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RETRIEVABLE STORAGE CONCEPT DESIGNS

FINAL REPORT

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by

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Abstract

Three tasks related to the reference design of retrievable storage canisters for radioactive waste have been completed. The three tasks consist of the reference design itself, the definition of failure modes most appropriate for structural integrity determinations for the reference canister, and the development of a failure methodology for the structural integrity of the containers. The reference design is a sealed storage canister concept based upon the waste isolation pilot plant (WIPP) design, with slight modifications. The modifications consist of an alternate lifting yoke arrangement for the top head and a revised bottom head design for absorption of impact energy. Welded closures provide the seal at each end. Overpacking is considered as a possibility, but is not included in the preliminary reference design. The four failure modes that are deemed the most appropriate for the design of the reference canister are: (i) a loss of functional capability; (ii) ductile rupture of the canister; (iii) buckling of the structural members; and (iv) stress corrosion cracking. Failure scenarios are provided for each of the relevant failure modes. In addition, a failure methodology based upon the distribution of demand and the distribution of capacity for the structural members, with respect to each failure mode, is proffered.

1. Introduction

The identification and quantification of failure modes, in conjunction with iterative structural design, is a crucial step in the evaluation of the risks associated with high-level radioactive waste disposal. Deonigi [1]* has used the term "failure mode analysis" to describe this procedure. Similar considerations are necessary for evaluating the risks associated with the interim storage of spent nuclear fuel from commercial power reactors, regardless of the mode of storage. It should also be noted that the quality assurance level demanded of nuclear power reactor vessels is ensured, according to the ASME Boiler and Pressure Vessel Code, Section III, by such procedures.

The geologic storage of spent nuclear fuel will involve hazards associated with transportation from the power plant spent fuel storage pool to

* References are listed in order at the end of the text.

the geologic repository site; these risks are described in [2]. Surface storage may involve a number of repository sites, with decreased transportation risk. Geologic storage may impose certain additional penalties, such as the possibility of handling incidents during the descent into the mine and the possibility of interactive loading with the subterranean environment. Surface storage may derive penalties associated with exposure to missiles, whether these are caused by tornadoes, airplane crashes, or other incidents.

The failure mode analysis should be based upon reference designs, reference materials, and judgment with regard to loading intensities. Insofar as possible, knowledge of previous work should be factored into the analyses. For this reason, the design information from other investigators is cited extensively.

The probability of failure of a structural component can be determined in several possible ways, provided that sufficient operating and service data is available. The most obvious and the most reliable estimates are based upon data collected from service experience with the actual structural components themselves. A typical example would be the data collected by the Edison Electric Institute (EEI) and the Tennessee Valley Authority (TVA), from 55 different utilities, on the performance of power boiler steam drums designed and fabricated according to Section I of the ASME Boiler and Pressure Vessel Code [3]. Such data is directly useful in estimating the reliability of other power boilers.

If insufficient data are available on the actual components, either because of the limited service experience, or because of the extremely high reliability demanded of the component, data from related components can be collected and the reliability estimate may be attempted by extrapolation. An example of this type of reasoning is the survey conducted by EEI for the United States Atomic Energy Commission on steam drums and fossil-fired pressure vessels, for the purpose of estimating the reliability of nuclear steam supply vessels [4]. The survey was restricted to those non-nuclear vessels that had sufficient similarity (wall thickness greater than 1.5

inches (3.75 cm), internal pressure greater than 600 psi (4 MPa), and operating temperatures between 200°F (93 C) and 800°F (427 C)) to light-water-cooled reactor vessels to be credible, and which were designed and fabricated to either Sections I or VIII of the ASME Code.

Assuming that such service data on related structural components is unavailable, a third and more fundamental choice is to base the reliability estimates on analysis and laboratory testing. Even at this juncture, alternatives should be examined. For instance, if the structure is to be designed to a safety standard (for example, Section III of the ASME Code for Safety Class 1 Components), the design stresses that are allowed by the Code for particular failure modes can be used in lieu of calculated stresses. In this case the estimator may be incurring a substantial penalty for a particular design, but the accumulated experience of the Code bodies is brought directly to bear.

