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CONSIDERATIONS FOR GROUT FORMULATIONS FOR FACILITY CLOSURES USING *IN SITU* STRATEGIES

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ABSTRACT

The U.S. Department of Energy (DOE) is conducting *in situ* closures (entombment) at a large number of facilities throughout the complex. Among the largest closure actions currently underway are the closures of the P and R Reactors at the Savannah River Site (SRS), near Aiken, South Carolina. In these facilities, subgrade open spaces are being stabilized with grout; this ensures the long term structural integrity of the facilities and permanently immobilizes and isolates residual contamination.

The large size and structural complexity of these facilities present a wide variety of challenges for the identification and selection of appropriate fill materials. Considerations for grout formulations must account for flowability, long term stability, set times, heat generation and interactions with materials within the structure. The large size and configuration of the facility necessitates that grout must be pumped from the exterior to the spaces to be filled, which requires that the material must retain a high degree of flowability to move through piping without clogging while achieving the required leveling properties at the pour site. Set times and curing properties must be controlled to meet operations schedules, while not generating sufficient heat to compromise the properties of the fill material.

The properties of residual materials can result in additional requirements for grout formulations. If significant quantities of aluminum are present in the facility, common formulations of highly alkaline grouts may not be appropriate because of the potential for hydrogen generation with the resultant risks. SRS is developing specialized inorganic grout formulations that are designed to address this issue. One circum-neutral chemical grout formulation identified for initial consideration did not possess the proper chemical characteristics, having exceptionally short set times and high heat of hydration. Research efforts are directed toward developing grout formulations that can meet operational requirements for chemical compatibility, extended set times and reduced heat generation.

INTRODUCTION

The R and P Reactors at SRS are currently undergoing closure using the *In Situ* Decommissioning (ISD) strategy. ISD is the permanent entombment of a facility and has been adopted by the DOE for a certain class of facilities where this strategy presents a safer and more cost effective closure methodology than complete removal and transport to a disposal facility. Advantages of the ISD strategy have been discussed elsewhere in detail (Ref 1, 2) and are summarized as follows:

- permanently stabilizes residual contaminants; and
- is less costly and poses fewer worker risks than dismantling, transporting, and disposing large contaminated structures.

However, because it is an important concept that will be in play for many years in the future, the following definition has been proposed for incorporation within DOE documents:

"[ISD] is the permanent entombment of a facility that contains radiological contamination, with or without chemical contamination. Achievement of the entombed end-state is a result of established regulatory review and approval processes for decommissioning of DOE facilities."

The R and P Reactors were operated for the production of special nuclear materials for the US weapons program and operated from 1953-1964 and 1954-1988, respectively. Under the DOE closure program to accelerate the reduction of risk and cost associated with excess facilities, a strategy was developed with the appropriate state and federal agencies to close these facilities with Early Action Records of Decision for the closure strategies addressing these specific facilities within their respective Operable Units at the SRS.

The SRS P Reactor (105-P) is shown in Figure 1; it is very similar to the R Reactor (105-R). The ISD concepts for both reactors are illustrated in schematic cross-sections in Figures 2 and 3. (The red line on Figure 1 marks the line of cross-section shown on Figures 2 and 3.) The complexity of the spaces which must be filled and limitations on floor loading in some of these facilities necessitates that grout delivery occur outside of the structure and that the fill material be pumped along sometimes complex paths to the fill site. The structural fills and placement strategy developed for the SRS R Reactor Disassembly Basin are also applicable to decommissioning the P Reactor Disassembly Basin and the below grade portions of both the 105-P and 105-R facilities. The 105-R Reactor Disassembly Basin is the first SRS reactor facility to undergo the ISD process. The process consists of placing cementitious grout materials below grade up to ground surface in the disassembly basin areas. The above grade structure over the disassembly basin areas will be demolished and removed. A concrete cap will cover the grouted area of the disassembly basin and this will be the final configuration. Other below grade areas in the two reactors will be filled as indicated in Figure 3. The ISD process for the entire 105-P and 105-R facilities will require approximately 250,000 cubic yards (191,140 cubic meters) of grout and 2,400 cubic yards (1,835 cubic meters) of structural concrete which are expected to be placed on an accelerated schedule.

The planning for these closures necessitates the preparation of Reactor Grout Placement Strategy documents which provide an initial dataset for planning the *in situ* reactor decommissioning projects and address the following topics.

