1 Introduction

In the United States, about a hundred million gallons of high-level nuclear waste are stored in underground containments. Basically, these containments are of two different designs: single-shell and double-shell structures. The single-shell structures consist of reinforced concrete cylindrical walls seated on circular mats and enclosed on top with torispherical domes (Figure 1) or circular flat roofs. The walls and the basemats are lined with carbon steel. The double-shell structures provide another layer of protection and constitute a completely enclosed steel containment within the single-shell structure leaving an annular space between the two walls (Figure 2). Single-shell containments are of earlier vintage and were built in the period 1945 - 1965. Double-shell structures were built through the 1960s and 1970s. Experience gained in building and operating the single-shell containments was used in enhancing the design and construction of the double-shell structures.

Currently, there are about 250 underground single-shell and double-shell structures containing the high-level waste with an inventory of about 800 million curies. During their service lives, especially in early stages, these structures were subjected to thermal excursions of varying extents; also, they have aged in the chemical environment. Furthermore, in their remaining service lives, the structures may be subjected to loads for which they were not designed, such as larger earthquakes or chemical explosions. As a result, the demonstration of safety of these underground nuclear containments poses a challenge to structural engineers, which increases with time. Regardless of current plans for gradual retrieval of the waste and subsequent solidification for disposal, many of these structures are expected to continue to contain the waste through the next 20 - 40 years. In order to verify their structural capabilities in fulfilling this mission, several studies were recently performed at Brookhaven National Laboratory.

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1 The work was performed under the auspices of the U.S. Department of Energy.
This paper presents the results of some of these studies and, in particular, discusses the following aspects of the waste containments:

- waste characteristics
- structural and site characteristics
- loading considerations emphasizing earthquake loads
- shell buckling
- material degradation
- ultimate pressure-retaining capability under a potential accident scenario

A typical double-shell design will be considered in presenting the results. Comparisons will be made with single-shell designs, as appropriate.

2 Waste characteristics

The physical and chemical characteristics of the wastes are needed for determination of certain structural loads, such as seismic loads and for estimation of material degradation.

The waste was generated during the chemical separation processes that were used for recovery of plutonium from nuclear fuels irradiated in reactors. Many types of separation processes were used over the years especially as experience was progressively gained in separating them better and in generating lesser volume of wastes. In all chemical processes, the separation was achieved in acidic environments. In most cases, the waste stream was first converted to an alkaline state by adding chemicals and then stored in carbon steel containments. In other cases, although few, the waste remained highly acidic and was stored in stainless steel containments. Subsequently, with the rapid generation of the waste compared to the available storage space, further treatments became necessary. In some cases, the fission products were separated from the waste by differential settlement (e.g., for strontium 90) or by scavenging with other chemicals (e.g., for cesium 137). The waste volume was reduced and concentrated using evaporators. For control of the waste chemistry and maintaining a desirable pH level that would minimize metallic corrosion, chemicals were periodically added in some instances.

As a result of all these chemical treatments and the diverse composition of the fission products, a large number of chemical species, probably composed of half the elements in the Periodic Table, are present in the waste. Chemical reactions also occurred over the years in the radioactive environment. Thus,
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although there is a historical track record of chemical streams that went into the containments, in many instances, an adequate knowledge of the present waste characteristics does not exist. Despite this deficiency of precise characterization, the following general physical and chemical characteristics of the waste can be postulated for structural engineering needs.

Most containments store highly alkaline waste (pH greater than 10). A few stainless steel containments store acidic wastes of pH less than 1. The alkaline waste includes a large amount of sodium nitrate and nitrite. The physical state of the waste varies widely from clear liquid to dense sludge or salt cake. Wastes in many containments are layered, with liquid on top and sludge or salt cake at the bottom. Again, in many other cases, they are almost all liquid or all sludge or salt cake. Although the wastes initially were very hot and self boiling in many cases, currently their temperature is about 100°F - 200°F. The specific gravity of the stored waste is between 1 and 2. Although the supernatant liquid is not very viscous (e.g., less than 10,000 centipoise), the sludge/salt cake could be highly viscous (e.g., consistency similar to peanut butter or even moist cake). In many cases, the heat-generating radionuclides are distributed heterogeneously.

