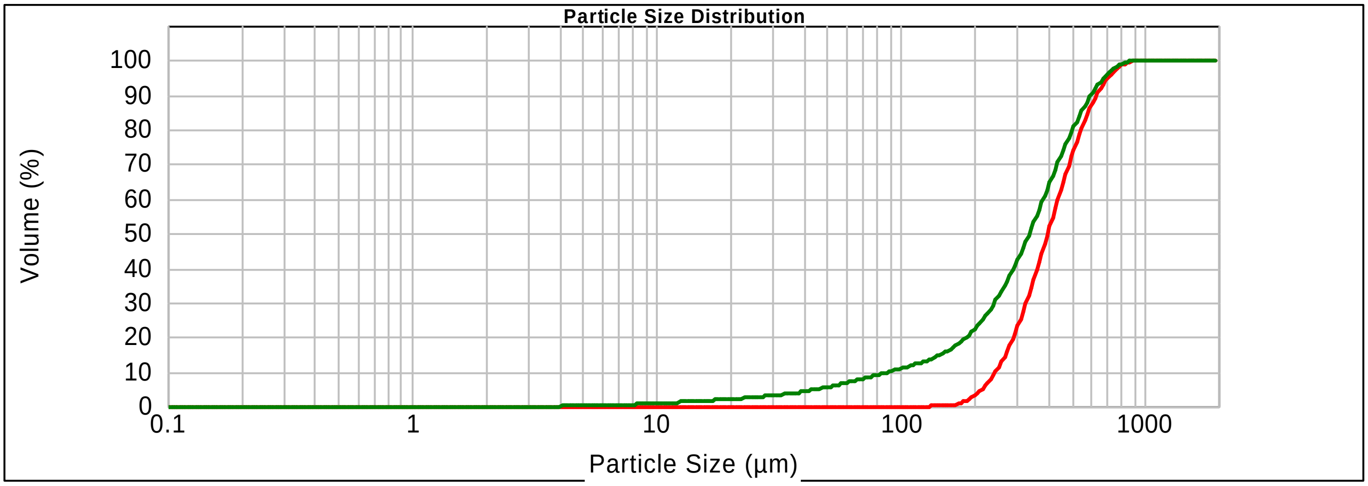
# Particle Size Distribution Comparison - Sugar

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | | 0.00 | 0.00 |
| | 0.353 | | |
| 2 | | 0.00 | 0.00 |
| | 0.416 | | |
| 3 | | 0.00 | 0.00 |
| | 0.489 | | |
| 4 | | 0.00 | 0.00 |
| | 0.576 | | |
| 5 | | 0.00 | 0.00 |
| | 0.678 | | |
| 6 | | 0.00 | 0.00 |
| | 0.798 | | |
| 7 | | 0.00 | 0.00 |
| | 0.939 | | |
| 8 | | 0.00 | 0.00 |
| | 1.106 | | |
| 9 | | 0.00 | 0.00 |
| | 1.301 | | |
| 10 | | 0.00 | 0.00 |
| | 1.532 | | |
| 11 | | 0.00 | 0.00 |
| | 1.803 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | | 0.00 | 0.00 |
| | 2.123 | | |
| 13 | | 0.00 | 0.00 |
| | 2.499 | | |
| 14 | | 0.00 | 0.00 |
| | 2.941 | | |
| 15 | | 0.00 | 0.00 |
| | 3.462 | | |
| 16 | | 0.00 | 0.00 |
| | 4.075 | | |
| 17 | | 0.00 | 0.09 |
| | 4.797 | | |
| 18 | | 0.00 | 0.11 |
| | 5.646 | | |
| 19 | | 0.00 | 0.14 |
| | 6.646 | | |
| 20 | | 0.00 | 0.17 |
| | 7.823 | | |
| 21 | | 0.00 | 0.20 |
| | 9.209 | | |
| 22 | | 0.00 | 0.23 |
| | 10.840 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | | 0.00 | 0.26 |
| | 12.759 | | |
| 24 | | 0.00 | 0.28 |
| | 15.019 | | |
| 25 | | 0.00 | 0.31 |
| | 17.679 | | |
| 26 | | 0.00 | 0.33 |
| | 20.810 | | |
| 27 | | 0.00 | 0.38 |
| | 24.495 | | |
| 28 | | 0.00 | 0.45 |
| | 28.833 | | |
| 29 | | 0.00 | 0.56 |
| | 33.939 | | |
| 30 | | 0.00 | 0.71 |
| | 39.950 | | |
| 31 | | 0.00 | 0.89 |
| | 47.025 | | |
| 32 | | 0.00 | 1.07 |
| | 55.353 | | |
| 33 | | 0.00 | 1.21 |
| | 65.156 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | | 0.00 | 1.30 |
| | 76.695 | | |
| 35 | | 0.00 | 1.33 |
| | 90.278 | | |
| 36 | | 0.00 | 1.37 |
| | 106.266 | | |
| 37 | | 0.00 | 1.55 |
| | 125.085 | | |
| 38 | | 0.03 | 2.05 |
| | 147.238 | | |
| 39 | | 0.65 | 3.04 |
| | 173.314 | | |
| 40 | | 2.55 | 4.62 |
| | 204.008 | | |
| 41 | | 5.59 | 6.68 |
| | 240.137 | | |
| 42 | | 8.99 | 9.53 |
| | 282.665 | | |
| 43 | | 10.99 | 13.39 |
| | 332.725 | | |
| 44 | | 12.18 | 16.08 |
| | 391.651 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | | 12.11 | 16.61 |
| | 461.012 | | |
| 46 | | 10.69 | 14.72 |
| | 542.656 | | |
| 47 | | 8.19 | 11.03 |
| | 638.761 | | |
| 48 | | 5.24 | 6.69 |
| | 751.885 | | |
| 49 | | 2.14 | 2.89 |
| | 885.043 | | |
| 50 | | 0.13 | 0.25 |
| | 1041.784 | | |
| 51 | | 0.00 | 0.00 |
| | 1226.283 | | |
| 52 | | 0.00 | 0.00 |
| | 1443.457 | | |
| 53 | | 0.00 | 0.00 |
| | 1699.092 | | |
| 54 | | 0.00 | 0.00 |
| | 2000.000 | | |

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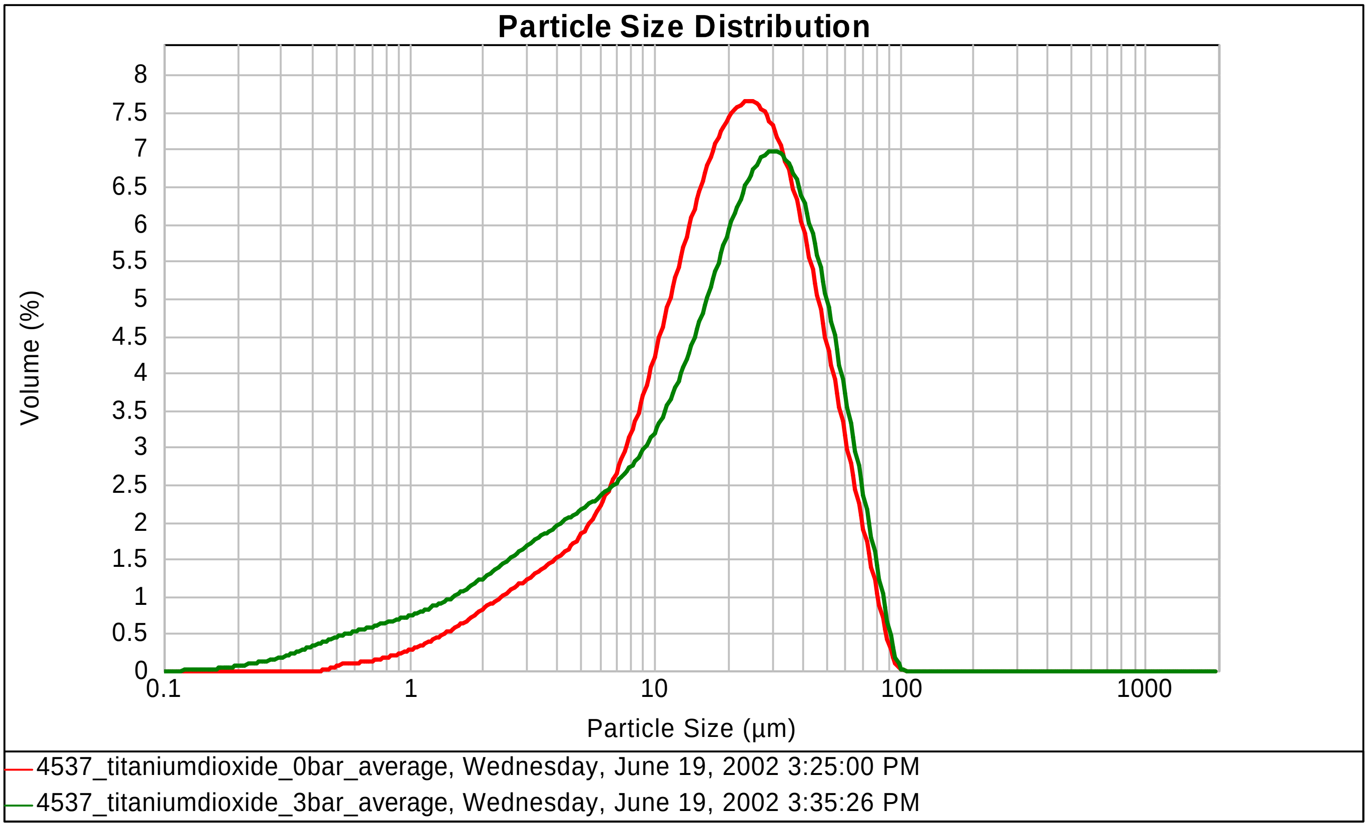
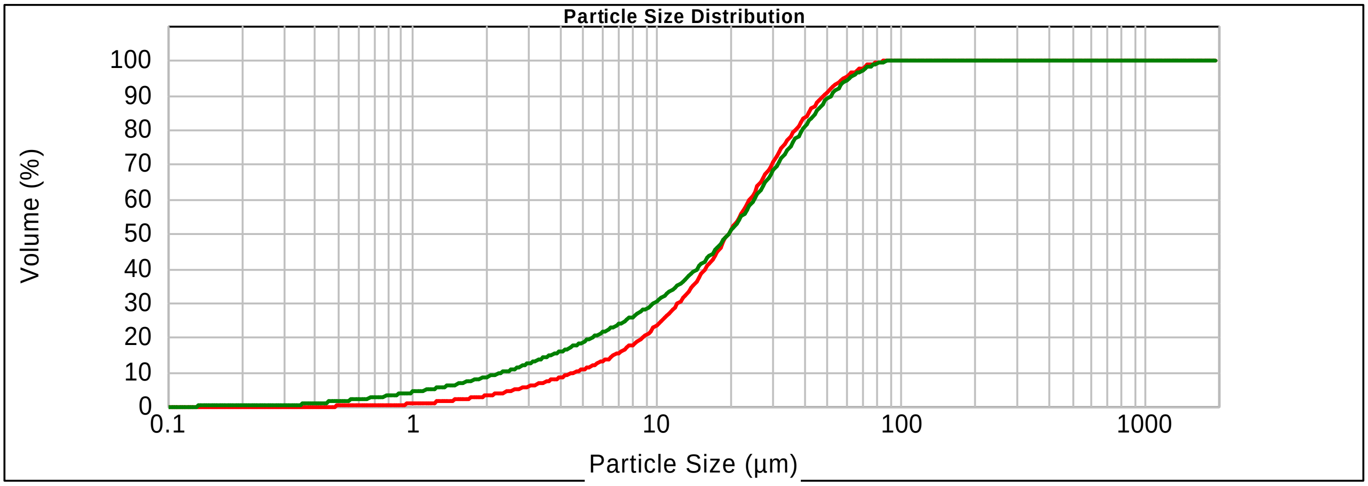
# Particle Size Distribution Comparison - Titanium dioxide

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 1 | 0.300 | 0.00 | 0.22 |
| 2 | 0.353 | 0.00 | 0.32 |
| 3 | 0.416 | 0.00 | 0.42 |
| 4 | 0.489 | 0.08 | 0.50 |
| 5 | 0.576 | 0.11 | 0.58 |
| 6 | 0.678 | 0.15 | 0.64 |
| 7 | 0.798 | 0.21 | 0.71 |
| 8 | 0.939 | 0.29 | 0.79 |
| 9 | 1.106 | 0.40 | 0.88 |
| 10 | 1.301 | 0.53 | 1.00 |
| 11 | 1.532 | 0.68 | 1.14 |
|  | 1.803 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 12 | 1.803 | 0.85 | 1.30 |
| 13 | 2.123 | 1.02 | 1.47 |
| 14 | 2.499 | 1.19 | 1.65 |
| 15 | 2.941 | 1.35 | 1.83 |
| 16 | 3.462 | 1.52 | 2.00 |
| 17 | 4.075 | 1.73 | 2.17 |
| 18 | 4.797 | 2.00 | 2.33 |
| 19 | 5.646 | 2.39 | 2.51 |
| 20 | 6.646 | 2.73 | 2.93 |
| 21 | 7.823 | 3.02 | 3.62 |
| 22 | 9.209 | 3.40 | 4.47 |
|  | 10.840 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 23 | 10.840 | 3.91 | 5.39 |
| 24 | 12.759 | 4.53 | 6.32 |
| 25 | 15.019 | 5.27 | 7.14 |
| 26 | 17.679 | 6.05 | 7.77 |
| 27 | 20.810 | 6.77 | 8.10 |
| 28 | 24.495 | 7.27 | 8.08 |
| 29 | 28.833 | 7.42 | 7.69 |
| 30 | 33.939 | 6.94 | 7.13 |
| 31 | 39.950 | 5.88 | 6.38 |
| 32 | 47.025 | 4.65 | 5.27 |
| 33 | 55.353 | 3.35 | 3.95 |
|  | 65.156 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 34 | 65.156 | 2.12 | 2.61 |
| 35 | 76.695 | 0.94 | 1.31 |
| 36 | 90.278 | 0.09 | 0.15 |
| 37 | 106.266 | 0.00 | 0.00 |
| 38 | 125.085 | 0.00 | 0.00 |
| 39 | 147.238 | 0.00 | 0.00 |
| 40 | 173.314 | 0.00 | 0.00 |
| 41 | 204.008 | 0.00 | 0.00 |
| 42 | 240.137 | 0.00 | 0.00 |
| 43 | 282.665 | 0.00 | 0.00 |
| 44 | 332.725 | 0.00 | 0.00 |
|  | 391.651 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 45 | 391.651 | 0.00 | 0.00 |
| 46 | 461.012 | 0.00 | 0.00 |
| 47 | 542.656 | 0.00 | 0.00 |
| 48 | 638.761 | 0.00 | 0.00 |
| 49 | 751.885 | 0.00 | 0.00 |
| 50 | 885.043 | 0.00 | 0.00 |
| 51 | 1041.784 | 0.00 | 0.00 |
| 52 | 1226.283 | 0.00 | 0.00 |
| 53 | 1443.457 | 0.00 | 0.00 |
| 54 | 1699.092 | 0.00 | 0.00 |
|  | 2000.000 |  |  |

Malvern Instruments Ltd.
Malvern, UK
Tel := +[44] (0) 1684-892456 Fax +[44] (0) 1684-892789

Mastersizer 2000 Ver. Version 4.00
Serial Number : 34403/27

File name: 4537_Titanium Dioxide.mea
Record Number: 15
25 Jun 2002 03:22:50 PM

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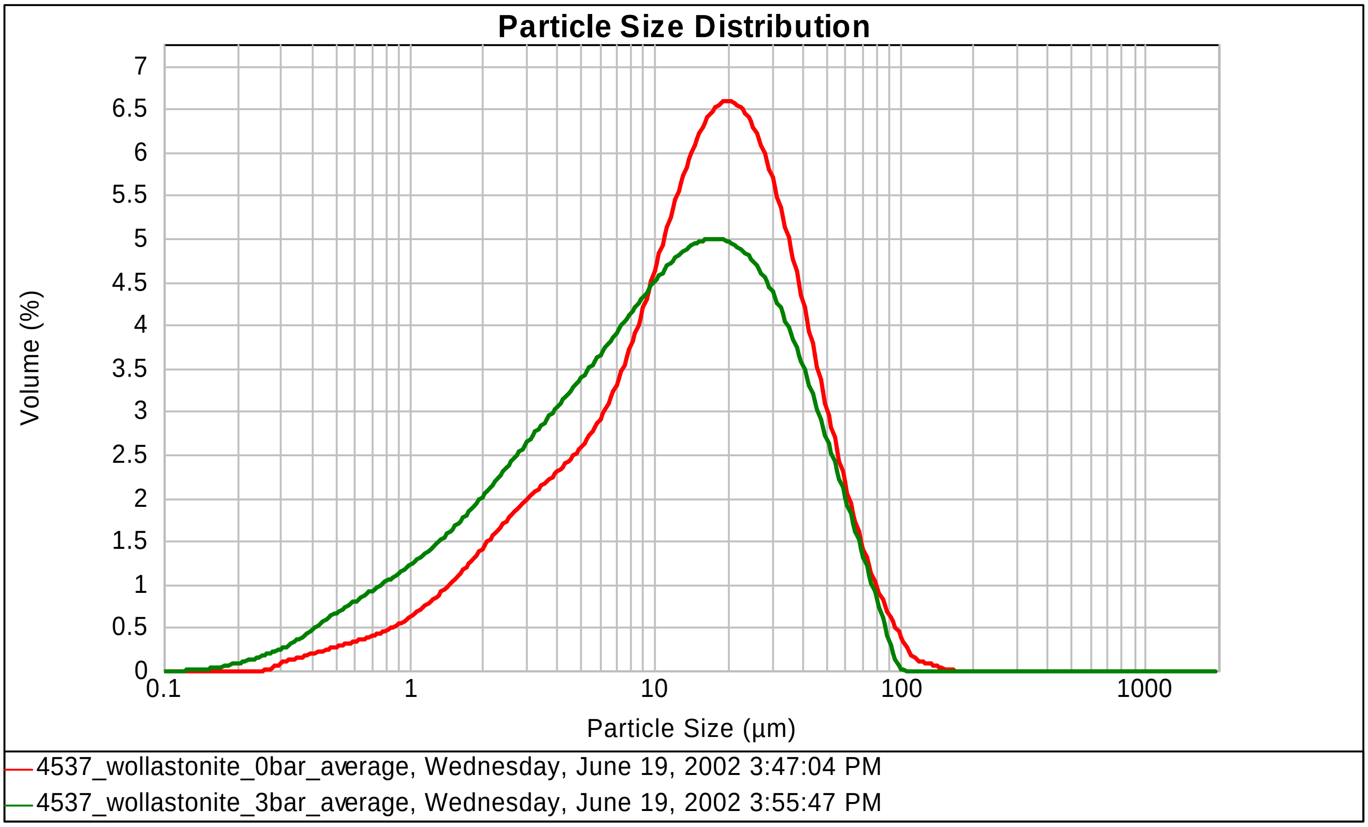
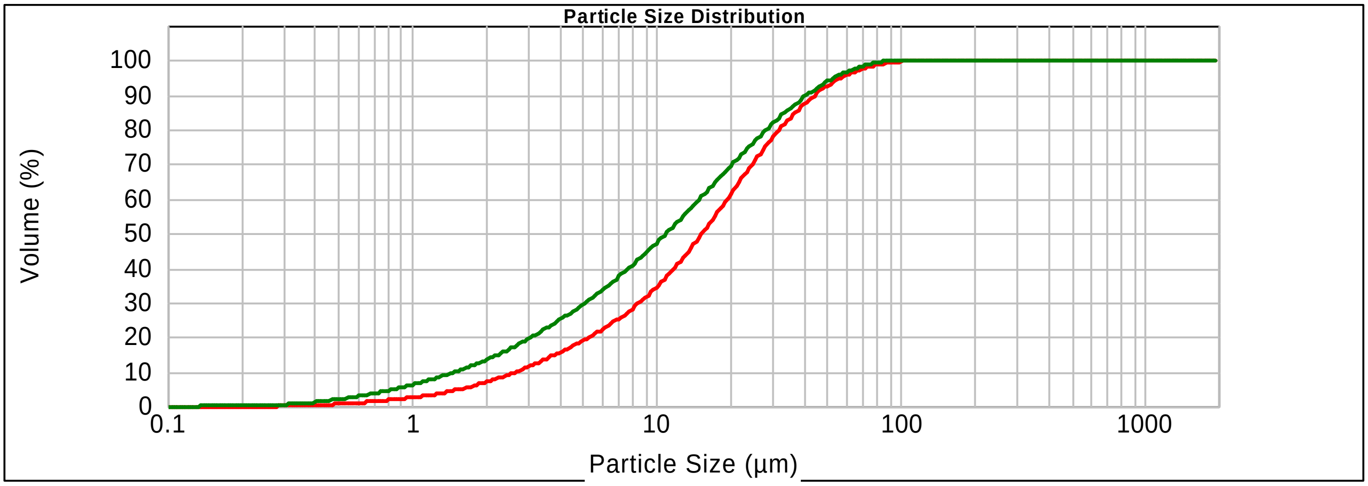
# Particle Size Distribution Comparison - Wollastonite

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | | 0.13 | 0.31 |
| | 0.353 | | |
| 2 | | 0.19 | 0.45 |
| | 0.416 | | |
| 3 | | 0.25 | 0.61 |
| | 0.489 | | |
| 4 | | 0.31 | 0.75 |
| | 0.576 | | |
| 5 | | 0.37 | 0.88 |
| | 0.678 | | |
| 6 | | 0.45 | 1.02 |
| | 0.798 | | |
| 7 | | 0.54 | 1.15 |
| | 0.939 | | |
| 8 | | 0.66 | 1.30 |
| | 1.106 | | |
| 9 | | 0.82 | 1.47 |
| | 1.301 | | |
| 10 | | 1.01 | 1.66 |
| | 1.532 | | |
| 11 | | 1.23 | 1.87 |
| | 1.803 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | | 1.48 | 2.11 |
| | 2.123 | | |
| 13 | | 1.72 | 2.36 |
| | 2.499 | | |
| 14 | | 1.96 | 2.62 |
| | 2.941 | | |
| 15 | | 2.17 | 2.88 |
| | 3.462 | | |
| 16 | | 2.36 | 3.14 |
| | 4.075 | | |
| 17 | | 2.56 | 3.39 |
| | 4.797 | | |
| 18 | | 2.80 | 3.65 |
| | 5.646 | | |
| 19 | | 3.14 | 3.92 |
| | 6.646 | | |
| 20 | | 3.60 | 4.20 |
| | 7.823 | | |
| 21 | | 4.20 | 4.49 |
| | 9.209 | | |
| 22 | | 4.78 | 4.90 |
| | 10.840 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | | 5.03 | 5.63 |
| | 12.759 | | |
| 24 | | 5.21 | 6.28 |
| | 15.019 | | |
| 25 | | 5.30 | 6.77 |
| | 17.679 | | |
| 26 | | 5.30 | 7.00 |
| | 20.810 | | |
| 27 | | 5.19 | 6.93 |
| | 24.495 | | |
| 28 | | 4.95 | 6.57 |
| | 28.833 | | |
| 29 | | 4.59 | 5.93 |
| | 33.939 | | |
| 30 | | 4.10 | 5.10 |
| | 39.950 | | |
| 31 | | 3.50 | 4.16 |
| | 47.025 | | |
| 32 | | 2.83 | 3.21 |
| | 55.353 | | |
| 33 | | 2.14 | 2.31 |
| | 65.156 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | | 1.44 | 1.54 |
| | 76.695 | | |
| 35 | | 0.77 | 0.94 |
| | 90.278 | | |
| 36 | | 0.10 | 0.50 |
| | 106.266 | | |
| 37 | | 0.00 | 0.17 |
| | 125.085 | | |
| 38 | | 0.00 | 0.07 |
| | 147.238 | | |
| 39 | | 0.00 | 0.01 |
| | 173.314 | | |
| 40 | | 0.00 | 0.00 |
| | 204.008 | | |
| 41 | | 0.00 | 0.00 |
| | 240.137 | | |
| 42 | | 0.00 | 0.00 |
| | 282.665 | | |
| 43 | | 0.00 | 0.00 |
| | 332.725 | | |
| 44 | | 0.00 | 0.00 |
| | 391.651 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | | 0.00 | 0.00 |
| | 461.012 | | |
| 46 | | 0.00 | 0.00 |
| | 542.656 | | |
| 47 | | 0.00 | 0.00 |
| | 638.761 | | |
| 48 | | 0.00 | 0.00 |
| | 751.885 | | |
| 49 | | 0.00 | 0.00 |
| | 885.043 | | |
| 50 | | 0.00 | 0.00 |
| | 1041.784 | | |
| 51 | | 0.00 | 0.00 |
| | 1226.283 | | |
| 52 | | 0.00 | 0.00 |
| | 1443.457 | | |
| 53 | | 0.00 | 0.00 |
| | 1699.092 | | |
| 54 | | 0.00 | 0.00 |
| | 2000.000 | | |

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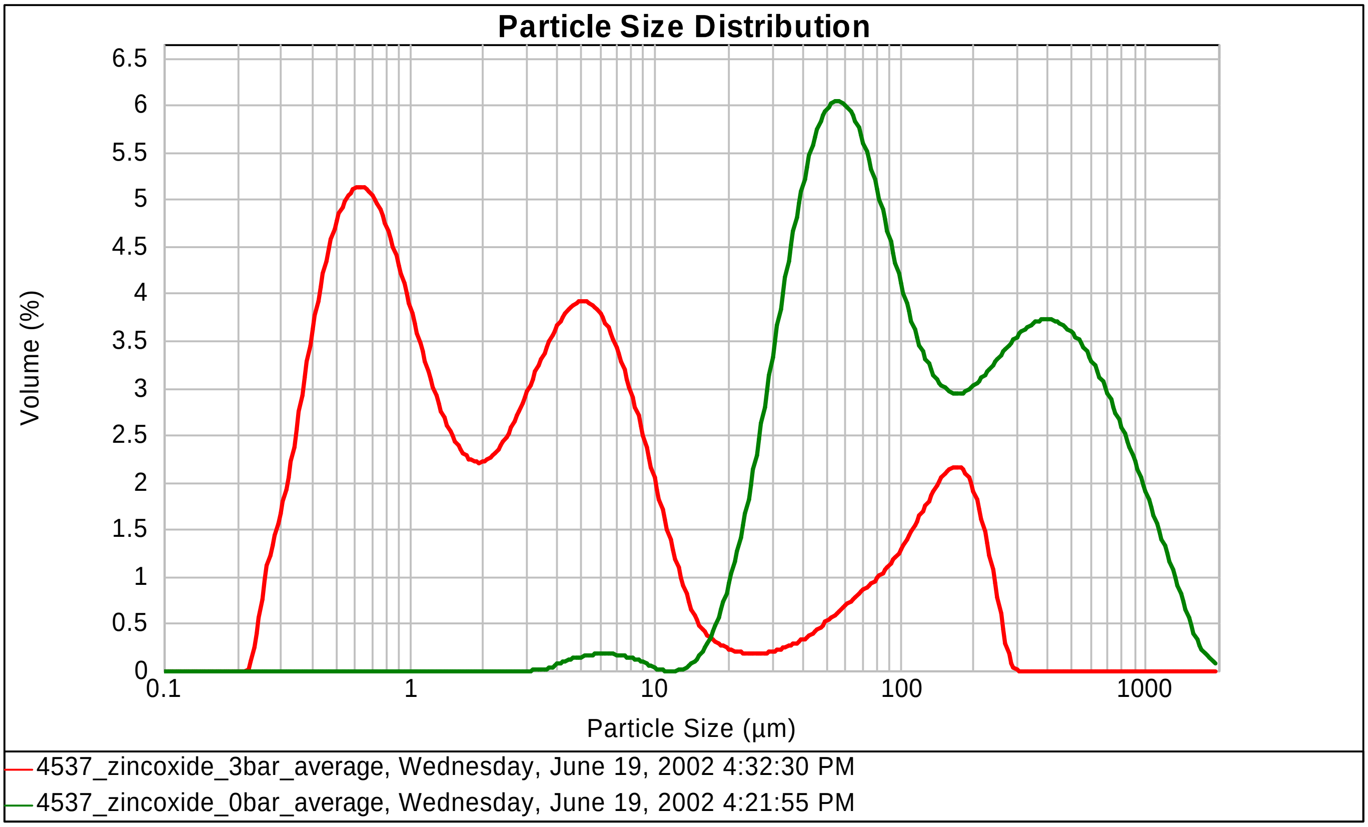
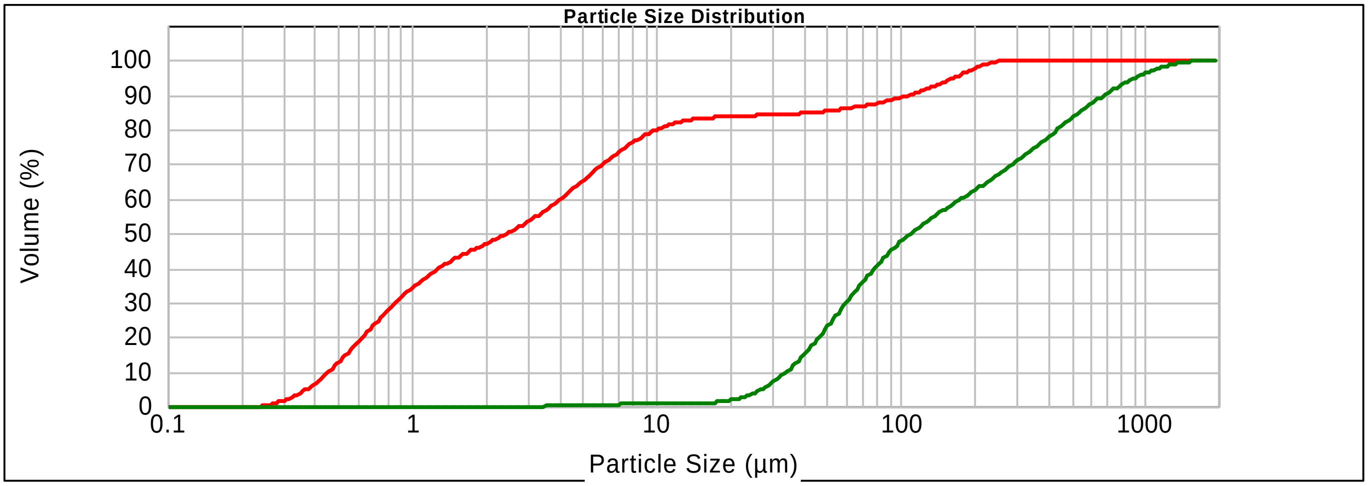
# Particle Size Distribution Comparison - Zinc oxide

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 0.300 | | |
| 1 | | 0.00 | 2.24 |
| | 0.353 | | |
| 2 | | 0.00 | 3.43 |
| | 0.416 | | |
| 3 | | 0.00 | 4.50 |
| | 0.489 | | |
| 4 | | 0.00 | 5.20 |
| | 0.576 | | |
| 5 | | 0.00 | 5.46 |
| | 0.678 | | |
| 6 | | 0.00 | 5.29 |
| | 0.798 | | |
| 7 | | 0.00 | 4.78 |
| | 0.939 | | |
| 8 | | 0.00 | 4.09 |
| | 1.106 | | |
| 9 | | 0.00 | 3.39 |
| | 1.301 | | |
| 10 | | 0.00 | 2.82 |
| | 1.532 | | |
| 11 | | 0.00 | 2.46 |
| | 1.803 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 1.803 | | |
| 12 | | 0.00 | 2.35 |
| | 2.123 | | |
| 13 | | 0.00 | 2.48 |
| | 2.499 | | |
| 14 | | 0.00 | 2.82 |
| | 2.941 | | |
| 15 | | 0.00 | 3.27 |
| | 3.462 | | |
| 16 | | 0.03 | 3.73 |
| | 4.075 | | |
| 17 | | 0.12 | 4.06 |
| | 4.797 | | |
| 18 | | 0.17 | 4.17 |
| | 5.646 | | |
| 19 | | 0.19 | 4.00 |
| | 6.646 | | |
| 20 | | 0.17 | 3.57 |
| | 7.823 | | |
| 21 | | 0.13 | 2.93 |
| | 9.209 | | |
| 22 | | 0.03 | 2.18 |
| | 10.840 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 10.840 | | |
| 23 | | 0.00 | 1.43 |
| | 12.759 | | |
| 24 | | 0.05 | 0.79 |
| | 15.019 | | |
| 25 | | 0.28 | 0.42 |
| | 17.679 | | |
| 26 | | 0.27 | 0.76 |
| | 20.810 | | |
| 27 | | 0.20 | 1.53 |
| | 24.495 | | |
| 28 | | 0.19 | 2.56 |
| | 28.833 | | |
| 29 | | 0.23 | 3.75 |
| | 33.939 | | |
| 30 | | 0.29 | 4.90 |
| | 39.950 | | |
| 31 | | 0.40 | 5.82 |
| | 47.025 | | |
| 32 | | 0.56 | 6.34 |
| | 55.353 | | |
| 33 | | 0.73 | 6.39 |
| | 65.156 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 65.156 | | |
| 34 | | 0.90 | 6.00 |
| | 76.695 | | |
| 35 | | 1.07 | 5.32 |
| | 90.278 | | |
| 36 | | 1.30 | 4.55 |
| | 106.266 | | |
| 37 | | 1.62 | 3.86 |
| | 125.085 | | |
| 38 | | 2.00 | 3.38 |
| | 147.238 | | |
| 39 | | 2.27 | 3.15 |
| | 173.314 | | |
| 40 | | 2.21 | 3.16 |
| | 204.008 | | |
| 41 | | 1.60 | 3.32 |
| | 240.137 | | |
| 42 | | 0.60 | 3.57 |
| | 282.665 | | |
| 43 | | 0.00 | 3.79 |
| | 332.725 | | |
| 44 | | 0.00 | 3.93 |
| | 391.651 | | |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| | 391.651 | | |
| 45 | | 0.00 | 3.95 |
| | 461.012 | | |
| 46 | | 0.00 | 3.83 |
| | 542.656 | | |
| 47 | | 0.00 | 3.57 |
| | 638.761 | | |
| 48 | | 0.00 | 3.19 |
| | 751.885 | | |
| 49 | | 0.00 | 2.72 |
| | 885.043 | | |
| 50 | | 0.00 | 2.19 |
| | 1041.784 | | |
| 51 | | 0.00 | 1.63 |
| | 1226.283 | | |
| 52 | | 0.00 | 1.07 |
| | 1443.457 | | |
| 53 | | 0.00 | 0.47 |
| | 1699.092 | | |
| 54 | | 0.00 | 0.15 |
| | 2000.000 | | |

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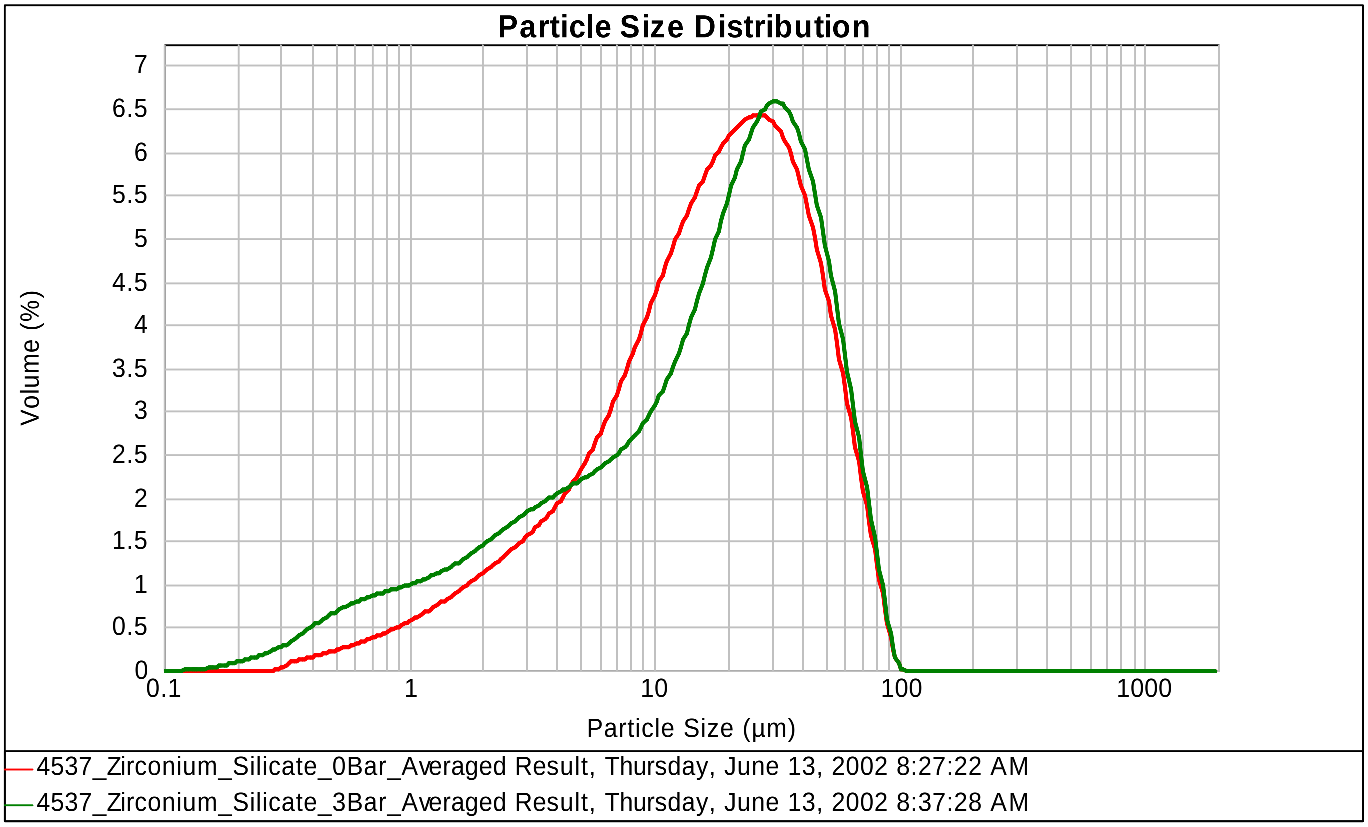
Serial Number : 34403/27

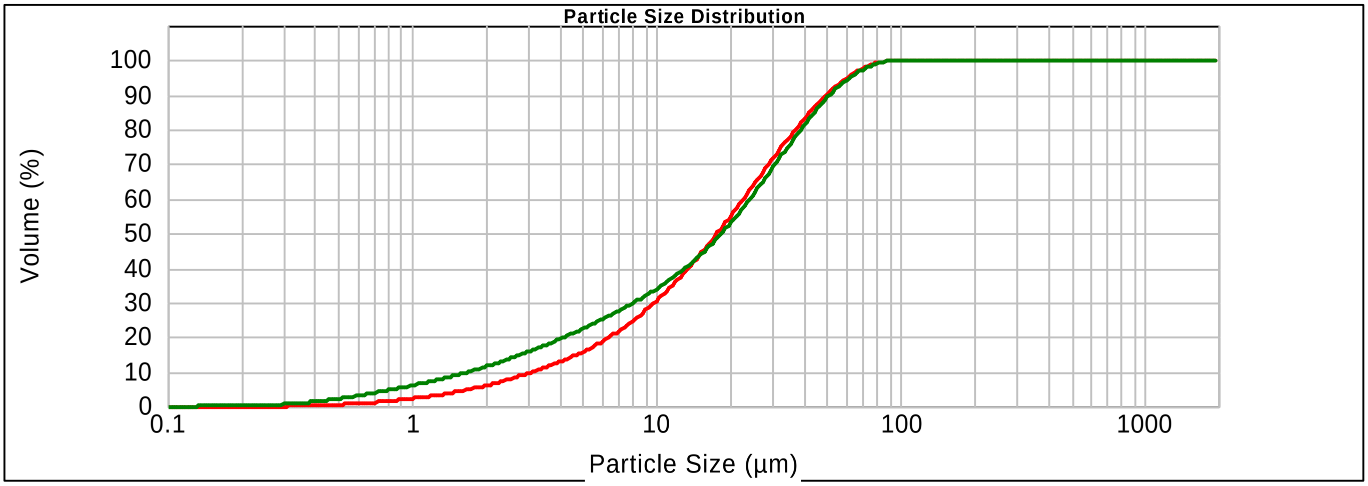
File name: 4537_Zinc Oxide.mea
Record Number: 8
25 Jun 2002 03:04:01 PM

JENIKE & JOHANSON

# Particle Size Distribution Comparison - Zircon flour

**See individual plots for complete analysis**





| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 1 | 0.300 | 0.08 | 0.35 |
| 2 | 0.353 | 0.15 | 0.49 |
| 3 | 0.416 | 0.21 | 0.64 |
| 4 | 0.489 | 0.27 | 0.76 |
| 5 | 0.576 | 0.34 | 0.86 |
| 6 | 0.678 | 0.42 | 0.93 |
| 7 | 0.798 | 0.51 | 1.00 |
| 8 | 0.939 | 0.61 | 1.06 |
| 9 | 1.106 | 0.73 | 1.14 |
| 10 | 1.301 | 0.87 | 1.24 |
| 11 | 1.532 | 1.02 | 1.37 |
|  | 1.803 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 12 | 1.803 | 1.18 | 1.51 |
| 13 | 2.123 | 1.34 | 1.67 |
| 14 | 2.499 | 1.52 | 1.84 |
| 15 | 2.941 | 1.71 | 1.99 |
| 16 | 3.462 | 1.94 | 2.13 |
| 17 | 4.075 | 2.21 | 2.25 |
| 18 | 4.797 | 2.37 | 2.55 |
| 19 | 5.646 | 2.51 | 2.97 |
| 20 | 6.646 | 2.68 | 3.47 |
| 21 | 7.823 | 2.92 | 4.03 |
| 22 | 9.209 | 3.26 | 4.61 |
|  | 10.840 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 23 | 10.840 | 3.69 | 5.17 |
| 24 | 12.759 | 4.25 | 5.68 |
| 25 | 15.019 | 4.90 | 6.12 |
| 26 | 17.679 | 5.61 | 6.48 |
| 27 | 20.810 | 6.30 | 6.74 |
| 28 | 24.495 | 6.81 | 6.84 |
| 29 | 28.833 | 6.71 | 7.01 |
| 30 | 33.939 | 6.30 | 6.80 |
| 31 | 39.950 | 5.58 | 6.14 |
| 32 | 47.025 | 4.61 | 5.12 |
| 33 | 55.353 | 3.47 | 3.87 |
|  | 65.156 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 34 | 65.156 | 2.30 | 2.56 |
| 35 | 76.695 | 1.13 | 1.25 |
| 36 | 90.278 | 0.13 | 0.14 |
| 37 | 106.266 | 0.00 | 0.00 |
| 38 | 125.085 | 0.00 | 0.00 |
| 39 | 147.238 | 0.00 | 0.00 |
| 40 | 173.314 | 0.00 | 0.00 |
| 41 | 204.008 | 0.00 | 0.00 |
| 42 | 240.137 | 0.00 | 0.00 |
| 43 | 282.665 | 0.00 | 0.00 |
| 44 | 332.725 | 0.00 | 0.00 |
|  | 391.651 |  |  |

| No | Size (µm) | Min In % | Max In % |
|---|---|---|---|
| 45 | 391.651 | 0.00 | 0.00 |
| 46 | 461.012 | 0.00 | 0.00 |
| 47 | 542.656 | 0.00 | 0.00 |
| 48 | 638.761 | 0.00 | 0.00 |
| 49 | 751.885 | 0.00 | 0.00 |
| 50 | 885.043 | 0.00 | 0.00 |
| 51 | 1041.784 | 0.00 | 0.00 |
| 52 | 1226.283 | 0.00 | 0.00 |
| 53 | 1443.457 | 0.00 | 0.00 |
| 54 | 1699.092 | 0.00 | 0.00 |
|  | 2000.000 |  |  |

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Serial Number : 34403-27

File name: 4537_Zirconium Silicate.mea
Record Number: 9
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# Table of Contents – Appendix

Page

FIGURES

## SELECTION OF BIN AND FEEDER

### Types of bins

A bin (silo, bunker) generally consists of a vertical cylinder and a sloping, converging hopper.

The first step in the process of bin selection is to decide on the type of bin required. From the standpoint of flow, there are three types: mass flow, funnel flow and expanded flow.

### Mass Flow Bins

In a mass flow bin, the hopper is sufficiently steep and smooth to cause flow of all the solids without stagnant regions whenever any solids are withdrawn.

Mass flow bins, examples of which are shown in Fig. A1, have certain advantages. Flow is uniform, and the feed density is practically independent of the head of solids in the bin. This frequently permits the use of volumetric feeders for feed rate control. Since stagnant regions are eliminated, low level indicators work reliably. Even though the solids may segregate at the point of charge into the bin, segregation of the discharge is minimized by the first-in-first-out flow sequence associated with mass flow. This flow sequence also ensures uniform residence time and deaeration of a fine powder.

Mass flow bins are recommended when handling cohesive materials, powders, materials which degrade with time, and when segregation needs to be minimized.

Ledges and protrusions are not permitted in a mass flow hopper. In addition the outlet must be fully effective. If the hopper is equipped with a shut-off gate, the gate must not prevent flow of material along the hopper wall. If a feeder is used, it must draw material across the full outlet area. (See "Feeders" below)

Mass flow bins can be used for in-bin blending. Of particular benefit in this regard is Jenike & Johanson's patented BINSERT® system. This device controls the flow pattern of solids in a bin.

### Funnel Flow Bins

Funnel flow occurs when the hopper is not sufficiently steep and smooth to force material to slide along the walls. It also occurs when the outlet of a mass flow bin is not fully effective. Examples of funnel flow bins are shown in Fig. A2.

In a funnel flow bin, solids flow toward the outlet through a channel that forms within stagnant material. With non-free-flowing solids, this channel expands to a diameter that approximates the largest dimension of the outlet. When the outlet is fully effective, this dimension is its diameter if circular, or the diagonal if it is square or rectangular. The channel will be stable if its diameter is less than the critical rathole diameter.

With free-flowing solids, the flow channel expands at an angle which depends on the effective angle of friction of the material. The resulting flow channel is generally circular with a diameter in excess of the outlet diameter or diagonal.

When the bin discharge rate is greater than the charge rate, the level of solids within the channel drops causing layers to slough off the top of the stagnant mass and fall into the channel. This spasmodic behavior is detrimental with cohesive solids since the falling solid packs on impact, thereby increasing the chance of arching. With sufficient cohesion sloughing may cease, allowing the channel to empty out completely and form a stable rathole. Aerated solids charged into this empty rathole might overflow the feeder.

When a fluidized powder is charged directly into a funnel flow channel at a sufficiently high rate and is withdrawn at the same time, it has no chance to deaerate. It therefore remains fluidized in the channel and floods when exiting the bin. A rotary valve is often used under these conditions to contain the material, but a uniform flow rate cannot be ensured because flow into the valve is erratic.

In general funnel flow bins are only suitable for coarse, free-flowing or slightly cohesive, non-degrading solids when segregation is unimportant.

Converting funnel flow bins to mass flow can often be achieved with relatively little expense. One way to do this is to use the BINSERT® system referred to in the paragraph on blending above. Another way is to install a low friction liner.

### Expanded Flow Bins

Examples of expanded flow bins are shown in Fig. A3. The lower part of such a bin operates with flow along the hopper walls (similar to mass flow) while the upper part operates in funnel flow. The mass flow outlet usually requires a smaller feeder than would be the case for a funnel flow bin. The mass flow hopper section should expand the flow channel to a diagonal or diameter equal to or greater than the critical rathole diameter. This eliminates the likelihood of ratholing in the funnel flow section.

These bins are used for storage of large quantities of non-degrading solids. This design is also useful as a modification of existing funnel flow bins to correct erratic flow caused by arching, ratholing or flooding.

This concept can be used with multiple outlets as shown in Fig. A3 (b) where simultaneously flowing mass flow hoppers are placed close enough together to cause a combined flow channel larger than the critical rathole diameter.

With extremely free-flowing solids such as plastic pellets, cement clinker and coarse sand, both funnel flow and expanded flow bins may pulsate. This is caused by the flow pattern suddenly switching from a steady state, central channel-type flow to a much more extensive secondary flow pattern that may extend to the bin walls. Such a condition may reduce segregation problems, but the shock loads imposed may seriously challenge the structural integrity of the bin.

## Feeders

Feeders are used to control the rate of material discharge from a bin (hopper, silo, bunker) outlet. They must not be confused with conveyors, which simply transport material from one point to another. Common feeders include screws, belts, rotary vanes, rotary plows, rotary tables, vibrating pans, and vibrating louvers. The rate of material being discharged is most commonly controlled volumetrically from these feeders, *i.e.*, the volume of material per unit time may be varied by changing feeder speed, amplitude or frequency. Several of these feeders may also operate gravimetrically, *i.e.*, the mass of material per unit time is measured and controlled.

Proper feeder selection depends on a number of factors based on the bin choice and feed requirements.

Two major objectives for efficient feeder design are uniform withdrawal of the material from the entire bin outlet area (*i.e.*, fully effective) and minimizing the material loads on the feeder, all within the process requirements of flow rate and layout. In order to ensure that the outlet is fully effective, the choice of feeder must be based on the outlet size and shape. If the requirements of bin selection dictate that the outlet be slotted, the feeder must increase in capacity in the direction of feed to ensure a uniform draw of material across the entire outlet. The choice of feeders is generally limited to either a belt or screw. If the feeder's capacity does not increase properly, the feeder will tend to draw material either from the front or back of the slot resulting in a high velocity flow channel having a diameter only one to two times the width of the slot. This becomes critical when feeding powders as the powder may remain fluidized within this channel and flood on exiting the bin.

To limit high initial loads and starting torque caused by differential settlement between the hopper and the feeder, it is essential that the feeder be either suspended from the bin itself or supported on a flexible frame so as to readily deflect with the bin as solids are added to it.

Detailed feeder selection guidelines are explained in technical papers available from Jenike & Johanson, several of which are listed in the Technical Papers Reference at the end of this Appendix.

## DISCUSSION OF TEST REPORT DATA

In the discussion that follows, each Section of the test report is explained in general terms. Please refer to Figs. A1, A2, and A3 where many of the symbols are shown. The symbols and other terms used in the text are explained in the Glossary of Terms and Symbols on pages A12 to A14. The concepts of gravity flow of solids and examples of application of solids flow data are described in technical papers available from Jenike & Johanson. (See the Technical Papers Reference at the end of this Appendix).

### Moisture

Unless otherwise noted, moisture values quoted in this report have been determined by preparing three samples, approximately 15 g. each. If the material contains coarse particles, each sample was first screened to -6 mesh. The samples were then dried at 107°C for two hours in a forced convection oven. The three values of loss in weight of each sample divided by its original weight were averaged and denoted as the sample's *moisture*.

### Section I - Bin Dimensions for Dependable Flow

This section specifies the bin outlet dimensions necessary for dependable flow in both mass flow and funnel flow bins. These dimensions have been calculated on the basis of the frictional and cohesive properties of the solid given in a subsequent part of the report. In all cases, it is assumed that flow takes place only under the action of gravity, *i.e.*, without internal or external assistance.

In general these dimensions are a function of the time the solid remains in storage at rest, its moisture content, temperature, particle size and overpressure, if any, that is applied to it during storage. The P-FACTORs given in the table are ratios of applied compaction pressure to that pressure resulting from gravity flow only. If there are no overpressures present, the critical dimensions for P-FACTOR = 1.0 should be used. If the P-FACTOR is greater than 1.0, it is assumed that overpressures have been exerted on the solid during storage, but are removed when the solid is required to flow. See pages A5 to A6 for calculation of P-FACTORs. If overpressures are applied during discharge, additional considerations are required; contact a Jenike & Johanson engineer to discuss your specific application.

When considering the effect of overpressure, which acts on a solid during time of storage at rest, it is not necessary that the overpressure act during the entire time at rest. Soon after an overpressure has been applied, a solid reaches the maximum densification associated with the overpressure. Hence, the critical outlet dimensions will be essentially the same whether the overpressure acts for a short time or continuously during the entire time at rest.

Mass flow bins have hopper walls that are smooth enough and steep enough to cause flow along them; hence, stable channels within the material (ratholes) do not develop. Only two dimensions, both of which are shown in Fig. A1, are specified: BC, the minimum outlet diameter for a conical hopper; and BP, the minimum width for a slotted or oval outlet. The length of the slot or oval should be at least three times its width or the end walls must be vertical and smooth for BP to apply. These outlet dimensions are recommended to prevent cohesive arching. Particle interlocking should also be considered.

A funnel flow bin is created whenever the hopper walls are not steep enough and smooth enough to cause flow along them. Slotted outlets are recommended for these bins unless the material is quite free flowing. To prevent stable arches from forming, the width of the slot must be at least equal to BF. In a funnel flow bin the solid is held up at the walls and flows only within a circular channel whose diameter is approximately equal to the diameter or length of the effective outlet. If this flow channel diameter is less than the critical rathole diameter DF given in the report, a stable rathole is likely to form, and the live capacity of the bin will be essentially only that material which is in the flow channel above the outlet. To prevent stable ratholes from forming, funnel flow bins should be designed with slotted outlets of length at least as long as DF.

In general DF is proportional to the consolidating pressure imposed on the solid during filling of the bin. Hence, in the upper regions of a bin where pressures are low, the critical rathole diameter DF is small and the flow channel diameter may exceed DF. This causes the rathole to be unstable at this point allowing the material to collapse into the stable rathole below. A partial emptying of the bin will result.

Calculation of Effective Head, EH

The critical rathole diameter DF is a function of the major consolidating pressure which acts on the solids in the bin. It is convenient to express this pressure in terms of EH, the effective consolidating head of solid in the bin, as follows:

$$EH = [R/(\mu\ k)]\ [1 - e^{-\mu k\ H/R}] \quad \text{or} \quad EH = 2R \qquad (1)$$

whichever is larger. The parameters are:

R = hydraulic radius of the cylindrical portion of the bin, *i.e.*, ratio of cross sectional area to circumference
R = D/4 for a circular cylinder of diameter D or a square cylinder of side D

R = W/2 for a long rectangular cylinder of width W

$\mu$ = tan (PHI-PRIME), coefficient of friction between the stored solid and the cylinder walls (see Section III)

k = ratio of horizontal to vertical solids pressure. A value of 0.4 is usually acceptable within cylinders

H = height of the cylindrical portion of a bin

When the feeder is properly designed for uniform flow and when convergence of the hopper extends to the feeder, the effective head, EH, of solid on the feeder during flow in a mass flow bin is approximately

$$\begin{aligned} EH &= BP \text{ for a transition mass flow hopper} \\ EH &= BC/2 \text{ for a conical mass flow hopper} \end{aligned} \tag{2}$$

See page A4 for definitions of BP and BC.

Initial loads may be several times these values.

Calculation of P-FACTORs

The magnitude of the overpressure factor can be estimated for vibration, impact during charging into the bin, external loading, and fluid flow loading as follows (note these are valid only if applied prior to flow):

Vibration. Vibration has two effects: while it tends to break arches that obstruct flow, it also packs the solid in stagnant regions thereby giving it greater strength. In order to allow for this packing, the recommended outlet dimensions at zero time at rest for a P-FACTOR of 1.5 may be used as an approximation when calculating critical arching dimensions for use with vibrating equipment.

Vibrators are suitable for materials which are free flowing under conditions of continuous flow but cake and gain strength when stored at rest for hours or days. Hoppers for these materials should be equipped with pads for mounting external vibrators. Vibrators should be used only to initiate flow and turned off once flow has started.

Fine powders and wet materials tend to pack severely when vibrated; hence, vibrating equipment is generally not recommended for them.

$$\text{P-FACTOR} = (1 + a_z/g) \text{ or } a_y/g \tag{3}$$

whichever is larger, where:

$a_z$ = vertical upward component of acceleration imposed on the solid
$a_y$ = horizontal component of acceleration imposed on the solid
$g$ = gravitational acceleration constant

Impact pressure from fall into a bin. A coarse material compacts as it is charged into a bin under the impact of the falling particles. When the material contains fines and the impact area is close to the outlet, the impact P-FACTOR should be used in the design.

$$\text{P-FACTOR} = (1 + m)\,[w/(A\ B\ \text{GAMMA})]\sqrt{2h/g} \qquad (4)$$

where:

w = weight flow rate into the bin
h = height of fall
m = 0 for a long rectangular outlet
m = 1 for a circular or square outlet
A = area impacted by the falling stream of solids
B = outlet size or bin dimensions in the region of impact, *i.e.*, the diameter in a conical hopper or the width in a wedge shaped or transition hopper
GAMMA = bulk density of solid

External loading. If the solid has been compacted by an external load F (such as the weight of a tractor passing over an outside stockpile), the overpressure factor at the point of application is given by

$$\text{P-FACTOR} = (1 + m)\,F/(A\ B\ \text{GAMMA}) \qquad (5)$$

where:

A = area of load application

Liquid or gas flow loading. If the solid has been subjected during storage to fluid or gas flow such as may have been imposed by an air blaster, draining of a saturated solid or the flow of air or gas during drying or chemical processing, the overpressure factor is given by

$$\text{P-FACTOR} = 1 + (dp/dz)/(\text{GAMMA}) \qquad (6)$$

where:

dp/dz = the (vertical) liquid or gas pressure gradient at the bin outlet where z is positive upward.

Limits on bin sizes

The bin dimensions in part A of this Section I apply to bins of unlimited maximum size. However, some materials will compact in large bins causing large stable arches in the upper part of the hopper while the lower portion may discharge without a problem. This can lead to a very dangerous condition when a large arch is broken high in the hopper. The impact of the falling material may cause structural damage to the bin and possibly tear the hopper from the vertical bin section. If the material is capable of this type of behavior, an additional part B is included which gives the maximum allowable mass flow bin and hopper dimensions.

Often the upper limits on bin size occur only for compaction with time or for significant overpressure conditions. If this is the case, the bin can be designed for an unlimited size provided the critical time and overpressure values are not exceeded during the bin operation.

## Section II - Bulk density

The bulk density GAMMA of a material is used in bin load and capacity calculations. Values of bulk density of the sample tested are given in Section II as a function of the Effective Head of solid EH and the major principal consolidating pressure SIGMA1. The relationship is:

SIGMA1 = EH GAMMA (7)

Within the cylindrical part of a bin, the effective consolidating head EH is given by eq.(1). At the outlet of a mass flow bin, the head is given by eq.(2).

Note that if the sample tested is the fine fraction of a material having a wide range of particle size, inclusion of the coarser particles will usually increase the bulk densities above those given in this section.

Bulk density values have been computed from measured compressibility parameters of the material, which are also given in Section II. In general, all materials have a minimum density GAMMA MINIMUM without fluidization. The relationship between bulk density and consolidating pressure only applies when densities are greater than GAMMA MINIMUM.

## Section III - Maximum hopper angles for mass flow

A solid sliding on a bin wall encounters frictional resistance proportional to the tangent of the wall friction angle PHI-PRIME. This angle generally depends not only on the roughness of the wall but also on the pressure that the solid exerts on the wall. For many hard wall surfaces, the friction angle decreases as the solids contact pressure increases. This pressure, which varies with position in the bin, is usually smallest at the outlet; therefore, the hopper angle required is often dictated by the outlet size selected.

THETA-C and THETA-P are the recommended maximum hopper wall angles, measured from the vertical, for conical and transition mass flow hoppers, respectively. See Fig. A1. These values have been calculated from the friction tests (wall yield loci) included at the end of the report and are tabulated for a series of widths of oval hoppers and diameters of conical hoppers.

To minimize headroom consider changing the slope of the hopper wall as a function of position. For example, if a conical hopper is to be designed with an outlet diameter of 1 ft. and the recommended THETA-C is 14° at 1 ft. diameter and 23° at 2 ft. and larger diameters, use two conical sections. In the lower section where the diameter varies from 1 ft. to 2 ft., use a hopper angle of 14°. Above the 2 ft. diameter, use a hopper angle of 23°.

Often, both continuous flow and time friction tests are run on a material. If the solid adheres to the wall with time, the time test results will indicate an increase in friction angles. To overcome this time effect, the hopper walls should be made steeper, as recommended, or other means – such as vibration of the bin walls – should be provided to initiate flow.

## Section IV - Critical solids flow rate

### Coarse bulk solids

The maximum rate Q at which a coarse solid (say, 95% plus 1/4 in.) flows out of a mass flow hopper is practically independent of the head of solid and is approximately given by

$$Q = (A\ GAMMA)\sqrt{B\ g/[2(1 + m)\ \tan(THETA)]} \qquad (8)$$

where:

A = area of the outlet
B = diameter or width of the outlet
THETA = planar hopper wall angle for rectangular or oval outlets, or
= conical hopper wall angle for circular outlets

### Fine bulk solids

Predicting the flow rate of fine solids from mass flow bins is more complicated because their outflow is critically affected by the amount of air entrained in the solid.

Two limiting cases may occur: first, the bin may be charged and discharged at such a rapid rate that a large amount of air is entrained within the solid. As a result the solid may flood uncontrollably from the outlet independent of feeder speeds. The prediction of this critical flooding condition requires an extensive two-phase flow calculation using a Jenike & Johanson proprietary computer program and is not a part of this Flow Properties Test Report.

Second, the bin may be filled intermittently with sufficient retention time before discharging so that the powder is deaerated. As a result there may be a deficiency of air as the solids expand upon discharging. This generally causes a critical flow rate at the outlet which is tabulated in this section as a function of Effective Head of solid in the bin. Above this critical rate, flow will be non-steady.

The critical rates are computed on the assumption that there is no air in-flow or out-flow along the height of the bin, that air pressure at the outlet of the bin is the same as at the top of the bin, and that the feeder outlet is not sealed against air in-flow. Should the operating conditions deviate from these assumptions, a controlled rate different from the critical may be possible.

If the tabulated flow rates are smaller than desired, it may be necessary to: use an air permeation system to increase the rate; increase the outlet size; decrease the bin size; or limit the storage time to prevent deaeration of the solid. Jenike & Johanson can analyze the system and make recommendations.

If the specified flow rate from a bin is close to critical values, it is particularly important that the feeder withdraw uniformly across the entire outlet. If this is not done, localized limiting rate effects may occur at the outlet, especially at the ends of a slotted outlet. This may result in pulsating flow from the bin, the development of fast flowing columns and an uncontrolled rate of withdrawal with flooding.

All the above comments apply as well when a gas other than air is used in the bin. The critical property is the viscosity of the gas. The permeability tests run by Jenike & Johanson are usually done with air at room temperature. When the gas or the temperature is different, the coefficient of permeability needs to be modified, as discussed below.

## Section V - Air permeability test results

Values of air permeability are expressed as a function of the bulk density of the solid. These values are used in the calculation of critical flow rates, given in Section IV, and in the design of air permeation systems. Permeability is also used for purge vessel or dryer design and when fluidization is recommended.

The equation given in this section and the test method are both based on the assumption of laminar flow of gas. This assumption is generally valid for all powders and for most materials which have a significant portion of particles less than 20 mesh in size.

The permeability factor K has dimensions of velocity and is inversely proportional to the viscosity of the gas. The results can be adjusted to elevated temperatures and to other gases by multiplying the constant $K_0$ by the ratio of the viscosity of air at room temperature to that of the gas at the temperature in question.