- Reactor Areas and Work Phases
- Grout Mix Designs
- Grout Placement Strategy and Delivery System Configurations
- Grout Placement Construction Verification Scheme

More detailed information describing the grout placement strategy for the P and R Reactor Disassembly Basins is provided elsewhere (Ref 3). The resolution of these issues and implementation of the solutions will be discussed largely in the context of closure of the R Reactor disassembly basin which is nearing completion. Data and information related to grout formulations and concrete mix designs, placement strategy and concepts will also be applied to the decommissioning of the 105-P Reactor Disassembly Basin and to both the 105-P and 105-R Main Reactor Buildings.

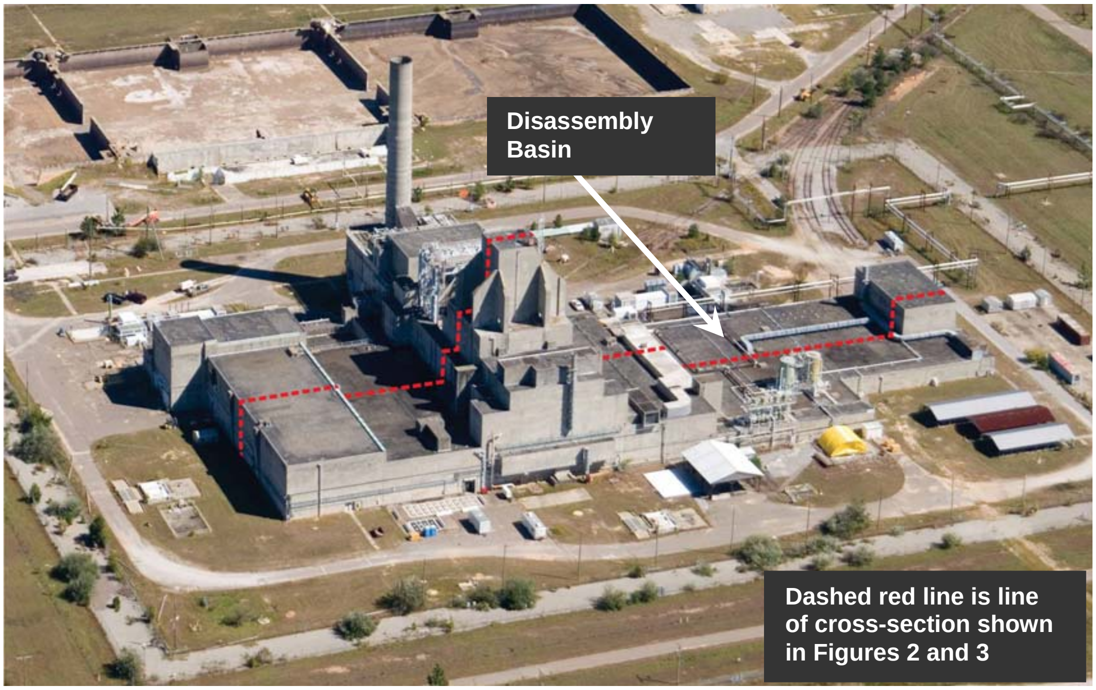


FIGURE 1. PHOTO OF THE 105-P REACTOR BUILDING (SIMILAR TO THE 105-R BUILDING)