Much of the waste contains organic materials. In some cases, wastes generate flammable gases, such as hydrogen, as a result of chemical reactions and radiolysis of water. Oxidants, such as nitrous oxides also are present. In some instances, the flammable gases remain stored in the waste for a long time (e.g., a few months) and are suddenly released into the dome space creating a hazardous condition when the lower flammability limits are exceeded. Certain waste types are highly organic or contain species that could be explosive under favorable circumstances (such as dry conditions and high temperatures). Currently, such potentials for explosion or deflagration are being monitored and mitigated by several means, such as mechanical mixing of the wastes.

These data on waste characteristics will be used in the following sections for estimating loads and obtaining structural responses.

3 Structural and site characteristics

Most containment structures are about 80 feet in diameter and have a nominal storage capacity of 3/4 or 1 million gallons. The cylindrical walls below the dome are 25 - 35 feet high. The top of the dome is 5 - 10 feet below the ground level. The reinforced concrete is 1 foot - 2 feet thick, and the steel liner and primary containment are 3/8 - 7/8 inch thick. The steel liners are anchored to
the concrete wall. For double-shell structures, the inner steel containment is simply seated on the basemat (i.e., not anchored to it) and is anchored to the concrete roof. Penetrations of varying diameters (from 4 inches to 40 inches) provide access to the inner space for pumping, treating or monitoring wastes. All containments are atmospheric in that the air pressure in the dome space is roughly atmospheric. For some containments, a slightly negative pressure is maintained so that if air leaks, the flow should be inward, thereby reducing the potential for environmental contamination. Transfer pipelines are inserted above the liquid surface so that the waste cannot escape by gravity.

There are variations in the structural details from those described above. For example, in some applications, the roofs are flat instead of domes and are supported on columns (Figure 3). The concrete is thicker for these structures. There are containments of smaller storage capacities (e.g., 300,000 to 50,000 gallons). Some of the inner containments are free-standing in that they are separated from, and not anchored to, the concrete roof. Some enclosing structures are octagonal rather than cylindrical, and are made of precast slabs. Some containments that store granular calcined wastes are long cylinders clustered together and enclosed by concrete walls.

The high-level waste containment structures are located at four sites where the environmental conditions are very different. Most containments are located in arid climates with sandy/gravel soils and groundwater level about 200 feet below the ground surface. At another extreme, the groundwater level is above the bottom of the containment structure and the soil is moderately soft, underlain by porous geologic layers.

4 Loading considerations

Under normal conditions, the major loading for most high-level waste containment structures is the overburden soil above the roof. In addition, the static soil pressure acts inwards on the wall and basemat. The waste inside the containment imparts outward static pressure on the wall and basemat. Thus, for single-shell structures, these two pressure loads counter each other. But, for double-shell structure walls, the soil pressure acts on the concrete wall whereas the waste pressure acts on the inner steel wall. Another consideration is the thermal load. Initially, many of the wastes were boiling and the temperature gradient across the concrete wall was high. However, currently for almost all containments, the waste temperature is well below the boiling point and the thermal effect on structures is not significant. Another source of static loads is
the test pressure that is imparted on the containment structure before it is declared to be fit for operation.

