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TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

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M E M O R A N D U M

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DURABILITY OF CONTAINERS FOR WASTE STORAGE

INTRODUCTION

One of the alternatives under development for long-term storage of highly radioactive liquid waste involves conversion of the waste to a solid form, such as concrete or glass, and retreivable storage in a near-surface facility on the Plant site.[1] In the reference processes,[2,3] the waste is converted to sludge containing ^{90}Sr, ion-exchange resin loaded with ^{137}Cs and decontaminated salt cake. The sludge and resin are combined and processed to give either a concrete or glass waste form. The decontaminated salt cake and concrete, or glass, are stored for up to 100 yr in individual metal containers cooled by natural convection. Ultimately, the containers would be shipped to some Federal repository for permanent storage.

Two considerations will be major factors in the final selection of materials for waste containers; the compatibility between waste forms and container materials, and the durability of the container materials at the temperatures and stresses expected during service and possible accidents. A test program is in progress to measure compatibility by heating small capsules of candidate materials containing the waste forms for up to 50,000 hr (5.7 yr) at expected service temperatures and at slightly higher temperatures (up to 350°C) to accelerate any reactions that might occur during the long service life.[4]

This memorandum assesses the durability of candidate container materials for concrete and glass waste under expected service, and possible accident conditions using published values for the mechanical and thermal properties of the materials. This assessment serves not only as one basis for selection of container material(s), but also as a guide in container design and safety analysis of the waste storage process. For example, where total container weight is a factor, a range of container sizes will be considered to indicate where costs could be reduced by minimizing the number of containers required. Possible accidents will be considered without regard to their probability, or suitability as design bases, to indicate the degree of protection against radioactive releases that can be expected from the containers.

Analysis of durability in permanent storage (Federal Repository) will be deferred until alternative sites are identified and their environments characterized. Since these environments may be particulary corrosive, samples will be obtained for corrosion tests. For example, samples of salty water will be obtained from deep wells at SRP (triassic cavern) and samples of salt (containing water and H_2S) will be obtained from the Waste Isolation Pilot Plant (Sandia Corp), Carlsbad, N. M.

SUMMARY

When the cost of materials for waste containers is included, 1020 carbon steel appears to be a better candidate than any of the other alloys considered; "Cor-Ten A",* Type 304 stainless steel, "Inconel"+ 600 and "Inconel" 625. This choice is based on the oxidation resistance and creep and rupture strengths of the alloys under the conditions expected during 100-yr storage, melting of glass by either in-can or continuous-melter processes, and impact and thermal accidents, such as loss of cooling and fires. The minimum wall thickness required for satisfactory performance is not sufficiently thin for the stronger, more oxidation resistant alloys, such as 304 stainless steel, to justify the higher cost per pound.

A carbon steel container 2-ft diameter by 10-ft high (reference design) with wall thickness $<$0.5 inch would be expected to survive with most combinations of waste form and service and accident environments. In this analysis survival is defined conservatively as $<$1% deformation by creep during storage, $\approx$1% creep in a loss of cooling accident, no penetration in an impact accident, and creep $>$1%, but not rupture, in a fire.

* Trademark of the United States Steel Corp.
\+ Trademark of the International Nickel Co.

Because of the high internal pressures associated with concrete-filled containers in thermal accidents and the high temperatures associated with in-can melting of glass, much thicker walls (up to 10 in.) would be required to survive these conditions.

Comparison of the minimum wall thickness required for survival suggests several alternatives with a potential for lower total container costs. These alternatives illustrate the strong dependency between the choice of waste form and which accident conditions, if any, are finally selected as the bases for design. For example, if 100-yr storage is the only criterion, containers with walls $\approx$0.5-inch thick, but capacities approximately four times larger than those of the reference design could be used with the concrete waste form. If thermal accidents were considered as design bases, containers with nearly the same dimensions could be used if continuously-melted glass were selected as the waste form. In either case, a secondary container could not be justified solely on the basis of durability during storage on the Plant site. However a second container, perhaps of a different material, may be required for final storage in the Federal repository.

DISCUSSION

Description of Reference Processes

In the reference waste management processes,[2,3] waste from current tank storage is separated by centrifugation into an insoluble sludge containing ^{90}Sr and ^{239}Pu and a supernate containing ^{137}Cs. The sludge is washed and dried and the supernate is passed through ion exchange columns (to remove >99% of the ^{137}Cs. For the concrete waste form, sludge and Cs-loaded Zeolite resin are combined directly with cement and water in carbon steel inner containers that are sealed by welding and then re-encapsulated in stainless steel outer containers for storage. For the glass waste form, sludge, Cs-loaded Duolite resin, and borosilicate glass frit are melted either directly in the stainless steel inner containers or in a separate ceramic melter from which the containers are filled continuously. The inner containers are sealed and re-encapsulated in stainless steel outer containers for storage.

The remaining liquid is evaporated to solid salt (principally $NaNO_3$) that contains <0.04% of the total biological hazard, and the salt is placed in stainless steel containers for storage. All containers are to be stored for up to 100 yr in a building on the Plant site. Cooling will be by natural convection with unconditioned air. Pertinent properties of the waste forms and container dimensions are summarized in Table I.