## Section VI Chutes

A chute, unlike a hopper, does not operate full of material. As an example, a transfer chute between two conveyors encloses and directs the stream of material, but discharges the material before any level accumulates.

The chute design concepts given below apply only to a *fast* (i.e., accelerated) flow mode in which material flows in contact with the chute bottom and side walls without contact with the top surface. A good rule of thumb is that a chute should be sized such that it is no more than one-third full in cross section over the entire chute length. If the chute fills with enough material, it may have to be considered a hopper. This case would require a proper hopper design to ensure reliable flow.

In order to maintain material flow in a chute, its inside surface walls must be steep enough and have sufficiently low friction to allow the material to flow along them. This is dictated by the friction between the chute surface and the bulk material. This friction is dependent upon the roughness of the surface and the impact pressure caused by the material hitting it.

The chute angle test measures the critical chute angles required for cleanoff as a function of impact pressure for the limiting case where the material adheres to the surface. These angles are used to determine the minimum chute angle required at an impact point to overcome adhesion and ensure flow.

The test consists of loading a sample of the bulk solid on a representative coupon of the chute surface with a range of loads to represent different impact pressures. After each load is applied for a few seconds, the load is removed and the coupon is inclined about a distant pivot point. The angle at which the bulk solid slides is plotted as a function of impact pressure. Results are given in Section VI of the test report.

The impact pressure, $\sigma$, may be approximated using the following formula:

$$\sigma = \text{impact pressure} = \frac{\gamma V_1^2 \sin^2\theta}{g}$$

where:

$\gamma$ = bulk density (pcf).
$V_1$ = velocity before impact (for the case of a simple freefall, $V_1^2 = 2gh$) (ft/s).
$\theta$ = angle of impact between incoming stream and chute surface (degrees).
$g$ = acceleration due to gravity (32.2 ft/s$^2$).

A factor of 5º to 10º should be added to the highest measured value given to ensure cleanoff.

Other design considerations include: controlling the particle stream, minimizing (de)accelerations of particles, minimizing wear and power requirements on downstream conveyors, minimizing abrasive wear of the chute itself, controlling dust, minimizing attrition. For additional information on many of these considerations, see Jenike & Johanson's paper #145, “Design Principles for Chutes to Handle Bulk Solids.

## GLOSSARY OF TERMS AND SYMBOLS

| | |
|---|---|
| Arching | - a no-flow condition in which material forms a stable arch (dome, bridge) across the bin |
| Bin | - container for bulk solids with one or more outlets for withdrawal either by gravity alone or by flow-promoting devices which assist gravity |
| Bunker | - same as bin, often used in reference to storing coal |
| Chute | - means of collecting material which, unlike a hopper, does not operate full |
| Cylinder | - vertical part of a bin |
| Discharger | - device used to enhance material flow from a bin but which is not capable of controlling the rate of withdrawal |
| Effective Head | - convenient way to express consolidating pressure by dividing it by bulk density, see eqs. (1) and (2) |
| Elevator | - same as bin, often used in reference to storing grains |
| Expanded flow | - flow pattern which is a combination of mass flow and funnel flow |
| Feeder | - device for controlling the rate of withdrawal of bulk solid from a bin |
| Flow channel | - space in a bin through which a bulk solid is actually flowing during withdrawal |
| Flooding, flushing | - condition where an aerated bulk solid behaves like a fluid and flows uncontrollably through an outlet or feeder |
| Funnel flow | - flow pattern in which solid flows in a channel formed within stagnant material |
| Hopper | - converging part of a bin |
| Mass flow | - flow pattern in which all solid in a bin is in motion whenever any of it is withdrawn |
| Piping | - same as ratholing |
| P-FACTOR | - the ratio of the applied solids compacting pressure to the solids pressure during steady gravity flow, see eqs. (3) to (6) |
| Ratholing | - a no-flow condition in which material forms a stable vertical hole within the bin |
| Silo | - same a bin |

$A$ - area of impact of falling stream of solids, area over which external load is applied, or area of outlet, $ft^2$

$a$ - acceleration along a chute surface, $ft/sec^2$, see eq. (11)

$a_z$, $a_y$ - vertical and horizontal accelerations, respectively, $ft/sec^2$

$B$ - span across a bin at any elevation of the bin, ft.

$BC$ - minimum diameter of a circular outlet in a mass flow bin, ft.

$BF$ - minimum width of a rectangular outlet in a funnel flow bin, ft.

$BP$ - minimum width of an oval outlet in a mass flow bin, ft.

$D$ - diameter of cylindrical portion of a bin, ft.

$DF$ - critical ratholing (piping) dimension, ft.

$EH$ - effective consolidating head, ft.

$F$ - force from an external load on material, lb.

$f_c$ - unconfined compressive strength of a solid, psf

$g$ - gravitational constant = 32.2 $ft/sec^2$

$H$ - height of cylinder, ft.

$h$ - height of fall of material, ft.

$k$ - ratio of horizontal to vertical pressure

$K$ - permeability, ft/sec.

$K_0$ - permeability constant, ft/sec.

$L$ - length of hopper outlet, ft.

$m$ - parameter equal to 0 for rectangular outlet and equal to 1 for circular or square outlet

$p$ - liquid or gas pressure, psf

$Q$ - maximum discharge rate of a coarse solid, lb/sec.

$R$ - hydraulic radius, ft.

$S$ - shearing force applied to a shear cell, lb.; distance along chute surface, ft.

$V$ - normal force applied to a shear cell, lb.

$V_1$ - velocity of stream of particles just before impact on a chute surface, ft/sec.

W - width of rectangular bin cylinder, ft.

w - weight flow rate into the bin, lb/sec.

y - horizontal coordinate, ft.

z - vertical coordinate, ft.

$\gamma$, GAMMA - bulk density, pcf

$\delta$, DELTA - effective angle of internal friction of a solid during flow, degrees

$\theta$ - impact angle on chute surface, degrees

$\theta_c$, THETA-C - maximum recommended angle (from vertical) of conical hoppers and end walls of transition hoppers for mass flow, degrees

$\theta_p$, THETA-P - maximum recommended angle (from vertical) of side walls of transition or wedge-shaped hoppers for mass flow, degrees

$\mu$, MU - tan (PHI-PRIME)

$\sigma$, SIGMA - normal stress applied to a shear cell, psf

$\sigma_1$, SIGMA1 - major consolidating pressure, psf

$\tau$, TAU - shearing stress applied to a shear cell, psf

$\phi'$, PHI-PRIME - kinematic angle of friction between a solid and a wall, degrees

$\phi$, PHI - angle of internal friction of a solid in incipient flow, degrees

# TECHNICAL PAPERS REFERENCE

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Storage & Flow of Solids – Bulletin 123, Utah Engineering Experiment Station
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133. Feeding Solids into a Fluidized Bed Combustor
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142. Fine Powder Flow Phenomena in Bins, Hoppers and Processing Vessels
149. Solve Solids Flow Problems in Bins, Hoppers, and Feeders
153. Use Screw Feeders Effectively
165. Mass Flow Purge and Conditioning Vessels

## Testing

158. Quality Control Tester to Measure Relative Flowability of Powders
162. Characterize Bulk Solids to Ensure Smooth Flow
179. Wall Friction: A Complex Variable in the Design of Bulk Solids Storage Systems

## Chutes

145. Design Principles for Chutes to Handle Bulk Solids

## Case Histories

35. A Silo for Ground Anthracite
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116. Bin Design Gets System Moving Again
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107. Understanding and Eliminating Particle Segregation Problems
139. In-Bin Blending Improves Process Control
161. Tumble Blending with Mass Flow Containers Improves Productivity and Quality
166. Blending and Segregation (capabilities available from Jenike & Johanson)
178. How to Mix Dry Bulk Solids and Maintain Blend Integrity

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88a. Controlling Flow Patterns in Bins by Use of an Insert

119. Versatile BINSERT® System Solves Wide Range of Flow Problems

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**Pneumatic Conveying**

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115. Pneumatic Conveying: Principles of Operation
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**Stockpile Design**

185. Tunnel Reclaim from Ore Stockpiles

**Miscellaneous**

89. Measuring and Use of Wear Properties for Predicting Life of Bulk Materials Handling Equipment
105. Ultrahigh Molecular Weight Polyethylene Abrasion Resistant Liners Facilitate Solids Flow in Hoppers
135. Modeling Bulk Solids Flow
163. Identifying and Controlling Silo Vibration Mechanisms: Part I and Part II
164. Survey of Industrial Plants Handling Bulk Solids

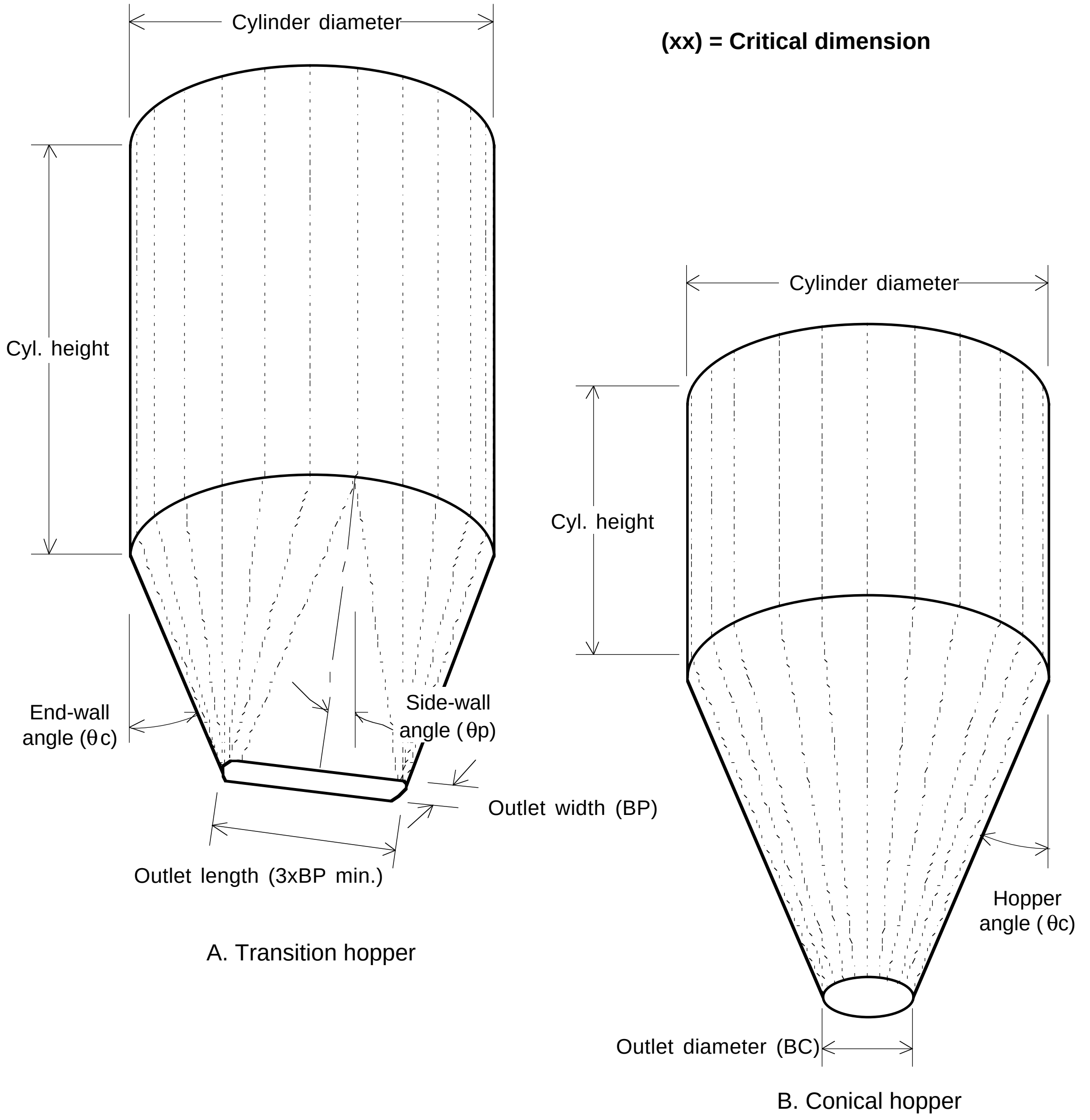


Figure A1
Examples of Mass Flow Bins

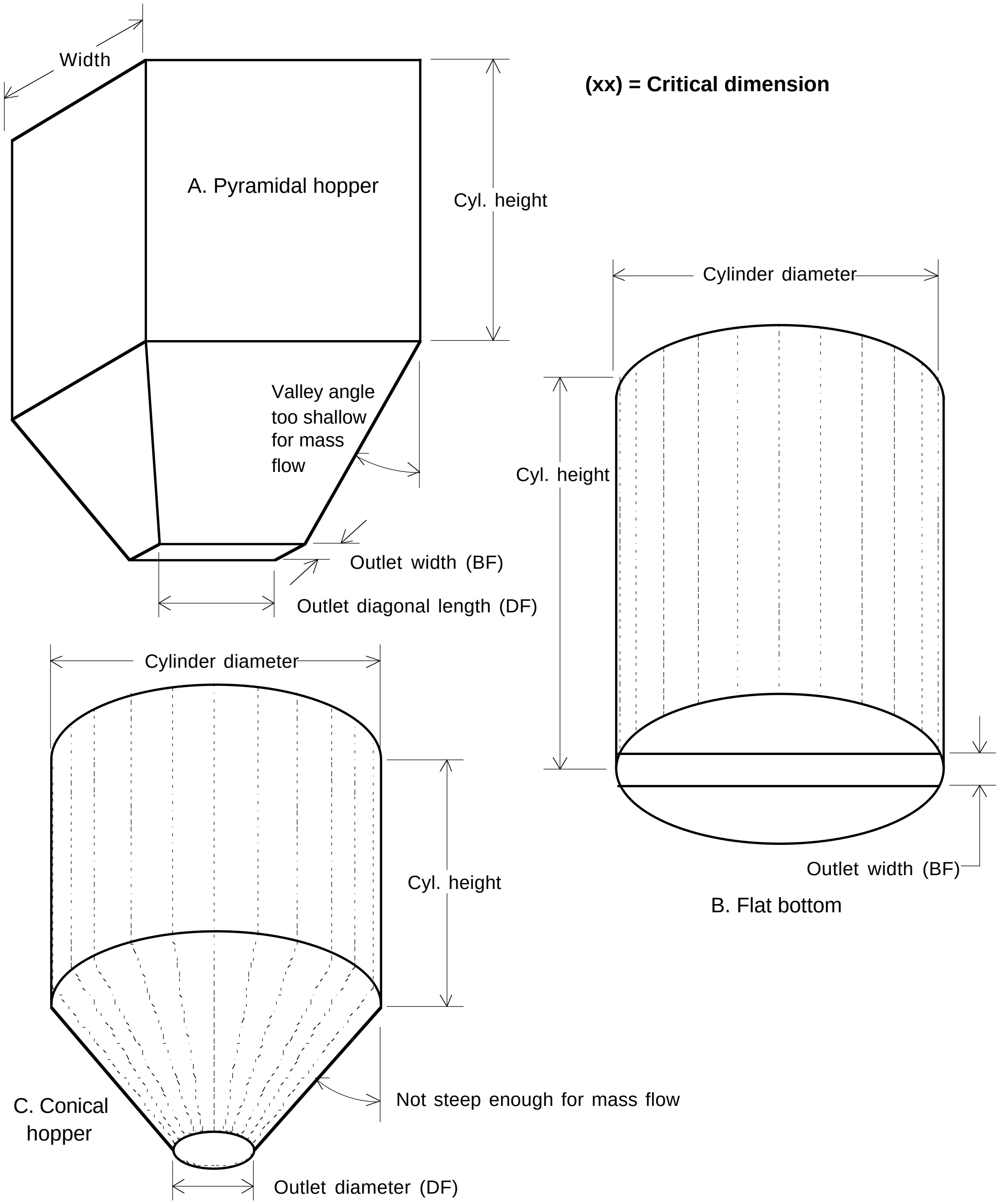
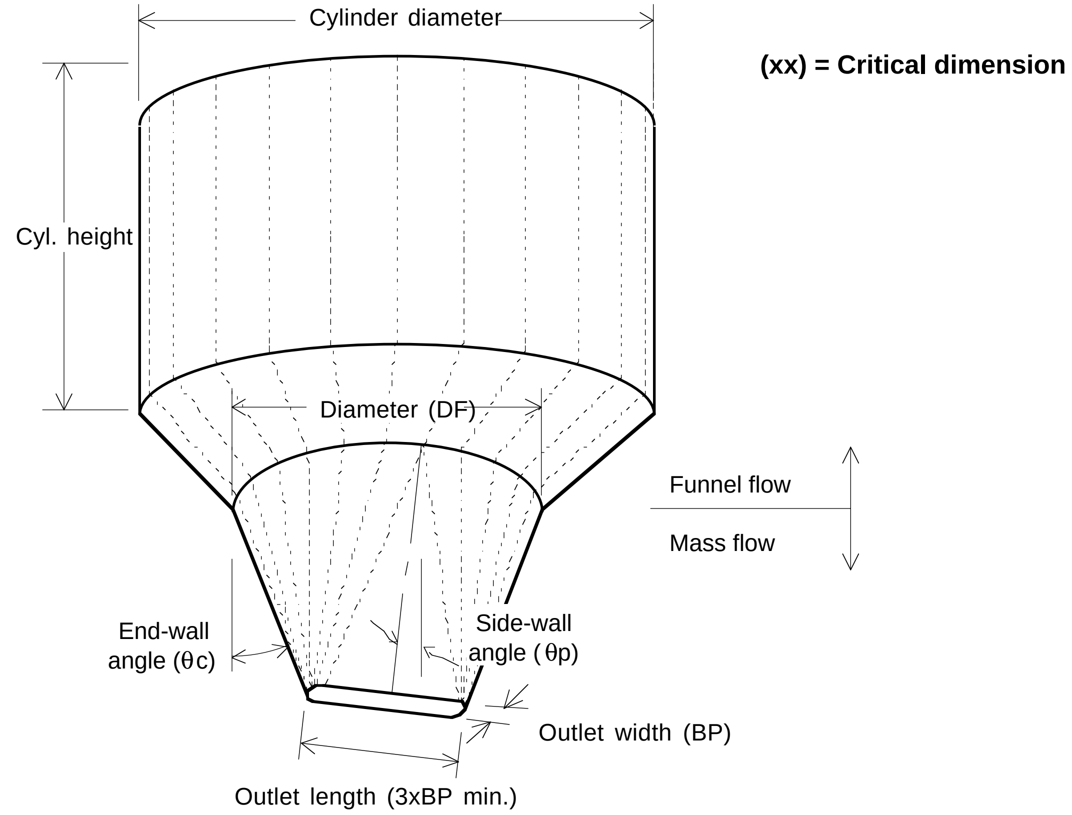


Figure A2
Examples of Funnel Flow Bins



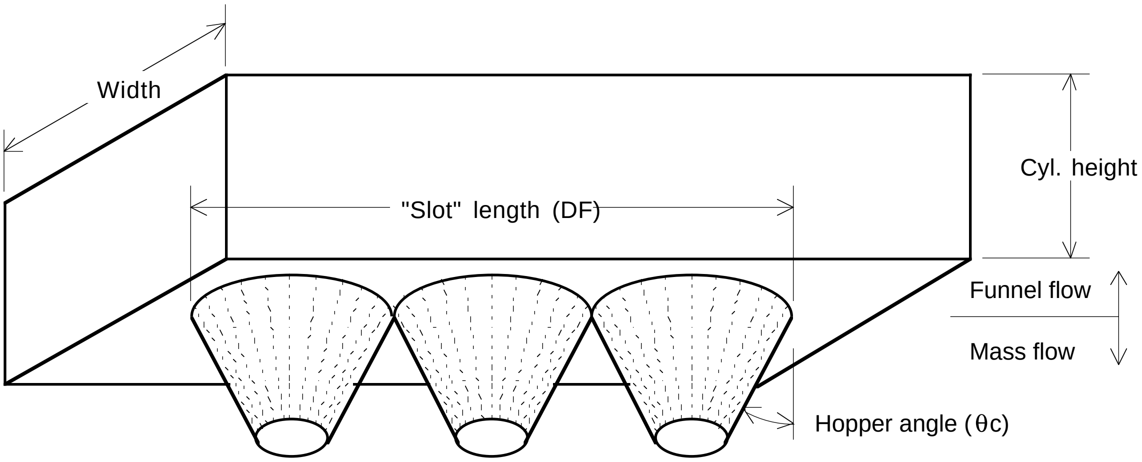
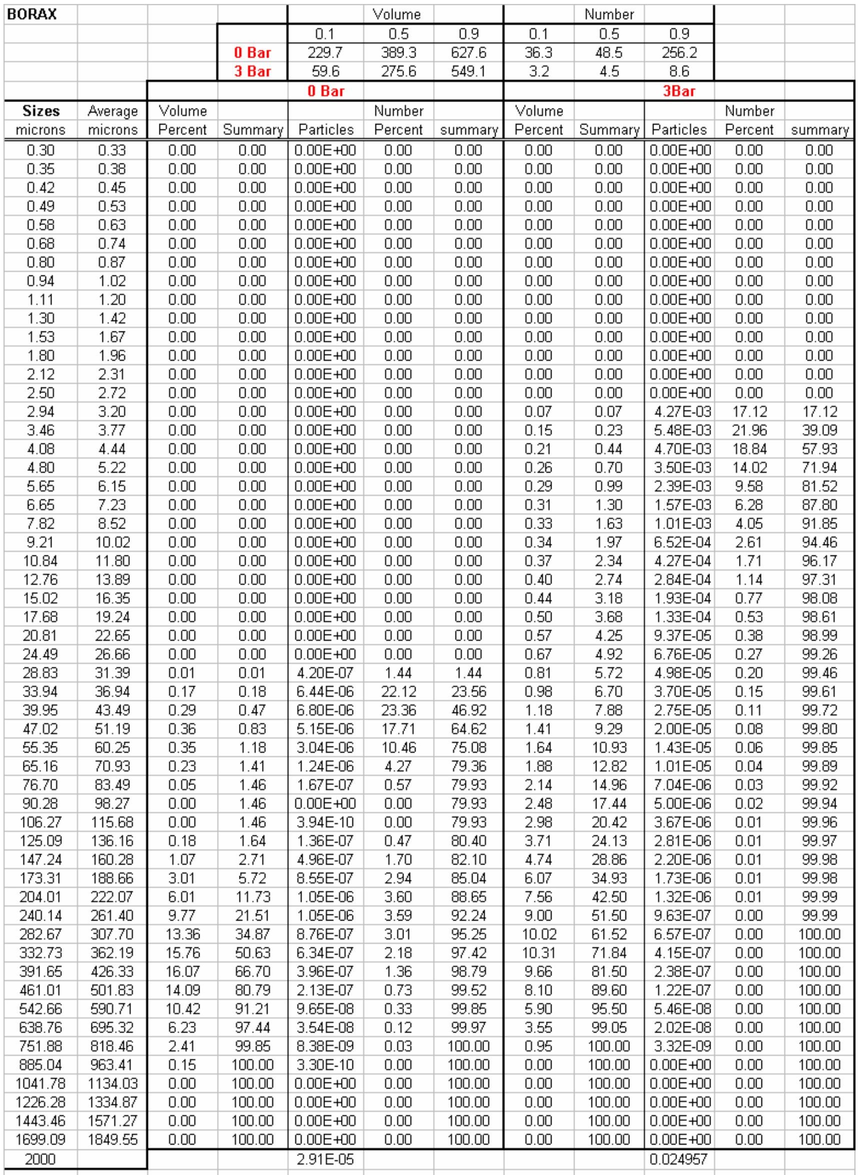


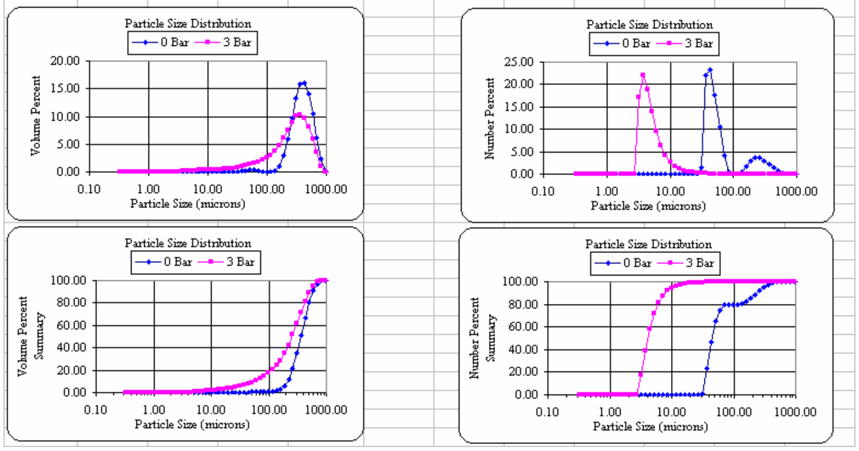
Figure A3
Examples of Expanded Flow Bins

# APPENDIX E. CALCULATIONS – PARTICLE SIZE DISTRIBUTION

# Figure E.1: J&J Particle Size Distribution: Borax

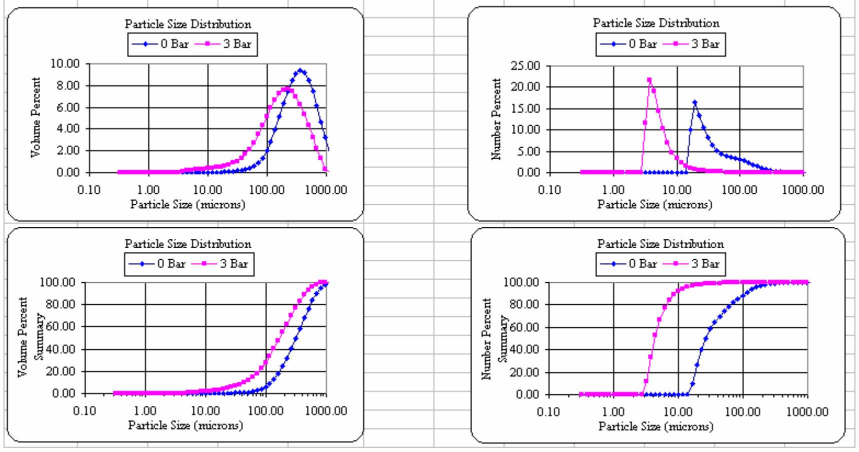


| BORAX | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0 Bar** | 229.7 | 389.3 | 627.6 | 36.3 | 48.5 | 256.2 | | |
| | | | **3 Bar** | 59.6 | 275.6 | 549.1 | 3.2 | 4.5 | 8.6 | | |
| | | | | **0 Bar** | | | | | **3Bar** | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.42 | 0.45 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.49 | 0.53 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.58 | 0.63 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.68 | 0.74 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.80 | 0.87 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.94 | 1.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.11 | 1.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.30 | 1.42 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.53 | 1.67 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.80 | 1.96 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.12 | 2.31 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.50 | 2.72 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.94 | 3.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.07 | 0.07 | 4.27E-03 | 17.12 | 17.12 |
| 3.46 | 3.77 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.15 | 0.23 | 5.48E-03 | 21.96 | 39.09 |
| 4.08 | 4.44 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.21 | 0.44 | 4.70E-03 | 18.84 | 57.93 |
| 4.80 | 5.22 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.26 | 0.70 | 3.50E-03 | 14.02 | 71.94 |
| 5.65 | 6.15 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.29 | 0.99 | 2.39E-03 | 9.58 | 81.52 |
| 6.65 | 7.23 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.31 | 1.30 | 1.57E-03 | 6.28 | 87.80 |
| 7.82 | 8.52 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.33 | 1.63 | 1.01E-03 | 4.05 | 91.85 |
| 9.21 | 10.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.34 | 1.97 | 6.52E-04 | 2.61 | 94.46 |
| 10.84 | 11.80 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.37 | 2.34 | 4.27E-04 | 1.71 | 96.17 |
| 12.76 | 13.89 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.40 | 2.74 | 2.84E-04 | 1.14 | 97.31 |
| 15.02 | 16.35 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.44 | 3.18 | 1.93E-04 | 0.77 | 98.08 |
| 17.68 | 19.24 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.50 | 3.68 | 1.33E-04 | 0.53 | 98.61 |
| 20.81 | 22.65 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.57 | 4.25 | 9.37E-05 | 0.38 | 98.99 |
| 24.49 | 26.66 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.67 | 4.92 | 6.76E-05 | 0.27 | 99.26 |
| 28.83 | 31.39 | 0.01 | 0.01 | 4.20E-07 | 1.44 | 1.44 | 0.81 | 5.72 | 4.98E-05 | 0.20 | 99.46 |
| 33.94 | 36.94 | 0.17 | 0.18 | 6.44E-06 | 22.12 | 23.56 | 0.98 | 6.70 | 3.70E-05 | 0.15 | 99.61 |
| 39.95 | 43.49 | 0.29 | 0.47 | 6.80E-06 | 23.36 | 46.92 | 1.18 | 7.88 | 2.75E-05 | 0.11 | 99.72 |
| 47.02 | 51.19 | 0.36 | 0.83 | 5.15E-06 | 17.71 | 64.62 | 1.41 | 9.29 | 2.00E-05 | 0.08 | 99.80 |
| 55.35 | 60.25 | 0.35 | 1.18 | 3.04E-06 | 10.46 | 75.08 | 1.64 | 10.93 | 1.43E-05 | 0.06 | 99.85 |
| 65.16 | 70.93 | 0.23 | 1.41 | 1.24E-06 | 4.27 | 79.36 | 1.88 | 12.82 | 1.01E-05 | 0.04 | 99.89 |
| 76.70 | 83.49 | 0.05 | 1.46 | 1.67E-07 | 0.57 | 79.93 | 2.14 | 14.96 | 7.04E-06 | 0.03 | 99.92 |
| 90.28 | 98.27 | 0.00 | 1.46 | 0.00E+00 | 0.00 | 79.93 | 2.48 | 17.44 | 5.00E-06 | 0.02 | 99.94 |
| 106.27 | 115.68 | 0.00 | 1.46 | 3.94E-10 | 0.00 | 79.93 | 2.98 | 20.42 | 3.67E-06 | 0.01 | 99.96 |
| 125.09 | 136.16 | 0.18 | 1.64 | 1.36E-07 | 0.47 | 80.40 | 3.71 | 24.13 | 2.81E-06 | 0.01 | 99.97 |
| 147.24 | 160.28 | 1.07 | 2.71 | 4.96E-07 | 1.70 | 82.10 | 4.74 | 28.86 | 2.20E-06 | 0.01 | 99.98 |
| 173.31 | 188.66 | 3.01 | 5.72 | 8.55E-07 | 2.94 | 85.04 | 6.07 | 34.93 | 1.73E-06 | 0.01 | 99.98 |
| 204.01 | 222.07 | 6.01 | 11.73 | 1.05E-06 | 3.60 | 88.65 | 7.56 | 42.50 | 1.32E-06 | 0.01 | 99.99 |
| 240.14 | 261.40 | 9.77 | 21.51 | 1.05E-06 | 3.59 | 92.24 | 9.00 | 51.50 | 9.63E-07 | 0.00 | 99.99 |
| 282.67 | 307.70 | 13.36 | 34.87 | 8.76E-07 | 3.01 | 95.25 | 10.02 | 61.52 | 6.57E-07 | 0.00 | 100.00 |
| 332.73 | 362.19 | 15.76 | 50.63 | 6.34E-07 | 2.18 | 97.42 | 10.31 | 71.84 | 4.15E-07 | 0.00 | 100.00 |
| 391.65 | 426.33 | 16.07 | 66.70 | 3.96E-07 | 1.36 | 98.79 | 9.66 | 81.50 | 2.38E-07 | 0.00 | 100.00 |
| 461.01 | 501.83 | 14.09 | 80.79 | 2.13E-07 | 0.73 | 99.52 | 8.10 | 89.60 | 1.22E-07 | 0.00 | 100.00 |
| 542.66 | 590.71 | 10.42 | 91.21 | 9.65E-08 | 0.33 | 99.85 | 5.90 | 95.50 | 5.46E-08 | 0.00 | 100.00 |
| 638.76 | 695.32 | 6.23 | 97.44 | 3.54E-08 | 0.12 | 99.97 | 3.55 | 99.05 | 2.02E-08 | 0.00 | 100.00 |
| 751.88 | 818.46 | 2.41 | 99.85 | 8.38E-09 | 0.03 | 100.00 | 0.95 | 100.00 | 3.32E-09 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.15 | 100.00 | 3.30E-10 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 2.91E-05 | | | | | 0.024957 | | |



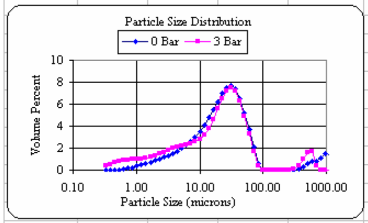
# Figure E.2: J&J Particle Size Distribution – Boric Acid

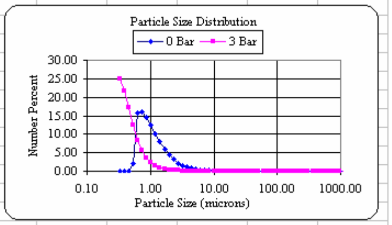
| **BORIC ACID** | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0 Bar** | 130.8 | 336.1 | 750.1 | 17.7 | 28.7 | 115.3 | | |
| | | | **3 Bar** | 48.6 | 183.7 | 487.0 | 3.4 | 4.7 | 9.8 | | |
| | | | | **0 Bar** | | | | | **3Bar** | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.42 | 0.45 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.49 | 0.53 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.58 | 0.63 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.68 | 0.74 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.80 | 0.87 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.94 | 1.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.11 | 1.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.30 | 1.42 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.53 | 1.67 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.80 | 1.96 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.12 | 2.31 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.50 | 2.72 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.94 | 3.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.04 | 0.04 | 2.54E-03 | 11.63 | 11.63 |
| 3.46 | 3.77 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.13 | 0.18 | 4.76E-03 | 21.76 | 33.39 |
| 4.08 | 4.44 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.19 | 0.37 | 4.17E-03 | 19.10 | 52.49 |
| 4.80 | 5.22 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.24 | 0.60 | 3.16E-03 | 14.45 | 66.94 |
| 5.65 | 6.15 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.27 | 0.87 | 2.24E-03 | 10.23 | 77.17 |
| 6.65 | 7.23 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.30 | 1.18 | 1.53E-03 | 7.00 | 84.17 |
| 7.82 | 8.52 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.34 | 1.51 | 1.04E-03 | 4.75 | 88.92 |
| 9.21 | 10.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.37 | 1.89 | 7.08E-04 | 3.24 | 92.16 |
| 10.84 | 11.80 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.42 | 2.31 | 4.89E-04 | 2.24 | 94.39 |
| 12.76 | 13.89 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.48 | 2.78 | 3.40E-04 | 1.56 | 95.95 |
| 15.02 | 16.35 | 0.03 | 0.03 | 1.26E-05 | 9.98 | 9.98 | 0.54 | 3.33 | 2.38E-04 | 1.09 | 97.04 |
| 17.68 | 19.24 | 0.08 | 0.11 | 2.09E-05 | 16.50 | 26.49 | 0.63 | 3.95 | 1.68E-04 | 0.77 | 97.81 |
| 20.81 | 22.65 | 0.10 | 0.21 | 1.70E-05 | 13.43 | 39.92 | 0.73 | 4.68 | 1.19E-04 | 0.55 | 98.35 |
| 24.49 | 26.66 | 0.13 | 0.34 | 1.33E-05 | 10.49 | 50.41 | 0.86 | 5.54 | 8.66E-05 | 0.40 | 98.75 |
| 28.83 | 31.39 | 0.17 | 0.51 | 1.03E-05 | 8.16 | 58.57 | 1.05 | 6.59 | 6.48E-05 | 0.30 | 99.05 |
| 33.94 | 36.94 | 0.21 | 0.72 | 8.05E-06 | 6.36 | 64.93 | 1.31 | 7.90 | 4.97E-05 | 0.23 | 99.28 |
| 39.95 | 43.49 | 0.28 | 1.00 | 6.49E-06 | 5.13 | 70.07 | 1.68 | 9.58 | 3.90E-05 | 0.18 | 99.45 |
| 47.02 | 51.19 | 0.39 | 1.39 | 5.52E-06 | 4.37 | 74.43 | 2.17 | 11.75 | 3.08E-05 | 0.14 | 99.59 |
| 55.35 | 60.25 | 0.57 | 1.96 | 4.98E-06 | 3.94 | 78.37 | 2.78 | 14.52 | 2.42E-05 | 0.11 | 99.71 |
| 65.16 | 70.93 | 0.87 | 2.83 | 4.65E-06 | 3.68 | 82.05 | 3.50 | 18.02 | 1.87E-05 | 0.09 | 99.79 |
| 76.70 | 83.49 | 1.33 | 4.16 | 4.36E-06 | 3.45 | 85.50 | 4.31 | 22.33 | 1.41E-05 | 0.06 | 99.86 |
| 90.28 | 98.27 | 1.99 | 6.14 | 4.00E-06 | 3.16 | 88.66 | 5.15 | 27.48 | 1.04E-05 | 0.05 | 99.90 |
| 106.27 | 115.68 | 2.85 | 9.00 | 3.52E-06 | 2.78 | 91.45 | 5.98 | 33.46 | 7.37E-06 | 0.03 | 99.94 |
| 125.09 | 136.16 | 3.92 | 12.92 | 2.97E-06 | 2.35 | 93.79 | 6.70 | 40.16 | 5.07E-06 | 0.02 | 99.96 |
| 147.24 | 160.28 | 5.11 | 18.03 | 2.37E-06 | 1.88 | 95.67 | 7.26 | 47.42 | 3.37E-06 | 0.02 | 99.98 |
| 173.31 | 188.66 | 6.36 | 24.38 | 1.81E-06 | 1.43 | 97.10 | 7.59 | 55.01 | 2.16E-06 | 0.01 | 99.99 |
| 204.01 | 222.07 | 7.51 | 31.89 | 1.31E-06 | 1.04 | 98.13 | 7.65 | 62.67 | 1.33E-06 | 0.01 | 99.99 |
| 240.14 | 261.40 | 8.47 | 40.36 | 9.06E-07 | 0.72 | 98.85 | 7.44 | 70.11 | 7.95E-07 | 0.00 | 100.00 |
| 282.67 | 307.70 | 9.11 | 49.47 | 5.97E-07 | 0.47 | 99.32 | 6.96 | 77.06 | 4.56E-07 | 0.00 | 100.00 |
| 332.73 | 362.19 | 9.35 | 58.82 | 3.76E-07 | 0.30 | 99.62 | 6.24 | 83.30 | 2.51E-07 | 0.00 | 100.00 |
| 391.65 | 426.33 | 9.15 | 67.97 | 2.26E-07 | 0.18 | 99.80 | 5.33 | 88.63 | 1.31E-07 | 0.00 | 100.00 |
| 461.01 | 501.83 | 8.51 | 76.48 | 1.29E-07 | 0.10 | 99.90 | 4.30 | 92.94 | 6.51E-08 | 0.00 | 100.00 |
| 542.66 | 590.71 | 7.48 | 83.95 | 6.93E-08 | 0.05 | 99.95 | 3.24 | 96.18 | 3.01E-08 | 0.00 | 100.00 |
| 638.76 | 695.32 | 6.15 | 90.10 | 3.49E-08 | 0.03 | 99.98 | 2.21 | 98.39 | 1.26E-08 | 0.00 | 100.00 |
| 751.88 | 818.46 | 4.68 | 94.78 | 1.63E-08 | 0.01 | 99.99 | 1.33 | 99.72 | 4.62E-09 | 0.00 | 100.00 |
| 885.04 | 963.41 | 3.19 | 97.96 | 6.81E-09 | 0.01 | 100.00 | 0.27 | 99.99 | 5.76E-10 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 1.83 | 99.79 | 2.39E-09 | 0.00 | 100.00 | 0.01 | 100.00 | 1.56E-11 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.21 | 100.00 | 1.68E-10 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 7.16E-13 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 0.0001264 | | | | | 0.021849 | | |

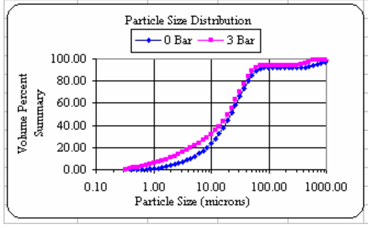


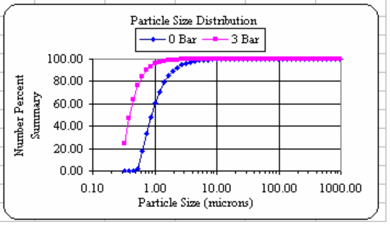
# Figure E.3: J&J Particle Size Distribution – Iron Oxide

| IRON OXIDE | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0 Bar** | 4.7 | 23.8 | 69.9 | 0.6 | 1.0 | 2.2 | | |
| | | | **3 Bar** | 2.0 | 21.3 | 58.7 | 0.3 | 0.4 | 0.8 | | |
| | | | | **0 Bar** | | | | | **3Bar** | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.356648 | 0.36 | 1.96E+01 | 24.91 | 24.91 |
| 0.35 | 0.38 | 0 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.506226 | 0.86 | 1.70E+01 | 21.68 | 46.58 |
| 0.42 | 0.45 | 0 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.651436 | 1.51 | 1.34E+01 | 17.10 | 63.69 |
| 0.49 | 0.53 | 0.007861 | 0.01 | 9.94E-02 | 1.99 | 1.99 | 0.766577 | 2.28 | 9.69E+00 | 12.34 | 76.03 |
| 0.58 | 0.63 | 0.10206 | 0.11 | 7.91E-01 | 15.82 | 17.81 | 0.851811 | 3.13 | 6.60E+00 | 8.41 | 84.43 |
| 0.68 | 0.74 | 0.167877 | 0.28 | 7.98E-01 | 15.95 | 33.76 | 0.909841 | 4.04 | 4.32E+00 | 5.51 | 89.94 |
| 0.80 | 0.87 | 0.249505 | 0.53 | 7.27E-01 | 14.54 | 48.30 | 0.950178 | 4.99 | 2.77E+00 | 3.53 | 93.47 |
| 0.94 | 1.02 | 0.35077 | 0.88 | 6.27E-01 | 12.53 | 60.83 | 0.985153 | 5.98 | 1.76E+00 | 2.24 | 95.71 |
| 1.11 | 1.20 | 0.466383 | 1.34 | 5.11E-01 | 10.22 | 71.05 | 1.028744 | 7.01 | 1.13E+00 | 1.44 | 97.14 |
| 1.30 | 1.42 | 0.594537 | 1.94 | 3.99E-01 | 7.99 | 79.03 | 1.093279 | 8.10 | 7.34E-01 | 0.94 | 98.08 |
| 1.53 | 1.67 | 0.730761 | 2.67 | 3.01E-01 | 6.02 | 85.05 | 1.186129 | 9.29 | 4.88E-01 | 0.62 | 98.70 |
| 1.80 | 1.96 | 0.873577 | 3.54 | 2.21E-01 | 4.41 | 89.46 | 1.310915 | 10.60 | 3.31E-01 | 0.42 | 99.12 |
| 2.12 | 2.31 | 1.019254 | 4.56 | 1.58E-01 | 3.16 | 92.62 | 1.462416 | 12.06 | 2.26E-01 | 0.29 | 99.41 |
| 2.50 | 2.72 | 1.170935 | 5.73 | 1.11E-01 | 2.22 | 94.84 | 1.633443 | 13.69 | 1.55E-01 | 0.20 | 99.61 |
| 2.94 | 3.20 | 1.329716 | 7.06 | 7.74E-02 | 1.55 | 96.39 | 1.806644 | 15.50 | 1.05E-01 | 0.13 | 99.74 |
| 3.46 | 3.77 | 1.506962 | 8.57 | 5.38E-02 | 1.08 | 97.46 | 1.970728 | 17.47 | 7.03E-02 | 0.09 | 99.83 |
| 4.08 | 4.44 | 1.710732 | 10.28 | 3.74E-02 | 0.75 | 98.21 | 2.110897 | 19.58 | 4.62E-02 | 0.06 | 99.89 |
| 4.80 | 5.22 | 1.957427 | 12.24 | 2.63E-02 | 0.53 | 98.74 | 2.225612 | 21.81 | 2.99E-02 | 0.04 | 99.93 |
| 5.65 | 6.15 | 2.256412 | 14.49 | 1.86E-02 | 0.37 | 99.11 | 2.322277 | 24.13 | 1.91E-02 | 0.02 | 99.95 |
| 6.65 | 7.23 | 2.619343 | 17.11 | 1.32E-02 | 0.26 | 99.37 | 2.426589 | 26.56 | 1.22E-02 | 0.02 | 99.97 |
| 7.82 | 8.52 | 3.048723 | 20.16 | 9.43E-03 | 0.19 | 99.56 | 2.577803 | 29.13 | 7.97E-03 | 0.01 | 99.98 |
| 9.21 | 10.02 | 3.546285 | 23.71 | 6.72E-03 | 0.13 | 99.70 | 2.826824 | 31.96 | 5.36E-03 | 0.01 | 99.98 |
| 10.84 | 11.80 | 4.115459 | 27.82 | 4.78E-03 | 0.10 | 99.79 | 3.229071 | 35.19 | 3.75E-03 | 0.00 | 99.99 |
| 12.76 | 13.89 | 4.758122 | 32.58 | 3.39E-03 | 0.07 | 99.86 | 3.82586 | 39.02 | 2.73E-03 | 0.00 | 99.99 |
| 15.02 | 16.35 | 5.477584 | 38.06 | 2.39E-03 | 0.05 | 99.91 | 4.630233 | 43.65 | 2.02E-03 | 0.00 | 99.99 |
| 17.68 | 19.24 | 6.232685 | 44.29 | 1.67E-03 | 0.03 | 99.94 | 5.571416 | 49.22 | 1.49E-03 | 0.00 | 100.00 |
| 20.81 | 22.65 | 6.950994 | 51.24 | 1.14E-03 | 0.02 | 99.96 | 6.517648 | 55.73 | 1.07E-03 | 0.00 | 100.00 |
| 24.49 | 26.66 | 7.480685 | 58.72 | 7.54E-04 | 0.02 | 99.98 | 7.23821 | 62.97 | 7.29E-04 | 0.00 | 100.00 |
| 28.83 | 31.39 | 7.663594 | 66.39 | 4.73E-04 | 0.01 | 99.99 | 7.521387 | 70.49 | 4.65E-04 | 0.00 | 100.00 |
| 33.94 | 36.94 | 7.356346 | 73.74 | 2.79E-04 | 0.01 | 99.99 | 7.208091 | 77.70 | 2.73E-04 | 0.00 | 100.00 |
| 39.95 | 43.49 | 6.506543 | 80.25 | 1.51E-04 | 0.00 | 100.00 | 6.280235 | 83.98 | 1.46E-04 | 0.00 | 100.00 |
| 47.02 | 51.19 | 5.205033 | 85.46 | 7.41E-05 | 0.00 | 100.00 | 4.890164 | 88.87 | 6.96E-05 | 0.00 | 100.00 |
| 55.35 | 60.25 | 3.659328 | 89.12 | 3.19E-05 | 0.00 | 100.00 | 3.301227 | 92.17 | 2.88E-05 | 0.00 | 100.00 |
| 65.16 | 70.93 | 2.141964 | 91.26 | 1.15E-05 | 0.00 | 100.00 | 1.723653 | 93.90 | 9.23E-06 | 0.00 | 100.00 |
| 76.70 | 83.49 | 0.63094 | 91.89 | 2.07E-06 | 0.00 | 100.00 | 0.353081 | 94.25 | 1.16E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 0 | 91.89 | 0.00E+00 | 0.00 | 100.00 | 0 | 94.25 | 0.00E+00 | 0.00 | 100.00 |
| 106.27 | 115.68 | 0 | 91.89 | 0.00E+00 | 0.00 | 100.00 | 0 | 94.25 | 0.00E+00 | 0.00 | 100.00 |
| 125.09 | 136.16 | 0 | 91.89 | 0.00E+00 | 0.00 | 100.00 | 0 | 94.25 | 0.00E+00 | 0.00 | 100.00 |
| 147.24 | 160.28 | 0 | 91.89 | 0.00E+00 | 0.00 | 100.00 | 0 | 94.25 | 0.00E+00 | 0.00 | 100.00 |
| 173.31 | 188.66 | 0 | 91.89 | 0.00E+00 | 0.00 | 100.00 | 0 | 94.25 | 0.00E+00 | 0.00 | 100.00 |
| 204.01 | 222.07 | 0.000189 | 91.89 | 3.30E-11 | 0.00 | 100.00 | 0.000593 | 94.25 | 1.03E-10 | 0.00 | 100.00 |
| 240.14 | 261.40 | 0.002431 | 91.89 | 2.60E-10 | 0.00 | 100.00 | 0.003442 | 94.25 | 3.68E-10 | 0.00 | 100.00 |
| 282.67 | 307.70 | 0.039155 | 91.93 | 2.57E-09 | 0.00 | 100.00 | 0.101895 | 94.36 | 6.68E-09 | 0.00 | 100.00 |
| 332.73 | 362.19 | 0.14184 | 92.07 | 5.70E-09 | 0.00 | 100.00 | 0.414637 | 94.77 | 1.67E-08 | 0.00 | 100.00 |
| 391.65 | 426.33 | 0.327728 | 92.40 | 8.08E-09 | 0.00 | 100.00 | 0.995014 | 95.77 | 2.45E-08 | 0.00 | 100.00 |
| 461.01 | 501.83 | 0.569325 | 92.97 | 8.60E-09 | 0.00 | 100.00 | 1.580696 | 97.35 | 2.39E-08 | 0.00 | 100.00 |
| 542.66 | 590.71 | 0.766234 | 93.74 | 7.10E-09 | 0.00 | 100.00 | 1.659912 | 99.01 | 1.54E-08 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.836255 | 94.57 | 4.75E-09 | 0.00 | 100.00 | 0.393348 | 99.40 | 2.23E-09 | 0.00 | 100.00 |
| 751.88 | 818.46 | 1.127172 | 95.70 | 3.93E-09 | 0.00 | 100.00 | 0 | 99.40 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 1.451578 | 97.15 | 3.10E-09 | 0.00 | 100.00 | 0 | 99.40 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 1.37306 | 98.52 | 1.80E-09 | 0.00 | 100.00 | 0 | 99.40 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.954423 | 99.48 | 7.66E-10 | 0.00 | 100.00 | 0 | 99.40 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.438548 | 99.92 | 2.16E-10 | 0.00 | 100.00 | 0 | 99.40 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.083662 | 100.00 | 2.53E-11 | 0.00 | 100.00 | 0 | 99.40 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 5.0004654 | | | | | 78.52583 | | |

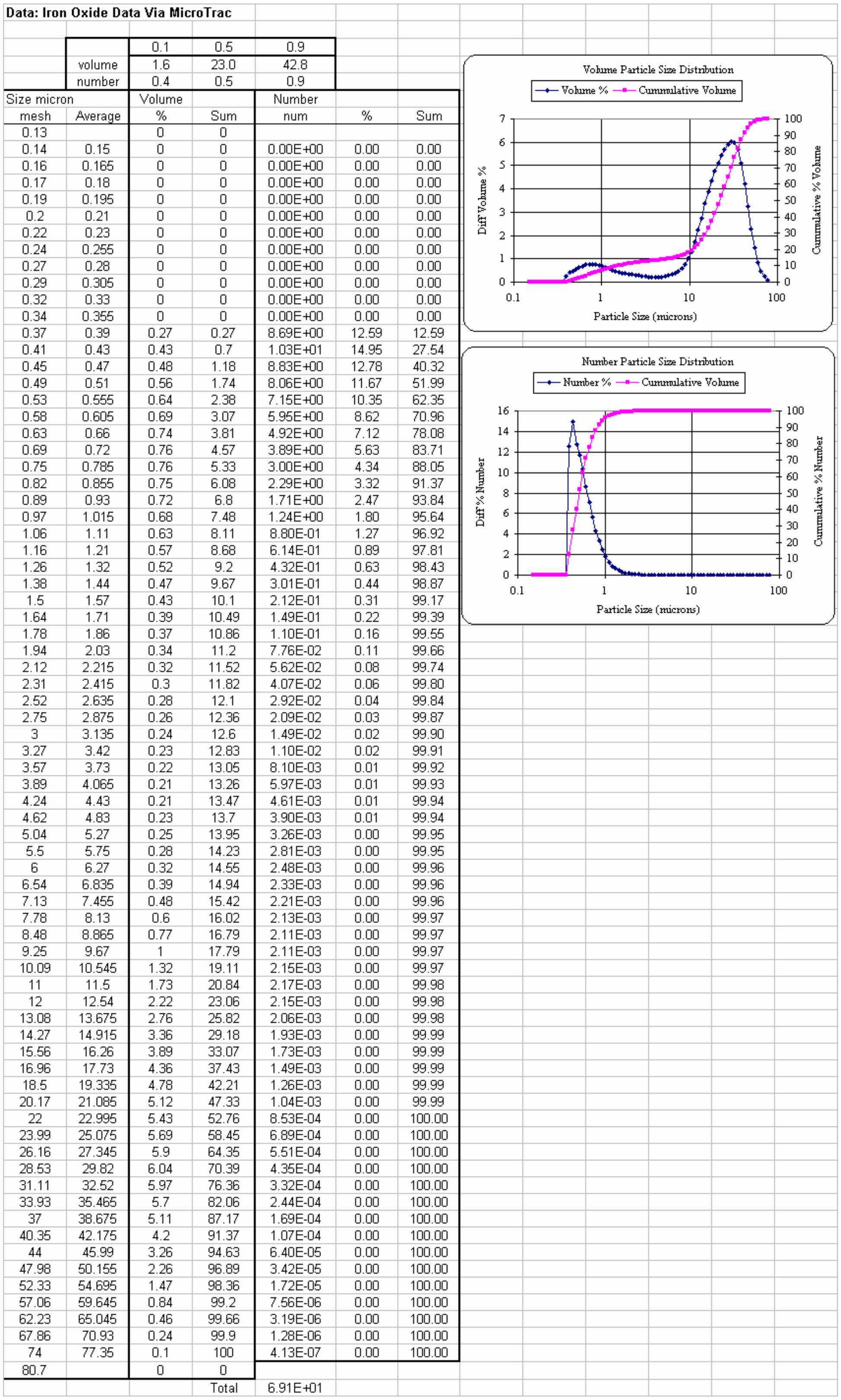








# Figure E.4: Vendor Particle Size Distribution – Iron Oxide

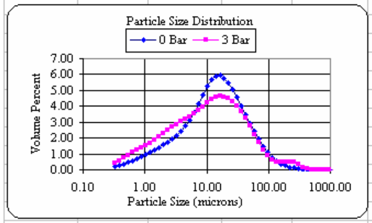


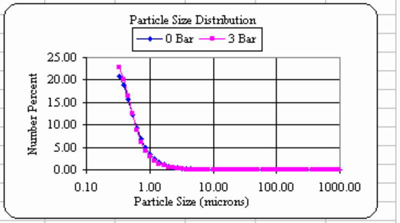
**Data: Iron Oxide Data Via MicroTrac**

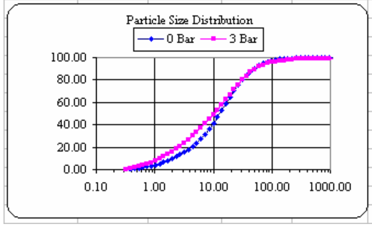
| | | | | | | |
|---|---|---|---|---|---|---|
| | | 0.1 | 0.5 | 0.9 | | |
| | volume | 1.6 | 23.0 | 42.8 | | |
| | number | 0.4 | 0.5 | 0.9 | | |
| Size micron | | Volume | | Number | | |
| mesh | Average | % | Sum | num | % | Sum |
| 0.13 | | 0 | 0 | | | |
| 0.14 | 0.15 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.16 | 0.165 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.17 | 0.18 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.19 | 0.195 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.2 | 0.21 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.22 | 0.23 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.24 | 0.255 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.27 | 0.28 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.29 | 0.305 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.32 | 0.33 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.34 | 0.355 | 0 | 0 | 0.00E+00 | 0.00 | 0.00 |
| 0.37 | 0.39 | 0.27 | 0.27 | 8.69E+00 | 12.59 | 12.59 |
| 0.41 | 0.43 | 0.43 | 0.7 | 1.03E+01 | 14.95 | 27.54 |
| 0.45 | 0.47 | 0.48 | 1.18 | 8.83E+00 | 12.78 | 40.32 |
| 0.49 | 0.51 | 0.56 | 1.74 | 8.06E+00 | 11.67 | 51.99 |
| 0.53 | 0.555 | 0.64 | 2.38 | 7.15E+00 | 10.35 | 62.35 |
| 0.58 | 0.605 | 0.69 | 3.07 | 5.95E+00 | 8.62 | 70.96 |
| 0.63 | 0.66 | 0.74 | 3.81 | 4.92E+00 | 7.12 | 78.08 |
| 0.69 | 0.72 | 0.76 | 4.57 | 3.89E+00 | 5.63 | 83.71 |
| 0.75 | 0.785 | 0.76 | 5.33 | 3.00E+00 | 4.34 | 88.05 |
| 0.82 | 0.855 | 0.75 | 6.08 | 2.29E+00 | 3.32 | 91.37 |
| 0.89 | 0.93 | 0.72 | 6.8 | 1.71E+00 | 2.47 | 93.84 |
| 0.97 | 1.015 | 0.68 | 7.48 | 1.24E+00 | 1.80 | 95.64 |
| 1.06 | 1.11 | 0.63 | 8.11 | 8.80E-01 | 1.27 | 96.92 |
| 1.16 | 1.21 | 0.57 | 8.68 | 6.14E-01 | 0.89 | 97.81 |
| 1.26 | 1.32 | 0.52 | 9.2 | 4.32E-01 | 0.63 | 98.43 |
| 1.38 | 1.44 | 0.47 | 9.67 | 3.01E-01 | 0.44 | 98.87 |
| 1.5 | 1.57 | 0.43 | 10.1 | 2.12E-01 | 0.31 | 99.17 |
| 1.64 | 1.71 | 0.39 | 10.49 | 1.49E-01 | 0.22 | 99.39 |
| 1.78 | 1.86 | 0.37 | 10.86 | 1.10E-01 | 0.16 | 99.55 |
| 1.94 | 2.03 | 0.34 | 11.2 | 7.76E-02 | 0.11 | 99.66 |
| 2.12 | 2.215 | 0.32 | 11.52 | 5.62E-02 | 0.08 | 99.74 |
| 2.31 | 2.415 | 0.3 | 11.82 | 4.07E-02 | 0.06 | 99.80 |
| 2.52 | 2.635 | 0.28 | 12.1 | 2.92E-02 | 0.04 | 99.84 |
| 2.75 | 2.875 | 0.26 | 12.36 | 2.09E-02 | 0.03 | 99.87 |
| 3 | 3.135 | 0.24 | 12.6 | 1.49E-02 | 0.02 | 99.90 |
| 3.27 | 3.42 | 0.23 | 12.83 | 1.10E-02 | 0.02 | 99.91 |
| 3.57 | 3.73 | 0.22 | 13.05 | 8.10E-03 | 0.01 | 99.92 |
| 3.89 | 4.065 | 0.21 | 13.26 | 5.97E-03 | 0.01 | 99.93 |
| 4.24 | 4.43 | 0.21 | 13.47 | 4.61E-03 | 0.01 | 99.94 |
| 4.62 | 4.83 | 0.23 | 13.7 | 3.90E-03 | 0.01 | 99.94 |
| 5.04 | 5.27 | 0.25 | 13.95 | 3.26E-03 | 0.00 | 99.95 |
| 5.5 | 5.75 | 0.28 | 14.23 | 2.81E-03 | 0.00 | 99.95 |
| 6 | 6.27 | 0.32 | 14.55 | 2.48E-03 | 0.00 | 99.96 |
| 6.54 | 6.835 | 0.39 | 14.94 | 2.33E-03 | 0.00 | 99.96 |
| 7.13 | 7.455 | 0.48 | 15.42 | 2.21E-03 | 0.00 | 99.96 |
| 7.78 | 8.13 | 0.6 | 16.02 | 2.13E-03 | 0.00 | 99.97 |
| 8.48 | 8.865 | 0.77 | 16.79 | 2.11E-03 | 0.00 | 99.97 |
| 9.25 | 9.67 | 1 | 17.79 | 2.11E-03 | 0.00 | 99.97 |
| 10.09 | 10.545 | 1.32 | 19.11 | 2.15E-03 | 0.00 | 99.97 |
| 11 | 11.5 | 1.73 | 20.84 | 2.17E-03 | 0.00 | 99.98 |
| 12 | 12.54 | 2.22 | 23.06 | 2.15E-03 | 0.00 | 99.98 |
| 13.08 | 13.675 | 2.76 | 25.82 | 2.06E-03 | 0.00 | 99.98 |
| 14.27 | 14.915 | 3.36 | 29.18 | 1.93E-03 | 0.00 | 99.99 |
| 15.56 | 16.26 | 3.89 | 33.07 | 1.73E-03 | 0.00 | 99.99 |
| 16.96 | 17.73 | 4.36 | 37.43 | 1.49E-03 | 0.00 | 99.99 |
| 18.5 | 19.335 | 4.78 | 42.21 | 1.26E-03 | 0.00 | 99.99 |
| 20.17 | 21.085 | 5.12 | 47.33 | 1.04E-03 | 0.00 | 99.99 |
| 22 | 22.995 | 5.43 | 52.76 | 8.53E-04 | 0.00 | 100.00 |
| 23.99 | 25.075 | 5.69 | 58.45 | 6.89E-04 | 0.00 | 100.00 |
| 26.16 | 27.345 | 5.9 | 64.35 | 5.51E-04 | 0.00 | 100.00 |
| 28.53 | 29.82 | 6.04 | 70.39 | 4.35E-04 | 0.00 | 100.00 |
| 31.11 | 32.52 | 5.97 | 76.36 | 3.32E-04 | 0.00 | 100.00 |
| 33.93 | 35.465 | 5.7 | 82.06 | 2.44E-04 | 0.00 | 100.00 |
| 37 | 38.675 | 5.11 | 87.17 | 1.69E-04 | 0.00 | 100.00 |
| 40.35 | 42.175 | 4.2 | 91.37 | 1.07E-04 | 0.00 | 100.00 |
| 44 | 45.99 | 3.26 | 94.63 | 6.40E-05 | 0.00 | 100.00 |
| 47.98 | 50.155 | 2.26 | 96.89 | 3.42E-05 | 0.00 | 100.00 |
| 52.33 | 54.695 | 1.47 | 98.36 | 1.72E-05 | 0.00 | 100.00 |
| 57.06 | 59.645 | 0.84 | 99.2 | 7.56E-06 | 0.00 | 100.00 |
| 62.23 | 65.045 | 0.46 | 99.66 | 3.19E-06 | 0.00 | 100.00 |
| 67.86 | 70.93 | 0.24 | 99.9 | 1.28E-06 | 0.00 | 100.00 |
| 74 | 77.35 | 0.1 | 100 | 4.13E-07 | 0.00 | 100.00 |
| 80.7 | | 0 | 0 | | | |
| | | | Total | 6.91E+01 | | |

