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SRNL REVIEW AND ASSESSMENT OF WTP UFP-02 SPARGER DESIGN AND TESTING

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March 2014

SRNL-STI-2013-00590, Revision 1

SRNL.DOE.GOV

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Printed in the United States of America

Prepared for
U.S. Department of Energy

Keywords: WTP, Sparger

Retention: *Permanent*

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Prepared for the U.S. Department of Energy under contract number DE-AC09-08SR22470.

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REVIEWS AND APPROVALS

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LIST OF REVISIONS		
Revision Number	**Summary of Changes**	**Date**
0	Initial	Feb 2014
1	Page vii, 2nd bullet: changed to "…100X the hydrogen generation rate…"	Mar 2014
1	Page 5, 2nd paragraph: rewritten with updated information on the bubbler provided by DOE and BNI.	Mar 2014
1	Page 5: added 3rd paragraph to describe air sparger in more detail	Mar 2014
1	Page 6, Figure 1: Modified to include bubbler and air sparger	Mar 2014
1	Page 10: Added paragraph to discuss bubblers	Mar 2014
1	Table 1: Changed inside diameter of WTP Design to 1.939 inches	Mar 2014
1	Page 13, last bullet: changed to "…100X the hydrogen generation rate…"	Mar 2014
1	Appendix A: Moved calculation of effective discharge area and effect discharge diameter to appendix and expanded discussion	Mar 2014

Summary

During aerosol testing conducted by Parsons Constructors and Fabricators, Inc. (PCFI), air sparger plugging was observed in small-scale and medium-scale testing. Because of this observation, personnel identified a concern that the steam spargers in Pretreatment Facility vessel UFP-02 could plug during Waste Treatment and Immobilization Plant (WTP) operation. The U. S. Department of Energy (DOE) requested that Savannah River National Laboratory (SRNL) provide consultation on the evaluation of known WTP bubbler, and air and steam sparger issues.

The authors used the following approach for this task: reviewed previous test reports (including small-scale testing, medium-scale testing, and Pretreatment Engineering Platform [PEP] testing), met with Bechtel National, Inc. (BNI) personnel to discuss sparger design, reviewed BNI documents supporting the sparger design, discussed sparger experience with Savannah River Site Defense Waste Processing Facility (DWPF) and Sellafield personnel, talked to sparger manufacturers about relevant operating experience and design issues, and reviewed UFP-02 vessel and sparger drawings.

The conclusions from this review follow.

- The BNI design effort for the bubblers and steam sparger is thorough and well thought out, but plugging (air spargers in particular) can still be a challenge that needs to be better understood.
- Less data exists for the design of the air spargers.
- BNI has performed calculations and testing to assess the effectiveness of the steam spargers and made design changes to reduce plugging and prevent erosion.
    - The enhanced design changed the direction of the steam sparger discharge orifices to prevent corrosion/erosion of the vessel walls.
    - The design revisions added Stellite inserts to the steam sparger orifices to reduce or eliminate risks of corrosion and erosion of the steam sparger tube.
    - The design includes an air purge to prevent slurry from entering the steam sparger when the steam is turned off.
    - BNI conducted computational fluid dynamics (CFD) calculations to determine operating conditions to select the steam sparger design and to examine the predicted flow patterns.
    - BNI conducted testing of the steam spargers to assess efficiency of heat transfer and to observe induced mixing patterns.
- The following concerns and conclusions were identified during the current SRNL evaluation
    - Bubbler plugging - DWPF and PEP testing experienced bubbler plugging. The design of the WTP vessels incorporates the lessons learned by virtue of larger diameters and provisions for clearing plugs through application of air and water purging which have been shown effective in limited WTP testing and in extensive DWPF operational experience. Given these design features, probability for plugging of WTP bubblers is judged as low.
    - Steam Sparger plugging – The design follows the steam sparge with an air purge to prevent solids being drawn into the steam sparger. Any residue not removed by the reintroduction of steam could remain with each cycle and accumulate, eventually plugging the steam sparger. This design should reduce the probability of steam sparger plugging, but we recommend verifying and establishing exact operating parameters during commissioning tests.
    - Equipment erosion - The steam sparger ring holes are at least 24 inches from any internal structures in agreement with typical vendor design experience, so equipment erosion should not be a concern in the UFP-02 design.

  - Steam sparger erosion - The basis for the corrosion/erosion allowance for the steam sparger rings appears based largely on engineering judgment. The unverified design assumptions warrant further review and analysis. WTP has mitigated the risk by inclusion of Stellite inserts in the design. The final design drawings for the inserts were not available. Caution needs to be exercised in the final design to allow for differences in thermal coefficients of expansion and consideration given to prior DOE complex experience with erosion of Stellite parts.
  - Air Sparger Plugging – The design of the air sparger incorporates a large diameter tube (2 inch schedule 160 (1.687 inch ID) with four triangle cuts bent slightly inward at the end giving an ID of 1.19 inches) and an air purge. The air purge rate was selected to prevent plugging and to exceed 100X the hydrogen generation rate in UFP-02. A basis for the purge rate being sufficient to prevent air sparger plugging is needed.

The authors make the following recommendations.

- Although the exact cause of air sparger plugging in prior testing is unproven, the rapid plugging events may reflect the combined chemical composition of the slurries tested and the specific operating conditions of the tests either of which in turn may be non-representative of expected conditions in UFP-02. If a more definitive understanding of the cause is desired, one option to assess the cause is to conduct differential laboratory-scale testing to examine the propensity of the prior test simulant to form solids during heating and contrasting to more representative UFP-02 process simulants or operating conditions.
- Test effectiveness of steam sparger operation including cleaning. The testing should also assess the reliability and effectiveness of the air purge in preventing solids from entering the steam sparger and causing plugging. This testing should be considered as part of commissioning. Similarly, the start-up plan for operations should include features that maintain a focus on monitoring for evidence of fouling.
- BNI should verify the assumptions used in the steam sparger design calculations prioritizing based on technical and commercial risk to the project. Verification of assumptions is required by design procedure and will be monitored by the Department.
- BNI should provide the basis for erosion of steam sparger holes as is standard protocol for documentation of design
- Subject the final design for the steam sparger ring to review by appropriate experts. Assess selection of Stellite for the inserts versus other candidate materials. Assess design features for risk due to differences in thermal expansion coefficient for the insert and the base metal.
- Monitor steam sparger pressure and gas flows during UFP-02 operation to identify plugging or erosion issues early. Establishing a baseline understanding for sensitivity of these measurements prior to start of radiological operations is integral to this monitoring approach.
- BNI should provide a basis for the air sparger purge rate being sufficient to prevent plugging of the air spargers and a plan for establishing the frequency of cleaning operations and capabilities.

TABLE OF CONTENTS

Introduction

The WTP has three methods for gas introduction into UFP-VSL-00002. These methods are bubblers, air spargers, and steam spargers. The bubblers measure vessel fluid level and fluid density by injecting air in to the vessel and measuring the air pressure as a function of flow rate. The air spargers inject air into vessels containing non-Newtonian fluids to improve fluid mixing in the upper and lower regions of the vessel. The steam spargers heat the vessel prior to caustic leaching by the direct injection of steam.