This approach may not be useful for those structures with no readily applicable design safety standards. Canisters for reprocessed nuclear waste or spent nuclear fuel interim storage probably lie within this category. In order for failure probabilities to be estimated for retrievable canisters, in the absence of safety standards, one particularly attractive approach could be used--termed the "stress-strength" overlap method by Witt and Zemanick [5]. This method can be considered as an application of first principles to design against failure, provided that the distributions of the random variables (stresses, strains, displacements, uniaxial failure data, etc.) are known.

In the next section, the failure modes and the failure scenarios will be described. Sections following that will be concerned with the development of the reference designs themselves, modifications of existing designs, and a description of the "stress-strength" overlap method and its application to these considerations.

2. Failure Modes

The failure modes against which the canister should be designed are reasonably well established, as a result of many decades of engineering

experience. A general categorization that seems to cover the range of possibilities is:

1. Loss of Function. A typical example is excessive deformation, leading to an intolerable change of shape, or to leakage at non-integral joints. This excessive deformation may be due to a variety of loadings that lead to elastic, elastic-plastic, or creep material response.

2. Ductile Rupture. Ductile rupture is typically due to a structural design with one or two small dimensions (thicknesses), compared to other dimensions (length, radius), combined with a local material instability (necking) under sufficiently high gross section (membrane) tensile stress. The rupture may be the result of predominantly plastic or creep deformation, or a combination of the two, in the necking zone. It should be noted that a tensile instability of the type associated with "ballooning", or locally reduced wall thickness, should be considered in the same class.

3. Brittle Fracture. Brittle fracture is typically due to a sufficiently high degree of triaxiality of stress in a structure of sufficient thickness to suppress preferred microstructure accommodation of the deformation. The material is unable to sense the free surfaces and the triaxiality offers no possibilities for grain boundary adjustment, which leads to local voids, cavitation ahead of existing crack tips, and eventual coalescence and crack extension.

4. Buckling. Buckling is due to the same structural design features as ductile rupture, except that the sense of the gross section stress is reversed. These compressive stresses can be superimposed upon local bending deformations, however, and the onset of structural instability accelerated. Buckling need not result in rupture; instead, the net result may be a loss of load-carrying capacity only. The acceleration of the instability may be due to either plastic or creep deformation.

5. Fatigue. Fatigue in this sense includes both low-cycle (high strain) or high-cycle (low strain) fatigue. The only apparent difference is the degree to which plastic deformation influences the residual stress state

during a cycle, and whether the plastic deformation (and the associated residual stresses) is confined to local regions around crack tips, or influences the entire structural cross section. When creep deformation is allowed to take place during hold periods between strain or load reversal, the triaxiality of the residual stresses is affected. The extent to which fatigue life is influenced by this change in triaxiality is referred to as "creep-fatigue" interaction. The combination of triaxiality (to cause voids, cavitation, coalescence) and maximum shear stress (to overcome any surface bonding energies) determine the fatigue crack growth rate.

6. Corrosion. This includes stress corrosion cracking, corrosion-assisted fatigue, wastage, surface pitting, and other manifestations of electro-chemical attack. For stress corrosion cracking the major concern is the residual stress state and the heat-affected zones of the welds, since these stresses are tensile and can have a high degree of triaxiality, depending upon the thickness of the part, the number of weld passes, the heat treatment, and other factors. The values of these stresses often approach the yield stress so that, when combined with welding flaws (porosity, lamellar tearing, hot cracking, etc.), possible carbide precipitation, and the presence of corrosive agents, cracking or fatigue can occur at applied stresses well below presumed failure levels. When creep deformation or high temperature exposure is permitted, the situation becomes even more complex, primarily because of the possibility of intergranular extension of transgranular cracks. Presumably, the simultaneous effects of creep (on stress triaxiality) and high temperature (on sensitization) are synergistic, enhancing diffusion-controlled processes.