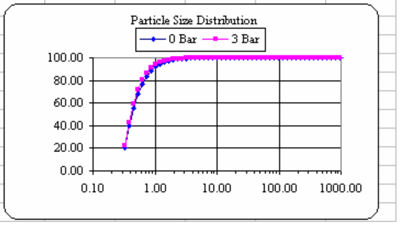
# Figure E.5: J&J Particle Size Distribution - Kyanite

| KYANITE | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | 0 Bar | 2.2 | 13.8 | 54.2 | 0.3 | 0.5 | 1.0 | | |
| | | | 3 Bar | 1.4 | 11.3 | 56.9 | 0.3 | 0.4 | 0.9 | | |
| | | | | 0 Bar | | | | | 3Bar | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.18 | 0.18 | 1.00E+01 | 20.74 | 20.74 | 0.39 | 0.39 | 2.16E+01 | 22.75 | 22.75 |
| 0.35 | 0.38 | 0.27 | 0.45 | 9.06E+00 | 18.78 | 39.52 | 0.57 | 0.96 | 1.91E+01 | 20.19 | 42.94 |
| 0.42 | 0.45 | 0.37 | 0.82 | 7.61E+00 | 15.77 | 55.29 | 0.76 | 1.72 | 1.56E+01 | 16.45 | 59.39 |
| 0.49 | 0.53 | 0.47 | 1.29 | 5.95E+00 | 12.33 | 67.62 | 0.93 | 2.65 | 1.17E+01 | 12.38 | 71.78 |
| 0.58 | 0.63 | 0.58 | 1.87 | 4.47E+00 | 9.27 | 76.89 | 1.09 | 3.74 | 8.43E+00 | 8.90 | 80.68 |
| 0.68 | 0.74 | 0.69 | 2.56 | 3.27E+00 | 6.78 | 83.67 | 1.24 | 4.97 | 5.88E+00 | 6.21 | 86.88 |
| 0.80 | 0.87 | 0.81 | 3.36 | 2.35E+00 | 4.88 | 88.55 | 1.38 | 6.36 | 4.03E+00 | 4.26 | 91.14 |
| 0.94 | 1.02 | 0.94 | 4.30 | 1.68E+00 | 3.47 | 92.02 | 1.54 | 7.89 | 2.74E+00 | 2.89 | 94.03 |
| 1.11 | 1.20 | 1.08 | 5.38 | 1.18E+00 | 2.45 | 94.47 | 1.70 | 9.59 | 1.86E+00 | 1.96 | 95.99 |
| 1.30 | 1.42 | 1.23 | 6.61 | 8.28E-01 | 1.72 | 96.19 | 1.88 | 11.47 | 1.26E+00 | 1.33 | 97.32 |
| 1.53 | 1.67 | 1.40 | 8.01 | 5.75E-01 | 1.19 | 97.38 | 2.07 | 13.54 | 8.52E-01 | 0.90 | 98.22 |
| 1.80 | 1.96 | 1.57 | 9.58 | 3.97E-01 | 0.82 | 98.20 | 2.27 | 15.81 | 5.74E-01 | 0.61 | 98.83 |
| 2.12 | 2.31 | 1.76 | 11.34 | 2.72E-01 | 0.56 | 98.77 | 2.48 | 18.29 | 3.84E-01 | 0.41 | 99.23 |
| 2.50 | 2.72 | 1.96 | 13.29 | 1.86E-01 | 0.38 | 99.15 | 2.68 | 20.97 | 2.55E-01 | 0.27 | 99.50 |
| 2.94 | 3.20 | 2.18 | 15.47 | 1.27E-01 | 0.26 | 99.41 | 2.87 | 23.84 | 1.67E-01 | 0.18 | 99.68 |
| 3.46 | 3.77 | 2.44 | 17.91 | 8.71E-02 | 0.18 | 99.60 | 3.04 | 26.87 | 1.08E-01 | 0.11 | 99.79 |
| 4.08 | 4.44 | 2.76 | 20.67 | 6.03E-02 | 0.13 | 99.72 | 3.20 | 30.07 | 6.99E-02 | 0.07 | 99.87 |
| 4.80 | 5.22 | 3.15 | 23.82 | 4.23E-02 | 0.09 | 99.81 | 3.36 | 33.43 | 4.50E-02 | 0.05 | 99.91 |
| 5.65 | 6.15 | 3.63 | 27.45 | 2.98E-02 | 0.06 | 99.87 | 3.53 | 36.96 | 2.91E-02 | 0.03 | 99.94 |
| 6.65 | 7.23 | 4.17 | 31.62 | 2.10E-02 | 0.04 | 99.91 | 3.74 | 40.70 | 1.89E-02 | 0.02 | 99.96 |
| 7.82 | 8.52 | 4.74 | 36.36 | 1.47E-02 | 0.03 | 99.94 | 3.97 | 44.67 | 1.23E-02 | 0.01 | 99.98 |
| 9.21 | 10.02 | 5.27 | 41.63 | 9.99E-03 | 0.02 | 99.96 | 4.20 | 48.87 | 7.97E-03 | 0.01 | 99.99 |
| 10.84 | 11.80 | 5.68 | 47.31 | 6.61E-03 | 0.01 | 99.98 | 4.41 | 53.28 | 5.12E-03 | 0.01 | 99.99 |
| 12.76 | 13.89 | 5.91 | 53.23 | 4.22E-03 | 0.01 | 99.99 | 4.55 | 57.83 | 3.25E-03 | 0.00 | 99.99 |
| 15.02 | 16.35 | 5.95 | 59.17 | 2.60E-03 | 0.01 | 99.99 | 4.62 | 62.45 | 2.02E-03 | 0.00 | 100.00 |
| 17.68 | 19.24 | 5.78 | 64.96 | 1.55E-03 | 0.00 | 100.00 | 4.60 | 67.05 | 1.23E-03 | 0.00 | 100.00 |
| 20.81 | 22.65 | 5.47 | 70.43 | 8.98E-04 | 0.00 | 100.00 | 4.50 | 71.56 | 7.40E-04 | 0.00 | 100.00 |
| 24.49 | 26.66 | 5.04 | 75.47 | 5.08E-04 | 0.00 | 100.00 | 4.32 | 75.88 | 4.35E-04 | 0.00 | 100.00 |
| 28.83 | 31.39 | 4.54 | 80.01 | 2.80E-04 | 0.00 | 100.00 | 4.05 | 79.93 | 2.50E-04 | 0.00 | 100.00 |
| 33.94 | 36.94 | 4.01 | 84.02 | 1.52E-04 | 0.00 | 100.00 | 3.69 | 83.62 | 1.40E-04 | 0.00 | 100.00 |
| 39.95 | 43.49 | 3.47 | 87.48 | 8.05E-05 | 0.00 | 100.00 | 3.26 | 86.88 | 7.57E-05 | 0.00 | 100.00 |
| 47.02 | 51.19 | 2.94 | 90.42 | 4.18E-05 | 0.00 | 100.00 | 2.77 | 89.64 | 3.94E-05 | 0.00 | 100.00 |
| 55.35 | 60.25 | 2.42 | 92.84 | 2.11E-05 | 0.00 | 100.00 | 2.24 | 91.88 | 1.95E-05 | 0.00 | 100.00 |
| 65.16 | 70.93 | 1.93 | 94.77 | 1.03E-05 | 0.00 | 100.00 | 1.72 | 93.60 | 9.19E-06 | 0.00 | 100.00 |
| 76.70 | 83.49 | 1.48 | 96.25 | 4.87E-06 | 0.00 | 100.00 | 1.25 | 94.85 | 4.10E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 1.10 | 97.35 | 2.22E-06 | 0.00 | 100.00 | 0.88 | 95.72 | 1.77E-06 | 0.00 | 100.00 |
| 106.27 | 115.68 | 0.79 | 98.14 | 9.78E-07 | 0.00 | 100.00 | 0.63 | 96.35 | 7.75E-07 | 0.00 | 100.00 |
| 125.09 | 136.16 | 0.55 | 98.69 | 4.16E-07 | 0.00 | 100.00 | 0.50 | 96.85 | 3.75E-07 | 0.00 | 100.00 |
| 147.24 | 160.28 | 0.37 | 99.07 | 1.72E-07 | 0.00 | 100.00 | 0.46 | 97.31 | 2.13E-07 | 0.00 | 100.00 |
| 173.31 | 188.66 | 0.25 | 99.31 | 7.01E-08 | 0.00 | 100.00 | 0.48 | 97.79 | 1.38E-07 | 0.00 | 100.00 |
| 204.01 | 222.07 | 0.17 | 99.48 | 2.90E-08 | 0.00 | 100.00 | 0.51 | 98.30 | 8.92E-08 | 0.00 | 100.00 |
| 240.14 | 261.40 | 0.12 | 99.60 | 1.25E-08 | 0.00 | 100.00 | 0.48 | 98.79 | 5.17E-08 | 0.00 | 100.00 |
| 282.67 | 307.70 | 0.08 | 99.68 | 5.32E-09 | 0.00 | 100.00 | 0.35 | 99.14 | 2.29E-08 | 0.00 | 100.00 |
| 332.73 | 362.19 | 0.02 | 99.69 | 6.79E-10 | 0.00 | 100.00 | 0.15 | 99.28 | 5.85E-09 | 0.00 | 100.00 |
| 391.65 | 426.33 | 0.01 | 99.70 | 2.13E-10 | 0.00 | 100.00 | 0.07 | 99.35 | 1.64E-09 | 0.00 | 100.00 |
| 461.01 | 501.83 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 542.66 | 590.71 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 99.70 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.35 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 48.240738 | | | | | 94.76998 | | |



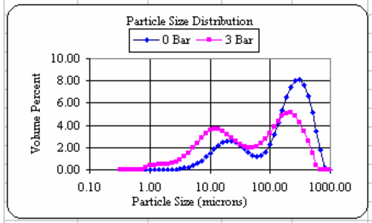


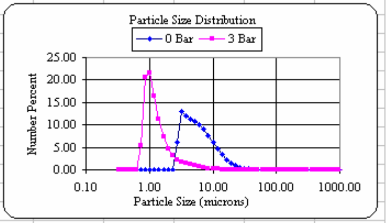


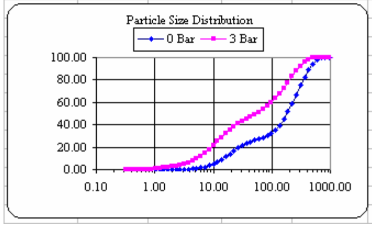


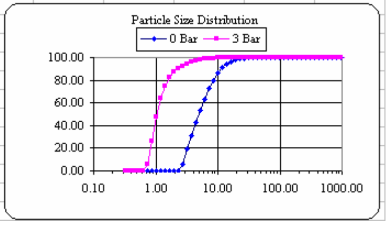
# Figure E.6: J&J Particle Size Distribution – Lithium Carbonate

| Lithium Carbonate | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | 0 Bar | 16.0 | 197.0 | 470.9 | 3.1 | 5.4 | 12.4 | | |
| | | | 3 Bar | 5.9 | 59.0 | 308.2 | 0.8 | 1.1 | 2.5 | | |
| | | | | 0 Bar | | | | | 3Bar | | |
| Sizes microns | Average microns | Volume Percent | Summary | Particles | Number Percent | summary | Volume Percent | Summary | Particles | Number Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.42 | 0.45 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.49 | 0.53 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.58 | 0.63 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.68 | 0.74 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.03 | 0.03 | 1.56E-01 | 5.41 | 5.41 |
| 0.80 | 0.87 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.20 | 0.24 | 5.91E-01 | 20.49 | 25.90 |
| 0.94 | 1.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.35 | 0.59 | 6.25E-01 | 21.68 | 47.58 |
| 1.11 | 1.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.43 | 1.01 | 4.70E-01 | 16.30 | 63.88 |
| 1.30 | 1.42 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.48 | 1.50 | 3.24E-01 | 11.22 | 75.10 |
| 1.53 | 1.67 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.51 | 2.01 | 2.10E-01 | 7.28 | 82.37 |
| 1.80 | 1.96 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.54 | 2.54 | 1.36E-01 | 4.72 | 87.09 |
| 2.12 | 2.31 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.59 | 3.14 | 9.20E-02 | 3.19 | 90.28 |
| 2.50 | 2.72 | 0.03 | 0.03 | 2.89E-03 | 6.16 | 6.16 | 0.70 | 3.84 | 6.68E-02 | 2.32 | 92.59 |
| 2.94 | 3.20 | 0.10 | 0.14 | 6.09E-03 | 12.98 | 19.14 | 0.89 | 4.73 | 5.17E-02 | 1.79 | 94.38 |
| 3.46 | 3.77 | 0.16 | 0.29 | 5.60E-03 | 11.94 | 31.08 | 1.16 | 5.89 | 4.14E-02 | 1.44 | 95.82 |
| 4.08 | 4.44 | 0.24 | 0.54 | 5.33E-03 | 11.36 | 42.44 | 1.52 | 7.41 | 3.32E-02 | 1.15 | 96.97 |
| 4.80 | 5.22 | 0.38 | 0.92 | 5.10E-03 | 10.88 | 53.32 | 1.95 | 9.36 | 2.61E-02 | 0.91 | 97.88 |
| 5.65 | 6.15 | 0.58 | 1.49 | 4.74E-03 | 10.10 | 63.42 | 2.41 | 11.76 | 1.98E-02 | 0.69 | 98.56 |
| 6.65 | 7.23 | 0.84 | 2.33 | 4.22E-03 | 9.00 | 72.42 | 2.86 | 14.62 | 1.44E-02 | 0.50 | 99.06 |
| 7.82 | 8.52 | 1.16 | 3.49 | 3.57E-03 | 7.61 | 80.03 | 3.25 | 17.87 | 1.00E-02 | 0.35 | 99.41 |
| 9.21 | 10.02 | 1.51 | 5.00 | 2.87E-03 | 6.11 | 86.15 | 3.52 | 21.39 | 6.67E-03 | 0.23 | 99.64 |
| 10.84 | 11.80 | 1.88 | 6.88 | 2.18E-03 | 4.65 | 90.80 | 3.65 | 25.03 | 4.24E-03 | 0.15 | 99.79 |
| 12.76 | 13.89 | 2.21 | 9.09 | 1.57E-03 | 3.35 | 94.16 | 3.62 | 28.65 | 2.58E-03 | 0.09 | 99.88 |
| 15.02 | 16.35 | 2.46 | 11.55 | 1.07E-03 | 2.29 | 96.45 | 3.45 | 32.10 | 1.51E-03 | 0.05 | 99.93 |
| 17.68 | 19.24 | 2.59 | 14.14 | 6.95E-04 | 1.48 | 97.93 | 3.19 | 35.29 | 8.55E-04 | 0.03 | 99.96 |
| 20.81 | 22.65 | 2.59 | 16.73 | 4.25E-04 | 0.91 | 98.83 | 2.89 | 38.18 | 4.75E-04 | 0.02 | 99.98 |
| 24.49 | 26.66 | 2.45 | 19.17 | 2.46E-04 | 0.53 | 99.36 | 2.59 | 40.77 | 2.61E-04 | 0.01 | 99.99 |
| 28.83 | 31.39 | 2.19 | 21.36 | 1.35E-04 | 0.29 | 99.65 | 2.32 | 43.09 | 1.43E-04 | 0.00 | 99.99 |
| 33.94 | 36.94 | 1.87 | 23.23 | 7.07E-05 | 0.15 | 99.80 | 2.12 | 45.21 | 8.02E-05 | 0.00 | 100.00 |
| 39.95 | 43.49 | 1.54 | 24.77 | 3.57E-05 | 0.08 | 99.87 | 2.00 | 47.21 | 4.65E-05 | 0.00 | 100.00 |
| 47.02 | 51.19 | 1.28 | 26.05 | 1.82E-05 | 0.04 | 99.91 | 2.00 | 49.21 | 2.85E-05 | 0.00 | 100.00 |
| 55.35 | 60.25 | 1.16 | 27.20 | 1.01E-05 | 0.02 | 99.93 | 2.12 | 51.33 | 1.85E-05 | 0.00 | 100.00 |
| 65.16 | 70.93 | 1.24 | 28.45 | 6.66E-06 | 0.01 | 99.95 | 2.37 | 53.70 | 1.27E-05 | 0.00 | 100.00 |
| 76.70 | 83.49 | 1.59 | 30.04 | 5.23E-06 | 0.01 | 99.96 | 2.77 | 56.47 | 9.08E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 2.23 | 32.27 | 4.48E-06 | 0.01 | 99.97 | 3.27 | 59.74 | 6.58E-06 | 0.00 | 100.00 |
| 106.27 | 115.68 | 3.12 | 35.39 | 3.85E-06 | 0.01 | 99.98 | 3.84 | 63.57 | 4.73E-06 | 0.00 | 100.00 |
| 125.09 | 136.16 | 4.21 | 39.60 | 3.18E-06 | 0.01 | 99.98 | 4.38 | 67.96 | 3.32E-06 | 0.00 | 100.00 |
| 147.24 | 160.28 | 5.38 | 44.98 | 2.49E-06 | 0.01 | 99.99 | 4.82 | 72.78 | 2.24E-06 | 0.00 | 100.00 |
| 173.31 | 188.66 | 6.51 | 51.49 | 1.85E-06 | 0.00 | 99.99 | 5.08 | 77.87 | 1.45E-06 | 0.00 | 100.00 |
| 204.01 | 222.07 | 7.43 | 58.92 | 1.30E-06 | 0.00 | 100.00 | 5.10 | 82.97 | 8.90E-07 | 0.00 | 100.00 |
| 240.14 | 261.40 | 8.02 | 66.94 | 8.57E-07 | 0.00 | 100.00 | 4.84 | 87.81 | 5.17E-07 | 0.00 | 100.00 |
| 282.67 | 307.70 | 8.12 | 75.06 | 5.32E-07 | 0.00 | 100.00 | 4.30 | 92.11 | 2.82E-07 | 0.00 | 100.00 |
| 332.73 | 362.19 | 7.66 | 82.72 | 3.08E-07 | 0.00 | 100.00 | 3.51 | 95.61 | 1.41E-07 | 0.00 | 100.00 |
| 391.65 | 426.33 | 6.65 | 89.37 | 1.64E-07 | 0.00 | 100.00 | 2.53 | 98.14 | 6.24E-08 | 0.00 | 100.00 |
| 461.01 | 501.83 | 5.18 | 94.55 | 7.83E-08 | 0.00 | 100.00 | 1.47 | 99.61 | 2.22E-08 | 0.00 | 100.00 |
| 542.66 | 590.71 | 3.48 | 98.03 | 3.22E-08 | 0.00 | 100.00 | 0.37 | 99.98 | 3.43E-09 | 0.00 | 100.00 |
| 638.76 | 695.32 | 1.76 | 99.79 | 1.00E-08 | 0.00 | 100.00 | 0.02 | 100.00 | 9.40E-11 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.21 | 100.00 | 7.34E-10 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 0.0469281 | | | | | 2.884379 | | |



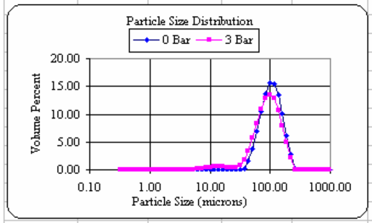


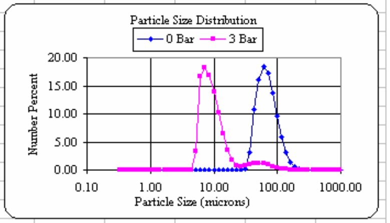


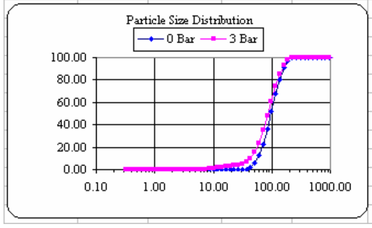


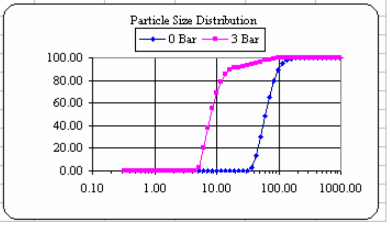
# Figure E.7: J&J Particle Size Distribution - Olivine

| OLIVINE | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0 Bar** | 61.9 | 104.3 | 171.0 | 44.4 | 66.3 | 109.8 | | |
| | | | **3 Bar** | 47.2 | 92.9 | 164.1 | 6.05 | 8.80 | 19.2 | | |
| | | | | **0 Bar** | | | | | **3Bar** | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.42 | 0.45 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.49 | 0.53 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.58 | 0.63 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.68 | 0.74 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.80 | 0.87 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.94 | 1.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.11 | 1.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.30 | 1.42 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.53 | 1.67 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.80 | 1.96 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.12 | 2.31 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.50 | 2.72 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.94 | 3.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 3.46 | 3.77 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 4.08 | 4.44 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 4.80 | 5.22 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.02 | 0.02 | 2.15E-04 | 3.31 | 3.31 |
| 5.65 | 6.15 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.13 | 0.15 | 1.08E-03 | 16.61 | 19.92 |
| 6.65 | 7.23 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.23 | 0.38 | 1.18E-03 | 18.23 | 38.16 |
| 7.82 | 8.52 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.35 | 0.73 | 1.09E-03 | 16.82 | 54.97 |
| 9.21 | 10.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.48 | 1.21 | 9.01E-04 | 13.91 | 68.88 |
| 10.84 | 11.80 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.57 | 1.78 | 6.59E-04 | 10.16 | 79.05 |
| 12.76 | 13.89 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.59 | 2.37 | 4.23E-04 | 6.53 | 85.58 |
| 15.02 | 16.35 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.54 | 2.91 | 2.34E-04 | 3.62 | 89.19 |
| 17.68 | 19.24 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.41 | 3.32 | 1.11E-04 | 1.71 | 90.90 |
| 20.81 | 22.65 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.30 | 3.62 | 4.96E-05 | 0.77 | 91.67 |
| 24.49 | 26.66 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.35 | 3.97 | 3.54E-05 | 0.55 | 92.21 |
| 28.83 | 31.39 | 0.01 | 0.01 | 4.52E-07 | 0.14 | 0.14 | 0.77 | 4.74 | 4.74E-05 | 0.73 | 92.94 |
| 33.94 | 36.94 | 0.26 | 0.27 | 9.98E-06 | 3.07 | 3.20 | 1.74 | 6.48 | 6.60E-05 | 1.02 | 93.96 |
| 39.95 | 43.49 | 1.50 | 1.77 | 3.48E-05 | 10.70 | 13.90 | 3.42 | 9.90 | 7.94E-05 | 1.22 | 95.19 |
| 47.02 | 51.19 | 3.67 | 5.44 | 5.23E-05 | 16.05 | 29.96 | 5.72 | 15.62 | 8.14E-05 | 1.26 | 96.44 |
| 55.35 | 60.25 | 6.85 | 12.29 | 5.98E-05 | 18.36 | 48.31 | 8.39 | 24.01 | 7.33E-05 | 1.13 | 97.57 |
| 65.16 | 70.93 | 10.45 | 22.74 | 5.60E-05 | 17.19 | 65.50 | 10.94 | 34.96 | 5.86E-05 | 0.90 | 98.48 |
| 76.70 | 83.49 | 13.67 | 36.41 | 4.49E-05 | 13.78 | 79.28 | 12.81 | 47.77 | 4.20E-05 | 0.65 | 99.13 |
| 90.28 | 98.27 | 15.55 | 51.96 | 3.13E-05 | 9.61 | 88.89 | 13.50 | 61.26 | 2.72E-05 | 0.42 | 99.55 |
| 106.27 | 115.68 | 15.48 | 67.44 | 1.91E-05 | 5.87 | 94.76 | 12.78 | 74.04 | 1.58E-05 | 0.24 | 99.79 |
| 125.09 | 136.16 | 13.42 | 80.86 | 1.02E-05 | 3.12 | 97.88 | 10.79 | 84.83 | 8.16E-06 | 0.13 | 99.91 |
| 147.24 | 160.28 | 10.03 | 90.88 | 4.65E-06 | 1.43 | 99.30 | 7.99 | 92.82 | 3.70E-06 | 0.06 | 99.97 |
| 173.31 | 188.66 | 6.20 | 97.09 | 1.76E-06 | 0.54 | 99.85 | 5.03 | 97.85 | 1.43E-06 | 0.02 | 99.99 |
| 204.01 | 222.07 | 2.80 | 99.89 | 4.88E-07 | 0.15 | 100.00 | 2.15 | 100.00 | 3.75E-07 | 0.01 | 100.00 |
| 240.14 | 261.40 | 0.11 | 100.00 | 1.20E-08 | 0.00 | 100.00 | 0.00 | 100.00 | 1.23E-10 | 0.00 | 100.00 |
| 282.67 | 307.70 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 332.73 | 362.19 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 391.65 | 426.33 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 461.01 | 501.83 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 542.66 | 590.71 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 0.0003256 | | | | | 0.006481 | | |



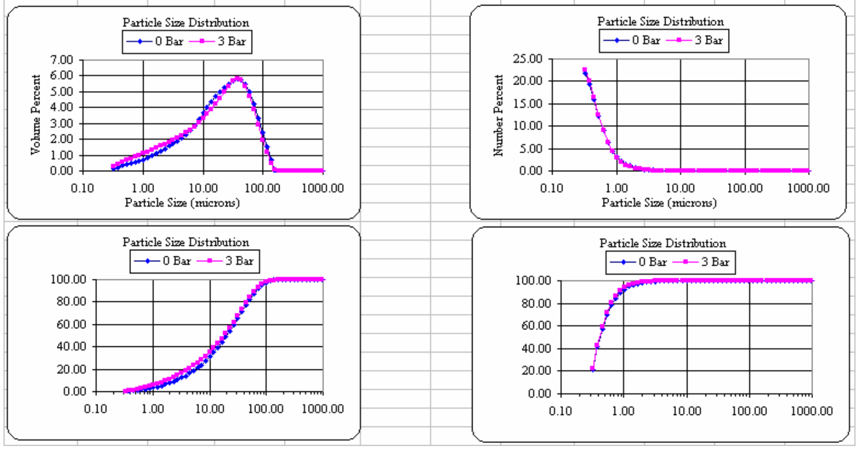






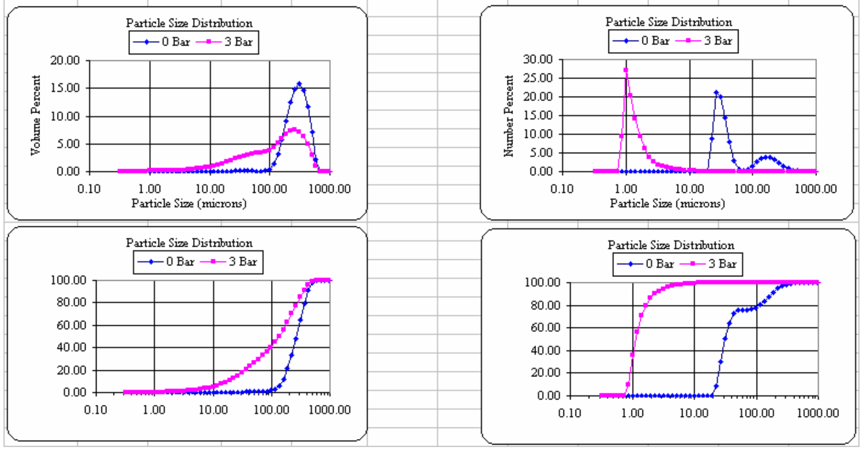
# Figure E.8: J&J Particle Size Distribution - Silica

| SILICA | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | 0 Bar | 2.8 | 21.5 | 72.0 | 0.3 | 0.5 | 1.0 | | |
| | | | 3 Bar | 1.9 | 19.8 | 67.8 | 0.3 | 0.4 | 0.9 | | |
| | | | | 0 Bar | | | | | 3Bar | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.16 | 0.16 | 8.89E+00 | 21.83 | 21.83 | 0.28 | 0.28 | 1.52E+01 | 22.59 | 22.59 |
| 0.35 | 0.38 | 0.24 | 0.40 | 7.94E+00 | 19.48 | 41.31 | 0.40 | 0.68 | 1.35E+01 | 20.12 | 42.71 |
| 0.42 | 0.45 | 0.32 | 0.71 | 6.53E+00 | 16.02 | 57.34 | 0.54 | 1.21 | 1.10E+01 | 16.46 | 59.17 |
| 0.49 | 0.53 | 0.39 | 1.11 | 4.98E+00 | 12.23 | 69.56 | 0.66 | 1.87 | 8.35E+00 | 12.45 | 71.62 |
| 0.58 | 0.63 | 0.47 | 1.58 | 3.65E+00 | 8.96 | 78.52 | 0.78 | 2.65 | 6.03E+00 | 8.99 | 80.60 |
| 0.68 | 0.74 | 0.55 | 2.13 | 2.61E+00 | 6.40 | 84.92 | 0.89 | 3.54 | 4.21E+00 | 6.28 | 86.88 |
| 0.80 | 0.87 | 0.63 | 2.76 | 1.84E+00 | 4.53 | 89.44 | 0.99 | 4.53 | 2.89E+00 | 4.31 | 91.19 |
| 0.94 | 1.02 | 0.73 | 3.49 | 1.30E+00 | 3.19 | 92.63 | 1.10 | 5.63 | 1.96E+00 | 2.92 | 94.11 |
| 1.11 | 1.20 | 0.83 | 4.32 | 9.14E-01 | 2.25 | 94.88 | 1.20 | 6.83 | 1.32E+00 | 1.96 | 96.07 |
| 1.30 | 1.42 | 0.96 | 5.28 | 6.44E-01 | 1.58 | 96.46 | 1.32 | 8.14 | 8.83E-01 | 1.32 | 97.39 |
| 1.53 | 1.67 | 1.10 | 6.38 | 4.52E-01 | 1.11 | 97.57 | 1.43 | 9.58 | 5.91E-01 | 0.88 | 98.27 |
| 1.80 | 1.96 | 1.25 | 7.62 | 3.15E-01 | 0.77 | 98.34 | 1.56 | 11.14 | 3.94E-01 | 0.59 | 98.85 |
| 2.12 | 2.31 | 1.40 | 9.03 | 2.17E-01 | 0.53 | 98.88 | 1.69 | 12.83 | 2.62E-01 | 0.39 | 99.24 |
| 2.50 | 2.72 | 1.56 | 10.59 | 1.48E-01 | 0.36 | 99.24 | 1.83 | 14.66 | 1.73E-01 | 0.26 | 99.50 |
| 2.94 | 3.20 | 1.72 | 12.31 | 1.00E-01 | 0.25 | 99.49 | 1.96 | 16.62 | 1.14E-01 | 0.17 | 99.67 |
| 3.46 | 3.77 | 1.89 | 14.20 | 6.74E-02 | 0.17 | 99.65 | 2.10 | 18.72 | 7.50E-02 | 0.11 | 99.78 |
| 4.08 | 4.44 | 2.07 | 16.27 | 4.53E-02 | 0.11 | 99.76 | 2.25 | 20.97 | 4.92E-02 | 0.07 | 99.86 |
| 4.80 | 5.22 | 2.28 | 18.56 | 3.06E-02 | 0.08 | 99.84 | 2.41 | 23.38 | 3.23E-02 | 0.05 | 99.91 |
| 5.65 | 6.15 | 2.55 | 21.10 | 2.10E-02 | 0.05 | 99.89 | 2.59 | 25.97 | 2.13E-02 | 0.03 | 99.94 |
| 6.65 | 7.23 | 2.88 | 23.98 | 1.45E-02 | 0.04 | 99.93 | 2.81 | 28.78 | 1.42E-02 | 0.02 | 99.96 |
| 7.82 | 8.52 | 3.25 | 27.23 | 1.01E-02 | 0.02 | 99.95 | 3.05 | 31.83 | 9.43E-03 | 0.01 | 99.97 |
| 9.21 | 10.02 | 3.65 | 30.89 | 6.93E-03 | 0.02 | 99.97 | 3.32 | 35.15 | 6.29E-03 | 0.01 | 99.98 |
| 10.84 | 11.80 | 4.05 | 34.93 | 4.70E-03 | 0.01 | 99.98 | 3.61 | 38.75 | 4.19E-03 | 0.01 | 99.99 |
| 12.76 | 13.89 | 4.40 | 39.33 | 3.13E-03 | 0.01 | 99.99 | 3.91 | 42.66 | 2.79E-03 | 0.00 | 99.99 |
| 15.02 | 16.35 | 4.71 | 44.04 | 2.06E-03 | 0.01 | 99.99 | 4.24 | 46.90 | 1.85E-03 | 0.00 | 99.99 |
| 17.68 | 19.24 | 4.98 | 49.02 | 1.34E-03 | 0.00 | 99.99 | 4.60 | 51.51 | 1.23E-03 | 0.00 | 100.00 |
| 20.81 | 22.65 | 5.25 | 54.27 | 8.62E-04 | 0.00 | 100.00 | 4.99 | 56.50 | 8.20E-04 | 0.00 | 100.00 |
| 24.49 | 26.66 | 5.49 | 59.76 | 5.53E-04 | 0.00 | 100.00 | 5.37 | 61.86 | 5.41E-04 | 0.00 | 100.00 |
| 28.83 | 31.39 | 5.70 | 65.46 | 3.52E-04 | 0.00 | 100.00 | 5.67 | 67.53 | 3.50E-04 | 0.00 | 100.00 |
| 33.94 | 36.94 | 5.80 | 71.26 | 2.20E-04 | 0.00 | 100.00 | 5.81 | 73.34 | 2.20E-04 | 0.00 | 100.00 |
| 39.95 | 43.49 | 5.76 | 77.02 | 1.34E-04 | 0.00 | 100.00 | 5.72 | 79.07 | 1.33E-04 | 0.00 | 100.00 |
| 47.02 | 51.19 | 5.49 | 82.50 | 7.82E-05 | 0.00 | 100.00 | 5.36 | 84.42 | 7.63E-05 | 0.00 | 100.00 |
| 55.35 | 60.25 | 4.97 | 87.48 | 4.34E-05 | 0.00 | 100.00 | 4.71 | 89.13 | 4.11E-05 | 0.00 | 100.00 |
| 65.16 | 70.93 | 4.24 | 91.72 | 2.27E-05 | 0.00 | 100.00 | 3.85 | 92.98 | 2.06E-05 | 0.00 | 100.00 |
| 76.70 | 83.49 | 3.35 | 95.07 | 1.10E-05 | 0.00 | 100.00 | 2.89 | 95.87 | 9.48E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 2.43 | 97.49 | 4.88E-06 | 0.00 | 100.00 | 1.95 | 97.82 | 3.93E-06 | 0.00 | 100.00 |
| 106.27 | 115.68 | 1.52 | 99.02 | 1.88E-06 | 0.00 | 100.00 | 1.15 | 98.97 | 1.42E-06 | 0.00 | 100.00 |
| 125.09 | 136.16 | 0.68 | 99.70 | 5.17E-07 | 0.00 | 100.00 | 0.51 | 99.48 | 3.82E-07 | 0.00 | 100.00 |
| 147.24 | 160.28 | 0.03 | 99.73 | 1.54E-08 | 0.00 | 100.00 | 0.06 | 99.54 | 2.98E-08 | 0.00 | 100.00 |
| 173.31 | 188.66 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 4.86E-10 | 0.00 | 100.00 |
| 204.01 | 222.07 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 240.14 | 261.40 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 282.67 | 307.70 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 332.73 | 362.19 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 391.65 | 426.33 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 461.01 | 501.83 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 542.66 | 590.71 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 99.73 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.54 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 40.724807 | | | | | 67.10109 | | |



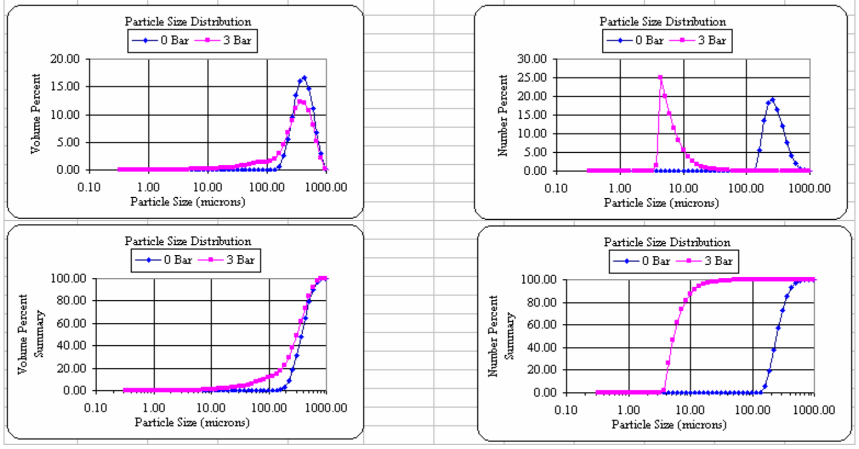
# Figure E.9: J&J Particle Size Distribution – Soda Ash

| SODA ASH | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | 0 Bar | 164.0 | 287.4 | 456.5 | 24.7 | 33.9 | 191.4 | | |
| | | | 3 Bar | 19.8 | 147.5 | 380.6 | 0.9 | 1.2 | 2.5 | | |
| | | | | 0 Bar | | | | | 3Bar | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.42 | 0.45 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.49 | 0.53 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.58 | 0.63 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.68 | 0.74 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.80 | 0.87 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.02 | 0.02 | 6.58E-02 | 9.34 | 9.34 |
| 0.94 | 1.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.11 | 0.13 | 1.90E-01 | 26.92 | 36.26 |
| 1.11 | 1.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.13 | 0.26 | 1.43E-01 | 20.30 | 56.56 |
| 1.30 | 1.42 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.15 | 0.41 | 9.94E-02 | 14.11 | 70.67 |
| 1.53 | 1.67 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.16 | 0.57 | 6.57E-02 | 9.34 | 80.01 |
| 1.80 | 1.96 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.17 | 0.73 | 4.25E-02 | 6.03 | 86.04 |
| 2.12 | 2.31 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.18 | 0.91 | 2.78E-02 | 3.95 | 89.98 |
| 2.50 | 2.72 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.20 | 1.11 | 1.89E-02 | 2.68 | 92.66 |
| 2.94 | 3.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.23 | 1.34 | 1.34E-02 | 1.90 | 94.56 |
| 3.46 | 3.77 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.28 | 1.62 | 9.84E-03 | 1.40 | 95.96 |
| 4.08 | 4.44 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.34 | 1.96 | 7.38E-03 | 1.05 | 97.01 |
| 4.80 | 5.22 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.42 | 2.37 | 5.57E-03 | 0.79 | 97.80 |
| 5.65 | 6.15 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.51 | 2.88 | 4.18E-03 | 0.59 | 98.39 |
| 6.65 | 7.23 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.62 | 3.50 | 3.12E-03 | 0.44 | 98.84 |
| 7.82 | 8.52 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.74 | 4.24 | 2.30E-03 | 0.33 | 99.16 |
| 9.21 | 10.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.89 | 5.13 | 1.68E-03 | 0.24 | 99.40 |
| 10.84 | 11.80 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.05 | 6.18 | 1.22E-03 | 0.17 | 99.57 |
| 12.76 | 13.89 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.24 | 7.41 | 8.81E-04 | 0.13 | 99.70 |
| 15.02 | 16.35 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.45 | 8.87 | 6.35E-04 | 0.09 | 99.79 |
| 17.68 | 19.24 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.70 | 10.57 | 4.56E-04 | 0.06 | 99.86 |
| 20.81 | 22.65 | 0.04 | 0.04 | 6.15E-06 | 8.95 | 8.95 | 1.98 | 12.55 | 3.26E-04 | 0.05 | 99.90 |
| 24.49 | 26.66 | 0.14 | 0.18 | 1.46E-05 | 21.18 | 30.13 | 2.28 | 14.83 | 2.30E-04 | 0.03 | 99.93 |
| 28.83 | 31.39 | 0.22 | 0.40 | 1.37E-05 | 19.98 | 50.11 | 2.57 | 17.40 | 1.59E-04 | 0.02 | 99.96 |
| 33.94 | 36.94 | 0.26 | 0.67 | 9.88E-06 | 14.39 | 64.50 | 2.84 | 20.24 | 1.07E-04 | 0.02 | 99.97 |
| 39.95 | 43.49 | 0.24 | 0.90 | 5.46E-06 | 7.95 | 72.45 | 3.04 | 23.28 | 7.07E-05 | 0.01 | 99.98 |
| 47.02 | 51.19 | 0.14 | 1.04 | 1.96E-06 | 2.85 | 75.30 | 3.18 | 26.47 | 4.53E-05 | 0.01 | 99.99 |
| 55.35 | 60.25 | 0.04 | 1.07 | 3.17E-07 | 0.46 | 75.76 | 3.27 | 29.74 | 2.86E-05 | 0.00 | 99.99 |
| 65.16 | 70.93 | 0.03 | 1.11 | 1.69E-07 | 0.25 | 76.01 | 3.36 | 33.10 | 1.80E-05 | 0.00 | 99.99 |
| 76.70 | 83.49 | 0.10 | 1.21 | 3.28E-07 | 0.48 | 76.49 | 3.52 | 36.62 | 1.16E-05 | 0.00 | 100.00 |
| 90.28 | 98.27 | 0.45 | 1.66 | 9.14E-07 | 1.33 | 77.82 | 3.84 | 40.46 | 7.73E-06 | 0.00 | 100.00 |
| 106.27 | 115.68 | 1.41 | 3.07 | 1.74E-06 | 2.53 | 80.34 | 4.37 | 44.83 | 5.39E-06 | 0.00 | 100.00 |
| 125.09 | 136.16 | 3.18 | 6.25 | 2.41E-06 | 3.50 | 83.85 | 5.11 | 49.94 | 3.86E-06 | 0.00 | 100.00 |
| 147.24 | 160.28 | 5.82 | 12.07 | 2.70E-06 | 3.93 | 87.78 | 5.96 | 55.90 | 2.77E-06 | 0.00 | 100.00 |
| 173.31 | 188.66 | 9.12 | 21.19 | 2.59E-06 | 3.77 | 91.55 | 6.80 | 62.70 | 1.93E-06 | 0.00 | 100.00 |
| 204.01 | 222.07 | 12.40 | 33.59 | 2.16E-06 | 3.15 | 94.70 | 7.40 | 70.10 | 1.29E-06 | 0.00 | 100.00 |
| 240.14 | 261.40 | 14.92 | 48.51 | 1.59E-06 | 2.32 | 97.02 | 7.58 | 77.68 | 8.10E-07 | 0.00 | 100.00 |
| 282.67 | 307.70 | 15.82 | 64.33 | 1.04E-06 | 1.51 | 98.53 | 7.22 | 84.90 | 4.73E-07 | 0.00 | 100.00 |
| 332.73 | 362.19 | 14.70 | 79.03 | 5.91E-07 | 0.86 | 99.39 | 6.28 | 91.17 | 2.52E-07 | 0.00 | 100.00 |
| 391.65 | 426.33 | 11.74 | 90.77 | 2.89E-07 | 0.42 | 99.82 | 4.88 | 96.05 | 1.20E-07 | 0.00 | 100.00 |
| 461.01 | 501.83 | 7.11 | 97.88 | 1.07E-07 | 0.16 | 99.97 | 3.00 | 99.05 | 4.53E-08 | 0.00 | 100.00 |
| 542.66 | 590.71 | 2.12 | 100.00 | 1.97E-08 | 0.03 | 100.00 | 0.95 | 100.00 | 8.81E-09 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 6.87E-05 | | | | | 0.704087 | | |



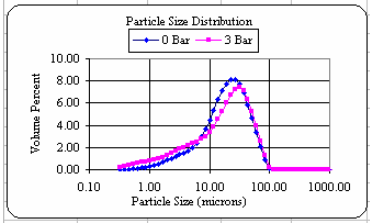
# Figure E.10: J&J Particle Size Distribution - Sugar

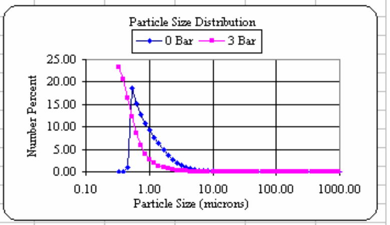
| **SUGAR** | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0.5 Bar** | 245.5 | 381.3 | 637.3 | 182.3 | 267.4 | 433.7 | | |
| | | | **3 Bar** | 90.1 | 336.0 | 609.5 | 4.3 | 5.9 | 12.1 | | |
| | | | | **0.5 Bar** | | | | | **3Bar** | | |
| **Sizes** microns | Average microns | Volume Percent | Summary | Particles | Number Percent | summary | Volume Percent | Summary | Particles | Number Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.42 | 0.45 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.49 | 0.53 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.58 | 0.63 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.68 | 0.74 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.80 | 0.87 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 0.94 | 1.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.11 | 1.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.30 | 1.42 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.53 | 1.67 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 1.80 | 1.96 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.12 | 2.31 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.50 | 2.72 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 2.94 | 3.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 |
| 3.46 | 3.77 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.15E-04 | 1.50 | 1.50 |
| 4.08 | 4.44 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.09 | 0.09 | 1.92E-03 | 25.12 | 26.62 |
| 4.80 | 5.22 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.11 | 0.21 | 1.54E-03 | 20.07 | 46.69 |
| 5.65 | 6.15 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.14 | 0.35 | 1.18E-03 | 15.42 | 62.12 |
| 6.65 | 7.23 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.17 | 0.52 | 8.73E-04 | 11.41 | 73.53 |
| 7.82 | 8.52 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.20 | 0.72 | 6.26E-04 | 8.18 | 81.71 |
| 9.21 | 10.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.23 | 0.96 | 4.38E-04 | 5.72 | 87.43 |
| 10.84 | 11.80 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.26 | 1.21 | 3.00E-04 | 3.91 | 91.34 |
| 12.76 | 13.89 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.28 | 1.50 | 2.01E-04 | 2.63 | 93.97 |
| 15.02 | 16.35 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.31 | 1.80 | 1.34E-04 | 1.75 | 95.71 |
| 17.68 | 19.24 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.33 | 2.13 | 8.94E-05 | 1.17 | 96.88 |
| 20.81 | 22.65 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.38 | 2.51 | 6.19E-05 | 0.81 | 97.69 |
| 24.49 | 26.66 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.45 | 2.96 | 4.50E-05 | 0.59 | 98.28 |
| 28.83 | 31.39 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.56 | 3.51 | 3.44E-05 | 0.45 | 98.73 |
| 33.94 | 36.94 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.71 | 4.22 | 2.67E-05 | 0.35 | 99.08 |
| 39.95 | 43.49 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.89 | 5.11 | 2.06E-05 | 0.27 | 99.35 |
| 47.02 | 51.19 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.07 | 6.17 | 1.52E-05 | 0.20 | 99.55 |
| 55.35 | 60.25 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.21 | 7.39 | 1.06E-05 | 0.14 | 99.68 |
| 65.16 | 70.93 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.30 | 8.69 | 6.96E-06 | 0.09 | 99.77 |
| 76.70 | 83.49 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.33 | 10.02 | 4.37E-06 | 0.06 | 99.83 |
| 90.28 | 98.27 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.37 | 11.40 | 2.76E-06 | 0.04 | 99.87 |
| 106.27 | 115.68 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 1.55 | 12.95 | 1.92E-06 | 0.03 | 99.89 |
| 125.09 | 136.16 | 0.03 | 0.03 | 1.93E-08 | 0.36 | 0.36 | 2.05 | 15.00 | 1.55E-06 | 0.02 | 99.91 |
| 147.24 | 160.28 | 0.65 | 0.68 | 3.03E-07 | 5.66 | 6.02 | 3.04 | 18.04 | 1.41E-06 | 0.02 | 99.93 |
| 173.31 | 188.66 | 2.55 | 3.22 | 7.24E-07 | 13.54 | 19.57 | 4.62 | 22.65 | 1.31E-06 | 0.02 | 99.95 |
| 204.01 | 222.07 | 5.59 | 8.81 | 9.74E-07 | 18.22 | 37.79 | 6.68 | 29.34 | 1.17E-06 | 0.02 | 99.96 |
| 240.14 | 261.40 | 9.53 | 18.34 | 1.02E-06 | 19.06 | 56.85 | 8.99 | 38.33 | 9.61E-07 | 0.01 | 99.98 |
| 282.67 | 307.70 | 13.39 | 31.73 | 8.78E-07 | 16.42 | 73.27 | 10.99 | 49.32 | 7.21E-07 | 0.01 | 99.99 |
| 332.73 | 362.19 | 16.08 | 47.81 | 6.46E-07 | 12.09 | 85.36 | 12.18 | 61.50 | 4.90E-07 | 0.01 | 99.99 |
| 391.65 | 426.33 | 16.61 | 64.41 | 4.09E-07 | 7.66 | 93.02 | 12.11 | 73.62 | 2.99E-07 | 0.00 | 100.00 |
| 461.01 | 501.83 | 14.72 | 79.13 | 2.22E-07 | 4.16 | 97.18 | 10.69 | 84.31 | 1.62E-07 | 0.00 | 100.00 |
| 542.66 | 590.71 | 11.03 | 90.16 | 1.02E-07 | 1.91 | 99.09 | 8.19 | 92.49 | 7.58E-08 | 0.00 | 100.00 |
| 638.76 | 695.32 | 6.69 | 96.86 | 3.80E-08 | 0.71 | 99.80 | 5.24 | 97.73 | 2.98E-08 | 0.00 | 100.00 |
| 751.88 | 818.46 | 2.89 | 99.75 | 1.01E-08 | 0.19 | 99.99 | 2.14 | 99.87 | 7.44E-09 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.25 | 100.00 | 5.30E-10 | 0.01 | 100.00 | 0.13 | 100.00 | 2.85E-10 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 5.346E-06 | | | | | 0.007652 | | |

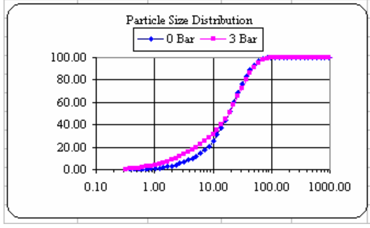


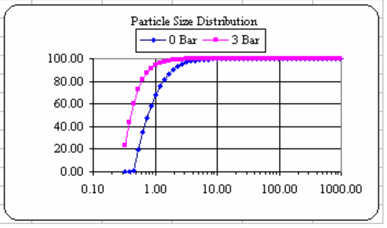
# Figure E.11: J&J Particle Size Distribution – Titanium Dioxide

| **Titanium Dioxide** | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0 Bar** | 4.7 | 19.9 | 49.1 | 0.5 | 0.8 | 2.1 | | |
| | | | **3 Bar** | 2.5 | 20.1 | 52.8 | 0.3 | 0.4 | 0.9 | | |
| | | | | **0 Bar** | | | | | **3Bar** | | |
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.22 | 0.22 | 1.21E+01 | 23.41 | 23.41 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 0.32 | 0.54 | 1.07E+01 | 20.57 | 43.98 |
| 0.42 | 0.45 | 0.00 | 0.00 | 6.15E-02 | 1.08 | 1.08 | 0.42 | 0.95 | 8.56E+00 | 16.51 | 60.49 |
| 0.49 | 0.53 | 0.08 | 0.09 | 1.06E+00 | 18.67 | 19.75 | 0.50 | 1.45 | 6.33E+00 | 12.21 | 72.70 |
| 0.58 | 0.63 | 0.11 | 0.20 | 8.61E-01 | 15.12 | 34.87 | 0.58 | 2.03 | 4.47E+00 | 8.61 | 81.31 |
| 0.68 | 0.74 | 0.15 | 0.35 | 7.30E-01 | 12.82 | 47.68 | 0.64 | 2.68 | 3.06E+00 | 5.91 | 87.22 |
| 0.80 | 0.87 | 0.21 | 0.56 | 6.21E-01 | 10.89 | 58.58 | 0.71 | 3.39 | 2.08E+00 | 4.01 | 91.22 |
| 0.94 | 1.02 | 0.29 | 0.86 | 5.26E-01 | 9.24 | 67.81 | 0.79 | 4.18 | 1.41E+00 | 2.72 | 93.94 |
| 1.11 | 1.20 | 0.40 | 1.26 | 4.39E-01 | 7.71 | 75.52 | 0.88 | 5.06 | 9.67E-01 | 1.87 | 95.81 |
| 1.30 | 1.42 | 0.53 | 1.79 | 3.57E-01 | 6.27 | 81.80 | 1.00 | 6.06 | 6.71E-01 | 1.29 | 97.10 |
| 1.53 | 1.67 | 0.68 | 2.48 | 2.81E-01 | 4.94 | 86.74 | 1.14 | 7.20 | 4.68E-01 | 0.90 | 98.01 |
| 1.80 | 1.96 | 0.85 | 3.32 | 2.14E-01 | 3.76 | 90.50 | 1.30 | 8.49 | 3.28E-01 | 0.63 | 98.64 |
| 2.12 | 2.31 | 1.02 | 4.34 | 1.58E-01 | 2.77 | 93.27 | 1.47 | 9.97 | 2.28E-01 | 0.44 | 99.08 |
| 2.50 | 2.72 | 1.19 | 5.53 | 1.13E-01 | 1.98 | 95.24 | 1.65 | 11.62 | 1.57E-01 | 0.30 | 99.38 |
| 2.94 | 3.20 | 1.35 | 6.88 | 7.87E-02 | 1.38 | 96.63 | 1.83 | 13.45 | 1.07E-01 | 0.21 | 99.59 |
| 3.46 | 3.77 | 1.52 | 8.41 | 5.44E-02 | 0.95 | 97.58 | 2.00 | 15.46 | 7.15E-02 | 0.14 | 99.72 |
| 4.08 | 4.44 | 1.73 | 10.13 | 3.78E-02 | 0.66 | 98.24 | 2.17 | 17.62 | 4.74E-02 | 0.09 | 99.81 |
| 4.80 | 5.22 | 2.00 | 12.14 | 2.69E-02 | 0.47 | 98.72 | 2.33 | 19.95 | 3.12E-02 | 0.06 | 99.88 |
| 5.65 | 6.15 | 2.39 | 14.53 | 1.96E-02 | 0.34 | 99.06 | 2.51 | 22.46 | 2.06E-02 | 0.04 | 99.92 |
| 6.65 | 7.23 | 2.93 | 17.45 | 1.48E-02 | 0.26 | 99.32 | 2.73 | 25.19 | 1.38E-02 | 0.03 | 99.94 |
| 7.82 | 8.52 | 3.62 | 21.08 | 1.12E-02 | 0.20 | 99.52 | 3.02 | 28.20 | 9.33E-03 | 0.02 | 99.96 |
| 9.21 | 10.02 | 4.47 | 25.54 | 8.47E-03 | 0.15 | 99.66 | 3.40 | 31.60 | 6.45E-03 | 0.01 | 99.97 |
| 10.84 | 11.80 | 5.39 | 30.94 | 6.27E-03 | 0.11 | 99.77 | 3.91 | 35.51 | 4.54E-03 | 0.01 | 99.98 |
| 12.76 | 13.89 | 6.32 | 37.26 | 4.50E-03 | 0.08 | 99.85 | 4.53 | 40.05 | 3.23E-03 | 0.01 | 99.99 |
| 15.02 | 16.35 | 7.14 | 44.40 | 3.12E-03 | 0.05 | 99.91 | 5.27 | 45.32 | 2.30E-03 | 0.00 | 99.99 |
| 17.68 | 19.24 | 7.77 | 52.17 | 2.08E-03 | 0.04 | 99.95 | 6.05 | 51.36 | 1.62E-03 | 0.00 | 99.99 |
| 20.81 | 22.65 | 8.10 | 60.27 | 1.33E-03 | 0.02 | 99.97 | 6.77 | 58.13 | 1.11E-03 | 0.00 | 100.00 |
| 24.49 | 26.66 | 8.08 | 68.35 | 8.14E-04 | 0.01 | 99.98 | 7.27 | 65.40 | 7.32E-04 | 0.00 | 100.00 |
| 28.83 | 31.39 | 7.69 | 76.04 | 4.75E-04 | 0.01 | 99.99 | 7.42 | 72.82 | 4.58E-04 | 0.00 | 100.00 |
| 33.94 | 36.94 | 6.94 | 82.97 | 2.63E-04 | 0.00 | 100.00 | 7.13 | 79.95 | 2.70E-04 | 0.00 | 100.00 |
| 39.95 | 43.49 | 5.88 | 88.86 | 1.37E-04 | 0.00 | 100.00 | 6.38 | 86.33 | 1.48E-04 | 0.00 | 100.00 |
| 47.02 | 51.19 | 4.65 | 93.50 | 6.62E-05 | 0.00 | 100.00 | 5.27 | 91.60 | 7.50E-05 | 0.00 | 100.00 |
| 55.35 | 60.25 | 3.35 | 96.86 | 2.93E-05 | 0.00 | 100.00 | 3.95 | 95.55 | 3.45E-05 | 0.00 | 100.00 |
| 65.16 | 70.93 | 2.12 | 98.98 | 1.14E-05 | 0.00 | 100.00 | 2.61 | 98.17 | 1.40E-05 | 0.00 | 100.00 |
| 76.70 | 83.49 | 0.94 | 99.91 | 3.07E-06 | 0.00 | 100.00 | 1.31 | 99.48 | 4.30E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 0.09 | 100.00 | 1.75E-07 | 0.00 | 100.00 | 0.15 | 99.63 | 3.09E-07 | 0.00 | 100.00 |
| 106.27 | 115.68 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 125.09 | 136.16 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 147.24 | 160.28 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 173.31 | 188.66 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 204.01 | 222.07 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 240.14 | 261.40 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 282.67 | 307.70 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 332.73 | 362.19 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 391.65 | 426.33 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 461.01 | 501.83 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 542.66 | 590.71 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.63 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 5.6968037 | | | | | 51.85647 | | |



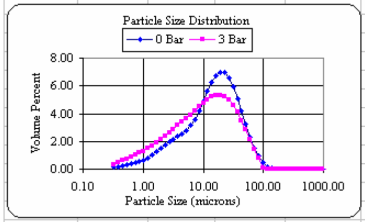


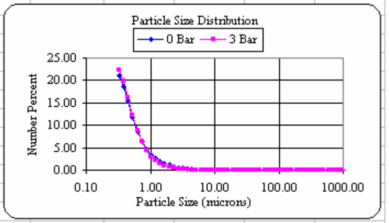


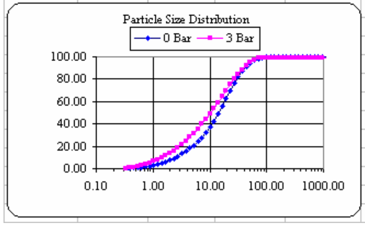


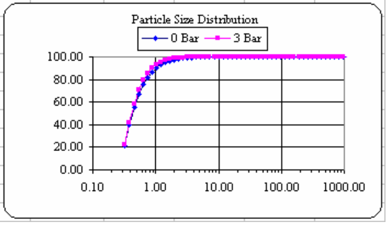
# Figure E.12: J&J Particle Size Distribution - Wollastonite

| **Wollastonite** | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0 Bar** | 2.7 | 15.5 | 45.0 | 0.3 | 0.5 | 1.1 | | |
| | | | **3 Bar** | 1.6 | 11.2 | 42.6 | 0.3 | 0.5 | 0.9 | | |
| | | | | **0 Bar** | | | | | **3Bar** | | |
| **Sizes** microns | Average microns | Volume Percent | Summary | Particles | Number Percent | summary | Volume Percent | Summary | Particles | Number Percent | summary |
| 0.30 | 0.33 | 0.13 | 0.13 | 7.00E+00 | 21.04 | 21.04 | 0.31 | 0.31 | 1.71E+01 | 22.31 | 22.31 |
| 0.35 | 0.38 | 0.19 | 0.31 | 6.23E+00 | 18.71 | 39.75 | 0.45 | 0.77 | 1.53E+01 | 19.85 | 42.16 |
| 0.42 | 0.45 | 0.25 | 0.56 | 5.11E+00 | 15.36 | 55.11 | 0.61 | 1.37 | 1.25E+01 | 16.24 | 58.41 |
| 0.49 | 0.53 | 0.31 | 0.87 | 3.90E+00 | 11.70 | 66.81 | 0.75 | 2.12 | 9.46E+00 | 12.30 | 70.71 |
| 0.58 | 0.63 | 0.37 | 1.24 | 2.88E+00 | 8.66 | 75.47 | 0.88 | 3.00 | 6.85E+00 | 8.92 | 79.63 |
| 0.68 | 0.74 | 0.45 | 1.69 | 2.12E+00 | 6.36 | 81.83 | 1.02 | 4.02 | 4.83E+00 | 6.29 | 85.92 |
| 0.80 | 0.87 | 0.54 | 2.23 | 1.57E+00 | 4.72 | 86.55 | 1.15 | 5.18 | 3.36E+00 | 4.37 | 90.29 |
| 0.94 | 1.02 | 0.66 | 2.89 | 1.18E+00 | 3.55 | 90.09 | 1.30 | 6.48 | 2.33E+00 | 3.03 | 93.32 |
| 1.11 | 1.20 | 0.82 | 3.70 | 8.96E-01 | 2.69 | 92.78 | 1.47 | 7.95 | 1.61E+00 | 2.09 | 95.41 |
| 1.30 | 1.42 | 1.01 | 4.72 | 6.79E-01 | 2.04 | 94.82 | 1.66 | 9.60 | 1.11E+00 | 1.45 | 96.86 |
| 1.53 | 1.67 | 1.23 | 5.95 | 5.08E-01 | 1.53 | 96.35 | 1.87 | 11.48 | 7.71E-01 | 1.00 | 97.86 |
| 1.80 | 1.96 | 1.48 | 7.43 | 3.73E-01 | 1.12 | 97.47 | 2.11 | 13.59 | 5.33E-01 | 0.69 | 98.56 |
| 2.12 | 2.31 | 1.72 | 9.15 | 2.67E-01 | 0.80 | 98.27 | 2.36 | 15.95 | 3.66E-01 | 0.48 | 99.03 |
| 2.50 | 2.72 | 1.96 | 11.11 | 1.86E-01 | 0.56 | 98.83 | 2.62 | 18.57 | 2.49E-01 | 0.32 | 99.36 |
| 2.94 | 3.20 | 2.17 | 13.28 | 1.26E-01 | 0.38 | 99.21 | 2.88 | 21.46 | 1.68E-01 | 0.22 | 99.57 |
| 3.46 | 3.77 | 2.36 | 15.64 | 8.44E-02 | 0.25 | 99.46 | 3.14 | 24.60 | 1.12E-01 | 0.15 | 99.72 |
| 4.08 | 4.44 | 2.56 | 18.21 | 5.60E-02 | 0.17 | 99.63 | 3.39 | 27.99 | 7.43E-02 | 0.10 | 99.82 |
| 4.80 | 5.22 | 2.80 | 21.01 | 3.76E-02 | 0.11 | 99.75 | 3.65 | 31.64 | 4.90E-02 | 0.06 | 99.88 |
| 5.65 | 6.15 | 3.14 | 24.14 | 2.58E-02 | 0.08 | 99.82 | 3.92 | 35.56 | 3.22E-02 | 0.04 | 99.92 |
| 6.65 | 7.23 | 3.60 | 27.74 | 1.82E-02 | 0.05 | 99.88 | 4.20 | 39.76 | 2.12E-02 | 0.03 | 99.95 |
| 7.82 | 8.52 | 4.20 | 31.94 | 1.30E-02 | 0.04 | 99.92 | 4.49 | 44.26 | 1.39E-02 | 0.02 | 99.97 |
| 9.21 | 10.02 | 4.90 | 36.84 | 9.29E-03 | 0.03 | 99.94 | 4.78 | 49.04 | 9.06E-03 | 0.01 | 99.98 |
| 10.84 | 11.80 | 5.63 | 42.47 | 6.54E-03 | 0.02 | 99.96 | 5.03 | 54.06 | 5.85E-03 | 0.01 | 99.99 |
| 12.76 | 13.89 | 6.28 | 48.75 | 4.48E-03 | 0.01 | 99.98 | 5.21 | 59.27 | 3.71E-03 | 0.00 | 99.99 |
| 15.02 | 16.35 | 6.77 | 55.52 | 2.96E-03 | 0.01 | 99.99 | 5.30 | 64.58 | 2.32E-03 | 0.00 | 100.00 |
| 17.68 | 19.24 | 7.00 | 62.52 | 1.88E-03 | 0.01 | 99.99 | 5.30 | 69.88 | 1.42E-03 | 0.00 | 100.00 |
| 20.81 | 22.65 | 6.93 | 69.45 | 1.14E-03 | 0.00 | 100.00 | 5.19 | 75.07 | 8.53E-04 | 0.00 | 100.00 |
| 24.49 | 26.66 | 6.57 | 76.01 | 6.62E-04 | 0.00 | 100.00 | 4.95 | 80.02 | 4.99E-04 | 0.00 | 100.00 |
| 28.83 | 31.39 | 5.93 | 81.94 | 3.66E-04 | 0.00 | 100.00 | 4.59 | 84.61 | 2.83E-04 | 0.00 | 100.00 |
| 33.94 | 36.94 | 5.10 | 87.05 | 1.93E-04 | 0.00 | 100.00 | 4.10 | 88.70 | 1.55E-04 | 0.00 | 100.00 |
| 39.95 | 43.49 | 4.16 | 91.21 | 9.66E-05 | 0.00 | 100.00 | 3.50 | 92.20 | 8.12E-05 | 0.00 | 100.00 |
| 47.02 | 51.19 | 3.21 | 94.42 | 4.57E-05 | 0.00 | 100.00 | 2.83 | 95.03 | 4.03E-05 | 0.00 | 100.00 |
| 55.35 | 60.25 | 2.31 | 96.73 | 2.02E-05 | 0.00 | 100.00 | 2.14 | 97.17 | 1.87E-05 | 0.00 | 100.00 |
| 65.16 | 70.93 | 1.54 | 98.27 | 8.26E-06 | 0.00 | 100.00 | 1.44 | 98.61 | 7.72E-06 | 0.00 | 100.00 |
| 76.70 | 83.49 | 0.94 | 99.22 | 3.09E-06 | 0.00 | 100.00 | 0.77 | 99.38 | 2.53E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 0.50 | 99.72 | 1.01E-06 | 0.00 | 100.00 | 0.10 | 99.48 | 2.05E-07 | 0.00 | 100.00 |
| 106.27 | 115.68 | 0.17 | 99.89 | 2.06E-07 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 125.09 | 136.16 | 0.07 | 99.96 | 5.59E-08 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 147.24 | 160.28 | 0.01 | 99.97 | 3.38E-09 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 173.31 | 188.66 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 204.01 | 222.07 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 240.14 | 261.40 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 282.67 | 307.70 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 332.73 | 362.19 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 391.65 | 426.33 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 461.01 | 501.83 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 542.66 | 590.71 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 99.97 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.48 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 33.297656 | | | | | 76.85531 | | |