Service and Accident Conditions

As a guide in evaluating container materials and assessing the integrity of containers, the conditions expected during filling and storage of containers and possible accidents were reviewed. Accidents were considered without regard to their probability to determine which material properties or design features might be limiting. Container design is important because the effects of many accidents depend on the dimensions of the container.

Service Environments

Container Filling

The conditions expected as the containers are filled are important only for glass waste, because of the high temperatures involved, ≈1150°C. Simplified considerations of heat transfer properties indicate that the container will rapidly (in <0.1 hr) heat to 1150°C whether the container is used as a crucible in which the glass is formed ("in-can melting") or a mold in which glass from a continuous melter is cast.[5] The time at the melt temperature will be ≈10 hr for in-can melting (based on the reference process) and ≈1 hr for continuous melting (based on estimates of the temperature profile in a glass cylinder cooled by natural convection). A stress will be produced in the container wall from the "head" of liquid glass in the container; ≈10 psi for a nearly full container during in-can melting and ≈1 psi during filling from a continuous melter (1-ft liquid height).

Pertinent properties of container materials under these conditions are oxidation resistance and rupture strength. Unless an inert-gas shroud or other protection were provided, oxidation would thin the container wall and spalled oxide could constitute a maintenance problem. Since rupture of a container would be unacceptable, the rupture stresses at 1150°C for both 10 and 1 hr, respectively, will be considered the critical mechanical properties.

Some permanent deformation of the container wall will occur because the thermal expansion of steel is greater than that of glass. Most of the stress resulting from these differences in thermal expansion will be relaxed during cooling from melting temperatures.

Container Storage

The expected storage environment is air at ≈100°C for up to 100 yr. The actual container surface temperature may differ slightly from 100°C depending upon the final design of the container and the storage building. The principal factors affecting container life are corrosion of the external surface and stress in the walls from pressures inside the container. Since the containers are to be cooled by natural convection with nonconditioned air, resistance to atmospheric corrosion is a pertinent material property. Internal pressure would cause creep. To conservatively avoid extensive deformation of the container, the stress required to produce 1% creep during 100 yr (8.76×10^5 hr) will be used as the pertinent mechanical property.

There are three sources of pressure inside a concrete-filled container; air in the freeboard space when the container is sealed will expand as it heats to the storage temperature, steam will be liberated from the concrete, and O_2 and H_2 will be generated by radiolysis. The contribution of air pressure will depend upon the conditions at the time the container is sealed, but at the storage temperature (100°C) will not be much greater than one atmosphere (15 psi will be used in the analysis).

The steam pressure in a container will correspond to the equilibrium value given in standard Steam Tables, as shown by small-scale tests.[6] In these tests, a small concrete cylinder was sealed in a container equipped to monitor the temperature and pressure in the void space above the concrete continuously. The unit was heated in various temperature stages up to 240°C. For each temperature stage, the pressure rose much more slowly than the temperature, but ultimately reached the equilibrium pressure predicted by steam tables. For example, on heating from 200 to 240°C ≈2 hr were required for the temperature to reach equilibrium, and ≈24 hr for the pressure to reach equilibrium. This time delay probably represents the time required for the steam to diffuse out of the concrete and saturate the void space.

During storage, radiolysis will generate O_2 from nitrate in the waste and H_2 from water, or any organics present.[7] Using data for the reference process, O_2 and H_2 pressures at 100°C would be ≈315 and 25 psi, respectively. No adverse effects on mechanical properties of the container material are expected from this small amount of hydrogen.[8] The indicated oxygen pressure may never be attained because oxidation of the inner suface of the container will consume a large portion of this oxygen. However, no credit for this effect will be taken in the analysis.

The only identifiable source of pressure during storage of a glass-filled container is expansion of the air inside. As indicated above for concrete, a pressure of 15 psi at 100°C will be assumed in the analysis.

Accident Environments

Possible accidents can be divided into two categories: thermal accidents, such as loss of cooling in the storage building or fire; and impact accidents, such as dropping a container from a crane or truck or being hit by a high velocity missile. Thermal events cause oxidation of container surfaces and increased internal pressure. Impact accidents cause plastic deformation, and possibly penetration, of the container wall.

Thermal Accidents

In the very unlikely event of loss of cooling in the storage building, the expected container temperature is ≈325°C.[9] Considering the expected design of the building, 30 days (720 hr) is a conservative estimate of the delay before normal cooling is restored. Corresponding internal pressures would be 2300 psi for a concrete-filled container and 25 psi for a glass-filled container. The stress required to produce 1% creep during 720 hr at 325°C will be used as the critical mechanical property, assuming that some deformation is tolerable, but rupture is unacceptable because of the large number of containers involved.

The estimated conditions resulting from a fire are a container wall temperature of 790°C for 0.5 hr with internal pressures of 4000 psi, for a concrete-filled container, or 45 psi, for a glass-filled container. These estimates assume the fire has a flame temperature of

790°C and lasts for 0.5 hr, as used in analyzing the effects of fires on shipping casks for radioactive materials.[10] From a simplified analysis of non-steady state heat transfer in a 2-ft diameter container with 0.5-inch thick wall,[5] the wall and the air-filled freeboard are expected to reach the fire temperature in ≈0.5 hr, but only the outer surface of the waste form (>R/2) would experience any temperature rise. The pressure contributions from air (45 psi) and radiolytic gases (965 psi) were based on their expansion as they heated to the fire temperature. The pressure contribution from steam in a concrete-filled container (2995 psi) corresponds to the equilibrium temperature calculated on an energy balance basis (370°C).