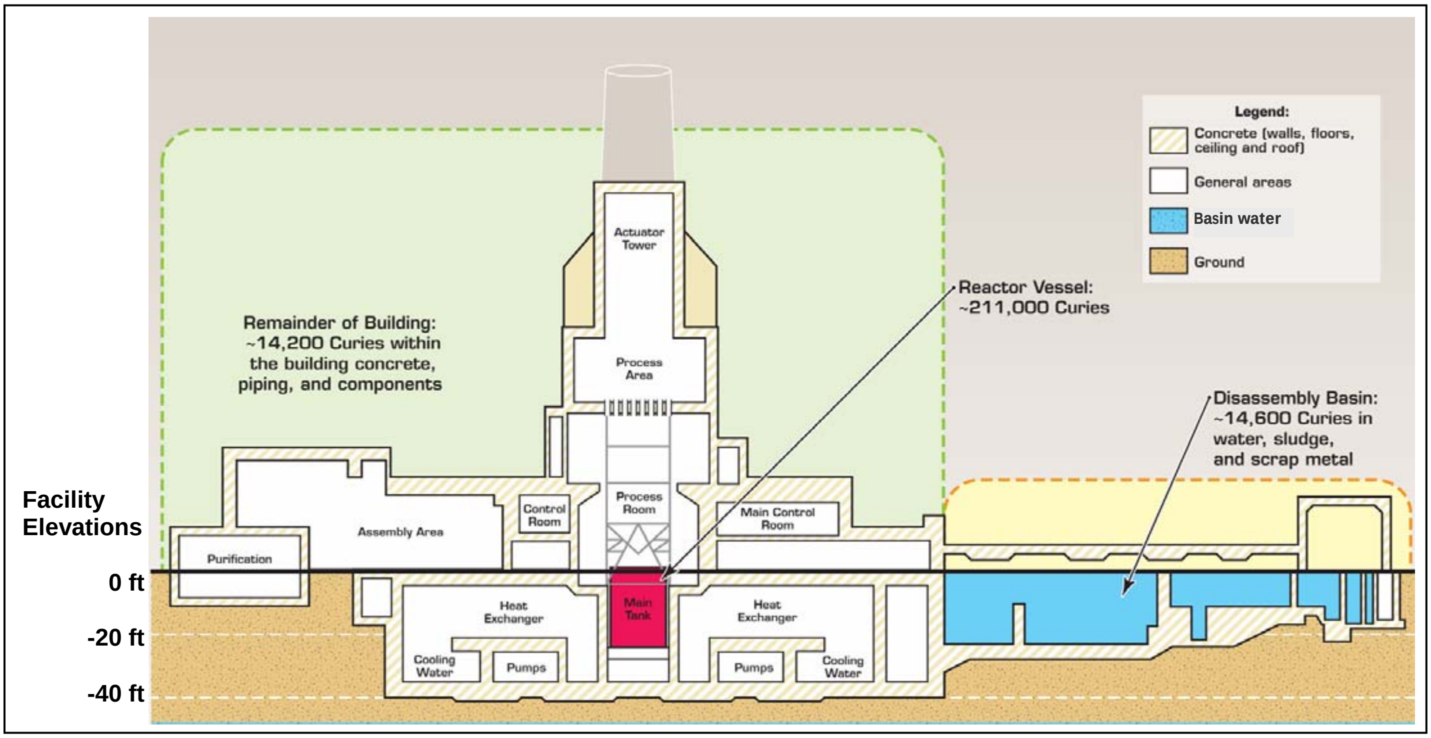
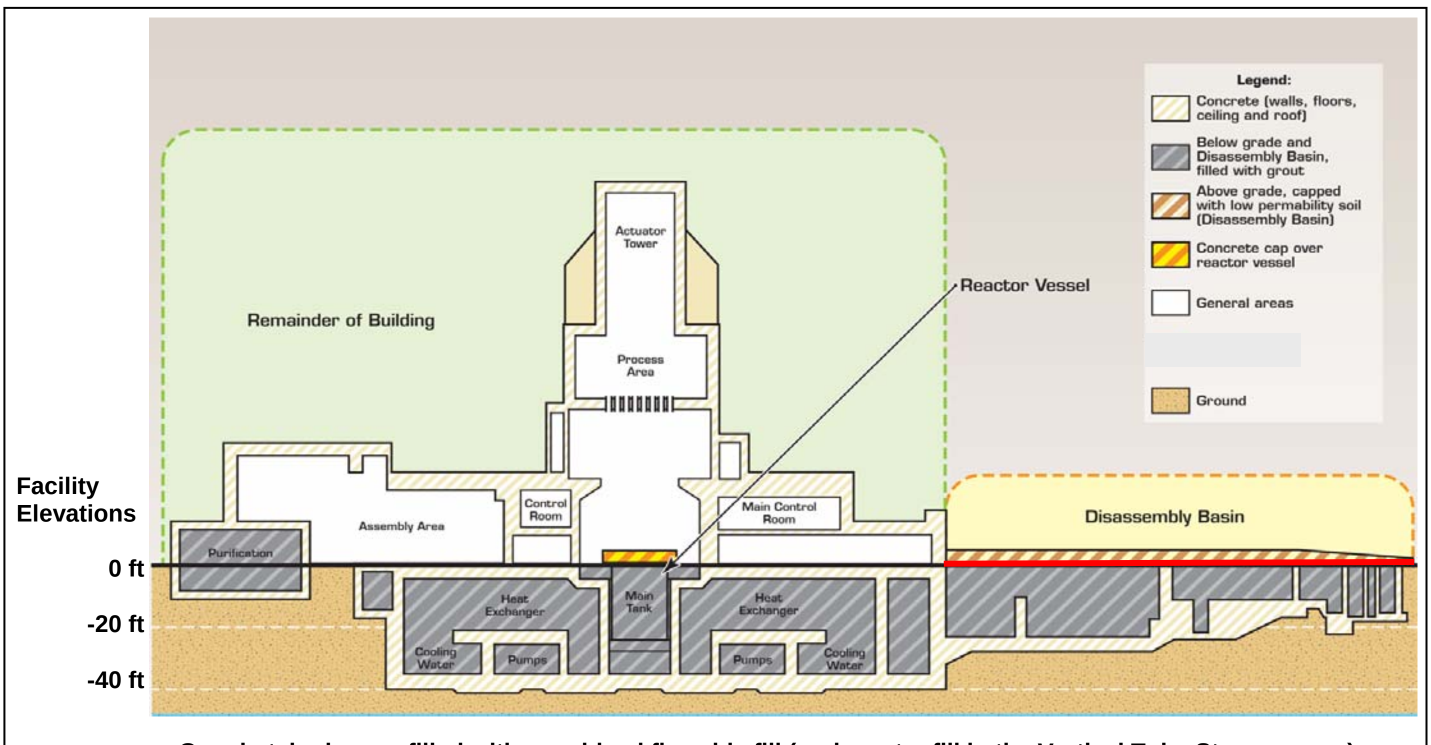


