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Assessment of the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility Vault Concrete Data

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EXECUTIVE SUMMARY

The Idaho National Laboratory has constructed a low-level waste (LLW) disposal facility to receive remote-handled (RH) LLW, defined as LLW having greater than 200 R/hour on contact with the container, generated onsite or currently in storage onsite. The disposal facility is constructed as a series of reinforced concrete vertical vaults composed of a hexagonal base section with an integral cylindrical riser (i.e., pipe), upper riser section, and hexagonal plug. The vaults are arranged in four vault arrays to receive RH-LLW generated on-site at the Advanced Test Reactor Complex, the Naval Reactors Facility, and Materials and Fuels Complex. The facility will be operated in compliance with the requirements of U.S. Department of Energy (DOE) Order 435.1, "Radioactive Waste Management".

The performance assessment for the RH-LLW Disposal Facility is required to demonstrate the facility design will meet the performance objectives established for long-term protection of the public and environment following closure of the facility as outlined in DOE Order 435.1. Protectiveness of the facility in terms of the groundwater pathway is a function of the design features that control hydrologic and geochemical conditions within and below the vault system. The performance assessment's groundwater pathway model credits protection of the steel waste liners provided by interlocking reinforced concrete waste vaults, strength and stability of a final engineered cover that will be placed over the vaults when the facility is closed, and accounts for a cement-impacted geochemical environment within and below the vault system to inhibit corrosion of stainless steel waste containers (i.e., waste liners). To ensure the quality and performance of the concrete vault system, a thorough quality design and review process was implemented.

This document provides a summary of the concrete performance data collected during vault fabrication and installation. It also includes the process by which quality data were collected during vault fabrication and installation, inspection requirements, and a summary of resulting test data with the potential to impact vault system durability.

In addition, this report includes quantitative data collected on cured concrete samples poured for random concrete batches throughout the concrete component fabrication process. Quantitative data includes total porosity, bulk density, absorption, effective porosity, and gas-phase permeability. Chloride diffusivity data collected during the concrete mix selection process are also included for completeness.

Data show that the vault quality assurance program resulted in fabrication and installation of components with insignificant defects and damaged areas. Data collected on the cured concrete samples show gas-phase permeability and effective porosity are slightly higher than data used to select concrete mix designs. These differences are evaluated in the PA (DOE-ID 2017).

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ACRONYMS

ACI	American Concrete Institute
API	American Petroleum Institute
ASR	alkali-silica reaction
ASTM	American Society of Testing and Materials
BEA	Battelle Energy Alliance
CAR	corrective action report
CVAS	cask-to-vault adapting structure
DOE	U.S. Department of Energy
DOE-ID	U.S. Department of Energy Idaho Operations Office
FTC	facility transport container
HFEF	Hot Fuel Examination Facility
INL	Idaho National Laboratory
LCC	large concept cask
LLW	low-level waste
MFTC	modified facility transport container
NCR	nonconformance report
PA	performance assessment
RH	remote-handled
SNR	supplier nonconformance report
TFR	technical and functional requirements

Assessment of the Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility Vault Concrete Data

1. BACKGROUND

A performance assessment (PA) for the Idaho National Laboratory (INL) Remote-Handled Low-Level Waste (RH-LLW) disposal facility is required to demonstrate the facility design will meet the performance objectives established for long-term protection of the public and environment following closure of the facility as outlined in DOE Order 435.1, "Radioactive Waste Management." Protectiveness of the facility in terms of the groundwater pathway is a function of the design features that control hydrologic and geochemical conditions within and below the vault system. The PA groundwater pathway model credits protection of the steel waste liners provided by interlocking reinforced concrete waste vaults, the strength and stability of a final engineered cover that will be placed over the vaults when the facility is closed, and accounts for a cement-impacted geochemical environment within and below the vault system to inhibit corrosion of stainless steel waste containers (i.e., waste liners). To ensure the quality and performance of the concrete vault system, a thorough quality design and review process was implemented.

This document provides an overview of the vault concrete-related design process, quality review process, test data, and quality review results.

2. VAULT COMPONENT FABRICATION AND INSTALLATION QUALITY ASSURANCE PROCESS

The RH-LLW Disposal Facility vault system (see SDD-410, "System Design Description for the Remote-Handled Low-Level Waste Disposal Vault System") was fabricated using the following design-build process:

1. The vault system installed at the RH-LLW Disposal Facility was designed and built according to the "Technical and Functional Requirements (TFRs) for the Remote-Handled Low-Level Waste Disposal Project" (TFR-483 2015) and the "Design-Build-Operate Performance Specification for the Remote-Handled Low-Level Waste Disposal Project" (for vault-specific requirements, see Section H of SPC-1437 2012). These documents provide technical requirements for the vault system in terms of functional capability. Functional requirements were specified based on assumptions made in the PA (DOE-ID 2012). Bids for the RH-LLW Disposal Facility project were solicited, reviewed, and the most acceptable bid was accepted.
2. A vault system design was then developed by AREVA and documented in the following:
   - INL Drawings:
     - 788644, Site Layout Plan, Revision 1
     - 788645, 55-Ton Cask Vault Array, Revision 1
     - 788648, NUPAC 14 210L Cask Vault Array, Revision 1
     - 788651, HFEF-5 Cask and Large Concept Cask Vault Arrays, Revision 1
     - 788652, HFEF-5 Cask and Large Concept Cask Vaults, Revision 2
     - 788654, Modified FTC Cask Vault Array, Revision 1
     - 788655, Modified FTC Cask Vaults, Revision 2
     - 788657, Performance Assessment Vault Array, Revision 1
     - 788658, Installation Section and Detail, Revision 2

    - 788766, Excavation Plan, Revision 1
    - 788767, Excavation Sections, Revision 1
    - 788768, Grading Plan – Vault Yard, Revision 1
    - 788769, Vault Yard Sections, Revision 0
    - 788770, Vault Yard Section, Revision 1
  - *Vault System Structural Design* (ECAR-2810)
  - *Vault Concrete Mix Design Report* (PLN-4953).
3. The concrete design mix was submitted for testing by AREVA according to the following test plans:
   - *Vault Concrete Durability Test Plan* (PLN-4989)
   - *Vault Compliance Test Plan* (PLN-4956)

   and documented in the following:
   - *Vault Concrete Safety-Related Design Parameters* (PLN-4954)
   - *Vault Concrete Selection Report* (PLN-4952).

   Concrete test results were input into a concrete transport model for analysis conducted by Battelle Energy Alliance (BEA) (BEA is the prime contractor at the DOE-ID site) PA Development Team (i.e., Annette L. Schafer and A. Jeff Sondrup). This analysis was conducted to evaluate the total vault system's hydraulic performance and potential for concrete vaults to meet a 500-year period of performance. The analysis is documented as the *Vault Hydraulic and Concrete Performance Analysis* (which is an appendix in the PA).
4. The vault system design, test results, and performance analysis were all reviewed by BEA, DOE, DOE's technical reviewers, and the DOE LLW Disposal Facility Federal Review Group, who determined the vault system would be able to meet the 50-year operational requirements for concrete density and strength and to provide reasonable expectations of being able to meet a 500-year vault system structural performance period as assumed in the PA.
5. Vault quality inspection test plans were then developed for use during vault component fabrication and vault system installation. These plans are documented in the following:
   - *Vault Component and Cask-To-Vault Adapting Structures (CVAS) Fabrication Quality Inspection Plan* (PLN-5077)
   - *Vault Component and Cask-To-Vault Adapting Structures (CVAS) Fabrication Quality Inspection/Test Plan* (PLN-5460, superseded PLN-5077)
   - *Vault Array Field Inspection, Sampling, and Testing Procedure* (VDR-536953 2017).
6. The vaults were then fabricated according to the requirements of *Construction Specification – Vault and Cask-to-vault Adapting Structure Fabrication for the RH LLW Disposal Project* (SPC-1857). As vault components were being fabricated, the following occurred:
   - Concrete used during fabrication was submitted for testing and subsequent analysis by the BEA PA development team
   - Fabricated vault components were inspected for defects and/or damage using the PLN-5077 or PLN-5460 inspection test plan. Defects and damage were reported by the precast concrete contractor (i.e., Oldcastle) to AREVA on a corrective action report (CAR); the CAR was evaluated by the engineer-of-record; and a supplier nonconformance report (SNR), which included the technical justification for proposed corrective actions, was submitted to BEA for final disposition approval.

- Components were either accepted as use-as-is, repaired using an approved repair procedure and transported to the disposal facility location, or they were rejected based on the BEA review of the SNR.

7. Prior to and during installation at the RH-LLW Disposal Facility location, vault components were again re-inspected according to requirements in *Vault Array Field Inspection, Sampling, and Testing Procedure* (VDR-536953 2017). This inspection plan provides defect and damage limits that are consistent with those in PLN-5077 and PLN-5460.
   - If Level 2 or Level 3 damage occurred during transport (according to the criteria documented in SPC-1857), the components were evaluated using a process similar to that used during vault fabrication as follows:
     - Damage was recorded by submitting a non-conformance report (NCR) or an SNR, including the technical evaluation for proposed corrective actions it was submitted by AREVA engineering to BEA for final disposition approval.
     - If necessary, repairs using the approved repair procedure were made and a final inspection was performed to ensure the repairs were successful.

3. VAULT PERFORMANCE REQUIREMENTS AND CONCRETE MIX DESIGN

3.1 Concrete Technical and Functional Requirements

Early in the design process, it was determined that two concrete mix designs would meet the TFRs established to provide reasonable expectations of the vault system being able to meet a 500-year period of structural stability (SPC-1437). The TFRs for the vaults are as follows:

1. SPC-1437 H.1.C.1: Vaults shall be designed to be top-loading, reinforced, precast concrete cylinders with structurally supportive bases and a removable plug for top access and shielding. Unless specifically required, component sizes and thicknesses shall be based on the strength required to meet static and dynamic loading criteria during the disposal operation (Section H.1.K), dynamic and static loads imposed during operations on the interim soil cover (Section H.1.L.2), and static load of the engineered cover after facility closure (Section H.1.K.3).

2. SPC-1437 H.1.C.2: Vaults shall be precast concrete with a minimum 28-day compressive strength of 5,000 pounds per square inch (psi). Reinforcement shall be uncoated carbon steel.

3. SPC-1437 H.1.C.3: Material used in vault construction shall not adversely impact corrosion of stainless steel, Zircaloy, Inconel, carbon steel, or aluminum and shall not decrease the sorption capacity of resins beyond the range considered in the facility PA.

4. SPC-1437 H.1.C.5: Cement specifications shall consider the standards for resistance to degradation as specified by Annex 5 of the AMERICAN Society of Testing and Materials (ASTM) C1562-10, “Standard Guide for Evaluation of Materials Used in Extended Service of Interim Spent Nuclear Fuel Dry Storage,” specifically, the following:
   - ASTM C1562: Cement shall meet standards for freeze-thaw protection (A5.4.2), leaching of calcium hydroxide (A5.4.3), aggressive chemicals (A5.4.4), reactions with aggregates (A5.4.5), corrosion of embedded steel (A5.4.6), elevated temperatures (A5.4.7), irradiation (A5.4.8), creep (A5.4.9), shrinkage(A5.4.10), and managing aging-related degradation effects (A5.4.11).
   - Concrete mix design should meet the requirements of American Concrete Institute (ACI) 318-08, Table 4.2.1 for the following exposure classes:

- Freezing and thawing Class F2; air content should be determined in accordance with Table 4.3.1 of ACI 318-08
- Sulfate Class S2 (total sulfate in soil is in the range 22 to 87 mg/kg, corresponding water soluble sulfate (SO_4) is 200 ppm)
- Low permeability Class P1
- Corrosion protection of reinforcement Class C2.

In determining the mix designs, ACI 318-11 was used for concrete mix design because it was the latest code adopted by STD-139, superseding ACI 318-08, and referenced in SPC-1437.

5. SPC-1437 H.1.C.6: Aggregates, including rock, pozzolans, fly ash, and slag, shall be selected to minimize alkali-aggregate reaction (which includes alkali-carbonate reaction and alkali-silica reaction [ASR]) using the guidance provided in ACI 201.2R.
6. SPC-1437 H.1.C.7: All materials used in the vault system, including materials placed beneath and between individual vaults and between the steel liner and concrete vault to reduce the void space, shall withstand the expected radiolytic dose ranges provided in the facility PA without degrading during the first 500 years and shall not be degraded during the first 500 years via chemical or biological means. Degradation in this context refers to creation of additional void space in the concrete that would increase the concrete porosity and permeability. Examples of materials subject to radiolytic degradation include polymers, plastics, rubber, and so forth.
7. SPC-1437 H.1.C.8: All materials used in the vault system, including materials placed beneath and between individual vaults and between the steel liner and concrete vault to reduce the void space, shall not adversely impact the corrosion of stainless steel, Zircaloy, Inconel, carbon steel, or aluminum and shall not decrease the sorption capacity of resins, sub-base, and alluvium beneath the vaults beyond the range considered in the facility PA.

3.2 Concrete Mix Designs

Two mix designs selected for use (Mix #2 and Mix #3) are detailed in the *Vault Concrete Mix Design Report* (PLN-4953) and are shown in Figures 1 and 2. The mix design report includes the requirements for all additives, aggregates, cement, fly ash, entrained air, and water quality. The two mix designs differ only in inclusion of an air-entraining admixture in Mix #2 used to protect the vault shield plugs, cask-to-vault adapting structures (CVASs), and perimeter blocking from potential freeze-thaw damage (see Section 3.2). Components installed below the frost line include vault upper riser sections and bases. These components were fabricated using Mix #3, which did not include the air-entraining admixture. The two mix designs were selected in consideration of the TFRs (Section 3.1), applicable codes and standards (Section 3.3), and environmental conditions expected in and adjacent to the RH-LLW Disposal Facility vaults (Section 3.4).

3.2.1 Additives

Additives specified for Mix #2 and Mix #3 were certified to be compatible with TFRs for concrete and with all other admixtures, including the following:

- Air-entraining admixture: ASTM C260 certified by the manufacturer to be compatible with other required admixtures
- Chemical admixtures: Certified by the manufacturer to be compatible with other admixtures and to not contain calcium chloride or more than 0.15% chloride ions or other salts by weight of admixture:
  - Accelerating admixture: ASTM C 494, Type C
  - High-range water reducer: Conform to ASTM C 494, Type A or F

- Lithium/ASR inhibitor: ASTM C 494, Type S.

3.2.2 Aggregates

To ensure aggregates met the ASTM C33 specification, all aggregates were supplied by the specified supplier from the same pit location. The suppliers are Burns Concrete and Aggregate for the 3/4-in. course aggregate and Rhodehouse for the sand fine aggregate. These pits are both Idaho Transportation Department-approved pits, which helped ensure aggregate consistency and the aggregates met the following specifications:

- Normal-weight aggregates: ASTM C33 (except as modified by Precast Concrete Institute MNL 116), C.20 with maximum coarse aggregate size of 3/4-in.
- Source Bn-152-c (Burns Concrete) is located in Sec. 11, T. 1 N., R. 37 E., B.M., South of Idaho Falls, Idaho
- Source Jf-103-c (Rhodehouse Golden Valley Pit) is located in a portion of the SE, SW & SW, SE of Sec. 15, & NE, NW & NW, NE of Sec. 22 T. 4 N., R. 37 E., B.M., North of Idaho Falls, Idaho.

3.2.3 Cement

The cement (i.e., Type II with C3A less than 5%) was selected based on the most conservative requirements discussed in the *Vault Concrete Selection Repor*t (PLN-4952). A sulfate category S2 requires Type II cement with a C_3A less than 5%. The specified cement was supplied by Ashgrove and meets ASTM C150, Type II with C_3A less than 5% requirements.

3.2.4 Fly Ash Selection

Fly ash was used to help achieve low permeability and porosity in the concrete. It also provides increased resistance to ASR in concrete as discussed in *Vault Concrete Selection Report* (PLN-4952). To ensure consistent fly ash, Class F Bridger fly ash (supplied by Headwaters) was specified. The following requirements apply:

- ASTM C618, Class F, except loss on ignition shall be less than 2%
- Strength activity index at 28 days shall be at least 95% of the control
- Sum of SiO_2 plus Al_2O_3 plus Fe_2O_3 shall be greater than 77%.

3.2.5 Entrained Air

The air quantity in concrete Mix #2 has been selected based on the most conservative requirements of ACI 318. A freeze-thaw category F2 requires an air content of 6% ±1.5%. The air quantity was reduced by 1% for concrete with a 28-day compressive strength of 5,000 psi or greater as specified in SPC-1437.

3.2.6 Water

Water used in fabrication of the vault components was taken from a municipal water supply. The water/cement ratio was specified to be less than 0.38 (see Table 4 in the *Vault Concrete Selection Report*, PLN-4952).

Mix ID # :	Areva Mix Design #2	Date:	3-Feb-15
Required Strength:	5000 psi	Designed By:	M. Blackham
Job Name:	RHLLW Project	Concrete Class:	SCC

Initial Design:

Material	Source	Batch Weight (lbs)	S.G.	Unit Weight (lb/ft^3)	Batch Volume (ft^3)
Cement T-II	Ashgrove	575	3.15	196.56	2.925
F Fly ash	Bridger	165	2.36	147.26	1.120
Water	Potable(ADD)	281.0	1.00	62.40	4.503
Admixtures	BASF	20.5	1.00	62.40	0.329
Rock (3/4")	Burns	1322	2.63	164.11	8.055
Sand	Rhodehouse	1322	2.428	151.51	8.726
Air	(5%+-1.5%)	5%			1.350
	Batch Totals:	3685.50		136.46	27.0

Water/Cement Ratio:	0.380	Desired (Admixtures Neglected)
Rock/Aggregates:	50.0%	

Admixtures:

Product	Description	Dosage (oz.)	Dosage (oz/100 wgt)	
GLENIUM	Superplasticizer	32	5.57	**As Needed
Micro Air	Air	7	1.22	
NC534	Accelerator	44	7.65	**If/As needed
ASR 30	Lithium	245	1.91	Gallon per yard (Max Dosage)

Notes:

1. Aggregate gradations are done on a monthly* basis for SCC Concrete.
2. Aggregate weights in mix design are adjusted according to gradations for SCC Concrete.
3. Admixtures are adjusted based on concrete consistency for SCC Concrete.
4. Copies of batch reports and concrete testing are available for specific projects.

