SP 158-1

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

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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 ft^3 (142,000 m^3) 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.

<u>Mix Design</u>

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, 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% ± 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 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 modelled 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 lifes.

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 CO_2 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.