The actual pressures attained may be less than the above estimates for two reasons. First, the duration of the fire may be short enough that the equilibrium pressure would not be attained because of the time delay that was observed in the heating tests described above. Second, the internal volume of the container would increase due to thermal expansion and reduce the pressure. However, no credit for these effects will be taken in this analysis.

Impact Accidents

A number of empirical equations to predict penetration on impact have been developed for different applications; design-basis accidents to shipping casks for radioactive materials,[10] response of nuclear reactor tanks to tornado-generated missiles,[11,12] and high velocity ballistic technology.[13,14] These equations are similar in that they relate penetration to the kinetic energy of impact. The relation developed for cask design (a 40-inch drop onto a 6-inch diameter unyielding peg) will be used in the present analysis because, for typical waste containers, the impact energy is similar to that for typical high velocity missiles (10-ft long section of 3-inch diameter, Schedule 40 steel pipe traveling at 100 mph).

Properties of Candidate Container Materials

Five alloys were considered in the analysis; AISI 1020 carbon steel, "Cor-Ten A", Type 304L stainless steel, "Inconel" 600, and "Inconel" 625. "Cor-Ten A" is a low-alloy steel containing 1% Cr, 0.5% Ni, and 0.35% Cu that is noted for its resistance to atmospheric corrosion. Data on the creep strength of "Cor-Ten A", or alloys of similar composition, are limited, but suggest that strength at elevated temperatures is similar to that of 1020 carbon steel. The two "Inconel" alloys are nickel-based superalloys noted for their strength and resistance to oxidation at high temperatures. These five commercially available alloys represent the range of materials expected to be suitable for waste containers and, except for "Inconel" 625, are included in the matrix of compatibility tests.[4] Other steels and superalloys (such as 18Ni(300), a maraging steel; and Rene' 41) offer no particular advantage because their very high strengths are not maintained at the elevated temperatures expected in accidents. Other alloys, such as those based on aluminum, can be eliminated from consideration for one or more reasons, such as cost, expected incompatibility with concrete, or low melting point.

The costs and pertinent physical and mechanical properties of these five alloys are summarized in Table II.[15-19] Values for creep and rupture strengths were obtained by extrapolating the literature data using the Larsen-Miller parameter; this parameter relates the time and temperature of stress application to either the allowable deformation or rupture.[20] Typical examples of Larsen-Miller curves are shown in Figure 1.

Materials Behavior in Service and Accident Environments

Atmospheric Corrosion

Under the expected storage conditions (100 yr at 100°C), the exterior container surface will oxidize at a rate that can be estimated from data on the atmospheric corrosion of the representative alloys, or ones of similar composition.[21-24] These data are reported as weight lost, from which a uniform penetration was calculated, for exposures to various rural, industrial and marine atmospheres for up to 15 years. To provide conservative estimates of corrosion resistance, data for the more aggressive marine atmosphere were used. The penetration increased parabolically with time, Figure 2, as expected for an oxidation reaction and as observed for high temperature oxidation in air.[25] The fact that this relationship is observed for these extreme conditions provides confidence in extrapolating the data toward 100-yr exposures.

Uniform penetration in 100 yr of 0.05 to 0.1 inch would be expected for 1020 carbon steel, 0.01 to 0.02 inch for Cor-Ten A, and <0.001 inch for 304 stainless steel and the Inconels. Pits two to three times deeper than the uniform attack would also be expected;[21] such pitting should have little effect on mechanical properties. Although no quantitative data are available for 304 stainless steel, the expected penetration is equal to or less than that observed for "Inconel" 600; inspections of 300 series stainless steels used on the exteriors of the Empire State and Chrysler Buildings in New York City showed only pitting attack a few mils deep after 20 to 30 years.[26]

High Temperature Oxidation

At the high temperatures associated with various service and accident conditions, the exterior surface of the container will oxidize. The extent of oxidation can be evaluated from literature data that are summarized in Figure 3 as the uniform penetration measured after 1000-hr exposures at various temperatures. The values for carbon steel (representative of 1020 and Cor-Ten) and 304 stainless steel were calculated from measured weight losses;[27,28] actual depths of penetration may be slightly larger depending upon the contributions of pitting and grain boundary oxidation. The data for "Inconel" 600 are from metallographic measurements that include grain boundary effects.[25] Oxidation for times other than 1000 hr can be calculated from the observed parabolic rate of oxidation.

Significant (>0.01 inch) oxidation of any of the alloys would be expected only during filling the containers with glass. The oxide layer on carbon or stainless steel containers would be 0.030- to 0.045-inch thick for in-can melting and 0.010 to 0.025 inch for continuous melting. On the "Inconels," the oxide layer would be ≈0.005 inch. Most of this layer would spall off as the containers cooled. While this oxidation is not considered sufficiently severe to eliminate any of the alloys from consideration, the process would have to be designed to compensate for the loss by increasing the initial wall thickness and to prevent accumulation of the spalled scale (a 0.045-inch thick layer on a reference-size container corresponds to 0.24 ft^3 or 77 lb). Alternatively, a blanket of flowing inert gas might minimize this oxidation.