Assuming that these failure modes are a complete set, the most likely candidates for canister failure appear to be loss of function, ductile rupture, corrosion and buckling. Brittle fracture has been neglected for at least two reasons. First, in the absence of corrosive agents, the structural materials selected for the canister should be characterized by extremely high fracture toughness properties. Second, the construction dimensions for the canisters should be such as to preclude the type of triaxiality required for

brittle fracture extension. Both high-cycle and low-cycle fatigue have been neglected because of the absence of any significant cyclic loading condition anticipated in a geologic repository. The loss of function failure mode, although discussed in terms of scenarios, will be deferred until a better definition of medium/canister interaction is developed.

3. Failure Scenarios

The loss-of-function failure mode is meant to cover instances where material failure does not occur, yet the structure or component fails to meet its functional requirements. An example for a nuclear power plant would be leakage in a valve caused by improper seating or failure to seal, caused by excessive deformation or local surface wear. A scenario for loss of function for a spent nuclear fuel retrievable canister might involve the inability to extract the canister from a mined cavity after a number of years of interim storage, as the result of excessive motion. No material failure might be produced, but the combination of creep of the surrounding salt, as a function of lithostatic stresses, mining operations, and temperature excursions, and brine migration may create such a situation. An analysis of a canister in a lined hole, with appropriate coefficients of friction, and an analysis of the creep deformation locally around the canister, including the effects of local temperature perturbations due to angular rotation, would be required to assess the importance of this failure mode. Pariseau [6], as a consultant to RE/SPEC, has shown that a sophisticated thermomechanical model of a waste canister and the surrounding salt geometry will yield conservative estimates of the interaction stresses of about 4000 psi (28 MPa). Such stresses indicate significant loading for canister materials during the first five to ten years of emplacement. It should be pointed out that, while Pariseau mentions both elastic-plastic (short time) and viscoelastic (long time) solutions, the only analysis discussed in detail is a two-dimensional, elastic-plastic, anisotropic calculation of the effects of mining sequences and canister thermal energy on the short-time interaction stresses. For instance, the model assumes that the room above the canister is refilled, following emplacement, with salt from adjacent rooms as they are mined.

Ductile rupture might be incurred through a handling accident that involves "slapdown" of the canister onto an uneven surface (for example, a rigid surface with a step). Such an incident should provide an indication of susceptibility to ductile rupture. The bending strains (compressive on the top and tensile on the bottom), plus the local shell strains at the point of impact, should be quite severe, even if the scenario is restricted to a toppling incident. At least two other types of events could be selected as ductile rupture failure scenarios as well. First, an end drop of somewhere between 10 and 15 feet (3 to 5 meters) could induce rupture. Second, the thermal stress interaction with the surrounding salt formation, similar to that discussed in terms of the loss of function failure mode, could be considered.

The principal scenario for canister buckling would be concerned with an end drop of the canister, with an initial velocity of between 25 to 50 feet per second (8 to 16 meters per second), considering an axisymmetric buckling calculation for the canister walls. The analysis should be repeated with several different initial imperfections, in order to determine the range of buckling loads as a function of initial canister deformation. Buckling could also be induced by the slapdown event mentioned above, or through a side drop from an elevation similar to that of the end drop.

The controlling event for a stress corrosion cracking failure incident for a canister is most likely to occur during retrieval after 25 years of interim storage. A 30-foot (10-meter) drop onto an unyielding surface at an orientation that will produce maximum stress at the closure weld seams (top and bottom of the canister) is suggested. However, if this accident is deemed too severe, a recommended alternative is the toppling incident that has been discussed with reference to the ductile rupture failure mode, except that this event now will involve possible brittle fracture. Data from the stress corrosion studies should be directed toward the "reduced" dynamic fracture toughness of welds after exposure to the salt environment and toward any dramatic increase in transition temperature from lower to upper shelf fracture toughness values.