*NPCA requires gradations to be done on a monthly basis.

Figure 1. Concrete Mix Design #2 for use in vault shield plugs, CVASs, and perimeter blocking installed above the frost line.

Mix ID # : Areva Mix Design #3

Date: 3-Feb-15

Required Strength: 5000 psi

Designed By: M. Blackham

Job Name: RHLLW Project

Concrete Class: SCC

Initial Design:

Material	Source	Batch Weight (lbs)	S.G.	Unit Weight (lb/ft^3)	Batch Volume (ft^3)
Cement T-II	Ashgrove	580	3.15	196.56	2.951
F Fly ash	Bridger	160	2.36	147.26	1.086
Water	Potable(ADD)	274.0	1.00	62.40	4.391
Admixtures	BASF	20.6	1.00	62.40	0.330
Rock (3/4")	Burns	1385	2.63	164.11	8.439
Sand	Rhodehouse	1383	2.428	151.51	9.128
Air	No Air Spec.	3%			0.675
	Batch Totals:	3802.56		140.83	27.0

Water/Cement Ratio: 0.370 Desired (Admixtures Neglected)

Rock/Aggregates: 50.0%

Admixtures:

Product	Description	Dosage (oz.)	Dosage (oz/100 wgt)	
GLENIUM	Superplasticizer	40	6.90	**As Needed
NC534	Accelerator	44	7.59	**If/As needed
ASR 30	Lithium	245	1.91	Gallon per yard (Max Dosage)

Notes:

1. Aggregate gradations are done on a monthly* basis for SCC Concrete.
2. Aggregate weights in mix design are adjusted according to gradations for SCC Concrete.
3. Admixtures are adjusted based on concrete consistency for SCC Concrete.
4. Copies of batch reports and concrete testing are available for specific projects.

*NPCA requires gradations to be done on a monthly basis.

Figure 2. Concrete Mix Design #3 for use in vault bases and vault upper risers installed below the frost line.

3.3 Codes and Standards

The following codes and standards used in development of the concrete mix design were determined to be applicable based on standard building practices augmented to meet nuclear facility TFRs:

- "Guide to Durable Concrete" (ACI 201.2R-08, reapproved 2011) was used as a guide to specify the considerations and requirements for the concrete mix design provided in SPC-1437.
- "Building Code Requirements for Structural Concrete and Commentary" (ACI 318-11 2011) provides exposure categories for consideration in selecting concrete mix components for the vaults. In some cases, SPC-1437 provided more restrictive specifications than would have been used following the recommendations of ACI 318-11.
- "Code Requirements for Nuclear Safety-Related Concrete Structures and Commentary" (ACI 349-06) provides concrete design recommendations used in high-temperature environments. Other requirements of ACI 349 are very similar to those of ACI 318-11. As discussed in subsequent sections, the temperature environment in the vaults does not result in modifications to the limits specified in Table 1.

Table 1 summarizes the exposure categories specified by SPC-1437 and corresponding recommendations of ACI 318-11.

Table 1. Summary of the freeze/thaw, sulfate, and chloride exposure class parameters according to ACI 318-11 and bounding design mix requirements.

Exposure Class[1]	Maximum Water/Cement Ratio (w/cm)	Minimum Compressive Strength at 28-days (f'_c) (psi)	Additional Minimum Requirements	
F1	0.45	2,500	Air content per ACI 318-11, Table 4.4.1	NA
F2	0.45	4,500	Air content per ACI 318-11, Table 4.4.1	NA
S2	0.45	4,500	Cementitious materials[2] - Type V cement or Type II with C_3A (tricalcium aluminate) content less than 5%	Calcium chloride admixture not permitted
C2	0.40	5,000	Maximum water-soluble chloride ion (Cl) content in concrete by weight of cement for reinforced concrete = 0.15%	Related provisions of ACI 318-11

Most restrictive requirements:

Maximum water/cement ratio: 0.40
Minimum 28-day compressive strength: 5,000 psi
Cementitious materials: Type II cement with C_3A content less than 5%
Maximum chloride ion content: 0.15% by weight of cement

1. See Section 4 or ACI 318-11 for definitions of exposure classes
2. Type I or III cement can be used if C_3A content is less than 5% and 8%, respectively.

3.4 Environmental Conditions, Specified Exposure Design Limits, and Concrete Mix Design Parameters

Section 4 of the *Vault Concrete Selection Report* (PLN-4952) summarizes the environmental conditions expected at the RH-LLW disposal vault location and correlates them to the design limits specified in SPC-1437 and to the selected concrete mix parameters for the two selected concrete mix designs. The environmental conditions and concrete mix parameters related to performance requirements are discussed in the following subsections.

3.4.1 Physical Damage

Physical damage to the disposal vaults was most likely to occur during transportation or lifting and handling activities during construction or operations. Components suffering physical damage during transportation and construction were inspected and determined to be acceptable (i.e., use-as-is), rejected or repaired subject to requirements of the *Vault Compliance Test Plan* (PLN-4956) and *Construction Specification – Vault Fabrication for the RH LLW Disposal Project* (SPC-1857).

3.4.2 Generation of Explosive Gases

Material safety data sheets in the *Vault Concrete Mix Design Report* (PLN-4953) are provided for chemical admixtures as an indication of the chemical composition and associated hazards. All admixtures have National Fire Protection Association Hazard codes of 0 for fire and reactivity.

3.4.3 Thermal Degradation

Low-temperature (i.e., freeze-thaw) conditions and high-temperature effects (from radiolytic exposure) were considered in the design. The resistance of concrete vault components to freeze-thaw degradation was addressed through a combination of vault system design, which placed the vault base and riser sections below the frost line with the perimeter blocks, vault plugs, and CVASs above the frost line and through the use of an air-entraining admixture for the components placed above the frost line. According to ACI 318-11, the following four freeze-thaw exposure classes for concrete are defined:

- F0: Concrete not exposed to freezing-and-thawing cycles.
- F1: Concrete exposed to freezing-and-thawing cycles and occasional exposure to moisture.
- F2: Concrete exposed to freezing-and-thawing cycles and continuous contact with moisture.
- F3: Concrete exposed to freezing and thawing cycles, in continuous contact with moisture, and where exposure to deicing minerals is expected.

Using these definitions, the vault risers and bases are Class F0 and, in the absence of deicing minerals, the components above the frost line fall in the F2 class. The worst-case exposure conditions of Class F3 can be avoided during operations by not using deicing minerals near the vaults. Therefore, two concrete mix designs were specified, with Mix #2 containing an air-entraining admixture for use in components placed above the frost line and Mix #3 designated for components installed below the frost line. The requirements for concrete Classes F2 and F3 from ACI 318-11, Section 4.4.1 and Tables 4.3.1 and 4.4.1 are met by both concrete mix designs as indicated in Table 2.

Table 2. Thermal degradation requirements from ACI 318-11and measured batch test values.

Parameter	Concrete Mix #2 Values for Components above the Frost Line (Perimeter Pieces, CVAS, and Shielding Plugs)	Concrete Mix #3 Values for below Frost Line Components (Risers and Bases)	Test Values
Maximum water cement ratio (w/cm)	w/cm ≤ 0.38*	w/cm ≤ 0.38*	NA
Minimum 28-day compressive strength	5,000 psi	5,000 psi	>6,000 psi
Air content (3/4-in. maximum aggregate size)	5% ±1.5%	NA	5.8% for Mix 2 3.0% for Mix 3

*There are allowable tolerances on w/cm per the applicable standards referenced in *Vault Compliance Test Plan* (PLN-4956).

For high-temperature environments, ACI 349 places limits on the long-term temperature exposure of in-place concrete to 150°F. The limit is permitted to increase to 180°F if actual concrete compressive strengths are 115% of the specified 28-day compressive strength. Temperatures inside the storage vaults are expected to be slightly above the average soil temperature for INL, which is close to 55°F. The maximum short-term high temperature inside the vaults is about 85°F (DOE-ID 2012). The minimum strength from test results included in *Vault Concrete Safety-Related Design Parameters* (PLN-4954, Appendix A) from samples of design mixes was 6,520 psi, which is 130% of the specified 28-day design compressive strength.

3.4.4 Aggressive Chemicals (Sulfate Exposure)

Four sulfate exposure classes exist for concrete in ACI 318-11, which are determined by the percent mass of SO_4 in the soil and the dissolved SO_4 in the water (ppm) as shown in Table 3.

Table 3. Building code requirements for structural concrete (ACI 318-11) for exposure to sulfate.

Class	Water Soluble Sulfate (SO_4) in Soil (Percent by Mass)	Dissolved Sulfate (SO_4) in Water (ppm)
S0	SO_4< 0.1	SO_4<150
S1	0.1 ≤ SO_4≤0.2	150 ≤ SO_4<1,500
S2	0.2 ≤ SO_4≤2	1,500≤ SO_4≤10,000

SPC-1437 provided a range for total sulfate in soil equal to 22 to 87 mg/kg, with a maximum of 0.009%. Therefore, INL soils correspond to ACI Class S0. However, designing to ACI 318-11 Class S2 was required by SPC-1437, Section 3.2.2, even though it is not required based on the potential for exposure to sulfate in the soils. To provide additional chemical resistance, Type II concrete C_3A (i.e., tricalcium aluminate) concentrations less than 5% were specified for Mix #2 and Mix #3 concrete designs as recommended by ACI 318-11. The other concrete mix design requirements (i.e., water/cement ratio and 28-day compressive strength) for Class S2 are the same as those for Class F2.

SPC-1437 H.1.C.3: Material used in vault construction shall not adversely impact corrosion of stainless steel, Zircaloy, Inconel, carbon steel, or aluminum and shall not decrease the sorption capacity of resins beyond the range considered in the facility PA.

Table 4. RH-LLW site conditions, ACI 318-11 and SPC-1437 requirements, and concrete mix design values.

Requirement Description	Report Discussion (Section in PLN-4952)	Bounding Range of Conditions	SPC-1437 Bounding Parameters	ACI Bounding Parameters	Method of Substantiation	Concrete Mix Parameters
500-year structural stability	General	NA	500-year structural stability	None	Analysis using service life prediction software	See durability parameters listed below and in Table 5
Corrosion of waste containers and subsequent release of radionuclides	General	Concrete that has not been degraded has a high pH	No impact to corrosion of waste containers	None	Mix design documentation	All
Generation of explosive gases		Potential for explosion in vaults	No explosive gas generation	None	Material safety data sheets for admixtures and cement	Minimal volatile organic compounds in components
Freeze-thaw resistance	3.4.3	Vault plug, CVASs, and perimeter and end blocks above frost line for up to 50 years Other vault components below frost line	ACI 318 Class F2 for plugs, F0 for below grade vault components	For Class F2: w/cm ≤ 0.4 f'c≥4500 psi Air content per ACI Table 4.4.1	Ensure design mix for the vault plug complies with or is better than bounding parameters ACI 318 Exposure Class F2	w/cm ≤ 0.38 fc'≥ 5,000 psi air content 5% ±1.5%
Carbonation	4.9	Pore water chemistry Unsaturated concrete pores and voids	500-year structural stability	None	Concrete carbonation model	Permeability of concrete and surrounding environment
Leaching of calcium hydroxide (related to water flow)	3.4.9	Pore water chemistry Unsaturated concrete pores and voids	ACI 318 Exposure Class P1 ASTM A1562 Guidelines	For Class P1: w/cm ≤ 0.5 fc'≥4,000 psi	Ensure design mix complies with or is better than bounding parameters for ACI 318 Exposure Class P1	w/cm ≤ 0.38 fc'≥5,000 psi
Sulfate attack resistance	3.4.4	Total sulfate in soils 5 to 86 mg/kg (0.0005 to 0.0086% by mass) Equates to ACI 318 Exposure Class S0 for soil	ACI 318 Exposure Class S2	w/cm ≤ 0.45 fc'≥4,500 psi Type V cement or Type II cement with C_3A < 5%	Ensure design mix complies with or is better than bounding parameters for ACI 318 Exposure Class S2	w/cm ≤ 0.38 fc'≥5,000 psi Type V cement or Type II cement with C_3A < 5%
Reactions with aggregate	3.4.6		ASTM A1562 Guidelines	None in the reference ACI standards	Aggregate ASR potential testing	Design mix uses a durable aggregate, lithium admixture, and fly ash to eliminate the potential for ASR

Table 4. (continued).

Requirement Description	Report Discussion (Section in PLN-4952)	Bounding Range of Conditions	SPC-1437 Bounding Parameters	ACI Bounding Parameters	Method of Substantiation	Concrete Mix Parameters
Corrosion protection of reinforcing steel (water and chloride ingress)	3.4.5	RH-LLW site soil chloride range = 5 to 83 mg/kg (0.0005 to 0.0083% by mass) Equates to ACI 318 Exposure Class C1	ACI 318 Exposure Class P1 and C2	w/cm ≤ 0.4 fc'≥5,000 psi Maximum water-soluble chloride ion percent by weight of cement ≤ 0.15	Design mix complies with or is better than ACI bounding parameters	w/cm ≤ 0.38 fc'≥5,000 psi
Elevated temperatures	4.3	Temperature inside the disposal vaults slightly above soil temperatures (i.e., about 55ºF); likely short-term maximum less than 85˚F	ASTM A1562 Guidelines	ACI 349 E.4 requires that long-term temperature be limited to 150˚F.	Comparison of vault internal temperature to ACI 349 limit	None
Irradiation	3.4.12	60,000 R/hour maximum source term	ASTM A1562 Guidelines	None		Not directly applicable to the design mix
Creep	3.4.7	Ratio of design maximum compressive stress to design compressive strength = 0.48 for vault walls	ASTM A1562 Guidelines	None	No long-term creep cracking expected due to fairly low stress-to-strength ratio and the fact that the stresses are mainly compressive in nature	Not applicable to the design mix
Shrinkage	3.4.8	Drying conditions during curing	ASTM A1562 Guidelines	A typical shrinkage limit is 0.040%	Inspection for shrinkage cracks	w/cm ≤ 0.38
Managing aging-related effects	3.4.13	Site conditions	ASTM A1562 Guidelines	Not applicable	Restrict use of deicing salts or other deleterious chemicals during operations in the vicinity of the disposal vaults	Applicable to operations and maintenance

3.4.5 Exposure to Salts and Chemicals from Soil Water and Concrete (Chloride Exposure)

Exposure to chloride ions in solution will be mitigated during operations through restrictions on using deicing salts near the vaults. For unmitigated chloride exposure, ACI 318-11 defines the following three chloride exposure classes for concrete:

- C0 – Concrete dry or protected from moisture
- C1 – Concrete exposed to moisture, but not to external sources of chlorides
- C2 – Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources.

The American Geotechnics Report (American Geotechnics 2011) reports the pore water chloride mass concentration at the RH-LLW site to be 0.0083%. The pore water chloride concentration falls in the ACI 318-11 Class of C0. However, SPC-1437 specified the more stringent design criteria of C1. During most of the 500-year design life, the vaults will be covered with a final engineered cover that will further protect the vaults from excessive moisture.

ACI 318-11, Table 4.3.1 provides the Class C1 requirements reproduced in Table 5, which are met by the maximum w/cm ratio of 0.38 required for freeze/thaw protection and by the minimum 5,000-psi compressive strength specified in SPC-1437.

Table 5. Building code requirements for structural concrete (ACI 318-11) for exposure to chloride.

Requirement	Class C1	Class C2
Maximum water cement ratio (w/cm)	NA	0.40*
Minimum design 28-day compressive strength	2,500 psi	5,000 psi
Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement where the allowable water-soluble chloride ion content that is contributed from the ingredients (including water, aggregates, cementitious materials, and admixtures) is determined on the concrete mixture by ASTM C1218 at an age between 28 and 42 days	0.30%	0.15%

* Maximum w/cm ratio less than 0.38 was specified by both mix designs for freeze/thaw protection.

3.4.6 Reactions with Aggregates

Aggregate sources across eastern Idaho have been characterized in the report entitled, "Lithologic Characterization of Active ITD Aggregate Sources and Implications for Aggregate Quality" (Report RP-212 2014; prepared for the Idaho Transportation Department by the Idaho Geological Survey). The sources from which the aggregate were extracted are pit BN-155C and pit JF-103C as specified in the *Vault Concrete Mix Design Report* (PLN-4953).

The BN-152C pit from which the course aggregate was taken is about 2.5 miles south of the BN-155C pit just south of Idaho Falls. These pits are equal distances from the Snake River and are located along HW-91. The BN-155C pit is characterized in the RP-212 report as alluvium of Snake River glacial outwash with 65% quartzite, 10% rhyolite and dacite, 10% sandstone, and less than 1% obsidian. This mineralogy will be durable in concrete.

Fine aggregate came from the JF-103C pit, which is a volcanic lithic sand containing 15% quartzite, 40% rhyolite and dacite, 20% basalt and gabbro, with 25% chert, chalk, and obsidian. This aggregate is dominated by durable minerals and will contribute to durable concrete.

As determined in the RP-212 report and confirmed in concrete mix design trials for RH-LLW vault components, these aggregate sources are subject to ASR with concrete. To mitigate the ASR potential, the concrete mix designs for vault components shown in the *Vault Concrete Mix Design Report* (PLN-4953) (i.e., a low-alkali cement, a pozzolan [fly ash], and a lithium-based chemical admixture) were used as recommended by ACI 318-11. With these specific admixtures, the potential for ASR was reduced to 0.02% average length change as shown in Figure 3 (reproduced from Attachment 2 of the *Vault Concrete Selection Report*, PLN-4952).

3.4.7 Creep

Sustained stresses in the RH-LLW vaults are low relative to concrete design strength and are compressive in nature. The ratio of design maximum compressive stress to design compressive strength = 0.48 for the vault walls according the *Vault System Structural Design* (ECAR-2810). The maximum compressive stress includes stress from short-term or dynamic loading, which does not contribute to creep. Because of the fairly low sustained stress level and the mainly compressive nature of the stress, cracks due to creep are not expected.