FIGURE 2. CROSS-SECTION THROUGH 105-P (105-R) REACTOR BUILDING BEFORE ISD.



- **Gray hatched areas filled with zero bleed flowable fill (underwater fill in the Vertical Tube Storage area.)**
- **Yellow/orange hatched area filled with shrinkage-compensating capping concrete containing an integral waterproofing admixture.**

FIGURE 3. CROSS-SECTION THROUGH 105-P (105-R) REACTOR BUILDING AFTER ISD

The approach for developing the grout placement strategy for the R Reactor Disassembly Basin was to:

- assemble a team of on-site personnel with the appropriate skill mix;
- develop a CAD model and rapid prototype model of the basin to facilitate visualization of the facility and proposed work activities;
- group areas within the disassembly basin according to relevant conditions and stabilization needs;
- identify stabilization material requirements for the various areas in the disassembly basin;
- develop cementitious fill formulations that meet both the ISD requirements and construction needs;
- test the cementitious materials to confirm material requirements are met;
- identify construction verification activities to confirm material placement; and
- support procurement of fill materials for the R Reactor disassembly basin and for the R Reactor ISD.

105-R REACTOR DISASSEMBLY BASIN DESCRIPTION

The 105-R Reactor Disassembly Basin comprises thirteen major, distinct areas listed below and shown at Figure 4.

1. Maintenance Bay Pit & Sump
2. Seismic Gap
3. D&E Utility Chase & Canal
4. Isolation Tank
5. Deep Wells (3; submerged within Machine Basins)
6. Vertical Tube Storage (VTS)
7. Machine Basins (3)
8. Monitor Pin Basin
9. Dry Cave
10. Horizontal Tube Storage (HTS)
11. Transfer Pit
12. Maintenance Bay (remaining portion)
13. Emergency Basin (currently filled with soil and capped with concrete)

Figure 4 provides the general locations for the designated areas. Depths in the disassembly basin range from 51.3 ft (15.6 m) to 5 ft (1.5 m). Approximately 42 inches (107 cm) of water remain in the VTS, HTS, Isolation Tank, Machine Basins, and Transfer Canals to provide shielding for irradiated metal debris which will be left in the basin. The Emergency Basin Area was previously filled with clay and backfill and capped with concrete. Backfill settlement underneath the concrete slab requires grouting to occupy the void.

A 3-D CAD model and rapid prototype model of the entire the 105-R Reactor Disassembly Basin were completed to facilitate the grouting phase of this project (Ref 4). These models were crucial in developing and visualizing the overall grout placement strategy and grout delivery system configuration.