4. Reference Canister Design

A useful treatment of the design of waste container is given in [7] and, although the motive was management of defense high-level waste, the design criteria are of value for retrievable spent fuel storage. For surface storage, double containment must be provided, both in terms of an overpack and in terms of sealing concepts. For geologic storage, single containment might be sufficient because of the protection provided by the surrounding medium. However, it should be noted that, if the stress corrosion cracking failure mode turns out to be too severe for single containment design, some type of overpacking arrangement will be required. Carbon steel is recommended for geologic storage, while stainless steel with a thick carbon steel overpack is recommended for surface storage. It should be pointed out that the current WIPP canister is a 12.75 inch (32.4 cm) outside diameter stainless steel cylinder with a 14 inch (35.6 cm) outside diameter carbon steel overpack. The dimensions are given in Figure 1. The most significant design parameters for this type of design are the canister material, the internal pressure, the temperature distribution, corrosion, and the overpack structure, and surrounding medium properties.

In addition to these considerations, the Hanford Report emphasizes the use of on-site basaltic caverns, rather than the transference of wastes to an off-site geologic repository, such as WIPP. Again, the waste addressed are of the defense high-level variety, but similar advantages may accrue to interim spent fuel storage. Therefore, thought should be given to basaltic formation about 150 feet (50 meters) thick and 3000 feet (1000 meters) below the surface.

A somewhat similar design is depicted in Figure 2 where the Kaiser Engineers SURF (Spent Unreprocessed Fuel) storage facility spent fuel canister for PWR (Pressurized Water Reactor) fuel assembly is shown. Of special note in the SURF design is the lifting bale arrangement for the top head, the flat bottom, and the double containment provided.

Figure 1. WIPP Double Containment Design

Figure 2. SURF Spent Fuel Canister

Both the high-level waste canister proposed for WIPP [8] and the SURF canister [9] can be easily modified to eliminate a protruding lifting lug or lifting bale that presents such a vulnerable impact target. Several alternatives have been proposed [10], and one has been incorporated into the reference design of Figure 3. Details of the lifting arrangement are shown in Figure 4. This design is intended to accommodate a single fuel assembly from a pressurized water reactor (in particular, the fuel assembly for a Combustion Engineering PWR having cross-sectional dimensions 7.980 inches (± 0.27 cm) by 7.540 inches (19.15 cm) and a length of 14 feet (4.27 meters)). Various internal baskets will have to be designed to accommodate other types of assemblies; however, the baskets will have the characteristics of a snug fit at maximum temperature, in order to promote effective heat transfer to the canister walls.

The bottom heads for both the WIPP and SURF designs are flat, presenting an inviting target for ductile rupture at the seams of the cask bottom head during impact. Originally, the flat 1 inch (2.5 cm) thick WIPP design was selected. However, one of the basic design principles for structures subjected to impact is that the impact surface should be able to absorb energy in flexure without severe in-plane (membrane) constraint. The combination of the flat bottom, which tends to generate large membrane stresses during impact, and the changes in thicknesses, slope, and curvature at the intersection of the cylindrical shell and the bottom end plate produce an undesirable state of stress and deformation during an end drop from even modest heights.

Because of this, and because of a possible need to stabilize the erect canister with respect to tipping from brine migration, a new end design was developed. This new design features a shape that augments energy absorption with controlled vertical deflection, and is based upon the work of Updike [11], Jones and Wagner [12], and Jones and Jarrett [13]. The conceptual principle is that of a hemispherical shell loaded through a rigid plate, as shown in Figure 5. The three distinct regions of deformation are indicated by letters on the sketch, as a function of the amplitude of the apex displacement Δ due to the load, P .

Figure 3. Reference Design

Figure 4. Lifting Arrangement

Figure 5. Hemispherical Shell Deformation Under Impact

The points in the shell that lie between the clamp support circle and the circle of rapidly increasing curvature (AB) undergo small elastic deformation, which can be virtually neglected in terms of peak deflection and energy absorption. The points between the circle of increasing curvature and the circle of contact with the rigid plate (BC), and continuing on to the circle of curvature reversal (CD), the shell undergoes large plastic deformation. Depending upon those factors that influence the elastic-plastic flexural stiffness, such as thickness, strain rate, and hardening modulus, the circles denoted by B and D can vary in distance from the contact circle, C. A very thin shell, for example, would have a concentrated region of plasticity (a single hinge circle), whereas a thicker shell would have two regions of plasticity, at the two circles of curvature change. The points in the shell between the curvature reversal and the apex (DE) which previously were loaded plastically, have now unloaded as the plastic hinge circles propagate outward and downward.

