

Concrete and Grout in Nuclear and Hazardous Waste Disposal

Editors

A.A. Al-Manaseer

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PREFACE

This peer-reviewed special publication discusses the properties and applications of concrete and grout used in the disposal of nuclear and hazardous waste. The volume includes updated papers from the symposium, held in March, 1991, at the Annual Convention of the American Concrete Institute in Boston, Massachusetts.

Within the variety of topics on concrete and grout used for nuclear and hazardous waste disposal, the volume should provide the reader with a wealth of information for the design and analysis of structures used in low-level radioactive waste disposal facilities. The design and construction issues related to completed low-level radioactive waste disposal facilities are discussed. The long-term performance and behavior of reinforced concrete structures in disposal units are examined. The volume also gives guidelines on the performance and use of concrete for sealing high-level nuclear waste disposal facilities.

This publication is the first of its kind to be issued by the American Concrete Institute covering the subject of nuclear and hazardous waste. The publication was sponsored by ACI Committee 227, Radioactive and Hazardous Waste Management.

A. A. Al-Manaseer and D. M. Roy, Editors
April 1995

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**Considerations for the Design and
Construction of a Reinforced Concrete
Low-Level Radioactive Waste Disposal
Facility**

by J. W. Grindstaff, S. C. St. John, and N. J. Antonas

Synopsis: Low-level radioactive waste (LLRW) must be disposed in a manner that safeguards the environment and future generations. To this end, engineers should provide reasonable assurance that the proposed methods of disposal and materials of construction will function as intended throughout the design life. This paper addresses design and construction issues related to concrete for the nation's first commercial, above-grade, engineered LLRW disposal facility.

Keywords: Conservation; radiation shielding; radioactivity; wastes

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INTRODUCTION

The Low-Level Radioactive Waste Policy Act of 1980 and revisions in 1985 authorized that individual states should jointly form regional compacts for managing their non-federal LLRW. To comply with these Congressional mandates, the Central Interstate Compact (CIC) was formed in 1985 by Arkansas, Kansas, Louisiana, Nebraska, and Oklahoma. In 1987, the compact selected US Ecology, Inc. to site, design, license, construct, operate, and close the disposal facility. Bechtel National, Inc. is a prime subcontractor to US Ecology. Following detailed site characteristics, a 320-acre (130 ha) site near Butte, Nebraska was selected as the preferred site in January 1989. The project submitted a license application to the state of Nebraska in July 1990. Subject to license approval, facility construction is scheduled to commence in the fall of 1994, followed by receipt of the first LLRW in 1995.

LLRW is comprised of three waste classifications (A,B, and C) in accordance with federal regulations (1), as promulgated by the U.S. Nuclear Regulatory Commission. Class A represents the least radiological hazard and constitutes by far the largest percentage of the waste volume. Classes B and C represent progressively greater radiological hazards.

Although the natural characteristics of the disposal site can adequately isolate the LLRW, additional protection is afforded by the reinforced concrete disposal cells and other engineered enhancements. Redundancy is provided in several key areas to meet a zero-release objective. The waste will be disposed in an estimated 21 above-grade, reinforced concrete cells. The operational period for the disposal facility is 30 years or until 5,000,000 ft³ (142,000 m³) of waste are disposed, whichever occurs

first. Following the operational period, the disposal cells will be entombed inside an earthen mound and covered with an engineered multi-media cover. The post-closure design life is for an indefinite future, with a minimum of 500 years for the Class C waste. Walls and roofs of the cells are at least 3 ft (1 m) thick to maintain radiation exposure to levels that are as low as reasonably achievable (ALARA) during the operational period.

The concrete disposal cells satisfy multiple functions including:

- Providing structural strength to resist loads that include soil pressures, seismic activity, tornados, and tornado missiles
- Preventing inadvertent intrusion
- Minimizing water infiltration into the cell and water contact with the disposed wastes

In discussing the long-term functions of the disposal cells, it is important to note that the cells are well above groundwater, outside the floodplain of the probable maximum flood, and are protected from significant water infiltration by the engineered closure cover. Therefore, the cells need not be watertight. In fact, the cells are provided with flood drains to preclude the possibility that a "bath-tub effect" could ever fill the cells with water.

Design and construction employ conservative, established methods and materials of construction to ensure long-term durability and service life. Special attention is given to constructibility to ensure that the design can be fully implemented.

Table 1 lists the overall dimensions of the disposal cells and summarizes the material quantities for concrete and reinforcing steel. Figure 1 illustrates the layout of the waste disposal facility. The disposal unit and closure cover for Class A waste are shown on Figure 2, and the Class A concrete cell is shown on Figure 3. Figure 4 illustrates the combined disposal cell for Class B and Class Kc waste. The closure cover for the Class B/C cell is essentially the same as for the Class A cell.

DESIGN CONSIDERATIONS

The disposal cells are designed to satisfy the intended functions, with special attention given to durability and constructibility. Key design considerations include design loads, steel reinforcement, mix design, crack control, thermal shrinkage stresses, and expected service life.

Design Loads

Design loads include internal and external effects. The cells are designed to withstand the effects of a tornado having parameters defined by AEC Regulatory Guide 1.76(2) and the accompanying tornado missiles. Live loads of snow and wind are considered. Temperature and shrinkage produce large strains and stresses in massive concrete structures, the effects of which were predicted by finite element modelling as described under "Thermal and Shrinkage Stresses." The engineered multi-media cover produces approximately 20 feet (6 m) of overburden soil pressure and yields large lateral soil pressures on the concrete walls.

Although the disposal site is in an area of low seismic hazard based on the Uniform Building Code (UBC) (3), a site-specific seismic investigation was performed to determine a maximum credible earthquake for definitive design. This investigation yielded a maximum ground-level acceleration for design purposes of 0.15g. The analysis was performed according to traditional procedures associated with the design of nuclear power plants (4). The disposal cells were modelled by developing an equivalent lumped-mass stick model, with "foundation springs" to simulate the soil-structure interaction effects of the foundation media. A response spectrum analysis was performed using the spectrum given by AEC Regulatory Guide 1.60 (5), with the resulting accelerations used to develop forces for structural design.

Functional requirements mandate a design approach that provides structural strength sufficient to keep service-level stresses low. Although the given design loads produce high shears and moments in the structure, the stated approach is obtainable because of the thick sections needed for radiation shielding. This approach also limits deflection and creep and minimizes flexural stresses, thereby minimizing cracking due to loads.

Steel Reinforcement

The use of steel reinforcement in a LLRW disposal cell presents an apparent dilemma. Steel reinforcement is required for carrying the tensile forces within the concrete section. On the other hand, corrosion of reinforcing steel is a frequent cause of concrete deterioration. The CIC concrete disposal cells include steel reinforcement; however, corrosion damage is deterred by minimizing the total volume of steel, uniformly dispersing the steel, increasing the concrete cover, and employing other measures to mitigate steel corrosion.

Reinforcement is designed per ACI 318 (6) and ACI 349 (7) requirements using Grade 60 (414 MPa) deformed bars to provide the necessary structural strength. No reinforcement larger than #11 bars is used to allow for lap splicing and avoid the difficulties associated with the mechanical splices required with larger bars. Splices and embedment lengths are Class B per ACI 318. Due to the

aspect ratio of the disposal cells, the roofs and slabs are designed essentially as one-way slabs, with main reinforcement running in the short direction and with temperature and shrinkage requirements essentially governing reinforcement in the long direction. This paragraph allows for placing the steel reinforcement via pre-assembled "cages," which will help maintain correct final location of the reinforcement.