3.4.8 Shrinkage

The design mix for the RH-LLW vaults has a low quantity of excess water (the design water cementitious ratio is 0.38); therefore, the vaults should not experience shrinkage cracking. Degradation (i.e., cracks) caused by curing shrinkage was observed and corrected in the acceptance inspection of the vault components as specified in the *Vault Compliance Test Plan* (PLN-4956).

ASH GROVE

Ash Grove Technical Center
11011 Cody Street, Suite 125
Overland Park, Kan. 66210
February 3, 2015 – Preliminary Report

Report No.: R19715
Work Order No.: WO-150006

SUBJECT

On January 7, 2015, a request for technical service was issued on behalf of Mike Blackham of Oldcastle Precast in Idaho Falls, Idaho. Mr. Stuart Malley requested that the Technical Center conduct C1567 with blends of the submitted aggregates along with lithium admixture and fly ash.

SAMPLE IDENTIFICATION

Sample No.	Sample Description	Date Received
S-140985	(1) 55-gal. drum of Ash Grove Durkee Type I/II/V cement, AGTC std. lot, Durkee, Oregon	05/22/2014
S-141541	(1) 5-gal. bucket of Bridger Class F fly ash (retain sample)	07/22/2014
S-142389	(1) 5-gal. bucket of Bridger Class F fly ash (originally mis-labeled as cement)	12/30/2014
S-142390	(2) 5-gal. buckets of Rhodehouse sand	12/30/2014
S-142392	(2) 5-gal. buckets of Burns 3/4" Rock	12/30/2014
S-142393	(1) 1-gal. paint can of MasterLife ASR 30 Lithium	12/30/2014

SUMMARY

The bucket of Bridger Class F fly ash (S-142389) was originally labeled as Durkee Type I/II/V cement. It was examined in powder mount and found to be fly ash. The composition was then confirmed to be Bridger fly ash by comparing an x-ray diffraction (XRD) and an x-ray fluorescence (XRF) analysis of the submitted sample to an XRD and XRF analysis of a retained sample of Bridger fly ash. A Durkee Type I/II/V standard lot was then used in the mixtures.

Mortar mixtures were proportioned according to a modified methodology. Mortar bars were cast, cured for two days, and then stored per ASTM C1260 in 1N NaOH solution at 80°C. Length change was recorded intermittently over the storage period. Mortar bar expansion results are plotted vs. age.

CONCLUSION

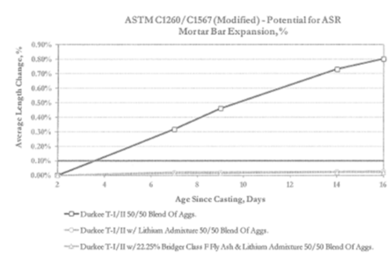
Both the addition of lithium (ASRx) and the lithium with the Bridger Class F fly ash (22.25%) mitigated the reaction to 0.03% and 0.02%, respectively.

TEST RESULTS

ASTM C1260 (Modified) - Potential Alkali Silica Reactivity of Aggregates, Mortar Bar Method
ASTM C1567 (Modified) - Potential Alkali Silica Reactivity of Cementitious-Aggregate Combinations

Mortar Proportions		Durkee T-I/II 50/50 Blend Of Aggs.	Durkee T-I/II w/ Lithium Admixture 50/50 Blend Of Aggs.	Durkee T-I/II w/22.25% Bridger Class F Fly Ash & Lithium Admixture 50/50 Blend Of Aggs.
Sample No.	Description	D-011415-01	D-011415-02	D-011415--03
S-140985	Durkee T-I/II	440 g	440 g	342.10 g
S-142389	Bridger Class F Fly Ash	-	-	97.90 g
S-142390	Rhodehouse Sand	495 g	495 g	495 g
S-142392	Burns 3/4" Rock	495 g	495 g	495 g
	NaOH		2.27 g	1.77 g
S-142393	ASRx Lithium Admixture		20.00 g	15.74 g
-	water	207 mL	191.0 mL	148.2 mL

Average Length Change, %:	Age, days	D-011415-01	D-011415-02	D-011415--03
	2	0.00%	0.00%	0.00%
	7	0.32%	0.02%	0.01%
	9	0.46%	0.02%	0.01%
	14	0.73%	0.03%	0.02%
	16	**0.80%**	**0.03%**	**0.02%**



R19715 2

Figure 3. Test results for ASR showing average length change versus curing time with and without fly ash and lithium added to the concrete mix designs.

3.4.9 Leaching of Calcium Hydroxide

Water passing through cracks, joints, pores, and voids in the cured concrete may slowly dissolve calcium compounds in concrete. Water can either migrate through the concrete via Darcy Flow, capillary imbibition, or by diffusion. The dominant mechanism is, in part, dictated by permeability of the cured concrete and by water availability, which is dictated by materials (i.e., backfill and gravel infill) surrounding the vault components. Saturation of the vault area components has been quantitatively assessed in the "Vault Hydraulic and Concrete Performance Analyses" provided in the revised PA (DOE-ID 2017). Based on materials selected for vault infill materials, the pore space adjacent to the concrete and within the concrete should be near residual moisture content (i.e., the moisture content should be less than 1%). This means that significant leaching is not expected to occur because significant quantities of water will not be adjacent to or available for imbibition into the concrete components.

3.4.10 Low Permeability Concrete

ACI 318-11 defines a P0 and P1 permeability exposure class. For exposure Class P0, there are no provided recommendations. The requirements for Class P1 from Table 4.3.1 in ACI 318-11 are as follows:

- Maximum water cement ratio (w/cm) = 0.50
- Minimum design 28-day compressive strength = 4,000 psi.

ACI 318-11 Class P1 concrete is required by SPC-1437 (Section 3.2.2). Based on test data during selection of the two concrete mix designs, gas-phase permeability was measured after 28 days of curing at 3.4×10^{-8} cm/sec (see Attachment 7 in the *Vault Concrete Selection Report*, PLN-4952). Gas-phase permeability is typically higher than permeability to water due to the Klinkenberg effect (Klinkenberg 1941) This effect is due to slip flow of gas at pore walls, which enhances gas flow when pore sizes are very small, resulting in gas permeability being larger than water permeability by several times to one order of magnitude. In addition, the permeability of concrete decreases with curing time, with the decrease larger for concrete containing fly ash. For this test value, the combined effect should reduce concrete permeability to within the 1×10^{-10} cm/sec range reported for mature good quality concrete (Thouvenot et al. 2013).

Quantitative permeability values for cured test cylinders collected during vault fabrication are provided in Section 5.2.

3.4.11 Carbonation and Corrosion of Reinforcing Materials

As discussed in the *Vault Concrete Selection Report* (PLN-4952), exposure conditions, primarily the pore-water saturation, have a significant effect on the depth of carbonation and the amount of CO_2 absorbed over time. In general, carbonation only occurs when water saturation is between 40 and 90%. If saturation is too low, then there is insufficient water in the pores for CO_2 to dissolve into to form the carbonic acid needed to react with the calcium compounds. If the saturation is too high, then the pore network is full of water and ingress of carbon dioxide is inhibited. When saturation is in a moderate range, conditions are ideal to promote a greater carbonation depth and a higher CO_2 absorption. As discussed in the *Assessment of Idaho National Laboratory Remote-Handled Low-Level Waste Disposal Facility Hydraulic Performance* (INL 2017), the hydraulic drainage system installed adjacent and between the vault arrays is expected to keep the moisture content below 1.5% (saturation less than 9%), except for very short (i.e., 1 to 2-day) time periods following extreme precipitation events. After installation of the final infiltration-reducing engineered cover, moisture content should be even lower adjacent to the vaults.

Normal carbonation results in a decrease of porosity, making the carbonated paste stronger. It increases both the compressive and tensile strength. Initially, the pH of pore water in the concrete should be in excess of 13. As carbonation occurs, depletion of calcium hydroxide will cause the concrete pore solution to drop below pH 13, with the pH reaching as low as 8 for fully carbonated concrete. As discussed in the PA (DOE-ID 2017), at a pH 13, corrosion of reinforcement is inhibited and it would take centuries for reinforcement in the vault components to corrode sufficiently to cause significant concrete cracking/degradation.

3.4.12 Irradiation

The maximum design-level radiation exposure level for the Naval Reactors Facility-activated metal vaults is provided in TFR-483 as: “The maximum unshielded dose rate of the waste that will be disposed of at the remote-handled LLW facility will be 60,000 R/hour.” The quantitative effects on concrete resulting from this exposure rate are evaluated in an Appendix to the PA entitled, "Vault Hydraulic and Concrete Performance Analyses" (DOE-ID 2017).

3.4.13 Managing Other Aging-Related Degradation Effects

The shield plugs are the only portions of the vaults that may be accessible for replacement or repair due to degradation. However, they are the portion of the vault system that is more likely to see an effect from exposure to atmosphere, freeze-thaw effects, salt exposure, or other environmental concerns. Restrictions will be placed on operations, prohibiting the use of deicers or similar products in the vicinity of the disposal vaults.

4. VAULT COMPONENT FABRICATION AND INSTALLATION QUALITY ASSURANCE

The vault component inspection process was established in Engineering Change Notice SPC-1857 (Engineering Change Notice #8) to the *Construction Specification -Vault and Cask-to-Vault Adapting Structure Fabrication for the RH-LLW Disposal Project* (SPC-1857). Inspection results for defects and damage to vault concrete components were evaluated by an independent inspection agency using forms provided in *Vault Component and Cask-To-Vault Adapting Structures (CVAS) Fabrication Quality Inspection/Test Plan* (PLN-4952 superseded by PLN-5460). Concrete units that did not comply with requirements of the design documents or were damaged were identified as nonconforming and a CAR or nonconformance report (NCR) was prepared (See Section 4.1 for criteria related to nonconforming requirements.). The CAR or NCR was evaluated by the engineer-of-record and an SNR that included technical justifications for proposed corrective actions was submitted to BEA for approval of the final disposition. Units not accepted for use-as-is or approved for repair were discarded and replaced. Repairs were permitted if structural adequacy, serviceability, and durability of units were not impaired.

4.1 Concrete Inspection Criteria for Defects and Damage

The independent inspection agency categorized all damage (i.e., chipping or spalling) and defects (i.e., cracks, bugholes, honeycombing, air bubble marks, or seam offsets) into one of three levels to determine the approved reporting path as follows:

- Level 1 – Acceptable defect/damage. No action is necessary unless additional criteria are noted.
- Level 2 – Minor defect/damage. These repairs may be performed by the fabricator using an approved procedure for repairs without requiring a nonconformance being written by the fabricator.
- Level 3 – Nonconforming defect/damage. These items require a CAR be prepared by the fabrication contractor. The CAR will be evaluated by the engineer-of-record and an SNR that includes technical justification for proposed corrective actions will be submitted to BEA for final disposition approval.

All cracks and repairs, regardless of level, were documented, and if a defect or damage was not addressed by the criteria given as follows, it was considered to be a Level 3 nonconforming defect/damage. Defects and damaged areas were evaluated according to the following from PLN-5460, which superseded earlier more restrictive reporting criteria contained in PLN-5077:

- Top edge (tongue base flat surface of bases and upper risers)
  - Chipping/spalling: unlimited length, ≤1-in. deep and ≤1-in. horizontal along the flat, and ≤1-in. vertical along the barrel. Level 1 no repair except to remove rough edges that will impede fit-up of the next component.
  - Chipping/spalling: unlimited length, ≤1/2-in. deep and ≤2-in. horizontal along the flat, and ≤2-in. vertical along the barrel. Level 1 no repair except to remove rough edges that will impede fit-up of the next component.

- Chipping/spalling: unlimited length, >1/2-in. but ≤1-in. deep and >1-in. but ≤2-in. horizontal, or >1-in. but ≤2-in.vertical along the barrel. Level 2 minor repair.
- Chipping/spalling: unlimited length, >1-in. deep or >2-in. horizontal along the flat, or >2-in. vertical along the barrel. Level 3 write CAR.
- Bubble marks: ≤1/2-in. deep. Level 1 no repair.
- Bubble marks: >1/2-in. deep, but ≤1-in. deep. Level 2 minor repair.
- Bubble marks: >1-in. deep. Level 3 write CAR.

• Top tongue of bases and upper risers
  - Unlimited length, ≤1-in. deep. Level 1 no repair, except to remove rough edges that will impede fit-up of the next component.
  - Unlimited length, >1-in. deep. Level 3 write CAR.

• Bottom edge of all components
  - Chipping/spalling: unlimited length, ≤1-in. deep and ≤1-in. horizontal along the flat, and ≤1-in. vertical along the barrel. Level 1 no repair, except to remove rough edges that will impede fit-up of the next component.
  - Chipping/spalling: unlimited length, ≤1/2-in. deep and ≤2-in. horizontal along the flat. and ≤2-inch vertical along the barrel. Level 1 no repair, except to remove rough edges that will impede fit-up of the next component.
  - Chipping/spalling: unlimited length, >1/2-in. but ≤1-in. deep, and >1-in. but ≤2-in. horizontal, or >1-in. but ≤2-in. vertical along the barrel. Level 2 minor repair.
  - Chipping/spalling: unlimited length, >1-in. deep or >2-in. horizontal along the flat, or >2-in. vertical along the barrel. Level 3 write CAR.

• Bugholes and bubble marks (all concrete components, excluding top edge and top tongue)
  - Single surface void ≤1/2-in. deep. Level 1 no repair.
  - Single surface void >1/2-in. deep but ≤1-in. deep. Level 2 minor repair.
  - Single surface void >1-in. deep. Level 3 write CAR.

• Honeycombing (all concrete components excluding top edge and top tongue) (defined as voids typically characterized by presence of aggregate)
  - Honeycombing with void depths ≤1/2-in. deep. Level 1 no repair.
  - Honeycombing with void depths >1/2-in. deep, but ≤1-in. deep. Level 2 minor repair.
  - Honeycombing with void depths >1-in. deep. Level 3 write CAR.

• Lift lug area (all concrete components)
  - Within a 6-in. radius from the center of the lift lug and ≤1/2-in. deep. Level 1 no repair.
  - Within a 6-in. radius from the center of the lift lug and >1/2-in. deep but ≤1-in. deep. Level 2 minor repair.
  - Within a 6-in. radius from the center of the lift lug and >1-in. deep. Level 3 write CAR.

• Cracks – general (all concrete components)
  - ≤0.01-in. width (unlimited length). Level 1 no repair; however, for visible cracks >0.005-in. width and ≤0.01-in. width mark ends of cracks and write date using a permanent marker.
  - Note: Visible cracks are cracks that are observed under normal lighting conditions without magnification and without adding solutions or other means to illuminate the crack. >0.01-in. width (any length). Level 3 write CAR.

• Cracks – spider (all concrete components)

  - Spider cracks (three or more visible cracks, all within 2 in. of each other at some point) 0.005-in. width (any length). Level 1 no repair; however, for visible spider cracks ≤0.005-in. in width mark the extent of the spider crack by circling the area and write date using a permanent marker.
  - Note: Visible cracks are cracks that are observed under normal lighting conditions without magnification and without adding solutions or other means to illuminate the crack.
  - Spider cracks (three or more visible cracks all within 2 in. of each other at some point) >0.005-in. width (any length). Level 3 write CAR.
- Plug edges
  - Unlimited length, ≤1-in. perpendicular from the edge and ≤1/2-in. deep. Level 1 no repair, except to remove rough edges.
  - Unlimited length, >1-in. but ≤1 1/2-in. perpendicular from the edge and >1/2-in. but ≤1-in. deep. Level 2 minor repair.
  - Unlimited length, >1 1/2-in. perpendicular from the edge or >1-in. deep. Level 3 write CAR.
- Hex base
  - If the base has a defect/damage that does not expose rebar or loose aggregate, repair is left to the discretion of the fabricator based on their quality assurance/quality control program. Level 1 no repair or Level 2 minor repair.
  - If the base has a defect/damage that exposes rebar or loose aggregate. Level 3 write CAR.
- Perimeter/end block or end wall edges
  - Unlimited length, ≤1 1/2-in. perpendicular from the edge and ≤1/2-in. deep. Level 1 no repair.
  - Unlimited length, ≤1 1/2-in. perpendicular from the edge and >1/2-in. deep, but ≤1-in. deep. Level 2 minor repair.
  - Unlimited length, >1 1/2-in. perpendicular from the edge or >1-in. deep. Level 3 write CAR.
- Vault barrel seams
  - Seam offset ≤1/4-in. Level 1 no repair, except rub or grind seams as needed to eliminate protrusions.
  - Seam offset >1/4-in. Level 3 write CAR.
- Drilled lift holes between partition voids on the facility transfer container (FTC or equivalent, MFTC) base and upper section vault components)
  - Chipping/spalling: a ≤6-in. radius from the center of the drilled lift hole (applies to both sides of the hole) and ≤1 1/8-in. total depth from both sides combined (i.e., minimum wall thickness of remaining concrete at any horizontal point in the hole is ≥3-in.). Level 1 no repair.
  - Chipping/spalling: apply the following criterial independently to both sides of the hole: >6-in., but ≤12-in. radius from the center of the drilled lift hole and ≤3/8-in. deep. Level 1 no repair.
  - Chipping/spalling: unlimited radius, ≥1 1/8-in. total depth from both sides combined (i.e., minimum wall thickness of remaining concrete at any horizontal point in the hole is <3-in.). Level 3 write CAR.
  - Chipping/spalling: Apply the following criterial independently to both sides of the hole: >6-in., but ≤12-in. radius from the center of the drilled lift hole and >3/8–in. deep. Level 3 write CAR.
  - Chipping/spalling: >12-in. radius from center of the drilled lift hole, any depth. Level 3 write CAR.