During aerosol testing conducted by PCFI, air sparger plugging was observed during small-scale and medium-scale testing.[1,2,3,4] Because of this observation, personnel identified a concern that the steam spargers in vessel UFP-02 could plug during WTP operation. DOE requested that SRNL provide consultation on the evaluation of known WTP sparger issues.

The Scope of Work elements for this effort follow: review current WTP sparger design drawings, review existing test and operational data reports relevant to air and steam sparger operation, review and validate currently documented technical issues associated with air and steam spargers, issue letter report with a definitive statement regarding technical issues affecting WTP sparger systems in the conclusion section, and discuss the findings with DOE-ORP Staff.[5]

The authors used the following approach for this task: reviewed previous test reports (including small-scale testing, medium-scale testing, and PEP testing), met with BNI personnel to discuss steam and air sparger design, reviewed BNI documents supporting the steam and air sparger design, discussed sparger and bubbler experience with SRS DWPF and Sellafield personnel, talked to sparger manufacturers about relevant operating experience and sparger issues, and reviewed UFP-02 vessel and steam/air sparger drawings.[1,2,3,4,6,7,8,9,10,11,12,13,14,15,16,17,18,19]

Previous Testing

Small-Scale Aerosol Tests

PCFI conducted small-scale air sparger testing to measure aerosol entrainment coefficients for BNI. The supernate simulant for these tests contained varying concentrations of sodium oxalate, aluminum nitrate, sodium phosphate, sodium nitrate, sodium hydroxide, sodium nitrite, and sodium carbonate. The liquid composition of the aerosol testing simulant was the same as the one used in PEP with varying Na concentrations. The solid component of the simulant contained hydroxides of manganese, calcium, cerium, iron, lanthanum, magnesium, neodymium, nickel, strontium, and zirconium, as well as calcium fluoride. The small-scale air sparger was designed to produce 1/8 inch bubbles. The testing was not designed to assess air sparger plugging, and the simulant was not prototypic of UFP-02 operation.

During the testing, personnel observed air sparger plugging with "high density"[a] simulants. These high density simulants were saturated, so the plugging occurred due to salting out of the solids or drying out the solution. In addition, many of the tests were conducted at high temperatures (45 – 90 °C), which led to evaporation of water, which could have increased the tendency for solids forming inside the air spargers. Analysis of the solids plugging the air sparger showed Na_3PO_4-NaF and CaF_2. The CaF_2 was added as an "inert" solid and is not typical of expected WTP feed, especially in the concentrations used. This lack of prototypical simulant makes it difficult to directly assess the risk for normal UFP-02 operations; it is possible that the plugging observed in these tests is more extreme than will occur in the process. At times during testing, air flow was interrupted which likely provided higher

[a] "High density" refers to higher salt concentrations and "low density" refers to low salt concentrations.

risk of plugging. Subsequent to this testing, DOE adopted a lower upper bound for operating temperature (85 ºC reduced from 98 ºC) to mitigate evaporation and precipitation risks.[9] During the small-scale testing, the diameter of air sparger holes was 0.07 mm (0.0028 inch). The steam spargers in the WTP design have larger 0.125 inch holes. The larger diameter also mitigates the risk of plugging.

Medium-Scale Aerosol Tests

PCFI conducted medium-scale air sparger testing to confirm that the small-scale test results for aerosol entrainment coefficients are bounding. The simulant in this testing was the same as in the small-scale testing. Tests were conducted at 45 ºC. Like the small-scale testing, this testing was not designed to assess air sparger plugging. The air sparger was designed to represent a typical WTP single outlet air sparger nozzle scaled to maintain the required gas velocity at the nozzle outlet while providing headspace superficial air velocities similar to those in the small scale tests. UFP-02 has multiple nozzle outlets (0.125 inch diameter) on a steam ring. In the medium-scale test, the air sparger was a 2 inch diameter pipe that increased to 3 inch diameter at the end rather than the 0.125 inch holes of the WTP steam sparger ring. The air sparger in UFP-02 is a dip tube style sparger with an inner diameter of 1.687 inches (2 inch schedule 160 pipe) and an opening of 1.19 inches based on the end being tapered inward.[14]

During testing, personnel observed air sparger plugging occurred with “high density” and “low density” simulants. Analysis of the solids plugging the air sparger showed Na_3PO_4-NaF and CaF_2. The air sparger was cleaned with muriatic acid, but that is not a viable cleaning solution for the WTP. The intent of this testing was to assess entrainment from dip style tube air spargers, rather than ring style steam spargers.

The following common observations were noted with the small-scale and medium-scale testing. The testing was designed to measure aerosol entrainment and not steam sparger performance. The sparging was performed with air rather than steam. The air sparger in the small-scale testing consisted of a manifold with many holes that were much smaller than the holes in the steam sparger ring in UFP-02. The air sparger in the medium-scale testing was a dip tube sparger with a single hole rather than a steam sparger ring as in UFP-02. The simulants may have been atypical of the process and contributed to the observed behavior (i.e., they may have been overly conservative). The gas flow was off during periods of the testing. Turning the gas flow off would create a vacuum and cause slurry from the test vessel to enter the air sparger. The test vessels were mixed with impellers rather than with pulsed jet mixers.

The small-scale and medium-scale test designs were not prototypic of the WTP steam spargers. The steam sparger design is different from the sparger designs in the small-scale testing and the medium-scale testing. The plugging observed in these tests does not provide direct evidence that plugging will occur in the UFP-02 steam spargers.

While the air sparger in UFP-02 has a similar size to the air sparger used in the medium-scale testing, the air sparger in UFP-02 has a low flow rate purge when it is not being used for mixing and a flush system to prevent the accumulation of solid particles. The normal flow rate is ~ 321 SCFM for 16 air spargers, and the purge (or “idle”) flow rate is 32 SCFM for 16 spargers (2 SCFM per sparger).[20] The basis for the purge rate in UFP-02 being sufficient to prevent plugging is needed.

PEP Tests

The Pretreatment Engineering Platform (PEP) was designed, constructed, and operated to address issue M12, Understanding Leaching Processes. The PEP is a 1:4.5 scale test platform designed to simulate the WTP Pretreatment caustic leaching, oxidative leaching, insoluble solids concentration, and slurry washing processes. Testing was conducted to evaluate the caustic leaching process; observations relative to risk of plugging provided secondary – or opportunistic -- data.[21,22,23,24]

The simulant used in this testing contained boehmite, gibbsite, chromium oxyhydroxide, sodium oxalate, filtration simulant, and supernate. This simulant was selected to investigate caustic leaching, oxidative leaching, and washing. It was not selected to investigate steam sparger, air sparger, or bubbler performance. The duration of the PEP testing was approximately 39 days.

The test reports indicated that the bubblers were susceptible to plugging, but did not give the basis for this conclusion. The reports indicated that high pressure air, steam condensate, and inhibited water were used to clean the bubblers, and that the cleaning was somewhat effective although no explicit metrics were provided in the report. The bubblers in the PEP testing had a ½ inch diameter rather than the 1.939 inch ID of the bubblers in the WTP Pretreatment Facility.[24] The smaller diameter would increase the propensity of the bubbler to plug and would not be prototypic of the bubblers in the WTP. The larger diameter of the WTP bubbler will allow cleaning to be more effective if fouling occurs.