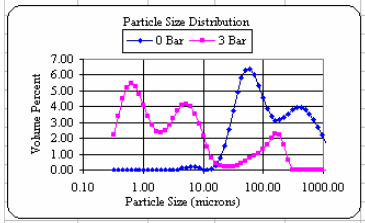


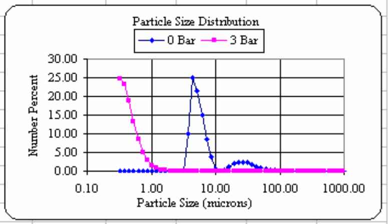
# Figure E.13: J&J Particle Size Distribution – Zinc Oxide

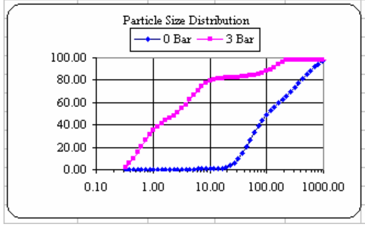
**Zinc Oxide**

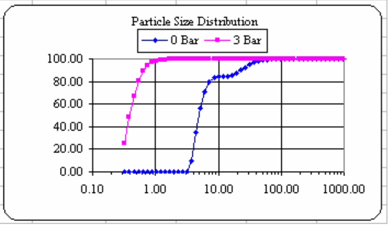
| | Volume | | | Number | | |
|---|---|---|---|---|---|---|
| | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 |
| 0 Bar | 34.2 | 110.7 | 688.9 | 4.1 | 5.4 | 24.4 |
| 3 Bar | 0.5 | 2.7 | 129.2 | 0.3 | 0.4 | 0.7 |

| | | | | 0 Bar | | | | | 3Bar | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sizes** | Average | Volume | | | Number | | Volume | | | Number | |
| microns | microns | Percent | Summary | Particles | Percent | summary | Percent | Summary | Particles | Percent | summary |
| 0.30 | 0.33 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 2.24 | 2.24 | 1.23E+02 | 24.85 | 24.85 |
| 0.35 | 0.38 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 3.43 | 5.66 | 1.15E+02 | 23.34 | 48.19 |
| 0.42 | 0.45 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 4.50 | 10.17 | 9.29E+01 | 18.82 | 67.00 |
| 0.49 | 0.53 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 5.20 | 15.37 | 6.58E+01 | 13.33 | 80.33 |
| 0.58 | 0.63 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 5.46 | 20.83 | 4.23E+01 | 8.58 | 88.90 |
| 0.68 | 0.74 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 5.29 | 26.12 | 2.51E+01 | 5.09 | 93.99 |
| 0.80 | 0.87 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 4.78 | 30.90 | 1.39E+01 | 2.82 | 96.82 |
| 0.94 | 1.02 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 4.09 | 34.99 | 7.31E+00 | 1.48 | 98.30 |
| 1.11 | 1.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 3.39 | 38.38 | 3.72E+00 | 0.75 | 99.05 |
| 1.30 | 1.42 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 2.82 | 41.20 | 1.89E+00 | 0.38 | 99.43 |
| 1.53 | 1.67 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 2.46 | 43.66 | 1.01E+00 | 0.21 | 99.64 |
| 1.80 | 1.96 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 2.35 | 46.01 | 5.93E-01 | 0.12 | 99.76 |
| 2.12 | 2.31 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 2.48 | 48.49 | 3.85E-01 | 0.08 | 99.84 |
| 2.50 | 2.72 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 2.82 | 51.32 | 2.68E-01 | 0.05 | 99.89 |
| 2.94 | 3.20 | 0.00 | 0.00 | 0.00E+00 | 0.00 | 0.00 | 3.27 | 54.59 | 1.90E-01 | 0.04 | 99.93 |
| 3.46 | 3.77 | 0.03 | 0.03 | 1.02E-03 | 9.88 | 9.88 | 3.73 | 58.32 | 1.33E-01 | 0.03 | 99.96 |
| 4.08 | 4.44 | 0.12 | 0.15 | 2.58E-03 | 24.96 | 34.84 | 4.06 | 62.38 | 8.88E-02 | 0.02 | 99.98 |
| 4.80 | 5.22 | 0.17 | 0.31 | 2.22E-03 | 21.44 | 56.27 | 4.17 | 66.55 | 5.59E-02 | 0.01 | 99.99 |
| 5.65 | 6.15 | 0.19 | 0.50 | 1.54E-03 | 14.92 | 71.20 | 4.00 | 70.55 | 3.29E-02 | 0.01 | 99.99 |
| 6.65 | 7.23 | 0.17 | 0.67 | 8.81E-04 | 8.52 | 79.71 | 3.57 | 74.11 | 1.80E-02 | 0.00 | 100.00 |
| 7.82 | 8.52 | 0.13 | 0.80 | 3.94E-04 | 3.81 | 83.52 | 2.93 | 77.04 | 9.05E-03 | 0.00 | 100.00 |
| 9.21 | 10.02 | 0.03 | 0.84 | 6.56E-05 | 0.63 | 84.16 | 2.18 | 79.21 | 4.13E-03 | 0.00 | 100.00 |
| 10.84 | 11.80 | 0.00 | 0.84 | 0.00E+00 | 0.00 | 84.16 | 1.43 | 80.64 | 1.66E-03 | 0.00 | 100.00 |
| 12.76 | 13.89 | 0.05 | 0.88 | 3.39E-05 | 0.33 | 84.48 | 0.79 | 81.43 | 5.63E-04 | 0.00 | 100.00 |
| 15.02 | 16.35 | 0.28 | 1.16 | 1.23E-04 | 1.19 | 85.67 | 0.42 | 81.85 | 1.84E-04 | 0.00 | 100.00 |
| 17.68 | 19.24 | 0.76 | 1.92 | 2.03E-04 | 1.96 | 87.63 | 0.27 | 82.13 | 7.36E-05 | 0.00 | 100.00 |
| 20.81 | 22.65 | 1.53 | 3.46 | 2.52E-04 | 2.44 | 90.07 | 0.20 | 82.33 | 3.32E-05 | 0.00 | 100.00 |
| 24.49 | 26.66 | 2.56 | 6.02 | 2.58E-04 | 2.50 | 92.57 | 0.19 | 82.52 | 1.91E-05 | 0.00 | 100.00 |
| 28.83 | 31.39 | 3.75 | 9.77 | 2.32E-04 | 2.24 | 94.81 | 0.23 | 82.75 | 1.39E-05 | 0.00 | 100.00 |
| 33.94 | 36.94 | 4.90 | 14.67 | 1.86E-04 | 1.79 | 96.60 | 0.29 | 83.04 | 1.11E-05 | 0.00 | 100.00 |
| 39.95 | 43.49 | 5.82 | 20.49 | 1.35E-04 | 1.31 | 97.91 | 0.40 | 83.44 | 9.33E-06 | 0.00 | 100.00 |
| 47.02 | 51.19 | 6.34 | 26.83 | 9.03E-05 | 0.87 | 98.78 | 0.56 | 84.00 | 7.96E-06 | 0.00 | 100.00 |
| 55.35 | 60.25 | 6.39 | 33.21 | 5.58E-05 | 0.54 | 99.32 | 0.73 | 84.73 | 6.39E-06 | 0.00 | 100.00 |
| 65.16 | 70.93 | 6.00 | 39.21 | 3.21E-05 | 0.31 | 99.63 | 0.90 | 85.63 | 4.80E-06 | 0.00 | 100.00 |
| 76.70 | 83.49 | 5.32 | 44.54 | 1.75E-05 | 0.17 | 99.80 | 1.07 | 86.70 | 3.52E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 4.55 | 49.08 | 9.15E-06 | 0.09 | 99.89 | 1.30 | 88.00 | 2.62E-06 | 0.00 | 100.00 |
| 106.27 | 115.68 | 3.86 | 52.94 | 4.76E-06 | 0.05 | 99.94 | 1.62 | 89.63 | 2.00E-06 | 0.00 | 100.00 |
| 125.09 | 136.16 | 3.38 | 56.32 | 2.55E-06 | 0.02 | 99.96 | 2.00 | 91.62 | 1.51E-06 | 0.00 | 100.00 |
| 147.24 | 160.28 | 3.15 | 59.47 | 1.46E-06 | 0.01 | 99.98 | 2.27 | 93.89 | 1.05E-06 | 0.00 | 100.00 |
| 173.31 | 188.66 | 3.16 | 62.63 | 8.98E-07 | 0.01 | 99.98 | 2.21 | 96.10 | 6.28E-07 | 0.00 | 100.00 |
| 204.01 | 222.07 | 3.32 | 65.95 | 5.80E-07 | 0.01 | 99.99 | 1.60 | 97.70 | 2.80E-07 | 0.00 | 100.00 |
| 240.14 | 261.40 | 3.57 | 69.52 | 3.81E-07 | 0.00 | 99.99 | 0.60 | 98.30 | 6.38E-08 | 0.00 | 100.00 |
| 282.67 | 307.70 | 3.79 | 73.31 | 2.48E-07 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 332.73 | 362.19 | 3.93 | 77.24 | 1.58E-07 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 391.65 | 426.33 | 3.95 | 81.19 | 9.74E-08 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 461.01 | 501.83 | 3.83 | 85.02 | 5.78E-08 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 542.66 | 590.71 | 3.57 | 88.59 | 3.31E-08 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 638.76 | 695.32 | 3.19 | 91.78 | 1.81E-08 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 2.72 | 94.49 | 9.46E-09 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 2.19 | 96.68 | 4.68E-09 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 1.63 | 98.31 | 2.13E-09 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 1.07 | 99.38 | 8.56E-10 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.47 | 99.85 | 2.33E-10 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.15 | 100.00 | 4.43E-11 | 0.00 | 100.00 | 0.00 | 98.30 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 0.010339 | | | | | 493.5564 | | |



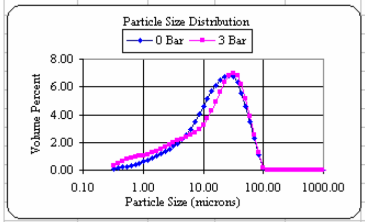


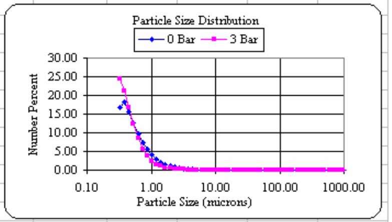


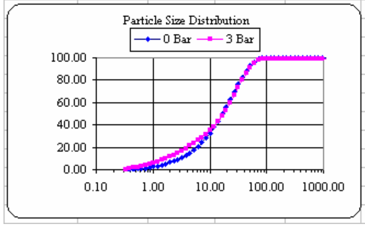


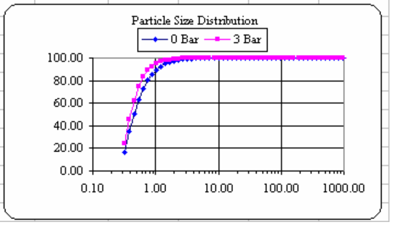
# Figure E.14: J&J Particle Size Distribution – Zircon Flour

| **Zircon Flour** | | | | | Volume | | | Number | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0.1 | 0.5 | 0.9 | 0.1 | 0.5 | 0.9 | | |
| | | | **0 Bar** | 3.17 | 17.8 | 50.0 | 0.3 | 0.5 | 1.1 | | |
| | | | **3 Bar** | 1.84 | 18.90 | 52.7 | 0.3 | 0.4 | 0.8 | | |
| | | | | **0 Bar** | | | | | **3Bar** | | |
| **Sizes** microns | Average microns | Volume Percent | Summary | Particles | Number Percent | summary | Volume Percent | Summary | Particles | Number Percent | summary |
| 0.30 | 0.33 | 0.08 | 0.08 | 4.56E+00 | 16.78 | 16.78 | 0.35 | 0.35 | 1.90E+01 | 24.33 | 24.33 |
| 0.35 | 0.38 | 0.15 | 0.23 | 4.97E+00 | 18.30 | 35.08 | 0.49 | 0.84 | 1.66E+01 | 21.26 | 45.59 |
| 0.42 | 0.45 | 0.21 | 0.44 | 4.26E+00 | 15.68 | 50.76 | 0.64 | 1.48 | 1.32E+01 | 16.89 | 62.47 |
| 0.49 | 0.53 | 0.27 | 0.71 | 3.40E+00 | 12.52 | 63.28 | 0.76 | 2.24 | 9.61E+00 | 12.31 | 74.78 |
| 0.58 | 0.63 | 0.34 | 1.05 | 2.63E+00 | 9.66 | 72.94 | 0.86 | 3.10 | 6.64E+00 | 8.51 | 83.29 |
| 0.68 | 0.74 | 0.42 | 1.46 | 1.98E+00 | 7.30 | 80.24 | 0.93 | 4.03 | 4.43E+00 | 5.68 | 88.97 |
| 0.80 | 0.87 | 0.51 | 1.97 | 1.48E+00 | 5.45 | 85.69 | 1.00 | 5.03 | 2.91E+00 | 3.73 | 92.69 |
| 0.94 | 1.02 | 0.61 | 2.59 | 1.10E+00 | 4.04 | 89.73 | 1.06 | 6.09 | 1.90E+00 | 2.44 | 95.13 |
| 1.11 | 1.20 | 0.73 | 3.32 | 8.05E-01 | 2.96 | 92.69 | 1.14 | 7.24 | 1.25E+00 | 1.60 | 96.73 |
| 1.30 | 1.42 | 0.87 | 4.19 | 5.85E-01 | 2.15 | 94.84 | 1.24 | 8.48 | 8.35E-01 | 1.07 | 97.80 |
| 1.53 | 1.67 | 1.02 | 5.21 | 4.20E-01 | 1.54 | 96.39 | 1.37 | 9.85 | 5.63E-01 | 0.72 | 98.53 |
| 1.80 | 1.96 | 1.18 | 6.39 | 2.98E-01 | 1.09 | 97.48 | 1.51 | 11.36 | 3.82E-01 | 0.49 | 99.02 |
| 2.12 | 2.31 | 1.34 | 7.73 | 2.08E-01 | 0.77 | 98.25 | 1.67 | 13.03 | 2.59E-01 | 0.33 | 99.35 |
| 2.50 | 2.72 | 1.52 | 9.26 | 1.45E-01 | 0.53 | 98.78 | 1.84 | 14.87 | 1.74E-01 | 0.22 | 99.57 |
| 2.94 | 3.20 | 1.71 | 10.97 | 9.98E-02 | 0.37 | 99.15 | 1.99 | 16.85 | 1.16E-01 | 0.15 | 99.72 |
| 3.46 | 3.77 | 1.94 | 12.91 | 6.92E-02 | 0.25 | 99.40 | 2.13 | 18.98 | 7.59E-02 | 0.10 | 99.82 |
| 4.08 | 4.44 | 2.21 | 15.12 | 4.84E-02 | 0.18 | 99.58 | 2.25 | 21.23 | 4.93E-02 | 0.06 | 99.88 |
| 4.80 | 5.22 | 2.55 | 17.67 | 3.42E-02 | 0.13 | 99.70 | 2.37 | 23.60 | 3.18E-02 | 0.04 | 99.92 |
| 5.65 | 6.15 | 2.97 | 20.64 | 2.44E-02 | 0.09 | 99.79 | 2.51 | 26.11 | 2.06E-02 | 0.03 | 99.95 |
| 6.65 | 7.23 | 3.47 | 24.11 | 1.75E-02 | 0.06 | 99.86 | 2.68 | 28.79 | 1.35E-02 | 0.02 | 99.96 |
| 7.82 | 8.52 | 4.03 | 28.14 | 1.25E-02 | 0.05 | 99.90 | 2.92 | 31.72 | 9.04E-03 | 0.01 | 99.97 |
| 9.21 | 10.02 | 4.61 | 32.75 | 8.74E-03 | 0.03 | 99.94 | 3.26 | 34.97 | 6.17E-03 | 0.01 | 99.98 |
| 10.84 | 11.80 | 5.17 | 37.92 | 6.01E-03 | 0.02 | 99.96 | 3.69 | 38.67 | 4.30E-03 | 0.01 | 99.99 |
| 12.76 | 13.89 | 5.68 | 43.60 | 4.05E-03 | 0.01 | 99.97 | 4.25 | 42.91 | 3.03E-03 | 0.00 | 99.99 |
| 15.02 | 16.35 | 6.12 | 49.72 | 2.68E-03 | 0.01 | 99.98 | 4.90 | 47.82 | 2.14E-03 | 0.00 | 99.99 |
| 17.68 | 19.24 | 6.48 | 56.20 | 1.74E-03 | 0.01 | 99.99 | 5.61 | 53.43 | 1.50E-03 | 0.00 | 100.00 |
| 20.81 | 22.65 | 6.74 | 62.94 | 1.11E-03 | 0.00 | 99.99 | 6.30 | 59.73 | 1.03E-03 | 0.00 | 100.00 |
| 24.49 | 26.66 | 6.84 | 69.78 | 6.89E-04 | 0.00 | 100.00 | 6.81 | 66.54 | 6.86E-04 | 0.00 | 100.00 |
| 28.83 | 31.39 | 6.71 | 76.49 | 4.15E-04 | 0.00 | 100.00 | 7.01 | 73.55 | 4.33E-04 | 0.00 | 100.00 |
| 33.94 | 36.94 | 6.30 | 82.79 | 2.39E-04 | 0.00 | 100.00 | 6.80 | 80.34 | 2.57E-04 | 0.00 | 100.00 |
| 39.95 | 43.49 | 5.58 | 88.38 | 1.30E-04 | 0.00 | 100.00 | 6.14 | 86.49 | 1.43E-04 | 0.00 | 100.00 |
| 47.02 | 51.19 | 4.61 | 92.98 | 6.56E-05 | 0.00 | 100.00 | 5.12 | 91.61 | 7.29E-05 | 0.00 | 100.00 |
| 55.35 | 60.25 | 3.47 | 96.45 | 3.03E-05 | 0.00 | 100.00 | 3.87 | 95.48 | 3.38E-05 | 0.00 | 100.00 |
| 65.16 | 70.93 | 2.30 | 98.75 | 1.23E-05 | 0.00 | 100.00 | 2.56 | 98.03 | 1.37E-05 | 0.00 | 100.00 |
| 76.70 | 83.49 | 1.13 | 99.87 | 3.70E-06 | 0.00 | 100.00 | 1.25 | 99.28 | 4.10E-06 | 0.00 | 100.00 |
| 90.28 | 98.27 | 0.13 | 100.00 | 2.55E-07 | 0.00 | 100.00 | 0.14 | 99.42 | 2.79E-07 | 0.00 | 100.00 |
| 106.27 | 115.68 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 125.09 | 136.16 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 147.24 | 160.28 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 173.31 | 188.66 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 204.01 | 222.07 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 240.14 | 261.40 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 282.67 | 307.70 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 332.73 | 362.19 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 391.65 | 426.33 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 461.01 | 501.83 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 542.66 | 590.71 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 638.76 | 695.32 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 751.88 | 818.46 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 885.04 | 963.41 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 1041.78 | 1134.03 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 1226.28 | 1334.87 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 1443.46 | 1571.27 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 1699.09 | 1849.55 | 0.00 | 100.00 | 0.00E+00 | 0.00 | 100.00 | 0.00 | 99.42 | 0.00E+00 | 0.00 | 100.00 |
| 2000 | | | | 27.178892 | | | | | 78.05978 | | |









# APPENDIX F. J&J SILO DESIGN RECOMMENDATIONS FOR HANDLING GLASS FORMING CHEMICALS

JENIKE & JOHANSON
INCORPORATED

July 25, 2002

Ray Schumacher
Senior Fellow Ceramist
Westinghouse Savannah River Company
SRTC-773-43A
Aiken, SC 29808

Dear Ray,

Attached is our recommendations report for the glass forming chemicals silos. After you have reviewed the report, please contact me so we can discuss any questions you may have.

I look forward to continuing to work with you and your colleagues on this project.

Sincerely,

Eric P. Maynard

Eric P. Maynard

Project Engineer

Attachments

cc: John W. Carson, Ph.D., President

cc: Thomas Miniard, WSRC Procurement Specialist

One Technology Park Drive • Westford, MA 01886-3189 • Tel: (978) 392-0300 • FAX: (978) 392-9980
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JENIKE & JOHANSON
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Bulk Solids: Science/Engineering/Design

# Silo Design Recommendations for Handling Glass Forming Chemicals

Westinghouse Savannah River Company
4537-2

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JENIKE&
JOHANSON

July 25, 2002

# Silo Design Recommendations for Handling Glass Forming Chemicals

Westinghouse Savannah River Company

4537-2

## 1 BACKGROUND

Westinghouse Savannah River Company (WSRC) continues to develop the design of a nuclear waste treatment facility to be implemented at the Department of Energy (DOE) Hanford, Washington site. A liquid vitrification system will be utilized at this facility to treat both high and low activity waste (LAW, HLW) streams, and materials utilized in this process will consist partly of glass forming chemicals. The glass forming chemicals (GFCs) to be used in the processes are “bulk solids” and as such, can be susceptible to flow difficulties. Poor handling characteristics of bulk solids can negatively impact processing efficiency and possibly create dangerous operating conditions.

To this end, WSRC has requested that Jenike & Johanson, Inc. (J&J) provide bulk solids consulting services to ensure reliable handling of the glass forming chemicals in the proposed process. An integral portion of this project involved flow properties characterization of each of the GFCs and custom GFC blends, and the results from these studies have been reported in J&J report 4537-1, dated June 26, 2002.

The GFC flow properties information was utilized in the development of storage silo designs, which will ensure reliable flow of the bulk solids. To this end, this report herein contains the GFC silo designs. Additionally, an analysis of the GFC blend transfer chute has been included.

## 2 SUMMARY OF FLOW PROPERTIES

Samples of GFCs and custom GFC blends (ref. Tables 1 and 2) were tested by J&J at their Westford, Massachusetts facility during May and June of 2002. Complete flow properties test results can be found in the aforementioned J&J report. In general, the materials were found to be:

- Highly cohesive, and thus prone to flow obstructions such as bridging and ratholing
- Highly frictional, and thus prone to discharge in a funnel flow pattern
- Compressible, and thus prone to have erratic variations in bulk density
- Highly impermeable, and thus prone to discharge rate limitations; also, once aerated, may remain fluidized for extended times

Note that not <u>all</u> of the glass forming chemicals exhibited these behaviors; however, each material has at least two of the four qualities listed above. Results from these tests have been utilized in developing the storage silo designs, which are presented in the next section.

**Table 1: Glass forming chemicals (GFCs)**

| GFCs | Moisture content |
|---|---|
| Borax (ten mole) | 8.0% |
| Boric acid | 0.1% |
| Iron oxide | 0.3% |
| Kyanite | 0.1% |
| Lithium carbonate | 0.1% |
| Olivine | 0.2% |
| Silica | 0.1% |
| Soda ash | 0.2% |
| Sugar | 0.1% |
| Titanium dioxide | 0.2% |
| Wollastonite | 0.2% |
| Zinc oxide | 0.2% |
| Zircon flour | 0.1% |

**Table 2: Glass forming chemical blend compositions**

| | LAW A | LAW B | LAW C | HLW D | HLW D |
|---|---|---|---|---|---|
| | AN105 | AZ101 | AN107 | AZ102 | C106/AY10 |
| GFCs | Weight % | Weight % | Weight % | Weight % | Weight % |
| Borax (ten mole) | -- | -- | -- | 12.61% | 9.76% |
| Boric acid | 18.35% | 19.93% | 18.65% | -- | 13.71% |
| Iron oxide | 7.69% | 4.30% | 5.34% | -- | -- |
| Kyanite | 4.26% | 8.42% | 10.09% | -- | -- |
| Lithium carbonate | -- | 10.38% | 6.47% | 14.72% | 16.03% |
| Olivine | 4.75% | 5.60% | 3.27% | -- | -- |
| Silica | 42.65% | 29.49% | 35.30% | 56.92% | 57.24% |
| Soda ash | -- | -- | -- | 15.75% | -- |
| Sugar | 6.57% | 2.12% | 0.63% | -- | -- |
| Titanium dioxide | 2.42% | -- | 1.26% | -- | -- |
| Wollastonite | 4.77% | 12.60% | 11.07% | -- | -- |
| Zinc oxide | 3.37% | 2.84% | 3.16% | -- | 3.27% |
| Zircon flour | 5.18% | 4.33% | 4.75% | -- | -- |

## 3 SILO FLOW PATTERNS AND FLOW PROBLEMS

Before presentation of the storage silo recommendations, one must first understand how bulk solids flow through silos. There are two primary flow patterns that can develop in a bin: *funnel flow* and *mass flow*. Both patterns are shown below in Fig. 1.

In *funnel flow*, an active flow channel forms above the outlet, with non-flowing material at the periphery. As the level of material in the bin decreases, layers of the non-flowing material may or may not slide into the flowing channel, which can result in the formation of stable ratholes. In addition, funnel flow can cause product caking, provide a first-in-last-out flow sequence, and increase the extent to which sifting segregation impacts the discharging material.

*Ratholing* occurs when a stable, empty channel (typically vertical) forms within material in a funnel flow bin. Ratholing can occur with *cohesive* materials handled in funnel flow bins; however, ratholing will not occur with *free-flowing* materials discharging in funnel flow.

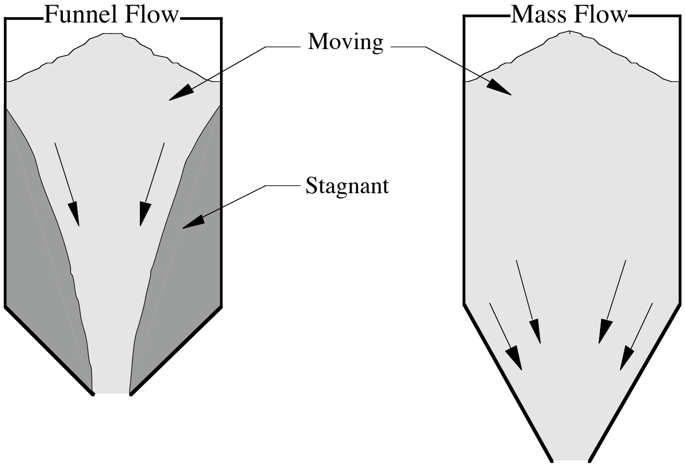

**Fig. 1: Two flow patterns that can occur in a bin; funnel flow and mass flow**

In *mass flow*, all of the material is in motion whenever any is withdrawn from the hopper. Material from the center as well as the periphery moves toward the outlet. Mass flow hoppers provide a first-in-first-out flow sequence, eliminate stagnant material, reduce sifting segregation, and provide a steady discharge with a consistent bulk density and a flow which is uniform and well-controlled. Requirements for achieving mass flow include sizing the outlet large enough to prevent arching and ensuring the hopper walls are sufficiently smooth and steep enough to promote flow at the walls.

A third type of flow pattern, called *expanded flow*, can develop when a mass flow hopper (or hoppers) is placed beneath a funnel flow hopper. As shown in Fig. 2, the mass flow hopper is designed to activate a flow channel in the conical funnel flow hopper, which is sized to prevent the formation of a stable rathole.

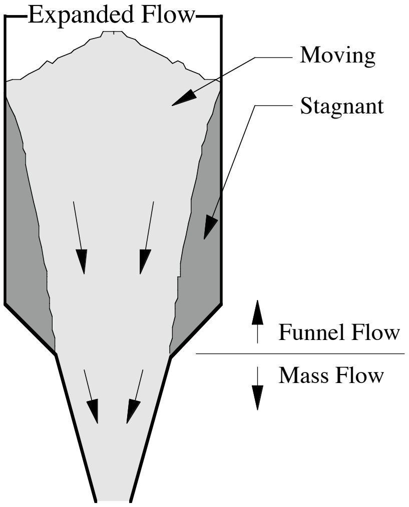

**Fig. 2: Example of expanded flow silo**

The major advantage of an expanded flow discharge pattern is the savings in headroom. The wall angles of the funnel flow hopper are more shallow than the angles necessary for a mass flow hopper; therefore, the height of the funnel flow hopper section is decreased. The mass flow hopper beneath the funnel flow hopper still has the benefits of discharging material with a consistent bulk density while preventing flooding[1]. An additional concern with expanded flow results from stagnant regions of material forming on the walls of the funnel flow hopper. If the material level is not brought down below the funnel flow hopper section, then severe caking of the stagnant material could result.

## 4 GFC STORAGE SILO RECOMMENDATIONS

Preliminary storage silo specifications were provided by WSRC/Bechtel and can be found in a February 3, 2002 electronic memorandum from Christine Tevis of Bechtel to Ray Schumacher and Erich Hansen of WSRC. This memorandum contains specification data such as:

- Silo cylinder diameter
- Silo hopper geometry and angle from vertical
- Silo hopper outlet shape and size
- Silo material of construction
- Silo overall height
- Silo working capacity (volume)
- Feeder type
- Maximum and minimum discharge rates from each silo

These data, along with the material flow properties, were utilized in developing the functional designs of the GFC storage silos.

### Analysis of proposed silos

The following commentary has been based upon the proposed silo configurations (developed by Bechtel and presented in the aforementioned memorandum) and the flow properties of the GFCs. The flowability of each GFC in its specified silo design is discussed below.

Borax

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow, but will after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest (assuming bridging is overcome).
- Will not likely exhibit flooding behavior.
- Will not likely exhibit flow rate limitations based on required flow rates.

---

[1] Flooding is still a possibility in mass flow if the discharge rates are too high to allow material sufficient time to deaerate.

Boric acid

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will not rathole during continuous flow, but will after seven days storage at rest.
- Will not likely exhibit flooding behavior.
- Will not likely exhibit flow rate limitations based on required flow rates.

Iron oxide

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates (deficient by a factor of six).

Kyanite

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates (deficient by a factor of fifty!).

Lithium carbonate

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates (deficient by a factor of ten).

Olivine

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.

- Will rathole during both continuous flow and after seven days storage at rest.
- Will not likely exhibit flooding behavior.
- Will not likely exhibit flow rate limitations based on required flow rates.

<u>Silica</u>

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates (deficient by a factor of one hundred eight five!).

<u>Soda ash</u>

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will not rathole during continuous flow, but will after seven days storage at rest.
- Will not likely exhibit flooding behavior.
- Will not likely exhibit flow rate limitations based on required flow rates.

<u>Sugar</u>

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest. <u>Severe caking is imminent</u>.
- Will not likely exhibit flooding behavior.
- Will not likely exhibit flow rate limitations based on required flow rates.

<u>Titanium dioxide</u>

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates (deficient by a factor of two).

Wollastonite

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow, but will after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates (deficient by a factor of seventy!).

Zinc oxide

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will bridge during continuous flow and after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will not likely exhibit flooding behavior if a rathole collapses (very cohesive).
- Will not likely exhibit flow rate limitations based on required flow rates.

Zircon flour

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow or after seven days storage at rest.
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates (deficient by a factor of eight).

## Silo Recommendations

Due to the extremely poor flowability of most of the GFCs listed above, the proposed silo designs will not ensure reliable flow. Consequently, if these designs are implemented, severe flow problems and processing bottlenecks will result.

Thus, based on the material flow properties, we recommend the GFC silo and feeder designs shown in Figs. 1A through 13D. Each silo is designed to reliably discharge its GFC based on a maximum of seven days storage at rest. Most of the designs presented for each GFC have the option of utilizing a mass flow or expanded flow discharge option (hence, ratholing will not occur). For GFCs which are sensitive to caking during storage at rest (e.g., sugar), an expanded flow discharge pattern should not be utilized. As a general practice with expanded flow silo configurations, we recommend frequently drawing down the silo level below the funnel flow hopper to help prevent any caking from occurring. The drawdown frequency and volume can be determined through additional flow properties characterization.

The capacity for each GFC silo was based on the working volume stated in the aforementioned memorandum. If additional capacity is required, the vertical cylinder section can be increased without compromising the functionality of the design. Note, however, that if the cylinder height is extended and utilized for additional storage capacity, the material induced loads will increase and need to be considered.

The majority of the GFC silos presented in Figs. 1A through 13D can be fabricated from mild carbon steel; however, because of the extreme frictional properties of some of the GFCs, some of the hoppers (converging portion of the silo, not the cylinder) require lining with 304 stainless steel sheet with a #2B finish (see attached drawings for complete details).

Accompanying each GFC silo design is a functional design for a screw feeder. Along with the physical specifications for each screw (e.g., pitch, diameter, trough details), horsepower, torque, and operating speed (based on flow rate) have also been provided.

Note that some of the screw feeders use multiple screws; to ensure reliable flow from the silos, all of the screws must operate simultaneously. Silos have structurally failed because of lack of operation of one of a set of multiple screws located beneath a mass flow hopper.

To minimize fabrication costs, some of the GFC hoppers and feeders share a common design. For example, the hopper and feeder for the olivine silo design is similar to that specified for soda ash. Additionally, the hopper and feeder for the iron oxide silo design is similar to that specified for zircon flour.

Furthermore, it may be possible to design a silo that is capable of reliably handling several GFCs. If requested by WSRC, this can be further investigated and a design can be developed.

Silica handling

The silica silo design shown in Fig. 7A requires a large mass flow transition hopper and screw feeder. As an alternative to this design, the silica could be handled in a fluidized mode. It may be possible to utilize a fluidizing discharger to overcome the ratholing and rate limited tendencies of the silica. This discharger could be incorporated into an expanded flow design, which would save headroom, and also eliminate the need for a large screw feeder.

In order to determine feasibility of the fluidized handling option, we recommend that we perform fluidization tests with the silica. A quote for this service can be provided upon request. Furthermore, some of the other fine, impermeable GFCs (e.g., kyanite, iron oxide) may be good candidates for handling in a fluidized mode. Ultimately, fluidization studies will be the most scientific and cost-effective approach for determining this alternative’s feasibility (vs. a trial-and-error approach).

## 5 GFC BLEND TRANSFER CHUTE ANALYSIS

A 4 in. diameter pipe is proposed to be utilized to transfer the LAW and HLW GFC blends to the LAW and HLW blend preparation vessels. The LAW system will discharge a blend into a 25 ft. tall vertical pipe, connected to a pipe sloped at 60 deg. (from horizontal), then re-orienting towards the vertical before mating to the blend preparation vessel. Though both systems reportedly have a similar design, the HLW system will have a 40 ft. vertical drop before the first pipe bend.

Based on the flow properties of the five custom GFC blends tested and the proposed chute geometry, two modes of flow could result; either fluidized or deaerated. [Without full-scale modeling of the proposed chute configuration, it is difficult to predict the exact behavior.]

1. Fluidized – the GFC blend will be aerated and behave like a fluid. If this occurs, the GFC blends should not plug the transfer chutes. However, *severe dusting in the blend preparation vessel is likely*. This is due to an estimated particle velocity of approximately 30 ft./sec. at the inlet of the vessel. Once the fast moving stream of material hits the liquid/slurry interface in the vessel, copious amounts of air will be released from the stream and will carry away the fine particles in the blend (i.e., the dust). The dust will then migrate towards the circumference of the vessel and also towards the demisting filter where a vacuum is being drawn. Gradually, it can be expected that this filter could become heavily clogged with the fine dust and affect processing efficiency. Furthermore, the dust cake buildup in the tank may be an operating concern (e.g., loss of GFC chemical activity in mixture or cause of equipment failure).
2. Deaerated – the GFC blend will act as a cohesive bulk solid and has the potential to pack and plug. If the GFC blend stream does not stall on the 60 deg. pipe bend, then plugging should not result. However, if buildup of the material occurs over time, then material will collect at this location and the pipe will not be sufficiently steep or low enough in friction to allow clean-off. Therefore, plugging will result.

## Chute Recommendation

Assuming the blends will be transferred through the chute in a fluidized mode, to minimize dusting, we recommend that a “kick-plate” be installed at the inlet to the vessel to direct the aerated stream into a paddle-induced vortex within the liquid. Modifying the chute to handle a fluidized material is not feasible, hence, techniques need to be employed to handle the fluidized material. Another alternative may be to incorporate a large dust collector to handle the high dust loading, yet be capable of “cleaning” its filters of dust cake and dropping the dust back into the vessel.

A far better alternative to handling the material in a fluidized mode, whereby significant dusting can result, is handling the blends in a properly designed chute. The *key factor in minimizing dusting is to avoid aerating the GFC blends*. This can be achieved with a correctly designed chute. If space allows, we recommend either a spiral chute or a chute shaped like a “ski-jump”. In both designs, the material will not be allowed to aerate and create dust upon impact, rather, the stream will be kept in contact with the pipe surface avoiding aeration. The advantage of a spiral chute is that the stream of material will quickly reach a limiting velocity and will flow in a controlled fashion into the blend preparation vessel. The amount of dust generated from using either of these chute concepts will be far less than if the blends are fluidized going into the vessel.

Currently we have not been provided with sufficient information to develop these chute designs. A request for additional information has already been made and when it is supplied, we can continue forward with this design effort. We strongly recommend that these transfer chutes be further analyzed and designed to prevent plugging and excessive dusting, else a significant bottleneck will develop.

Note that a pre-slurrying option, i.e., incorporating the GFC blends into a slurry before they are transferred through the long chute and added to the preparation vessel, may eliminate the dusting and plugging issues entirely. Reportedly, WSRC and Bechtel are further investigating this option.

## 6 GFC WEIGH HOPPERS – COMMENTS ON GFC FLOWABILITY

The following commentary on flowability has been based upon the proposed weigh hopper configurations (developed by Bechtel and presented in the aforementioned memorandum) and the flow properties of the GFCs.

<u>Weigh hoppers</u>

- Will experience funnel flow discharge because hopper is not steep or low enough in friction to allow mass flow.
- Will experience bridging and ratholing with most of the GFCs.
- Will likely experience flooding behavior if a rathole collapses.
- Will experience flow rate limitations based on required flow rates.

Based on this analysis, reliable flow from these hoppers is highly questionable. Additionally, weight variations may occur during blend preparation because of these flow difficulties. For instance, if flooding from the weigh hopper results, too much material may enter the transfer vessel below.

Consequently, we recommend that we develop functional designs for these hoppers to ensure consistent flow can be achieved and flow problems do not result.

## 7 GFC BLEND SILOS – COMMENTS ON GFC FLOWABILITY

The following commentary on flowability has been based upon the proposed blend silo configurations (developed by Bechtel and presented in the aforementioned memorandum) and the flow properties of the GFCs.

<u>LAW, HLW blend silos</u>

- Will discharge in funnel flow because hopper is not steep or low enough in friction to allow mass flow.
- Will not bridge during continuous flow, but will after storage at rest (either one or three days, depending upon the blend).
- Will rathole during both continuous flow and after seven days storage at rest.
- Will likely exhibit flooding behavior if a rathole collapses.
- Will exhibit flow rate limitations based on required flow rates.
- Segregation (de-mixing) of the blend can occur during discharge from the silo.

Based on this analysis, reliable flow from these silos is highly questionable, even with the fluidizing effect of a blending/aerating head located at the hopper outlet. If a rathole does develop, the blending head will likely be rendered ineffective because the air will go up into the rathole and not into the material.

Consequently, we recommend that we develop functional designs for the blend silos to ensure consistent flow can be achieved and flow problems do not result. Furthermore, modeling studies should be performed to determine the feasibility of using a blending/aerating head for mixing of the highly cohesive GFC blends.

## 8 COMMENTS ON FLOW AIDS

Mechanical flow aids, such as vibrators, air cannons, etc., can be helpful at times to get some materials flowing; however, they are usually ineffective with extremely cohesive, frictional materials like most of the GFCs and the GFC blends. Often times, when misapplied, vibrators tend to pack material in a hopper and create more frequent arching and ratholing problems. Air cannons may be effective in initiating flow of material after the material has remained at rest for a period of time; however, if the material is cohesive even during continuous flow, then air cannons are usually not a good solution because they must be fired repeatedly to maintain flow. Furthermore, even though air cannons may be effective in breaking arches which form after storage at rest, they are generally ineffective in breaking up ratholes that form in silos.

## 9 CONCLUSIONS

We conclude that the silo and feeder designs presented in this report are necessary to ensure consistent flow of the GFCs tested. Based on the flow characteristics of the GFCs and the silo designs proposed in the aforementioned memorandum, reliable flow will not occur. Flow problems, such as, bridging, ratholing, and flooding will likely plague the operation and negatively impact start-up commissioning and the operational time-line of the facility.

If our recommended silo and feeder designs are implemented, reliable flow of the cohesive, frictional, and impermeable GFCs can be realized. Furthermore, operating efficiency will be increased and costly bottlenecks due to poor solids handling will be prevented.

## 10 GENERAL COMMENTS

### Mass flow conditions

In a mass flow silo, the hopper section must be sufficiently steep and low enough in friction to cause all the material to flow, without stagnant regions, whenever any material is withdrawn. Saying that "all the material is flowing" does not imply or require that all the particles are flowing at the same *velocity*. This is particularly true of particles which are in the converging hopper section. Material flows more slowly at the walls than at the centerline of the hopper, due to friction with the walls. This effect becomes visibly apparent when the material level is just above or within the hopper. It also becomes more pronounced here because of the lack of head pressure.

In some cases, such a velocity differential may be beneficial (e.g., for in-bin blending). In other applications, a uniform velocity may be required to minimize particle segregation effects, enforce uniform residence time, or provide a well defined transition from one material to another. It is essential that the design engineer be aware of any such requirements, and that they be properly taken into account when designing a silo.

In addition to a proper design for a mass flow silo, the quality of construction is critical. Protrusions into the flow channel caused by horizontal welds, incorrectly lapped liner plates, or poorly constructed mating flanges will prevent mass flow. Similarly, poor quality surface finish caused by weld spatter, poor quality workmanship, or simply not using the liner material specified may prevent mass flow.

Conditions below the outlet are just as important as the hopper design. Gates must allow the bulk solid to flow uniformly, and feeders must withdraw the bulk solid from the entire outlet area.

It is imperative that the fabricator be made aware of both the design intent and the need for good quality workmanship. In addition, the engineer should carefully inspect the fabrication of the hopper and feeder.

Interior surface finish. Whenever possible, welding should be done on the outside of the hopper. If interior welding is necessary, all welds on sloping surfaces must be ground flush and power brushed to retain a smooth surface. After welding, all sloping surfaces must be clean and free of weld spatter.

The surface finish is most critical in the region of the hopper outlet; therefore, any blisters from exterior welding in this area must be brushed smooth. Horizontal or diagonal welded connections should preferably be lapped with the upper section on the inside so that the resulting ledge does not impede flow. If horizontal butt welds are used, care must be taken to avoid any protrusion into the flowing solid. Vertical welds coinciding with the direction of material flow should preferably be butted, then ground flush and power brushed as noted above.

Mating flanges. The lower of two mating flanges must be oversized to prevent any protrusions into the flowing solid. The amount of oversize depends on the accuracy of the construction and erection; usually one inch overall is sufficient.

All flanges should be attached to the outside of the hopper, with the hopper wall material being the surface in contact with the flowing solids. This ensures that the flange does not protrude into the flowing solids.

Feeder or gate below hopper. Either a feeder, a cutoff gate or both may be used below the hopper outlet. The key to feeder and gate design is to provide uniform withdrawal of the bulk solid from the entire area of the outlet.

If a gate is used below a mass flow hopper, the gate must be either fully open or fully closed. A partially opened gate creates a flow obstruction and will convert what would otherwise be a mass flow design into funnel flow.

It is equally important that the gate be selected carefully to ensure that the actual opening size is larger than the silo outlet opening. The port size of commonly used knife gate valves is often significantly smaller than the nominal valve size. As an example, the actual port openings for typical metal seated and elastomer seated 12 in. knife gates are, respectively, 11-3/8 in. and 10-5/8 in. Therefore, even if the outlet of a mass flow silo designed with a nominal outlet diameter of 12 inches were undersized by a full inch to 11 inches, it would still be too large for the elastomer seated valve. This example emphasizes the importance of checking the valve specifications and sizing the valve and outlet accordingly.

Modulation of flow rate must be accomplished with a feeder, not a gate.

When using a feeder under a slotted outlet, the capacity of the feeder must increase along its length in the discharge direction. This is generally accomplished using a specially designed screw or belt.

For specific feeder information, refer to the *Recommendations* section of this report.

### Poke holes and access doors

In general, poke holes are not recommended in mass flow silo designs, as they have a tendency to prevent flow along the walls, thus creating a problem that mass flow silos are intended to solve.

Access doors are also a frequent cause of problems. If they are essential, it is better to locate them in a vertical, cylindrical section rather than in the hopper section.

### Stainless steel

Stainless steel plate and sheet can be obtained in a variety of surface finishes. Generally, a given finish is smoother for sheet thicknesses (10 gauge or thinner) than for plate thicknesses (3/16 inch or thicker). Some finishes—such as 2B—may be available only in sheet thicknesses. Unless otherwise specified, all recommendations in this report concerning the use of stainless steel are based on a surface finish normally associated with sheet thickness material in contact with the bulk solid.

### Liner attachment

Inside liners such as stainless sheet on sloping surfaces must be butted with the weld ground to the same smoothness as the adjacent sheet. Also, proper design steps must be taken to avoid an upward facing ledge if the liner thickness varies; e.g., a 1/4 in. lower liner section butted to a 10 ga upper liner section will interfere with mass flow and cause material hangups.

Steel liners on a steel substrate are usually intermittently welded into place along the edges to prevent warping and then welded continuously along the top edge. The sides and bottom can also be continuously welded as required. If necessary with large sheets, plug welds can be used, provided the plug area is polished with all polish lines in the direction of material flow.

### Abrasive wear considerations

In mass flow, a bulk solid flows against the hopper and cylinder walls. Handling an abrasive bulk solid, *such as the kyanite, olivine, silica, and wollastonite,* may result in significant abrasive wear of the wall material, including coatings and liners. Therefore, when designing a mass flow hopper, it is important to assess the potential for abrasive wear. Excessive wear may result in costly repair and/or replacement of the hopper wall materials. Generally, the hopper surface becomes smoother with wear; however, occasionally the wall becomes rougher, which may upset mass flow.

Wear is a function of the bulk solid, wall surface, solids pressure, and velocity. The life of a given wall material can be estimated by conducting wear tests. J&J has developed a unique method to quantify the wear rate on a wall material for a given bulk solid. As part of the wear tests, wall friction tests are conducted to analyze changes in the hopper surface due to wear. A proposal for wear tests will be supplied upon request.

### Screw feeder

The running torque for the screws given in the attached figures is based on the initial, unpolished condition of the screw. As the screw flights become polished with use, this torque will decrease slightly. The starting torque will be about 2.5 times the running torque and will occur only when the empty silo is filled without running the screw. Once the screw has turned, the torque will reduce to the running condition. With some types of drives, it is possible to use a motor sized for the running torque, provided the starting torque is available at startup.

If a slide gate is used, the increased height between the screw and hopper outlet will result in increased loads on the screw and must be considered in the torque calculations. The torque increases roughly in direct proportion to the ratio: 2.5 x (vertical distance between converging hopper outlet and screw flight)/(screw diameter). For example, a vertical distance of 6 in. with a 12 in. diameter screw increases the torque and horsepower by about 125% above the values given in our figure.

Maintenance slide gate. To remove the screw in order to perform maintenance, it may be necessary to isolate the feeder trough from the hopper. The recommended method for accomplishing this is to install a slide gate between the hopper outlet and screw. The slide gate should be used only in a fully open or fully closed position, not to throttle flow. The effective opening between the feed screw and silo must remain at the specified dimensions; therefore, adequate clearance for the bolted flanges must be provided.

To remove the screw, we recommend unbolting one end of the screw trough and pulling or rotating the screw from this open end.

Hanger bearings. The screw feeder must be designed to prevent the screw from deflecting so much that it contacts the screw trough. This typically is done by adequately sizing the shaft for the span or through the use of hanger bearings.

Since mass flow screw feeders typically operate at 90% or more capacity just outside of the hopper outlet section, the use of hanger bearings can lead to significant problems of bearing wear, excessive power consumption, and losses in screw efficiency. In addition, the use of hanger bearings may prevent mass flow in the hopper. Therefore, if a long feed screw span is necessary, a separate screw conveyor can be used to convey the material to a remote point from the feeder outlet; otherwise, the capacity of the screw beyond the shroud must be increased enough to allow the use of hanger bearings.

This can be accomplished by increasing both the flight diameter and pitch beyond the shroud on the order of 40% and mounting the first hanger bearing at least one pitch distance downstream from this transition point.

The additional torque and power required for the lengthened conveying section should be added to that given in this report.

Screw pitch. The recommended mass flow screw consists of an increasing capacity section followed by a constant pitch conveying section. The former is comprised of several one revolution flights which add up in length to the specified value for that section. This provides a continuous increase in screw capacity that is relatively simple to fabricate and inspect.

The specified pitch tolerance must be observed in order to prevent a decrease in screw capacity, which would result in a funnel flow pattern and excessive power requirements.

Screw fabrication. It is imperative that the fabricator be cognizant of the intended use of the recommended mass flow screw feeder. Too often, seemingly minor design changes are made to reduce the cost of the feeder. Typically, these changes result in a feeder that is no longer capable of reliably handling the material as originally designed.

J&J has developed in-house capabilities to efficiently build high quality feeders, within tolerances of fabrication necessary to ensure proper operation. For additional information on the supply of such feeders, please refer to our *Mass Flow Screw Feeders* technical bulletin, or contact us for a quotation.

## Warning

These recommendations are based upon samples and information provided by WSRC/Bechtel, and upon expected operating conditions as described by WSRC/Bechtel. We assume that the information furnished by WSRC/Bechtel is accurate and complete, that the samples and expected operating conditions are representative of those which will exist in the completed facility, and that the end-user will carry out routine tests and maintenance during periods of operation in accordance with prudent industrial practice.

Bulk materials of inferior flowability (e.g., more cohesive, with larger critical arching and ratholing dimensions, or more frictional, requiring steeper wall angles) should not be placed in the silo since flow obstructions are then likely to occur. This may lead to the development of voids within the silo and impose dynamic loads when material collapses into the voids. Failures of silos have occurred under such conditions.

If the silo is to store material whose properties may vary over a wide range of flowability and density, we recommend that the end-user routinely test the flow properties and bulk density of the material prior to placing it in the silo in order to avoid the above-described operating and safety hazards.

Mass flow in silos may cause unusually high localized loads at the transition between the vertical section and the mass flow hopper. In using mass flow designs or converting an existing silo to mass flow, the structure must be checked to be sure it is sufficiently strong to withstand these loads.

### Prefabrication drawing review

We strongly recommend that we review, before fabrication, any detail drawings resulting from our recommendations. This review will ensure that the design follows our recommendations and that any design details or changes are consistent with reliable material flow.

Only those aspects of the design that affect material flow will be addressed. Review of structural or mechanical details or calculations is not included.

There will be no fee for this review if our recommendations are closely followed; however, if substantial changes are made and redesign is necessary, the client will be notified of this and we will provide a quotation for this work.

# LIST OF FIGURES

## LIST OF FIGURES (continued)

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 1,200 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 8 ft. diameter cylinder, a volume increase of 50 cu.ft. per foot of height can be achieved.
5. See Fig. 1B for recommended mass flow 18 in. diameter screw feeder.

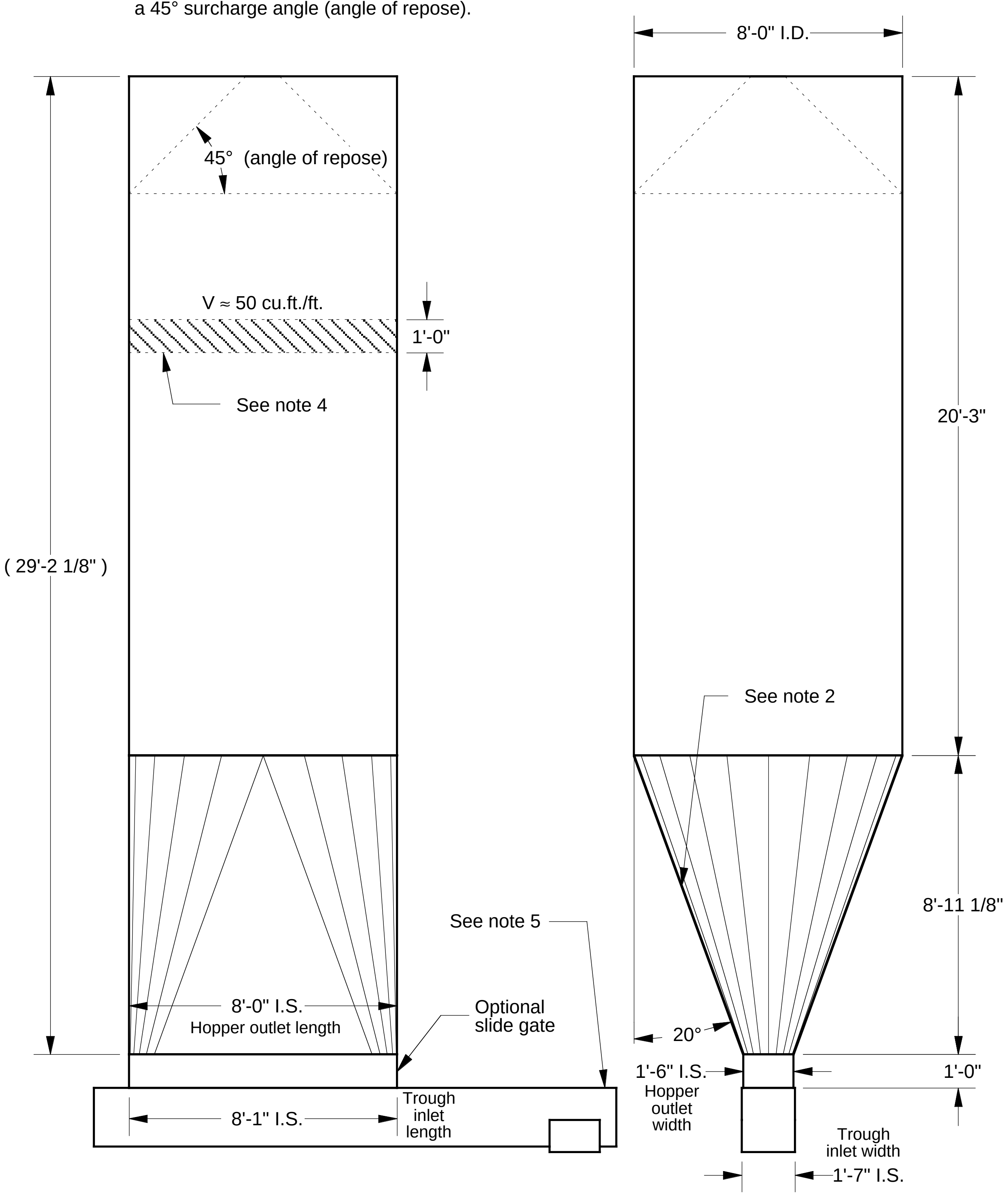

Fig. 1A
Recommended mass flow storage silo for borax - Option A

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| Material | Borax | |
|---|---|---|
| Bulk density, lb./cu.ft. | 52 | |
| Rate, lb./hr. | 14,500 | 16,000 |
| RPM | 2.5 | 3 |
| Running torque, in.lb., see note 4 | 44,500 | 44,500 |
| Rec. motor HP see note 4 | 5 | 5 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 36" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 18" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 6 5/8" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/2"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.

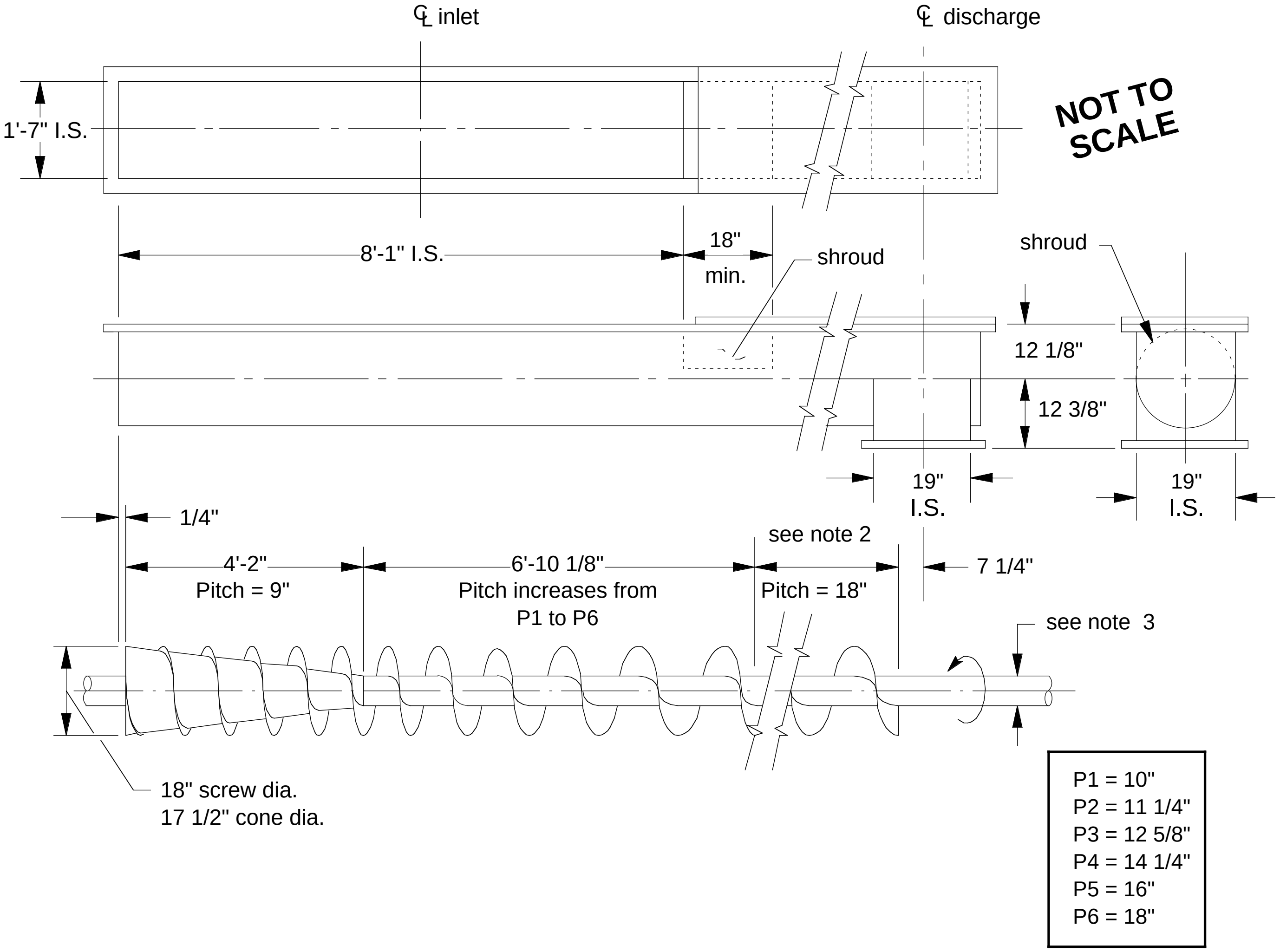

Fig. 1B
Recommended 18 in. diameter mass flow screw feeder

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 1,200 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 8 ft. diameter cylinder, a volume increase of 50 cu.ft. per foot of height can be achieved.
5. See Fig. 1D for recommended mass flow twin 9 in. diameter screw feeder.