Expansive forces in the concrete caused by rebar corrosion are limited by the total volume of steel and the size and spacing of the steel. The total volume of reinforcement is kept to a practical minimum to reduce the amount of steel that can corrode. Because shielding requirements mandate concrete sections that are thicker than required for the given loads, the steel volume is reduced accordingly. Corrosion damage is further impeded by using relatively small bars at close spacing. This "dispersion" of steel reinforcement distributes the expansive forces induced by any rebar corrosion.

Reinforcement is covered by 3 in. (7.6 cm) of concrete, rather than 3/4 to 3 in. (1.9 to 7.6 cm) required by ACI 318. This increased thickness reduces corrosion by (1) restricting the amount of oxygen, moisture, chlorides, and other corrosive agents from contacting the steel and (2) extending the lifetime of chemical passivity (i.e., high pH) around the rebar. Should corrosion occur, the thickened cover increases resistance to spalling. Because curing mostly affects the outer concrete surface, the increased cover also minimizes any damage caused by inadequate curing.

The potential for damage induced by rebar corrosion is greatly minimized by the aforementioned design considerations and good construction practices that provide a dense concrete with very low permeability. Additional measures being considered for increased protection include adding corrosion inhibitors and/or silica fume to the concrete mix.

Mix Design

The concrete mix is designed for durability, strength, impermeability, and workability. With the exception of workability, these factors tend to be intimately related, and improvements in one factor generally produce improvements in the others. Workability is critical because the concrete must be workable if the required durability, strength, and low permeability are to be achieved.

The 28-day design compressive strength is 4,000 psi (28 MPa). Slump is 2 to 4 in. (5 to 10 cm) before adding any water reducer. The maximum water/cement ration is 0.40. The total chloride ion concentration in the concrete mix is limited to 0.10% of the cement weight.

The concrete mix includes coarse aggregate, fine aggregate,

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portland cement, fly ash, water, air entraining admixture, and a water reducer. At least three trial mixes will be designed and tested per ACI 211.1 (8) and a single mix selected based on the test results.

Aggregate in Nebraska is often highly reactive and gap graded. Material surveys and initial tests, however, indicate that suitable aggregates are available. Selected aggregates comply with appropriate codes and standards, including ASTM C 33 (9). Fine aggregate is graded per ASTM C 33, Section 5, except that the reduction in fines allowed in Section 5.2 is not permitted. Coarse aggregate is size number 4 (3/4 to 1-1/2 in.; 19 to 38 mm) per ASTM C 33.

This cementitious portion of the cement mix consists of 80% portland cement and 20% fly ash. Portland cement is Type II cement per ASTM C 150 (10), including the optional chemical requirements. Fly ash is Class F fly ash per ASTM C 618 (11), including the optional chemical requirements. This combination of cementitious materials provides several important benefits, including resistance to sulfate attack; resistance to alkali-silica reaction, cement-aggregate reaction, and alkali-carbonate reaction; lower heat of hydration; reduced water requirement; and reduced permeability. Although fly ash also tends to reduce the rebar's passive protection by lowering porewater pH, its benefits significantly outweigh this disadvantage.

Water and ice for the concrete mix are per Section 4.1.3 of ASTM C 94 (12), with the additional requirements that the chloride content be limited to 250 ppm, total solids be limited to 2000 ppm, and pH be within the range of 6.0 to 8.0. Wash water is not allowed for mixing water. Ice may be included in the concrete mix to reduce the mix temperature as described under "Placement."

Air-entraining admixture (AEA) is included in the concrete mix to provide $5.5\% \pm 1.5\%$ total air content. AEA will be per ASTM C 260 (13).

Water-reducing admixture (WRA) or high-range water reducer (HRWR) is included in the concrete mix to improve workability without increasing the water/cement ratio. Water reducers will be per ASTM C 494 (14). The specific type of water reducer depends on the placement temperature and type of placement as indicated in Table 2.

Crack Control

Cracks in a LLRW disposal cell must be controlled to (1) limit the ingress of substances that might attack the rebar and (2) minimize the potential for long-term water infiltration. This section addresses the control of flexural cracking. Cracking due to temperature and shrinkage effects is addressed under "Thermal and Shrinkage Stresses."

ACI 224 (15) is used as a basis for flexural crack control considerations in the design. To meet the tolerable crack limitations recommended by Table 4.1 of ACI 224, the exposure conditions must be reorganized. As discussed previously, the cell is not intended to be watertight, so the strict tolerable crack width of 0.004 in. (0.10 mm) is not a requirement. A tolerable crack width was selected as 0.013 in. (0.33 mm), corresponding to $Z = 145 \text{ k/in. (16.4 kN/m)}$ in ACI 224 Equation 4.2a for an exposure condition of humidity, moist air, and soil. Designing to a Z value of 145 k/in. (16.4 kN/m) required closer spacing of smaller bars to reduce the area of concrete surrounding each reinforcing bar. The moderately low service-level stress, as discussed under "Design Loads," is the most important factor in meeting this crack control value.

The thickness of the concrete cover is a direct variable in the Gergely-Lutz equation (ACI 318 Commentary) for calculating crack width; a larger cover can lead to a larger surface crack, but as noted in ACI 224, "these values of crack width are not always a reliable indication of the corrosion and deterioration," and a greater cover "may sometimes be preferable for corrosion control in certain environments." Concrete cover thickness was, therefore, increased to 3 in. (7.6 cm) throughout the structure as described under "Steel Reinforcement."

Thermal and Shrinkage Stresses

The disposal cells are designed without expansion joints to reduce the opportunity for water infiltration. On the negative side, however, excluding these joints magnifies the large stresses induced by thermal movement.

Regions of elevated stress caused by both thermal and shrinkage effects were predicted using a finite element model developed to take advantage of the symmetry of the structure. The model included the basemat, internal and external walls, and roof slab. The expected shrinkage strain (0.0002) was converted to an equivalent temperature drop and added to the value corresponding to 2/3 of the difference between the normal daily maximum and minimum temperatures (16). This combined temperature differential was applied to the model in two separate cases. One case represents the structure partially entombed in the engineered closure cover, and the other case represents the cell completely exposed to ambient conditions.

The model output revealed localized regions of elevated stress resulting from the temperature differential and equivalent shrinkage strain. The cracking and elevated stress levels resulting from shrinkage and temperature are controlled by steel reinforcement. This design consideration is necessary for meeting the extended service life required for the structure.

Stresses induced by heat generated during the hydration of cementitious materials were considered during the design due to

the potential for cracking resulting from the temperature gradients through the thick concrete sections. The thermal cracking is minimized by proper selection of the concrete materials to minimize the heat of hydration, placement methods and requirements to control the maximum temperature of the concrete entering the forms, and formwork allowing controlled dissipation of heat to its final stable temperature. These considerations minimize the volume - change stresses and the accompanying thermal cracking. Specific temperature control measures are discussed under "Placement" and "Curing."

Expected Service Life

The Class A and Class B/C disposal cells were modeled to estimate their long-term ability to successfully isolate the waste from any infiltrating water. The BARRIER code (17), which was used for the analyses, was written specifically for performance assessments of LLRW disposal facilities. The BARRIER code models both chemical and physical attack of the reinforced concrete and predicts the long-term ability of the concrete to serve as a water barrier. The code simulates the year-to-year progressive degradation of the concrete and reinforcing steel and calculates the changes in stress. Once tensile stress at the concrete surface equals or exceeds the tensile strength of the concrete, the cracking penetrates the concrete cover. Loss of function as a water barrier is conservatively assumed to occur when the crack penetrates 75% of the section thickness.