In addition to the static loads, the containment structures are designed for potential earthquake loads. The design ground motions for the sites are selected considering seismicity in the respective regions, and the potential consequences in case of a breach of the containment. The design basis earthquakes at the sites are characterized by a peak ground acceleration in the range of 0.20 to 0.35g. The earthquake produces dynamic soil pressure on the exterior concrete structures and also shakes the containment structure thereby producing inertial loads. Liquid wastes impart both impulsive and convective hydrodynamic pressures on the wall. For free-standing conditions, the hydrodynamic loads can be calculated by use of formulas available in the literature (e.g., Reference 1). However, most high-level waste containments are restrained on top. For these special boundary conditions, as part of the BNL study, formulations for computing hydrodynamic responses were developed, starting from the fundamental principles (Reference 2). The effects of liquid-structure interaction for flexible containments are included in these publications. However, the waste may not necessarily act as liquid or may exist in layers. Highly viscous wastes can transfer a portion of the inertial load to the base by shear and, on the other hand, increase the impulsive pressure. Layering of the wastes can amplify motion. Currently, such physical aspects of the wastes are being studied for better characterization of their motions (References 3 and 4).

The interaction of the soil, structure and liquid during earthquakes is also a unique phenomenon for these underground waste containment structures. Specific guidelines for including such interaction effects were also developed as part of the BNL study (Reference 2).

In addition to the normal and earthquake loads discussed above, there could be accidental loads resulting from explosion or deflagration. For example, the burning of flammable gases can produce sudden, large pressure pulses. An example of such loads is included in a subsequent section of this paper. Currently, these loads are not considered as part of the normal design and evaluation process for high-level waste containments. Such scenarios are dealt with in the safety analysis domain.

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2 For larger consequences, higher earthquake levels may need to be considered.
5 Shell buckling

Buckling of shells is an important consideration for design and evaluation of the inner steel containments for the double-shell structures. There are extensive data on buckling of cylindrical shells under uniform membrane compressive loads. The buckling strength increases with a small amount of internal pressure but ultimately, there is little compressive strength left when the internal pressure is very high. These phenomena were investigated for high-level containments as part of the BNL study and compared with available data (Reference 5). The European recommendations (Reference 6) appear to be too conservative when the hoop stress is high. An example is shown in Figure 4. The BNL results were obtained for a stainless-steel alloy cylinder and compared with the corresponding European (Reference 6) and New Zealand (Reference 7) results. Earthquake experiences and experimental data also show higher axial compressive strengths at high hoop stresses (Reference 8). Recent BNL analysis results show some residual strength even when the hoop stress reaches the offset yield stress at 0.2% strain (Figure 5, Reference 9). In Figure 5, Curve A shows the buckling strength for an assumed elastic-perfectly-plastic stress-strain relationship and Curve B corresponds to an actual stress-strain relationship with strain hardening.

6 Material degradation

When the high-level waste containments were designed and constructed, it was not anticipated that these structures would be required to remain in service for so long. As part of the BNL study, a systematic assessment of potential degradation of the materials was performed. So far, the waste has breached about one-third of the containments and leaked to the soil or the annular space. Most of them are single-shell structures. The common cause is stress-corrosion cracking of carbon steel containments that were not heat treated after welding for relieving stress. Cracks were observed along welds in these structures. No cracking or leakage has been detected in stress-relieved containments. General corrosion is less than one mil per year except for certain containments storing zeolite wastes where the rate could be as high as 5 mils per year. Pitting corrosion could occur but has not been observed so far. Neither have any other forms of metal degradation been observed nor are they expected to occur in the steel containments (Reference 10). Adding nitrites to the waste seems to inhibit both pitting and stress corrosion cracking.
As part of the BNL study, an inspection plan was developed for the steel containments (Reference 11). Accessibility and radiation environment are the main constraints. It is expected that any generic degradation can be detected early if this inspection plan is implemented.

Some of the high-level waste containment structures were exposed to very hot waste (e.g., 300° - 600° F) early in their lives. At these temperatures, concrete loses its strength and stiffness (Reference 12). Thermal creep also is a concern. Therefore, the concrete components of the high-level waste containment structures may need to be evaluated with lower allowable stress and stiffness values. All such potential degradation effects need to be considered in performing structural assessments of the high-level waste containments (Reference 13).