A simple expression for the static load-deflection characteristics of hemispherical shells has been derived by Updike [11]:

$$P = 10.9 \cdot \sigma_0 \cdot t^{3/2} \cdot \Delta^{1/2}, \quad (1)$$

where P is the static load, σ_0 is the yield stress of the material, t is the thickness, and Δ is the apical deflection. Note that the expression is dimensionally correct and that the number 10.9 is a constant, with no dimensions. The energy absorbed due to plastic deformation is given by

$$W = 7.26 \cdot \sigma_0 \cdot t^{3/2} \cdot \Delta^{3/2}. \quad (2)$$

More recently, Jones and Wagner [12] have derived similar expressions for the static deformation of conical shells, and Jones and Jarrett [13] attempted to use both sets of formulas to fit the experimental data for dynamic drop tests on hemispherical shell impact limiters. Since the load does not remain constant during impact, an incremental procedure can be used to determine the maximum deflection:

1. Depending upon the estimated drop height, calculate the drop velocity and initial kinetic energy.
2. Estimate the bending strain rate for this velocity, and revise the yield stress, σ_0 , to reflect strain rate dependence.
3. Choose an increment of apex deflection, $\delta\Delta$.
4. Calculate the load, P , corresponding to the average apex displacement during the increment.
5. Subtract $P\delta\Delta$ from the remaining kinetic energy and compute the new velocity. Return to Step 2.

When the kinetic energy vanishes, the accumulated deflection represents the maximum deflection.

For a 12 inch (30 cm) schedule 60 pipe, as shown in Figure 6, with a wall thickness of .562 inches (1.34 cm) and a yield stress of 30 ksi (210 MPa), the total weight of the canister and its contents can be estimated at about 1 ton. If such a canister were dropped on its end from a height of 10 feet (300 cm), the resulting velocity is about 25 feet per second (750 cm/sec). The initial kinetic energy is approximately 20,000 ft-lb (27,000 J). Ignoring the effects of strain rate (conservative), and using crude steps of incremental apex displacement, the maximum deflection can be seen to be about 2 inches (5 cm). Accounting for the initial position of the plastic hinge circle (because of the reverse curvature, the plastic hinge does not initiate at the apex, but at a radius of about 3 inches (7.5 cm)) and would decrease this maximum deflection somewhat.

Figure 6. Canister Bottom Redesign

Therefore, the reference canister design follows the general guidelines of the WIPP and SURF canister designs, neglecting overpacking and adding lifting yoke arrangements and bottom head designs that promote impact resistance.

5. Loading

In order to develop reasonable loadings for the reference design, the interaction of the canister with its surroundings must be taken into account. Current storage plans can guide our thinking in this regard. The bedded salt storage scheme has been described by McClain and Boch [14]. Although the ultimate goal of this concept in its original form is the eventual closure of the storage rooms through inelastic deformation of the salt, the design has useful features for an interim storage study. The individual canister hole is defined by two parameters - diameter and depth. The diameter is governed by the canister diameter (currently shown to be 12.75 inches or 32.4 cm) which is, in turn, governed by the cross-sectional dimensions of light water reactor fuel assemblies. The depth of the hole is governed by shielding considerations. Since the canister will be placed at the bottom of the hole and presumably backfilled with a shielding material (in order to protect personnel in the room above), the dead weight of this backfill must be considered as loading for the canister. If crushed salt is used as backfill, fusing and subsequent retrieval difficulties will be encountered.

Another useful set of data concerns the gross deformation of the repository due to temperature-sensitive creep of the salt, resulting in pillar shortening, room closure (including roof sag and floor uplift), and canister hole bending. The major effect on a canister appears to be: (i) relative motion of the top of the canister away from the pillar (for a canister at the edge of the repository field), with respect to the bottom; and (ii) upward thrust on the canister. Both loadings must be taken into account in design.

In an effort to limit the number of variables under consideration the following assumptions are made:

1. The canister material chosen is carbon steel; as corrosion information becomes available, other material candidates may be selected; at the present time, heat transfer to the salt, basalt or other geological medium dominates the design. The reduced heat loads associated with spent fuel, as opposed to reprocessed waste, may influence this design process markedly.