Based on the specific parameters associated with the Class A disposal unit, the Class A cells will isolate the waste from infiltrating water for about 550 years. Floors of the Class A cells are predicted to function for an additional 120 years. The Class B/C cell is expected to isolate the waste from infiltrating water for approximately 3500 years. The Class B/C cell has much better expected performance than the Class A cells for two reasons: (1) thicker sections in the Class B/C cell, which are required for additional radiation shielding and (2) lower service-level stresses in the Class B/C cell.

Results of the analyses, which represent the best engineering estimates, provide reasonable assurance that the concrete disposal structures will function as intended throughout their design lives.

CONSTRUCTION CONSIDERATIONS

To meet the specified functional requirements of the disposal cells, construction practices must be considered to a degree beyond the usual. Such considerations include formwork, placement, curing, and quality control.

Formwork

Formwork includes high quality forms with a smooth face to

minimize local defects. The forms will be lightly coated with a form release agent compatible with any weatherproofing agent that may be used. She-bolt from ties will be used in wall placements. After form removal, depressions resulting from removal of she-bolt couplings will be filled with non-shrink grout or dry pack. These forms and form ties are preferred for reduced infiltration and improved constructibility.

Placement

Concrete placements will be via conveyors to minimize the drying effects of sun and wind. Placements will be scheduled to avoid hot and cold temperatures, high winds, and low humidity. For placements with the least dimension of the section less than 2.5 ft (0.76 m), the minimum and maximum temperatures of concrete at placement are restricted to 55°F (13°C) and 90°F (32°C), respectively. For placements with the least dimension of the section more than 2.5 ft (0.76 m), the same temperature limits are 40°F (4°C) and 70°F (21°C), respectively. These restrictions prevent freeze damage and help minimize thermal shock, plastic shrinkage, and desiccation. During cold weather concreting, temperature of the mix will be increased, if necessary, by heating the aggregate and mix water. During hot weather concreting, temperature of the mix will be reduced by using chilled water and/or ice during mixing, cooling the aggregate, shading materials and equipment from sunlight, and/or insulating the water supply lines.

To minimize shrinkage cracks, the wall placements are limited to 60 ft in length, and slab placements are limited to their full width and 60 ft in length. Placements are done in a staggered strip sequence. Adjoining placements have a minimum age difference of 28 days to allow approximately 40% of ultimate drying shrinkage to occur, thus minimizing crack widths at joints due to shrinkage. The use of numerous construction joints is also effective in the control of thermal cracking.

Curing

Curing is vital to producing quality concrete, particularly in the areas of durability; strength; permeability; and resistance to abrasion, freeze/thaw damage, and sulfate attack. Proper curing includes maintaining satisfactory moisture content and temperature of the concrete during the early stages after placement.

Concrete for the LLRW disposal cells will be moist cured for an extended period of time. Curing per ACI 308 (18) will begin immediately after concrete placement and will continue for at least 14 days or until the concrete attains 70% of the design strength, whichever is longer.

Covering the concrete with a 2-ply synthetic membrane cover is the preferred method for maintaining moisture content. The

inside of the cover (facing the concrete) is absorbent similar to burlap to provide water across the entire concrete surface. The outside of the cover is an impermeable plastic sheet to minimize moisture loss and is reflective to minimize solar heat gain. The concrete will be re-wetted as necessary throughout the curing process to maintain the concrete in a saturated condition. Cure water will meet the same requirements as mix water. Spray-on curing compounds will not be used.

Temperature control measures will be implemented throughout the curing process. Concrete will be maintained above 50°F (10°C) for at least the first 7 days after placement. Saturated concrete will not be subjected to freeze/thaw conditions before developing a compressive strength of 3500 psi (24 MPa). Temperature control measures will also reduce total heat rise, reduce moisture loss, and maintain a relatively uniform temperature throughout the concrete mass.

Temperature control measures begin with the mix design. Type II portland cement produces a slower rate of hydration, thereby reducing heat buildup. Fly ash also contributes by slowing heat gain. Temperature controls that assist in proper curing will also be implemented during concrete mixing and placement, as described under "Placement."

Temperature control measures will continue after concrete placement. Solar heat gain can be minimized by using a reflective curing membrane. Freezing can be prevented by covering the concrete with thermal insulation, although care must be taken to prevent thermal shock once the insulation is removed. Heaters might be necessary during cold weather but will be minimized to avoid surface desiccation. Combustion-type heaters promote carbonation via CO₂ output and will be avoided.

Quality Control

A comprehensive quality control (QC) program will be implemented throughout construction. The program will ensure that concrete quality meets design specifications and that proper documentation is maintained. Key areas of the program include material quality, mix accuracy and uniformity, formwork, steel reinforcement, concrete placement, curing, and compressive strength.

CONCLUSIONS

Low-level radioactive waste can be safely disposed inside above-grade, reinforced concrete cells that are properly designed and constructed. Current design techniques and materials of construction can provide reasonable assurance that the disposal cells will function as intended throughout the design life.

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TABLE 1 — SUMMARY OF LLRW DISPOSAL CELLS

	Class A	Class B/C	Total
Number of cells	20	1	21
Size	62' x 281' x 23' high	61' x 301' x 31' high	--
Volume of concrete			
o Each	8,020 cy	9,120 cy	--
o Total	160,400 cy	9,120 cy	169,500 cy
Weight of reinforcing steel			
o Each	1,120 tons	1,070 tons	--
o Total	22,400 tons	1,070 tons	23,500 tons

SI conversions: ft x 0.3048 = m; cy x 0.0283 = m³; tons x 907.2 = kg

TABLE 2 — WATER REDUCING AND SET RETARDING ADMIXTURES

Ambient Placement Temperature	Placement Description	Type of Admixture
70°F (20°C) or less	For normal conditions	A - Water reducing
70°F (20°C) or less	For additional retardation of members with least dimension 2 1/2 ft (0.8 m) or more	D - Water reducing and retarding
More than 70°F (20°C)	For all members except floor slabs	D - Water reducing and retarding
More than 70°F (20°C)	For all floor slabs	A - Water reducing

Type F (high range water reducing) and Type G (high range water reducing and retarding) admixtures may be used subject to approval by engineering.