Steam spargers were used for heating the vessel contents, air spargers were used for mixing, and bubblers were used for measuring level and density. The steam spargers operated for approximately 100 hours during this testing. The air purge of the steam spargers was shut off during portions of testing to increase the probability of steam sparger plugging. After the airflow was stopped, it was resumed and the response indicated significant plugging did not occur.[25]

Following Phase 1 testing, the steam spargers were inspected to determine extent of plugging and scale buildup. A camera was inserted through a spare nozzle on the vessel head to inspect the steam ring and the support bracket. The inspection was performed on Vessel T02A after a nitric acid wash of the filter loop and the inspection was performed on Vessel T01A after a hot inhibited water flush of the vessel. The acid wash and hot water flush were performed to replicate the expected operating conditions in UFP-01 and UFP-02. No plugging was evident in the steam sparger nozzles and no significant scale buildup was observed on the external surface of the steam sparger. The observations, combined with the behavior of the steam spargers after the air flow was resumed, show that if any solid plugs had formed, they were removed by normal process operations.

The final report recommended following the steam sparge with an air purge to prevent steam sparger plugging. This protocol has been added to the design.

The upper air spargers unintentionally lost flow at times during the dewatering of leached slurry, which led to air sparger plugging. The air spargers were cleaned with a water flush followed by high pressure air. The air spargers used in the PEP testing were ½ inch diameter compared to 1.687 inch inside diameter in UFP-02. The UFP-02 air spargers have a purge system to prevent the buildup of solid particles, and remove solid particles that accumulate inside the air spargers. The larger diameter and the incorporation of the purge and flush system in UFP-02 should reduce the probability of the air spargers plugging in UFP-02. The air purge (or "idle") rate was selected to prevent plugging and to exceed 100X the hydrogen generation rate in UFP-02 (32 SCFM for 16 sparger tubes or 2 SCFM per sparger tube).[20] The sparger airflow requirements calculation[22] lists the idle flow rates as not needing verification, but no basis or reference to substantiate this conclusion is provided.

BNI Steam Sparger Design

The authors (Poirier and Fink) held discussions with Eric Slaathaug, Doug Vo, Pietro Martinelli, and Michael Summers – BNI personnel involved in the design of the bubblers, steam spargers, and air spargers.

BNI has made a recommendation that bubblers should be designed with a means to clear blockages with air, water, chemical reagents, and/or steam.[26,27] Details of the design were not provided. DOE should monitor the implementation of these recommendations.

In developing the steam sparger design, BNI first evaluated four approaches for heating UFP-02 using computational fluid dynamics (CFD) and bench-scale testing.[10] The approaches included a 3/8" Severn Trent type 514 Steam Heater, a ¾" Severn Trent type 514 Steam Heater, a Komax Steam Heater, and a custom-designed Steam Sparge Ring. The Komax Heater was not selected because of a higher than desired risk of steam impingement on equipment within the vessel. The Severn Trent units produced better mixing than the ring steam sparger, but they had a higher risk of impingement on structures within the vessel. In addition, simulations showed that steam vapor could be drawn in to the PJMs during the suction phase. The Steam Sparge Ring was selected because it produced more even distribution of heat, had less potential to draw steam vapor into the PJMs, and had less impingement potential. Even though the improved mixing is desirable, reliable heating without impingement is the primary design concern.

The steam sparger is appropriately located in the PJM mixing zone to enhance heating efficiency and to mitigate risk of local solids formation. The orientation of the holes was selected to minimize the risk of wall erosion from steam sparger jets. BNI' s current design philosophy and envisioned operation requires air purging to avoid reverse flow during steam collapse, which mitigates the risk of plugging. The air sparge starts before steam sparge stops. The design includes a method to remove slurry from the steam sparger; they calculated the minimum airflow needed to remove slurry from steam sparger line.[6] The calculation has the following assumptions that require design verification.

- The purge air enters the header at 100 psig and 80º F.
- The vessel vent system can provide 495 scfm of purge air to the UFP-02 steam sparge rings
- The steam sparger will have 1/8 inch diameter holes that erode to 3/16 inch over the design life.
- The length of the steam lines is 175 feet.
- The air header to the vessel is 3 inch diameter pipe.
- The UFP-02 steam lines are 1 inch diameter pipe.
- The pipe for the steam sparger rings will be 4 inch schedule 80 pipe.

BNI included an erosion allowance of 1/16 inch in design, but the basis for erosion allowance is not well defined.[28] It is identified as open assumption that needs verification.

Following Phase 1 PEP testing, BNI inspected the steam spargers for plugging.[8,9] The purpose of the effort was to inspect the PEP steam spargers to determine the extent of any hole plugging or scale buildup. The air purge of the steam spargers was turned off during testing to increase the chance of steam sparger plugging. The inspection found no evidence of steam sparger plugging.

BNI has made a recommendation that air spargers should be designed with a means to clear blockages with air, water, chemical reagents, and/or steam.[6,10] Details of the design were not provided. DOE should monitor the implementation of these recommendations.

DWPF and Sellafield Experience

The authors (Poirier) talked with personnel at the SRS DWPF and British Sellafield to discuss their experience with spargers and bubblers.

The DWPF does not use spargers, but does use dip tube bubblers. Prior to 1997, the slurry preparation tanks that fed the DWPF melter used bubbler tubes to measure density at three heights. These tanks contain relatively concentrated or saturated slurries and operate at elevated temperatures (e.g., ~90 °C or to boiling), conceptually similar to the UFP-02 vessel conditions. Those tubes were approximately ¾-inch in diameter and readily plugged. Frequently, the plugs could be cleared by using 90 psig air pressure, but at times this air pressure was not sufficient to dislodge the plug causing DWPF to stop, so the bubbler could be cleared with a lance, or metal rod.

Testing was conducted to evaluate possible solutions to the bubbler plugging problem.[29] The testing showed that a large diameter tube bubbler (2.64 inch inside diameter) with suitable length (at least 12 inches) of the expanded diameter zone operated successfully throughout the 2-month test and did not plug with the glass-frit containing slurry.[30] The WTP bubblers have an internal diameter of 0.957 inches that expands to an internal diameter of 1.939 inches. The discharge has four triangular cuts that bend inward (see Figure 1). This design is different from the expanded diameter section of the DWPF bubblers. The purpose of the notches at the bubbler discharge is to produce a steady stream of small bubbles rather than an intermittent stream of large bubbles.[31] The triangular cuts also increase the effective discharge area of the bubblers. The calculation of the effective discharge area and effective tube diameter is given in Appendix A. The effective discharge area is 3.61 – 3.71 in^2. The equivalent pipe diameter for this area is 2.14 – 2.17 inches. The prior testing[33] (Table 1 in the Discussion Section of this report) suggests fouling will occur with smaller diameter bubblers and, unless monitored and routinely purged/cleaned, the probability of fouling is not negligible. While all of the smaller tubes (0.62 inch inside diameter) plugged during the test, the tubes (2.64 inch inside diameter) that are closest to the pipe diameter for WTP (1.94 inches inside diameter) did not plug in the 2 months duration of testing.