2. The internal pressure depends upon radiolytic decomposition, and has been chosen conservatively to be about 500 psi (3.5 MPa), yielding a wall thickness for circumferential stress of about .25 inches (.64 cm).

3. Corrosion allowances are based upon unstressed material; it is recognized that atmospherical corrosion rates estimated at .003 in/yr (.008 cm/yr) have been used in nominal designs to date; for some of the newer materials, such as Inconel 671, Inconel X750 or Incoloy 800, where a large chromium content is sought in order to force the oxidation process from internal oxidation to an external protective layer, such corrosion rates may be vastly overestimated. On the other hand, conventional materials, such as carbon and stainless steels, may have significantly higher in situ rates.

4. No overpack is being considered at present; until such time as a definite requirement is observed, the geologic medium itself will be considered as the second line of defense against radio-nuclide transport to the biosphere (the canister is the first line of defense, with the strength of the fuel assembly neglected for conservatism).

The temperature distribution is sufficiently complex to be discussed as a separate topic. A recent report from the WIPP Project [15] provides additional data. Three canister emplacement alternatives were studied for both thermal and salt deformation characteristics. The overall thermal load was assumed to be identical for three alternatives at 37 W/m^2 , which is almost a six-fold increase over the 65 kW/hectare thermal density used for

the ORNL studies [14]. One horizontal canister storage concept and two vertical canister storage concepts were examined. The horizontal emplacement alternative proved to be unattractive because of rapid hole closure (four years, although the lack of reliable creep data for the salt rendered this number qualitative only). This is true in spite of the fact that the temperatures were well under the 200 C design limit. The vertical emplacement alternatives, especially the one with the lowest extraction ratio, seemed to be satisfactory. The results tend to confirm the upward thrust on the canister, but the bending is not reproduced because of the symmetry assumptions in the model.

It should be noted that the analyses to date have tended to neglect some features that may prove to be extremely important at later stages in the design process, such as actual (as opposed to assumed) in situ stresses, pore water, and inhomogeneities and discontinuities in the surrounding medium.

The thermal stresses in the canister that result from the transient temperature distribution and the interaction with adjacent media have been studied only briefly. The most recent stress analysis of the canister wall appears to be that by RE/SPEC, Incorporated, under contract to ORNL/USAEC [16]. Transient temperatures were computed for a two-dimensional room and pillar configuration at the Lyons, Kansas, site and the results compared to previous ORNL calculations. Unfortunately, constant thermal conductivities were used in each of the two analyses, one analysis with 32°F (0 C) properties and the other analysis with properties at 392°F (200 C). The comparisons between the finite element results from RE/SPEC and the finite difference results from ORNL were tolerable. After this comparison, transient temperatures were computed for a room and pillar arrangement at the New Mexico pilot plant site, with dimensions given in Figure 7 [16]. For simplicity the canister was given an initial thermal output 5 kW, with a decay constant of .023 kW per year. The maximum temperatures along the canister center line and at the salt/canister interface were approximately 1050°F (565 C) and 250°F (120 C), respectively. The maxima were reached in about 6 months for the canister centerline and 4 years for the interface.

Figure 7. Re/Spec Analysis Geometry

The major concern in the two-dimensional, finite element thermoelastic analyses was the effect of interaction (various modes of contact and restraint) between the canister sleeve and the salt on the lateral pressure loading. Several sets of boundary conditions were examined, including: (a) radial fixity at the sleeve-salt interface (vertical motion is unrestrained); (b) complete fixity; and (c) assuming a solid steel cylinder to fill the drill hole. Also, two conditions with regard to overburden were examined. In one case, the vertical displacements were restrained (infinitely stiff overburden); in the other, the overburden stress was applied. The aim of these calculations was to scope the magnitude of the canister loading due to lithostatic and thermal stresses. Although the uncertainties are large and the assumptions (homogeneous, isotropic, elastic behavior) gross, estimates of the lateral pressure range from about 2000 psi (14 MPa) for the lithostatic field to about 4000 psi (28 MPa) for the thermoelastic field. These results are in general agreement with the calculations of Pariseau [6].