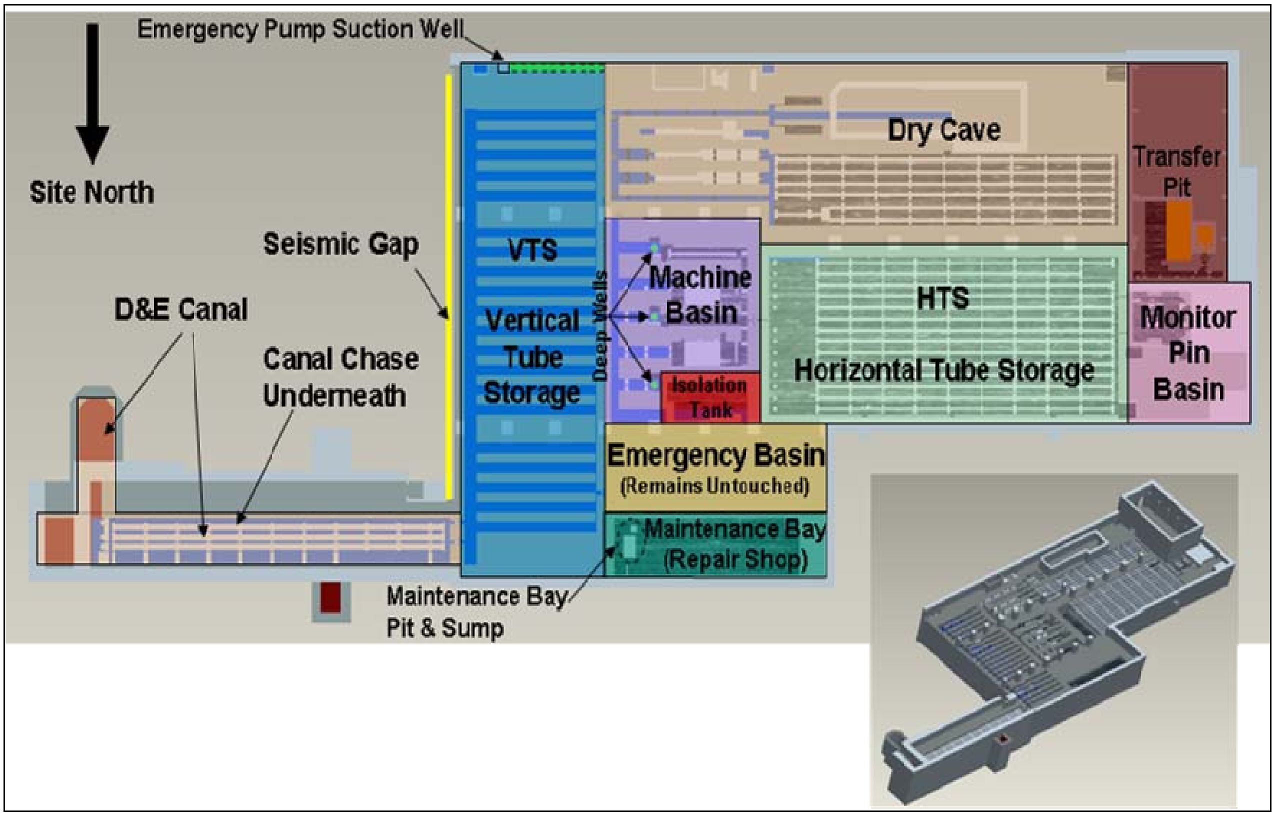


FIGURE 4. 105-R REACTOR DISASSEMBLY BASIN AREAS.

105-R REACTOR DISASSEMBLY BASIN ISD IMPLEMENTATION PLAN

Implementation of the ISD for the reactor disassembly basin consists of several work stages. The numerous areas within the basin were grouped according to current conditions and fill material placement requirements. Details of the R Reactor Disassembly Basin closure strategy are provided elsewhere (Ref 3). This overview focuses on the first five physical stabilization stages identified below in sequential order:

- stabilization of dry areas that are free of obstructions and relatively easily accessed;
- stabilization of wet contaminated areas (where water is used for shielding) using underwater flowable grout in 5 ft (1.5 m) lifts;
- collection of displaced water and transfer for evaporative processing;
- stabilization of remaining dry areas containing obstructions or that are more difficult to access; and
- placement of final cap over disassembly basin following removal of above grade structure.