The WTP air spargers have an internal diameter of 1.687 inches. The discharge has four triangular cuts that bend inward (see Figure 1). This design is different from the expanded diameter section of the DWPF bubblers. The purpose of the notches at the sparger discharge is to produce a steady stream of small bubbles rather than an intermittent stream of large bubbles.[31] The triangular cuts also increase the effective discharge area of the spargers. The calculation of the effective discharge area and effective tube diameter is given in Appendix A. This area is 2.59 – 2.69 in^2. The equivalent pipe diameter for this area is 1.82 – 1.85 inches.

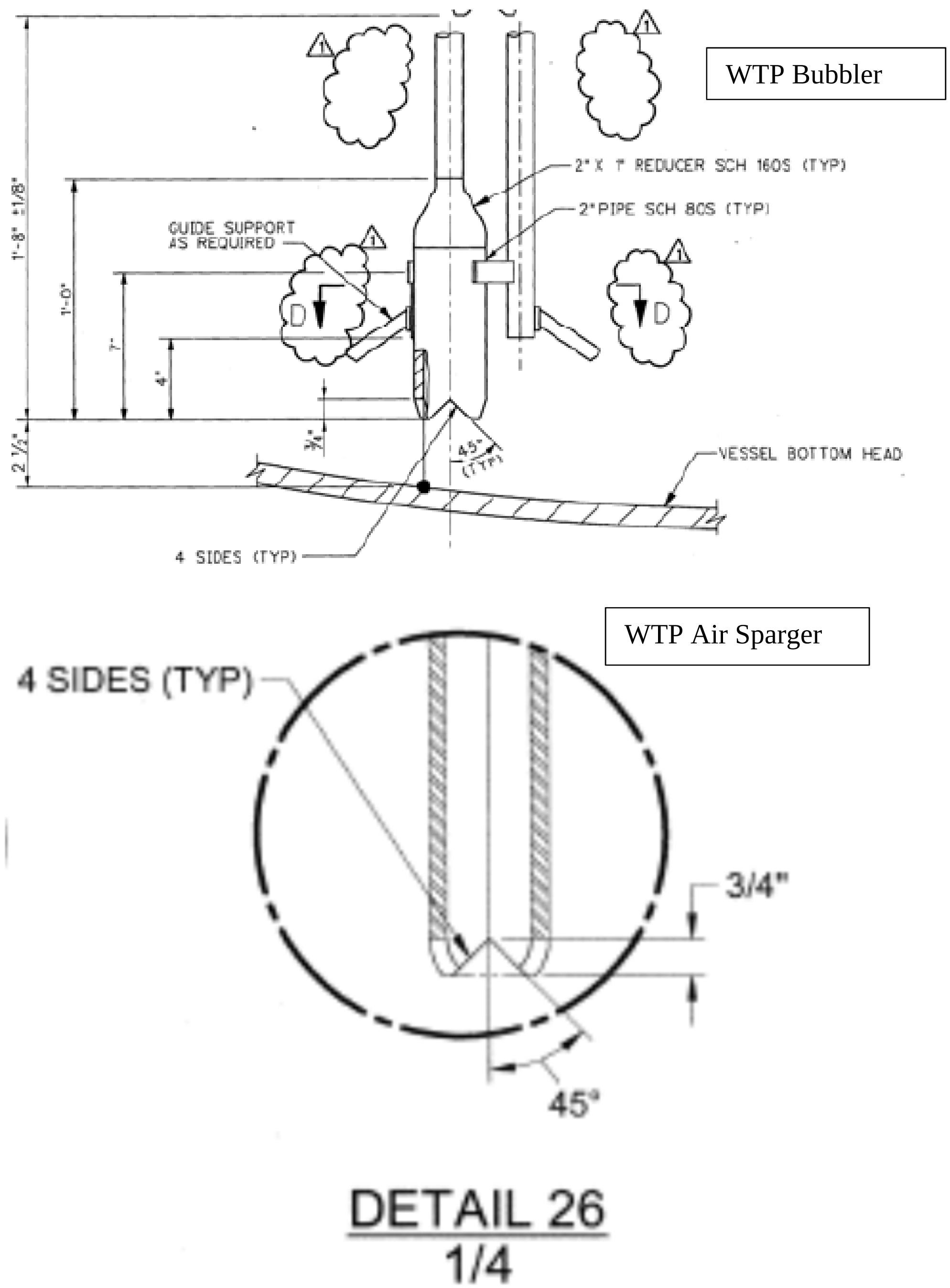


Figure 1. WTP UFP-02 Bubbler and Air Sparger Discharge Error! Bookmark not defined.,[32]

The authors (Duignan and Poirier) contacted Shawn Tester and Helen Boyd of DWPF to discuss their operating experience with bubblers. They could not recall any bubbler failures, but their experience is that cleaning is required more frequently than desired or expected from testing. They blow out bubbler two times per shift for approximately 5 minutes with 80 psi air or 40 psi water. This blowdown can be during operation or standby. Blowdowns are also required procedurally prior to verifying processing endpoints have been achieved. The blowdown process has been automated and is controlled through the DCS and Operations has the ability to blowdown any of the 4 bubbler legs. Other than the blowdown, there is no other cleaning operation. They have observed that new bubblers take ~ 5 years to start showing signs of plug formation.

The DWPF uses steam coils to heat up slurry. They have observed sludge buildup on the coils. In some instances, the buildup has been sufficient to require the removal of the coils.

The authors (Poirier) discussed sparger use at Sellafield with Les Sonneberg, Dawn James, and Geoff Randall. Sellafield does not use steam to heat or mix slurries. They use air sparging as part of the sand filter backwash on their SIXEP plant. The air sparge operates routinely and regularly. They have multifunction sparge lines with relatively large holes (millimeter in size) in their High Activity tanks.

The observations from DWPF and Sellafield are not applicable to ring steam spargers, but they are applicable to dip tube bubblers and air spargers. Based on DWPF experience and PEP testing, bubbler plugging is a concern. Design features were developed to reduce the frequency and severity of plugging. Larger diameter dip tube bubblers, like the ones in UFP-02, are less likely to plug than the ½ inch diameter bubblers in the PEP testing. Operational maintenance protocols for water and air purging have been developed to help mitigate the risk of plugging. The WTP design and operations have adopted these recommendations.

Sparger Manufacturer Operating Experience

The authors contacted the following sparger manufacturers to discuss their experiences: ProSonix, Hydro-Thermal, and Mott. The manufacturers identified the following concerns.

- Steam Spargers are relatively inefficient in heating vessels. While this inefficiency may increase steam usage, steam is not a significant cost for WTP operation and the increased steam usage is not a safety concern.
- When steam is turned off, it will condense and create a vacuum drawing slurry into the holes leading to steam sparger plugging. BNI has addressed this concern by using an air purge when the steam is off.
- Over time, steam will erode the holes. BNI plans to include a Stellite insert to the steam sparger holes to reduce erosion/corrosion.[19,30]
- Recommend switching to air flow when the steam is off. This practice is included in BNI design. The design also includes a lower flow rate air purge when the air spargers are not used for vessel mixing.
- Plugging can result from contaminated steam. BNI needs to ensure quality steam is used for the steam spargers.