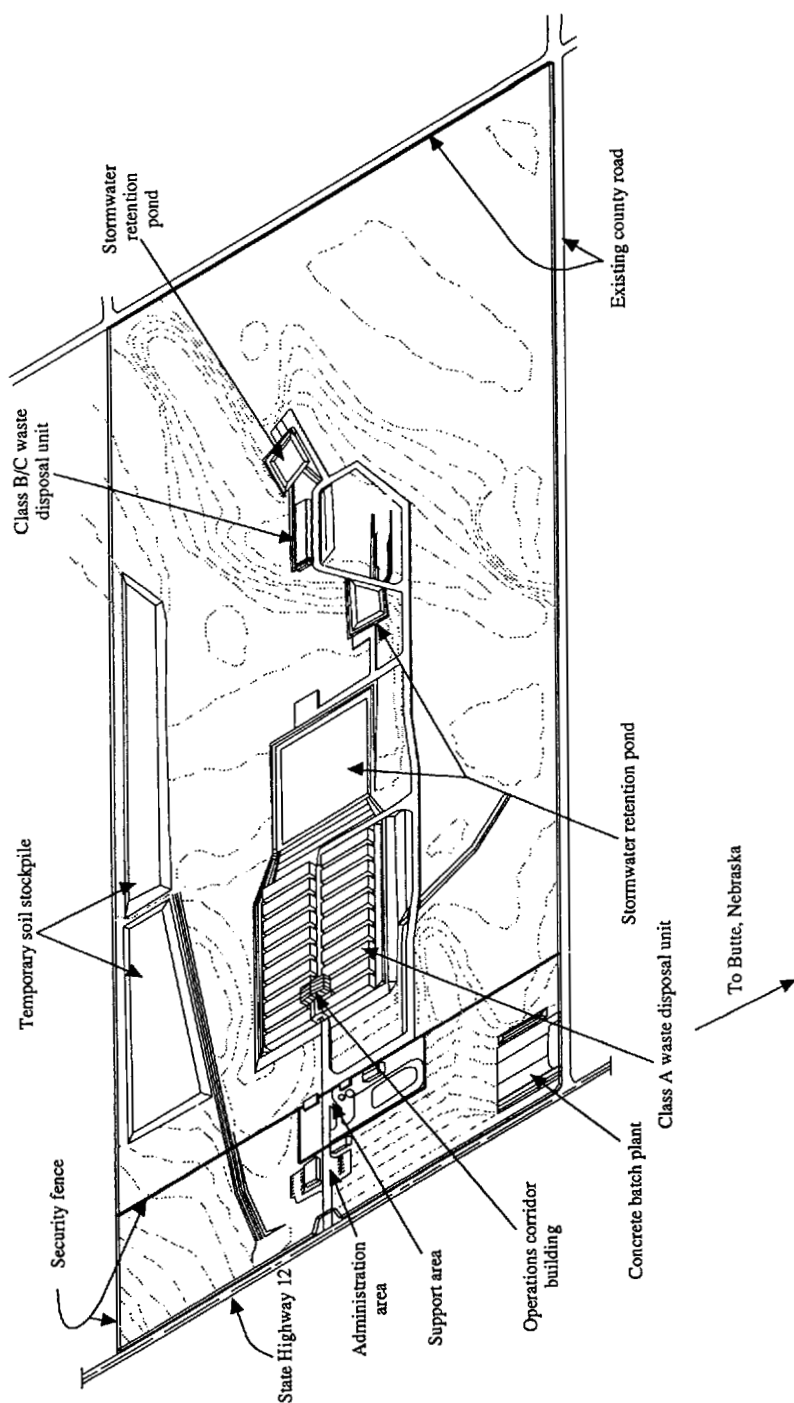
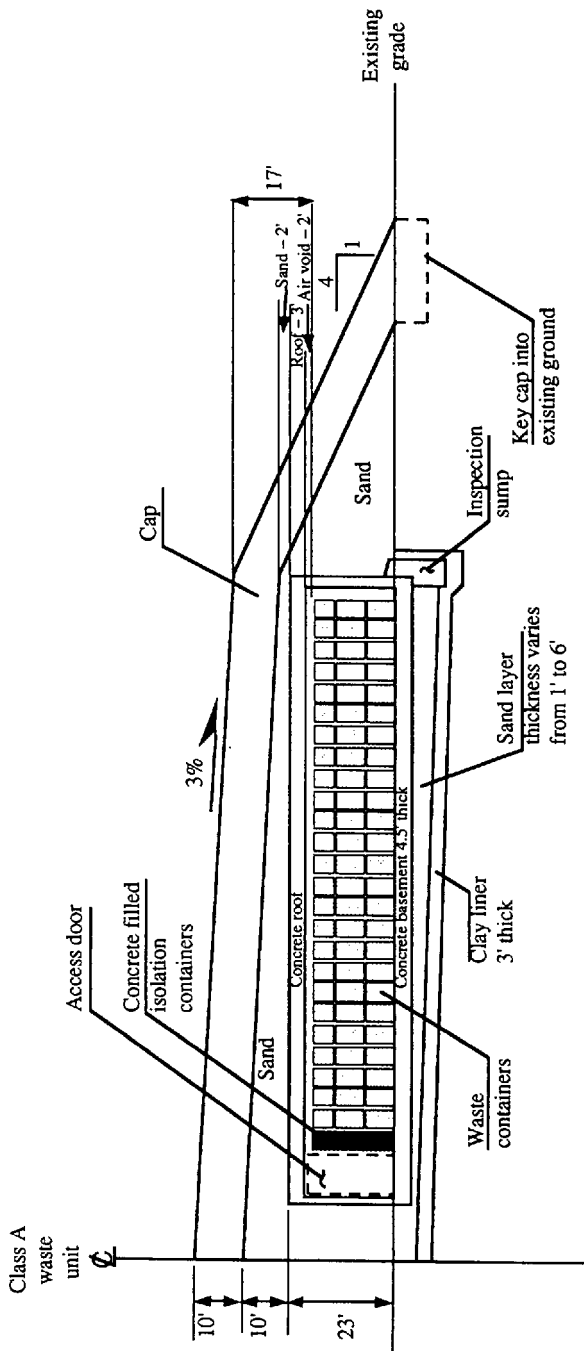