7 Ultimate pressure-retaining capability under an accident scenario

As part of the BNL study, the ultimate capacity of a double-shell containment was investigated for a hydrogen deflagration scenario (Reference 14). The structure was analyzed using a nonlinear finite element computer program, ABAQUS. The steel liner and containment were modeled with axisymmetric shell elements (Figure 6). The reinforced concrete containment was modeled with two layers of concrete elements embedded with reinforcing bars, based on the smeared hyper-elastic theory and considering tension stiffening, shear retention, and reinforcing bar/concrete interactions in both compression and tension. The mesh size in the dome region was refined with four layers of concrete elements across the thickness. The normal soil pressure and the tangential friction were modeled considering nonlinear springs. The foundation soil was modeled with uniform elastic springs (i.e., Winkler foundation).

The static analysis was continued up to 65 psig with best-estimate material properties. At this pressure, the highest hoop strain (3.8%) occurred at the mid-wall section of the primary containment while the highest meridional strain (5%) occurred at the bottom knuckle of the secondary containment. The concrete wall (which was not anchored to the basemat) separated from the basemat and slightly moved upward as a rigid body (Figure 7). The dome concrete was completely cracked at this pressure.

The static pressure-retaining capacity compared favorably with the pressure generated from a hydrogen deflagration scenario. It was concluded that such a structure would suffer substantial damage, especially cracking of concrete, but
would not collapse nor create a major leak path through the primary containment.

8 Conclusions and future containments

The containments for high-level nuclear wastes evolved through several designs and construction processes. A double-shell structure with two layers of containments as shown in Figure 2 (and analyzed for overpressurization) seems to be a mature design. For radioactive shielding, the structure needs to be underground with soil cover. The primary carbon steel containment must be stress-relieved after welding. If a favorable pH (e.g., 11 -14) cannot be maintained, an alternative material with greater resistance to corrosion (e.g., Alloy C-276) may need to be sought. Unlike some existing structures, the concrete wall should be dowelled to the concrete mat in order to achieve a high capability of withstanding overpressurization. The upper haunch of the concrete wall should be well reinforced with sufficient diagonal bars (Figure 6). Extensive monitoring and characterization programs need to be implemented (e.g., temperature, creep, corrosion, waste state, etc.) for an engineered operation of the nuclear storage structures.

9 Acknowledgements

The author is grateful to the U.S. Department of Energy, Office of Environmental Restoration and Waste Management for supporting the program. The author sincerely acknowledges the cooperation received from his associates at BNL and other members of the Tank Seismic Expert Panel and Tank Structural Integrity Panel.

References

Figure 1  A Typical Single-Shell Containment
Figure 2  A Typical Double-Shell Containment
Figure 3  A Double-Shell Containment with a Central Column
\[ \begin{align*}
\text{p} & = \text{Internal pressure} \\
\text{R} & = \text{Radius} \\
\text{t} & = \text{Thickness} \\
\text{Fy} & = \text{Offset yield stress at 0.2\% strain} \\
\sigma_{\text{cl}} & = \text{Classical buckling stress} \\
\sigma_{\text{axial}} & = \text{Axial compressive buckling/collapse stress}
\end{align*} \]

Figure 4  Axial Buckling of Cylindrical Shell under Internal Pressure  
\[ \frac{R}{t} = 900 \]
\[ \begin{align*}
p &= \text{Internal pressure} \\
R &= \text{Radius} \\
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F_y &= \text{Offset yield stress at 0.2\% strain} \\
\sigma_{cl} &= \text{Classical buckling stress} \\
\sigma_{axial} &= \text{Axial compressive buckling/collapse stress}
\end{align*} \]

Figure 5 Strain-Hardening Effect on Buckling of Cylindrical Shell

\[ R/t = 900 \]
Figure 6  Finite Element Model of a Double-Shell Containment
Overburden Soil

Large Meridional Strain in Secondary Liner

Large Hoop Strain in Primary Containment

Dome

Basemat

Lifting of Concrete Wall

Figure 7  Deformed Shape of Containment Structure at 65 psig

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