Two alternative methods of direct steam injection to heat the vessel were recommended by the vendors: direct steam injection and porous tube steam spargers.

Steam Injection devices are produced by ProSonix and Hydro-Thermal (see Figure 2). Some of the advantages follow.

- Steam Injection system creates a choked flow of steam that always has a constant mass flow rate.
- Injected steam at very high velocities transmits the steam energy to the tank more efficiently. While this increased efficiency may decrease steam usage, steam is not a significant cost for WTP operation.
- Injection systems typically use a plug to close off the injection ports that will help prevent solution suction into the steam sparger and hence plugging.

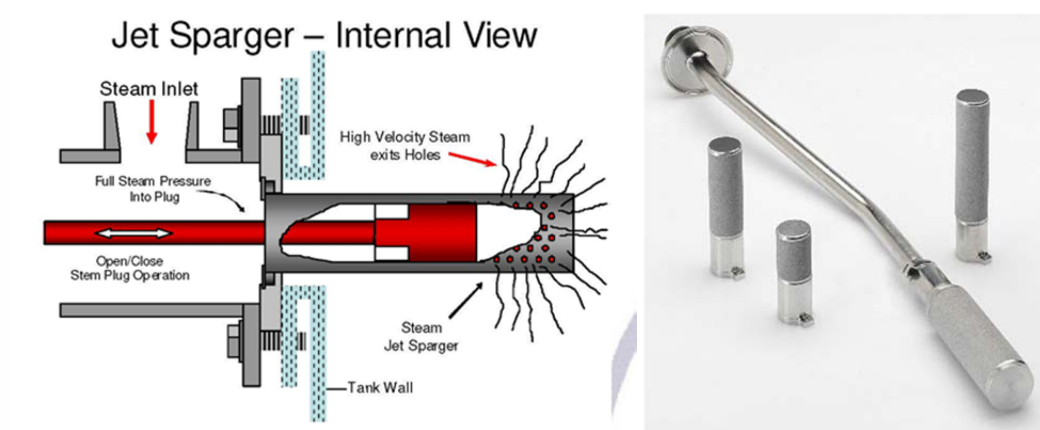


Figure 2. Alternative Steam Sparger Designs

However, injectors need maintenance on the steam fittings. These fittings can be located outside the tank wall or in the flow loop. A steam injector tube (stem) can be made up to 4 ft long so that it can penetrate well into the tank contents. The injector ports would only be at the very end of the injector stem so internally the stem would contain a long rod with the opening and closing plug at the end of the rod to turn the steam off and on. The purity of the steam is important (as it is also for spargers) to minimize corrosion inside the steam injector because the moving parts (i.e., the plug, may be damaged over time with corrosion).[33]

Because the environment is radioactive, the material of any seals to be used would need evaluation. However, some devices can be made with tight tolerances to eliminate seals and avoid the problem (e.g., see the Hydro-Thermal Solaris Hydroheater).

A common location of steam injector is in the process pipe of a flow loop, which allows the media to flow past the steam injector in a controlled manner, more efficiently transmitting the energy from the steam. The alternate design recommendation is to not use a steam sparger but rather to place a steam injector near the pump on the flowloop of the Ultrafiltration Process. The leaching process uses hot filtering; therefore, the filter loop can also be employed to heat the waste at it circulates. Steam injectors are designed to bring the temperature of the media to be processed to target temperature with a single pass. If the injector is located near the pump and in a "warm (grey)" cell then the steam injector diffuser can be serviced during the lifetime of its operation. Furthermore, by not installing the steam sparger ring in the mixing tank, it will not present an extra obstacle to pulse jet mixing.

BNI evaluated direct steam injectors, but chose the steam sparge ring because it produced more even distribution of heat, had less potential to draw steam vapor into the PJMs, and had less impingement potential.

Porous tube steam spargers are produced by Mott. Mott claims that the use of their steam sparger rather than a discrete hole tube prevents steam hammer. Standard porous tube lengths are made to 24 inches, so longer section are welded together. Mott stated that it can weld and bend a porous tube such that it can match the design of the steam sparger currently being considered. The big advantage of the porous tube is the very small bubbles that are injected from the porous surface as compared to any discrete hole system. With smaller and more numerous bubbles, the bubble surface area is increased leading to more efficient energy transfer. While this increased efficiency may decrease steam usage, steam is not a significant cost for WTP operation. Because of the much smaller bubbles and faster bubble collapse, the porous tube design will also minimize or eliminate steam hammers from the collapsing bubbles resulting in less vibration and less damage to equipment. BNI uses the air purge to remove collapsed steam from the steam spargers to prevent water hammer.

Plugging may still be a problem with a porous stream sparger when steam is shut off, but by switching to air flow when steam is not needed may help. This should be evaluated experimentally. Mott recommended Hastelloy C22 with 2 um pores would be best for the UFP-02 application.

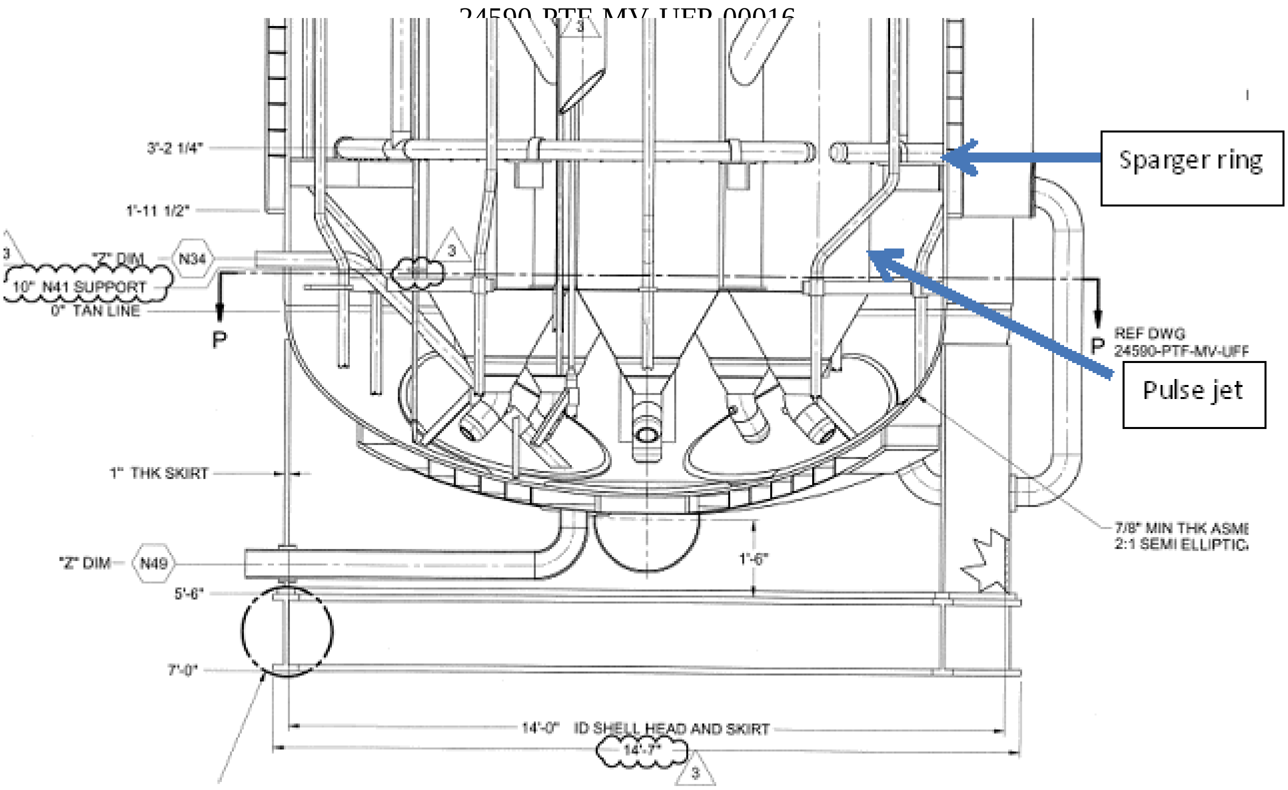
UFP-02 Vessel and Steam Sparger Drawing Review