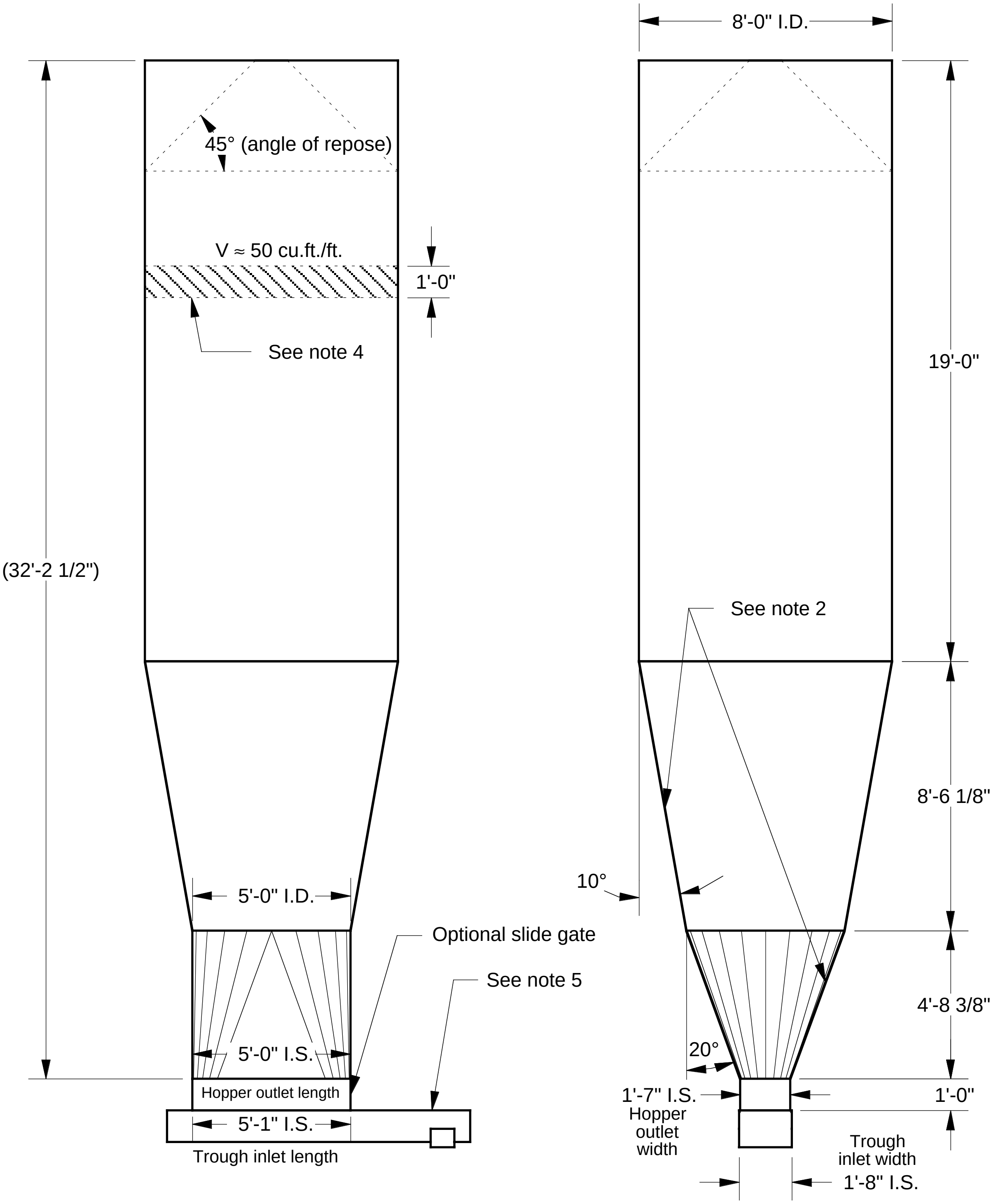

Fig. 1C
Recommended mass flow storage silo for borax - Option B

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| Material | Borax | |
|---|---|---|
| Bulk density, lb./cu.ft. | 52 | |
| Rate, lb./hr. | 14,500 | 16,000 |
| RPM | 9 | 10 |
| Running torque, in.lb., see note 4 | 5,800 (per screw) | 5,800 (per screw) |
| Rec. motor HP see note 4 | 5 (total) | 5 (total) |

Notes:
1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screws are stopped.
3. A pipe O.D. of 2 7/8" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/4"
6. Keep screws 180° out of phase for smoothest discharge.
7. The screws MUST turn simultaneously.
8. Screw trough opening is sized 1" larger in length and width than bin outlet.

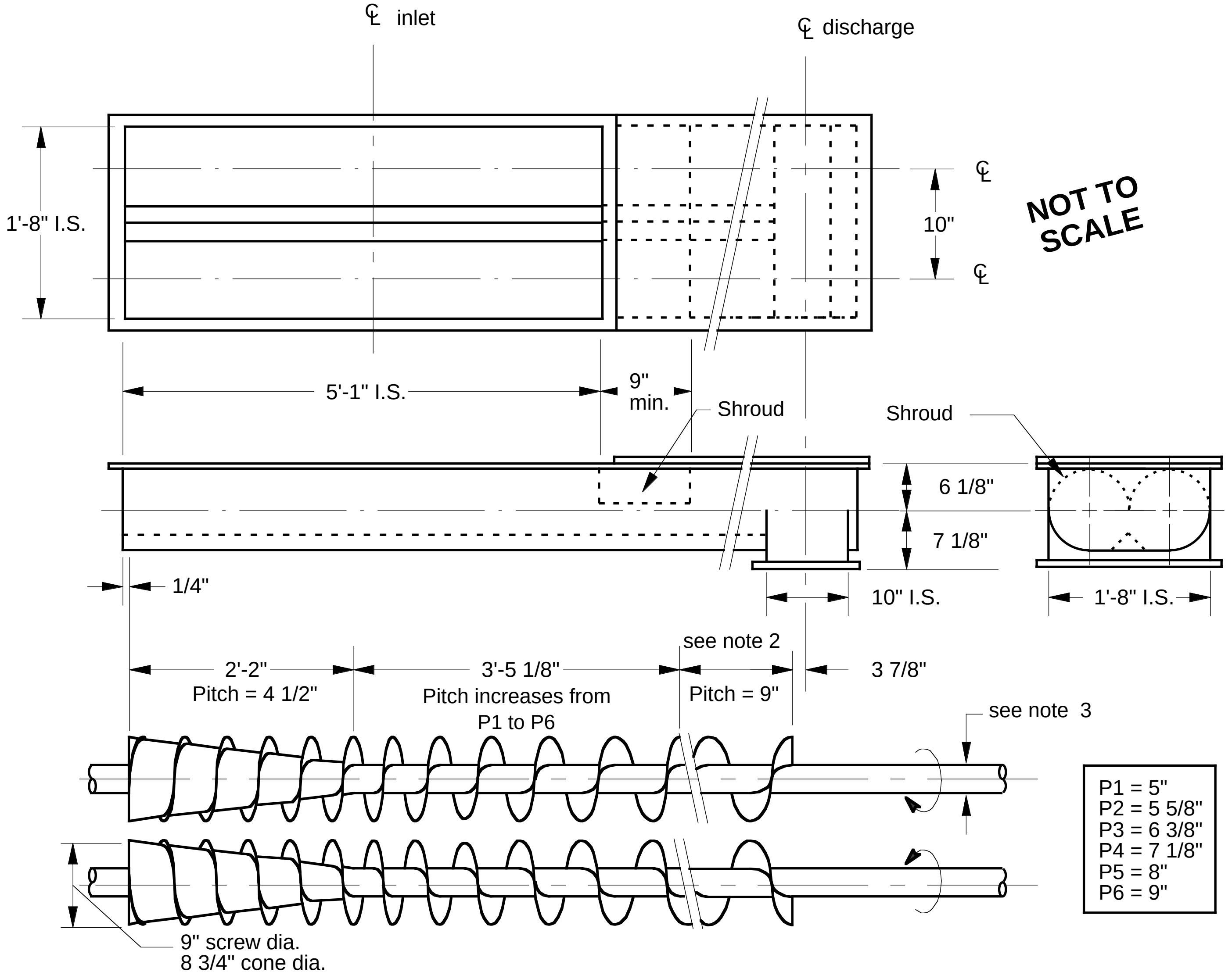

Fig. 1D
Recommended 9 in. diameter mass flow twin screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 5,500 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 14 ft. diameter cylinder, a volume increase of 154 cu.ft. per foot of height can be achieved.
5. See Fig. 2B for recommended mass flow 12 in. diameter screw feeder.

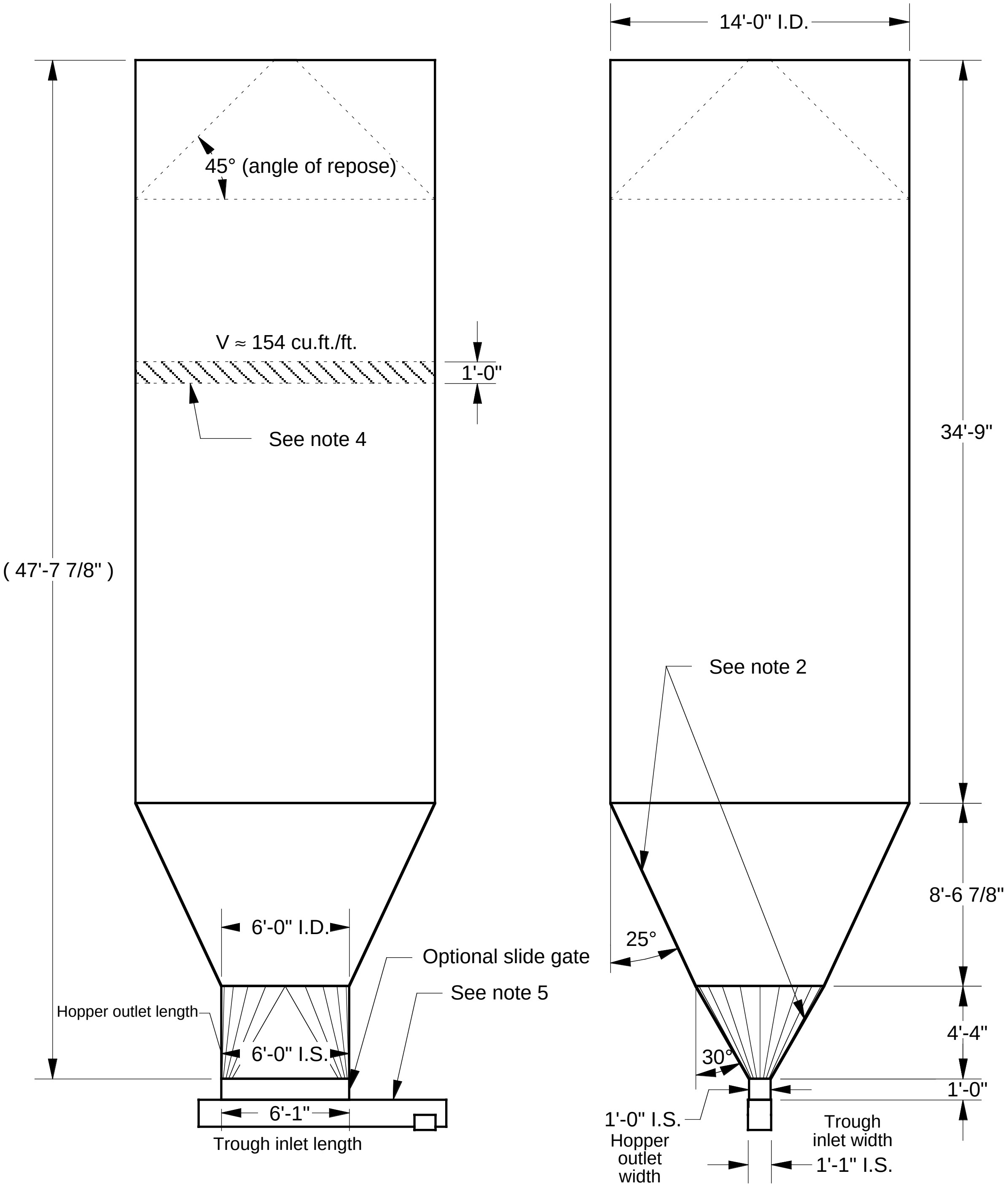

Fig. 2A
Recommended mass flow storage silo for boric acid - Option A

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| Material | Boric acid | |
|---|---|---|
| Bulk density, lb./cu.ft. | 57 | |
| Rate, lb./hr. | 14,500 | 16,000 |
| RPM | 7 | 8 |
| Running torque, in.lb., see note 4 | 11,400 | 11,400 |
| Rec. motor HP see note 4 | 3 | 3 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 4 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 3/8"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.

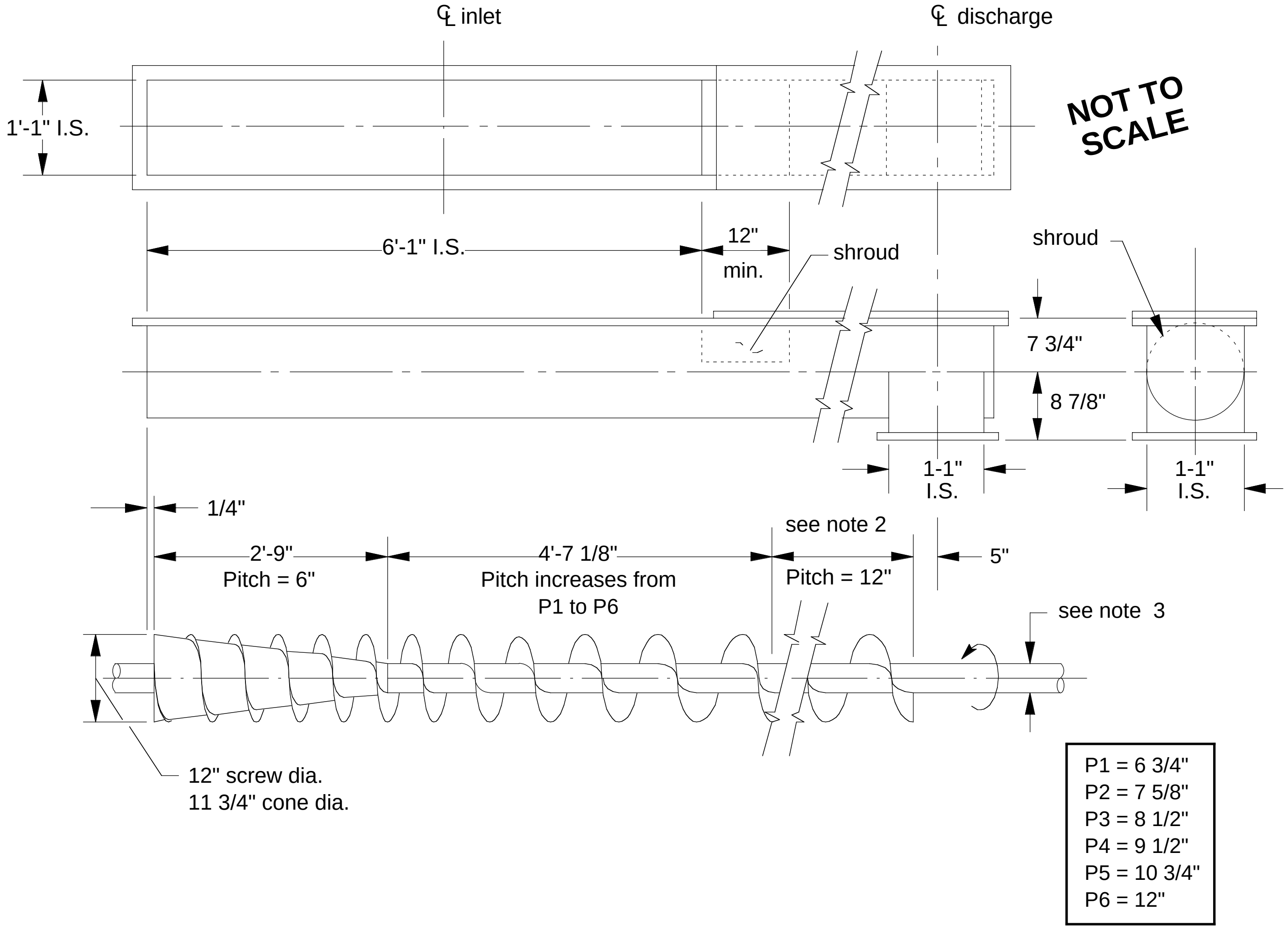

Fig. 2B
Recommended 12 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 5,500 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 14 ft. diameter cylinder, a volume increase of 154 cu.ft. per foot of height can be achieved.
5. See Fig. 2B for recommended mass flow 12 in. diameter screw feeder.

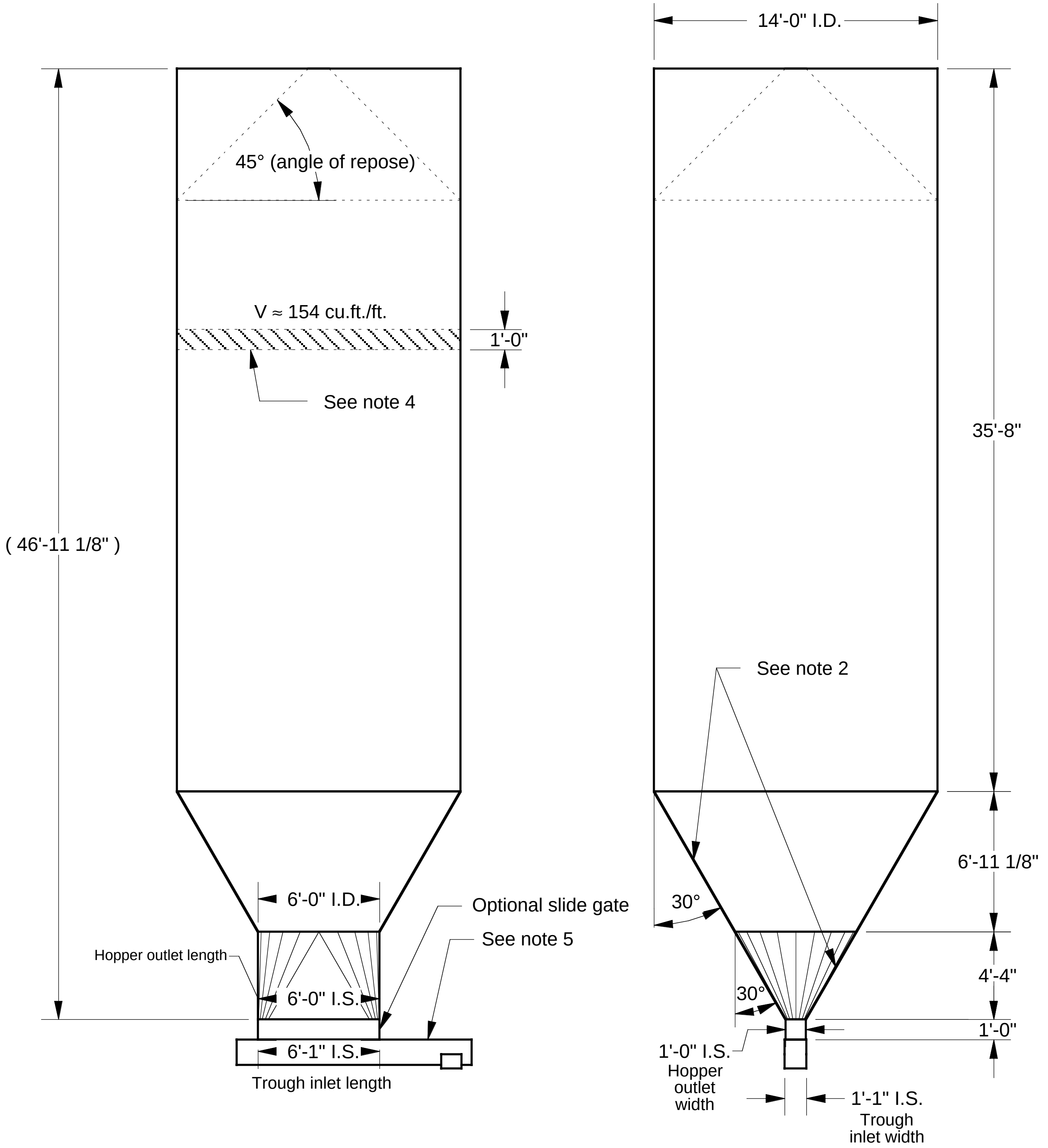

Fig. 2C
Recommended **expanded flow** storage silo for boric acid - Option B

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 800 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 8 ft. diameter cylinder, a volume increase of 50 cu.ft. per foot of height can be achieved.
5. See Fig. 3B for recommended mass flow 9 in. diameter screw feeder.

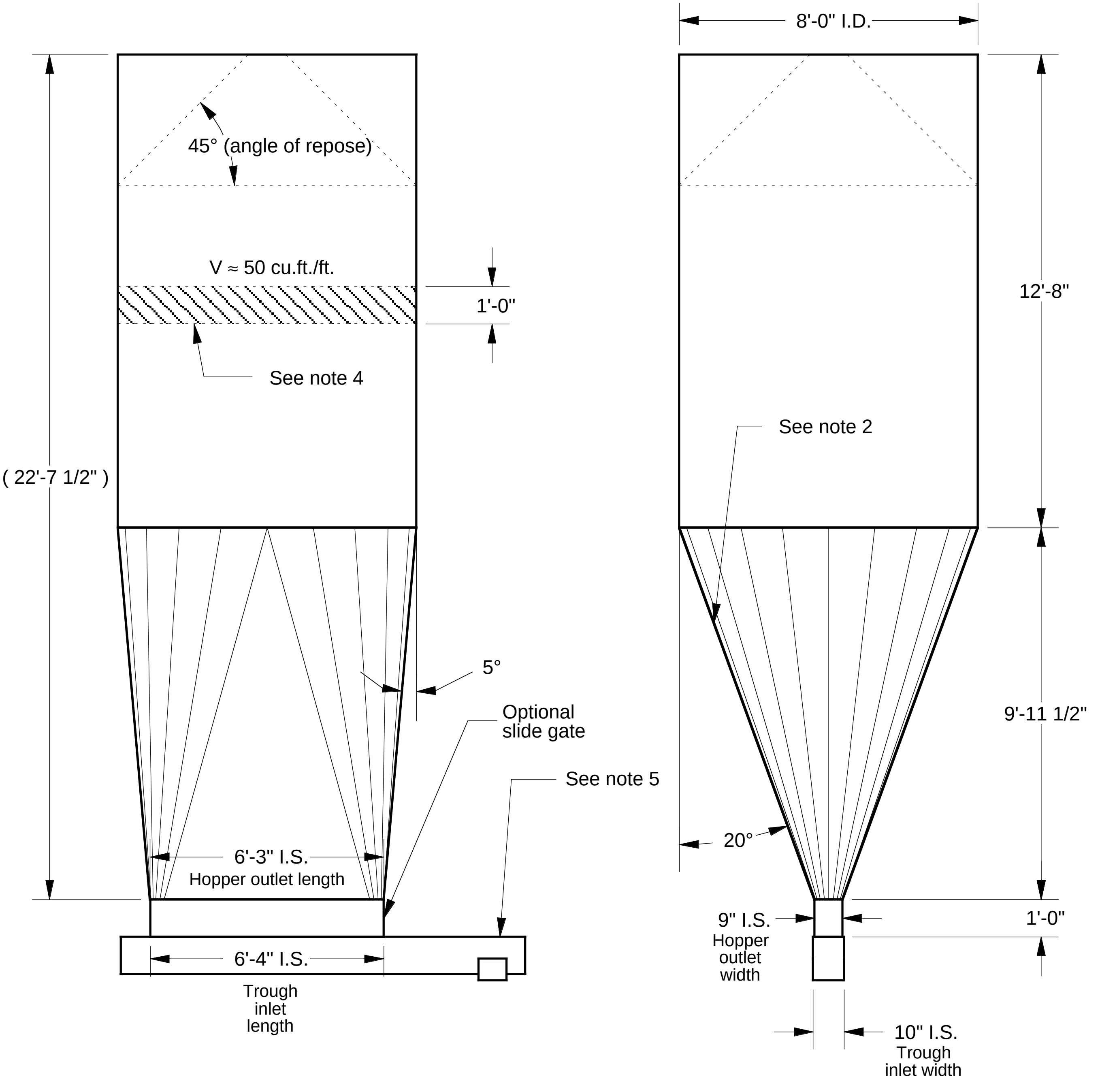

Fig. 3A
Recommended mass flow storage silo for iron oxide - Option A

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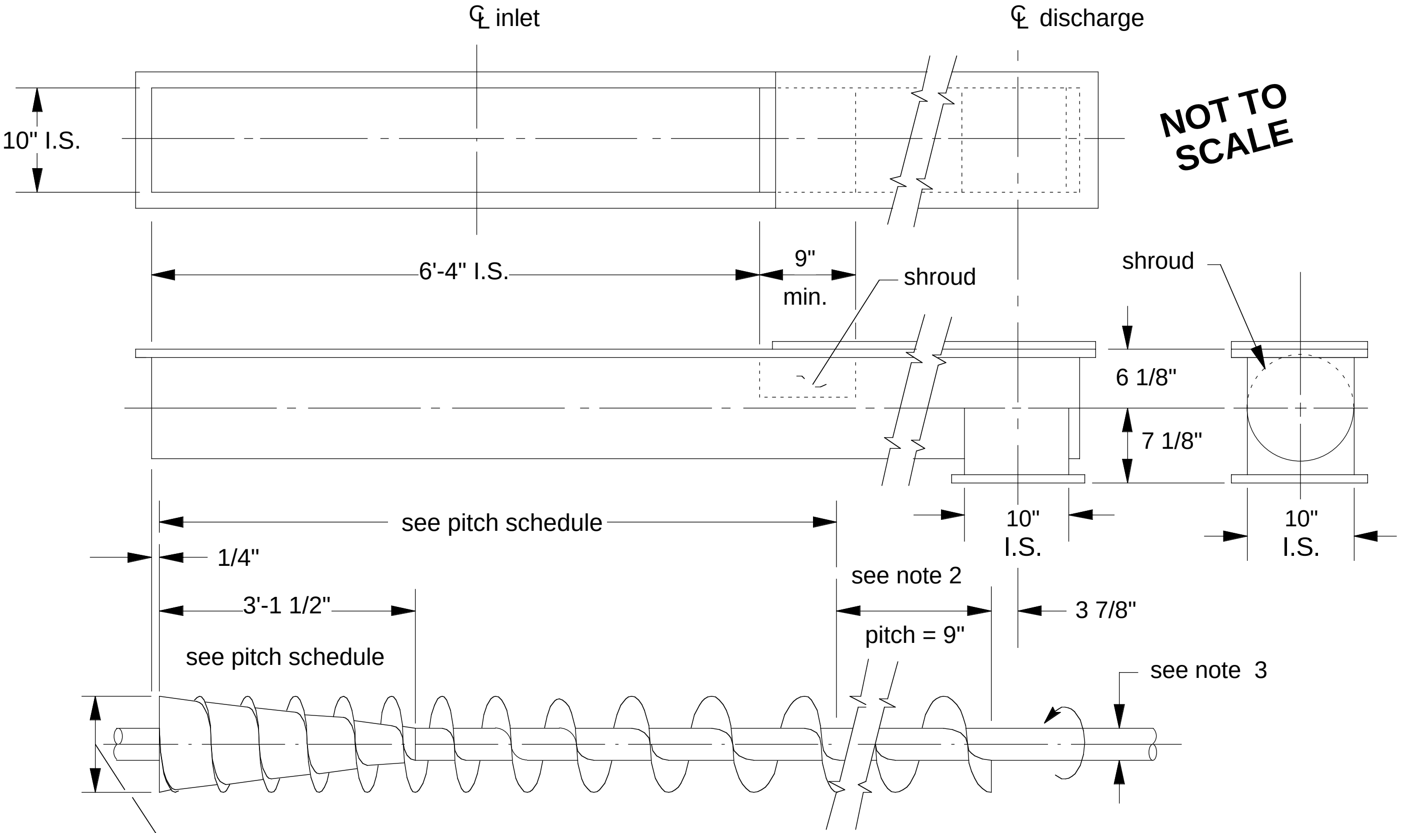
| Material | Iron oxide | |
|---|---|---|
| Bulk density, lb./cu.ft. | 119 | |
| Rate, lb./hr. | 4,100 | 5,800 |
| RPM | 2.5 | 4 |
| Running torque, in.lb., see note 4 | 11,000 | 11,000 |
| Rec. motor HP see note 4 | 1.5 | 2 |

Notes:
1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 9" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 3 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/16"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.



| | | |
|---|---|---|
| P1 = 3 1/2" | P7 = 3 5/8" | P13 = 5 1/2" |
| P2 = 3 1/2" | P8 = 3 3/4" | P14 = 6" |
| P3 = 3 1/2" | P9 = 3 7/8" | P15 = 6 3/4" |
| P4 = 3 1/2" | P10 = 4 1/8" | P16 = 7 1/2" |
| P5 = 3 1/2" | P11 = 4 3/8" | P17 = 8 3/8" |
| P6 = 3 1/2" | P12 = 4 7/8" | P18 = 9" |

Fig. 3B
Recommended 9 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 800 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 8 ft. diameter cylinder, a volume increase of 50 cu.ft. per foot of height can be achieved.
5. See Fig. 3D for recommended mass flow 12 in. diameter screw feeder.

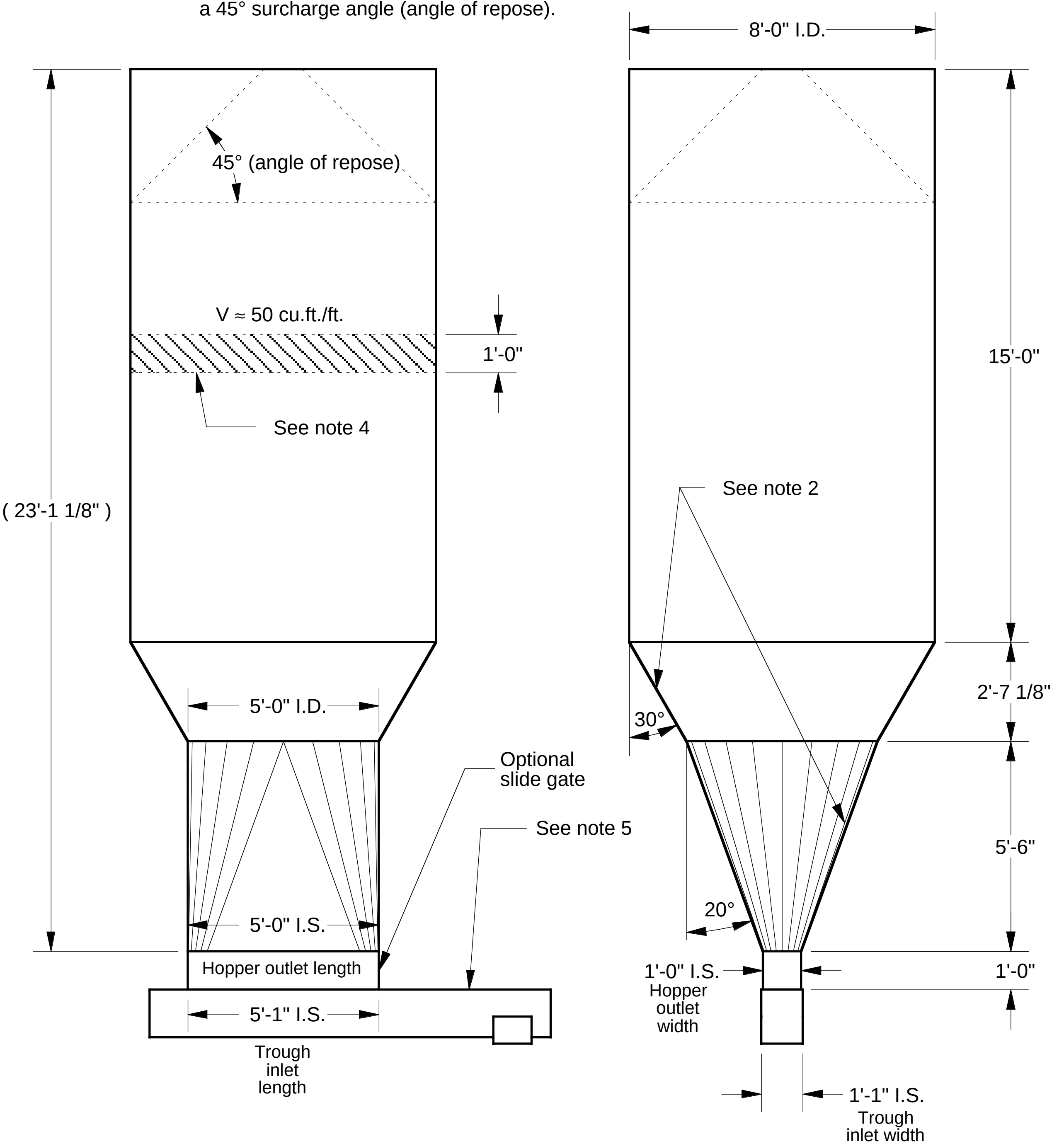

Fig. 3C
Recommended **expanded flow** storage silo for iron oxide - Option B

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| Material | Iron oxide | |
|---|---|---|
| Bulk density, lb./cu.ft. | 119 | |
| Rate, lb./hr. | 4,100 | 5,800 |
| RPM | 1.5 | 2 |
| Running torque, in.lb., see note 4 | 25,000 | 25,000 |
| Rec. motor HP see note 4 | 1.5 | 2 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 6 5/8" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 3/8"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.

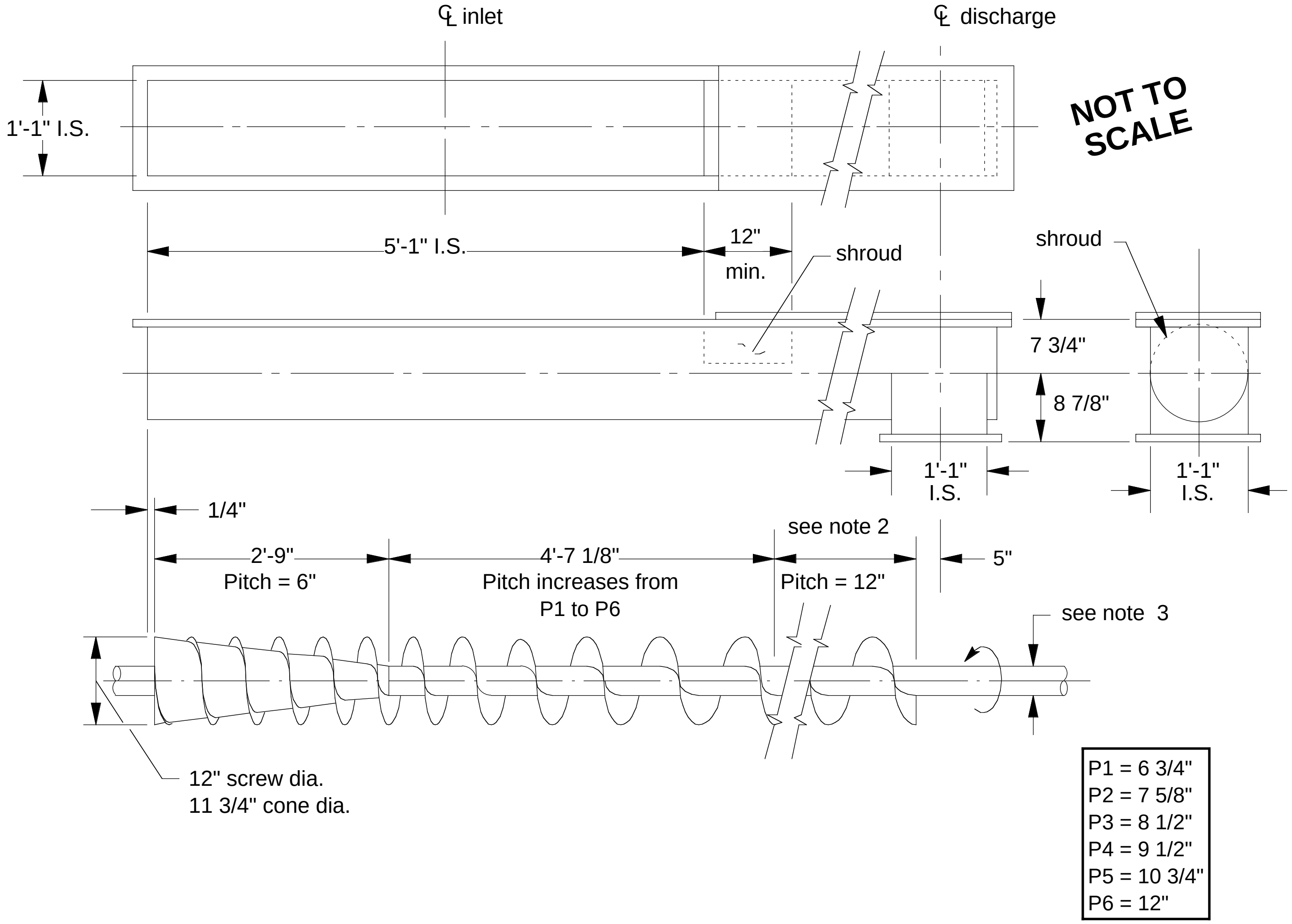

Fig. 3D
Recommended 12 in. diameter mass flow screw feeder

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 2,200 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 11 ft. diameter cylinder, a volume increase of 95 cu.ft. per foot of height can be achieved.
5. See Fig. 4B for recommended mass flow twin 12 in. diameter screw feeder.

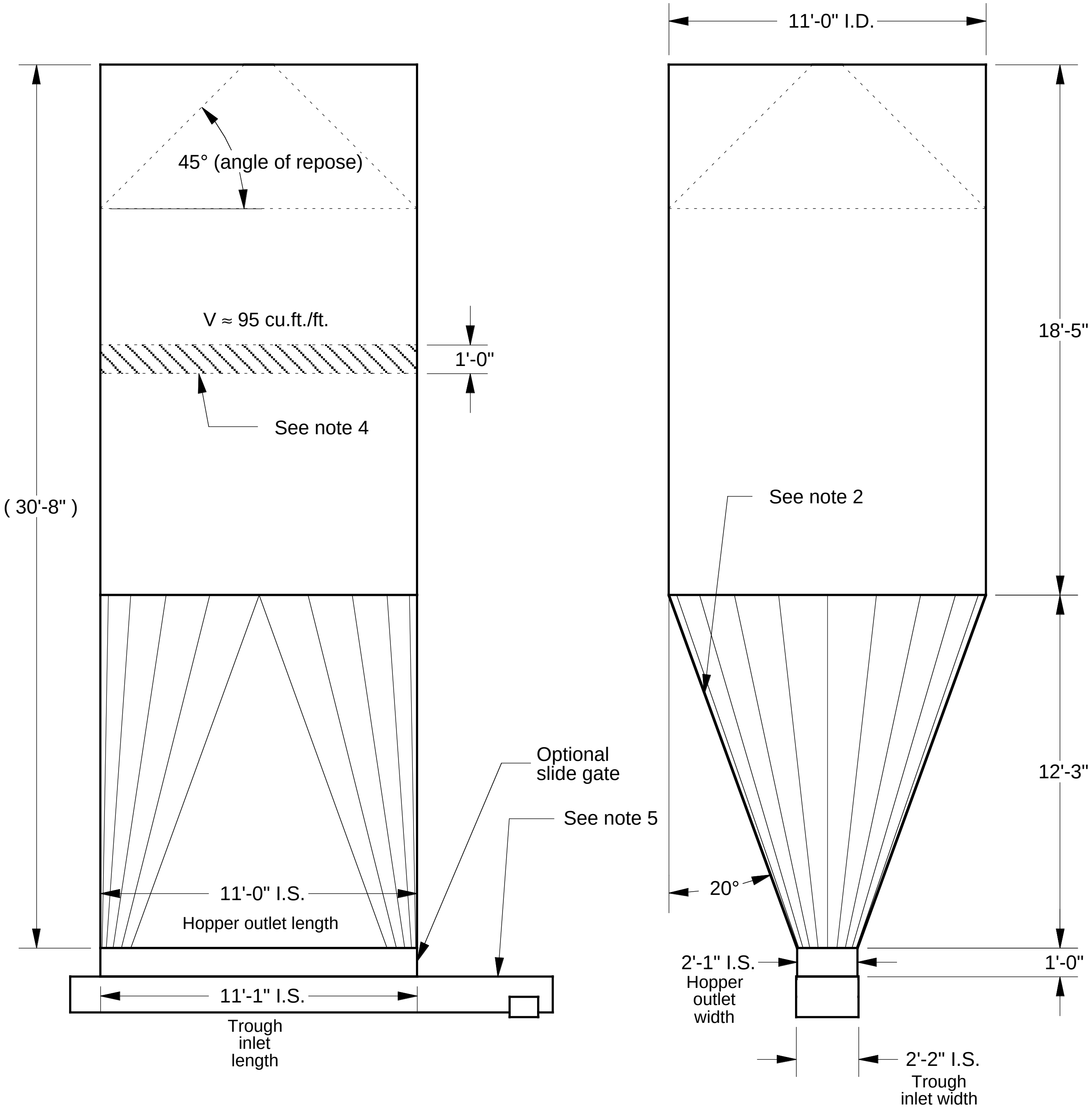

Fig. 4A
Recommended mass flow storage silo for kyanite - Option A

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| Material | Kyanite | |
|---|---|---|
| Bulk density, lb./cu.ft. | 81 | |
| Rate, lb./hr. | 2,400 | 10,000 |
| RPM | 0.5 | 1.5 |
| Running torque, in.lb., see note 4 | 83,000<br>(2 screws) | 83,000<br>(2 screws) |
| Rec. motor HP see note 4 | 2<br>(total) | 7.5<br>(total) |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screws are stopped.
3. A pipe O.D. of 6 5/8" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/8"
6. Keep screws 180° out of phase for smoothest discharge.
7. The screws MUST turn simultaneously.
8. Screw trough opening is sized 1" larger in length and width than bin outlet.

P1 = 4"
P2 = 4"
P3 = 4"
P4 = 4 1/8"
P5 = 4 1/4"
P6 = 4 1/2"
P7 = 4 5/8"
P8 = 4 3/4"
P9 = 4 7/8"
P10 = 5 1/8"
P11 = 5 1/4"
P12 = 5 3/8"
P13 = 5 1/2"
P14 = 5 5/8"
P15 = 5 7/8"
P16 = 6 3/8"
P17 = 6 7/8"
P18 = 7 1/2"
P19 = 8 1/8"
P20 = 8 7/8"
P21 = 9 5/8"
P22 = 10 3/8"
P23 = 11 1/4"
P24 = 12"

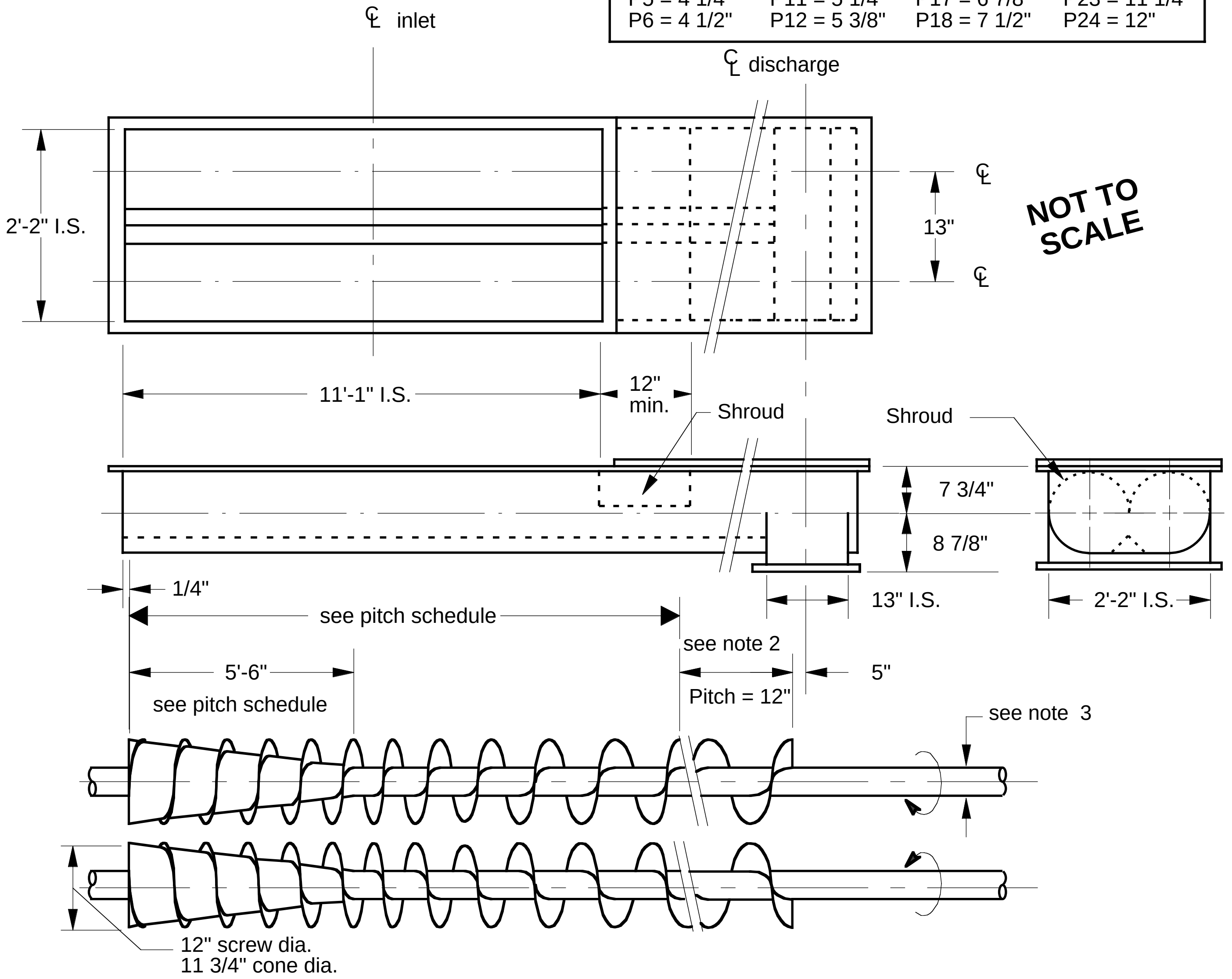

Fig. 4B
Recommended 12 in. diameter mass flow twin screw feeder

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 2,200 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 11 ft. diameter cylinder, a volume increase of 95 cu.ft. per foot of height can be achieved.
5. See Fig. 4D for recommended mass flow triple 12 in. diameter screw feeder.

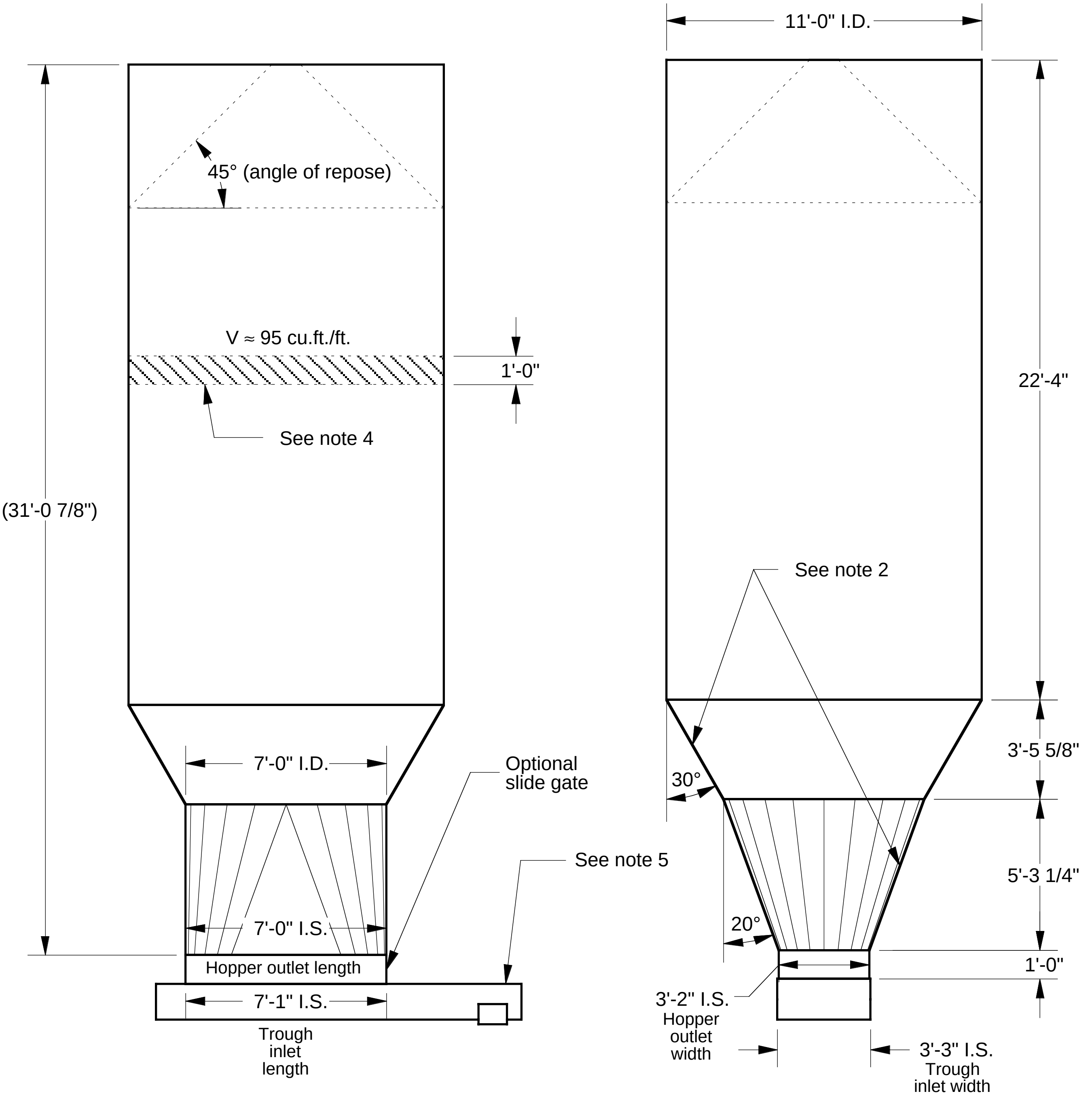

Fig. 4C
Recommended **expanded flow** storage silo for kyanite - Option B

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| Material | Kyanite | |
|---|---|---|
| Bulk density, lb./cu.ft. | 81 | |
| Rate, lb./hr. | 2,400 | 10,000 |
| RPM | 0.5 | 1.5 |
| Running torque, in.lb., see note 4 | 168,300<br>(3 screws) | 168,300<br>(3 screws) |
| Rec. motor HP see note 4 | 3<br>(total) | 7.5<br>(total) |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screws are stopped.
3. A pipe O.D. of 6 5/8" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/8"
6. Keep screws 120° out of phase for smoothest discharge.
7. The screws MUST turn simultaneously.
8. Screw trough opening is sized 1" larger in length and width than bin outlet.

P1 = 4"
P2 = 4"
P3 = 4"
P4 = 4 1/8"
P5 = 4 1/4"
P6 = 4 1/2"
P7 = 4 5/8"
P8 = 4 3/4"
P9 = 4 7/8"
P10 = 5 1/8"
P11 = 5 1/4"
P12 = 5 3/8"
P13 = 5 1/2"
P14 = 5 5/8"
P15 = 5 7/8"
P16 = 6 3/8"
P17 = 6 7/8"
P18 = 7 1/2"
P19 = 8 1/8"
P20 = 8 7/8"
P21 = 9 5/8"
P22 = 10 3/8"
P23 = 11 1/4"
P24 = 12"

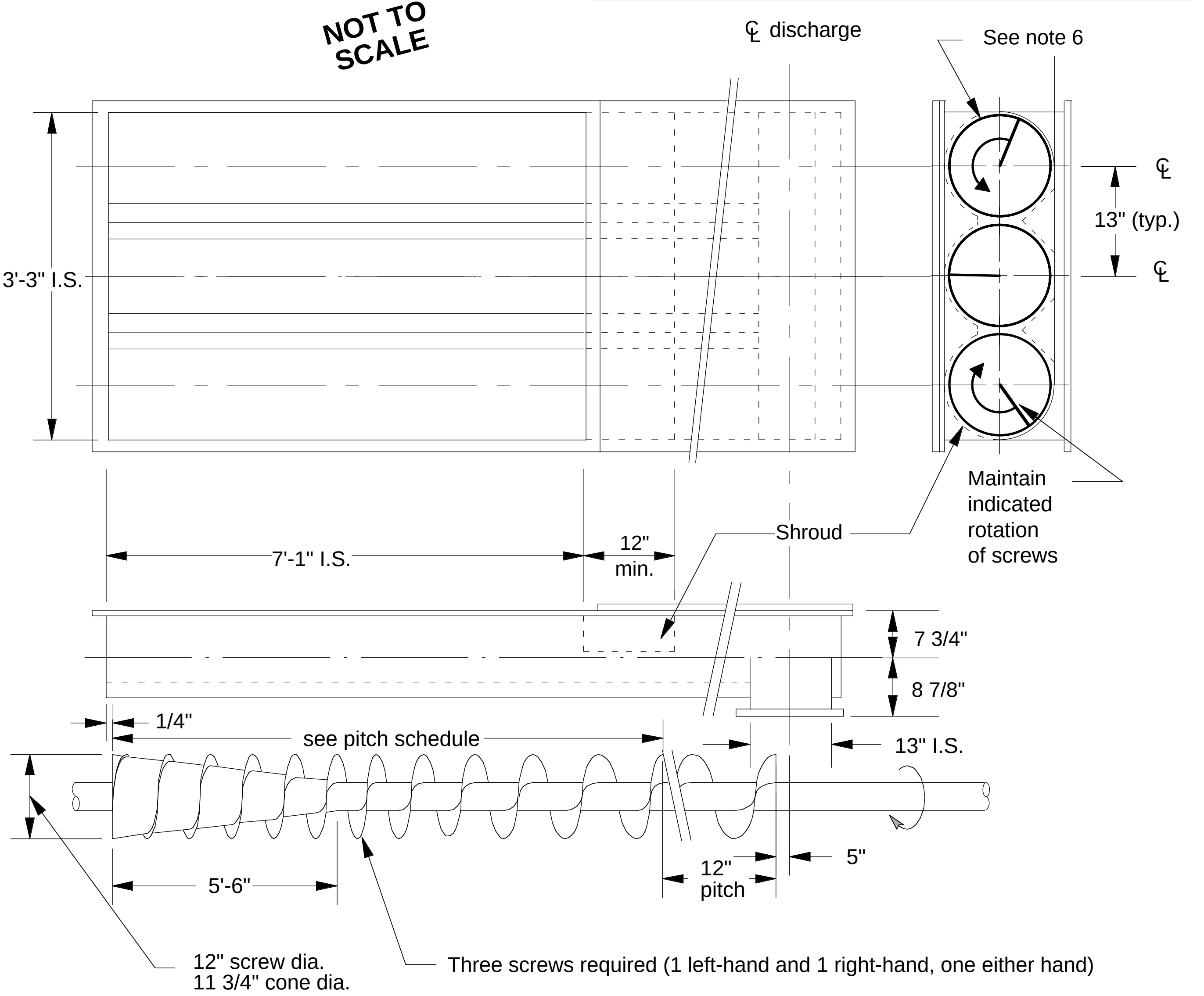

Fig. 4D
Recommended 12 in. diameter mass flow triple screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 3,600 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 13 ft. diameter cylinder, a volume increase of 133 cu.ft. per foot of height can be achieved.
5. See Fig. 5B for recommended mass flow 12 in. diameter screw feeder.

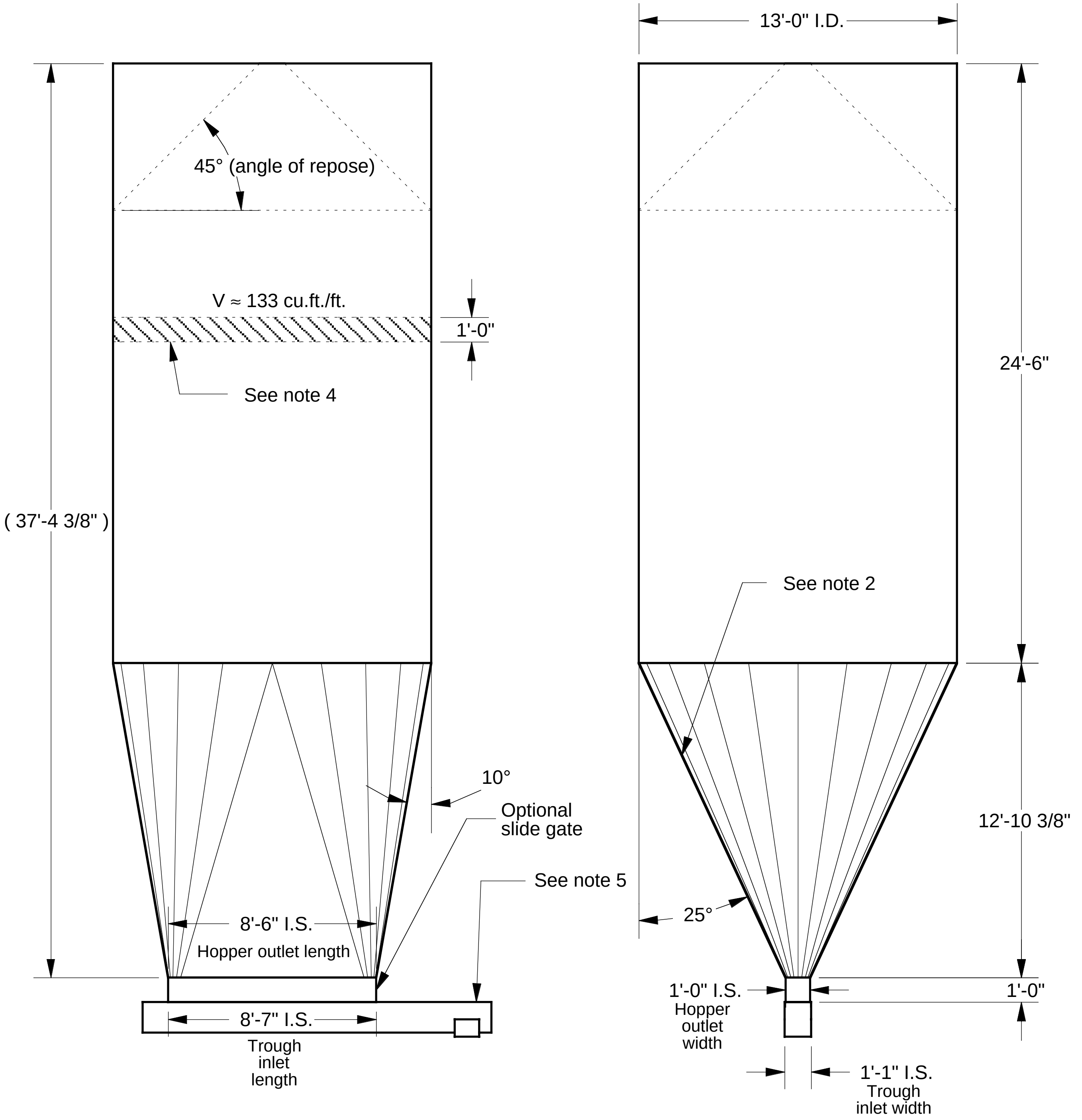

Fig. 5A
Recommended mass flow storage silo for lithium carbonate - Option A

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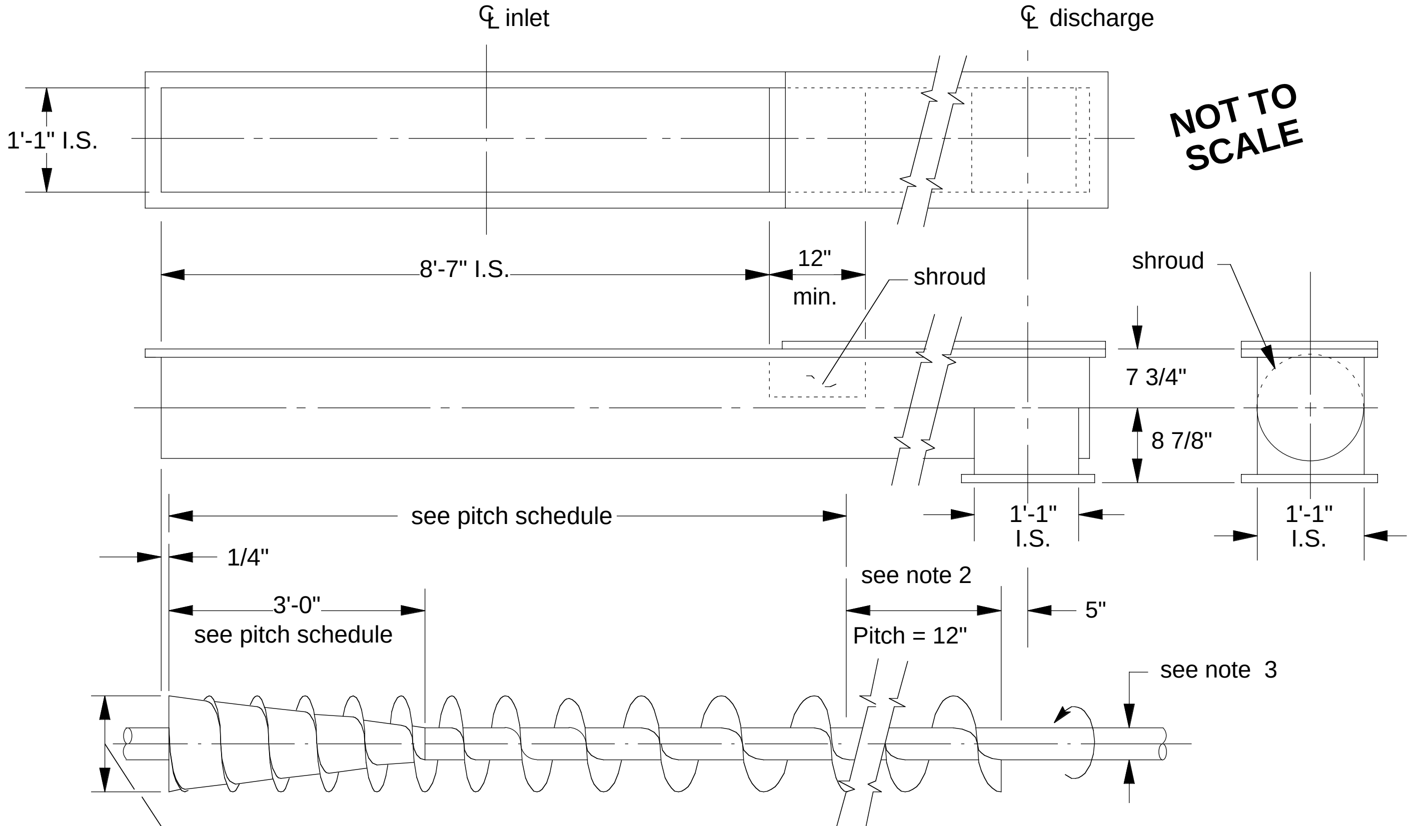
| | | |
|---|---|---|
| Material | Lithium carbonate | |
| Bulk density, lb./cu.ft. | 63 | |
| Rate, lb./hr. | 8,700 | 13,000 |
| RPM | 4 | 6 |
| Running torque, in.lb., see note 4 | 17,300 | 17,300 |
| Rec. motor HP see note 4 | 3 | 5 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 4 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/8"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.