Mechanical Stresses

To assess the response of container materials to the various mechanical stresses of service and accident environments, equations were developed that relate the dimensions of the containers to conventional properties, such as density, and tensile, creep and rupture strengths. These derivations result from simultaneous solution of the equations for the hoop (circumferential) stress in the container wall, thickness of container wall required to withstand a 40-inch drop onto a peg, and volumes of steel and waste in a container.

The hoop stress in the container wall, σ_h, is

$$\sigma_h = \frac{pR}{t} \tag{1}$$

where p is the internal pressure, R is the inside radius of the container, and t is the wall thickness of the container. A condition for survival of containers in various environments can be expressed by equating hoop stress to the allowable creep or rupture stress σ_c; Equation 1 becomes

$$t = \frac{pR}{\sigma_c} \tag{2}$$

For an individual container, the ratio of the volume of container, V_s, to the volume of waste, V_w, is

$$\frac{V_s}{V_w} = \frac{\pi h(2Rt+t^2)}{\pi hR^2} = \frac{2Rt+t^2}{R^2} \tag{3}$$

where h is the container height. Substituting Equation 2 into Equation 3 gives

$$\frac{V_s}{V_w} = \frac{p}{\sigma_c}\left(2+\frac{p}{\sigma_c}\right) \tag{4}$$

The empirical drop-test equation is

$$t_{min} = \left(\frac{W}{\sigma_\mu}\right)^{.71}$$

where t_{min} is the minimum wall thickness required to prevent penetration, W is the total weight, and σ_μ is the ultimate tensile strength of the container material.[10] Expressing W in terms of the volumes and densities of container and waste form, and substituting Equation 4 gives

$$(t_{min})^{1.41} = V_w \left[\frac{\rho_w\left(\frac{V_s}{V_w}\right) + \rho_w}{\sigma_\mu}\right]$$

$$(t_{min})^{1.41} = V_w \left(\frac{\rho_s p^2 + 2\rho_s p\sigma_c + \rho_w\sigma_c^2}{\sigma_\mu\sigma_c^2}\right) \qquad (5)$$

where σ_s and σ_w are the densities of container and waste form, respectively.

For design purposes, safety factors on both the allowable stress and the wall thickness are desirable. The hoop stress should be some fraction, a, of the creep or rupture strength, and Equation 2 becomes

$$t = \left(\frac{p}{a\sigma_c}\right) R \qquad (6)$$

The desired wall thickness should be some multiple, b, of t_{min}, and Equation 5 becomes

$$t^{1.41} = b^{1.41} A\, V_w \qquad (7)$$

where

$$A = \frac{\rho_s p^2 + 2\rho_s p\sigma_c + \rho_w\sigma_c^2}{\sigma_\mu\sigma_c^2} \qquad (8)$$

Equations 6 and 7, and the equation for V_w are plotted in Figure 4.

Use of these relationships will be illustrated by evaluating the dimensions of a 1020 carbon steel container for storage of concrete waste. Appropriate values for the material parameters A and p/σ_c were calculated for the storage conditions (100 yr at 100°C) and corrected for an assumed safety factor of 50% (a = 0.5 and b = 1.5). Using these values, Figure 4 gives corresponding values of t, R, and h that satisfy the relationships. For example, with a wall thickness of 0.2 in. the radius is 16.7 in. and the height is 5.2 ft, giving a container with a capacity of 30 ft^3.

The minimum wall thicknesses required for adequate strength in each service or accident environment were calculated for the reference-process container (2-ft diameter by 10-ft high), Table III. For each environment, different strengths (σ_c) and safety factors (a) were used for the effect of internal pressure to reflect "reasonable" limits for deformation of the container wall. For example, the stress required for 1% creep and a safety factor of 0.5 were used for storage to indicate that little deformation would be expected (or tolerated). Since a large number of containers would be affected by a loss of cooling accident, the stress for 1% creep was also used, but a safety factor a = 1 was assumed since in this accident moderate deformation of the containers could be accepted as long as they did not rupture. In glass melting, some deformation would be expected, but not rupture, so the rupture strength and a safety factor of 0.5 were used, since the stress for 1% creep was too restrictive. A constant safety factor of b = 1.5 was used for impact accidents.

These calculated wall thicknesses indicate that impact accidents are generally the most important considerations, except for the high pressures developed in thermal accidents to concrete-filled containers, or for the high temperatures required for in-can melting of glass.

Evaluation of Container Materials and Waste Forms

The container materials and waste forms were compared by calculating a "figure of merit" (M) for each material in the various service and accident environments, Table IV. Each value of M is the reciprocal of the cost of the metal in a container 2-ft diameter and 10-ft high that has the minimum wall thickness required to withstand the expected conditions. This wall thickness (t, in Table IV) is the sum of the thicknesses required for strength (from Table III), atmospheric corrosion (from Figure 2) and high-temperature oxidation (from Figure 3). Current prices (¢/lb) for 0.5-inch thick plate were used to reflect the cost of container materials.