Fig. 1—Proposed low-level radioactive waste disposal facility



SI Conversion: ft x 0.3048 = m

Fig. 2—Cross-section of Class A disposal unit and closure cap

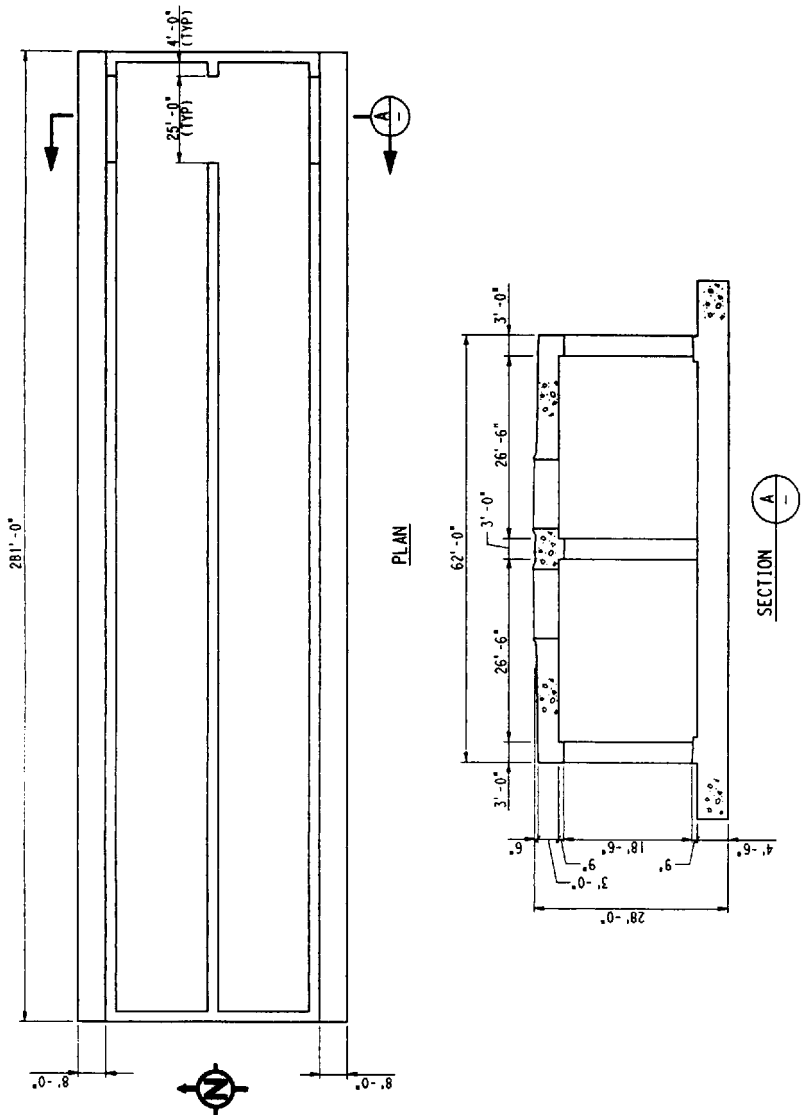


Fig. 3—Class A disposal cell plan and cross-section

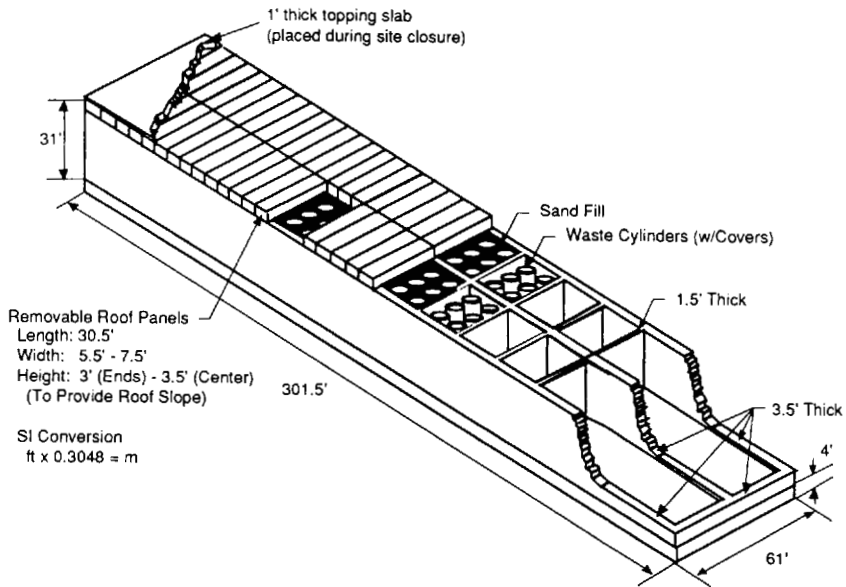


Fig. 4—Class B/C disposal unit

SP 158-2

Performance of Reinforced Concrete Structures in Low-Level Radioactive Waste Disposal Units

by Nam Chau, Robert D. Baird, and Vern C. Rogers

Synopsis: Several engineered disposal technologies involving concrete structures have been proposed for low-level radioactive waste disposal. The long-term performance and behavior of reinforced concrete structures in disposal units have been examined. Under most conditions, the reinforcing steel and concrete work well together to withstand the natural forces. Under certain conditions, however, the reinforcement and concrete may be subject to environmental attack which may cause degradation of the reinforced concrete. Water infiltration through the structure may increase as a result of cracking and increasing permeability and thereby increase the potential for contaminant release. The model for estimating time to onset of reinforcing steel corrosion due to presence of chloride is presented. Requirements for design of reinforced concrete structures for low-level radioactive waste disposal facilities are suggested.

Keywords: Chlorides; corrosion; deterioration; diffusion; performance; wastes

Nam Chau received his bachelor's degree from Tsing-Hwa University, Beijing, China, and his master's degree from the University of Utah. He has 29 years experience in hydraulic, civil, structural, and environmental engineering analysis and design. He is also an ACI member.

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LOW-LEVEL RADIOACTIVE WASTE

Low-level radioactive waste (LLW) is generated in the operation of nuclear power plants, from the use of radionuclides in research institutions and industrial companies, and in medical diagnostic and treatment procedures. LLW also may be generated from the decontamination and decommissioning of equipment, buildings, and land associated with radioactive material operations. LLW is normally shipped to disposal sites in waste containers such as steel drums, steel boxes, liners, and thick casks. The annual volume of LLW shipped is about 40,000 m³ (1.5x10⁶ ft³) in the U.S (1). LLW is classified as either Class A, B, or C, with the lower concentrations of key radionuclides assigned as Class A, higher concentration limits are allowed for Class C waste. Class B waste has concentration limits for short-lived nuclides that are intermediate between the Class A and Class C limits.

To date in the United States, most LLW has been disposed in shallow earthen trenches, a technology called shallow land burial. Some of the early shallow land burial sites have not contained radionuclides to the extent desired. Operating practices and institutional controls were also inadequate at some facilities. In part as a result of the experience with shallow land burial, several states

and compacts of states have adopted laws that forbid using shallow land burial as a means of LLW disposal. Even where shallow land burial has not been specifically forbidden by law, there is a strong interest in using alternatives to shallow land burial to dispose of LLW. Almost all of the new facilities being planned in the United States employ concrete barriers as an important part of the design. The one exception is a proposed LLW facility in the arid Southeast region of California. That facility allows shallow land burial with a 7-m (23-foot) earth cover for the lower activity Class A waste. However, the Class B and C waste is proposed to be placed in concrete overpacks before being placed into a trench.

Alternative disposal facility designs seek to overcome the problems experienced with shallow land burial by using concrete barriers that prevent structural failure, and prevent or reduce water flow and contaminant transport.

PROPOSED REINFORCED CONCRETE STRUCTURES

Reinforced concrete has advantages that make it attractive for use in LLW disposal facilities. For example, it is durable, is massive, has a high compressive strength, is relatively impermeable in nature, is resistant to fire, has low maintenance requirements, provides shielding of radiation, and helps contain radioactive constituents placed in the facility.

Numerous types of concrete structures are being considered for proposed LLW disposal facilities. The primary types are:

- Above grade vault disposal.
- Below grade vault disposal.
- Modular concrete canister disposal.

Table 1 contains a list of the types of LLW disposal facility technologies being considered and the host states for the facilities. Several proposed facilities include more than one of the above concepts. For example, North Carolina, Pennsylvania, and Illinois contemplate using modular concrete canisters inside a concrete vault. This concept provides yet an additional barrier for containing the waste and combines the benefits of both the concrete canister and vault technologies. However, it is significantly more costly and involves additional operations on the waste.

Above-grade vaults -- Disposing LLW in above-ground vaults involves placing the waste containers in an engineered concrete structure located above the surface of the ground and at a later time covering with earthen materials. The above-grade vault concept is envisioned as a large steel-reinforced concrete enclosure with either limited horizontal access (as through a doorway) or vertical access (as through an open top). The vaults are above the natural grade at the disposal site. The floor, walls, and roof of the structure are made from reinforced concrete. Fill material is used to fill the spaces among the waste containers inside the structure. In summary, the description of above-ground vaults implies that:

- The waste is disposed above ground.
- An engineered concrete cover exists over the waste, with an earthen cover applied later.
- The disposal units provide structural stability.

The inclusion of both a concrete vault and an earthen cover enhances the ability of this disposal concept to limit water infiltration into the waste, to prevent plant or animal intrusion, and to reduce gamma radiation exposure rates at the ground surface. The concrete vault also provides structural stability that is not present in the shallow land burial design. An above-grade vault with modular concrete canisters is illustrated in Figure 1.