P1 = 4"
P2 = 4"
P3 = 4"
P4 = 4"
P5 = 4"
P6 = 4"
P7 = 4"
P8 = 4"
P9 = 4"
P10 = 4 1/4"
P11 = 4 3/4"
P12 = 5 1/4"
P13 = 5 7/8"
P14 = 6 1/2"
P15 = 7 1/4"
P16 = 8"
P17 = 8 7/8"
P18 = 9 7/8"
P19 = 11"
P20 = 12"

Fig. 5B
Recommended 12 in. diameter mass flow screw feeder

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 3,600 cu.ft. assuming a 45° surcharge angle (angle of repose).
4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 13 ft. diameter cylinder, a volume increase of 133 cu.ft. per foot of height can be achieved.
5. See Fig. 5D for recommended mass flow 12 in. diameter screw feeder.

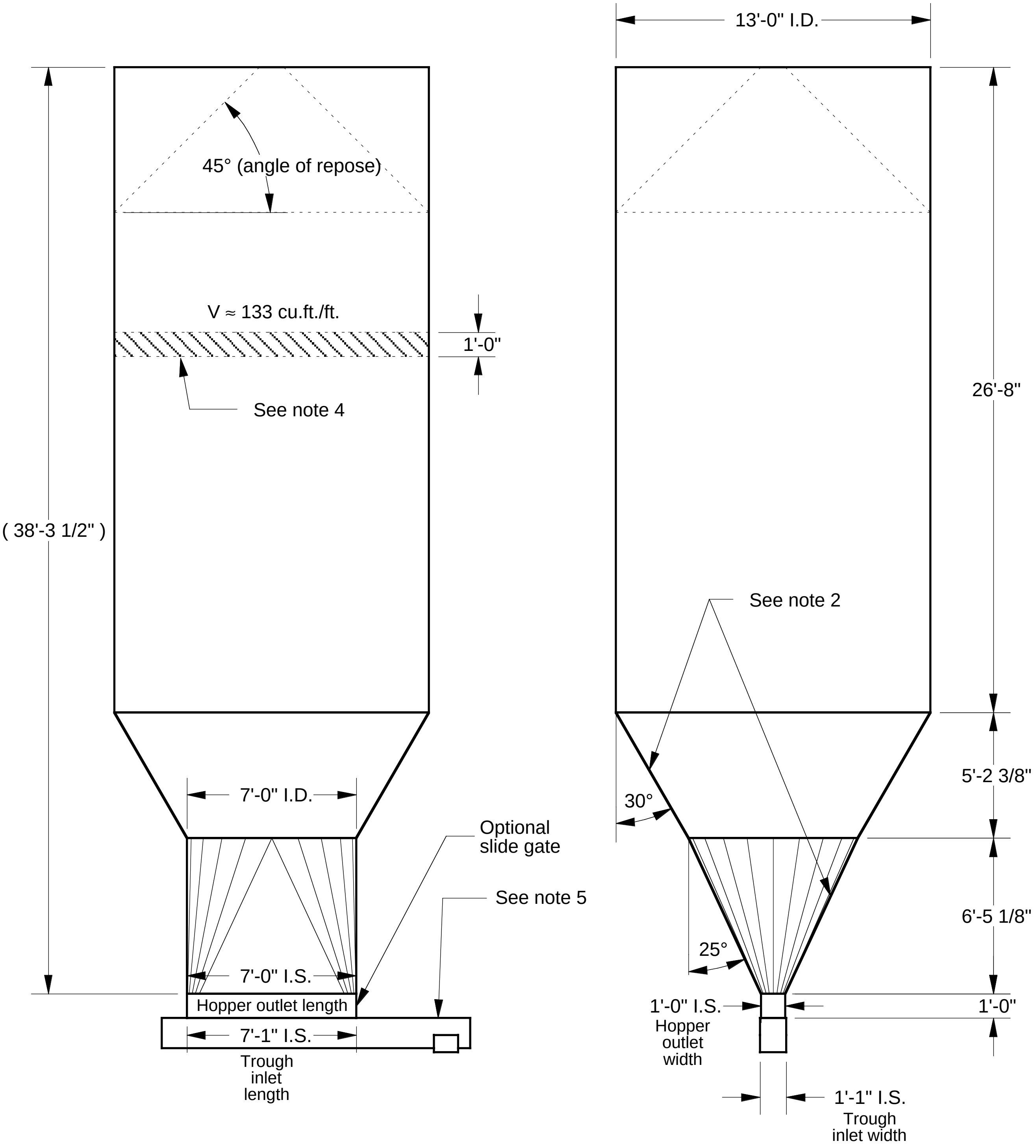

Fig. 5C
Recommended **expanded flow** storage silo for lithium carbonate - Option B

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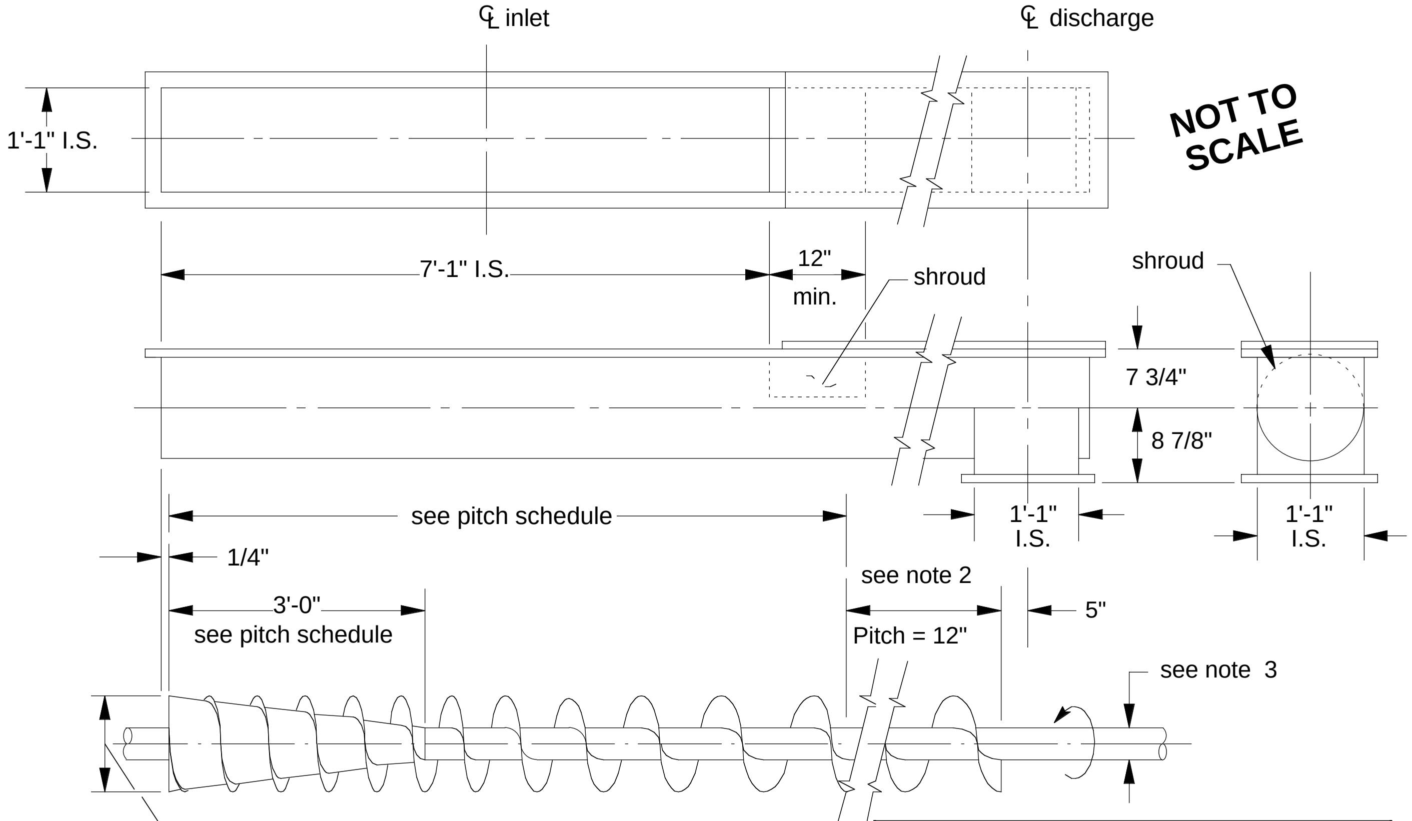
| Material | Lithium carbonate | |
|---|---|---|
| Bulk density, lb./cu.ft. | 63 | |
| Rate, lb./hr. | 8,700 | 13,000 |
| RPM | 4 | 6 |
| Running torque, in.lb., see note 4 | 14,200 | 14,200 |
| Rec. motor HP see note 4 | 2 | 3 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 4 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/8"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.



P1 = 4"
P2 = 4"
P3 = 4"
P4 = 4"
P5 = 4"
P6 = 4 1/8"
P7 = 4 3/8"
P8 = 4 1/2"
P9 = 4 7/8"
P10 = 5 1/2"
P11 = 6 1/4"
P12 = 7 1/8"
P13 = 8"
P14 = 9 1/8"
P15 = 10 3/8"
P16 = 11 3/4"
P17 = 11 3/4"
P18 = 12"

Fig. 5D
Recommended 12 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 1,100 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 9 ft. diameter cylinder, a volume increase of 64 cu.ft. per foot of height can be achieved.
5. See Fig. 6B for recommended mass flow 9 in. diameter screw feeder.

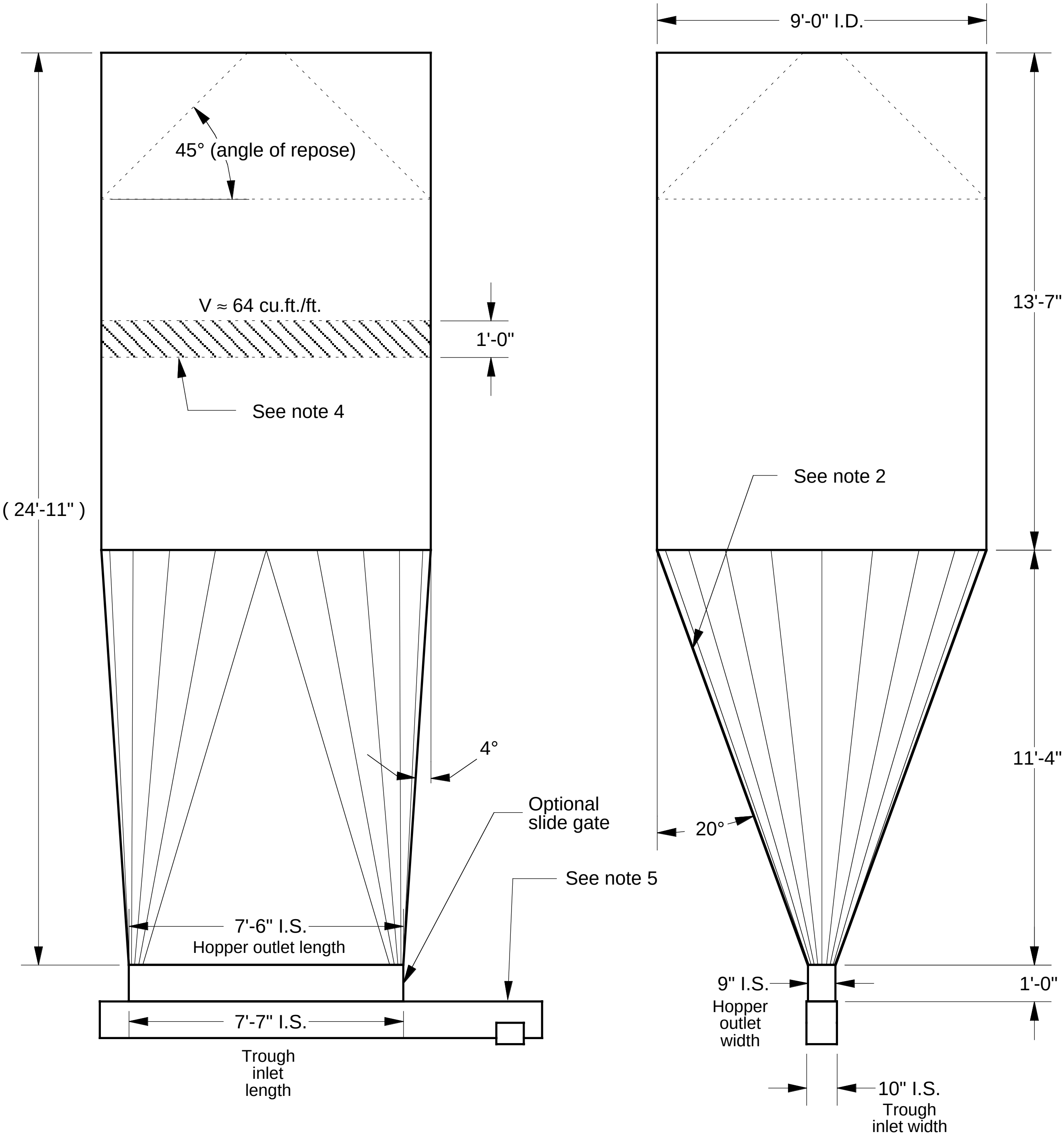

Fig. 6A
Recommended mass flow storage silo for olivine - Option A

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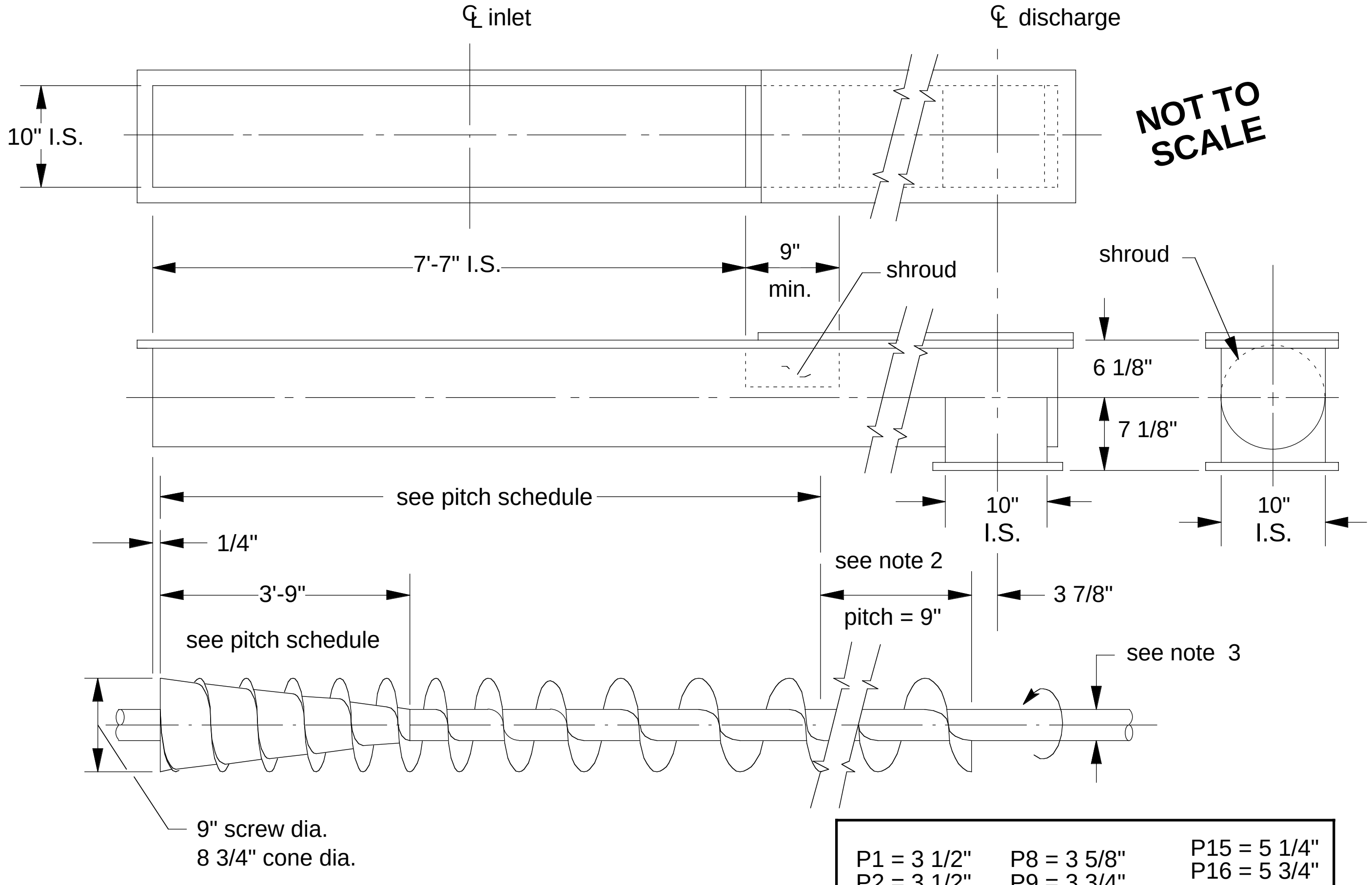
| Material | Olivine | |
|---|---|---|
| Bulk density, lb./cu.ft. | 95 | |
| Rate, lb./hr. | 3,700 | 5,600 |
| RPM | 3 | 4 |
| Running torque, in.lb., see note 4 | 10,300 | 10,300 |
| Rec. motor HP see note 4 | 1.5 | 2 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 9" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 4" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/16"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.



P1 = 3 1/2"
P2 = 3 1/2"
P3 = 3 1/2"
P4 = 3 /12"
P5 = 3 1/2"
P6 = 3 1/2"
P7 = 3 1/2"
P8 = 3 5/8"
P9 = 3 3/4"
P10 = 3 7/8"
P11 = 4"
P12 = 4 1/8"
P13 = 4 3/8"
P14 = 4 3/4"
P15 = 5 1/4"
P16 = 5 3/4"
P17 = 6 1/4"
P18 = 6 7/8"
P19 = 7 1/2"
P20 = 8 1/8"
P21 = 8 7/8"
P22 = 9"

Fig. 6B
Recommended 9 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 1,100 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 9 ft. diameter cylinder, a volume increase of 64 cu.ft. per foot of height can be achieved.
5. See Fig. 6D for recommended mass flow 9 in. diameter screw feeder.

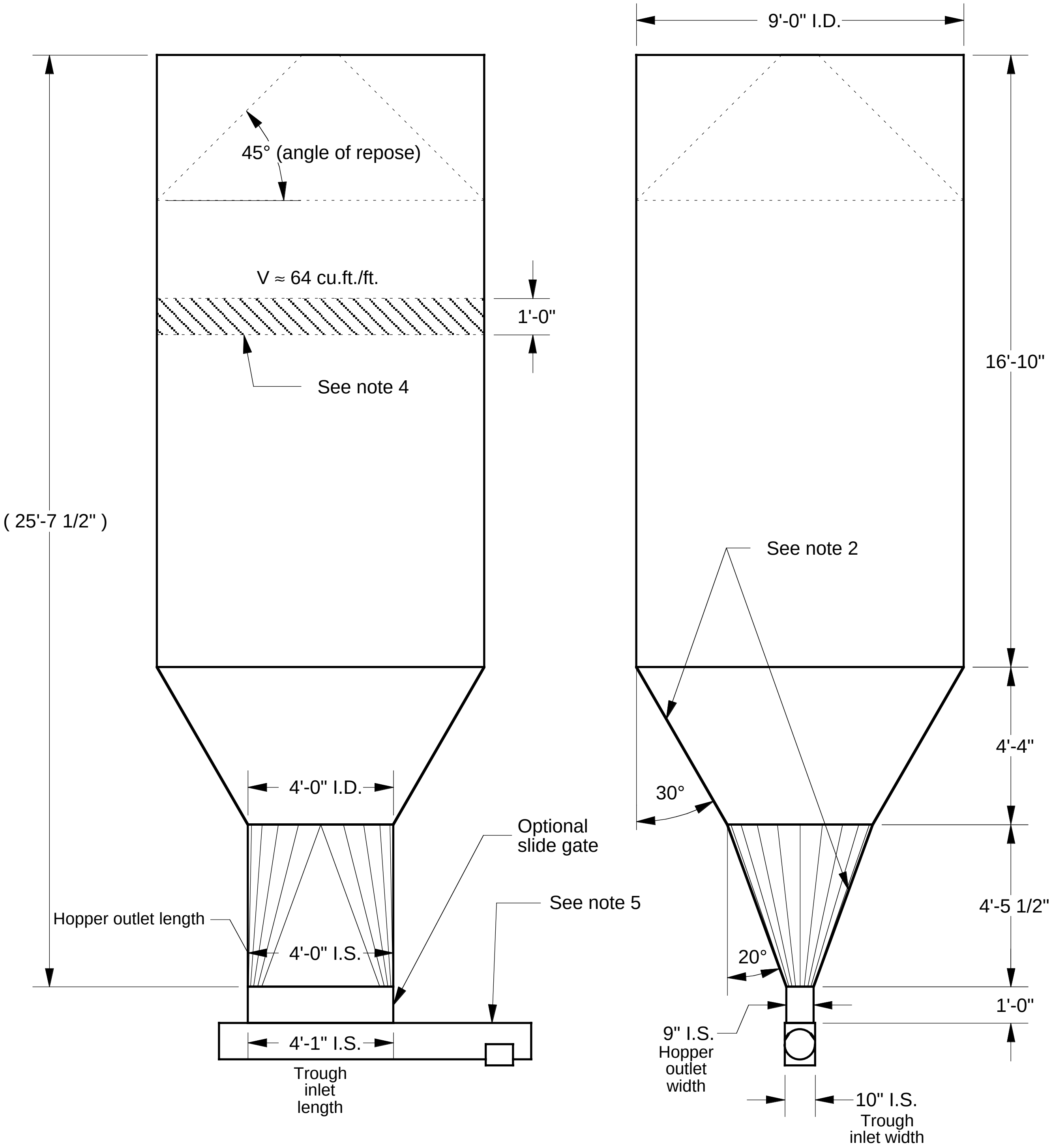

Fig. 6C
Recommended **expanded flow** storage silo for olivine - Option B

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| Material | Olivine | |
|---|---|---|
| Bulk density, lb./cu.ft. | 95 | |
| Rate, lb./hr. | 3,700 | 5,600 |
| RPM | 3 | 5 |
| Running torque, in.lb., see note 4 | 7,100 | 7,100 |
| Rec. motor HP see note 4 | 1 | 1.5 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 9" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 3 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/4"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.

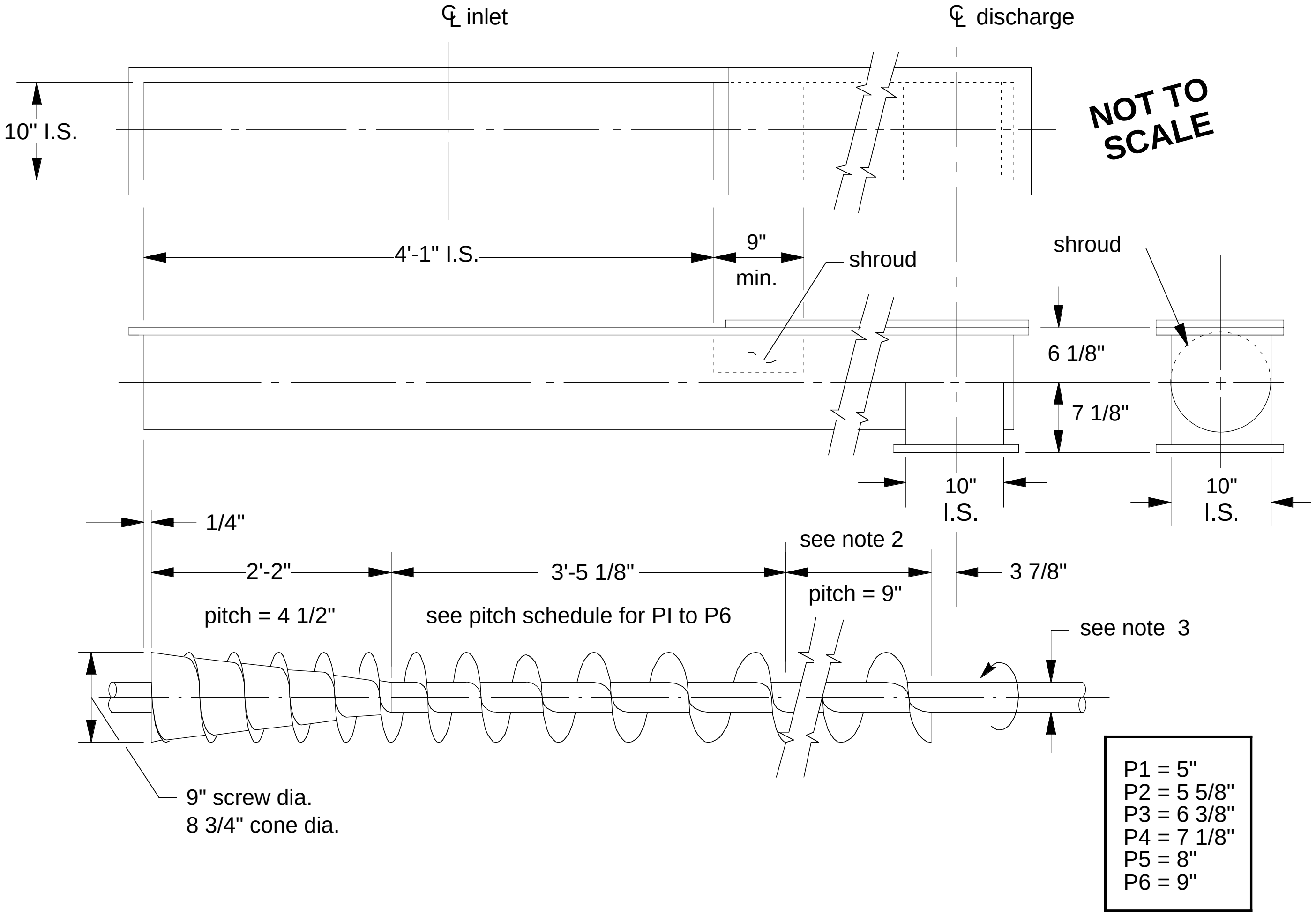

Fig. 6D
Recommended 9 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish, except for the 13 deg. conical hopper which is to be lined or fabricated from 304 stainless steel sheet with a #2B finish.
3. Working capacity ≈ 10,200 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 18 ft. diameter cylinder, a volume increase of 254 cu.ft. per foot of height can be achieved.
5. See Fig. 7B for recommended mass flow triple 18 in. diameter screw feeder.

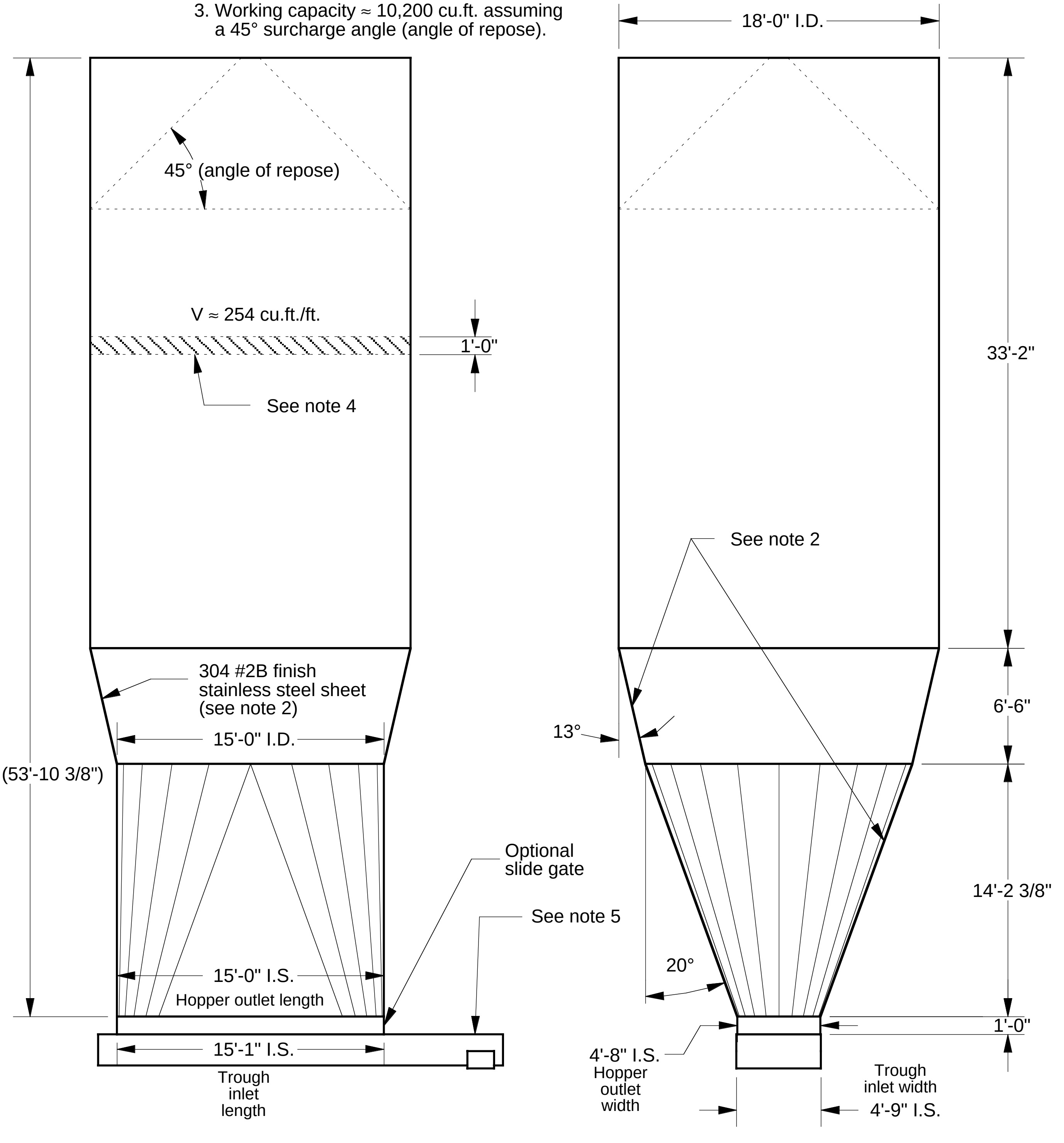

Fig. 7A
Recommended mass flow storage silo for silica - Option A

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| | | |
|---|---|---|
| Material | Silica | |
| Bulk density, lb./cu.ft. | 75 | |
| Rate, lb./hr. | 29,000 | 40,500 |
| RPM | 1.5 | 2.5 |
| Running torque, in.lb., see note 4 | 697,000<br>(3 screws) | 697,000<br>(3 screws) |
| Rec. motor HP see note 4 | 25<br>(total) | 40<br>(total) |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 36" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 18" in order to prevent discharge of material when the screws are stopped.
3. A pipe O.D. of 10 3/4" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 3/8"
6. Keep screws 120° out of phase for smoothest discharge.
7. The screws MUST turn simultaneously.
8. Screw trough opening is sized 1" larger in length and width than bin outlet.

P1 = 6"
P2 = 6"
P3 = 6"
P4 = 6"
P5 = 6"
P6 = 6"
P7 = 6"
P8 = 6"
P9 = 6"
P10 = 6 1/4"
P11 = 6 3/8"
P12 = 6 5/8"
P13 = 7 1/4"
P14 = 8"
P15 = 8 3/4"
P16 = 9 1/2"
P17 = 10 3/8"
P18 = 11 3/8"
P19 = 12 3/8"
P20 = 13 5/8"
P21 = 14 7/8"
P22 = 16 1/4"
P23 = 17 3/4"
P24 = 18"

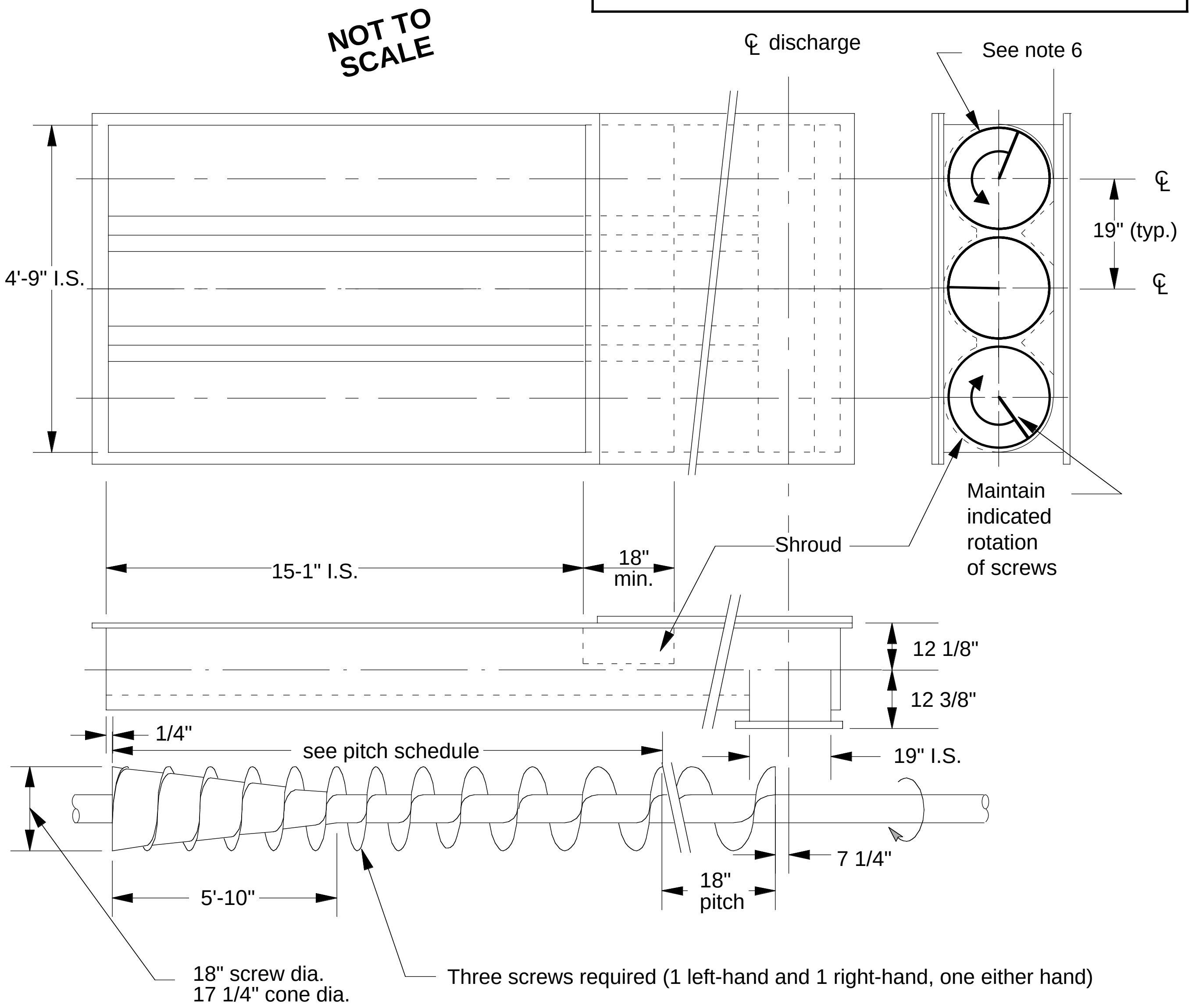

Fig. 7B
Recommended 18 in. diameter mass flow triple screw feeder

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 1,500 cu.ft. assuming a 45° surcharge angle (angle of repose).
4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 9 ft. diameter cylinder, a volume increase of 64 cu.ft. per foot of height can be achieved.
5. See Fig. 8B for recommended mass flow 9 in. diameter screw feeder. The design for this feeder and hopper is the same design as for the feeder and hopper shown in Figs. 6A and 6B.

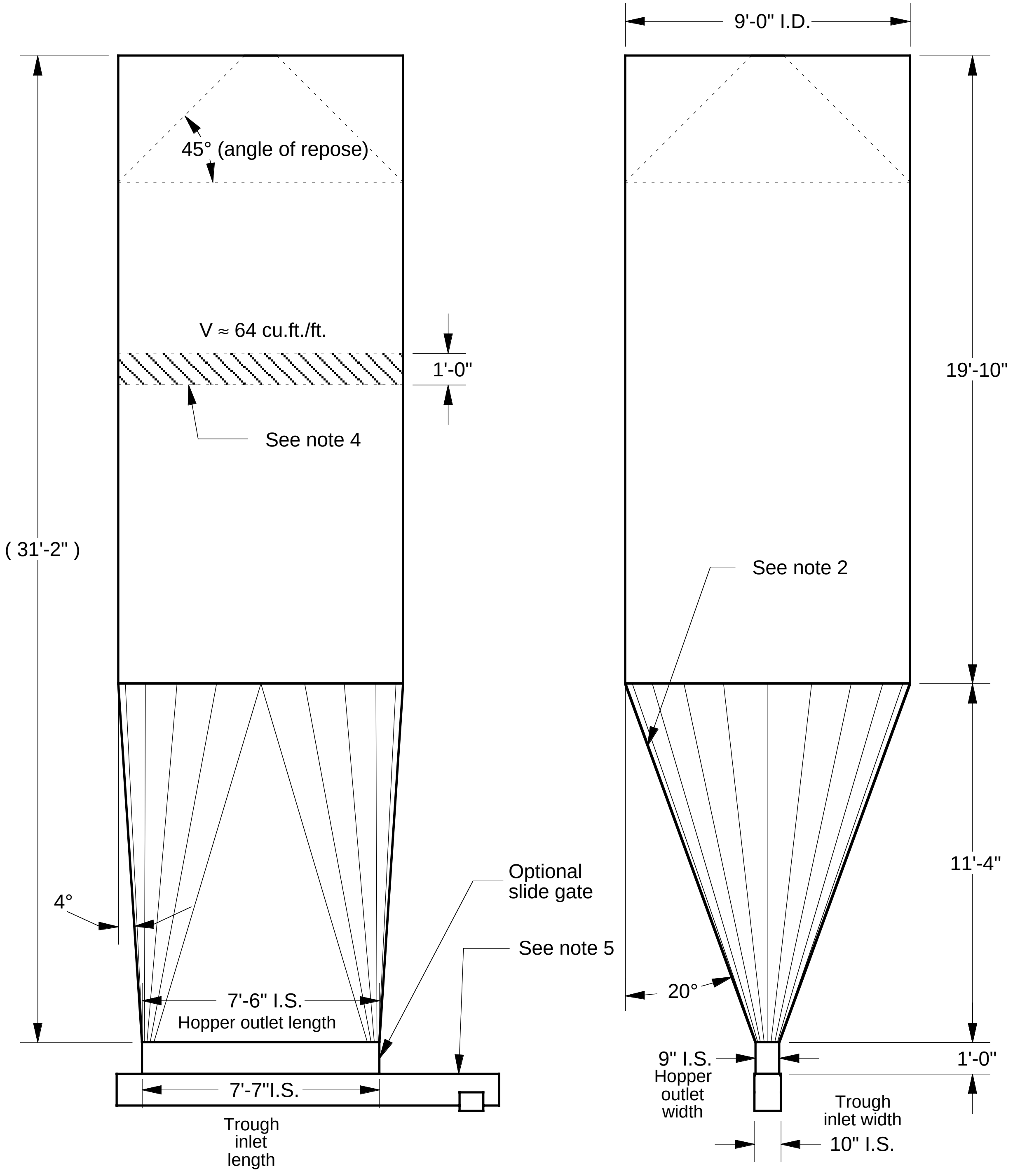

Fig. 8A
Recommended mass flow storage silo for soda ash - Option A

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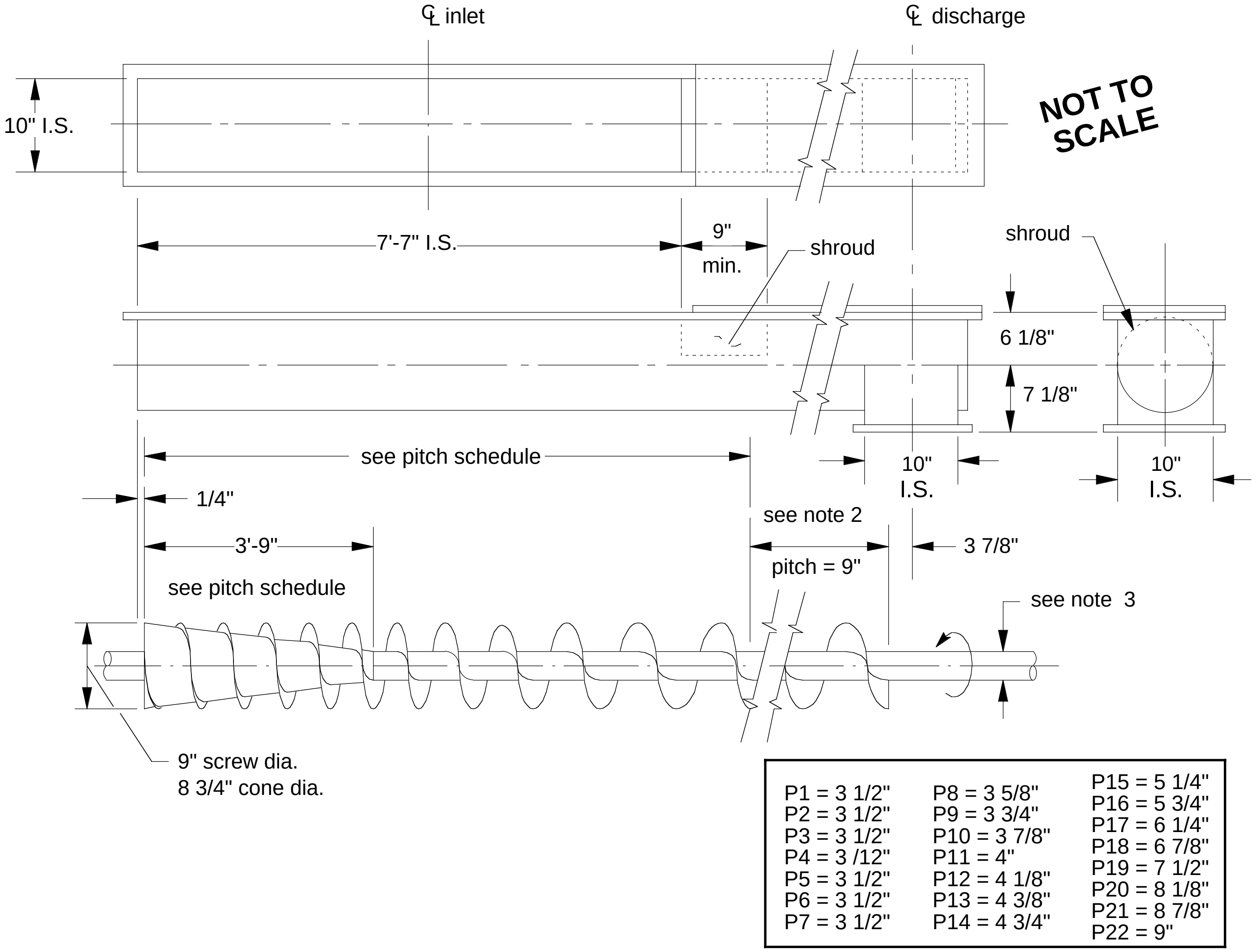
| | | |
|---|---|---|
| Material | Soda ash | |
| Bulk density, lb./cu.ft. | 66 | |
| Rate, lb./hr. | 1,500 | 12,400 |
| RPM | 1.5 | 13 |
| Running torque, in.lb., see note 4 | 7,200 | 7,200 |
| Rec. motor HP see note 4 | 1 | 3 |

Notes:
1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 9" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 3 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/16"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.
7. This screw feeder has the same design as the screw feeder shown in Fig. 6B.



P1 = 3 1/2"
P2 = 3 1/2"
P3 = 3 1/2"
P4 = 3 /12"
P5 = 3 1/2"
P6 = 3 1/2"
P7 = 3 1/2"
P8 = 3 5/8"
P9 = 3 3/4"
P10 = 3 7/8"
P11 = 4"
P12 = 4 1/8"
P13 = 4 3/8"
P14 = 4 3/4"
P15 = 5 1/4"
P16 = 5 3/4"
P17 = 6 1/4"
P18 = 6 7/8"
P19 = 7 1/2"
P20 = 8 1/8"
P21 = 8 7/8"
P22 = 9"

Fig. 8B
Recommended 9 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 1,500 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 9 ft. diameter cylinder, a volume increase of 64 cu.ft. per foot of height can be achieved.
5. See Fig. 8D for recommended mass flow 9 in. diameter screw feeder. The design for this feeder and hopper is the same design as for the feeder and hopper shown in Figs. 6C and 6D.

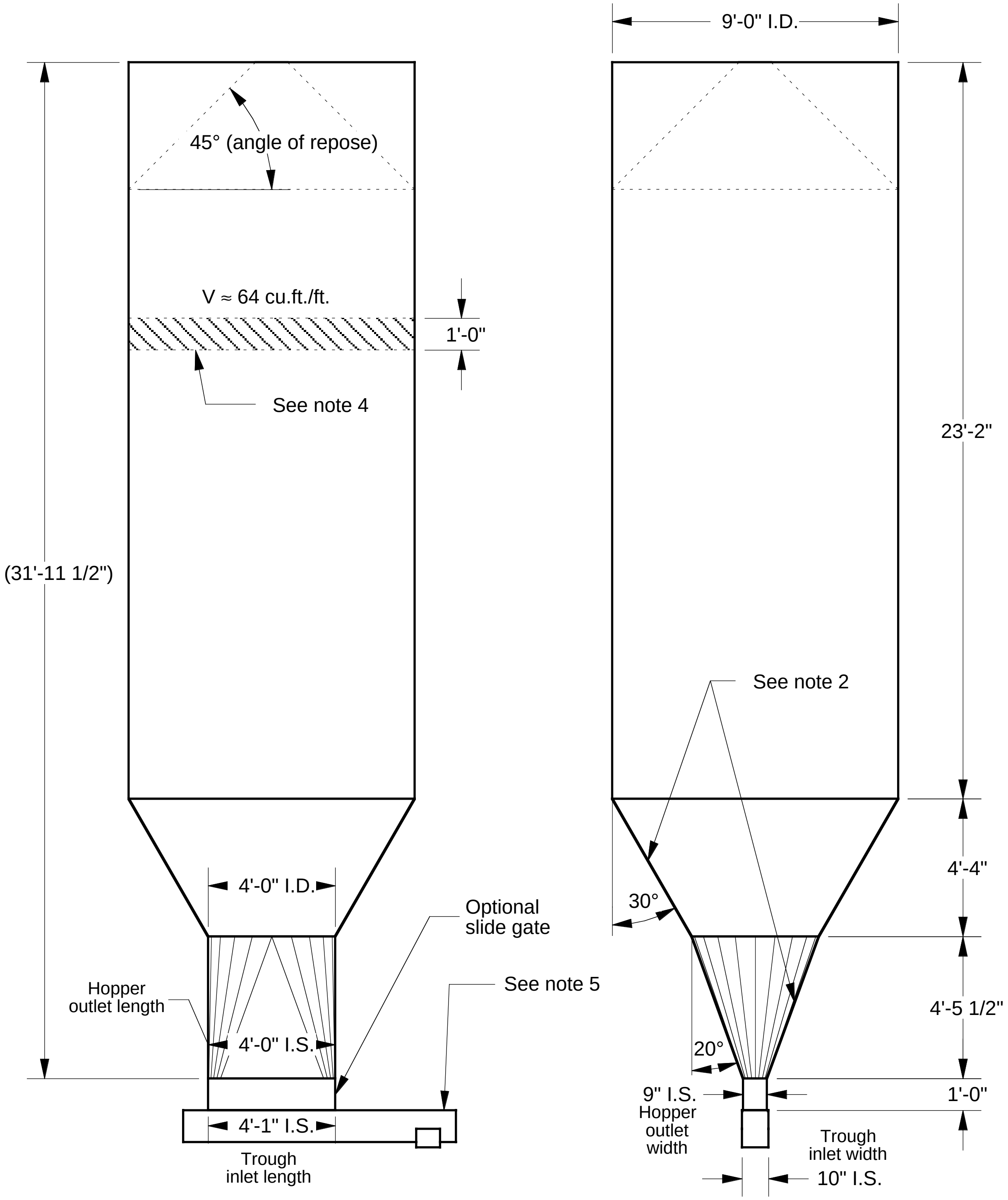

Fig. 8C
Recommended **expanded flow** storage silo for soda ash - Option B

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| | | |
|---|---|---|
| Material | Soda ash | |
| Bulk density, lb./cu.ft. | 66 | |
| Rate, lb./hr. | 1,500 | 12,400 |
| RPM | 2 | 15 |
| Running torque, in.lb., see note 4 | 5,000 | 5,000 |
| Rec. motor HP see note 4 | 1 | 3 |

Notes:
1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 9" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 3 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/4"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.
7. This screw feeder has the same design as the screw feeder shown in Fig. 6D.

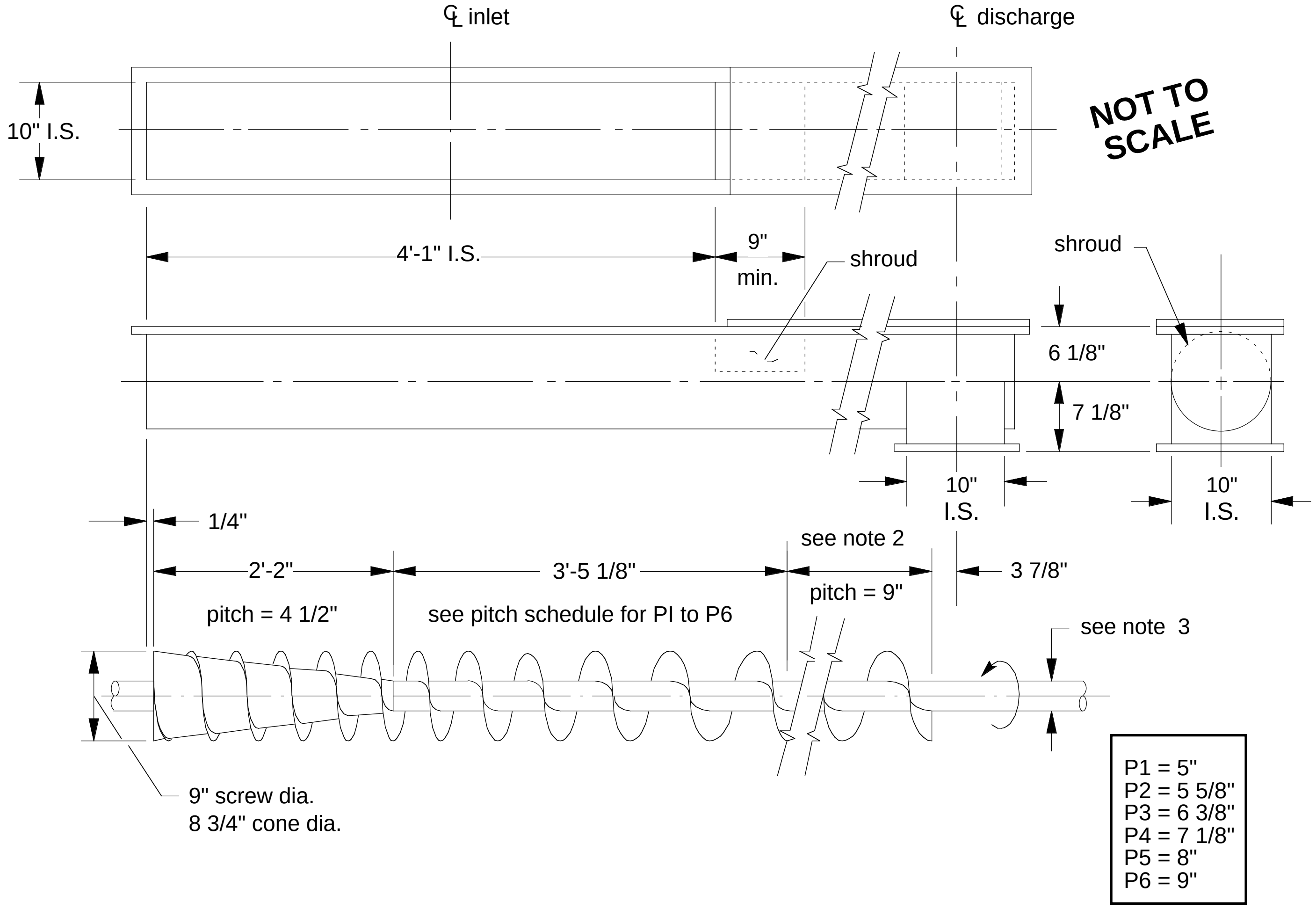

Fig. 8D
Recommended 9 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 2,300 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 11 ft. diameter cylinder, a volume increase of 95 cu.ft. per foot of height can be achieved.
5. See Fig. 9B for recommended mass flow 14 in. diameter screw feeder.

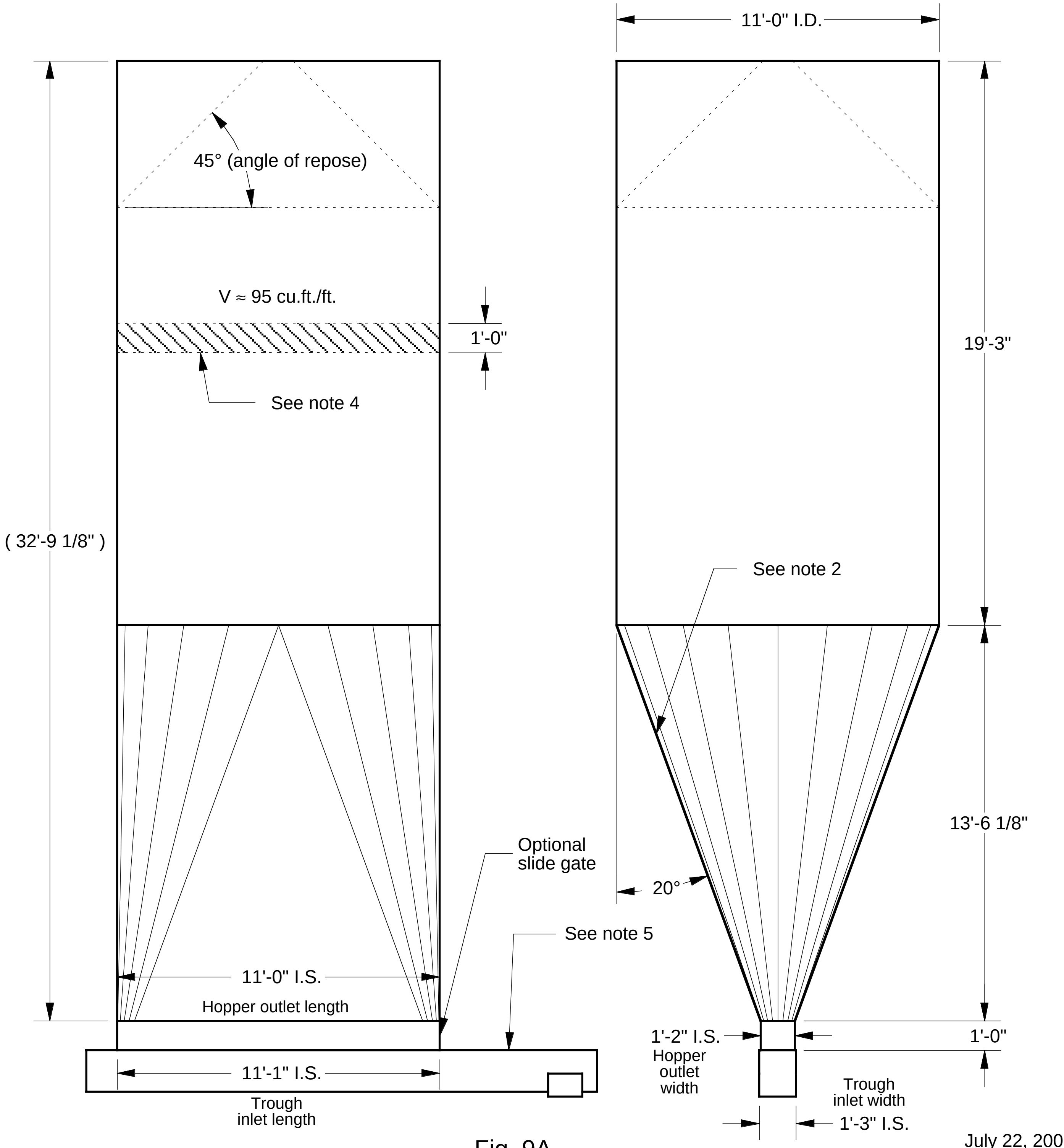

Fig. 9A
Recommended mass flow storage silo for sugar

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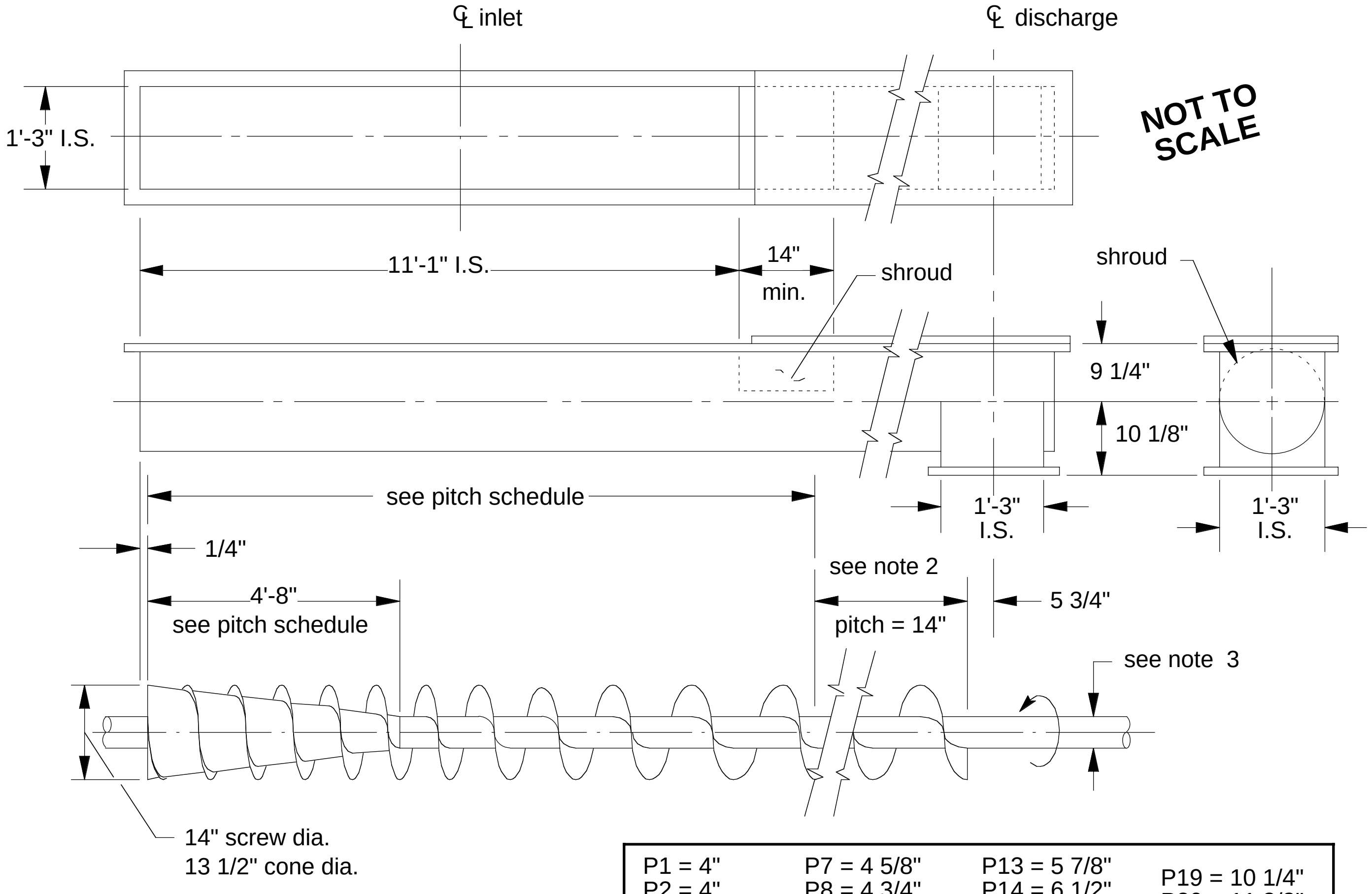
| Material | Sugar |
|---|---|
| Bulk density, lb./cu.ft. | 54 |
| Rate, lb./hr. | 6,600 |
| RPM | 3 |
| Running torque, in.lb., see note 4 | 28,000 |
| Rec. motor HP see note 4 | 3 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 28" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 14" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 6 5/8" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/8"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.



P1 = 4"
P2 = 4"
P3 = 4"
P4 = 4"
P5 = 4 1/8"
P6 = 4 3/8"
P7 = 4 5/8"
P8 = 4 3/4"
P9 = 5"
P10 = 5 1/8"
P11 = 5 3/8"
P12 = 5 1/2"
P13 = 5 7/8"
P14 = 6 1/2"
P15 = 7 1/8"
P16 = 7 3/4"
P17 = 8 1/2"
P18 = 9 3/8"
P19 = 10 1/4"
P20 = 11 3/8"
P21 = 12 3/8"
P22 = 13 5/8"
P23 = 14"

Fig. 9B
Recommended 14 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with 304 stainless steel sheet with a #2B finish.
3. Working capacity ≈ 1,800 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 10 ft. diameter cylinder, a volume increase of 79 cu.ft. per foot of height can be achieved.
5. See Fig. 10B for recommended mass flow 9 in. diameter screw feeder.