The steam sparger in vessel UFP-02 is used to heat the contents (see Figure 3). The ring has 110 holes on its underside. The hole diameter is 1/8". Half of the holes point straight down and half point inward at a 30 degree angle. If the steam bubbles were to collapse due to condensation adjacent to a solid surface they could cause erosion damage. Steam sparger manufactures recommend a minimum distance of 12 – 24 inches between the steam sparger and any surfaces.

The distance from the steam sparger ring to the tank bottom is 5 feet, which exceeds the 12 – 24 inches recommended by steam sparger manufacturers. Erosion on the tank bottom from the steam spargers is not a risk.

The horizontal distances from the steam sparger nozzles to the inner wall of the tank or the outer wall of the Pulse Jets are 15" and 18", respectively. Since the steam sparger nozzles are angled down and 30º inward, the distance from the nozzles to the inner wall of the vessel is greater than the 12 – 24 inches recommended by steam sparger manufacturers. The distance from the nozzles to the outer wall of the PJMs would be 18 inches/sin30º = 36 inches, which is greater than the 12 – 24 inches recommended by steam sparger manufacturers. Therefore, erosion of nearby structures should be a low probability.

The steam bubbles discharging vertically from the steam sparger could impact the underside of the steam sparger ring. The fluid motion in the vessel from the PJMs will cause the steam to move in a chaotic path rather than vertically down and vertically up, increasing the distance to the nearest surface.



24590-PTF-MV-UFP-00016

Figure 3. UFP-02 Steam Sparger Ring

The air spargers, not shown in Fig. 3, in UFP-02 are 2-inch schedule 160 pipe (1.687 inches ID) with four triangular cuts bent slightly inwards at the end, which reduces the discharge diameter to 1.19 inches (see Figure 1).

The bubblers (see Figure 1) are 1-inch schedule 160 pipe (0.815 inches ID) that expands to 2-inch schedule 80 pipe (1.939 inches ID) at the end with four triangular cuts bent slightly inwards at the end, which reduces the discharge diameter to ~1.5 inches.

Discussion

In this review of the spargers and bubblers in UFP-02, the authors assessed five potential concerns. These are steam sparger plugging, bubbler plugging, air sparger plugging, steam sparger orifice erosion, and nearby structure erosion.

PEP testing showed that the scaled bubblers were susceptible to plugging. DWPF operating experience has shown solids accumulation in their bubblers. However, with the larger diameter, the DWPF has been able to clean their bubblers with air or water purges. Table 1 shows the diameter of bubblers in DWPF, SRNL testing, PEP testing, and the WTP design. The table shows that larger diameter bubblers are less likely to plug.

Table 1. Comparison of Bubblers

Bubbler	Inside Diameter (in)	Experience
SRNL Testing	2.64	Did not plug in the 2 months duration of testing.
DWPF	2.25	Took 5 years to plug but required occasional cleaning during that period. Now plugs frequently and is cleaned daily
WTP Design[b]	1.939	To Be Determined
SRNL Testing	0.62	Plugged
PEP Testing	0.5	Susceptible to plugging

When the steam sparger stops or is turned off, the steam collapses and a vacuum forms in the steam sparger tube. This vacuum will draw slurry into the steam sparger, which could create a plug. BNI has addressed this concern in their design by introducing purge air through the steam sparger when steam is not being used to heat the vessel. The air purge starts before the steam sparge stops, which is a good design feature. The air purge will (conceptually) also remove condensed steam from the steam sparger to prevent a steam hammer from occurring when the steam flow is restarted. The BNI design to prevent steam sparger plugging is thorough and well-conceived. During the transition between steam and air flow, or during system upsets, slurry could enter holes of the steam sparger and fill the semi-circular rings. Some residue, not removed by the re-introduction of steam, could remain with each cycle and accumulate, eventually plugging the steam sparger. During final design, commissioning, and start-up testing is recommended to confirm the design features of valve sequencing.

Erosion of the steam sparger orifices is a concern. The sparger design includes a Stellite insert to reduce corrosion/erosion.[19,30] BNI assumed a corrosion/erosion of 1/16 inch over 40 years. This assumption has not been verified, and the basis for the assumption has not been provided. The basis for the corrosion/erosion needs to be provided and the assumption needs to be verified. Even so, the WTP has mitigated the risk by inclusion of Stellite inserts in the design.

Stellite has a different coefficient of thermal expansion than the base stainless steel and the authors did not receive the final design to assess whether this factor was adequately considered in the design. Stellite is known to provide significantly improved resistance to erosion by cavitation than stainless steel when applied as a coating and it may be possible to extract an approximation of the predicted erosion rate from the literature.[34] SRNL has examined Stellite materials as coatings for agitators in DWPF vessels with

[b] Equivalent diameter is 2.14 – 2.17 inches as discussed previously.

similar operating conditions but chose Ultimet® R31233 as the preferred material of construction.[35] Additional review of the final design for the steam sparger and inserts, when available, is warranted prior to fabrication.

The impingement and collapse of steam on nearby structures in UFP-02 could lead to corrosion/erosion of these structures. Designs typically allow a 12 – 24 inch clearance to mitigate the risk. BNI modified the steam sparger design to address this risk. The original design had half of the steam sparger holes angled 30º from vertical toward the vessel walls and the other half of the steam sparger holes angled 30º from vertical toward the vessel center. The design was modified so that half of the steam sparger holes were angled vertically downward and half of the steam sparger holes were angled 30º from vertical toward the vessel center. With this design, steam sparger holes are at least 24 inches from any internal structures.

Air sparger plugging was observed during medium-scale testing and PEP testing. In both tests, periods of no air flow through the sparger occurred, which likely caused the observed plugging. In addition, the PEP testing used a smaller diameter air sparger, which would be more likely to plug. The design of the air sparger incorporates a large diameter tube (nominal 2 inch, Schedule 160 – actual inner diameter of 1.687 inch) and an air purge, which should minimize or eliminate plugging of the air spargers.

Recommendations

The authors make the following recommendations.