R REACTOR DISASSEMBLY BASIN FILL MATERIALS

Cementitious fill (grout) is used to stabilize the disassembly basin. The fill material requirements for the 105-R Reactor Disassembly Basin decommissioning activities include: 1) providing a radiological shielding layer over irradiated debris and sludge; 2) filling void volume to provide physical stabilization of the below-grade space for the ISD; and 3) providing a durable non radioactive surface for the superstructure demolition (Ref 3). In general, the grout fill materials must be:

- flowable;
- self-consolidating and self-leveling;
- minimally prone to segregation / settling / phase separation;
- competent at >50 psi (0.3 MPa) unconfined compressive strength (support 50 psi [0.3 MPa] overburden).

A series of tests was identified to measure properties related to the desired characteristics of the R Reactor grouts. The test methods and screening test criteria (listed at Table 1) focus on identifying the fresh and cured properties of grout materials. Flow and set times are key for placement along with material heat of hydration to ensure proper curing. Compressive strength is the key material characteristic to ensure material stability and longevity. A shrinkage-compensating 3000 psi (20.7 MPa) concrete containing an integral water proofing admixture has been specified for the cap.

Laboratory testing was conducted to formulate grout mixes that are flowable, pumpable, self-leveling, and have low heat of hydration characteristics to support mass grout placement. The resultant grout mixes are similar to the consolidated low strength material (CLSM) typically used for non-structural geotechnical fill. More than 95 volume percent of the basin will be filled with “bulk fill” mixes. An underwater mix will be used to cover irradiated scrap metal that will be left in certain areas of the basin; this fill material will provide shielding while the 42 inches (107 cm) of water currently covering the scrap are displaced upward and then evaporated.

TABLE 1. TEST METHODS AND SCREENING CRITERIA FOR R REACTOR STRUCTURAL FILL MATERIALS.

Property	Test Methods	Screening Criteria	Basis
Flow	ASTM D 6103	>10 inches	Placement*
Slump-Flow	ASTM C 1611	24 ± 4 inches	Placement*
Underwater Slump-Flow	ASTM C 1611	18 ± 4 inches	Placement*
Bleed Water (segregation)	ASTM C 232	0 after 24 hours	Placement,* Uniform Material
Set Time	ASTM C 403	<24 hours	
Compressive Strength 7 days	ASTM D 4832	>50 psi	Self-supporting
Saturated Hydraulic Conductivity	ASTM D 5084	< 1E-06 cm/sec	Less than clay
Temperature Rise	SRS Adiabatic Calculations	<35°C**	Suitable for Mass Placement
Air Content	ASTM C 231	<8 volume %	Quality control
Unit Weight	ASTM C 138	> 80 lbs / cu ft	> water
Yield	ASTM C 138	1 ± 0.1	Balanced mix

* Minimize labor involved with placement
** Semi-adiabatic

FILL PLACEMENT STRATEGY AND DELIVERY SYSTEM CONFIGURATION

The structural fill (grout) for the R disassembly basin was procured from a nearby ready-mix plant about 40 minutes from R Area. A batch plant has been constructed in P Area to provide grout for the majority of the remaining fill requirements for both reactor buildings. Construction of an onsite plant reduces transportation costs, increases flexibility to modify grout mix designs, and reduces the potential for delays between initial mixing and placement. A delivery system consisting of several trunk lines, four-inch slick lines, configured to a series of valves and branch lines will be used for the bulk of the placements. Two-inch lines will be used to fill a few of the small areas.

Only the grout trunk-slick lines for the areas being filled will be charged with grout at any one time. The remaining lines will be isolated and capped until needed. The lift height is limited to 5 ft (1.5 m) in order to not overload walls and less robust barriers between areas. The set time of the fill material will be adjusted to meet the work schedule which in some cases may require daily 5 ft (1.5 m) lifts in certain parts of the basin.

Structural engineering analyses for several key areas were performed for the R Disassembly Basin ISD and revealed some areas of structural deterioration of floor areas resulting in restrictive floor loads, unsupported base for the D&E canal floor requiring initial filling of the underlying chase, and gates in the canal that would not support lateral loading from a 5 ft (1.5 m) lift.

The grout filled disassembly basin will provide the heavy equipment working platform to initiate demolition of the above ground structure over the disassembly basin. At the conclusion of the above ground structure demolition, a concrete cap will be installed over the grout-filled disassembly basin and this will serve as the final ISD project configuration for the 105-R Reactor Disassembly Basin.