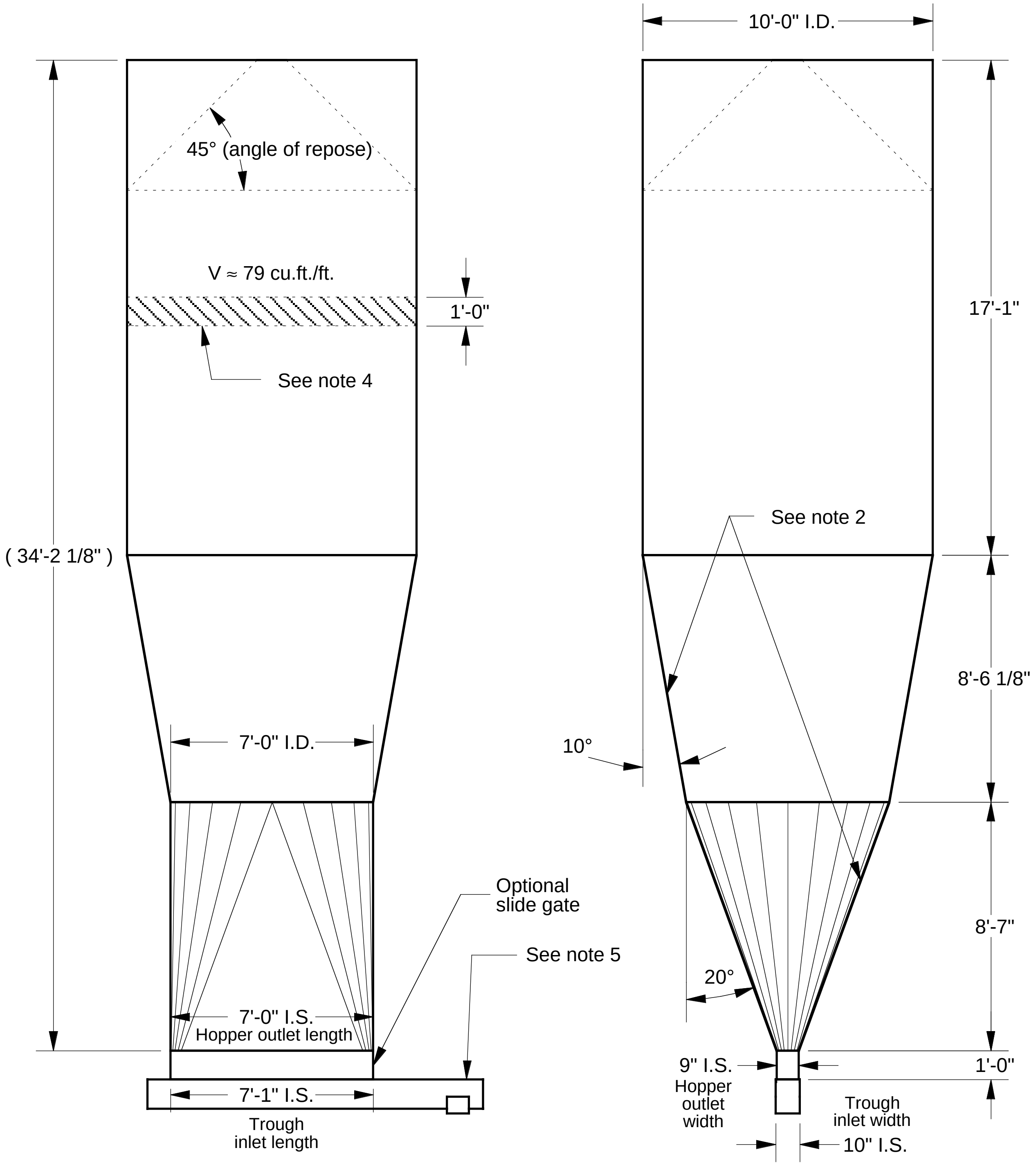

Fig. 10A
Recommended mass flow storage silo for titanium dioxide - Option A

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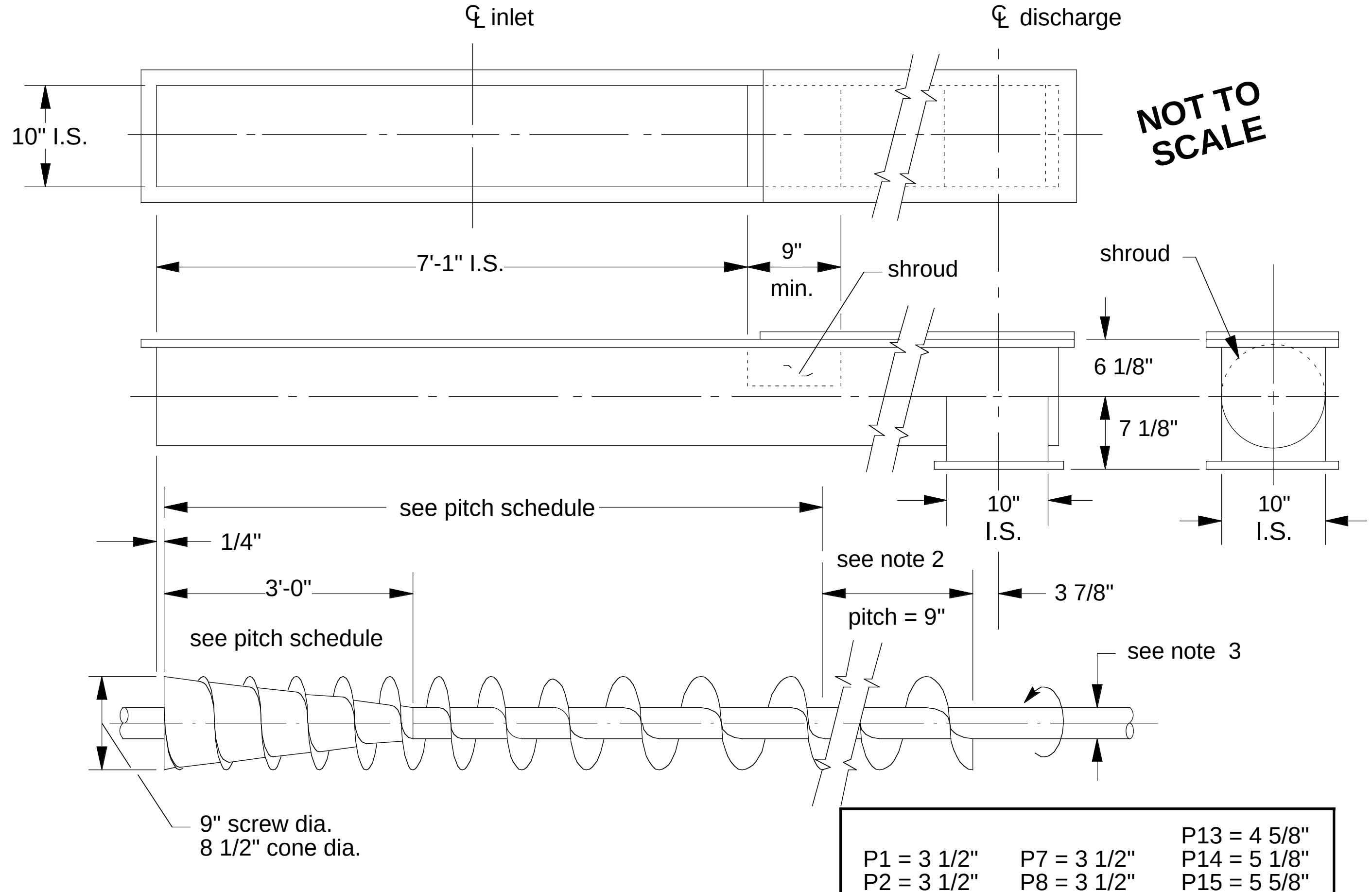
| Material | Titanium dioxide | |
|---|---|---|
| Bulk density, lb./cu.ft. | 117 | |
| Rate, lb./hr. | 1,300 | 1,800 |
| RPM | 1 | 1.5 |
| Running torque, in.lb., see note 4 | 12,200 | 12,200 |
| Rec. motor HP see note 4 | 1 | 1 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 9" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 4 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/16"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.



P1 = 3 1/2"
P2 = 3 1/2"
P3 = 3 1/2"
P4 = 3 1/2"
P5 = 3 1/2"
P6 = 3 1/2"
P7 = 3 1/2"
P8 = 3 1/2"
P9 = 3 1/2"
P10 = 3 5/8"
P11 = 3 7/8"
P12 = 4 1/4"
P13 = 4 5/8"
P14 = 5 1/8"
P15 = 5 5/8"
P16 = 6 1/8"
P17 = 6 3/4"
P18 = 7 3/8"
P19 = 8 1/8"
P20 = 9"

Fig. 10B
Recommended 9 in. diameter mass flow screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate transition hopper interior surfaces with 304 stainless steel sheet with a #2B finish. Line or fabrication 30 deg. conical hopper with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 1,800 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 10 ft. diameter cylinder, a volume increase of 79 cu.ft. per foot of height can be achieved.
5. See Fig. 10B for recommended mass flow 9 in. diameter screw feeder.

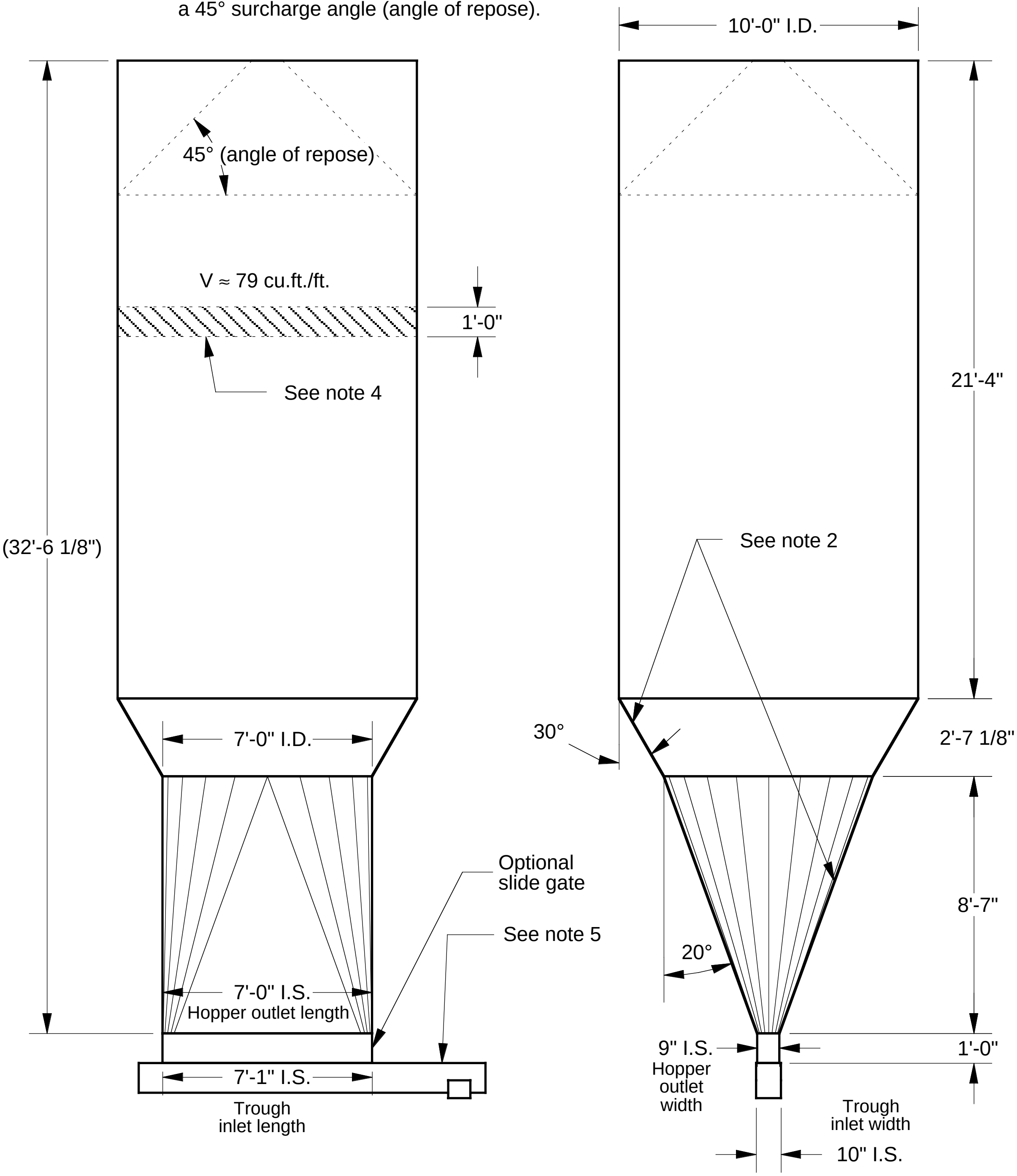

Fig. 10C
Recommended **expanded flow** storage silo for titanium dioxide - Option B

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with 304 stainless steel sheet with a #2B finish.
3. Working capacity ≈ 4,200 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 13 ft. diameter cylinder, a volume increase of 133 cu.ft. per foot of height can be achieved.
5. See Fig. 11B for recommended mass flow twin 12 in. diameter screw feeder.

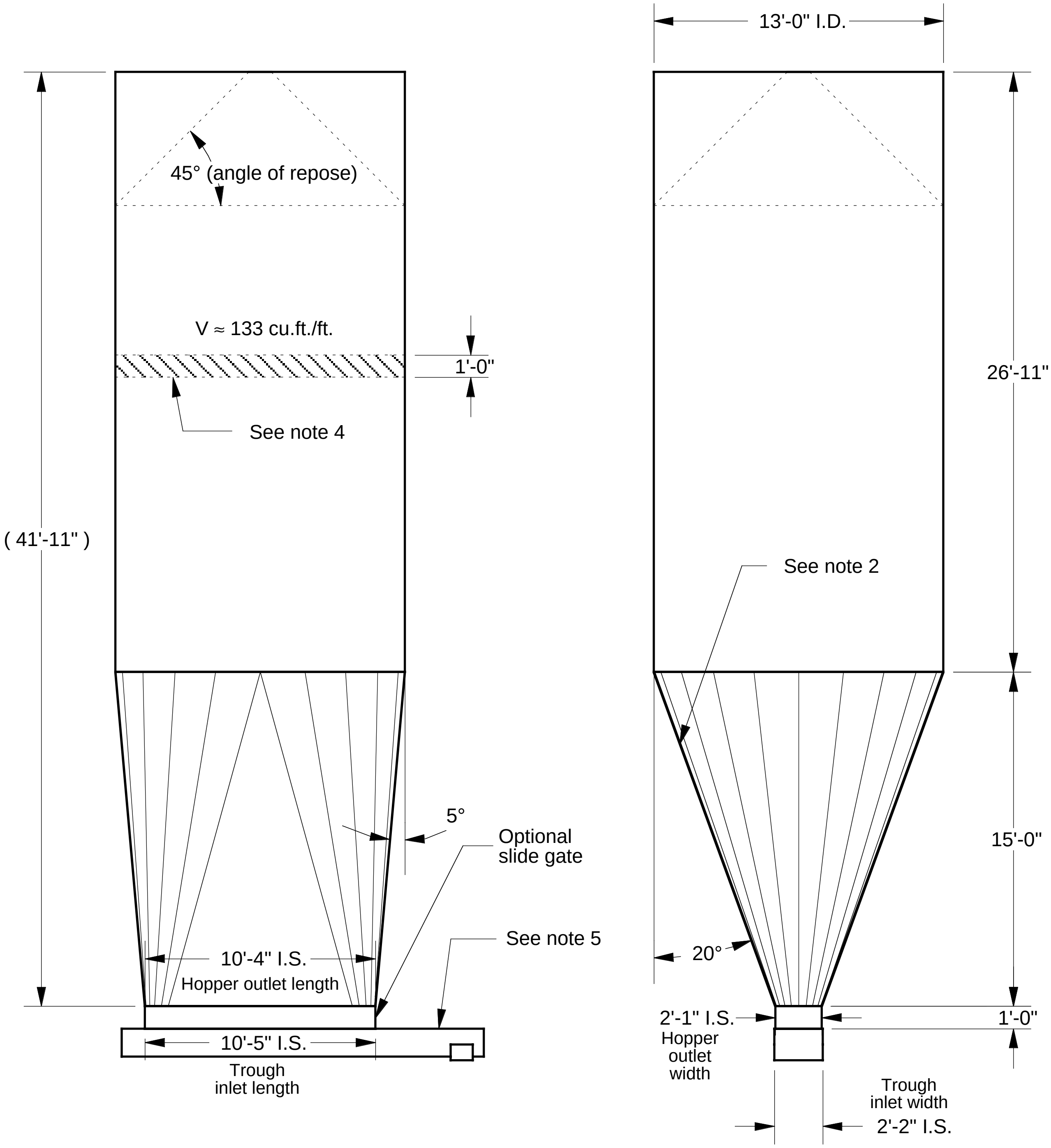

Fig. 11A
Recommended mass flow storage silo for wollastonite - Option A

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| | | |
|---|---|---|
| Material | Wollastonite | |
| Bulk density, lb./cu.ft. | 60 | |
| Rate, lb./hr. | 4,000 | 12,600 |
| RPM | 1 | 3 |
| Running torque, in.lb., see note 4 | 61,400<br>(2 screws) | 61,400<br>(2 screws) |
| Rec. motor HP see note 4 | 3<br>(total) | 7.5<br>(total) |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screws are stopped.
3. A pipe O.D. of 5 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/8"
6. Keep screws 180° out of phase for smoothest discharge.
7. The screws MUST turn simultaneously.
8. Screw trough opening is sized 1" larger in length and width than bin outlet.

P1 = 4"
P2 = 4"
P3 = 4"
P4 = 4"
P5 = 4"
P6 = 4"
P7 = 4"
P8 = 4"
P9 = 4"
P10 = 4"
P11 = 4"
P12 = 4 1/4"
P13 = 4 5/8"
P14 = 5 1/8"
P15 = 5 1/2"
P16 = 6"
P17 = 6 5/8"
P18 = 7 1/8"
P19 = 7 7/8"
P20 = 8 1/2"
P21 = 9 1/4"
P22 = 10 1/8"
P23 = 11"
P24 = 12"

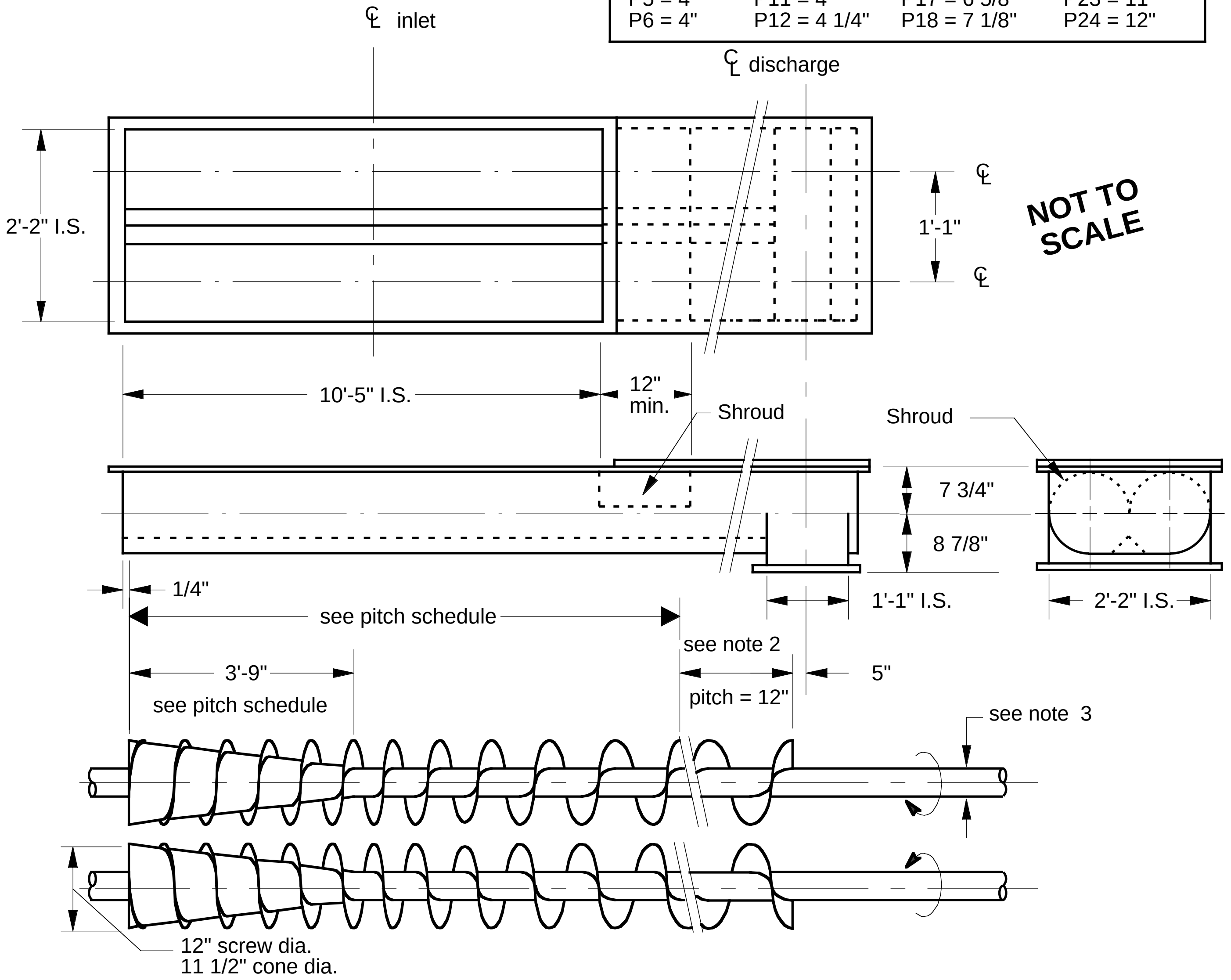

Fig. 11B
Recommended 12 in. diameter mass flow twin screw feeder

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Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with 304 stainless steel sheet with a #2B finish.
3. Working capacity ≈ 4,200 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 13 ft. diameter cylinder, a volume increase of 133 cu.ft. per foot of height can be achieved.
5. See Fig. 11B for recommended mass flow twin 12 in. diameter screw feeder.

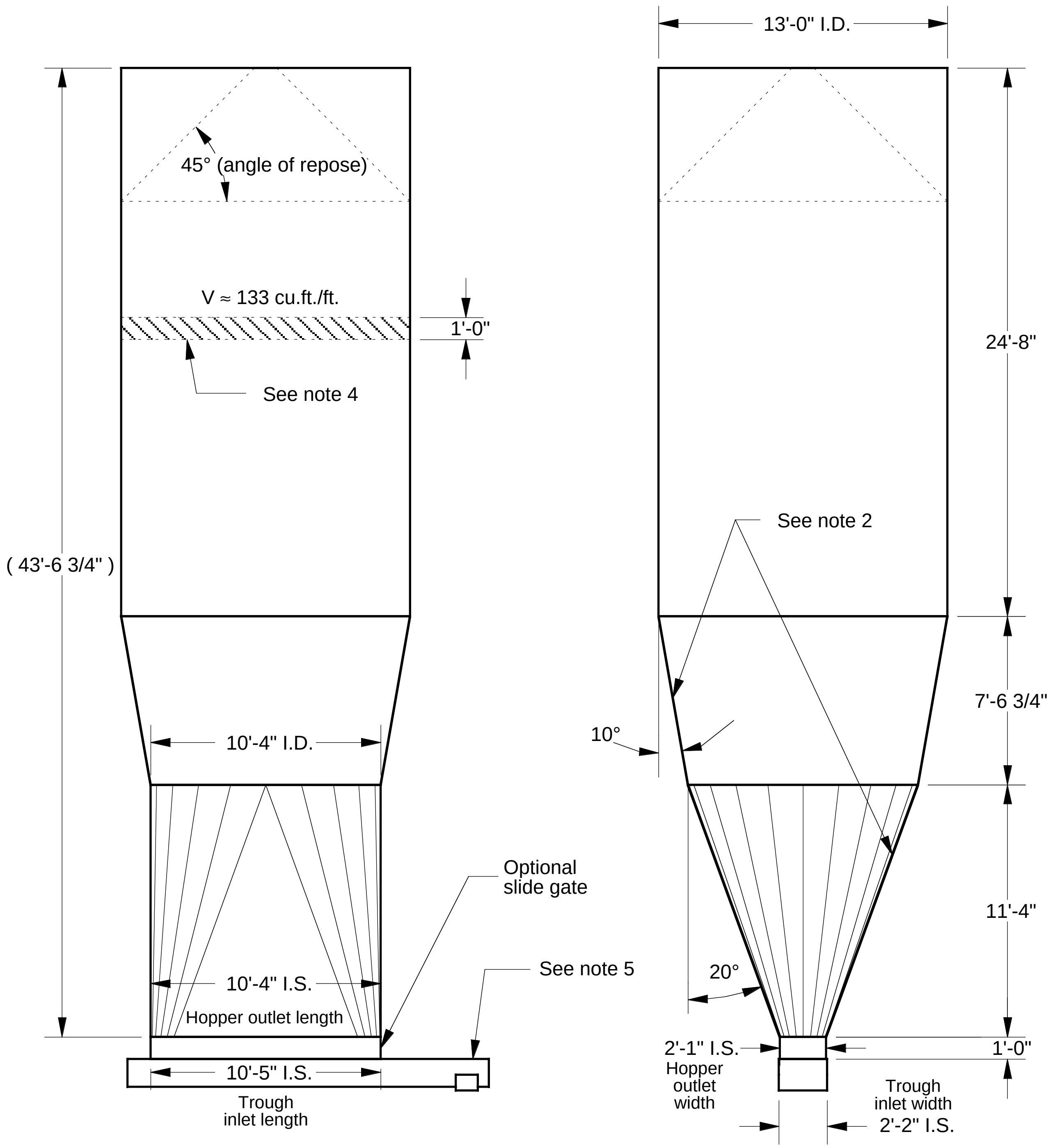

Fig. 11C
Recommended mass flow storage silo for wollastonite - Option B

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Notes:
1. See text for additional information on fabrication requirements.

2. Line or fabricate all interior sloping surfaces with 304 stainless steel sheet with a #2B finish.

3. Working capacity ≈ 2,000 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 10 ft. diameter cylinder, a volume increase of 79 cu.ft. per foot of height can be achieved.

5. See Fig. 12B for recommended mass flow triple 10 in. diameter screw feeder.

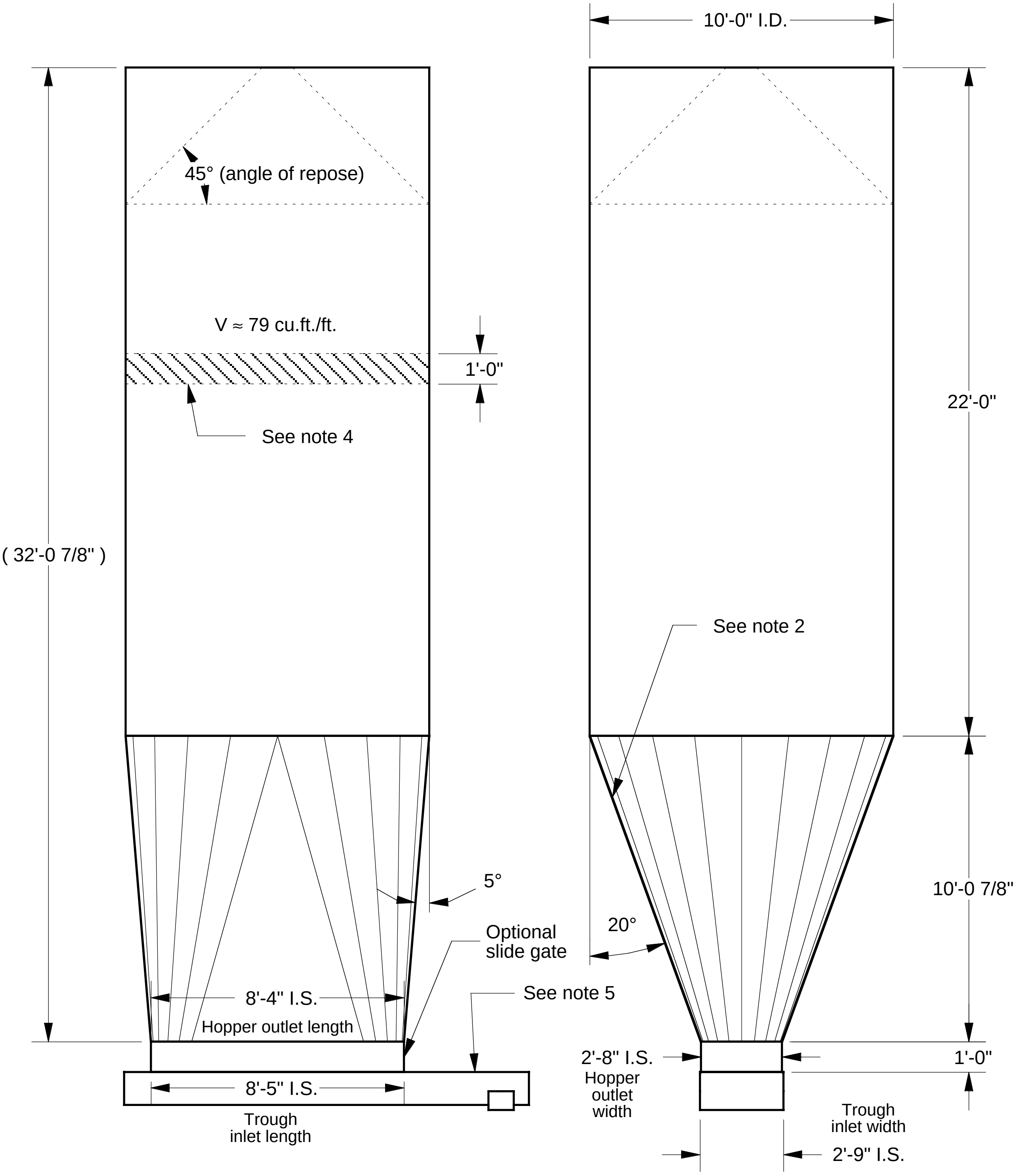

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Fig. 12A
Recommended mass flow storage silo for zinc oxide - Option A

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| Material | Zinc oxide | |
|---|---|---|
| Bulk density, lb./cu.ft. | 43 | |
| Rate, lb./hr. | 2,600 | 2,800 |
| RPM | 1 | 1 |
| Running torque, in.lb., see note 4 | 43,200<br>(3 screws) | 43,200<br>(3 screws) |
| Rec. motor HP see note 4 | 2<br>(total) | 2<br>(total) |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 20" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 10" in order to prevent discharge of material when the screws are stopped.
3. A pipe O.D. of 4 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/16"
6. Keep screws 120° out of phase for smoothest discharge.
7. The screws MUST turn simultaneously.
8. Screw trough opening is sized 1" larger in length and width than bin outlet.

P1 = 3 1/2"
P2 = 3 1/2"
P3 = 3 1/2"
P4 = 3 1/2"
P5 = 3 1/2"
P6 = 3 1/2"
P7 = 3 1/2"
P8 = 3 1/2"
P9 = 3 1/2"
P10 = 3 5/8"
P11 = 3 3/4"
P12 = 3 7/8"
P13 = 4 1/4"
P14 = 4 5/8"
P15 = 5 1/8"
P16 = 5 5/8"
P17 = 6 1/8"
P18 = 6 5/8"
P19 = 7 1/4"
P20 = 8"
P21 = 8 3/4"
P22 = 9 1/2"
P23 = 10"

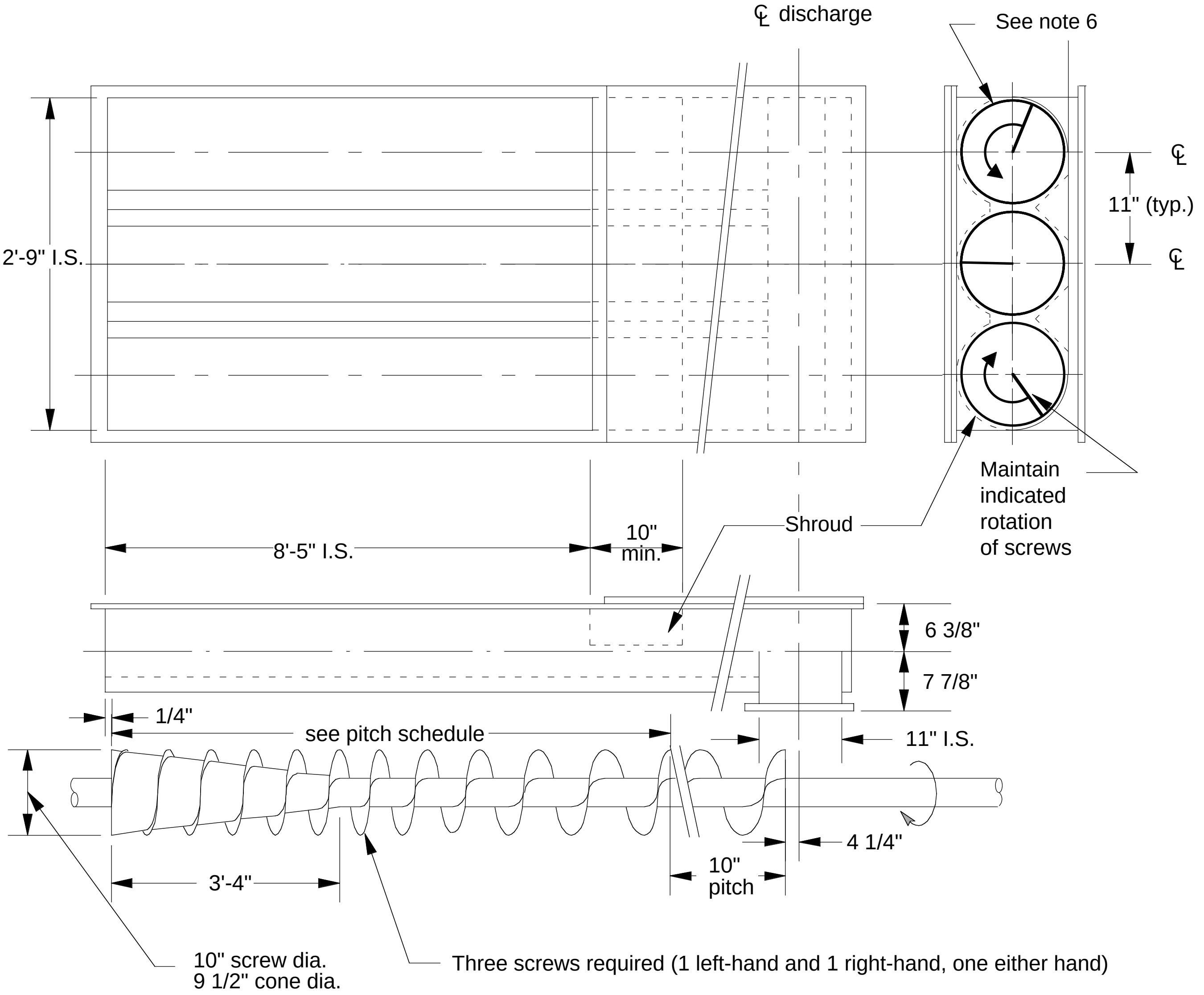

Fig. 12B
Recommended 10 in. diameter mass flow triple screw feeder

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Notes:

1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with 304 stainless steel sheet with a #2B finish.
3. Working capacity ≈ 2,000 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:

4. Additional storage capacity can be achieved by extending the cylinder height. Based on a 10 ft. diameter cylinder, a volume increase of 79 cu.ft. per foot of height can be achieved.
5. See Fig. 12D for recommended mass flow triple 10 in. diameter screw feeder.

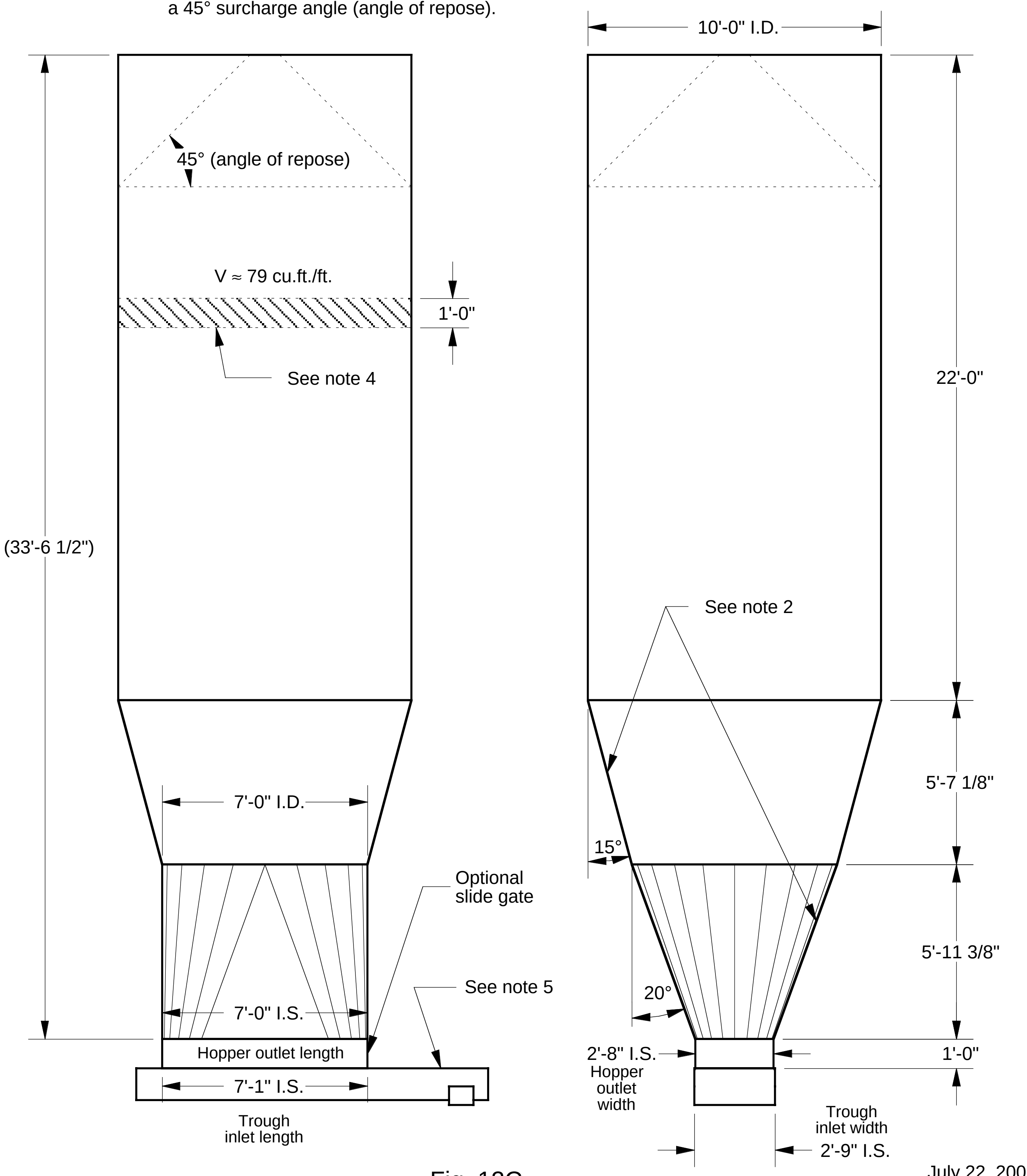

Fig. 12C
Recommended mass flow storage silo for zinc oxide - Option B

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| Material | Zinc oxide | |
|---|---|---|
| Bulk density, lb./cu.ft. | 43 | |
| Rate, lb./hr. | 2,600 | 2,800 |
| RPM | 1 | 1 |
| Running torque, in.lb., see note 4 | 36,000<br>(3 screws) | 36,000<br>(3 screws) |
| Rec. motor HP see note 4 | 2<br>(total) | 2<br>(total) |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 20" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 10" in order to prevent discharge of material when the screws are stopped.
3. A pipe O.D. of 4 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/16"
6. Keep screws 120° out of phase for smoothest discharge.
7. The screws MUST turn simultaneously.
8. Screw trough opening is sized 1" larger in length and width than bin outlet.

P1 = 3 1/2"
P2 = 3 1/2"
P3 = 3 1/2"
P4 = 3 1/2"
P5 = 3 1/2"
P6 = 3 1/2"
P7 = 3 3/4"
P8 = 3 7/8"
P9 = 4 1/8"
P10 = 4 1/4"
P11 = 4 1/2"
P12 = 5"
P13 = 5 1/2"
P14 = 6 1/8"
P15 = 6 3/4"
P16 = 7 1/2"
P17 = 8 3/8"
P18 = 9 3/8"
P19 = 10"

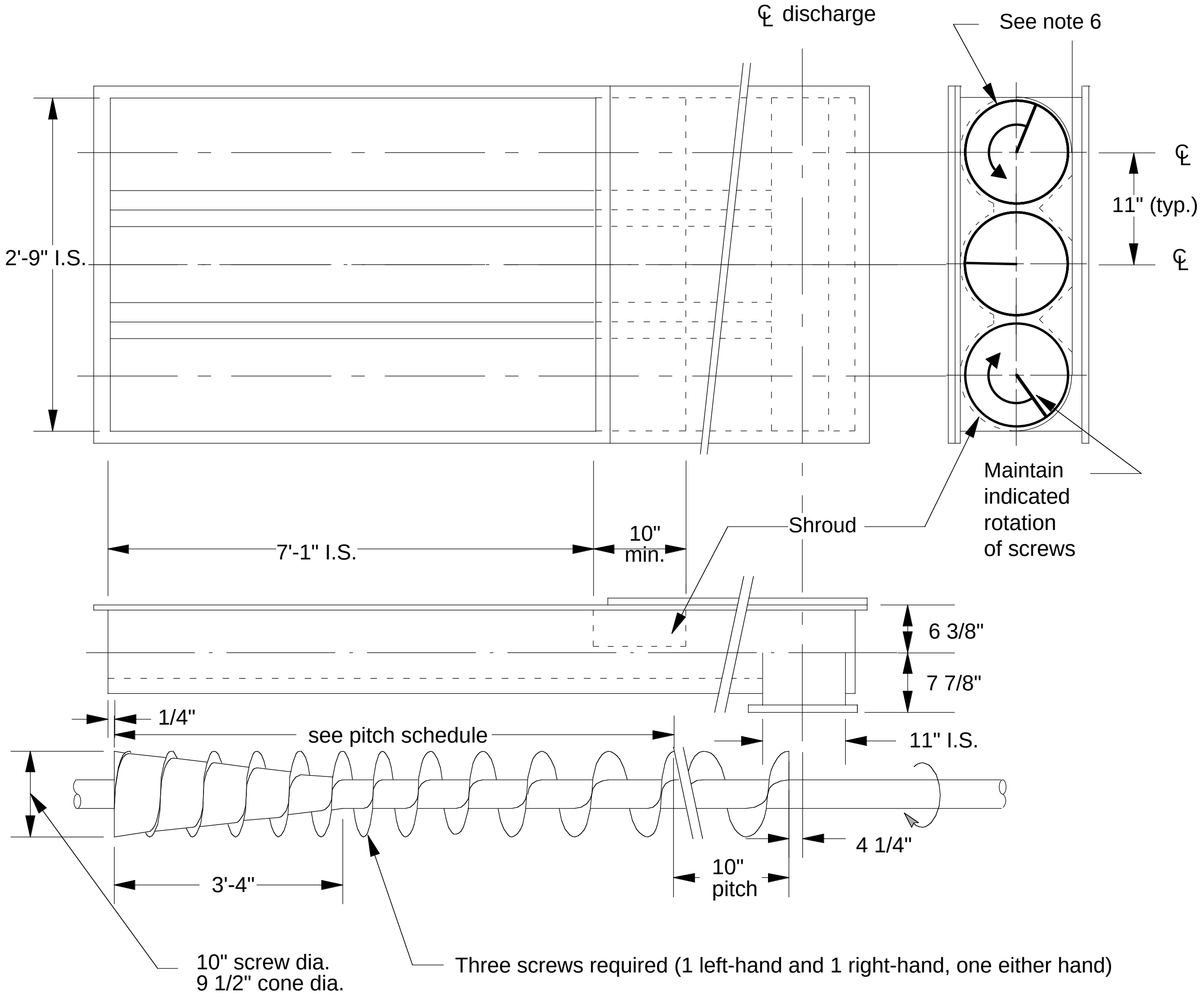

Fig. 12D
Recommended 10 in. diameter mass flow triple screw feeder

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4537-2
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JENIKE & JOHANSON

Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 900 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 8 ft. diameter cylinder, a volume increase of 50 cu.ft. per foot of height can be achieved.
5. See Fig. 13B for recommended mass flow 9 in. diameter screw feeder. This feeder and transition hopper design is the same as the feeder and transition hopper design to be used for the iron oxide silo.

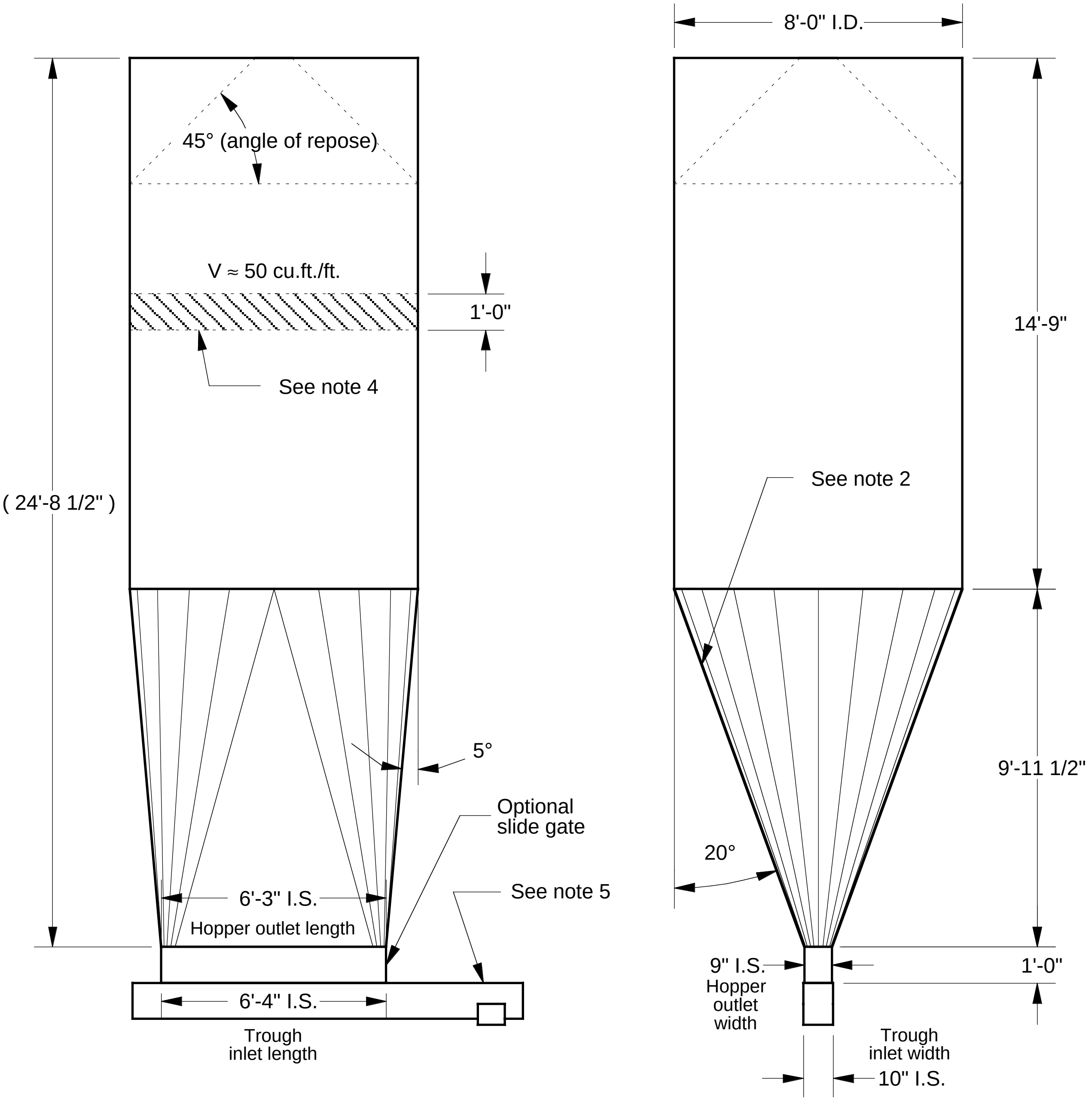

Fig. 13A
Recommended mass flow storage silo for zircon flour - Option A

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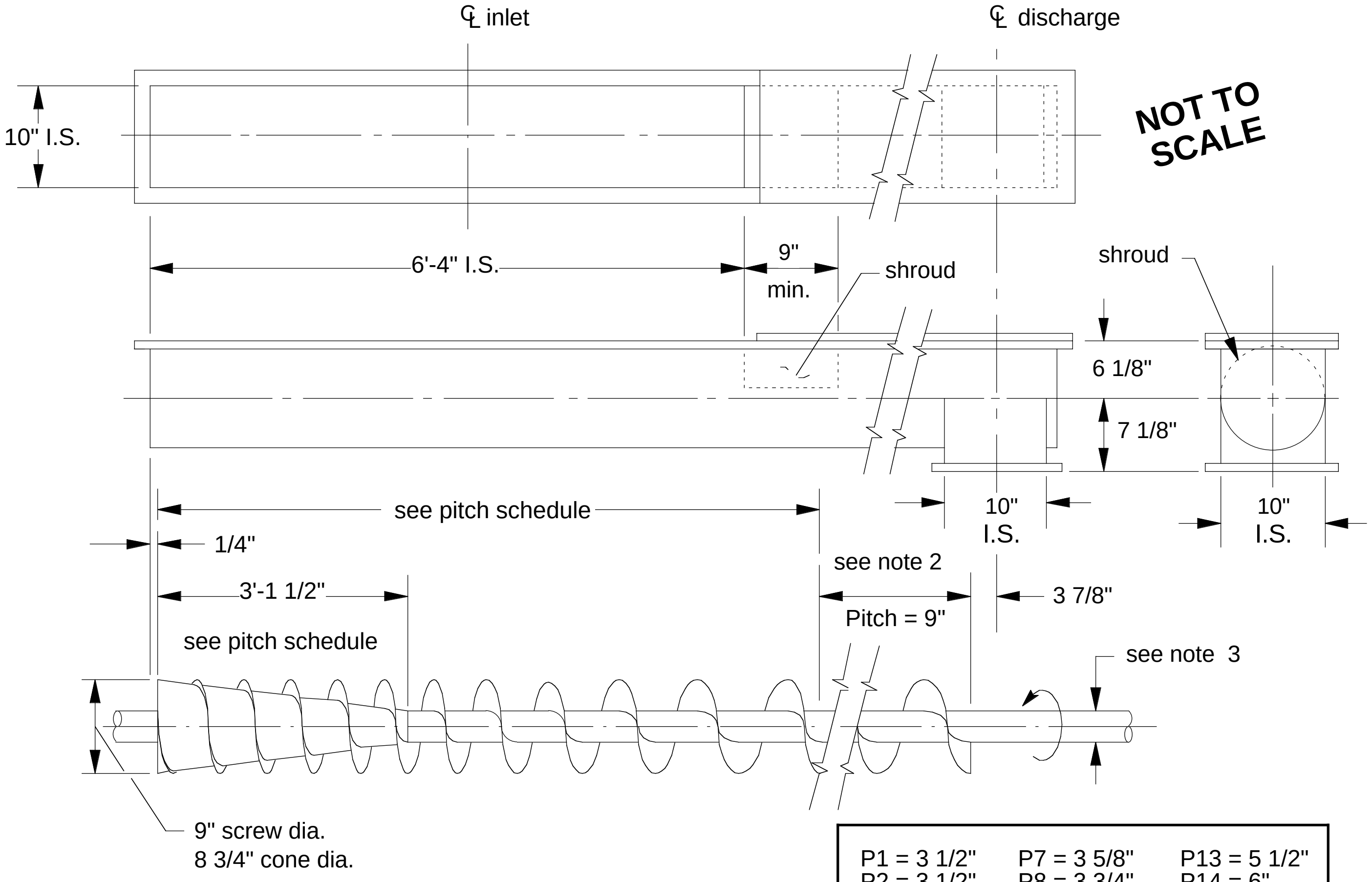
JENIKE & JOHANSON

| Material | Zircon flour | |
|---|---|---|
| Bulk density, lb./cu.ft. | 133 | |
| Rate, lb./hr. | 4,000 | 4,400 |
| RPM | 2 | 2.5 |
| Running torque, in.lb., see note 4 | 12,200 | 12,200 |
| Rec. motor HP see note 4 | 1.5 | 1.5 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 18" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 9" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 3 1/2" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 1/16"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.
7. This screw feeder has the same design as the screw feeder shown in Fig. 3B.



P1 = 3 1/2"
P2 = 3 1/2"
P3 = 3 1/2"
P4 = 3 1/2"
P5 = 3 1/2"
P6 = 3 1/2"
P7 = 3 5/8"
P8 = 3 3/4"
P9 = 3 7/8"
P10 = 4 1/8"
P11 = 4 3/8"
P12 = 4 7/8"
P13 = 5 1/2"
P14 = 6"
P15 = 6 3/4"
P16 = 7 1/2"
P17 = 8 3/8"
P18 = 9"

Fig. 13B
Recommended 9 in. diameter mass flow screw feeder

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4537-2
Rev. 0

JENIKE & JOHANSON

Notes:
1. See text for additional information on fabrication requirements.
2. Line or fabricate all interior sloping surfaces with mild carbon steel with a #1 mill finish.
3. Working capacity ≈ 900 cu.ft. assuming a 45° surcharge angle (angle of repose).

Notes:
4. Additional storage capacity can be achieved by extending the cylinder height. Based on an 8 ft. diameter cylinder, a volume increase of 50 cu.ft. per foot of height can be achieved.
5. See Fig. 13D for recommended mass flow 12 in. diameter screw feeder. The feeder and hoppers below are the same as those designed for the iron oxide silo (Figs. 3C, 3D).

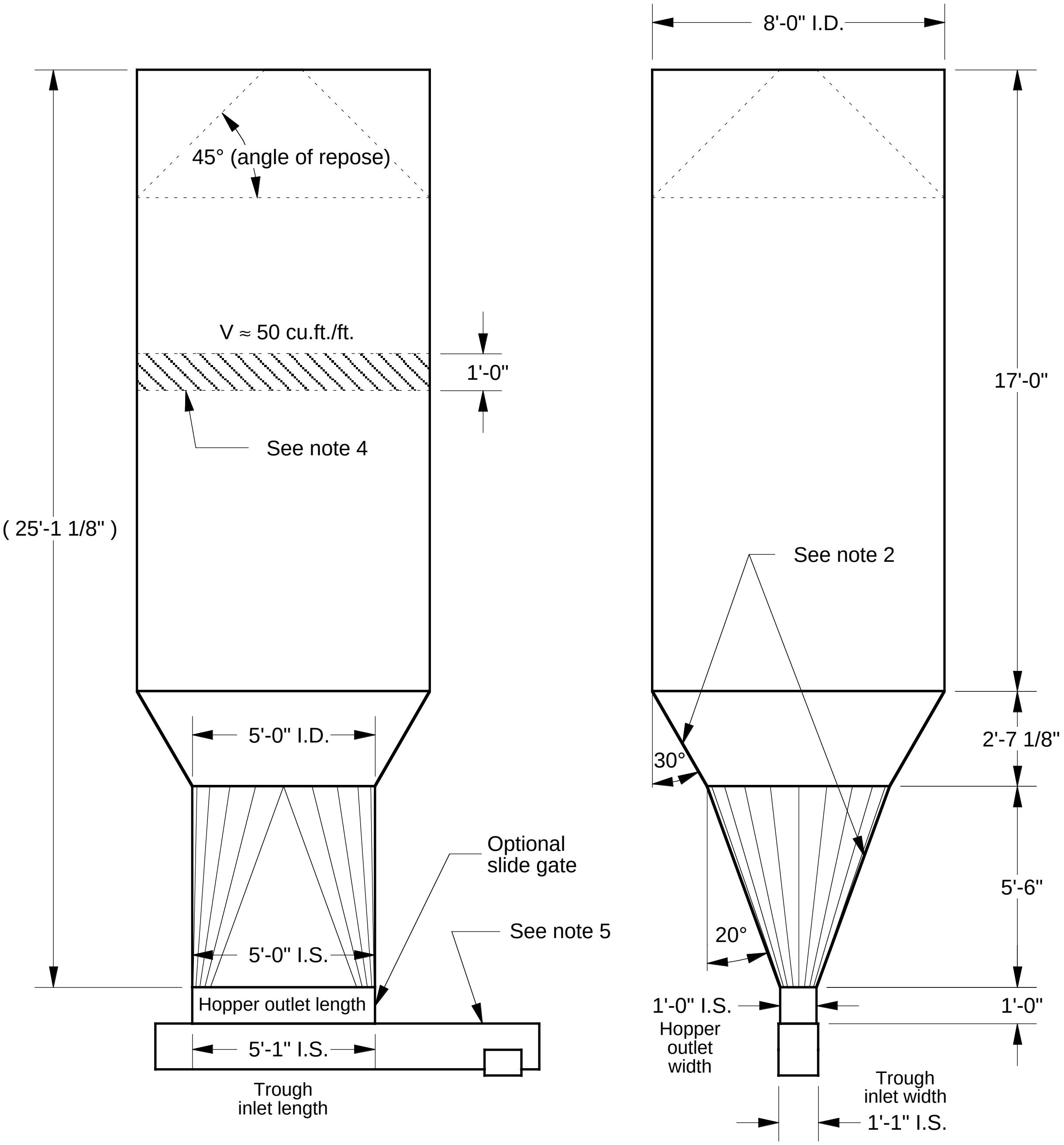

Fig. 13C
Recommended **expanded flow** storage silo for zircon flour - Option B

July 22, 2002
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Rev. 0

| Material | Zircon flour | |
|---|---|---|
| Bulk density, lb./cu.ft. | 133 | |
| Rate, lb./hr. | 4,000 | 4,400 |
| RPM | 1 | 1.5 |
| Running torque, in.lb., see note 4 | 28,000 | 28,000 |
| Rec. motor HP see note 4 | 1.5 | 1.5 |

Notes:

1. Internal hanger bearings should not be used (see text).
2. A length of 24" has been assumed for the constant pitch conveying section in order to calculate torque and horsepower. This length can be changed, but the minimum length is 12" in order to prevent discharge of material when the screw is stopped.
3. A pipe O.D. of 6 5/8" has been assumed for the RPM calculation. This must be checked for structural integrity.
4. Starting torque and power can be as much as 2 1/2 times values specified for running. Also, recommended motor size is based on assumed drive efficiency of 90% (see text).
5. Pitch tolerance = ± 3/8"
6. Screw trough opening is sized 1" larger in length and width than bin outlet.
7. This screw feeder has the same design as the screw feeder shown in Fig. 3D.

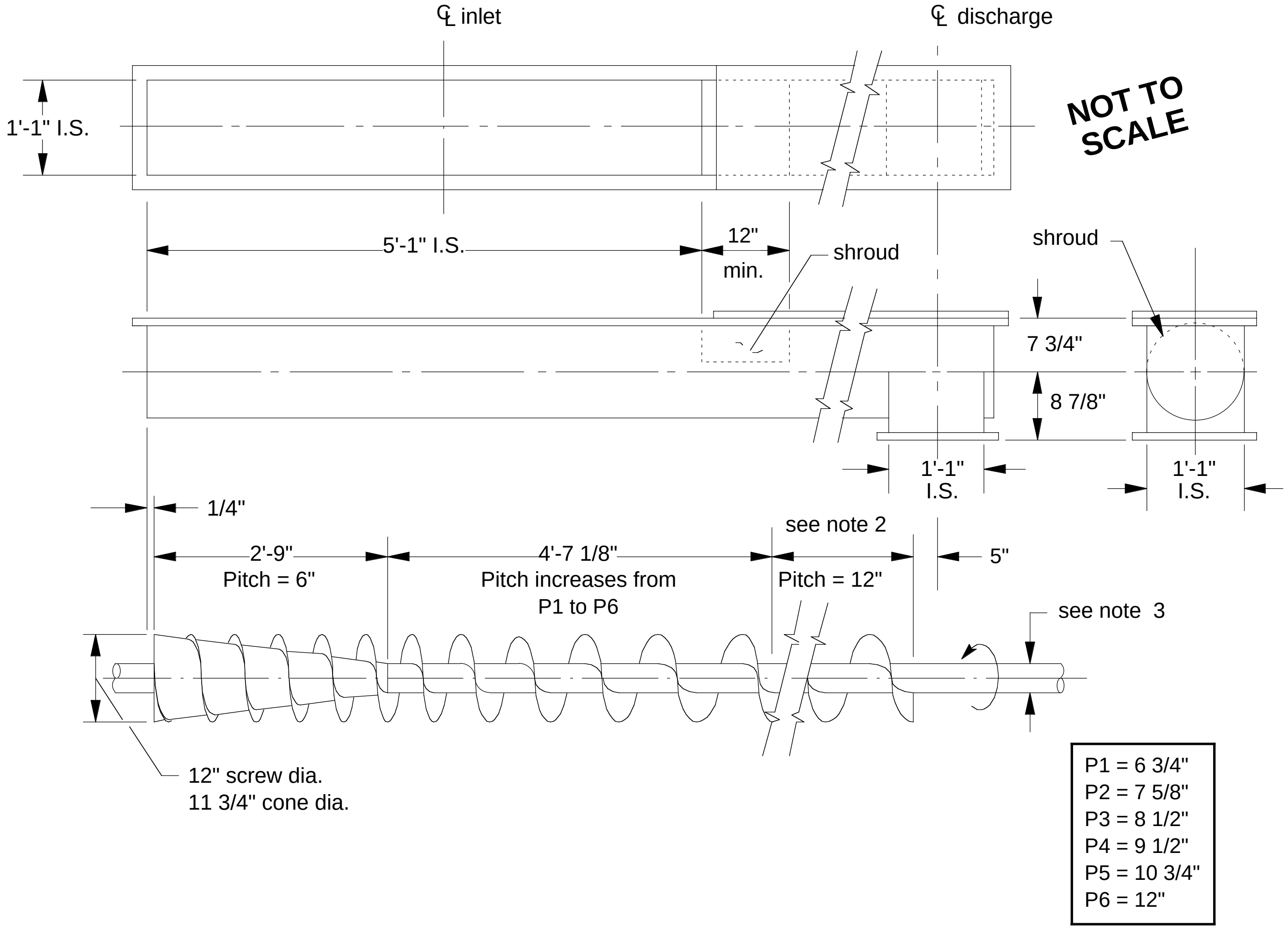

Fig. 13D
Recommended 12 in. diameter mass flow screw feeder

July 22, 2002
4537-2
Rev. 0

# APPENDIX G. DATA QUALIFICATION REPORT (WSRC-TR-2003-00252)

**WESTINGHOUSE SAVANNAH RIVER COMPANY**

# INTEROFFICE MEMORANDUM

SRT-RPP-2003-00116

June 24, 2003

**TO:** H. F. STURM, JR., 773-A

**FROM:** D. A. CROWLEY, 999-W dac 6/25/04

## DATA QUALIFICATION REPORT (WSRC-TR-2003-00252)

Attached is the Data Qualification Report, WSRC-TR-2003-00252. If you have any questions in reference to the attached document, please contact Ray Schumacher at 819-8419.

Att.

C: R. F. Schumacher, 999-W /346
E. K. Hansen, 999-W /400
✓J. C. George, 999-W /402
T. B. Calloway, 999-W /336
F. J. Leach, 773-A /A205
K. A. Howard, 773-42A /136
J. P. Vaughan, 773-41A
S. J. Boggs, RPP Files773-A /A256
QAE File, 773-41A /220

**WSRC-TR-2003-00252**

# Data Qualification Report

by
R. F. Schumacher
Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

SRS™
savannah river site
where excellence is achieved

Quality Assurance
River Protection Project
Data Qualification Report
Jenike & Johanson

# Data Qualification Report

R. F. Schumacher
R. F. Schumacher

6/16/03
Date

J. P. Vaughan
J. P. Vaughan, QA Engineer
Independent Reviewer

6/16/03
Date

David A. Crowley
D. A. Crowley
Process Development RPP ManagerSavannah River Technology Center

6/17/03
Date

# DATA QUALIFICATION REPORT

## A. Purpose

The purpose of this report is to qualify existing data that was produced by a subcontractor and procured by SRTC. The River Protection Project-Waste Treatment Plant (RPP-WTP) Quality Assurance (QA) requirements were not imposed on this data. The deficiency was documented in two reports: an SRTC Problem Identification Report, 2002-PIR-11-00052, and an RPP-WTP Supplier Corrective Action Report, 24590-WTP-SCAR-03-007.