For any combination of waste form and service, or accident, conditions, a carbon steel container with sufficiently thick walls to withstand expected stresses and losses by oxidation is better than any of the other materials by a factor of two, or more. Comparison of the values for wall thickness, t, and merit, M, shows that the higher strength and corrosion resistance of stainless steel and the Inconels are offset by their higher costs. Only in the cases of a concrete-filled container in a fire and in-can melting of glass is 304 stainless steel equivalent to carbon steel.

The merit values also provide one of many bases for evaluating the waste forms. This selection largely depends upon which of the service and accident conditions are ultimately selected as the bases for final design. For example, if loading and storage of containers are the only criteria, concrete has slightly higher merit than continuously-melted glass and an order of magnitude higher merit than in-can melted glass. However, essentially the same container that is required for continuously-melted glass will also withstand accidents, such as loss of cooling and fire. This anticipated durability under severe conditions may outweigh the greater investment in containers (7.4/5.1 = 1.45).

These considerations also indicate that double containment, as specified in the reference process, should not be required for durability during 100-yr storage. For most situations, the minimum required wall thickness is less than the 0.5 inch specified for the inner container in the reference process. Consequently a second container would be required only for some other consideration, such as providing a contamination-free outer surface or durability in the environment of final storage (Federal repository).

Many other factors can affect choice of waste form and container dimensions. As examples, container capacities as large as possible would be desirable to minimize the number and total costs of containers. A minimum wall thickness (for example, 0.5 inch) may be required for rigidity in handling empty containers and welding of the final closure. Radius may be limited to some maximum to prevent excessive centerline temperatures.* Using the above analysis, a container for storage of concrete, that would meet these additional criteria, would be 9-ft high with a radius of 2 ft and a wall thickness of 0.5 inch, weighing 7.3 tons and providing a capacity of 113 ft^3 (31.4 ft^3 for reference process container). The safety factors are a = 0.3 and b = 1.5. A similar container, but with walls 0.74-inch thick and weighing 11.5 tons, would be satisfactory for continuously-melted glass during storage and fire (safety factors a = .42 and b = 1.5). The thicker wall is required mainly because the density of glass is greater than that of concrete. Ultimately, container dimensions may be limited by the size of the cask used for shipping containers to the permanent storage site.

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* Assuming surface temperatures of 100°C and maximum centerline temperatures of 250°C for concrete,[2] and 500°C for glass[3] the maximum radius for transfer of heat from radioactive decay is 2.75 ft for concrete and $\geq$3.0 ft for glass.

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TABLE I

REFERENCE PROCESS DATA

	Waste Form	
	Concrete	Glass
Total volume, 10^6 gal	2.2	1.2
Density, lb/ft^3	118.6	187.3
Heat generation Btu/ft^3	27.1	50.5
Thermal conductivity, Btu/hr-ft-°F*	0.35	0.63
Thermal diffusivity, ft^2/hr*	0.14	0.19
Inner container dimensions		
Length, ft	10.0	10.0
Outside diameter, ft	2.0	2.0
Wall thickness, in	0.5	0.5
Fill height, ft	9.0	7.3
Outer container dimensions		
Length, ft	10.17	10.17
Outside diameter, ft	2.17	2.17
Wall thickness, in	0.5	0.5
Total weight per container, lb	5,867	6,745
Volume of waste per container, ft^3	26	21
Number of containers	11,100	7,400

* Typical Handbook values, neglects any potential effects of waste.

TABLE II

PROPERTIES OF CANDIDATE CONTAINER MATERIALS

Property	Material				
	1020 CS	Cor-Ten A	304 SS	Inc-600	Inc-625
Density, lb/in^3	.284	.283	.290	.304	.305
Melting Point, °C	1515	1510	1455	1425	1285
Tensile strength at 25°C, psi	65,000	70,000	75,000	90,000	120,000
Yield strength at 25°C, psi	38,000	50,000	28,000	36,000	60,000
Stress for 1% creep, psi					
Glass melting (10 hr at 1150°C)	<100	(1)	≈100	≈250	≈500
Storage (8.76×10^5 hr at 100°C)	60,000	-	60,000	75,000	100,000
Loss of cooling (720 hr at 825°C)	40,000	-	55,000	70,000	90,000
Fire (0.5 hr at 790°C)	2,000	-	13,000	5,000	30,000
Rupture strength, psi					
Glass melting - In-can (10 hr)	≈100	-	1000	1000	≈1000
- Continuous (1 hr)	≈200	-	2000	2000	≈1500
Storage	65,000	-	65,000	90,000	12,000
Loss of cooling	45,000	-	60,000	85,000	100,000
Fire	3,500	-	20,000	15,000	50,000
Cost, $/lb	.18	.35	.95	4.00	5.50