4.2 Justification for Acceptable Defects and Damaged Dimensions

Acceptable defects and damage dimensions were defined based on the vault component fabricator's experience and technical evaluation of the concrete longevity evaluated *Vault Hydraulic and Concrete Performance Analysis* (an appendix in the PA). This approach was taken because building codes and standards reviewed by the project were not developed to ensure the 500-year performance period specified by SPC-1437. The following justifications are provided for accepting the Level 1 defects without repair, repairing the Level 2 defects, and addressing the Level 3 defects as special cases:

- **Effect of Surface Defects and Damage on Concrete Longevity and Long-Term Structural Performance.** Surface defects are inherently common in concrete. Typical surface defects include bugholes, honeycombing, and bubble marks that are typically surface voids caused by air entrapped between the form and the concrete volume (but not within the concrete volume that is unable to escape during casting).
  - Level 1 criteria were established to identify minor defects or damaged areas occurring on the vault component concrete surfaces. Left unrepaired, these damaged areas are not expected to have a significant impact on concrete durability or structural performance of the vault components.
  - Level 2 criteria were established to identify repairable areas. Defects and damage falling into this criterion increases the potential of moisture penetration into the components. This moisture has the potential of freezing within the concrete matrix and causing further damage, has the potential of reaching and causing corrosion of steel reinforcement, or has potential of increasing other chemical degradation rates (i.e., carbonation). Thus, repairing defects and damage falling into this category was mandated in order to minimize the potential for moisture penetration. For surface defects, this assessment applies to damage such as bugholes, honeycombing, bubble marks, chipping, spalling, and damage in the lift lug area.

    For surface defect damage, the limiting dimension is the depth because it most directly affects the degree of moisture penetration into the concrete, shielding capability, and concrete longevity characteristics. For the allowable unrepaired loss of thickness due to Level 1 conditions, a thickness loss of 0.5-in. results in an 8.4% decrease in the 6-in. wall thickness of the vault upper riser or base components and a 0.84% decrease in plug thickness while maintaining a 2" thick cover over the reinforcement. This loss would have minimal impact to the radiation analysis provided ECAR-2747 and an acceptable loss to concrete durability. Repairs made for Level 2 conditions replaced the lost concrete, resulting in no decrease in shielding, strength, or concrete durability, or adverse conditions that affect vault fit-up, container fit, or vault alignment.

    The allowable repairable area for repairable bugholes, honeycombing, bubble marks, chipping, and spalling was initially defined in inspection criteria provided in PLN-5077, although the area of the defect is not limiting. The specified areal extents for allowable repairs corresponded to specifications in ACI 301, where surface defects larger than 1-1/2 in. wide are recommended to be repaired for an as-cast surface finish of SF-1.0 (which is the lowest surface criteria for exposed concrete surfaces).

    Level 3 criteria. Defects and damage exceeding the Level 2 criteria triggered a CAR. Repairs for Level 3 conditions were evaluated on a case-by-case basis. For the special case of damage occurring to the drilled lift holes in the MFTC bases and upper sections, the allowable spalling depth was defined in ECAR-3852, which determined the minimum required concrete thickness for lifting the components.

- **Effect of Cracks:** It is normal for concrete to have very small (e.g., hairline, microscopic, pattern, map, and crazing) cracking where the cracks are so small they typically cannot be seen without wetting the concrete surface. There are also more visible cracks that typically form as a result of thermal stresses occurring in the concrete during curing caused by the outside of the component curing at a faster rate than the inside. Curing cracks are more common in thicker components and were expected to be seen in higher numbers on the 5-ft thick vault plugs as opposed to the vault riser sections having 6-in thick vault walls. The following are taken from references related to this type of cracking:

  - ACI 224R states, "In general, microcracking that occurs before loading has little effect on the compressive strength of the concrete" and "surface cracking can appear as pattern cracking and results from a decrease in volume of the material near the surface or increase in volume below the surface."
  - The National Ready Mix Concrete Association has done research and has created publications talking about this type of cracking. One publication states the following, "Crazing cracks are sometimes referred to as shallow map or pattern cracking. They do not affect the structural integrity of concrete and rarely do they affect durability or wear resistance." These small hairline cracks are typically so small and have virtually no depth that to see them typically requires water or some other solution to be applied to the concrete. Per the National Ready Mix Concrete Association, this type of cracking does not affect the structural integrity of the concrete. These cracks are so small they cannot be accurately measured with common equipment.

  There are three primary reasons to be concerned with microcracking. The first is related to moisture infiltration that could impact long-term vault performance. The second is related to microcracking being a starting point for development of larger cracks (as stated in ACI 446.1R-91). The third reason is related to the potential for a reduction in compressive strength that could impact both short-term and long-term performance of the vault components.

  - Level 1 and 2 criteria.

    To establish the allowable crack width, a literature search was performed, resulting in a project-determined allowable crack width of 0.01 in. or less in the vault components. The justification for this is as follows and is based on the potential for cracks of this width to autogenously heal if located in a favorable environment:

    - Autogenous healing of concrete is reviewed by Neville (2002). Neville's literature review shows that autogenous healing of concrete is a function of carbon dioxide availability, chloride, water wetting cycles, and carbonation content of water.
    - Autogenous healing of concrete has also been shown to be a function of the local hydraulic gradient (Edvardson 1999). Under a hydraulic gradient of 15 m/m, a permissible crack width for autogenous healing ranges from 0.2 to 0.25 mm (0.008 to 0.01 in.) (see Table 2 Edvardson 1999).
    - The results of Edvardson are consistent with the American Water Works Association Standard C301-99 for pre-stressed concrete pipes, where "over non-pressurized zones of pipe, exterior cracks in mortar coating up to 0.01 in (0.25 mm) are acceptable without repair."
    - At the RH-LLW Disposal Facility, the chloride content of the water is in the non-aggressive range, water is close to saturated with respect to calcium, and the pore-environment should be minimally saturated, allowing the relative humidity to allow transport of carbon dioxide into the exterior concrete surfaces. Because of the drainage materials selected to be emplaced adjacent to and beneath the vault system, the local hydraulic gradient should be roughly 1 mm/1 mm (i.e., unit gradient conditions).

Therefore, given that the RH-LLW Disposal Facility subsurface environment has the potential to promote autogenous healing, a permissible crack width of 0.01 in. or less was applied for single cracks.

- Level 3 criteria. Crack widths exceeding 0.01 in. triggered a CAR. The presence of spider cracks, defined as three or more cracks >0.005-in. within a 2-in. area, triggers a CAR because of the propensity to develop larger cracks (as stated in ACI 446.1R-91, "Fracture Mechanics of Concrete").

- **Effect of Chipping, Spalling, and Other Damage to the Top Edges, Bottom Edges, Top Tongue, and Plug Edges.** Physical damage, typically occurring during removal of components from the forms or while moving components, can result in chipped areas, spalled areas, and abrasion damage to the lift lug area. Criteria were established to identify limits with respect to the following:

  - Level 1 criteria were defined to allow damage to edges of the upper riser section, base, and plug determined on the basis of not affecting shielding, structural, or environmental performance.
  - Level 2 criteria were defined to allow repairable damage with the following considerations:
    - Shielding: Impacts to environmental and shielding performance have been limited by specifying the depth of the repairable areas for the top edges and plugs.

      The repair material used is of lower density than concrete components. The effect on shielding for repairable areas was evaluated in consideration of the lower concrete density and the Level 2 defined allowable physical damage in ECAR-2747 not affect bulk shielding of the components. The dose rate on top of the shield plug is limited to 1 mrem/hour and the maximum calculated value in ECAR-2747 is 0.5 mrem/hour at the centerline of the shield plug, which is a factor of two below the limit. The proposed acceptable damage will not cause the dose rate limit to be exceeded.

      In the gap analysis, the gap between adjacent shield plugs is filled with pea gravel. The dose rate above the gap filled with pea gravel is 0.1 mrem/hour, which is a factor of 10 below the dose rate limit. The bulk shielding provided by the pea gravel is unaffected by minor damage to the various concrete components. Therefore, minor acceptable damage would have a negligible effect on the computed 0.1-mrem/hour dose rate. The proposed acceptable damage without repair will not cause the dose rate limit to be exceeded.
    - Structural Performance: The load bearing area with Level 2 repairable damage still allows vaults to meet design criteria during operations and with the final engineered cover, without the repairs having been performed. This allows not crediting the repaired area in the evaluation of structural performance impact.
    - Environmental Performance (Long-Term Durability): Impacts to environmental performance have been limited by specifying the depth of the repairable areas for the top edge of all components. Repairs for Level 2 conditions will replace the lost concrete with a slightly less dense repair material, resulting in an insignificant decrease in concrete durability. The distance between the concrete surface and reinforcement materials is larger on the vault top edges, bottom edges, and tongue areas than it is in the vault walls. The defined allowable repair thickness maintains a concrete-to-reinforcement-cover thickness in excess of 2.5-in. (i.e., higher than in the undamaged vault wall). Therefore, repaired damage to these areas will still leave concrete cover thicknesses comparable to that in the vault walls.
    - Vault Fitment and Container Fit-Up: Each of the damaged areas was independently evaluated to ensure a failed repair would not impact vault operations and disposal of waste containers.
  - Level 3 criteria. Spalling exceeding the Level 2 criteria triggered a CAR.

4.3 Concrete Repair Products

Concrete repair materials were used to meet the primary criteria specified in SPC-1437 for the vault component compressive strength and environmental durability and are as follows:

- Have a minimum compressive strength of 5,000 psi at 28 days, matching the requirements for concrete used in vault components. The Jet Set Complete Repair product used for all repairs has a 28-day compressive strength in excess of 6,000 psi, which exceeds the 5,000-psi design compressive strength of the vault mix design (see Table 6).
- To ensure long-term environmental durability of repaired areas, the repair material was selected on the basis of being comprised of low alkali cement and sand to ensure the repair materials did not degrade radiolytically. Bonding agents (i.e., acrylic polymer admixtures) were allowed to be used for minor repairs to increase the initial strength of the repair bond. However, bonding agents were not allowed to be used as an internal component to the repair material. Therefore, the repairs were made using two components as follows:
  - The Jet Set Complete Repair product used as the repair material is comprised of low alkali cement and sand (see Table 7).
  - The bonding agent, MasterEmaco 600, was used to provide early strength bonding of the repair material to the vault component cement (see Table 8). Bonding agents are used either in the repair grout mix or applied to the surfaces being repaired. These bonding agents are typically acrylic-polymers that could degrade over time.

    If the bonding agent had been mixed into the grout mix, the mixing proportions would have replaced roughly half the water added to the repair mix. As such, the relative water-cement ratio would be roughly the same as the vault cement mix. This material, applied as part of the grout, would be expected to remain in place during the vault transport and installation process and to remain in place through plug emplacement; however, it would be expected to degrade radiolytically after waste emplacement, resulting in a more porous and less dense repaired area.

    Instead, the bonding agent was just applied to the concrete surface prior to application of grout repair material. Therefore, it is expected that the repaired area will remain in place during vault transport, installation, and during plug and waste emplacement. After waste emplacement, it is expected the grout will remain in place and provide radiolytic protection for workers without degrading. Summary information for this product is given in Table 8.

Table 6. Performance characteristics for Jet Set Concrete Repair grout.

Performance Metric	Method of Determination	Days	Metric	Comment
Compressive strength (psi)	ASTM C109	1 7 14 28	3,570 4,800 5,300 6,000	Exceeds concrete compressive strength requirement of 5,000 psi at 28 days.
Flexural strength (psi)	ASTM C348	1 7 28	570 1,330 1,360	No requirement for this metric.
Shrinkage %	ASTM C596	7	0.087%	Very low shrinkage as required in SPC-1857.
Bond strength (psi)	ASTM C1042	1 3 7	574 850 939	Not specified in SPC-1857. Bond strength is sufficient to prevent repair fallout during normal handling operations.
Tensile strength (psi)	ASTM C190	28	507	Not specified in SPC-1857.
Set times	ASTM C191	Initial final	8 to 10 minutes 15 to 20 minutes	Quick setting, allowing repair, and removal to the yard.

Table 7. Composition information/ingredients for Jet Set Concrete Repair grout.

Ingredient	Total Percentage	Comment
Portland cement	10 to 70%	This is one of the primary ingredients in the vault concrete.
Silica sand	30 to 50%	This is comparable to the aggregate used in the vault concrete.
Calcium sulfate hemihydrate	10 to 70%	The natural form is gypsum (a mineral) and is formed during hydration of cement.
Calcium hydroxide	10 to 70%	The natural form is lime, which is a component of cement.
Magnesium hydroxide	1 to 10%	The natural form is the mineral brucite, which is a component of cement.
Silicon dioxide	1 to 20%	The natural form is quartz, which is a component of aggregate and cement.
Calcium aluminate	10 to 70%	A mineral formed by heating calcium oxide and aluminum oxide and formed during hydration of cement.

Table 8. Performance metrics for the MasterEmaco A660 admixture with sand/cement mortar samples.

Performance Metric	Method of Determination	With Water	With 1-to-1 MasterEmaco A660 and Water
Compressive strength (psi) at 28 days	ASTM C109	3,800	4,500
Tensile strength (psi) at 28 days	ASTM C190	225	350
Flexural strength (psi) at 28 days	ASTM C348	1,000	1,800

4.4 Concrete Defect and Damage Inspection Results

During inspection of the three reinforced concrete vault components (bases, risers, and plugs) out of all 1542 individual vault components (excluding perimeter blocking), a total of 394 vault components were found to contain a fabrication defect or to be damaged as a result of handling the component. Compiled data for individual components are summarized in Table 9, with examples shown in Figures 4 through 9. Columns 1 and 2 contain the SNR number or the NCR number submitted to BEA for review and approval prior to addressing the reported defects and damage for the component listed in Column 3. These SNR and NCR reports contain the full description of the defects or damage for each component listed in Column 3. For spalling, the damage location is given in Column 4. Honeycombing typically occurred at the bottom edge of the form; therefore, it occurs on the component bottom or top depending on whether the components were poured with the forms inverted or right side up. The specific non-conforming Level 3 condition is listed in Column 5. Dimensions of the bounding (i.e., largest) Level 3 defect are given in Columns 6 through 9. Measurements of the dimensions are illustrated in Figures 4 through 9, with the length corresponding to the longest dimension, which is typically the horizontal dimension for damage occurring on a component top or bottom edge. The two widths for edge damage are provided to allow calculation of the affected component volume. The widths are measured perpendicular to the length. In the case of honeycombing or bugholes, the depth was reported as measured perpendicular to the concrete wall. In the case of spalling, the depth was reported as shown in Figure 4; therefore, it provides a conservative estimate of concrete remaining over the steel reinforcement. It also results in overestimating the concrete volume affected by the defect or damage. Column 10 contains the number of Level 3 damaged areas on each component. When the total area affected by Level 3 damage was computed, it was conservatively assumed that the area of each affected area was equal to the largest (worst case) area reported. Column 11 contains the total affected area computed as the sum of the rectangle areas: A = length*(width 1 + width 2) * number of Level 3 damaged areas, and Column 12 contains the total volume computed as V = A*depth.

The summary of defects and damage by component type and vault array is provided in Table 10. Vault component data are contained in Columns 2 through 4, beginning with the number of components (i.e., the number of upper riser sections) in the 55-ton array, LCC array, HFEF, NuPac, MFTC, and PA arrays in Column 2 followed by the total surface area and concrete volume in each component type in Columns 3 and 4. The surface area for the upper vault riser section includes the inner and outer cylinder surface area and excludes the top and bottom tongue because they do not contribute significantly to the vault structural performance. Similarly, the surface area for the vault bases only includes the inner and outer cylinder surface area, while excluding the surface area contributed by the hexagonal base and tongue surface areas. The surface area of the plugs includes both the top and bottom surface area and six sides of the hexagonal plug. The total concrete volume was computed considering only the upper riser and base cylinder, conservatively neglecting the hexagonal base portion of the vault base and the concrete contained in the tongue mating surfaces for the risers and plugs.

Columns 5 through 7 of Table 9 contain the summary of defects for the specific vault array and component type. Column 5 provides the number of components with defects or damage. Column 6 contains the total defect or damaged area. Column 7 contains the volume of damaged concrete for each vault component type and each array type. The total impact on the array was assessed by computing the percentage relative to the vault array by component type. This information is provided in Columns 8 through 10. As shown in Column 8, the percentage of HFEF components exhibiting damage is relatively high compared to other vault components; however, the overall impact to surface area and volume is negligible.

Overall, the impact of this damage is superficial when quantified as a percentage of the total surface area within each array type and when quantified as a percentage of the overall concrete volume. There are no significant differences between the array types and no significant differences between component types within an array. Therefore, summary statistics support the assumption that defects/damage do not contribute to component failure in the overall concrete durability analysis.

Table 9. Summary of Level 3 defect and damage inspection results for individual components.