The method employed to qualify the data was to examine the difference between current controls and those when the non-qualified data was taken, and to determine what impact the difference in controls could have on the data.

## B. Qualification Methods Used

SRTC issued a purchase order to Jenike & Johanson Inc. (J&J) without specifying applicable NQA-1-1989 QA requirements required for RPP-WTP activities. J&J does not have a formal NQA-1 Program. The method selected to qualify J&J produced data was to examine the difference in controls between the non-qualified data and current RPP-WTP QA contractual requirements. Additionally an analysis was performed to determine how much impact the difference in controls could have had on the non-qualified data.

Rational for a comparison of program/laboratory controls exercised by J&J to the RPP-WTP QA requirements was based on J&J's position in the industry. J&J is not an equipment fabricator or supplier. J&J is one of the leading authorities on powder/bulk solids flow in the United States. J&J provides physical characterization of bulk solids, design of bulk solids processes based on the physical characterization of bulk solids, and troubleshoots/consults on bulk solids handling problems.

## C. Identification of Non-Qualified Data Set and Purpose of Qualified Data

J&J was selected to measure the physical and flow properties of 13 individual Glass Former Chemicals (GFC's), three representative LAW blends, and two representative HLW blends under "as received" and "at rest" conditions. These measurements were performed according to ASTM standards developed by J&J. This data can be incorporated into the performance specification developed by Design Engineering for the actual design and build of the facility which will be subcontracted to a bulk solids handling company. J&J was also tasked to provide the following:

- A review of the preliminary Glass Former Storage Facility (GFSF) conceptual design.
- Detailed mass flow and expanded flow designs for the thirteen GFC receiving silos.
- General information on the delivery of dry GFC's to the MFPV.
- General design issues relative to bulk solids handling.
- A document on recommendations for handling GFC's.

## D. Evaluation of QA Programs

What follows are the sections of NQA-1-1989 that have been identified as being applicable to the J&J work using a graded approach. The applicable elements of the graded QA program application to J&J has been documented in the Technical Task Plan, WSRC-TR-2001-00424, "Selection of HLW and LAW Glass Former", Revision 1, dated 3/05/03. The evaluation assessed NQA-1-1989 requirements with J&J internal processes and controls.

Detailed evaluation is provided as follows:

### NQA-1-1989, Part II Basic Requirements

1.0. Organization

The organizational structural, functional responsibilities, levels of authority, and lines of communications for activities affecting quality shall be documented.... Such persons or organizations shall have direct access to responsible management at a level where appropriate action can be effected. Such persons or organizations shall report to a management level such that required authority and organizational freedom are provided, including sufficient independence from cost and schedule considerations.

J&J Evaluation:

J&J has an established organizational structure defined for the President and other key personnel responsible for performing activities in accordance with established and proven processes and controls and procurement requirements. J&J implements proper laboratory protocol and training for the laboratory technicians including identifying problems to management as required. Responsible management reviews the test results as they are developed.

## 2.0. QA Program

A documented quality assurance program shall be planned, implemented, and maintained in accordance with this Standard or portions thereof. The program shall identify the activities and items to which it applies.... The program shall provide for indoctrination and training as necessary of personnel performing activities affecting quality to assure that suitable proficiency is achieved and maintained.

J&J Evaluation:

J&J implements stringent and rigorous corporate and laboratory training programs to ensure that proper laboratory testing protocol is undertaken by all technicians ensuring that data generated from material characterization is free from technician bias or equipment error.

Laboratory training for new technician
- Must undergo three months of intensive testing equipment training (technician under constant supervision of laboratory supervisor)
- Review of personal protective equipment procedures used in laboratory (e.g., respirator, powered air purifying respirator, gowning requirements, safety glasses/goggles, gloves, etc.)
- Review of techniques used for raw test data analyses
- Review of data collection and entry procedures
- Review of test equipment calibration procedures

QA programs at J&J
- All raw and refined data generated from bulk solids testing and characterization are reviewed by laboratory supervisor or laboratory manager
- All raw and refined data generated from bulk solids testing and characterization are reviewed by project or senior engineer before data are released for design purposes
- New test equipment is calibrated and checked against baseline to ensure proper performance
- Changes in test equipment operational procedures discussed with all personnel
- Strict test equipment calibration procedures are followed

## 5.0 Instruction, Procedures, and Drawings

Activities affecting quality shall be prescribed by and performed in accordance with documented instructions, procedures, or drawings of a type appropriated to the circumstances...These documents shall...have been satisfactorily accomplished.

J&J Evaluation:

Testing performed by J&J was performed in accordance with the purchase requirements, i.e., ASTM D 6128-97, Standard Shear Method for Bulk Solids Using the Jenike Shear Cell, (developed by J&J) and recently approved ASTM D-6683-01, Standard Test Method for Measuring Bulk Density of Powers and other Bulk Solids, for compressibility tests. These are industry-recognized standards. Additionally, SRTC and RPP-WTP project personnel witnessed the tests and recorded primary data during the testing phase (Refer to Attachment 2). No anomalies were noted by J&J or the representatives of SRTC/RPP-WTP. A video tape of the techniques utilized by J&J was made and is available.

## 6.0 Document Control

The preparation, issue, and change of documents that specify quality requirements or prescribe activity affecting quality shall be controlled to assure that correct documents are being employed…

J&J Evaluation:

See item 5.0 evaluation. Additionally, J&J Management reviews all final reports to ensure conclusions and recommendation are correctly drawn.

## 8.0 Identification and Control of Items

Controls shall be established to assure that only correct and accepted items are used or installed. Identification shall be maintained on the items or in documents traceable to the items, or in a manner which assure that identification is established and maintained.

J&J Evaluation:

Identification and control of items (samples of GFC) is established and maintained during normal laboratory protocol during the sampling and characterization process.

## 11.0 Test Control

Test required to verify conformance of an item or…Test required to collect data…shall be planned, executed, documented, and evaluated.

J&J Evaluation:

Testing/data collection was performed implementing the ASTM methods. Laboratory technicians collected the data which was evaluated by appropriate technical personnel and issued as a report to SRTC.

Additionally, ASME NQA-1-1989, Supplement 11S states that "In lieu of specially prepared written test procedures, appropriate sections of related documents, such as ASTM methods, Supplier manuals, equipment maintenance instructions, or approved drawings or travelers with acceptance criteria can be used.

## 12.0 Control of Measuring and Test Equipment

Tools, gages, instruments, and other measuring and test equipment used for activities affecting quality shall be controlled and at specified periods calibrated and adjusted to maintain accuracy within necessary limits.

J&J Evaluation:

J&J maintains an array of calibrated instruments. As the leading authority of the applicable ASTM Standards implemented during the testing it was imperative that measurement and test equipment is-maintained and within calibration limits to ensure correct results. Example of testing equipment calibration protocols are:

1. Jenike Direct Shear Tester
    a. Utilized span setting device to calibrate load cell
    b. Calibrate at 0 lb. and 9 lb. setting using pre-calibrated weights
    c. Calibration performed weekly
2. Jenike-Schulze Ring Shear Tester
    a. Utilized custom device to calibrate load cells
    b. Calibrate at specified settings using pre-calibrated weights
    c. Performed each time after tester is relocated
3. Compressibility Tester
    a. Utilized 0.75 in. gauge block to calibrate dial indicator
    b. Performed before each test

4. Laboratory Electronic Scales
    a. Used 200 g or 600 g calibrated weights to calibrate scales
    b. Performed monthly
5. Permeability Tester
    a. Leak check performed quarterly
    b. Depth gauge is calibrated before each test
6. Chute Tester - Calibration not required
7. Angle of Repose - Calibration not required
8. Malvern Particle Size Analyzer
    a. Calibration performed by Jenike & Johanson and vendor using calibrating sample
    b. Performed quarterly or more frequently as required
    c. Unit was calibrated in July, one month after the RPP tests. Unit was in calibration.
9. High Temperature Ovens
    a. Calibration performed with thermocouples
    b. Performed with each use
10. Environmental Chamber
    a. Calibration performed to check relative humidity and temperature
    b. Performed semi-annually or during each maintenance servicing

13.0 Handling, Storage, and Shipping

Handling, storage, cleaning, packaging, shipping, and preservation of items shall be controlled to prevent damage or loss and to minimize deterioration.

J&J Evaluation:

Handling, storage, and shipping applicable controls required by the purchase order were found to be satisfactory. J&J protocol, and as defined in the applicable ASTM Standard, places strict handling requirements on the samples. The purchase order required storage requirements of the samples prior to implementing the requested test. Shipping is not applicable to J&J, as the material and associated documentation was an SRS responsibility, and further directed J&J to dispose of all residual material.

17.0 Quality Assurance Records

Records that furnish documentary evidence of quality shall be specified, prepared, and maintained…

J&J Evaluation:

As stated in the purchase document, a report of findings, recommendations, suggestions, and cautions was to be delivered. J&J performed this activity issuing the report to SRTC.

## E. Conclusion

Based on the evaluation performed, the lack of a formal NQA-1 based program by J&J does not compromise the ability of J&J to perform the requested tasks or the validity of the resulting data. The difference between an NQA-1-1989 based program and the controls being executed by J&J does not have any significant technical effects upon the data generated.

J&J is capable of performing all the requested measurements and interpreting the test results for engineering solutions to prevent problems with bulk transfer storage and transport. J&J developed the required techniques and patented equipment to support these techniques. J&J maintains ASTM procedure, D6128, and has the infrastructure to support and perform all the tests specified in the purchase order.

The development and use of this ASTM procedure by J&J, J&J's position in the industry, the STRC/WTP-RPP technical site visit, and SRTC/QAD evaluation of J&J provides the basis for qualification of data produced by J&J to meet the QA requirements of RPP-WTP.

## F. Attachments

1. SRTC Problem Identification Report, 2002-PIR-11-00052, dated 11/27/02.
2. Letter F. J. Leach to H. N. Crotts, "Response to Bechtel National Finding 24590-WTP-SCAR-03-007", SRT-QAE-2003-00012, dated 02/27/03.

## G. Reference

1. WSRC E7 Conduct of Engineering Manual, Procedure 3.70, "Qualification of Existing Data", Revision 3, dated 09/28/01.

**Westinghouse**
**Savannah River Company**
**Aiken, SC 29808**

SRT-QAE-2003-00012

February 27, 2003

Mr. Harold N. Crotts
Supplier Quality Assurance Manager
Quality Assurance Department
Bechtel National Inc.
2435 Stevens Center Place
Richland, WA 99352

Dear Mr. Crotts:

RESPONSE TO BECHTEL NATIONAL FINDING 24590-WTP-SCAR-QA-03-007

Westinghouse Savannah River Company (WSRC) personnel have completed the evaluation of the Supplier Corrective Action Report (SCAR) 24590-WTP-QA-03-007, Revision 0. Response to the SCAR is provided as an attachment to this letter. In summary WSRC concurs with the finding of not identifying QA Requirements to its supplier, Jenike & Johannson. Corrective actions have been taken. An additional action including revising the final report and the Technical Task Plan associated with this activity is scheduled to be completed by March 15, 2003.

Please contact me at (803) 725-3786 if you have questions or concerns.

Sincerely,

Frederick J. Leach

Frederick J. Leach
Quality Assurance Manager
Savannah River Technical Center

cc: G. T. Wright, 773A
J. E. Marra, 773A
H. F. Sturm, 773A
J. A. Powell, 773-41A
D. A. Crowley, 773A
R. F. Schumacher, 999-W
SRTC QAD Files

OSR 25-82# (Rev 10-8-2002)
Stores: 26-15460.10

2/26/2003
Page 1/1

# SRTC Complete Response to 24590-WTP-SCAR-03-007

Description of Discrepancy

Contrary to the above requirements, WSRC/SRTC sub-contracted to Jenike and Johannson, Inc., the performance of test specified by the Service Requisition DOE-ORP/RL IWO work Order No. MOSRLE60 prior to :

- addressing the appropriated quality requirements; and
- properly evaluating the subcontractors quality assurance program

**1. What is the cause of the deficiency?**

SRTC Response

Inadvertent error. The purchase requisition to Jenike & Johannson (J&J) was written in a format to lead one to believe that the scope of activity was primarily one of consultant services. As a consultant, J&J would perform work under the SRS QA Program; hence the requisition was approved as a Level 3 procurement-no QA Requirements. To further promulgate the error, the purchase order was issued to J&J as sole source, based on their experience with the services requested. As a sole source vendor no pre-award qualification process was implemented.

**2. What actions have been taken to resolve the deficiency?**

SRTC Response

a. The deficiency was documented on SRTC's Problem Identification Report, 2002-PIR-11-00052, dated 11/27/02 (Attachment 1). Further clarification statements were provided to WTP-RPP QA Department dated 12/18/02 (Attachment 2). In addition, the data generated by J&J under the purchase order was qualified in accordance with our QA Program, E7 Procedure 3.70, "Qualification of Existing Data", Revision 3 (Attachment 3).

b. WTP-RPP has issued a Test Exception, 24590-WTP-TEF-RT-03-007, eliminating the QARD requirements for this task. The TTQAP and final report has been revised and is in the approval cycle reflecting the change in QA requirements. ECD of the TTQAP and final report is 3/15/03.

**3. What action has or will be taken to prevent recurrence?**

SRTC Response

SRTC believes that the deficiency was an isolated case. A review of purchase orders for the WTP-RPP activities noted that purchase orders issued to support WTP-RPP activities have been issued as at least a Level 2 procurement, i.e. requiring a QA Program. A memo dated (12/17/02) from the Project Manager to the leads of RPP has been issued to remind project personnel of the flow-down requirement to vendors and subcontractors of the WTP-RPP QA Requirements. Additionally, the Project Manager has directed SRTC RPP personnel to route all purchase requisitions in excess of $10K through a QA screening process (Memo dated 1/27/03), such that QA can evaluate that the QA Programmatic requirements have been properly identified for the requisition.

**4. When will the above actions be complete?**

SRTC Response

All actions have been completed with the exceptions of the revised TTQAP and final report associated with this task. The status of the TTQAP and final report is pending WTP-RPP review and concurrence. It is anticipated that WTP-RPP will complete this review and return back to SRTC such that the documents can be issued by 3/15/2003.

Revision 0, 1/25/2001

Attachment 1

**ORIGINAL**

# Problem Identification Report

CSATS Number 2002-0791
Corrective Action Number 1

PIR No. 2002-PIR-11-00052
Page 1 of 3

## A Problem Identification

| | | |
|---|---|---|
| Topic<br>QA Rquirements | Responsible Manager Department<br>WASTE MGMT & ENV TECHNOLOGY | Requirements Document(s)<br>1Q, QAP 4-1 |

**Specific Requirements**
1Q QAP 4-1 Revision 4, Section 4.A states in part, "...Specify the QA requirements applicable to suppliers or subcontractors depending on the type, use, procurement level or functional classification of items and services to be procured...."

**Problem**
Contrary to the above, Purchase Requisition 0F0806 issued to Jeinke & Johannson, did not specify any QA requirements as required. The purchase order was awarded to Jeinke & Johannson as a sole source vendor to provide characterization and material flow of GFCs. J & J is recognized as the leading authority in this field and has developed the US national standard, adopted by American Society for Testing & Materials (ASTM) which was required to be utilized within the scope of the contract.

Problem/Document Source ☒ QA ☐ SWO ☐ RC ☐ SA ☐ FEB ☐ ME ☐ PAAA ☐ ORPS ☐ DOE

Reported by (Print/Signature/Date) Hansen, E. K. / Emily Hansen 11/27/2002

Validation Determined By (Print/Signature/Date) JP Vaughan / J.P. Vaughan

DOE Reportability ☐ Yes ☒ No
ORPS No.

Determined By (Print/Signature/Date) K. R. Super / 11/27/02

## B Prob. Eval

Significance Category ☐ 1 ☐ 2 ☒ 3 ☐ 4

Nuclear Activity ☐ Yes ☒ No

RPOC (Print/Signature/Date) NA

Functional Area(s) 8

NCR ☐ Yes ☒ No

NCR No. N/A

Responsible Manager (Print/Signature/Date) CROWLEY, DAVID A. David A. Crowley 11/27/02

## C Corrective Action Development

**Action(s) to Remedy Problem**
1. Define NQA-1 attributes as it applies to the purchase requisition.
2. Evaluate Jeinke & Johannson QA program to the define NQA-1 attributes.

**Cause**
J & J was a sole source vendor. No pre-award qualification process was performed.

PAT Cause Code(s) A3B3C2

ISMS Code(s) 3

Lessons Learned Applicability ☐ Site ☐ Division ☐ Department ☐ Section ☒ None

**Action(s) to Prevent Recurrence**

Estimated Completion Date: 12/12/02

N/A

Closure Verification Required ☒ Yes ☐ No

Independent Verification ☒ Yes ☐ No

CA Recommended By (Print/Signature) JP Vaughan / J.P. Vaughan
Date 11/27/02

Responsible Manager Approval (Print/Signature) CROWLEY, DAVID A. David A. Crowley
Date 11/27/02

Other Approval (Print/Signature) NA
Date

## D Implementation & Closure

Corrective Action Completed (Print/Signature) JP Vaughan / J.P. Vaughan
Date 12/11/02

**Closure Verification Actions**

See attached

Closure Verification Completed By (Print/Signature) JP Vaughan / J.P. Vaughan
Date 12/11/02

Closure Re-Verification Completed By (Print/Signature) NA
Date

Effectiveness Evaluation & Due Date ☐ Yes ☒ No

Responsible Manager Closed (Print/Signature) CROWLEY, DAVID A. David A. Crowley
Date 12/11/02

2002-PIR-11-00052
Page 2/~~2~~3
12-11-02

SRTC QAD has reviewed and concurred with the Sole source justification provided with the purchase requisition to Jenike & Johannson (attached). The method (s) to test various bulk solids flow properties, as stated in the purchase requisition are associated with the Jenike Methods (ASTM D6128). Jenike & Johannson developed and maintains the integrity of the ASTM D6128.

The NQA-1 elements that should have been applied to this purchase requisitions on a graded approached are as follows: 1.0, Organization; 2.0, QA Program; 5.0, Procedures, Instructions and Drawings; 6.0, Document Control; 11.0, Test Control; 12.0, M&TE; and 17.0, Records. In conclusion the work performed using the ASTM standard by Jenike and Johannson as specified by the purchase requisition meets the graded QA elements of NQA-1. Data generated by this purchase requisition was derived under strict ASTM standard(s) and was found to be acceptable for use as is.

Rev 3-6-95)

2002-PIR-11-00052
P. 3 of 3

# Sole Source Justification

Westinghouse
Savannah River Company

*This form is to be used to justify Sole Source procurements as discussed in the Procurement Management manual (WSRC-7B), Procedures 1.1, 4.2, and 4.3.*

| | |
|---|---|
| Requisition No./Stores/Spare Parts Data Sheet No./Consolidated Materials Data Sheet No. | Date<br>1/24/2002 |

Name of Supplier/Manufacturer
Jenike and Johanson, Inc.

**1. Background**

WSRC has contracted with the Hanford River Protection Project to characterize the bulk solids handling capability of a series of glass forming chemicals and minerals. The Technical Task Plan supporting this effort states that ASTM procedure D 6128 will be used to meet the Quality Assurance requirements. Jenike and Johanson developed the required techniques as stated in ASTM D6128 and the patented equipment supporting this procedure. Jenike and Johanson Inc. have been in business of characterizing solids using the Jenike and Johanson method (ASTM D6128), designing dry handling systems and providing consulting for more than thirty five years. Their staff of engineers have worked with more than 2000 clients.

**2. Exclusive Capability of the Source**

Jenike and Johanson maintains the ASTM procedure D6128 and has the infrastructure to support all the tests as specified in the PO and provide engineering recommendations. Due to their vast experience, they have the ability to interpret the resulting data and predict potential problems with the flowability and storage of the dry materials. The use of this ASTM procedure provides an acceptable basis of measurement and will support the quality assurance requirements of this program.

**3. Other Extenuating Circumstances or Considerations**

Jenike & Johanson Inc. is the only known firm capable of performing all the requested measurements, use of the ASTM D6128 standard, and interpreting the test results to engineering solutions to prevent problems with bulk transfer storage and transport.

# Attachment 2

**James Vaughan**

12/18/2002 02:15 PM

To: "Prindiville, Kerry" <kprindiv@bechtel.com>
cc: david.crowley@srs.gov, Steven Loflin/WSRC/Srs@Srs, rdreed@bechtel.com, wmakeley@bechtel.com, James02 Powell/WSRC/Srs@Srs, Frederick Leach/WSRC/Srs@Srs, Ray Schumacher/WSRC/Srs@Srs
Subject: Re: PIR review by WTP QA

Find attached our response to WTP QA comments. I will be out of the office starting today until 1/6/03. If you have any questions or require any further clarification on this subject please contact Steve Loflin at the above email or phone at 803.725.3571. thanks, Pat.

J&J.doc J&J_att.pdf

"Prindiville, Kerry" <kprindiv@bechtel.com>

**"Prindiville, Kerry" <kprindiv@bechtel.com>**

12/17/2002 04:38 PM

To: "Vaughan, James" <james.vaughan@srs.gov>
cc: david.crowley@srs.gov
Subject: PIR review by WTP QA

James...

I had WTP QA review the PIR. Please read below for their comments. Please address WTP recommendations as listed below...these will need to be incorporated and approved by our QA before the project can close out this work. I would like to get this back to Todd no later than December 26th for his signature. Please call me if you have any questions.

Thanks,
Kerry

-----Original Message-----
From: WTP QA
Sent: Tuesday, December 17, 2002 10:20 AM
To: Akeley, Wayne
Cc: Reed, Ronald D
Subject: FW: review of QA

Kerry, Prindiville

As requested QA has reviewed the PIR document (2002-PIR-11-00052) and offers the following:

This is a programatic issue in that the requirements of QAP 4.1 were simply not complied with. The cause stated that Jenike and Johansen was a sole source vendor and that no qualification was performed. It was also stated that the work was performed using the ASTM standard that meets the graded elements of NQA-1.This is simply a statement and not a cause of why the QA requirements were not stipulated in the Purchase Requisition. Additionally, the actions necessary to prevent recurrence were not provided on the PIR. Based on theSole Source Justification documentation provided (i.e. Background; Exclusive Capability of the Source and Considerations) there is no doubt that the work performed was acomplished to the appropriate

Standard Test methods. However, without the flowdown of QA requirements to the Vendor there is no objective evidence that the work performed meets the graded QA elements of NQA-1.

The following Recommendations are provided to assure that the proper documentation captures the QA Deficiency.

1) A detailed cause as to exactly why the QA requirements were not properly flowed down to the Vendor.

2) Corrective Action measures to prevent recurrence are to be provided.

3) To effectively grade the NQA-1 QA elements objective evidence (Documentation) must be provided such as Applicable procedures, instructions, and drawings utilized in performing the work, Training of personnel records,appropriate test procedures, instrument and equipment maintenance records, calibration records and all other pertinent documentation).

Based on the above review and recommendations provided it is concluded that additional actions are warrented to provide assurance that adequate justification is provided for closure of the PIR.

3/3

**WTP-RPP QA Comments dated 12/17/02, on 2002-PIR-11-00052:**

The following Recommendations are provided to assure that the proper documentation captures the QA Deficiency.

1) A detailed cause as to exactly why the QA requirements were not properly flowed down to the Vendor.

Response

Inadvertent error. The purchase requisition to Jenike & Johannson (J&J) was written in a format to lead one to believe that the scope of activity was primarily one of consultant services. As a consultant, J&J would perform work under the SRS QA Program; hence the requisition was approved as a Level 3 procurement-no QA Requirements.

2) Corrective Action measures to prevent recurrence are to be provided.

Response

SRTC believes that the deficiency was an isolated case. A review of purchase orders for the WTP-RPP activities noted that purchase orders issued to support WTP-RPP activities have been issued as at least a Level 2 procurement, i.e. requiring a QA Program. A memo from the Project Manager to the leads of RPP has been issued to remind personnel of the RPP QA Requirements (see attached).

3) To effectively grade the NQA-1 QA elements objective evidence (Documentation) must be provided such as Applicable procedures, instructions, and drawings utilized in performing the work, Training of personnel records, appropriate test procedures, instrument and equipment maintenance records, calibration records and all other pertinent documentation).

Response:

Objective evidence of J&J implementation of procedures and instructions are provided by the bid proposal and the final report issued by J&J. Glass formers chemicals (GFC) testing is internal J&J procedures which provided the information necessary to recommend designs for the Glass Former Handling facility. The procedures and all of the interpretations are proprietary to J&J. SRTC subcontracted their expertise to arrive at the recommendations. They happened to describe their internal procedures (by listing ASTM standards). We did not specify the particular tests - J&1 did.

Additionally, SRTC and WTP-RPP representatives performed a weeklong site visit to review the testing activities. SRTC documented the measurements in Lab Notebooks during this period, observed the calibration of instruments (which are based on mass measurement), checked environmental conditions, and observed that the technicians were highly trained (many years of OTJ training). Highly trained and knowledgeable J&J engineers then interpreted the resulting measurements. J&1 proposal provided a listing of the qualifications of the J &J engineers and consultants, the procedures to be used, and the form of the results. (SRT -RPP-2002-0013, Attachment No.2).

Further objective evidence is provided by letter from J&1 dated 11/26/02 describing the training for its employees, basic QA program philosophy and test equipment protocol. (Attachment No.3)

A copy 2002-11-PIR-00052 with this document will be filed within the applicable Laboratory Notebook.

Attachment No. 1

1/1

**James Marra**

To: James Vaughan/BSRI/Srs@Srs
cc:
Subject: QA

12/18/2002 10:00 AM

----- Forwarded by James Marra/WSRC/Srs on 12/18/02 09:59 AM -----

**Harold Sturm**

To: James Marra/WSRC/Srs@Srs, David Crowley/WSRC/Srs@Srs, Cynthia Holding-Smith/WSRC/Srs@Srs, Dan Bums/WSRC/Srs@Srs, Bernice Rogers/WSRC/Srs@Srs
cc: John Marra/WSRC/Srs@Srs
Subject: QA

12/17/02 10:10 AM

**WE HAD A RECENT INCIDENT WHERE WE REALIZED THAT WE FORGOT TO SPECIFY THE QA REQUIREMENTS IN A SUB-CONTRACT WHICH IS REQUIRED BY THE PROJECT.
THIS REQUIRED A PIR ( NCR FOR SUB-CONTRACTS ).**

**PLEASE REMIND YOUR FOLKS THAT THE QA REQUIREMENTS MUST BE ADDRESSED AND TO WATCH FOR THE LITTLE THINGS THAT IF MISSED TAKE TO MUCH TIME TO CORRECT AND GET TO MUCH ATTENTION.**

Attachment No. 2

1/5

**Westinghouse**
**Savannah River Company**
**Aiken, SC 29808**

June 5, 2002

SRT-RPP-2002-00131

Mr. Steve Barnes
Bechtel National
3000 George Washington Way
Richland, WA 99352

Dear Mr. Barnes:

**RPP-WTP SUBMITTAL OF JENIKE AND JOHANSON, INC. POWDER FLOW SPECIALISTS, SUPPORTING S-139 TRIP REPORT, SRT-RPP-2002-00131**

Attached please find the "Jenike and Johanson, Inc. Powder Flow Specialists, Supporting S-139" trip report. Also enclosed is an electronic copy of this report.

Please contact Ray Schumacher (803-725-5991) if you have any questions.

Sincerely,

HF Sturm

Harold F. Sturm, Jr.
RPP-WTP Project Manager
Savannah River Technology Center

hfs/sjb
Att.
c: G. T. Wright, WTP
B. Jhaveri, WTP
K. Prindiville, WTP
C. Tevis, WTP
D. A. Crowley, 773-43A
E. K. Hansen, 773-41A
J. R. Harbour, 773-43A
J. C. Marra, 773-42A
C. T. Randall, 773-42A
R. F. Schumacher, 773-43A
H. F. Sturm, 773-A
S. J. Boggs, RPP File, 773-A, A206

Att. No. 2
2/5

**Westinghouse**
**Savannah River Company**
Aiken, SC 29808

SRT-RPP-2002-00131, Rev. 0

June 3, 2002

To: Harold Sturm, SRTC
David Crowley, SRTC
John Harbour, SRTC
Kerry Prindiville, WTP
Christine Tevis, WTP
Bipin Jhaveri, WTP

From: Dr. Ray F. Schumacher, Fellow Scientist, SRTC R.F. Schumacher 6/4/02
Erich Hansen, Principle Engineer, SRTC

**Trip Report: Jenike & Johanson, Inc. Powder Flow Specialists, Supporting S-139**
April 28 to May 3 and May 20 to May 24, 2002

## Summary:

Jenike and Johanson (J&J) is one of the leading powder/bulk solids flow consultants in the United States. J&J provides physical characterization of bulk solids, design of bulk solids processes based on the physical characterization of the bulk solids, and troubleshoots/consults on bulk solids handling processes. J&J is not an equipment fabricator or supplier. J&J has worked with thousands of bulk solids plants in many countries around the world in providing their technical knowledge in solving bulk solids issues. SRTC has contracted with J&J to measure/characterize the physical properties of the 13 WTP Glass Former Chemicals (GFC's), 2 typical HLW blends and 3 typical LAW blends covering the A, B and C tanks. During portions of this meeting, J&J presented a review of the problems often encountered when handling bulk solids. J&J also demonstrated their computer model which calculates the flowrate discharging out of specific silo/hopper designs, given the measured bulk solids flow properties for both funnel and mass flow conditions. J&J presented a review of their initial measurements of our GFC's flow properties. While this data is preliminary and incomplete at this time, it was sufficient to indicate that there would be problems with the present conceptual WTP solids handling system [1]. The starting conceptual WTP designs of the GFC storage vessels are cylindrical carbon steel silos with carbon steel conical hoppers. All of the conical hoppers have 60°slopes from horizontal and circular 12-inch openings. Discharge from each GFC storage silo is controlled using screw feeders.

The preliminary characterization of the GFC's indicated that nearly all of the 13 GFC's are expected to "Rat-Hole" based on the conceptual storage vessel designs, due to their cohesive nature. That is, the powder will flow down the central axis and could potentially leave a significant portion of the material stagnant and adhering to the side of the hopper/silo. This stagnant material will remain in the silo as it is emptied, and when fresh material is added, it too will flow down the rathole. These materials tend to gain cohesive strength with time at rest. This condition will result in erratic flow from the hopper and potentially could create a situation know as flooding or flushing where the material

Att No. 5
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cannot be controlled as it exits the hopper screw feeder. Rat-holing diminishes the active capacity of the silo. This problem can be corrected by properly designing the hopper section of the storage vessel, that is, by making it a "Mass-Flow" hopper. In a mass flow hopper all of the material in the silo moves as the material is removed from the hopper/silo in a first in – first out manner.

SRTC recommends that Jenike & Johanson present the results upon completion of their task with SRTC to the RPP-WTP personnel involved with the design and operations of the GFC's. WTP needs to determine the items to be discussed and contract directly with J&J if interested in having them make a presentation. The presentation could include an overview of how bulk solids are characterized and used to design bulk handling systems, a detailed explanation of the potential GFC flow problems, which could occur, and a shorter executive review for management. The discussion could also include how to properly design blending systems, select the proper method of pneumatic transport (dilute or dense phase), control/minimize dusting, and corrosion/erosion, and J&J's recommendations for control devices, instrumentation, etc.

## Discussion:

During the meeting, J&J discussed the difference between arching and rat-holing in a hopper. Arching completely halts the flow of material from the hopper opening. Rat-holing is where material flows from the center-line of the hopper but leaves a stable, stagnant amount of material along the side of the hopper/silo. Rat-holing (also known as funnel flow) results in a first in-last out situation. If the rat-hole fails due to an unexpected shock of the storage vessel, the material can become aerated and will flow more like a fluid. This may result in uncontrolled emptying of the silo by flushing from the feeder. The best solution for this problem is to install "Mass-Flow" hoppers that cause all of the material to move during emptying. The wedge shaped "Transition" hopper with a slotted opening is the optimal mass flow hopper design from a flow property perspective. A special screw auger feeder design must also be employed to maintain true mass flow in any hopper design. An incorrectly designed screw auger feeder can turn a mass flow hopper back into a funnel flow hopper.

J&J demonstrated a computer model that predicts the flowability of a bulk solid in a hopper, given the dimensions and materials of construction of the hopper and the physical properties of the bulk solid. A demonstration was provided to explain how a hopper/silo is designed starting from the initial capacity and throughput requirements and physical characterization of the bulk solid. This tool can also be used to determine if an existing design has issues such as limited throughput. This appeared to be an extremely powerful tool for hopper/silo design and troubleshooting.

The theory of pneumatic transfer was discussed as well as the difference between suspended and non-suspended pneumatic transfer (dilute or dense phase). Problems that can be encountered where there are changes in momentum (e.g. elbows) in the transfer line can lead to the attrition of the particles during transfers. While there are no first principle models for pneumatic transfer a great deal can be learned by testing under simulated conditions. J&J performs this type of work at their California facility. The proper design of a pneumatic transfer system can minimize the rate of erosion or wear in the transfer tube and the degree of particle attrition. J&J also presented information related to gas/solids separation (cyclones, baghouses, and filters).

Attachment No 4
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Additionally, time was spent discussing the potential for an explosion when handling organic powders such as sugar. The methods for reducing the force or mitigating the possibility of having explosions and the companies that tested for the explosivity of the materials were items of discussions.

**Preliminary Test Results:**

The following preliminary results are based on the present WTP conceptual design for the GFC storage vessels. All of the storage vessels are circular silos with carbon steel conical hoppers sections with 60° slopes from horizontal, and a circular 12 inch diameter openings that discharge into screw feeders [1]. **The data reported in the Table 1 below is preliminary and must not be used for design purposes at this time.** All of the GFC's tested would either not flow or would rat-hole, given the above storage vessel conditions. All of the materials tested will rat-hole, if flow were possible. All of the materials gain cohesive strength with time. Characterization measurements were carried out with three materials of construction: mild carbon steel, stainless steel with 2B finish, and Tivar 88™ (plastic insert)[2] for all the GFC's and blends. All slopes indicated below are relative to horizontal.

**Table 1: Preliminary Results of GFC Characterization Performed at J&J**

| Material | Preliminary Results |
|---|---|
| Kyanite 325 Raw | Flow rate discharge is limited between 220 to 250 lbs./hr, given the present design. Requires 2.5 ft. outlet for a cone hopper or a 12 to 14 inch slot opening for a transitional hopper. The material gains cohesive strength with time at rest and the minimum opening dimension will double after 7 days at rest. Mass flow was achieved with an 80° slope using a 2B stainless steel hopper section. |
| Boric Acid Tech Grade | Not a cohesive material and will not arch, but will rat-hole (assuming the material is not attritted during transfer). This is a dusty material that can be made to have mass flow with slight changes. |
| Ten Mole Borax | A free flow material but tends to have clumps. After seven days at rest, would required a 3 foot opening. Mass flow can be obtained with an 18 inch slot, Tivar liner and 75° slope. Low melting temperature. |
| Soda Ash-Dense | On an instantaneous basis is free flowing. After 7 days at rest will have bridging and rat-holing issues. Mass flow can be obtained with a transition hopper at 65° slope. |
| Wollastonite NYAD325 | Due to acicular nature of particles, it requires an unrealistic opening to prevent rat-holing. Vibration will increase tendency for arching. Problems increase with time at rest. Mass flow will be difficult |
| Iron Oxide 5001 | Not a good flowing material. Has a large arching and rat-holing potential. Mass flow would require an 80° slope. Flow will be rate limited (200 lbs/hr). Density is high at 140 PCF. |
| Lithium Carbonate Tech | Very much the same as iron oxide with respect to arching and rat-holing. Mass flow possible at 75° slope. |
| Olivine #180 | A good flowing material. Would require a 2.5 foot opening to prevent rat-holing. Mass flow possible with transition hopper at 70 to 75° slope. A very abrasive material |
| Silica SCS75 | Compaction increases density from 50 PCF to 70 to 90 PCF. A high tendency for bridging and requires a large outlet. Mass flow can be obtained with a transition hopper and an 80° slope. Under the conceptual design, output will be flow rate limited to 1/7 to 1/10 of required output |
| Zinc Oxide Kadox 920 | One of the worst flowing materials. Required outlet dimension is unrealistic for conceptual design. Material compacts from a density of 30 PCF to 65PCF. Will arch and rat-hole. Mass flow possible with Tivar-88 liner and a slope of 75°. |
| Zircon Flour | No data at this time, but is a very dense, fine material |
| Sugar | No data at this time, but has a potential for dust explosion, particularly if attrited during transfer. Attrited material tends to clump. |
| Blends | No data available at this time. |

J&J will recommend utilizing transitional mass-flow hoppers and special-design screw feeders for most of the GFC hoppers. J&J also noted that there will be issues, such as hang-ups, arching, etc. in many of the other blend hoppers, transporters, and weigh hoppers which may be utilized in the WTP process.

**Quality Assurance Testing Observations:**

Viewed the following tests that utilized the following standards:
ASTM D 6128-97, Standard Shear Testing Method for Bulk Solids Using the Jenike Shear Cell.
ASTM D 6683-01, Standard Test Method for Measuring Bulk Density of Powders and Other Bulk Solids

Shear testing measurements were made after calibrating the Jenike shear cell instrument with standard weights and gauge blocks. The calibrations were made and recorded weekly. The Compressibility Tester, the Permeability Tester, the Chute Tester, the Angle of Repose Measurement, and the Malvern Particle Size Analyzer are also calibrated at frequencies determined by J&J. Relative humidity in the laboratory is maintained near 30%.. All materials tested were sealed in double plastic bags with tie locks.

Witnessed and verified the blending of LAWA44, LAWB45, LAWC22, and HLW D-C-106/AY104. GFC's were pre-weighed and stored in plastic (zip-lock) bags. The materials were added to a Hobart Blender, by adding the material which seem to flow the best first and then adding the more cohesive materials last. The mixture was mixed for several minutes and at various times the mixer was turned off and the materials hand blended to insure complete mixing. The Hobart blender was operating at it lowest speed and dusting was noticed during the blending of the GFC's. The blended materials were then stored in double plastic bags with tie locks.

Testing of all 13 GFC's and 5 blends should be completed at J&J by mid June. J&J will prepare a functional design for the 13 GFC hopper/silos and the transfer chute to the feed mixing tank. This report should be completed by early July.

Meeting dates during which SRTC was present at J&J* to witness the testing are as follows: April 28 to May 3, 2002 and May 20 to May 24, 2002. SRTC representatives: R. Schumacher and E. Hansen, RPP-WTP representatives: K.Prindiville (R&T), C. Tevis (Process Engineering) and Bipin Jhaveri (Law Mechanical Systems).

* Jenike & Johanson Inc., One Technology Park Drive, Westford, MA, 01886-3189, www.jenike.com.

**References:**

1. RPP/WTP Memorandum: "Design Process Data for Glass Former Chemical Characterization," Christine Tevis, CCN: 027800, February 3, 2002.

2. Tivar 88, POLY HI SOLIDUR, Fort Wayne, IN, www.tivar88.com.

Attachment No. 3
1/3

JENIKE & JOHANSON
INCORPORATED

November 26, 2002

Erich Hansen
Westinghouse Savannah River Company
Aiken, SC 29808

**RE: Jenike & Johanson, Inc. quality assurance program**

Dear Erich,

In our recent telephone conversation (and email transcription: ref. Nov. 25 email from Erich Hansen to Eric Maynard), you indicated that Westinghouse Savannah River Company (WSRC) has inquired about the quality assurance (QA) programs implemented at Jenike & Johanson, Inc. (J&J). The purpose of this letter is to inform WSRC of the QA programs currently utilized at J&J.

The following questions were presented to J&J:

- Does J&J follow any ISO program?
- Does J&J have corporate procedures, which the lab technicians are trained to? Can they be referenced?
- What type of training does J&J provide their technicians and what frequency, if any?

Though J&J does not follow a formal ISO program, we do have stringent and rigorous corporate and laboratory training programs to ensure proper laboratory testing protocol is undertaken by all technicians so that data generated from material characterization can be free from technician bias or equipment error.

J&J does have a strict training regiment for all new laboratory technicians. The training incorporates equipment operational procedures, raw data analysis techniques, as well as health and safety policies to ensure personal protective equipment is used when necessary. The following referenced documents/procedures are utilized to address the corporate and laboratory training requirements:

**Corporate training for laboratory technician**

- Must undergo two-day "Flow of Solids in Bins, Hoppers, and Feeders" training
- Must undergo intensive safety training (review of the following: Material Safety Data Sheet procedures, Confined Entry procedures, Workplace Safety and Health Dictionary, Waste Disposal, Equipment Safety procedures, Fire Prevention, Safety Administrative Controls, Emergency Response, Personal Protection Controls)
- Complete safety training details can be found in J&J's "Health and Safety Plan" (Rev. 12/98)

Attachment No. 2
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## Laboratory training for new technician

Must undergo three months of intensive testing equipment training (technician under constant supervision of laboratory supervisor)
Review of personal protective equipment procedures used in laboratory (e.g., respirator, powered air purifying respirator, gowning requirements, safety glasses/goggles, gloves, etc.)
Review of techniques used for raw test data analyses
Review of data collection and entry procedures
Review of test equipment calibration procedures (see calibration information listed below)

## QA programs at J&J

All raw and refined data generated from bulk solids testing and characterization are reviewed by laboratory supervisor or laboratory manager
All raw and refined data generated from bulk solids testing and characterization are reviewed by project or senior engineer before data are released for design purposes
New test equipment is calibrated and checked against baseline to ensure proper performance
Changes in test equipment operational procedures discussed with all personnel
Strict test equipment calibration procedures are followed

## Testing equipment calibration protocols

1. Jenike Direct Shear Tester
    a. Utilize span setting device to calibrate load cell
    b. Calibrate at 0 lb. and 9 lb. setting using pre-calibrated weights
    c. Performed weekly

2. Jenike-Schulze Ring Shear Tester
    a. Utilize custom device to calibrate load cells
    b. Calibrate at specified settings using pre-calibrated weights
    c. Performed each time after tester is relocated

3. Compressibility Tester
    a. Utilize 0.75 in. gauge block to calibrate dial indicator
    b. Performed before each test

4. Laboratory Electronic Scales
    a. Use 200 g or 600 g calibrated weights to calibrate scales
    b. Performed monthly

5. Permeability Tester
    a. Leak check performed quarterly
    b. Depth gauge is calibrated before each test

Attachment No.

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6. Chute Tester
    a. Calibration not required

7. Angle of Repose
    a. Calibration not required

8. Malvern Particle Size Analyzer
    a. Calibration performed by Jenike & Johanson and vendor using calibrating sample
    b. Performed quarterly

9. High Temperature Ovens
    a. Calibration performed with thermocouples
    b. Performed with each use

10. Environmental Chamber
    a. Calibration performed to check relative humidity and temperature
    b. Performed semi-annually or during each maintenance servicing

Thus, it can be seen that J&J does institute the necessary corporate and laboratory training programs to ensure proper laboratory testing protocol is undertaken by all technicians. Furthermore, laboratory safety training is a critical part of the overall training.

Please contact me if you have any questions or need additional information. We look forward to continuing to work with you on the Hanford River Protection project.

Sincerely,

*Eric P. Maynard*

Eric P. Maynard

Project Engineer

1/4

**Attachment 3**

**James Vaughan**

To: kprindiv@bechtel.com
cc: David Crowley/WSRC/Srs@Srs, John Marra/WSRC/Srs@Srs, James02 Powell/WSRC/Srs@Srs
Subject: Re: Review of SRTC Response to CARs and PIRS

01/21/2003 11:01 AM

Kerry, I called Robert Nilsson this AM but he was not available. I left a voice mail with him on trying to status/resolve the J&J issues. I would appreciate any updates that you would have on this issue. Also, would greatly appreciate it if could "push" the issue to get the ball moving again. We are hoping to get a satisfactorily resolution on this matter in a timely manner. thanks, Pat.

----- Forwarded by James Vaughan/BSRI/Srs on 01/21/2003 10:44 AM -----

**James Vaughan**

To: "Nilsson, Robert" <rmnilsso@bechtel.com>
cc:
Subject: Re: Review of SRTC Response to CARs and PIRS

01/20/2003 08:30 AM

Robert, see the attachment. This is what was transmitted to R&T last wk. We have not hear anything on this. If you could please update me on what is happening in this area. Thanks, Pat.

J&J Mosley.doc

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Jeinke & Johanson Inc. (J&J) is one of the leading powder/bulk solids flow consultant in the United States. J&J provides physical characterization of bulk solids, design of bulk solids processes based on the physical characterization of bulk solids, and troubleshoots/consults on bulk solids handling problems. J&J is not an equipment fabricator or supplier.

SRTC issued a purchase order to J&J without specifying applicable NQA-1-1989 QA requirements required for RPP-WTP activities. J&J does not have a formal NQA-1 Program. Following are the applicable sections of NQA-1-1989 applicable to the purchase order placed with J&J. The J&J evaluation sections attempt to reconcile J&J internal processes and controls with the NQA-1-1989 requirements supporting the conclusion that the lack of an NQA-1-1989 QA Program does not compromise the ability of J&J to perform the requested tasks nor the validity of the resulting data.

## NQA-1-1989, Part II Basic Requirements

### 1.0, Organization

The organizational structural, functional responsibilities, levels of authority, and lines of communications for activities affecting quality shall be documented.... Such persons or organizations shall have direct access to responsible management at a level where appropriate action can be effected. Such persons or organizations shall report to a management level such that required authority and organizational freedom are provided, including sufficient independence from cost and schedule considerations.

J&J Evaluation:

J&J has an established organizational structure defined for the President and other key personnel responsible for performing activities in accordance with established and proven processes and controls and procurement requirements. J&J implements proper laboratory protocol and training for the laboratory technicians including identifying problems to management as required. Responsible management reviews the test results as they are developed.

### 2.0, QA Program

A documented quality assurance program shall be planned, implemented, and maintained in accordance with this Standard or portions thereof. The program shall identify the activities and items to which it applies.... The program shall provide for indoctrination and training as necessary of personnel performing activities affecting quality to assure that sui8table proficiency is achieved and maintained.

J&J Evaluation:

J&J implements a stringent and rigorous corporate and laboratory training programs to ensure that proper laboratory testing protocol is undertaken by all technicians ensuring that data generated from material characterization is free from technician bias or equipment error.

Laboratory training for new technician
  - Must undergo three months of intensive testing equipment training (technician under constant supervision of laboratory supervisor)
  - Review of personal protective equipment procedures used in laboratory (e.g., respirator, powered air purifying respirator, gowning requirements, safety glasses/goggles, gloves, etc.)
  - Review of techniques used for raw test data analyses
  - Review of data collection and entry procedures
  - Review of test equipment calibration procedures

QA programs at J&J
  - All raw and refined data generated from bulk solids testing and characterization are reviewed by laboratory supervisor or laboratory manager
  - All raw and refined data generated from bulk solids testing and characterization are reviewed by project or senior engineer before data are released for design purposes
  - New test equipment is calibrated and checked against baseline to ensure proper performance
  - Changes in test equipment operational procedures discussed with all personnel
  - Strict test equipment calibration procedures are followed

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## 5.0 Instruction, Procedures, and Drawings

Activities affecting quality shall be prescribed by and performed in accordance with documented instructions, procedures, or drawings of a type appropriated to the circumstances…These documents shall…have been satisfactorily accomplished.

J&J Evaluation:

Testing performed by J&J was performed in accordance with the purchase requirements, i.e. ASTM D 6128-97, Standard Shear Method for Bulk Solids Using the Jenike Shear Cell, (developed by J&J) and recently approved ASTM D-6683-01, Standard Test Method for Measuring Bulk Density of Powers and other Bulk Solids, for compressibility tests. These are industry-recognized standards. Additionally SRTC and RPP-WTP project personnel witnessed the tests and recorded primary data during the testing phase. No anomalies were noted by either J&J nor the representatives of SRTC/RPP-WTP. Videotapes of the techniques utilized by J&J was made and are available.

## 6.0 Document Control

The preparation, issue, and change of documents that specify quality requirements or prescribe activity-affecting quality shall be controlled to assure that correct documents are being employed…

J&J Evaluation:

See item 5.0 evaluation. Additionally, J&J Management reviews all final reports to ensure conclusions and recommendation are correctly drawn.

## 11.0 Test Control

Test required to verify conformance of an item or…Test required to collect data…shall be planned, executed, documented, and evaluated.

J&J Evaluation:

Testing/data collection was performed implementing the ASTM methods. Laboratory technicians collected the data which was evaluated by appropriate technical personnel and issued as a report to SRTC.

Additionally, ASME NQA-1-1989, Supplement 11S states that "In lieu of specially prepared written test procedures, appropriate sections of related documents, such as ASTM methods, Supplier manuals, equipment maintenance instructions, or approved drawings or travelers with acceptance criteria can be used.

## 12.0 Control of Measuring and Test Equipment

Tools, gages, instruments, and other measuring and test equipment used for activities affecting quality shall be controlled and at specified periods calibrated and adjusted to maintain accuracy within necessary limits.

J&J Evaluation:

J&J maintains an array of calibrated instruments. As the leading authority of the applicable ASTM Standards implemented during the testing it was imperative that measurement and test equipment is ~~are~~ maintained and within calibration limits to ensure correct results. Example of testing equipment calibration protocols are:

1. Jenike Direct Shear Tester
    a. Utilized span setting device to calibrate load cell
    b. Calibrate at 0 lb. and 9 lb. setting using pre-calibrated weights
    c. Calibration performed weekly
2. Jenike-Schulze Ring Shear Tester
    a. Utilized custom device to calibrate load cells
    b. Calibrate at specified settings using pre-calibrated weights
    c. Performed each time after tester is relocated

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3. Compressibility Tester
    a. Utilized 0.75 in. gauge block to calibrate dial indicator
    b. Performed before each test
4. Laboratory Electronic Scales
    a. Used 200 g or 600 g calibrated weights to calibrate scales
    b. Performed monthly
5. Permeability Tester
    a. Leak check performed quarterly
    b. Depth gauge is calibrated before each test
6. Chute Tester
    a. Calibration not required
7. Angle of Repose
    a. Calibration not required
8. Malvern Particle Size Analyzer
    a. Calibration performed by Jenike & Johanson and vendor using calibrating sample
    b. Performed quarterly or more frequently as required
    c. Unit was calibrated in July, one month after the RPP tests. Unit was in calibration.
9. High Temperature Ovens
    a. Calibration performed with thermocouples
    b. Performed with each use
10. Environmental Chamber
    a. Calibration performed to check relative humidity and temperature
    b. Performed semi-annually or during each maintenance servicing

## 17.0 Quality Assurance Records

Records that furnish documentary evidence of quality shall be specified, prepared, and maintained...

J&J Evaluation:

As stated in the purchase document, a report of findings, recommendations, suggestions, and cautions was to be delivered. J&J performed this activity issuing the report to SRTC.

## 18.0 Audits

Planned and schedule audits shall be performed to verify compliance with all aspects of the quality assurance program and to determine its effectiveness....

J&J Evaluation

J&J does not have a formal audit program. STRC and WTP technical personnel performed site visit to witness the implementation of the purchase order. Additionally, the task (S-139) has been the subject of not only an SRTC internal audit, but also RPP-WTP audit in 2002.

## Conclusion

As stated in the purchase requisition, ~~to~~ J&J is the only known firm capable of performing all the requested measurements and interpreting the test results for engineering solutions to prevent problems with bulk transfer storage and transport. J&J developed the required techniques and patented equipment to support these techniques. J&J maintains ASTM procedure, D6128, and has the infrastructure to support and perform all the tests ~~as~~ specified in the purchase order.

The development and use of this ASTM procedure by J&J, J&J's position in the industry, the STRC/WTP-RPP technical site visit, and SRTC/QAD evaluation of J&J provides the basis for acceptance of data produced by J&J satisfying the QA requirements of RPP.

Based on these conclusions the data generated by this work has not been compromised and is acceptable to use as is. Further, an assessment of the SRTC procedure (WSRC E7, 3.70) for Qualifying Existing Data shows that no further qualification evaluation would be required because the data meets current documentation and QA requirements.

Revision 0, 1/25/2001

**ORIGINAL**

CSATS Number 2002-0791
Corrective Action Number 1

# Problem Identification Report

PIR No. 2002-PIR-11-00052
Page 1 of 3

## A Problem Identification

| Topic | Responsible Manager Department | Requirements Document(s) |
|---|---|---|
| QA Rquirements | WASTE MGMT & ENV TECHNOLOGY | 1Q, QAP 4-1 |

**Specific Requirements**
1Q QAP 4-1 Revision 4, Section 4.A states in part, "...Specify the QA requirements applicable to suppliers or subcontractors depending on the type, use, procurement level or functional classification of items and services to be procured...."

**Problem**
Contrary to the above, Purchase Requisition 0F0806 issued to Jeinke & Johannson, did not specify any QA requirements as required. The purchase order was awarded to Jeinke & Johannson as a sole source vendor to provide characterization and material flow of GFCs. J & J is recognized as the leading authority in this field and has developed the US national standard, adopted by American Society for Testing & Materials (ASTM) which was required to be utilized within the scope of the contract.

**Problem/Document Source** ☐ SWO ☐ SA ☐ ME ☐ ORPS ☒ QA ☐ RC ☐ FEB ☐ PAAA ☐ DOE

**Reported by (Print/Signature/Date)** Hansen, E. K. 11/27/2002

**Validation Determined By (Print/Signature/Date)** JP Vaughan / J. P. Vaughan

**DOE Reportability** ☐ Yes ☒ No
ORPS No.

**Determined By (Print/Signature/Date)** 11/27/02

## B Prob. Eval

**Significance Category** ☐ 1 ☐ 2 ☒ 3 ☐ 4

**Nuclear Activity** ☐ Yes ☒ No

**RPOC (Print/Signature/Date)** NA

**Functional Area(s)** 8

**NCR** ☐ Yes ☒ No

**NCR No.** N/A

**Responsible Manager (Print/Signature/Date)** CROWLEY, DAVID A. David A. Crowley 11/27/02

## C Corrective Action Development

**Action(s) to Remedy Problem**
1. Define NQA-1 attributes as it applies to the purchase requisition.
2. Evaluate Jeinke & Johannson QA program to the define NQA-1 attributes.

**Cause**
J & J was a sole source vendor. No pre-award qualification process was performed.

**PAT Cause Code(s)** A3B3C2

**ISMS Code(s)** 3

**Lessons Learned Applicability** ☐ Site ☐ Division ☐ Department ☐ Section ☒ None

**Action(s) to Prevent Recurrence**

**Estimated Completion Date:** 12/12/02

N/A

**Closure Verification Required** ☒ Yes ☐ No

**Independent Verification** ☒ Yes ☐ No

**CA Recommended By (Print/Signature)** JP Vaughan / J. P. Vaughan **Date** 11/27/02

**Responsible Manager Approval (Print/Signature)** CROWLEY, DAVID A. **Date** 11/27/02

**Other Approval (Print/Signature)** NA **Date**

## D Implementation & Closure

**Corrective Action Completed (Print/Signature)** JP Vaughan / J. P. Vaughan **Date** 12/11/02

**Closure Verification Actions**

See attached

**Closure Verification Completed By (Print/Signature)** JP Vaughan / J. P. Vaughan **Date** 12/11/02

**Closure Re-Verification Completed By (Print/Signature)** NA **Date**

**Effectiveness Evaluation & Due Date** ☐ Yes ☒ No

**Responsible Manager Closed (Print/Signature)** CROWLEY, DAVID A. **Date** 12/11/02

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Page 2/~~2~~3
12-11-02

SRTC QAD has reviewed and concurred with the Sole source justification provided with the purchase requisition to Jenike & Johannson (attached). The method (s) to test various bulk solids flow properties, as stated in the purchase requisition are associated with the Jenike Methods (ASTM D6128). Jenike & Johannson developed and maintains the integrity of the ASTM D6128.

The NQA-1 elements that should have been applied to this purchase requisitions on a graded approached are as follows: 1.0, Organization; 2.0, QA Program; 5.0, Procedures, Instructions and Drawings; 6.0, Document Control; 11.0, Test Control; 12.0, M&TE; and 17.0, Records. In conclusion the work performed using the ASTM standard by Jenike and Johannson as specified by the purchase requisition meets the graded QA elements of NQA-1. Data generated by this purchase requisition was derived under strict ASTM standard(s) and was found to be acceptable for use as is.

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Rev 3-6-95

# Sole Source Justification

**Westinghouse Savannah River Company**

*This form is to be used to justify Sole Source procurements as discussed in the Procurement Management manual (WSRC-7B), Procedures 1.1, 4.2, and 4.3.*

| | |
|---|---|
| Requisition No./Stores/Spare Parts Data Sheet No./Consolidated Materials Data Sheet No. | Date<br>1/24/2002 |

Name of Supplier/Manufacturer
Jenike and Johanson, Inc.

1. Background
WSRC has contracted with the Hanford River Protection Project to characterize the bulk solids handling capability of a series of glass forming chemicals and minerals. The Technical Task Plan supporting this effort states that ASTM procedure D 6128 will be used to meet the Quality Assurance requirements. Jenike and Johanson developed the required techniques as stated in ASTM D6128 and the patented equipment supporting this procedure. Jenike and Johanson Inc. have been in business of characterizing solids using the Jenike and Johanson method (ASTM D6128), designing dry handling systems and providing consulting for more than thirty five years. Their staff of engineers have worked with more than 2000 clients.

2. Exclusive Capability of the Source
Jenike and Johanson maintains the ASTM procedure D6128 and has the infrastructure to support all the tests as specified in the PO and provide engineering recommendations. Due to their vast experience, they have the ability to interpret the resulting data and predict potential problems with the flowability and storage of the dry materials. The use of this ASTM procedure provides an acceptable basis of measurement and will support the quality assurance requirements of this program.

3. Other Extenuating Circumstances or Considerations
Jenike & Johanson Inc. is the only known firm capable of performing all the requested measurements, use of the ASTM D6128 standard, and interpreting the test results to engineering solutions to prevent problems with bulk transfer storage and transport.

3/10/2003

2003-PIR-11-00052

# Memo to File

Subject: 2003-PIR-11-00052

In response to client's review/comments of associated task plan relating to Jenike and Johanson (J&J) activities, WSRC-TR-2001-00424, "Selection of HLW and LAW Glass Former", Revision 1, dated 3/5/03 attached, the following additional NQA-1 elements were evaluated for consideration/applicability to this activity:

Section 8.0, "Identification and Control of Items".
Section 13.0, "Handling, Storage, and Shipping"

SRTC/QAD has evaluated the additional two attributes and has determined that J&J applies similar controls for its applicable work activities. Identification and control of items (samples of GFC) is established and maintained during normal laboratory protocol during the sampling and characterization process.

Handling, storage, and shipping applicable controls required by the purchase order were found to be satisfactory. J&J protocol, and as defined in the applicable ASTM Standard, places strict handling requirements on the samples. The purchase order required storage requirements of the samples prior to implementing the requested test. Shipping is not applicable to J&J, as the material and associated documentation was an SRS responsibility, and further directed J&J to dispose of all residual material.

Based on SRTC/QAD evaluation no further actions are required. This memo to file will be maintained with the associated PIR and a copy will be entered into the applicable Laboratory Notebook associated with this activity.

J. P. Vaughan
3/10/03

# COMMENT RESOLUTION FORM

Page 1 of 2

Return to: Kerry Prindiville

Comments Due: February 26, 2003

| | | | |
|---|---|---|---|
| Document Title: Selection of HLW and LAW Glass Formers (Task Technical and QA Plan) | Document No.<br>WSRC-TR-2001-00424 | Revision:<br>1 | Date:<br>2/19/03 |
| Reviewer: R. D. Reed,r1 Date: 2/20/03;3/5/03 | Response by: Date: | Comments Resolved: Date: | |

| Item No. | Section/ Paragraph | Comment | Response | Significance [a] | Resolution | Incorporated? |
|---|---|---|---|---|---|---|
| 1 | I.A, 2nd Par. | Provide NQA-1/2 matrix for subcontractor Jenike and Johanson Inc. | Added an additional QA Graded Approach Matrix to the Task Plan as Attachment C. | M | Partial, see 1a | |
| 1a | Attachment C | NQA-1 items 8, 13, and 13S-1 should be affirmed since there are requirements for identification, control and special handling and storage of GFCs, and J&J employees must perform these activities. | | M | | |
| 2 | III,Consultant Provides Report, last sentence | Explain what is meant by: The resulting data from the Jenike & Johanson characterizations will be verified later at SRTC. | Changed TTP to explain verification process. Data was independently reviewed by two engineers knowledgeable in the field of powder flow properties. This was followed up by questions on issues to J&J. Previous GFC characterizations by SRTC were compared to the J&J results. | M | Accepted | |
| 3 | VIII., QA Plan Checklist | Change "Subpart 2.7" to 'Part 2.7" | This was changed. Recommend that the IWO be changed to comply with this change. | | Accepted | |
| 4 | VIII., QA Plan Checklist | Provide justifcations in the checklist for items marked "No" [It appeared only 11.1 is justified.] | These changes were made although the original test specification did not require this. | M | Accepted | |
| 5 | VIII., QA Plan Checklist | Explain why 18-3, QA External Audits, is marked "No", when a subcontractor [J&J] is involved. | QA Audit is not applicable to this work, per WSRC program. The activity does not fall under audits as it is defined within the SRTC QA Program. | M | See 5a | |

## COMMENT RESOLUTION FORM

Sheet 2 of 6

Return to: Kerry Prindiville

Comments Due: February 26, 2003

| | | | |
|---|---|---|---|
| Document Title: Selection of HLW and LAW Glass Formers (Task Technical and QA Plan) | Document No.<br>WSRC-TR-2001-00424 | Revision:<br>1 | Date:<br>2/19/03 |
| Reviewer: R. D. Reed,r1 — Date: 2/20/03;3/5/03 | Response by: — Date: | Comments Resolved: — Date: | |

| Item No. | Section/ Paragraph | Comment | Response | Significance[a] | Resolution | Incorporated? |
|---|---|---|---|---|---|---|
| 5a | | Further explanation is needed. | | M | | |
| 6 | VIII., QA Plan Checklist | Explain why 18-6, QA Internal Audits, is marked "No", when a subcontractor {J&J] is involved. | Change to YES. | M | Accepted | |
| 7 | Author's Comment section | Delete this new section.<br>Delete any indication the final report is to be used for information only: The report and data are to conform to NQA-1 requirements and be suitable for design input. Rationale in the Test Exception related to including typical data in procurement packages is not intended to relieve SRTC of contractual requirements for providing NQA-1 qualified R&T data. | | M | | |
| | | | | | | |
| | | | | | | |
| | | | | | | |

[a] **Significance**: M = Mandatory; Mandatory comments are limited to those comments that are technical or requirements related. Mandatory comments must be resolved. If comments are not mandatory, leave this block blank.