(1) Creep and rupture properties similar to 1020 CS

TABLE III

WALL THICKNESSES REQUIRED FOR STRENGTH

Environment	Strength Criteria for Response to Internal Pressure	Minimum Wall Thickness, in.[1] 1020 CS	304 SS	Inc-600	Inc-625
Concrete:					
Storage	1% creep, a = .5	.22[b]	.20[b]	.17[b]	.14[b]
Loss of cooling	1% creep, a = 1	.70[a]	.51[a]	.40[a]	.32[a]
Fire	rupture, a = 1	10[a]	2.5[a]	3.4[a]	.98[a]
Glass:					
Melting - In-can	rupture, a = .5	2.5[a]	.61[a]	.98[a]	.24[a]
- Continuous	rupture, a = .5	.30[b]	.26[b]	.23[b]	.19[b]
Storage	1% creep, a = .5	.30[b]	.26[b]	.23[b]	.19[b]
Loss of cooling	1% creep, a = 1	.30[b]	.26[b]	.23[b]	.19[b]
Fire	rupture, a = 1	.31[b]	.27[b]	.23[b]	.19[b]
Fire	1% creep, a = 1	.32[b]	.27[b]	.24[b]	.20[b]

1. Assumed reference design container, R = 1 ft, h = 10 ft, $V_W = 31.4\ ft^3$; safety factor for impact, b, = 1.5.

a. Thickness is that required to resist deformation from internal pressure, but greater than that required for impact resistance.

b. Thickness is that required for impact resistance, but greater than required for internal pressure.

TABLE IV

RELATIVE MERIT OF CONTAINER MATERIALS

	1020 CS		Cor-Ten		304 SS		Inc-600		Inc-625	
	t[(a)]	M[(b)]	t	M	t	M	t	M	t	M
Concrete:										
Storage[(c)]	.290	7.4	.235	4.7	.200	2.0	.170	.53	.140	.47
Loss of cooling[(d)]	.770	2.7	.715	1.5	.510	.77	.400	.22	.320	.20
Fire[(e)]	>10	.15	>10	.079	2.500	.15	3.400	.023	.980	.064
Glass:										
In-can melting and storage[(c)]	2.615	.75	2.560	.39	.640	.61	.985	.088	.245	.27
Continuous melting and storage[(c)]	.395	5.4	.340	3.2	.270	1.5	.230	.39	.190	.34
Loss of cooling[(d)]	.395	5.4	.340	3.2	.270	1.5	.230	.39	.190	.34
Fire[(e)]	.405	5.2	.350	3.1	.280	1.4	.230	.39	.190	.34
Fire[(d)]	.415	5.1	.360	3.1	.280	1.4	.240	.37	.200	.33

a. t = minimum wall thickness required for strength (from Table III) and oxidation (from Figures 2 and 3).

b. $M = \frac{1000}{\pi h t (2R+t)(\rho)(C)}$; h = 120 in., R = 12 in., ρ = density, C = cost ($/lb).

c. Based on stress to produce 1% creep in 100 yr (safety factor a = 0.5).

d. Based on stress to produce 1% creep (safety factor a=1); rupture strength would not be exceeded.

e. Rupture strength would be exceeded.