Below-grade vaults -- Disposal of LLW in below-grade vaults involves placing the waste containers in a concrete engineered structure which is then covered with earth. The vault is below the natural grade. The structure consists of reinforced concrete floors, walls, and roof. Generally, the below-ground vault is a disposal design in which:

- The waste is disposed below ground level.
- Both an engineered concrete cover and an earthen cover exist over the waste.
- The disposal units provide structural stability.

Placement of the vaults below grade makes the facility less likely to attract intruders and less vulnerable to disruptive events and processes that can occur at the land surface. Covering the vault with soil may preserve the integrity of the disposal unit for a longer period than if it were exposed to the atmosphere.

Below-grade vaults should satisfy requirements for minimizing active maintenance after site closure. However, if remedial actions are found necessary, the waste may prove more difficult to remove than from a shallow land burial facility because the massive concrete structure must be breached and removed first.

Below-grade vaults could be appropriate for disposing all activities of LLW because the structure itself may provide the required structural integrity and the required protection from inadvertent intrusion. However, in order to meet these goals, the structure would have to endure without substantial degradation for at least 500 years. A general lack of long-term experience with concrete structures makes it difficult to project the performance of below-ground vaults for these time periods with a high degree of confidence.

Modular concrete canisters -- Modular concrete canister disposal consists of placing individual waste containers in modular concrete structures (i.e., placing the individual waste containers in reinforced concrete canisters) and placing the concrete canisters in trenches below natural grade. Except for the use of the concrete canisters, the physical details of below-ground modular concrete canister disposal resemble those of below-grade vaults. Each canister can be viewed as a mini-vault. Within the canisters, grout probably would be used as backfill between individual waste containers. The description implies that:

- The waste is disposed of below grade.
- An earthen cover exists over the waste.
- The disposal unit provides structural stability.

As in the case of below-grade vault disposal, the inclusion of both a concrete canister and an earthen cover as barriers enhances the ability of this disposal concept to restrict water infiltration into the waste, to prevent human, plant, or animal intrusion, and to reduce gamma exposure rates at the ground surface. The concrete canisters provide the structural stability that is not present in the shallow land burial concept. Covering the canisters with soil may preserve the integrity of the canisters for a longer time period than if they were exposed to the atmosphere. If a canister were breached, the soil covering would still provide a barrier to isolate the waste from the general environmental and water intrusion.

A major technical difference between disposal of LLW using modular concrete canister disposal and disposal using below-grade vaults is the modular nature of the structure. Using small self-contained structures reduces stresses and gives greater protection from earthquakes. Further, the failure of a single structure releases smaller amounts of radionuclides. The individual canisters would be easily transportable and, if a long canister life could be assured, remedial action would be much easier since the canisters could generally be removed intact. In most important technical respects, except for the modular nature of the structure and operating procedures for placement of the waste, modular concrete canister disposal and below-grade vaults are similar.

Table 2 summarizes the environmental conditions and various causes of potential deterioration of reinforced concrete for two representative types of disposal facilities.

Below-grade structures such as below ground vault or modular concrete canisters are covered with an earthen cover system whose composition and thickness would depend on the design of the facility. The earthen cover could be made thick enough to prevent damage to concrete from freeze/thaw cycles, extreme temperature gradients, and tornados. Abrasion and erosion will take place only if the earthen cover system fails. In the event that the concrete structure is impaired, the earthen cover will act as a barrier to waste migration.

For below grade structures, the roof, walls, and foundation would have large vertical loads from the weight of the cover system. The exterior walls of below ground vault would have received large pressure from the soil surrounding them. Chemical compounds that are corrosive to concrete or the reinforcement (such as sulfates and chlorides) may be sufficiently abundant in the earth and in groundwater to threaten the integrity of structures. Also some groundwater contains acids that can attack concrete.

The earthen covered above-grade structures are subject to large potential earthquake loads. Chemical attack on concrete or reinforcement depends upon the hazardous chemical element concentration in the earthen material backfilled surrounding the structures. Chemical attack would be less severe compared to below ground construction.

There is no evidence that low levels of ionizing radiation cause concrete to deteriorate. However, the waste containers may corrode with time due to chemical attack. The potential threats to reinforced concrete structures from the waste, therefore, depend on the physical

form of the waste, chemical properties of the waste, and the possibility of moisture entering the structure.

TIME DEPENDENCE OF CONCRETE PROPERTIES

ACI 209R-92(2) describes the increase of compressive strength of concrete in the early ages. Concrete will reach its maximum compressive strength after several years, after which it will decline. The tensile strength is a function of compressive strength of concrete. The modulus of elasticity is a measure of the inherent rigidity or stiffness of a material. Since concrete compressive strength is time dependence, the tensile strength and the modulus of elasticity of concrete also varies with time.

The time-dependent increase of strain in hardened concrete subject to sustained stress is defined as creep. The creep coefficient depends on factors allowing for the composition of the concrete mix, size of structural member, initial curing conditions, ambient relative humidity, age at loading, variation of the load with time, and reinforcing steel content in the concrete section. Thus, the modulus of elasticity must consider the effects of creep.

Permeability is the quality or state of permitting passage of fluids (including both liquids and gases). The measure of this characteristic is usually defined as the coefficient of permeability. Several factors affect the coefficient of permeability in concrete. These include water-cement ratio, grading of aggregate, aggregate size, and age of concrete. As the concrete degrades or cracks, its effective permeability may increase. In the long-term, the coefficient of permeability may change because bulk properties change due to various degrading processes including chemical reaction of aggregate, leaching of calcium hydroxide from concrete, or freeze/thaw damage which causes internal cracking.

Under normal conditions, good quality concrete with adequate protection against environmental attack assures that the dimensions of structures are stable during the service life. However, the thickness of concrete may be reduced due to physical abrasion, freeze/thaw damage or sulfate and acid attack. The concrete cover over reinforcement can also be reduced due to spalling caused by corrosion of reinforcing steel. Corrosion of reinforcing steel is a third category, and fourth category is formation of cracks in concrete due to applied loads.

The degradation of concrete will change concrete properties, including compressive strength, tensile strength, modulus of elasticity, permeability, diffusivity, effective thickness, and pH of concrete. Because degradation processes progress with time, these properties are also time dependent.

The methods used to calculate concrete degradation for LLW disposal facility design are described in a companion paper (3). However, it is beneficial to address the conditions for the onset of reinforcing steel corrosion in some detail.

PROCESSES OF DEGRADATION OF REINFORCED CONCRETE

The processes of reinforced concrete degradation can be divided into four categories as shown in Figure 2. Processes that affect the bulk properties of the concrete are exemplified by leaching of calcium from concrete and alkali aggregate reaction. Concrete surface degradation as a result of sulfate attack, acid attack, water erosion, abrasion, and freeze/thaw damage may cause both surface wear and concrete permeability change.

Steel corrosion is primarily an electrochemical process. Normally good quality concrete adequately protects embedded steel against corrosion. However, the protective concrete layer may be destroyed through such mechanisms as sulfate attack, acid attack, chloride attack, or carbonation reaction in the concrete. The effective area of steel decreases and the volume occupied by steel and corrosion product increases over time as the steel corrodes. The onset of reinforcing steel corrosion depends on the environment to which the structure is exposed, concrete properties, and conditions of steel in the concrete.