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
65		55T-U1		Bughole	2.00	1.00	0.00	0.50	1	2.0	1.0
47		55T-U2	Wall	Honeycombing	24.60	2.50	0.00	0.25	1	61.5	15.4
12		55T-U7	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
75		55T-U7		Honeycombing	7.00	3.00	0.00	0.63	2	42.0	26.2
47		55T-U9	Wall	Honeycombing	22.00	1.00	0.00	0.38	1	22.0	8.3
12		55T-U10	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
47		55T-U12	Wall	Honeycombing	6.00	1.50	0.00	0.38	1	9.0	3.4
47		55T-U13	Wall	Honeycombing	2.00	1.00	0.00	0.19	1	2.0	0.4
12		55T-U14	Wall	Bughole	1.88	1.88	0.00	0.14	1	3.5	0.5
	12	55T-U16	Edge	Spalling	4.50	2.50	0.50	0.50	1	13.5	6.8
47		55T-U17	Wall	Honeycombing	29.60	1.13	0.00	0.19	1	33.4	6.3
54		55T-U19		Honeycombing	1.75	2.50	0.00	0.63	2	8.8	5.5
46		55T-U21	Wall	Honeycombing	4.88	0.38	0.00	0.13	1	1.8	0.2
53		55T-U24	Tongue	Spalling	1.50	1.00	0.00	0.44	1	1.5	0.7
	11	55T-U25	Edge	Spalling	3.00	1.25	0.88	0.50	1	6.4	3.2
46		55T-U28	Wall	Bughole	1.75	1.25	0.00	0.38	3	6.6	2.5
47		55T-U31	Wall	Honeycombing	9.00	3.50	0.00	0.25	1	31.5	7.9
46		55T-U32	Wall	Honeycombing	2.00	0.75	0.00	0.13	1	1.5	0.2
	12	55T-U33	Edge	Spalling	1.00	0.75	1.00	0.25	1	1.8	0.4
	12	55T-U33	Edge	Spalling	1.19	1.00	0.19	0.31	1	1.4	0.4
65		55T-U40		Crack	3.00	0.03	0.00	0.03	1	0.1	0.0
65		55T-U40		Crack	1.42	0.04	0.00	0.03	1	0.1	0.0
	12	55T-U46	Edge	Spalling	3.50	4.50	1.00	1.00	1	19.2	19.2
75		55T-U48	Edge	Spalling	16.90	3.50	1.25	0.50	1	80.3	40.1
72		55T-U70	Edge	Spalling	5.00	3.00	0.75	0.75	1	18.8	14.1
75		55T-U77		Crack	2.94	0.01	0.00	0.06	1	0.0	0.0
93	25	55T-U82	Edge	Spalling	5.50	2.50	0.75	0.50	1	17.9	8.9
118		55T-U84	Tongue	Spalling	8.00	1.75	0.00	1.75	1	14.0	24.5

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
12		55T-B1	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
46		55T-B2	Wall	Honeycombing	5.00	1.50	0.00	0.19	1	7.5	1.4
12		55T-B3	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		55T-B4	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		55T-B5	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		55T-B6	Wall	Bughole	2.13	2.13	0.00	0.33	1	4.5	1.5
12		55T-B7	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		55T-B8	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		55T-B9	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
46		55T-B12	Wall	Honeycombing	5.19	1.25	0.00	0.25	5	32.4	8.1
12		55T-B13	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		55T-B14	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
46		55T-B14	Wall	Honeycombing	6.00	1.25	0.00	0.38	3	22.5	8.4
47		55T-B15	Wall	Honeycombing	5.00	1.00	0.00	0.50	1	5.0	2.5
47		55T-B15	Wall	Bughole	1.69	0.75	0.00	0.25	1	1.3	0.3
65		55T-B16		Bughole	1.63	1.25	0.00	0.88	3	6.1	5.4
48		55T-B19	Wall	Bughole	2.13	0.75	0.00	0.25	33	52.7	13.2
48		55T-B19	Edge	spalling	4.00	1.50	0.00	0.50	1	6.0	3.0
46		55T-B20	Wall	Bughole	1.69	0.63	0.00	0.13	7	7.4	0.9
46		55T-B20	Wall	Honeycombing	8.00	1.25	0.00	0.50	2	20.0	10.0
46		55T-B21	Wall	Honeycombing	1.75	0.25	0.00	0.06	1	0.4	0.0
48		55T-B22	Edge	spalling	4.00	2.00	0.00	0.50	1	8.0	4.0
48		55T-B22	Wall	Bughole	2.19	0.63	0.00	0.13	1	1.4	0.2
47		55T-B23	Wall	Bughole	1.88	0.75	0.00	0.25	1	1.4	0.4
46		55T-B24	Wall	Bughole	2.38	0.88	0.00	0.13	13	27.1	3.4
47		55T-B25	Wall	Bughole	1.88	1.25	0.00	0.25	1	2.4	0.6
46		55T-B26	Wall	Bughole	1.63	1.13	0.00	0.06	6	11.1	0.7
59		55T-B27	Tongue	Spalling	6.00	2.00	0.00	0.50	1	12.0	6.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
48		55T-B27	Wall	Honeycombing	2.50	2.00	0.00	0.50	1	5.0	2.5
46		55T-B30	Wall	Bughole	2.00	1.25	0.00	0.06	1	2.5	0.2
46		55T-B31	Wall	Honeycombing	5.50	1.50	0.00	0.38	3	24.8	9.3
46		55T-B31	Wall	Bughole	2.00	2.00	0.00	0.25	5	20.0	5.0
46		55T-B33	Wall	Bughole	1.75	1.00	0.00	0.38	3	5.3	2.0
	14	55T-B53	Edge	Spalling	4.00	1.75	0.38	0.25	1	8.5	2.1
91		55T-B54	Edge	spalling	7.50	6.00	0.50	0.50	1	48.8	24.4
75		55T-B75	Edge	Spalling	5.75	2.00	1.25	0.25	1	18.7	4.7
92	24	55T-B82	Edge	Spalling	8.50	3.50	1.00	1.00	1	38.2	38.2
92	24	55T-B82	Edge	Spalling	5.00	2.00	0.75	0.75	1	13.8	10.3
54		55T-P2		Honeycombing	1.88	1.25	0.00	0.38	1	2.4	0.9
12		55T-P5	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
12		55T-P6	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
49		55T-P7	Edge	spalling	3.00	1.75	0.50	0.50	1	6.8	3.4
156		55T-P7	Corner	Spalling	5.25	5.25	2.50	0.00	1	40.7	0.0
65		55T-P11	Edge	Spalling	54.00	1.50	0.50	0.50	1	108.0	54.0
12		55T-P12	Wall	Bughole	1.75	1.75	0.00	0.24	1	3.1	0.7
49		55T-P23	Wall	Bughole	1.75	1.00	0.00	0.38	1	1.8	0.7
49		55T-P25	Wall	Honeycombing	2.50	2.00	0.00	0.13	1	5.0	0.6
156		55T-P27	Edge	Spalling	4.00	2.75	0.63	0.50	1	13.5	6.8
49		55T-P28	Edge	spalling	3.00	3.25	0.00	0.13	1	9.8	1.2
49		55T-P31	Edge	spalling	2.50	4.50	0.00	0.13	2	22.5	2.8
156		55T-P32	Edge	Spalling	4.50	2.25	0.63	0.50	1	13.0	6.5
156		55T-P32	Corner	Spalling	2.50	2.50	2.50	0.00	1	12.5	0.0
49		55T-P33	Wall	Bughole	2.00	1.00	0.00	0.38	2	4.0	1.5
49		55T-P34	Edge	spalling	5.88	1.44	0.00	1.50	1	8.5	12.7
156		55T-P43	Corner	Spalling	4.00	4.50	2.00	0.00	1	26.0	0.0
156		55T-P44	Corner	Spalling	3.50	3.00	3.50	0.00	1	22.8	0.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
156		55T-P47	Edge	Spalling	6.00	2.50	0.75	0.75	1	19.5	14.6
82		55T-P53	Edge	Spalling	9.13	6.00	0.75	0.25	1	61.6	15.4
156		55T-P53	Edge	Spalling	6.50	3.00	0.63	0.75	1	23.6	17.7
156		55T-P53	Corner	Spalling	6.00	1.75	6.00	0.00	1	46.5	0.0
156		55T-P62	Corner	Spalling	6.50	4.25	6.50	0.00	1	69.9	0.0
114		55T-P77	Edge	Spalling	5.25	0.75	2.75	0.50	1	18.4	9.2
77		LC-U1		Crack	86.00	0.02	0.00	0.03	1	1.6	0.0
	19	LC-U1B-2	Edge	Spalling	3.50	1.50	3.50	0.19	1	17.5	3.3
	19	LC-U1B-2	Edge	Spalling	2.50	0.50	3.00	0.38	1	8.8	3.3
12		LC-U5	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
76		LC-U5		Honeycombing	5.00	4.00	0.00	0.25	2	40.0	10.0
57		LC-U6		Honeycombing	53.30	3.50	0.00	0.50	3	560.0	280.0
76		LC-U7		Honeycombing	13.00	2.00	0.00	0.50	3	78.0	39.0
12		LC-U8	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
57		LC-U11		Honeycombing	16.90	2.63	0.00	0.50	11	489.0	244.0
57		LC-U14		Honeycombing	9.00	2.25	0.00	0.31	2	40.5	12.7
57		LC-U15		Honeycombing	96.40	4.00	0.00	0.50	6	2310.0	1160.0
57		LC-U16		Honeycombing	5.63	0.88	0.00	0.19	6	29.6	5.6
57		LC-U17		Honeycombing	13.00	0.38	0.00	0.31	2	9.8	3.1
57		LC-U20		Honeycombing	79.80	2.00	0.00	0.31	4	638.0	200.0
57		LC-U21		Honeycombing	9.50	3.50	0.00	0.31	1	33.2	10.4
57		LC-U22		Honeycombing	6.00	1.06	0.00	0.25	6	38.2	9.5
57		LC-U28		Honeycombing	6.50	2.50	0.00	0.06	4	65.0	4.1
57		LC-U29		Honeycombing	2.63	0.38	0.00	0.13	1	1.0	0.1
57		LC-U34		Honeycombing	4.00	3.00	0.00	0.06	1	12.0	0.8
68		LC-U36		Honeycombing	2.75	1.16	0.00	0.31	5	15.9	5.0
76		LC-U39		Bughole	3.75	0.50	0.00	0.13	2	3.8	0.5
68		LC-U64	Top Edge	Spalling	3.25	1.25	0.00	1.00	1	4.1	4.1

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
	13	LC-U71-2	Edge	Spalling	0.75	0.75	0.75	0.25	1	1.1	0.3
	13	LC-U71-2	Edge	Spalling	4.00	2.50	3.50	0.50	1	24.0	12.0
	13	LC-U71-2	Edge	Spalling	3.00	1.38	2.50	0.50	1	11.6	5.8
	13	LC-U71-2	Edge	Spalling	2.25	1.63	2.25	0.50	1	8.7	4.4
	13	LC-U72-1	Edge	Spalling	8.00	3.63	5.75	0.88	1	75.0	65.7
88		LC-U94	Top Edge	Spalling	17.00	3.25	0.00	1.13	1	55.2	62.4
69		LC-U99-2	Edge	Spalling	12.00	4.00	0.00	0.75	1	48.0	36.0
81		LC-U116	Edge	spalling	5.00	1.00	3.13	1.25	1	20.7	25.8
137		LC-B1	Liftlug	spalling	1.00	1.00	0.00	0.63	1	1.0	0.6
68		LC-B1	Edge	Spalling	3.00	2.00	0.00	1.50	1	6.0	9.0
68		LC-B1B		Bughole	1.50	0.88	0.00	1.63	1	1.3	2.1
137		LC-B1	Base	Spalling	1.00	1.00	0.00	0.63	1	1.0	0.6
12		LC-B2	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		LC-B3	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		LC-B4	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		LC-B5	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
68		LC-B5		Honeycombing	2.25	1.38	0.00	0.50	1	3.1	1.6
12		LC-B7	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
76		LC-B9		Crack	0.25	0.01	0.00	0.03	1	0.0	0.0
12		LC-B9	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		LC-B10	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
68		55T-B11		Bughole	2.25	1.00	0.00	0.25	2	4.5	1.1
68		55T-B11		Honeycombing	3.75	1.00	0.00	0.63	9	33.8	21.1
12		LC-B11	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		LC-B12	Wall	Bughole	3.75	3.75	0.00	0.41	6	84.4	34.6
12		LC-B13	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		LC-B14	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
57		LC-B16		Honeycombing	2.00	1.88	0.00	0.44	1	3.8	1.7

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
68		LC-B17		Honeycombing	3.00	2.00	0.00	0.88	1	6.0	5.3
12		LC-B17	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
57		LC-B18		Honeycombing	2.00	1.00	0.00	1.25	3	6.0	7.5
57		LC-B18		Bughole	2.25	3.00	0.00	0.50	1	6.8	3.4
76		LC-B19		Bughole	1.25	1.00	0.00	1.25	6	7.5	9.4
76		LC-B20		Bughole	1.75	1.25	0.00	1.13	6	13.1	14.8
76		LC-B22	Edge	Spalling	3.00	2.00	0.00	2.00	1	6.0	12.0
57		LC-B23		Honeycombing	3.19	1.63	0.00	0.25	1	5.2	1.3
68		LC-B24		Honeycombing	8.50	2.50	0.00	0.25	1	21.2	5.3
68		LC-B26		Honeycombing	5.00	1.25	0.00	0.50	1	6.3	3.1
88		LC-B27	Top Edge	Spalling	3.00	2.00	0.00	1.50	1	6.0	9.0
68		LC-B28		Bughole	1.50	1.38	0.00	1.50	8	16.6	24.8
57		LC-B33		Bughole	1.75	1.00	0.00	0.13	5	8.8	1.1
57		LC-B34		Honeycombing	3.00	2.00	0.00	0.13	1	6.0	0.8
57		LC-B35		Bughole	2.25	0.75	0.00	0.88	5	8.4	7.4
68		LC-B36		Bughole	1.50	1.06	0.00	0.13	2	3.2	0.4
68		LC-B37		Bughole	1.63	0.63	0.00	0.25	1	1.0	0.3
57		LC-B38		Bughole	1.75	0.04	0.00	0.38	3	0.2	0.1
57		LC-B39		Honeycombing	2.25	1.13	0.00	0.44	2	5.1	2.2
68		55T-B73	Top Edge	Spalling	6.00	2.50	0.00	1.00	1	15.0	15.0
76		LC-B85	Tongue	Spalling	7.13	2.00	0.00	1.88	1	14.3	26.8
68		LC-B87	Top Edge	Spalling	11.50	1.88	0.00	1.75	1	21.6	37.8
76		LC-B87	Tongue	Spalling	11.50	1.88	0.00	1.75	1	21.6	37.8
76		LC-B122		Crack	3.63	0.02	0.00	0.03	1	0.1	0.0
76		LC-B123		Crack	0.75	0.02	0.00	0.03	1	0.0	0.0
104		LC-B130	Edge	Spalling	15.00	0.75	6.00	0.75	1	101.0	75.9
76		LC-B131	Tongue	Spalling	10.50	2.25	0.00	2.00	1	23.6	47.2
76		LC-B131		Bughole	1.13	1.75	0.00	1.13	1	2.0	2.2

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
76		LC-B134	Edge	Spalling	9.25	3.38	1.50	1.00	1	45.1	45.1
	37	LC-B146	Liftlug		9.13	8.25	0.00	1.00	1	75.3	75.3
137		LC-B152	Base	Spalling	1.00	1.00	0.00	0.31	1	1.0	0.3
137		LC-B152	Liftlug	spalling	1.00	1.00	0.00	0.31	1	1.0	0.3
	41	LC-B160	Base	spalling	3.00	3.00	0.00	0.50	1	9.0	4.5
	41	LC-B166	Base	spalling	5.00	5.00	0.00	0.81	1	25.0	20.3
	41	LC-B173	Base	spalling	4.75	4.75	0.00	1.00	1	22.6	22.6
	41	LC-B173	Base	spalling	4.75	4.75	0.00	0.50	1	22.6	11.3
	41	LC-B179	Base	spalling	3.00	3.00	0.00	0.31	1	9.0	2.8
101		LC-B180	Top Edge	Spalling	4.00	3.00	1.75	1.00	1	19.0	19.0
	41	LC-B182	Base	spalling	5.00	5.00	0.00	0.88	1	25.0	21.9
	41	LC-B183	Base	spalling	3.50	3.50	0.00	0.38	1	12.2	4.6
	41	LC-B184	Base	spalling	4.75	4.75	0.00	0.63	1	22.6	14.1
	41	LC-B185	Base	spalling	6.00	6.00	0.00	0.75	1	36.0	27.0
	41	LC-B188	Base	spalling	4.00	4.00	0.00	0.56	1	16.0	9.0
	34	LC-B192	Wall	Spalling	6.00	5.00	0.00	0.25	1	30.0	7.5
	41	LC-B193	Base	spalling	5.00	5.00	0.00	0.50	1	25.0	12.5
82		LC-P1A	Edge	Spalling	3.50	2.50	0.94	0.88	1	12.0	10.5
82		LC-P1	Edge	Spalling	1.50	1.50	1.00	0.50	1	3.8	1.9
108		LC-P2	Edge	Spalling	2.75	2.25	1.88	0.63	3	34.1	21.3
159		LC-P3	Edge	Spalling	10.00	7.50	1.50	1.25	1	90.0	112.0
12		LC-P7	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
159		LC-P7	Corner	Spalling	4.25	3.75	3.75	0.00	1	31.9	0.0
12		LC-P10	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
82		LC-P10	Edge	Spalling	2.00	2.25	1.88	0.50	1	8.3	4.1
157		LC-P11	Corner	Spalling	3.00	4.75	3.00	0.00	1	23.2	0.0
12		LC-P16	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
82		LC-P20	Edge	Spalling	3.50	1.13	1.88	0.63	1	10.5	6.6

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
	23	LC-P21	Wall	Crack	1.50	0.00	0.00	0.00	2	0.0	0.0
	23	LC-P23	Wall	Crack	9.00	0.01	0.00	0.00	1	0.1	0.0
108		LC-P29	Edge	Spalling	5.25	1.25	2.00	0.88	1	17.1	14.9
82		LC-P31		Honeycombing	3.00	1.00	1.06	0.06	1	6.2	0.4
82		LC-P59	Edge	Spalling	2.50	2.00	1.50	0.13	2	17.5	2.3
	29	LC-P65-2		Crack	8.00	0.01	0.00	0.00	1	0.1	0.0
82		LC-P71	Edge	Spalling	3.13	2.50	1.88	1.00	1	13.7	13.7
82		LC-P82	Edge	Spalling	5.63	1.75	1.00	0.88	1	15.5	13.5
82		LC-P95		Crack	1.75	0.02	0.00	0.03	0	0.0	0.0
124		LC-P95	Wall	Crack Depth	1.00	1.00	1.00	0.50	3	6.0	3.0
124		LC-P95	Wall	Crack	47.00	0.02	0.00	0.00	1	1.0	0.0
108		LC-P96	Edge	Spalling	4.13	3.50	1.13	0.25	5	95.6	23.9
	29	LC-P101		Crack	3.00	0.01	0.00	0.00	1	0.0	0.0
	29	LC-P105	Edge	Spalling	9.50	4.00	1.00	0.75	1	47.5	35.6
	22	LC-P105-	Edge	Spalling	9.50	4.00	1.00	0.75	1	47.5	35.6
108		LC-P107	Edge	Spalling	12.50	5.63	3.00	1.38	3	324.0	447.0
	29	LC-P112	Edge	Spalling	7.25	4.50	1.25	1.50	1	41.7	62.5
157		LC-P141	Corner	Spalling	5.25	3.00	5.25	0.00	1	43.3	0.0
157		LC-P153	Corner	Spalling	9.00	5.75	9.00	0.00	1	133.0	0.0
154		LC-P155	Edge	Spalling	6.75	3.63	1.13	0.88	1	32.1	28.3
108		LC-P163	Edge	Spalling	6.00	5.13	1.13	1.00	1	37.6	37.6
	24	LC-P164	Edge	Spalling	13.00	8.00	2.00	2.00	1	130.0	260.0
157		LC-P183	Edge	Spalling	26.00	3.50	1.25	0.88	1	124.0	109.0
154		LC-P188	Corner	Spalling	8.00	7.25	7.25	0.00	1	116.0	0.0
54		HFEF-U1		Honeycombing	1.88	0.38	0.00	0.38	1	0.7	0.3
56		HFEF-U3	Wall	Crack	2.00	0.03	0.00	0.03	1	0.1	0.0
56		HFEF-U3		Crack	2.00	0.03	0.00	0.03	1	0.1	0.0
56		HFEF-U3		Honeycombing	5.25	2.00	0.00	0.75	4	42.0	31.5