- Although the exact cause of air sparger plugging in prior testing is unproven, the rapid plugging events may reflect the combined chemical composition of the slurries tested and the specific operating conditions of the tests either of which in turn may be non-representative of expected conditions in UFP-02. If a more definitive understanding of the cause is desired, one option to assess the cause is to conduct differential laboratory-scale testing to examine the propensity of the prior test simulant to form solids during heating and contrasting to more representative UFP-02 process simulants or operating conditions.
- Test effectiveness of steam sparger operation including cleaning. The testing should also assess the reliability and effectiveness of the air purge in preventing solids from entering the steam sparger and causing plugging, especially over many years of operation. This testing should be considered as part of commissioning. Similarly, the start-up plan for operations should include features that maintain a focus on monitoring for evidence of fouling.
- BNI should verify the assumptions used in the steam sparger design calculations prioritizing based on technical and commercial risk to the project. Verification of assumptions is required by design procedure and will be monitored by the Department.
- BNI should provide the basis for erosion of steam sparger holes as is standard protocol for documentation of design
- Subject the final design for the steam sparger ring to review by appropriate experts. Assess selection of Stellite for the inserts versus other candidate materials. Assess design features for risk due to differences in thermal expansion coefficient for the insert and the base metal.
- Monitor steam sparger pressure and gas flows during UFP-02 operation to identify plugging or erosion issues early. Establishing a baseline understanding for sensitivity of these measurements prior to start of radiological operations is integral to this monitoring approach.
- BNI should provide a basis for the air sparger purge rate being sufficient to prevent plugging of the air spargers.

Conclusions

SRNL reviewed WTP sparger design, air and steam sparger testing, WTP sparger design calculations, literature, and DWPF/Sellafield sparger use. In addition, SRNL discussed steam sparging with vendors. The conclusions from this review follow.

- The BNI design effort for the bubblers and steam sparger is thorough and well thought out, but plugging (for air spargers in particular) can still be a challenge that needs to be better understood.
- Less data exists for the design of the air spargers.
- BNI has performed calculations and testing to assess the effectiveness of the steam spargers and made design changes to reduce plugging and prevent erosion.
  - The enhanced design changed the direction of the steam sparger discharge orifices to prevent corrosion/erosion of the vessel walls.
  - The design revisions added Stellite inserts to the steam sparger orifices to reduce or eliminate risks of corrosion and erosion of the steam sparger tube.
  - The design includes an air purge to prevent slurry from entering the steam sparger when the steam is turned off.
  - BNI conducted computational fluid dynamics (CFD) calculations to determine operating conditions to select the steam sparger design and to examine the predicted flow patterns.
  - BNI conducted testing of the steam spargers to assess efficiency of heat transfer and to observe induced mixing patterns.
- The following concerns and conclusions were identified during the current SRNL evaluation
  - Bubbler plugging - DWPF and PEP testing experienced bubbler plugging. The design of the WTP vessels incorporates the lessons learned by virtue of larger diameters and provisions for clearing plugs through application of air and water purging which have been shown effective in limited WTP testing and in extensive DWPF operational experience. Given these design features, probability for plugging of WTP bubblers is judged as low.
  - Steam Sparger plugging – The design follows the steam sparge with an air purge to prevent solids being drawn into the steam sparger. Any residue not removed by the reintroduction of steam could remain with each cycle and accumulate, eventually plugging the steam sparger. This design should reduce the probability of steam sparger plugging, but we recommend verifying and establishing exact operating parameters during commissioning tests.
  - Equipment erosion - The steam sparger ring holes are at least 24 inches from any internal structures in agreement with typical vendor design experience, so equipment erosion should not be a concern in the UFP-02 design.
  - Steam sparger erosion - The basis for the corrosion/erosion allowance for the steam sparger rings appears based largely on engineering judgment. The unverified design assumptions warrant further review and analysis. WTP has mitigated the risk by inclusion of Stellite inserts in the design. The final design drawings for the inserts were not available. Caution needs to be exercised in the final design to allow for differences in thermal coefficients of expansion and consideration given to prior DOE complex experience with erosion of Stellite parts.
  - Air Sparger Plugging – The design of the air sparger incorporates a large diameter tube (2 inch schedule 160 (1.687 inch ID) with four triangle cuts bent slightly inward at the end) and an air purge. The air purge rate was selected to exceed 100X the hydrogen

generation rate in UFP-02. A basis for the purge rate being sufficient to prevent air sparger plugging is needed.

Appendix A

Calculation of Effective Discharge Area and Effective Discharge Diameter

The following information is provided in the referenced drawings

- The sparger discharge piping is 2 inch schedule 160 pipe[14]
- The bubbler discharge piping is 2 inch schedule 80 pipe[32]

The following assumptions were made to perform these calculations

- The inner diameter of the sparger and bubbler were used for the calculations.
- The triangle cuts do not overlap.
- The triangles are cut prior to bending the tips inward.
- A triangular shape is maintained as the tips are bent inward.
- The base of the triangle cuts is ¼ of the circumference.
- The height of the triangle cuts is 0.75 inches as viewed from the side of the pipe.
- The diameter of the circle formed by the tips of the triangles for the air sparger is 1.19 inches based on discussions with DOE and BNI.
- The diameter of the circle formed by the tips of the triangles for the bubbler is 1.5 inches (as shown in drawing).

Figure A.1 shows the air sparger used in the medium-scale testing. The figure shows the curvature of the triangular cuts that would be typical of the triangular cuts in the air spargers in UFP-02.

Figure A.1. Air Sparger used in Medium-Scale Tests[2]

Air Sparger

<u>Closed triangle (i.e., the intact triangle remaining on the pipe) approach</u>

The discharge area is calculated from the surface area formed by the constricted pipe end minus the area of the intact triangles.

The area equals the area of the sides plus the area of the "circular" opening.

$A_{end} = A_{truncated\ cone\ side} + A_{circle}$

$A_{truncated\ cone\ side} = \pi(R_1 + R_2)[L^2 + (R_1 - R_2)^2]^{1/2}$

R_1 is the inside pipe radius at the entrance = 0.8435 inches

R_2 is the inside pipe radius at the exit = 0.595 inches

L = 0.75 inches is the vertical distance from the drawing

$A_{truncated\ cone\ side} = 3.57\ in^2$

$A_{circle} = \pi D_2^2/4 = \pi(1.19)^2/4 = 1.11\ in^2$

$A_{end} = A_{truncated\ cone\ side} + A_{circle} = 3.57 + 1.11 = 4.68\ in^2$

The area of each intact triangle = (1/2)b h

b = 1.32 in across the top (i.e., ~1/4 the circumference)

h is the height of the triangle region rather than the vertical distance

Taking the difference between 1.687 (the original inner pipe diameter) and 1.19 inches (the circle circumscribed by the points of the four constricted triangles) and dividing by 2 gives how far in the triangle leans. The value is 0.25 inches

Approximating this as a right triangle (i.e., ignoring the curvature of the triangular) with legs of 0.75 inches and 0.25 inches, the hypotenuse is 0.791 inches. Therefore, h = 0.791

$A_{triangle} = (0.5)(1.32)(0.791) = 0.523\ in^2$

The area of 4 triangles is $2.09\ in^2$

Subtracting the area of the triangles from the area of the end yields an open area of:

$4.68 – 2.09 = 2.59\ in^2$

The effective diameter that corresponds to this area is

$D_{effective} = (4\ A/\pi)^{1/2} = 1.82$ inches

<u>Truncated Cone Method</u>

The discharge area is calculated from the surface area formed by the constricted pipe end minus the area of the intact triangles.