In terms of dynamic loading, a crude estimate of the weight of the canister, including the fuel assembly and possible liquid coolant, is about 2200 lb (1000 kg), providing an average density of about 0.1 lb/in^3 (2700 kg/m^3).

If an end drop of the canister is assumed, with a corresponding axisymmetric distribution of deceleration stresses following impact with an assumed rigid target, the axial stress can be estimated to be on the order of 20 ksi (140 MPa). This figure is derived on an equivalent static design basis. Since the peak decelerations are not known until a dynamic analysis is completed, the impact stresses may be considerably higher, perhaps exceeding the static yield strength of the material. Strain rate effects for carbon and stainless steels will reduce the degree of inelastic deformation. More sophisticated analysis is needed for the quantitative assessment of the end drop, as well as the slapdown (or toppling) and side drop incidents, in order to insure a reasonable canister structure.

Other dynamic analyses may be required in order to establish the seismic loads on the canister due to ground motion. Without relative ground motion, the canister's stiffness should preclude significant structural deformation. However, faulting or shear band formation may lead to local relative displacements that should be considered.

In all cases, the effects of corrosion on the actual structural dimensions and on crack propagation properties have to be considered.

6. Failure Assessment

The approach recommended for failure assessment, considering the absence of reliability data on actual canister structures, is the "stress-strength" overlap method. This approach has been used for other radio-activity-containing structures of extremely high reliability, as referenced by Witt and Zemanick [5]. Although this particular probabilistic basis for safety evaluation is relatively new, its adoption provides for a quantitative analysis of reliability (and therefore, for consequences and risk) for this type of structure. In classical reliability terms, the structural stress-strength overlap is known as the "demand-capacity" overlap. The steps to be taken in order to implement the method are as follows:

1. Find the failure modes of the structure; this has been done in a previous section.

2. Define loading sequences and environments most likely to produce failure and determine a statistical distribution for the loading; part of this information has been made available in a previous section.

3. Identify the relevant design parameters, such as wall thickness, radius, length, etc., that serve to prevent failure and determine their statistical distribution; instead of this type of random variable identification, an alternative method has been chosen. A number of events can be postulated, as indicated in the previous section, each of which represents a necessary event to be considered by the designer, but which offer varying degrees of severity of loading to the canister structure; in this case, it

was decided that a conservative approach for finding the distribution would consist of assuming a probability of 1.0 for at least 3 off-normal events for each failure mode; these events would be somewhat analogous to the current design requirements for spent fuel shipping containers - namely, it is assumed in the design of a cask that a 30 ft (10 meter) drop will occur; this approach is standard for events that must be included in design; for instance, a shipping container must be able to withstand prescribed impact, puncture, and fire environments; therefore, the probability of such occurrences is 1.0.

4. Evaluate the failure data for the material, and for the particular failure mode, and determine its statistical distribution; note, that in some cases, the capacity of the material is not a strength variable, but may be a ductility variable instead.

5. Compute the stresses and deformations for different values of the design parameters in loading, in order to establish the statistical distribution of the "demand" on the structure.

6. Overlap the "demand" and "capacity" distributions, in order to compute the standard normal variable and the probability of failure for each of the failure modes considered.

For normal distributions of random variables, the standard normalized variable, Z , can be determined first; then, tables are available for relating the probability of failure to the calculated values of Z . For the demand-capacity or stress-strength overlap method, Z is found from the relationship

$$Z = \frac{|\bar{\sigma}_{um} - \bar{\sigma}_{cm}|}{\sqrt{\delta_u^2 + \delta_c^2}} \quad (3)$$

where $\bar{\sigma}_{um}$ and $\bar{\sigma}_{cm}$ are the mean values of the strength variable (shown here as ultimate stress, but may be a deformation parameter, such as ductility) and a stress variable (shown here as the computed stress, but may be a computed

deformation variable, such as effective strain), respectively; δ_u and δ_c are the corresponding standard deviations. While this method depends upon the normal distribution assumption, the conservatism of the normal distribution for low probability events can usually be demonstrated.

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