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
56		HFEF-U3	Wall	Honeycombing	5.25	2.00	0.00	0.75	1	10.5	7.9
56		HFEF-U4		Honeycombing	2.75	1.88	0.00	0.63	5	25.9	16.2
56		HFEF-U4		Crack	3.50	0.01	0.00	0.03	1	0.0	0.0
56		HFEF-U4	Wall	Crack	3.50	0.01	0.00	0.03	1	0.0	0.0
56		HFEF-U4	Wall	Honeycombing	2.75	1.88	0.00	0.63	1	5.2	3.2
56		HFEF-U5		Honeycombing	10.50	2.50	0.00	1.25	4	105.0	131.0
56		HFEF-U5	Edge	Spalling	35.00	1.25	0.00	0.25	1	43.8	10.9
56		HFEF-U5	Wall	Crack	12.00	0.03	0.00	0.03	1	0.4	0.0
56		HFEF-U5		Crack	12.00	0.03	0.00	0.03	1	0.4	0.0
56		HFEF-U5	Edge	Spalling	35.00	1.25	0.00	0.25	1	43.8	10.9
56		HFEF-U5	Wall	Honeycombing	10.50	2.50	0.00	1.25	1	26.2	32.8
54		HFEF-U6		Honeycombing	3.88	1.00	0.00	0.13	6	23.3	2.9
54		HFEF-U7		Honeycombing	3.13	1.19	0.00	0.13	1	3.7	0.5
56		HFEF-U8	Wall	Honeycombing	48.00	4.00	0.00	0.50	1	192.0	96.0
154		HFEF-U8	Edge	Spalling	14.50	7.00	1.75	1.75	1	127.0	222.0
56		HFEF-U8		Honeycombing	48.00	4.00	0.00	0.50	4	768.0	384.0
56		HFEF-U8		Crack	1.75	0.02	0.00	0.03	1	0.0	0.0
56		HFEF-U8	Wall	Crack	1.75	0.02	0.00	0.03	1	0.0	0.0
56		HFEF-U10	Wall	Bughole	1.75	1.00	0.00	0.50	1	1.8	0.9
56		HFEF-U10	Wall	Honeycombing	10.00	2.50	0.00	0.50	1	25.0	12.5
56		HFEF-U10		Honeycombing	10.00	2.50	0.00	0.13	7	175.0	21.9
56		HFEF-U10		Crack	5.00	0.01	0.00	0.03	1	0.1	0.0
56		HFEF-U10		Bughole	1.75	1.00	0.00	0.50	3	5.3	2.6
56		HFEF-U10	Wall	Crack	5.00	0.01	0.00	0.03	1	0.1	0.0
56		HFEF-U11	Wall	Crack	3.00	0.01	0.00	0.03	1	0.0	0.0
56		HFEF-U11		Crack	3.00	0.01	0.00	0.03	1	0.0	0.0
62	8	HFEF-U12	Edge	spalling	3.00	2.50	1.00	1.00	1	10.5	10.5
54		HFEF-U12		Honeycombing	3.00	2.00	0.00	0.06	1	6.0	0.4

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
55		HFEF-U13		Bughole	3.00	2.00	0.00	0.06	3	18.0	1.1
55		HFEF-U13		Honeycombing	2.50	1.00	0.00	0.25	1	2.5	0.6
55		HFEF-U13	Edge	Spalling	3.00	1.00	0.00	0.25	1	3.0	0.8
55		HFEF-U15	Edge	Spalling	12.00	4.50	0.00	1.75	1	54.0	94.5
55		HFEF-U15		Honeycombing	2.00	2.50	0.00	0.50	4	20.0	10.0
56		HFEF-U16	Wall	Crack	8.50	0.02	0.00	0.03	1	0.2	0.0
56		HFEF-U16	Edge	Spalling	8.00	1.13	0.00	0.50	1	9.0	4.5
56		HFEF-U16	Wall	Honeycombing	6.00	2.75	0.00	0.63	1	16.5	10.3
55		HFEF-BPT		Honeycombing	4.56	2.25	0.00	0.25	5	51.3	12.8
55		HFEF-BPT	Edge	Spalling	3.25	2.25	0.00	0.63	1	7.3	4.6
54		HFEF-B1		Honeycombing	13.10	2.94	0.00	0.38	9	347.0	130.0
54		HFEF-B2		Honeycombing	5.31	4.75	0.00	0.38	2	50.4	18.9
55		HFEF-B4	Edge	Spalling	6.00	2.38	0.00	1.06	1	14.3	15.1
54		HFEF-B5		Honeycombing	5.00	3.13	0.00	0.38	5	78.2	29.3
55		HFEF-B6	Edge	Spalling	4.88	1.88	0.00	1.13	1	9.2	10.4
55		HFEF-B7	Edge	Spalling	5.75	2.75	0.00	1.13	1	15.8	17.9
56		HFEF-B8	Wall	Honeycombing	3.25	0.75	0.00	0.25	1	2.4	0.6
56		HFEF-B8		Honeycombing	3.25	0.75	0.00	0.25	1	2.4	0.6
54		HFEF-B10		Honeycombing	2.00	1.25	0.00	0.63	6	15.0	9.4
54		HFEF-B14		Bughole	1.50	1.00	0.00	0.13	1	1.5	0.2
54		HFEF-B15		Honeycombing	6.00	1.00	0.00	0.06	4	24.0	1.5
	999	HFEF-P3	Corner	Spalling	4.00	4.50	4.00	0.00	1	34.0	0.0
154		HFEF-P3	Corner	Spalling	9.63	5.00	3.00	0.00	1	77.0	0.0
154		HFEF-P3	Edge	Spalling	24.00	2.00	4.88	1.50	1	165.0	248.0
156		HFEF-P8	Corner	Spalling	3.25	3.00	3.25	0.00	1	20.3	0.0
156		HFEF-P9	Corner	Spalling	3.25	2.75	3.25	0.00	1	19.5	0.0
157		HFEF-P13	Edge	Spalling	6.25	2.50	1.38	1.25	1	24.2	30.3
155		HFEF-P13	Edge	Spalling	24.00	1.00	2.50	0.75	1	84.0	63.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
55		HFEF-P14	Edge	Spalling	2.00	1.75	0.00	0.50	1	3.5	1.8
55		HFEF-P14		Honeycombing	2.50	2.00	0.00	0.25	2	10.0	2.5
155		HFEF-P15	Corner	Spalling	4.50	0.75	3.13	0.75	1	17.5	13.1
155		HFEF-P15	Corner	Spalling	16.00	2.00	4.00	2.50	1	96.0	240.0
155		HFEF-P15	Corner	Spalling	13.40	2.00	2.63	2.50	1	61.9	155.0
155		HFEF-P15	Corner	Spalling	2.75	1.00	3.00	0.75	1	11.0	8.3
42		NP-U1	Wall	Crack	1.00	0.03	0.00	0.03	1	0.0	0.0
42		NP-U1	Edge	Spalling	2.00	1.00	0.00	0.63	1	2.0	1.3
42		NP-U2	Wall	Honeycombing	3.00	1.00	0.00	0.63	1	3.0	1.9
41		NP-U3	Edge	Spalling	4.00	1.00	0.00	0.50	1	4.0	2.0
29		NP-U4	Lift Lug	Crack	2.00	0.03	0.00	0.00	5	0.3	0.0
29		NP-U4	Lift Lug	Crack	2.00	0.03	0.00	0.00	5	0.3	0.0
12		NP-U5	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
	10	NP-U5	Edge	Spalling	3.00	1.25	0.75	0.75	1	6.0	4.5
29		NP-U7	Lift Lug	Crack	2.00	0.02	0.00	0.00	2	0.1	0.0
29		NP-U7	Lift Lug	Crack	2.00	0.02	0.00	0.00	2	0.1	0.0
42		NP-U9	Edge	Spalling	4.94	1.38	0.00	0.50	1	6.8	3.4
42		NP-U9	Wall	Honeycombing	8.38	1.25	0.00	0.50	1	10.5	5.2
43		NP-U14	Wall	Bughole	2.00	2.13	0.00	0.56	2	8.5	4.8
31		NP-U17		Honeycombing	3.38	1.00	0.00	0.25	4	13.5	3.4
31		NP-U17	Wall	Honeycombing	3.38	1.00	0.00	0.25	4	13.5	3.4
35		NP-U19		Honeycombing	12.50	1.50	0.00	0.38	6	112.0	42.2
45		NP-U19	Wall	Crack Depth	2.38	0.88	0.00	0.38	1	2.1	0.8
71	13	NP-U19	Edge	Spalling	9.00	1.25	3.13	1.25	1	39.4	49.3
	35	NP-U19	Wall	Honeycombing	12.50	1.50	0.00	0.38	3	56.2	21.1
45		NP-U19	Wall	Crack	48.00	0.02	0.00	0.03	1	0.9	0.0
45		NP-U19	Wall	Crack Depth	2.38	0.88	0.00	0.38	1	2.1	0.8
45		NP-U19	Wall	Crack	48.00	0.02	0.00	0.38	1	0.9	0.3

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
35		NP-U19		Honeycombing	12.50	1.50	0.00	0.38	6	112.0	42.2
12		NP-U20	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
	6	NP-U21	Edge	Spalling	1.75	1.00	0.00	0.50	3	5.3	2.6
12		NP-U21	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
	6	NP-U21	Edge	Spalling	1.75	1.00	0.00	0.50	3	5.3	2.6
12		NP-U22	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
12		NP-U25	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
52		NP-U27	Tongue	Spalling	20.00	2.00	0.00	3.50	1	40.0	140.0
31		NP-U27	Wall	Honeycombing	35.00	2.00	0.00	0.25	4	280.0	70.0
31		NP-U27		Honeycombing	35.00	2.00	0.00	0.25	4	280.0	70.0
45		NP-U29	Wall	Spalling	18.00	10.00	0.00	0.13	2	360.0	45.0
	6	NP-U30	Edge	Spalling	1.50	1.00	0.00	0.25	1	1.5	0.4
	6	NP-U30	Edge	Spalling	1.50	1.00	0.00	0.25	1	1.5	0.4
12		NP-U31	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
	6	NP-U32	Edge	Spalling	2.00	1.00	0.00	0.38	1	2.0	0.8
	6	NP-U32	Edge	Spalling	2.00	1.00	0.00	0.38	1	2.0	0.8
12		NP-U33	Wall	Bughole	1.63	1.63	0.00	0.25	1	2.7	0.7
	6	NP-U39	Edge	Spalling	3.00	1.00	0.00	0.50	1	3.0	1.5
31		NP-U39	Wall	Honeycombing	26.40	1.19	0.00	0.31	4	126.0	39.3
31		NP-U39		Honeycombing	26.40	1.19	0.00	0.31	4	126.0	39.3
	6	NP-U39	Edge	Spalling	3.00	1.00	0.00	0.50	1	3.0	1.5
31		NP-U40	Wall	Honeycombing	51.40	0.63	0.00	0.19	5	161.0	30.2
31		NP-U40		Honeycombing	51.40	0.63	0.00	0.19	5	161.0	30.2
31		NP-U41	Wall	Honeycombing	10.90	0.38	0.00	0.19	3	12.3	2.3
60		NP-U41	Tongue	Spalling	25.00	2.63	0.00	4.50	1	65.8	296.0
60	1	NP-U41	Tongue	Spalling	25.00	2.63	0.00	4.25	1	65.8	279.0
31		NP-U41		Honeycombing	10.90	0.38	0.00	0.19	3	12.3	2.3
43		NP-U43	Wall	Honeycombing	1.88	1.25	0.00	0.63	2	4.7	2.9

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
43		NP-U43	Edge	Spalling	1.75	1.88	0.00	0.75	1	3.3	2.5
	6	NP-U46	Edge	Spalling	1.00	1.00	0.00	0.25	1	1.0	0.3
	6	NP-U46	Edge	Spalling	1.00	1.00	0.00	0.25	1	1.0	0.3
	10	NP-U49	Edge	Spalling	2.00	1.25	0.25	0.25	1	3.0	0.8
31		NP-U50		Honeycombing	4.00	2.00	0.00	0.25	2	16.0	4.0
31		NP-U50	Wall	Honeycombing	4.00	2.00	0.00	0.25	2	16.0	4.0
31		NP-U51		Bughole	2.63	0.13	0.00	0.06	1	0.3	0.0
31		NP-U51		Honeycombing	4.13	0.38	0.00	0.13	2	3.1	0.4
31		NP-U51	Wall	Bughole	2.63	0.13	0.00	0.06	1	0.3	0.0
31		NP-U51	Wall	Honeycombing	4.13	0.38	0.00	0.13	2	3.1	0.4
31		NP-U52		Bughole	2.25	0.06	0.00	0.06	1	0.1	0.0
31		NP-U52		Honeycombing	10.00	3.50	0.00	0.13	3	105.0	13.1
31		NP-U52	Wall	Honeycombing	10.00	3.50	0.00	0.13	7	245.0	30.6
31		NP-U53	Wall	Honeycombing	3.00	0.88	0.00	0.06	2	5.3	0.3
31		NP-U53		Honeycombing	3.00	0.88	0.00	0.06	2	5.3	0.3
31		NP-U54	Wall	Honeycombing	3.00	2.00	0.00	0.06	1	6.0	0.4
31		NP-U54		Bughole	2.50	0.25	0.00	0.06	1	0.6	0.0
31		NP-U54		Honeycombing	3.00	2.00	0.00	0.06	1	6.0	0.4
31		NP-U54	Wall	Bughole	2.50	0.25	0.00	0.06	1	0.6	0.0
31		NP-U55		Bughole	2.06	1.00	0.00	0.25	6	12.4	3.1
31		NP-U55	Wall	Bughole	2.06	1.00	0.00	0.25	6	12.4	3.1
	12	NP-U55	Edge	Spalling	3.00	0.50	0.44	0.44	1	2.8	1.2
112		NP-U55	Tongue	Spalling	7.00	2.00	1.75	0.75	1	26.2	19.7
31		NP-U55	Wall	Honeycombing	4.00	1.50	0.00	0.06	4	24.0	1.5
31		NP-U55		Honeycombing	4.00	1.50	0.00	0.06	4	24.0	1.5
35		NP-U56		Bughole	3.00	0.25	0.00	0.06	1	0.8	0.0
35		NP-U56		Honeycombing	20.00	2.00	0.00	0.25	3	120.0	30.0
	35	NP-U56	Wall	Honeycombing	20.00	2.00	0.00	0.25	2	80.0	20.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
	35	NP-U58	Wall	Bughole	2.00	0.50	0.00	0.25	3	3.0	0.8
35		NP-U58		Bughole	2.00	0.50	0.00	0.25	1	1.0	0.3
	35	NP-U58	Wall	Honeycombing	6.00	2.00	0.00	0.13	2	24.0	3.0
35		NP-U58		Honeycombing	6.00	2.00	0.00	0.13	1	12.0	1.5
35		NP-U59		Honeycombing	2.25	0.75	0.00	0.13	1	1.7	0.2
	35	NP-U59	Wall	Honeycombing	2.25	0.75	0.00	0.19	2	3.4	0.6
55		NP-U60		Honeycombing	2.50	0.69	0.00	0.25	3	5.2	1.3
12		NP-B1	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
45		NP-B2[b]	Wall	Bughole	2.25	1.00	0.00	0.25	3	6.8	1.7
45		NP-B2[b]	Wall	Bughole	2.25	1.00	0.00	0.25	2	4.5	1.1
45		NP-B2[b]	Wall	Crack	2.25	0.06	0.00	0.00	4	0.5	0.0
45		NP-B2[b]	Wall	Crack	2.25	0.06	0.00	0.00	4	0.5	0.0
12		NP-B3	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
34		NP-B3	Lift Lug	Crack	2.00	0.02	0.00	0.00	3	0.1	0.0
12		NP-B5	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
43		NP-B6	Wall	Bughole	1.75	0.50	0.00	0.25	1	0.9	0.2
31		NP-B7	Wall	Honeycombing	6.00	1.50	0.00	0.38	2	18.0	6.8
31		NP-B7		Honeycombing	6.00	1.50	0.00	0.38	2	18.0	6.8
29		NP-B7	Lift Lug	Crack	2.00	0.03	0.00	0.00	1	0.1	0.0
29		NP-B7	Lift Lug	Crack	2.00	0.03	0.00	0.00	1	0.1	0.0
29		NP-B8	Lift Lug	Crack	2.00	0.03	0.00	0.00	1	0.1	0.0
29		NP-B8	Lift Lug	Crack	2.00	0.03	0.00	0.00	1	0.1	0.0
12		NP-B9	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
29		NP-B9	Lift Lug	Crack	2.00	0.03	0.00	0.00	1	0.1	0.0
29		NP-B9	Lift Lug	Crack	2.00	0.03	0.00	0.00	1	0.1	0.0
12		NP-B10	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
43		NP-B12	Edge	Spalling	4.00	1.00	0.00	1.13	1	4.0	4.5
12		NP-B14	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
12		NP-B15	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B16	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B17	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B18	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B19	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B20	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B22	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
31		NP-B23	Wall	Honeycombing	3.00	1.00	0.00	0.06	1	3.0	0.2
31		NP-B23	Wall	Bughole	2.25	1.13	0.00	0.06	5	12.7	0.8
31		NP-B23		Bughole	2.25	1.13	0.00	0.06	5	12.7	0.8
31		NP-B23		Honeycombing	3.00	1.00	0.00	0.06	1	3.0	0.2
12		NP-B24	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B25	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B26	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B27	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
51		NP-B27	Edge	Spalling	10.00	2.50	0.50	0.50	1	30.0	15.0
12		NP-B28	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
	9	NP-B28	Edge	Spalling	3.00	1.25	0.50	0.50	1	5.3	2.6
45		NP-B29	Edge	Spalling	18.00	10.00	0.00	0.13	3	540.0	67.5
43		NP-B31	Edge	Spalling	2.00	1.00	0.00	0.06	1	2.0	0.1
43		NP-B31	Wall	Honeycombing	12.00	1.00	0.00	1.25	2	24.0	30.0
12		NP-B32	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B33	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
43		NP-B34	Edge	Spalling	10.90	13.00	0.00	0.13	1	142.0	17.7
12		NP-B34	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B35	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
12		NP-B37	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
29		NP-B38	Wall	Crack	1.00	0.01	0.00	0.00	2	0.0	0.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
12		NP-B38	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
29		NP-B38	Lift Lug	Crack	1.00	0.01	0.00	0.00	2	0.0	0.0
12		NP-B39	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
29		NP-B39	Wall	Crack	1.00	0.02	0.00	0.00	1	0.0	0.0
12		NP-B41	Wall	Bughole	3.75	3.75	0.00	0.41	1	14.1	5.8
29		NP-B42	Lift Lug	Crack	2.00	0.02	0.00	0.00	1	0.0	0.0
29		NP-B42	Lift Lug	Crack	2.00	0.02	0.00	0.00	1	0.0	0.0
43		NP-B42	Wall	Honeycombing	3.00	1.50	0.00	0.50	1	4.5	2.3
42		NP-B43	Wall	Honeycombing	2.75	1.25	0.00	0.50	2	6.9	3.4
36		NP-B47			0.00	0.00	0.00	0.00	0	0.0	0.0
42		NP-B49	Edge	Spalling	1.25	1.00	0.00	0.50	1	1.3	0.6
35		NP-B49		Bughole	2.50	1.25	0.00	0.50	11	34.4	17.2
35		NP-B49		Bughole	2.50	1.25	0.00	0.50	11	34.4	17.2
36		NP-B49			0.00	0.00	0.00	0.00	0	0.0	0.0
	35	NP-B49	Wall	Bughole	2.50	1.25	0.00	0.50	1	3.1	1.6
42		NP-B49	Wall	Bughole	1.50	0.75	0.00	0.38	11	12.4	4.6
35		NP-B51		Bughole	2.38	1.31	0.00	0.19	19	59.2	11.1
	35	NP-B51	Wall	Bughole	2.38	1.31	0.00	0.19	1	3.1	0.6
35		NP-B51		Bughole	2.38	1.31	0.00	0.19	19	59.2	11.1
35		NP-B53		Bughole	1.63	1.00	0.00	0.31	43	70.1	21.9
	35	NP-B53	Wall	Bughole	1.63	1.00	0.00	0.31	1	1.6	0.5
35		NP-B53		Bughole	1.63	1.00	0.00	0.31	43	70.1	21.9
35		NP-B54		Bughole	1.75	1.00	0.00	0.25	11	19.2	4.8
	35	NP-B54	Wall	Bughole	1.75	1.00	0.00	0.25	1	1.8	0.4
35		NP-B54		Bughole	1.75	1.00	0.00	0.25	11	19.2	4.8
39		NP-B55	Tongue	Spalling	2.50	1.75	0.00	0.25	1	4.4	1.1
	35	NP-B57	Wall	Honeycombing	3.00	2.00	0.00	0.06	1	6.0	0.4
35		NP-B57		Honeycombing	3.00	2.00	0.00	0.06	1	6.0	0.4