REACTOR VESSEL STABILIZATION

Reactor vessel stabilization is a critical element of the ISD strategy. The compatibility of grout materials and internal reactor components was evaluated to identify and eliminate possible adverse conditions during filling operations. The potential for hydrogen generation during grout placement was evaluated in several areas of the P and R Reactors because of the use of aluminum components in the reactor vessel (Ref 5). The focus was on the rate at which aluminum alloys react with corrosive high pH Portland cement based grout (pH > 12-12.5) to produce hydrogen gas, thereby creating a potential hazardous deflagration/explosion condition. The evaluation results for the R Disassembly basin concluded that:

> *"The risk of accumulation of a flammable mixture of hydrogen above the surface of the water during placement of grout-CLSM into the R-Basin VTS disassembly area is very low. Conservative calculations estimate that there is insufficient aluminum present in the basin VTS area to result in significant hydrogen evolution."*

Comparable results were derived for the P Reactor Disassembly Basin and the R Reactor Vessel. Nevertheless, the following recommendations were provided to further minimize the potential for hydrogen evolution.

- Minimize the initial temperature of the water and grout-CLSM as much as practical. Lower temperatures will mean lower hydrogen generation rates.
- Ventilate the building above the basin rim as much as practical (e.g., leave doors open) to further disperse hydrogen.
- As much as possible, minimize interruptions to the grout-CLSM placement process. Interruptions will result in higher water temperatures and hence higher hydrogen evolution rates.

The analysis reached a different conclusion for the P Reactor vessel where aluminum alloy Universal Sleeve Housings remain in place and significantly increase the surface area of aluminum exposed to corrosion relative to R Reactor. Conservative calculations indicated that there was potential for explosive levels of hydrogen to accumulate such that the condition would be difficult to mitigate using the recommendations noted above. The rate of hydrogen generation is demonstrated to increase as both temperature and grout pH increase (Ref 5).

Developing a grouting strategy for the P Reactor vessel was further complicated by the limited access to the interior of the vessel and the enclosed positioning of the vessel which limits air flow and heat dissipation. Current efforts are focused on developing a strategy that includes a grout formulation that is compatible with the contained materials while ensuring that the grout can be delivered to the vessel in a manner that minimizes the potential for delivery system maintenance which would result in additional worker exposure.

The search for a grout formulation with a lower pH (<10.5) began with Ceramicrete, a magnesium potassium phosphate grout formulation developed by Argonne National Laboratory (ANL). Initial testing of the original formulations revealed that the formulation had good placement properties and compressive strengths, but the reaction rates for the cementitious components were slow and the temperatures rose to a point approaching the upper limit for the reactor vessel application (Ref 6). Currently, alternative formulations of the circum-neutral pH magnesium phosphate and a calcium aluminate grout formulation are being tested for application to the reactor vessel stabilization. Scale-up testing of the formulations is focused on addressing the following issues:

- extending the grout working time;
- material flowability between and around obstacles;
- reduced chemical reaction temperature rise; and
- grout delivery configurations that support engineering, operations and safety requirements.

SUMMARY

Closure of SRS's P and R Reactors using the ISD strategy presents unique challenges relative to the development and delivery of grout formulations to meet project specific needs. The primary requirement is to develop grout formulations that can be pumped in large volumes, over long distances, to remote areas. To achieve this objective, conventional concrete mixing and delivery techniques must be modified. Additionally, because of the very large grout volumes involved, it is essential that commercial vendors be able to obtain, mix, and deliver grout mixes that satisfy these technical criteria.

Key issues addressed by the grout formulation and placement plans included:

- adequate flowability to allow pumping to remote placement locations;
- self-leveling properties;
- incorporation of additives to balance the need for set times required for project execution while managing the heat of hydration to minimize cracking in the pour;
- appropriate pumping pressures to prevent separation of grout components;
- compatibility between grout formulations and the materials to be encapsulated and isolated; and
- radiological influence on fresh and cured grout properties

A complete understanding of the physical configuration of the facility is critical to the successful completion of ISD projects. Where the ISD strategy involves placing large volumes of grout into complex facilities, the entire sequence, transit route, delivery mechanisms, and ultimate final condition of grout inside the facility must be well characterized. Safe and successful project execution demands a team that can manage the many diverse elements of ISD implementation; it is essential that the individual ISD strategy elements be identified and the project team assembled at the outset of ISD implementation.

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