The area equals the area of the sides plus the area of the "circular" opening.

$A_{end} = A_{truncated\ cone\ side} + A_{circle}$

$A_{truncated\ cone\ side} = \pi(R_1 + R_2)[L^2 + (R_1 – R_2)^2]^{1/2}$

R_1 is the inside pipe radius at the entrance = 0.8435 inches

R_2 is the inside pipe radius at the exit = 0.595 inches

L = 0.75 inches is the vertical distance from the drawing

$A_{truncated\ cone\ side} = 3.57\ in^2$

$A_{circle} = \pi D_2^2/4 = \pi(1.19)^2/4 = 1.11\ in^2$

$A_{end} = A_{truncated\ cone\ side} + A_{circle} = 3.57 + 1.11 = 4.68\ in^2$

Since the notches were likely cut before the tips of the end of the sparger were bent inward (see Figure A.1), the four triangular sections will occupy one half of the surface area of the side of the cylinder before the tips were bent inward

$A_{triangles} = (0.5)\ \pi\ D\ L = (0.5)\ \pi\ (1.687)\ (0.75) = 1.99$ inches

Subtracting the area of the triangles from the area of the end yields an open area of:

$4.68 - 1.99 = 2.69\ in^2$

The effective diameter that corresponds to this area is

$D_{effective} = (4\ A/\pi)^{1/2} = 1.85$ inches

This diameter is approximately equal to the diameter calculated with the closed triangle method. The differences are due to the closed triangle method neglecting the curvature of the triangular shapes.

Open triangle approach (i.e., calculating the area from the removed area of the triangular cuts)

The ends of the triangles are 4 points that form a circle.

The diameter of the circle is 1.19 inches.

The area of the open circle is $A_{circle} = \pi D_2^2/4 = \pi(1.19)^2/4 = 1.11\ in^2$

The base of the open triangles is ¼ of the circumference of the circle with diameter 1.19 inches

Base = $(1/4)\ \pi\ D = (1/4)\ \pi\ (1.19) = 0.935$ inches

The area of the open triangles is $4(1/2)b\ h = (4)(0.5)(0.935)(0.791) = 1.48\ in^2$.

Adding the area of the circle and the area of the open triangles produces an open area of $2.59\ in^2$.

The equivalent diameter that corresponds to this area is

$D_{equivalent} = (4\ A/\pi)^{1/2} = 1.82$ inches

This calculated equivalent diameter is the same as the diameter calculated by the closed triangle method and approximately the same as the diameter calculated by the truncated cone method.

Bubbler

Closed triangle (i.e., the intact triangle remaining on the pipe) approach

The discharge area is calculated from the surface area formed by the constricted pipe end minus the area of the intact triangles.

The area equals the area of the sides plus the area of the "circular" opening.

$A_{end} = A_{truncated\ cone\ side} + A_{circle}$

$A_{truncated\ cone\ side} = \pi(R_1 + R_2)[L^2 + (R_1 - R_2)^2]^{1/2}$

R_1 is the inside pipe radius at the entrance = 0.97

R_2 is the inside pipe radius at the exit = 0.75

L = 0.75 inches is the vertical distance from the drawing

$A_{truncated\ cone\ side} = 4.22\ in^2$

$A_{circle} = \pi D_2^2/4 = \pi(1.5)^2/4 = 1.77\ in^2$

$A_{end} = A_{truncated\ cone\ side} + A_{circle} = 4.22 + 1.77 = 5.99\ in^2$

The area of the triangles = $(1/2)b\ h$

b = 1.52 in across the top (i.e., ¼ of the circumference)

h is the height of the triangle rather than the vertical distance

Taking the difference between 1.939 (the original inner pipe diameter) and 1.5 inches (the circle circumscribed by the points of the four constructed triangles) and dividing by 2 gives how far in the triangle leans. The value is 0.22 inches

Approximating this as a right triangle (i.e., ignoring the curvature of the triangular cuts) with legs of 0.75 inches and 0.22 inches, the hypotenuse is 0.781 inches. Therefore, h = 0.781

$A_{triangle} = (0.5)(1.52)(0.781) = 0.594\ in^2$

The area of 4 triangles is 2.37 in^2.

Subtracting the area of the triangles from the area of the end yields an open area of 5.99 – 2.37 = 3.62 in^2

The effective diameter that corresponds to this area is

$D_{effective} = (4\ A/\pi)^{1/2} = 2.15$ inches

<u>Truncated Cone Method</u>

The discharge area is calculated from the surface area formed by the constricted pipe end minus the area of the intact triangles.

The area equals the area of the sides plus the area of the "circular" opening.

$A_{end} = A_{truncated\ cone\ side} + A_{circle}$

$A_{truncated\ cone\ side} = \pi(R_1 + R_2)[L^2 + (R_1 - R_2)^2]^{1/2}$

R_1 is the inside pipe radius at the entrance = 0.9695 inches

R_2 is the inside pipe radius at the exit = 0.75 inches

L = 0.75 inches is the vertical distance from the drawing

$A_{truncated\ cone\ side} = 4.22\ in^2$

$A_{circle} = \pi D_2^2/4 = \pi(1.19)^2/4 = 1.77\ in^2$

$A_{end} = A_{truncated\ cone\ side} + A_{circle} = 4.22 + 1.77 = 5.99\ in^2$

Since the notches were likely cut before the tips of the end of the sparger were bent inward, the triangular sections will occupy one half of the surface area of the side of the cylinder before the tips were bent inward

$A_{triangles} = (0.5)\ \pi\ D\ L = (0.5)\ \pi\ (1.939)\ (0.75) = 2.28$ inches

Subtracting the area of the triangles from the area of the end yields an open area of:

$5.99 - 2.28 = 3.71\ in^2$

The effective diameter that corresponds to this area is

$D_{effective} = (4\ A/\pi)^{1/2} = 2.17$ inches

This diameter is approximately equal to the diameter calculated with the closed triangle method. The differences are due to the closed triangle method neglecting the curvature of the triangular shapes.

Open triangle approach (i.e., calculating the area from the removed are of the triangular cuts)

The ends of the triangles are 4 points that form a circle.

The diameter of the circle is 1.5 inches.

The area of the open circle is $A_{circle} = \pi D_2^2/4 = \pi(1.5)^2/4 = 1.77\ in^2$

The base of the open triangles is ¼ of the circumference of the circle with diameter 1.5 inches

Base = $(1/4)\ \pi\ D = (1/4)\ \pi\ (1.5) = 1.18$ inches

The area of the open triangles is $4(1/2)b\ h = (4)(0.5)(1.18)(0.781) = 1.84\ in^2$.

Adding the area of the circle and the area of the open triangles produces an open area of 3.61 in^2.

The equivalent diameter that corresponds to this area is

$$D = (4\ A/\pi)^{1/2} = 2.14 \text{ inches}$$

This calculated equivalent diameter is approximately the same as the diameter calculated by the closed triangle method and the truncated cone method.

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