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
35		NP-B58		Bughole	2.00	0.50	0.00	0.13	1	1.0	0.1
	35	NP-B58	Wall	Bughole	2.00	0.50	0.00	0.13	1	1.0	0.1
36		NP-B58			0.00	0.00	0.00	0.00	0	0.0	0.0
35		NP-B59		Bughole	1.56	0.75	0.00	0.19	1	1.2	0.2
	35	NP-B59	Wall	Bughole	1.56	0.75	0.00	0.19	1	1.2	0.2
35		NP-B60		Bughole	2.00	1.00	0.00	0.50	1	2.0	1.0
	35	NP-B60	Wall	Bughole	2.00	1.00	0.00	0.50	1	2.0	1.0
37		NP-P1	Wall	Crack	4.00	0.04	0.00	0.06	1	0.2	0.0
37		NP-P1	Edge	Spalling	2.00	2.25	0.00	0.50	5	22.5	11.2
37		NP-P2	Edge	Spalling	3.00	2.50	0.00	0.50	3	22.5	11.2
12		NP-P2	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
86		NP-P2		Crack	11.50	0.01	0.00	0.00	1	0.1	0.0
37		NP-P3	Edge	Spalling	6.50	1.25	1.00	0.50	5	73.1	36.6
12		NP-P3	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
86		NP-P3		Crack	6.50	0.01	0.00	0.00	1	0.1	0.0
37		NP-P4	Edge	Spalling	7.88	1.50	1.25	0.63	1	21.7	13.5
37		NP-P4		Honeycombing	3.75	1.88	0.00	0.50	5	35.2	17.6
86		NP-P4		Crack	5.50	0.01	0.00	0.00	1	0.1	0.0
37		NP-P5	Edge	Spalling	2.00	1.25	0.00	0.50	1	2.5	1.3
86		NP-P5		Crack	11.00	0.01	0.00	0.00	1	0.1	0.0
12		NP-P5	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
86		NP-P6		Crack	7.00	0.01	0.00	0.00	1	0.1	0.0
115		NP-P6	Edge	Spalling	16.50	0.63	6.50	0.88	1	118.0	103.0
37		NP-P6	Edge	Spalling	11.90	1.25	1.00	0.50	6	161.0	80.3
86		NP-P7		Crack Depth	3.50	2.00	2.25	1.84	1	14.9	27.4
86		NP-P7		Crack Depth	5.00	2.50	0.00	0.41	1	12.5	5.1
158		NP-P7	Edge	Spalling	6.00	2.50	0.50	0.50	1	18.0	9.0
86		NP-P7		Crack Depth	5.00	1.38	1.50	0.88	1	14.4	12.6

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
86		NP-P7		Crack Depth	2.50	4.25	0.00	0.50	1	10.6	5.3
12		NP-P7	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
158		NP-P7	Edge	Spalling	6.00	1.50	0.50	0.50	1	12.0	6.0
86		NP-P7		Crack	20.00	0.02	0.00	0.00	1	0.4	0.0
37		NP-P7	Edge	Spalling	9.00	1.00	0.75	0.25	2	31.5	7.9
37		NP-P8		Honeycombing	1.50	1.00	0.00	0.88	1	1.5	1.3
12		NP-P8	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
37		NP-P8	Edge	Spalling	2.00	1.00	1.25	0.13	1	4.5	0.6
86		NP-P9		Crack	8.00	0.01	0.00	0.00	1	0.1	0.0
111		NP-P10	Edge	Spalling	8.50	1.25	4.50	0.75	1	48.9	36.7
37		NP-P10		Honeycombing	2.00	1.25	0.00	0.88	2	5.0	4.4
37		NP-P10	Edge	Spalling	2.00	1.25	0.88	0.63	3	12.8	8.0
37		NP-P11	Edge	Spalling	2.50	1.00	1.00	0.75	1	5.0	3.8
12		NP-P11	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
157		NP-P12	Edge	Spalling	24.00	2.50	1.00	0.88	1	84.0	73.9
37		NP-P12	Edge	Spalling	1.88	1.75	1.50	0.88	1	6.1	5.4
12		NP-P13	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
37		NP-P13	Edge	Spalling	1.88	1.00	1.25	0.63	1	4.2	2.6
37		NP-P13		Honeycombing	6.50	3.00	0.00	0.50	4	78.0	39.0
157		NP-P14	Corner	Spalling	6.75	8.00	6.75	0.00	1	99.6	0.0
12		NP-P14	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
37		NP-P15	Edge	Spalling	36.00	2.00	0.00	0.25	4	288.0	72.0
37		NP-P15	Edge	Spalling	2.63	1.25	0.00	0.25	1	3.3	0.8
37		NP-P15		Bughole	1.25	0.50	0.00	0.50	2	1.3	0.6
37		NP-P16	Edge	Spalling	2.00	1.25	0.00	0.50	1	2.5	1.3
37		NP-P18	Edge	Spalling	3.50	1.25	0.88	0.63	2	14.9	9.3
37		NP-P18		Honeycombing	2.13	1.25	0.00	0.50	2	5.3	2.7
37		NP-P19	Edge	Spalling	2.38	1.25	0.88	0.63	2	10.1	6.3

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
37		NP-P19		Honeycombing	5.00	2.75	0.00	0.38	7	96.2	36.1
86		NP-P19		Crack	11.00	0.01	0.00	0.00	1	0.1	0.0
157		NP-P20	Corner	Spalling	5.00	3.13	5.00	0.00	1	40.7	0.0
12		NP-P21	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
37		NP-P23	Edge	Spalling	1.25	0.88	0.38	0.25	4	6.3	1.6
37		NP-P23		Honeycombing	8.00	3.75	0.00	0.38	3	90.0	33.8
37		NP-P24	Edge	Spalling	1.50	1.25	0.88	0.25	3	9.6	2.4
37		NP-P25	Edge	Spalling	1.25	1.25	0.00	0.50	2	3.1	1.6
12		NP-P25	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
37		NP-P26		Honeycombing	8.50	3.50	0.00	0.38	2	59.5	22.3
37		NP-P26		Bughole	2.50	0.38	0.00	0.38	5	4.7	1.8
37		NP-P26	Edge	Spalling	3.50	0.88	0.25	0.25	2	7.9	2.0
157		NP-P26	Edge	Spalling	27.20	4.00	1.25	1.00	1	143.0	143.0
157		NP-P30	Corner	Spalling	8.50	3.50	8.50	0.00	1	102.0	0.0
12		NP-P31	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
12		NP-P35	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
35		NP-P37		Honeycombing	5.00	1.00	0.00	0.50	3	15.0	7.5
	35	NP-P37	Wall	Honeycombing	5.00	1.00	0.00	0.50	3	15.0	7.5
35		NP-P37		Honeycombing	5.00	1.00	0.00	0.50	3	15.0	7.5
37		NP-P37	Edge	Spalling	1.00	1.00	0.00	0.63	2	2.0	1.3
12		NP-P38	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9
157		NP-P38	Corner	Spalling	3.75	1.50	3.75	0.00	1	19.7	0.0
111		NP-P39	Edge	Spalling	8.00	1.25	3.00	0.75	1	34.0	25.5
111		NP-P39	Edge	Spalling	6.50	1.00	5.00	0.63	1	39.0	24.4
37		NP-P39	Edge	Spalling	2.50	1.00	0.75	0.75	1	4.4	3.3
157		NP-P42	Corner	Spalling	4.00	8.50	4.00	0.00	1	50.0	0.0
86		NP-P45		Crack	14.80	0.01	0.00	0.00	1	0.2	0.0
109		NP-P49	Edge	Spalling	4.50	0.75	3.50	0.75	1	19.1	14.3

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
109		NP-P49	Edge	Spalling	10.00	0.25	3.00	0.25	1	32.5	8.1
157		NP-P52	Edge	Spalling	18.80	3.00	1.00	1.00	1	75.0	75.0
86		NP-P53		Crack	11.80	0.01	0.00	0.00	1	0.1	0.0
37		NP-P53	Edge	Spalling	3.50	1.25	0.75	0.25	1	7.0	1.8
35		NP-P55		Bughole	1.75	0.50	0.00	0.25	1	0.9	0.2
	35	NP-P55	Wall	Bughole	1.75	0.50	0.00	0.25	1	0.9	0.2
35		NP-P56		Bughole	1.00	0.63	0.00	1.00	1	0.6	0.6
	35	NP-P56	Wall	Bughole	1.00	0.63	0.00	1.00	1	0.6	0.6
35		NP-P57		Bughole	4.00	1.00	0.00	0.13	1	4.0	0.5
	35	NP-P57	Wall	Bughole	4.00	1.00	0.00	0.13	3	12.0	1.5
77		FTC-U1A	Top Edge	Spalling	4.00	0.13	1.88	1.00	4	32.1	32.1
77		FTC-U1A		Honeycombing	8.25	0.88	0.00	0.06	2	14.4	0.9
77		FTC-U9	Bottom Edge	Spalling	10.50	3.63	2.00	1.88	2	118.0	222.0
76		FTC-U10		Bughole	1.00	0.75	0.00	1.06	1	0.8	0.8
95		FTC-U14	Tongue	Spalling	17.00	3.00	0.00	4.50	1	51.0	230.0
95		FTC-U14	Tongue	Spalling	17.00	2.63	0.00	4.25	1	44.7	190.0
98	18	FTC-U21	Edge	Spalling	16.00	2.00	3.00	3.50	1	80.0	280.0
98		FTC-U21	Edge	Spalling	16.00	3.00	0.00	3.50	1	48.0	168.0
	27	FTC-U22	Edge	Spalling	6.50	0.75	2.50	0.50	1	21.1	10.6
96	28	FTC-U24	Edge	Spalling	10.50	9.00	1.50	0.50	1	110.0	55.1
130	47	FTC-U24	Edge	Spalling	15.50	3.50	1.50	3.50	1	77.5	271.0
76		FTC-U26		Honeycombing	8.50	6.00	0.00	1.25	1	51.0	63.8
70	12	FTC-U29	Edge	Spalling	3.50	1.75	0.44	0.38	1	7.7	2.9
76		FTC-U31		Crack	6.75	0.01	0.00	0.03	1	0.1	0.0
76		FTC-U34		Honeycombing	7.50	5.00	1.25	1.38	1	46.9	64.7
120		FTC-U34	Edge	Spalling	10.00	5.00	0.00	0.88	1	50.0	43.8
77		FTC-U34		Honeycombing	7.50	5.00	0.00	1.38	1	37.5	51.8
77		FTC-U34		Crack	2.75	0.01	0.00	0.13	1	0.0	0.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
77		FTC-U37	Bottom Edge	Spalling	8.00	7.00	1.75	1.13	1	70.0	79.1
130	46	FTC-U37	Edge	Spalling	8.00	1.00	6.50	1.00	1	60.0	60.0
77		FTC-U37	Tongue	Spalling	27.10	3.25	0.00	3.25	1	88.1	286.0
130	46	FTC-U37	Edge	Spalling	23.00	3.50	2.00	3.50	1	126.0	443.0
	25	FTC-U50	Edge	Spalling	8.00	6.00	1.50	1.00	1	60.0	60.0
	21	FTC-U51	Edge	Spalling	10.00	7.00	1.00	0.63	1	80.0	50.0
77		FTC-U54		Parition	13.00	3.00	1.25	0.63	1	55.2	34.5
77		FTC-U54	Top Edge	Spalling	10.00	3.25	2.00	1.25	1	52.5	65.6
77		FTC-U79		Crack	5.25	0.02	0.00	0.00	1	0.1	0.0
127		FTC-U80	Inner partition	Crack	27.00	0.03	0.00	0.00	3	2.0	0.0
101		FTC-U80	Top Edge	Spalling	7.75	1.38	3.13	0.75	1	35.0	26.2
127		FTC-U80	Inner partition	Crack	10.50	0.02	0.00	0.00	1	0.2	0.0
120		FTC-U86		Honeycombing	49.00	3.00	0.00	1.25	1	147.0	184.0
123		FTC-U87	Inner partition	Spalling	11.00	3.25	0.00	1.25	1	35.8	44.7
123		FTC-U90	Inner partition	Spalling	24.00	8.50	0.00	2.00	1	204.0	408.0
132		FTC-U91	Edge	Spalling	57.00	3.50	3.50	0.50	1	399.0	200.0
77		FTC-B1A	Top Edge	Spalling	4.19	2.75	1.25	0.38	1	16.8	6.3
76		FTC-B8	Edge	Spalling	2.00	1.50	0.88	0.25	1	4.8	1.2
77		FTC-B10	Top Edge	Spalling	8.50	3.13	2.25	1.13	1	45.7	51.7
77		FTC-B13	Top Edge	Spalling	6.00	2.00	1.88	1.00	1	23.3	23.3
76		FTC-B15	Edge	Spalling	6.00	2.13	1.38	1.13	1	21.1	23.8
90	20	FTC-B26	Edge	Spalling	12.50	3.25	0.63	0.50	1	48.4	24.2
89	19	FTC-B28	Edge	Spalling	7.00	4.00	0.75	0.75	2	66.5	49.9
104		FTC-B34	Edge	Spalling	5.50	0.88	6.00	0.88	1	37.8	33.1
102		FTC-B72	Edge	Spalling	24.00	1.88	16.00	1.88	1	429.0	807.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
131		FTC-B79	Liftlug	Spalling	0.63	0.50	0.00	1.25	5	1.6	2.0
82		FTC-P4	Edge	Spalling	3.00	2.00	1.00	2.00	0	0.0	0.0
87		FTC-P4	Edge	Spalling	3.00	2.00	1.00	2.00	2	18.0	36.0
116		FTC-P7	Edge	Spalling	6.00	2.38	1.00	1.25	1	20.3	25.4
156		FTC-P10	Corner	Spalling	7.00	3.25	7.00	0.00	1	71.8	0.0
82		FTC-P11	Edge	Spalling	2.00	2.50	1.25	0.13	2	15.0	1.9
82		FTC-P13	Edge	Spalling	2.88	2.00	0.94	0.50	1	8.5	4.2
82		FTC-P17	Edge	Spalling	3.00	1.63	0.81	0.88	2	14.7	12.8
	29	FTC-P38	Edge	Spalling	5.00	0.44	1.75	0.25	1	10.9	2.7
156		FTC-P40	Edge	Spalling	5.00	2.50	1.25	0.75	1	18.8	14.1
158		FTC-P42	Corner	Spalling	4.50	2.00	4.50	0.00	1	29.2	0.0
	23	FTC-P46	Wall	Crack	9.00	0.01	0.00	0.00	2	0.2	0.0
82		FTC-P48	Edge	Spalling	8.50	6.50	3.04	1.75	1	81.1	142.0
87		FTC-P48	Edge	Spalling	8.50	6.50	2.00	1.75	1	72.2	126.0
	23	FTC-P50	Wall	Crack	4.50	0.01	0.00	0.00	1	0.0	0.0
116		FTC-P58	Edge	Spalling	3.38	2.50	0.50	0.50	1	10.1	5.1
	31	FTC-P60	Liftlug	Spalling	0.00	0.00	0.00	0.50	1	0.0	0.0
87		FTC-P62		Honeycombing	14.00	1.00	0.00	1.62	1	14.0	22.7
87		FTC-P62		Honeycombing	16.00	1.00	0.00	1.03	1	16.0	16.5
87		FTC-P64		Honeycombing	19.00	1.00	0.00	1.48	1	19.0	28.1
156		FTC-P64	Edge	Spalling	5.25	2.88	1.00	0.75	1	20.4	15.3
156		FTC-P66	Corner	Spalling	6.50	6.00	6.50	0.00	1	81.2	0.0
	29	FTC-P69		Crack	3.00	0.01	0.00	0.00	1	0.0	0.0
156		FTC-P84	Edge	Spalling	13.50	2.63	1.00	0.63	1	49.0	30.9
119		FTC-P84	Edge	Spalling	15.30	2.25	8.50	2.13	1	164.0	350.0
119		FTC-P84	Edge	Spalling	5.00	4.50	1.75	0.25	1	31.2	7.8
108		FTC-P88	Edge	Spalling	4.00	2.38	0.94	0.50	1	13.3	6.6
108		FTC-P88		Crack	2.50	0.01	0.00	0.00	1	0.0	0.0

Table 9. (continued).