The corrosion caused by the presence of chloride ions is considered to be the major cause in initiating reinforcing steel corrosion. The chloride ions destroy or reduce the effectiveness of the passivation layer on the steel, allowing oxygen to corrode the steel. When concrete carbonation reaches the surface of reinforcement, concrete pH is reduced and the chloride threshold concentration is significantly reduced. The corrosion rate is also controlled by the rate of oxygen diffusion through the concrete cover to reinforcing steel. Permeability and diffusion coefficient chloride and oxygen in concrete initial concrete pH and concrete cover thickness over

reinforcement influence steel corrosion because of their influence on chloride and oxygen migration.

The minimum quantity of chloride required to initiate corrosion of reinforcing steel is defined as threshold chloride concentration. Table 3 presents threshold chloride ion concentration for corrosion of reinforcing steel in concrete from observations of various researchers (4). The average value of threshold chloride is about 330 ppm for normal conditions.

The threshold chloride concentration depends on the concrete pH, moisture content, proportion of water soluble chloride, and the electrical potential of the steel. The pH is one of most important factors affecting the threshold value. The chloride threshold value is greater than 8000 ppm at a pH of 13.2 but is significantly reduced to about 70 ppm while at a pH of 11.6. Corrosion generally will not occur in a high-alkali environment (5).

The time at which the chloride content reaches the threshold value at the surface of the reinforcement is called the time onset of reinforcing steel corrosion in concrete due to chloride attack.

Chloride migration through concrete can be calculated using Fick's law of diffusion (3). Figure 3 gives the time to the onset of corrosion with the diffusion coefficient as a parameter. Higher values of the diffusion coefficient produce earlier times to the onset of corrosion. Figure 4 presents the dependence of the time to onset of corrosion with the concrete cover thickness over the reinforcement. Thicker concrete cover defers the time to onset of steel corrosion.

Other important observations include:

- If the chloride ion concentration is less than the threshold value, the chloride will not significantly affect reinforcement corrosion.
- Lower initial chloride ion concentrations in the concrete may defer the time to onset of reinforcing steel corrosion.
- In the short term, reducing the effective diffusion coefficient of chloride ion in concrete or increasing the thickness of concrete cover will significantly increase the resistance to chloride attack.

- In the long-term, lower diffusion coefficient and thicker concrete cover are not effective in increasing the resistance to chloride attack. Neither measure will protect steel from chloride attack where the reinforced concrete structures are exposed to moderate or severe chloride environments because the source of chloride in the soil or groundwater eventually may reach to the steel in the long term.

In LLW disposal unit design where structures are subjected to chlorides from the environment, use of coating or water-proof membranes on exterior faces of concrete may be more effective to ensure the required service life. Another more expensive measure is to artificially change the environmental condition by using borrow-site material with low chloride content or using washed sand and pea gravels to limit the chloride content of structural backfill surrounding the disposal unit.

INITIAL CRACKING AND CRACK PROPAGATION IN STRUCTURES

Cracks in reinforced concrete structures may be random or may result from applied loads and corrosion of reinforcement. The random cracking may be caused by shrinkage while the concrete cures, thermal contraction, freeze/thaw damage, and alkali-aggregate reaction. Normally, random cracking appears in cement paste or mortar joints around coarse aggregates. Crack depths and widths may gradually increase due to creep and shrinkage of concrete.

The working stress method is used for analysis of the long-term behaviors of reinforced concrete structures. The reinforced concrete structures are designed to resist all appropriate loads which develop the bending moment, shear, and axial tension or compression in the structural elements. Initial cracking of concrete may result from those forces. The simplest cracking criterion is based on the principal tensile stress or principle tensile strain theories of failure.

The crack width, crack spacing and crack depth can be estimated according to ACI Manual of Concrete Practice (6-8). The cracking will develop over time as concrete and steel gradually deteriorate.

For concrete sections in the cracked-elastic stress stage, a relation describing the mean crack width is expressed in terms of mean strain and crack spacing (9).

$$W_m = (\epsilon_m + \epsilon_{sh}) S_m \quad (1)$$

where

W_m	=	mean crack width (in)
ϵ_m	=	mean tension strain due to forces
ϵ_{sh}	=	long-term shrinkage strain of concrete
S_m	=	mean crack spacing (in).

The mean crack spacing varies depending on bending, tension, and shear forces. The crack spacing also depends on the concrete cover thickness and design arrangement. Since the elasticity modulus of concrete and reinforcement will be time dependent, the creep effect must also be considered.

Most reinforcement is placed near the surface of concrete element to carry the tensile stress, limiting the potential for concrete cracking. As the reinforcing steel corrodes, the strength of the structure decreases. As the steel corrosion products build up, internal tensile stresses are created in the concrete along the boundaries of the reinforcement. Based on the elasticity theory, the magnitude of this internal pressure can be calculated (3).

The stress field between cylindrical reinforcing steel and the surface of concrete can also be estimated. A general series form of stress function in bipolar coordinates was given by Jeffery (10). The function has been applied to the situation of a semi-infinite region with a circular hole under a uniform radial pressure. As corrosion progresses, concurrent with assumed concrete cover deterioration, the cracking will propagate toward the surface of the concrete element. Cracking due to corrosion normally occurs along the length of reinforcement. Spalling of concrete will occur if the concrete cover over reinforcing steel is thin.

WATER INFILTRATION THROUGH THE CONCRETE

Water is an important transport medium for radionuclides from a disposal unit. Since the concrete used in the construction of waste disposal units is a porous solid medium, moisture retention

within the concrete and infiltration through the concrete normally depend upon the permeability or hydraulic conductivity of concrete and moisture diffusivity. The calculation of water movement through either cracked concrete or uncracked concrete is accomplished by representing the concrete as an equivalent porous medium and applying groundwater flow equation.

Water infiltration through uncracked concrete will begin from the outer face of structure, where water infiltrating through soil may come in contact with the concrete. The initial permeability of concrete used in low-level waste disposal unit should be less than 10^{-10} cm/sec (4×10^{-11} in./sec) (11). Therefore, water infiltration from Darcy flow through concrete in its early years will be extremely low.

If cracks form throughout the section of the concrete or if joints begin to leak, water will migrate more rapidly. The hydraulic conductivity of concrete varies with the extent of cracking. At saturated levels, water will drain from the fractures at a rate proportional to the cube of the crack width. A honeycomb due to construction defect or a failure of the structure may also cause an expected pathway for water to pass easily through the concrete.

SUGGESTIONS FOR STRUCTURAL DESIGN

The primary concern regarding the reinforced concrete structural design is that the waste disposal facility meets the performance objectives and technical requirements. The disposal facility should be able to perform eleven required functions as follow (12):

- Minimize water infiltration.
- Ensure disposal unit integrity.
- Ensure structural stability.
- Minimize contact of waste with standing water.
- Provide site drainage.
- Facilitate site closure and stabilization.
- Avoid the need for long-term maintenance.

- Prove a barrier against inadvertent intrusion.
- Maintain occupational radiation exposures as low as reasonably achievable.
- Provide adequate disposal site monitoring.
- Provide adequate buffer zone.

Water is an important medium for transport of radionuclides from a disposal unit. Water will contribute significantly to structural degradation. Because of these, it is essential in the design of a low-level waste disposal facility to minimize the availability of water which may come in contact with concrete and waste. The following measures are suggested to limit infiltration of water through structures.