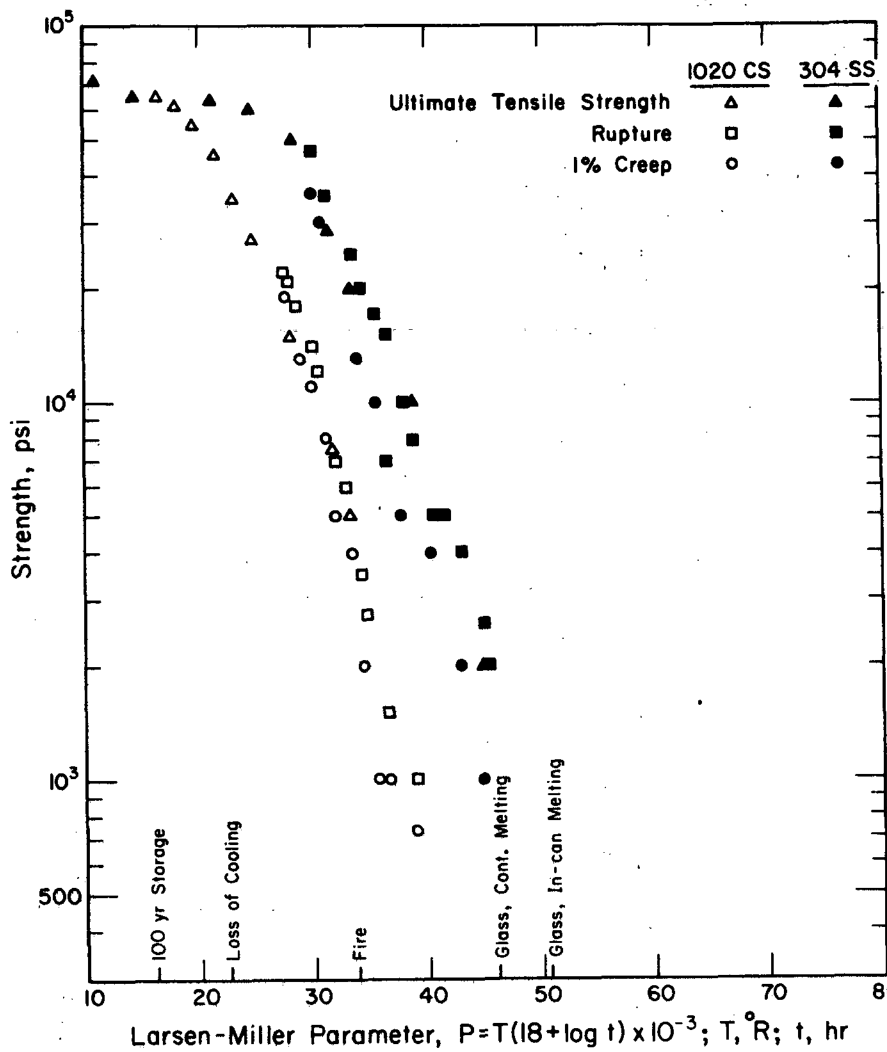

FIGURE 1. Typical Larsen-Miller Plots

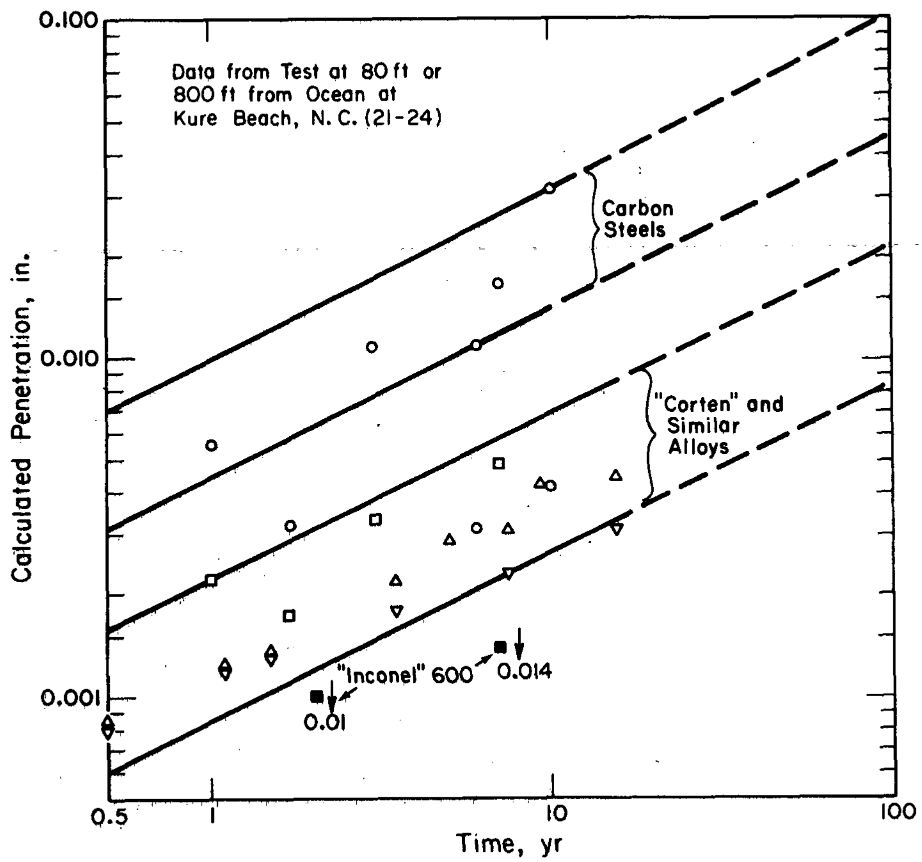

FIGURE 2. Atmospheric Corrosion of Candidate Alloys

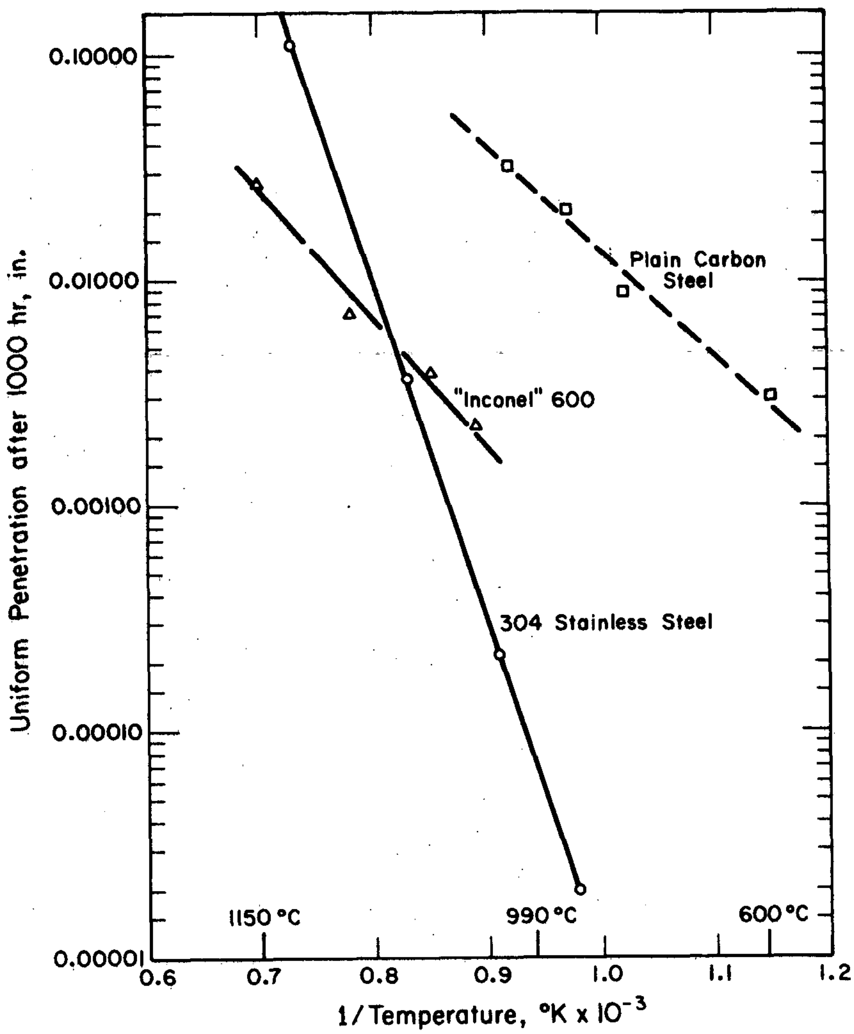

FIGURE 3. High-Temperature Oxidation of Candidate Alloys

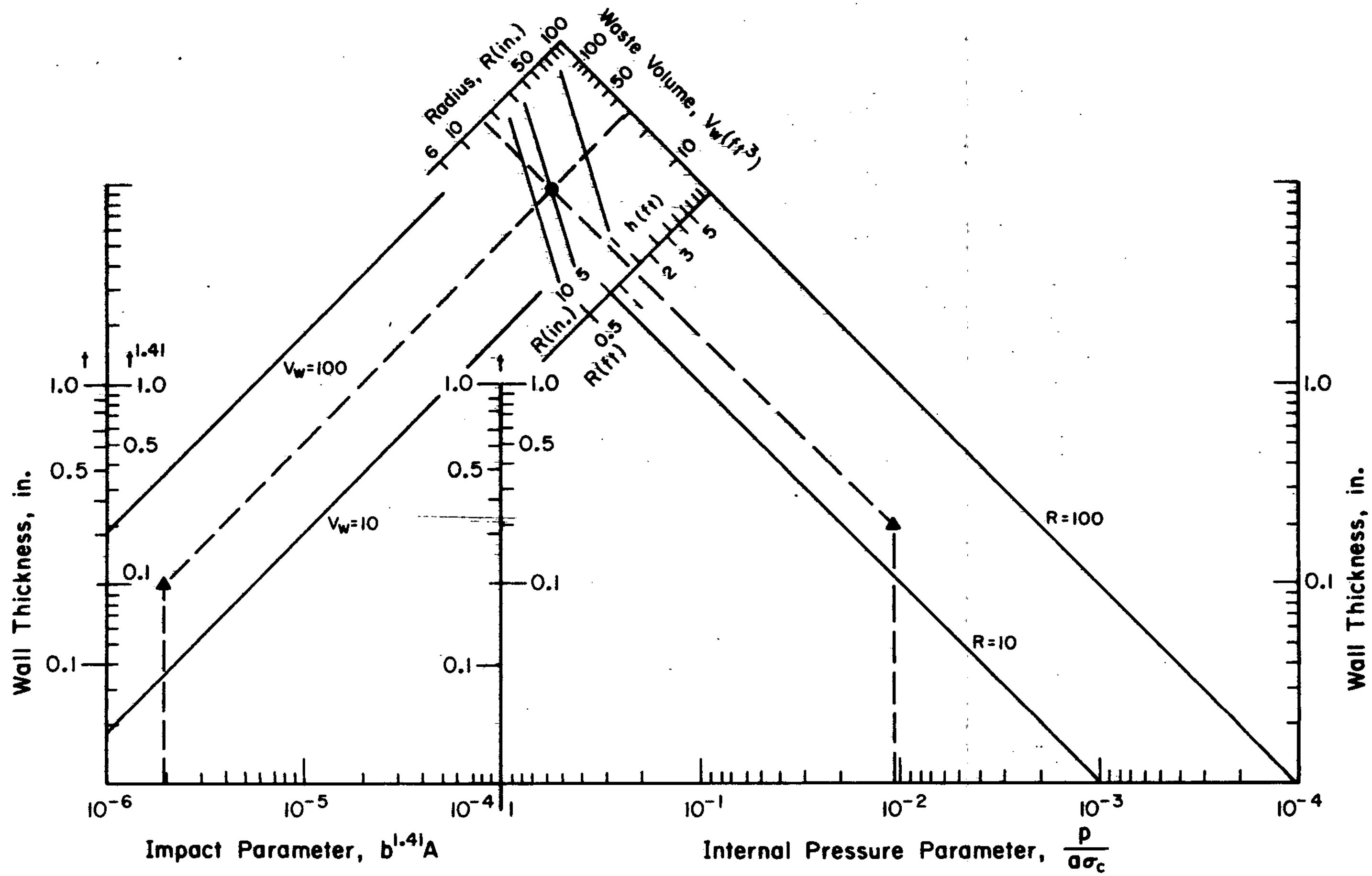

FIGURE 4. Effect of Materials Properties on Container Dimensions

For 100-yr storage of concrete in a 1020 carbon steel container and safety factors of b = 1.5 and a = 0.5, the Impact Parameter = 1.95×10^{-6} and the Pressure Parameter = 1.25×10^{-2}. Entering the graph with these values on the abscissa, extrapolation from a wall thickness of 0.2 in. gives container dimensions of 30 ft^3 volume, 16.7 in. radius, and 5.2 ft height.