Limit Water Contacting Concrete and Waste

The low-level radioactive waste disposal site must be located above the flood plain. The lowest elevation of disposal unit must be located above the water table. Providing an earthen cover system in disposal unit will limit the potential for concrete degradation. All drainage system components including site surface water drainage system, disposal surface drainage, percolating water drainage, and floor drainage system play vital roles in minimizing the water contacting the structure and in preventing water infiltration into the waste.

Provide Sufficient Strength

The structural design should conform to the industrial codes developed by ACI committee 349 (13), 350 (14), 224 (15), and 201 (16). ACI 349-85 (13) contains increased levels of conservatism over other codes such as ACI 318-89 (17), including specifically greater safety margin in ultimate design method under the assumed seismic event and increased minimum requirements of reinforcement in concrete walls, floors and roofs. Sufficient conservatism should be incorporated into the design to ensure that the structure can support the applied loads even after several hundred years of potential degradation.

On the basis of modified ACI 349-85, the required strength, U , is equal to or greater than the greatest of the following (12):

$$\begin{aligned} U_1 &= 1.4D + 1.4F + 1.7H + 1.7E \\ U_2 &= 1.4D + 1.4F + 1.7L + 1.7W \\ U_3 &= D + L + T + E + H \\ U_4 &= D + L + T + W + H \end{aligned} \quad (2)$$

where

D	=	dead loads, or related moments and forces
L	=	live loads, or related moments and forces
F	=	loads due to lateral and vertical pressure of incidental liquid, or related moments and forces, if applicable
H	=	loads due to earth pressure, or related moments and forces, where applicable
T	=	loads from temperature differences within the structure, or related moments and forces
W	=	loads from design wind pressure, or related moments and forces
E	=	loads generated by the design basis earthquake, or related moments and forces.

For the above loading combinations, any load which reduces the effects of other loads, should be assigned a coefficient of 0.9 if the load is always present or occurs simultaneously with the other loads.

The safety margins required should be correlated with the return period of the natural event being analyzed. The calculated safety margin should be correlated with the calculated methods and their assumptions. As more conservative methods are used and more conservative assumptions are made, lower safety margin will be accepted. When the probable maximum earthquake is used in loading combinations, the required strength of the structure may be reduced by one third of its ultimate strength to resist the moments and forces due to the nominal combination of the factored loads stated previously.

Because of the concern for water tightness and long service life, it is necessary to consider design requirements beyond ACI 349, because ACI 349-85 provides less conservatism in the limiting stresses and cracking control in structural elements than do ACI 350R-89 and ACI 224R-90. Moreover, ACI 349-85 does not emphasize durability considerations. Guidance for constructing durable concrete is provided in ACI 201.2R-92.

Enhance Cracking Control

In general, crack formation ultimately depends upon the ability of the structure to withstand the applied loads. The degradation processes lead to increased cracking of the concrete. Most regulatory agencies responsible for low-level radioactive waste disposal in the United States adapt ACI 349 code for the design of reinforced concrete structures in the waste disposal units. One of the most important assumptions in the code is that the tensile strength of concrete is negligible and tensile stresses in the concrete are carried by steel reinforcing. The design code allows concrete to crack and completely rely on steel to resist the tensile forces. However, the steel is subject to more rapid corrosion in cracked sections of concrete. Therefore, the long-term performance of concrete is enhanced by reducing and deferring the development of cracks that penetrate throughout the entire thickness of the concrete. Two approaches controlling crack in the design are described below.

Assume that concrete has no tensile strength -- The concrete is assumed to bear no tension force so that steel carries all tension forces. It is recommended that the calculated cracking width not exceed 0.008 inch under service loads and that the tensile strength capacity of concrete not be determined in the analysis. Therefore, even if cracks form, the width of the cracks remains sufficiently small, and water flow will be inhibited.

The main factor influencing the crack width is the spacing between reinforcing steel bars. Long-term performance may be enhanced by requiring relatively close reinforcement spacing. Although thicker concrete cover may cause wider surface cracks, it also defers and minimizes corrosion of the reinforcing steel. Therefore, it is desirable to have a thick concrete cover over the reinforcing steel to delay and retard the penetration of chlorine ions and oxygen to the steel, which causes the steel to corrode.

Assume that concrete has tensile strength -- The concrete has tensile strength sufficient to carry tension force which is, in turn, less than the tensile strength of the concrete. Design should preclude cracks under sustained service loads. Therefore, it is conservative to provide minimum thicknesses of concrete elements so that they are adequate to bear tension forces under service loads, assuming that no cracking has occurred. Once reinforcement is assumed to have corroded away, the remaining concrete core will provide the necessary strength to withstand sustained service loads. The thickness of concrete cover should include allowance for a

potential surface wear during the service life. In addition, the structural design should eliminate any vertical joints extending to the interior of waste disposal cells.

Select Construction Material

The durability considerations require selection of the best type of cement; control of the water-cement ratio; exclusion of reactive aggregate; use of small size of coarse aggregate; limiting initial chloride and sulfate concentration in concrete; proper use of admixtures such as air entraining agent or high range water reduction agent; proper use of silica fume; adequate dampproof coating on structures; and proper use of corrosion inhibitor.

Specify Low Water-Cement Ratios

Most of concrete degradation process depend on harmful materials migrating to and through the concrete via the groundwater. To prevent water infiltration, the concrete must have a low permeability and low diffusivity. The main factor that affects the permeability and diffusivity is water-cement ratio.

The low water-cement ratio generally increases the strength of the concrete while decreasing the permeability and diffusivity. The water-cement ratio should not exceed 0.4. Such a limitation should give permeability less than 10^{-10} cm/sec (4×10^{-11} in./sec) (11) and diffusion coefficients less than 5×10^{-8} cm²/sec (8×10^{-9} in.²/sec) in normal conditions (18). The trade-off for these beneficial effects of reducing water-cement ratio include increased difficulties in working with the concrete and thus in controlling concrete quality.

Use of Coatings and Waterproof Membranes

One of the causes of cracking is the limited ability of concrete to resist tensile stresses. Micro-cracking at early age due to temperature gradients and shrinkage at the concrete surface is difficult to eliminate completely. Synthetic fibers, such as polypropylene fiber or fiber mesh, placed near the surface of the concrete will inhibit shrinkage cracking and reduce concrete permeability, both desirable affects. A waterproof coating or

waterproof membrane can be used to fill the surface cracks and prevent water infiltration through the concrete. If concrete is subject to chemical attack, appropriate coatings should be used to enhance the durability by protecting concrete from contact with the immediate hostile environment. For above-ground vaults without earth cover system, a fiberglass coating system is recommended.

SUMMARY

In conclusion,

- Concrete is a desirable material for LLW disposal units.
- Concrete must have long service life in LLW disposal units.
- The degradation of concrete and reinforcement should be considered in the analysis and design of the reinforced concrete structures.
- Limiting cracking and crack propagation in the concrete is the key to proper performance of the structures.
- Time to onset of corrosion of reinforcing steel can be deferred by limiting chloride concentrations in contact with concrete, reducing the concrete diffusion coefficient of chloride, and increasing concrete cover or reinforcing steel.
- Long-term performance of reinforced concrete structures can be modeled.
- Important design measures include providing strength beyond ACI-349, enhancing cracking control, limiting chloride concentrations, and using coatings and waterproof membranes include ACI 201.2R-92, ACI 224R-90, and ACI 350R-89.