SNR	NCR	Component ID[a]	Where Damaged	Nonconforming Condition	Length (in)	Width 1 (in)	Width 2 (in)	Depth (in)	Number of Defects	Defect Area (in^2)	Defect Volume (in^3)
156		FTC-P90	Edge	Spalling	5.75	2.13	0.88	0.75	1	17.3	13.0
27		PA-U2	Wall	Bughole	2.25	2.25	0.00	0.11	1	5.1	0.6
27		PA-B1	Wall	Bughole	1.88	1.88	0.00	0.26	4	14.1	3.7
27		PA-B2	Wall	Bughole	1.88	1.88	0.00	0.26	4	14.1	3.7
154		PA-PA1	Edge	Spalling	6.25	2.75	2.00	0.00	1	29.7	0.0
154		PA-PA2	Edge	Spalling	5.00	1.00	2.25	0.75	1	16.2	12.2
28		PA-P1	Edge	Spalling	1.50	3.00	3.00	0.37	1	9.0	3.3
12		PA-P1	Wall	Bughole	2.00	2.00	0.00	0.23	1	4.0	0.9

a. U=upper riser, B=base, P=plug in the component ID.

b. Component NP-B2 was rejected based on the maximum crack width and the number of cracks found in this component. The defect/damage and crack dimensions are reported here for completeness.

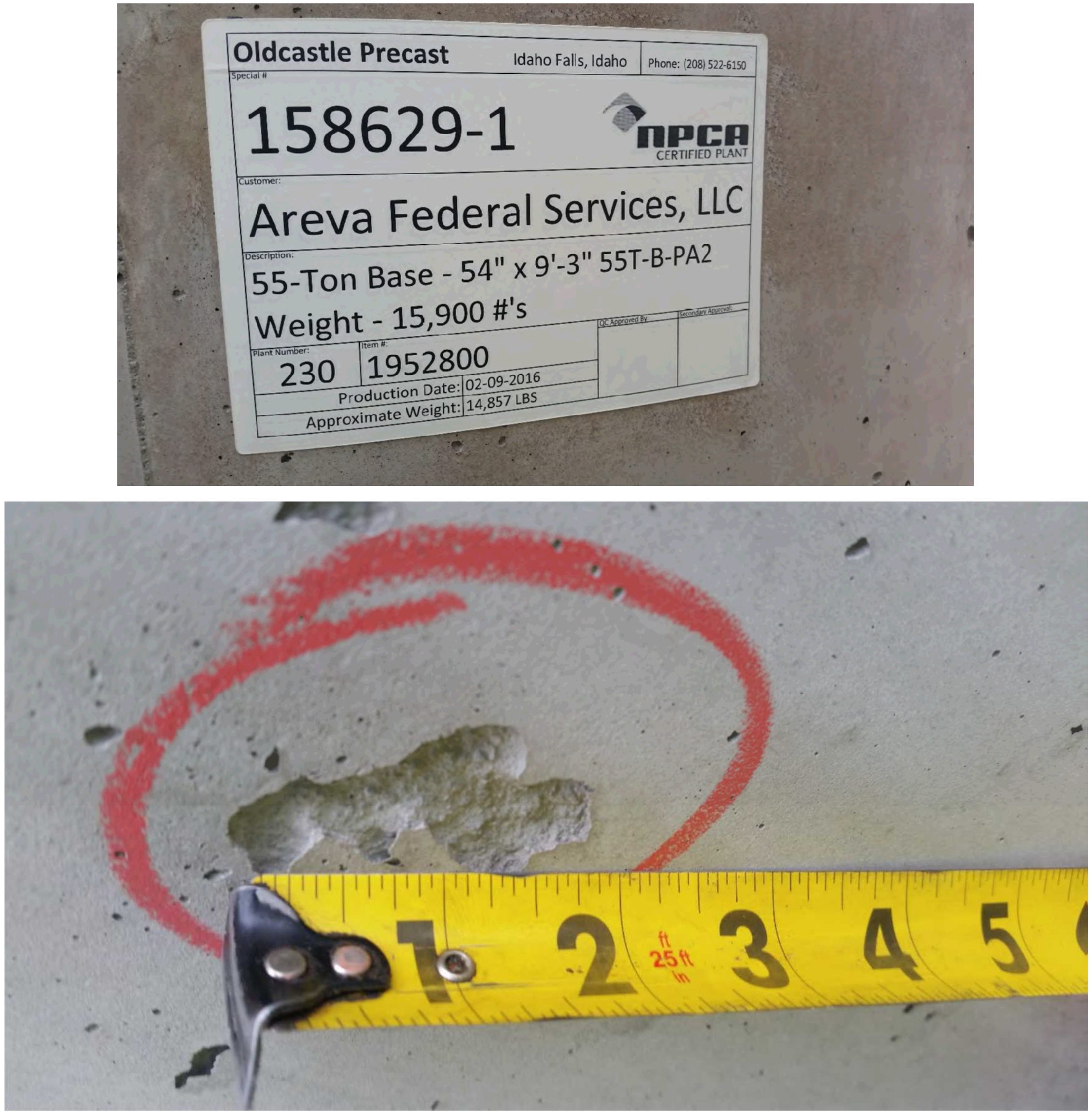


Figure 4. Example photograph of a bughole with measurement from SNR-027. The damage relative to the component dimensions is quantified in Table 9 and is insignificant.

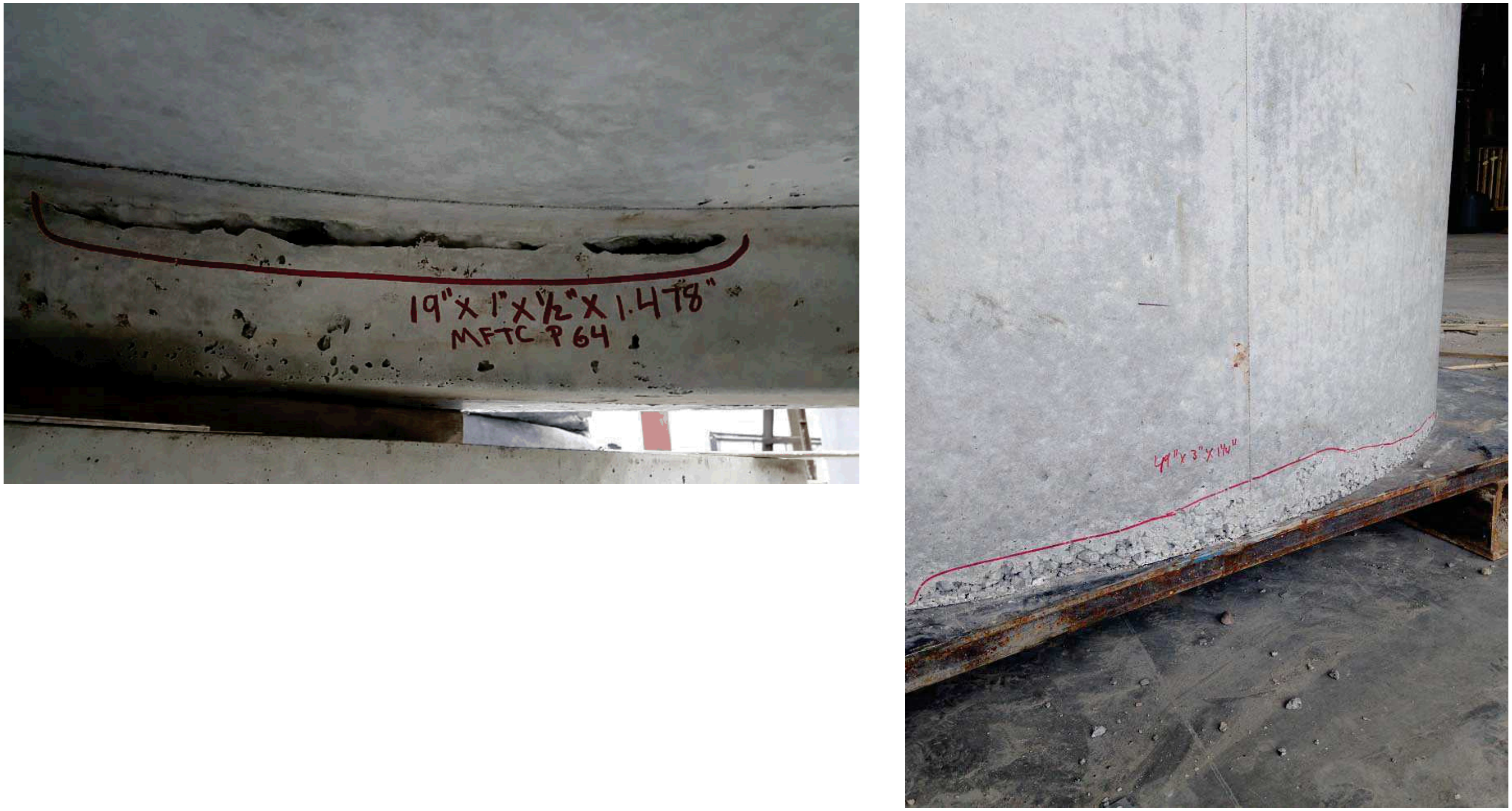


Figure 5. Example photograph of honeycombing along tongue edge from SNR-087 (left) and along bottom edge from SNR-120 (right). The damage relative to the component dimensions is quantified in Table 9 and is insignificant.

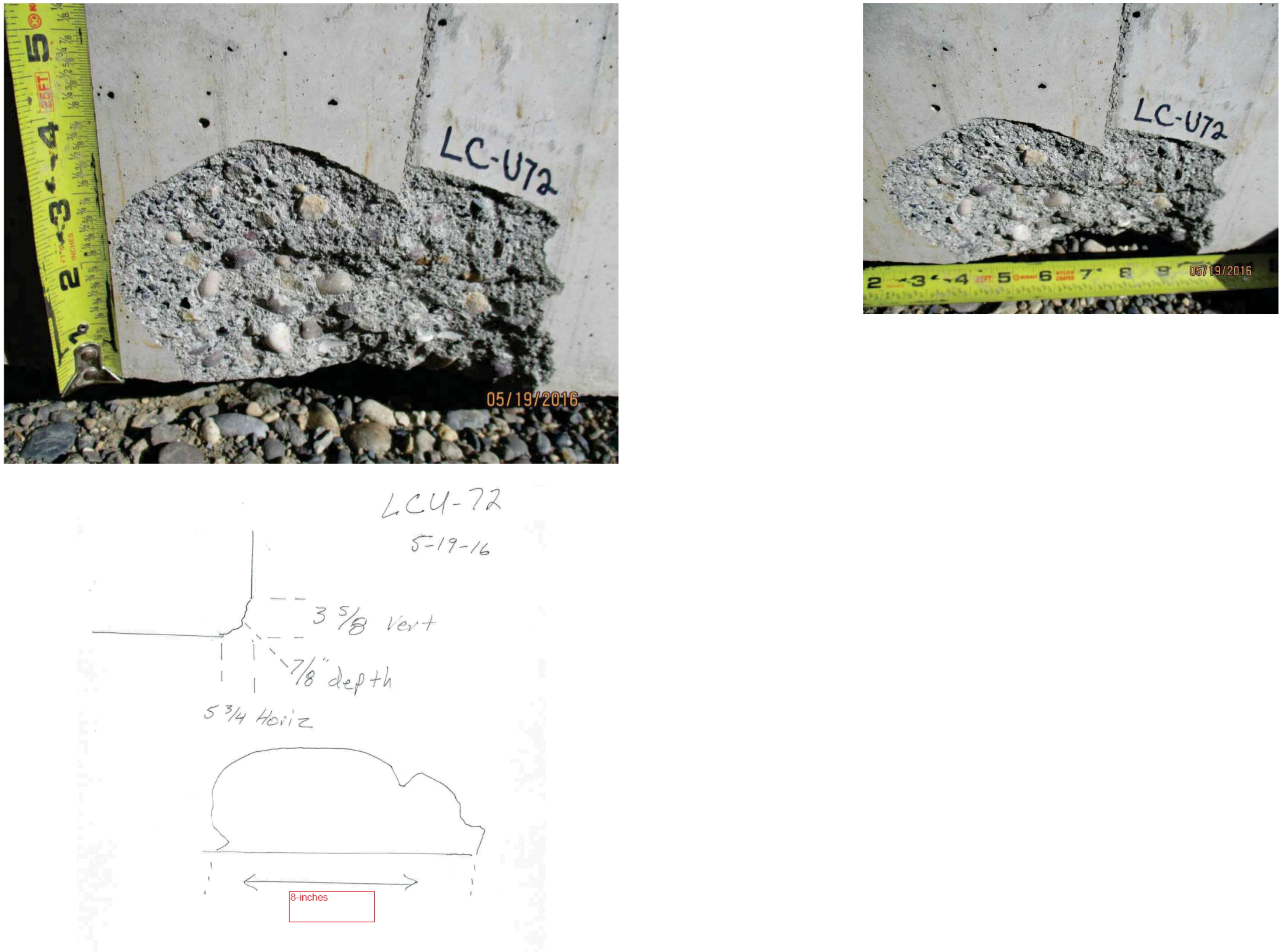


Figure 6. Diagram and photos showing the dimensions for damage during shipping for LCC vault riser LCU-72 from NCR-013. The damage relative to the component dimensions is quantified in Table 9 and is insignificant.

Figure 7. Example photograph of spalling on plug LC-P29 before and after repair from SNR-108. The damage relative to the component dimensions is quantified in Table 9 and is insignificant.

Figure 8. Level 3 crack with a width 0.03-in. on component HFEF-U5 from SNR-056 (left) and portion of crack in component LC-U1, exceeding 0.01-in. width from SNR-077. Note the widest cracks occur on the portion of the component not credited for durability; the longest crack parallels a seam in the concrete form. The damage relative to the component dimensions is quantified in Table 9 and is insignificant.

Table 10. Summary of Level 3 concrete component defects and damage by component type and vault array.

Vault Upper Riser Sections									
	Component Data			Summary Defect Data			Defect Impact to Components in Array		
Array	Number of Upper Risers in Array	Surface Area of a Single Upper Riser (in.^{2})	Volume of a Single Upper Riser (in.^{3})	Number of Upper Risers with Defects	Defect Area in Upper Risers (in.^{2})	Defect Volume in Upper Risers (in.^{3})	Percent of Upper Risers with Defects/Damage	Percent of Total Upper Riser Surface Area with Defect/Damage in the Array	Percent of Total Upper Riser Volume with Defect/Damage in the Array
55-Ton	84	44,108	125,538	25	406	197	30	0.011	1.25E-06
LCC[a]	255	42,072	118,074	25	4,650	2,210	10	0.043	1.59E-05
HFEF[a]	15	42,072	118,074	13	1,760	1,120	87	0.279	8.03E-06
NuPac	60	52,590	147,592	36	2,900	1,390	60	0.092	6.38E-06
FTC	92	52,590	147,592	21	2,210	3,630	23	0.046	1.67E-05
PA	2	44,108	125,538	1	5.1	0.6	50	0.006	3.53E-09
Vault Base Sections									
Array	Number of Bases in Array	Surface Area of a Single Base Riser (in.^{2})	Volume of a Single Base Riser (in.^{3})	Number of Bases with Defects	Defect Area in Bases (in.^{2})	Defect Volume in Bases (in.^{3})	Percent of Bases with Defects/ Damage	Percent of Total Array Base Riser Surface Area with Defect/Damage	Percent of Total Array Base Riser Volume with Defect/Damage
55-Ton	84	44,108	125,538	30	541	220	36	0.015	1.40E-06
LCC[a]	255	42,072	118,074	54	1,020	785	21	0.010	5.63E-06
HFEF[a]	15	42,072	118,074	11	619	251	73	0.098	1.80E-06
NuPac	60	52,590	147,592	46	1,620	435	77	0.051	2.00E-06
FTC	92	52,590	147,592	10	695	1,020	11	0.014	4.68E-06
PA	2	44,108	125,538	2	28.3	7.4	100	0.032	4.66E-08
Vault Shield Plugs									
Array	Number of Plugs in Array	Surface Area of a Single Plug (in.^{2})	Volume of a Single Plug (in.^{3})	Number of Plugs with Defects	Defect Area in Plugs (in.^{2})	Defect Volume in Plugs (in.^{3})	Percent of Plugs with Defects/ Damage	Percent of Total Vault Array Plug Surface Area with Defect/Damage	Percent of Total Array Plug Volume with Defect/Damage
55-Ton	84	22,364	244,518	20	548	151	24	0.029	2.53E-07
LCC[a]	255	28,005	340,657	31	1,470	1,250	12	0.021	1.08E-06
HFEF[a]	15	28,005	340,657	7	624	761	47	0.149	6.56E-07
NuPac	60	35,951	479,995	38	2,210	1,050	63	0.102	4.56E-07
FTC	92	35,951	479,995	21	797	862	23	0.024	3.74E-07
PA	2	22,364	244,518	3	58.9	16.4	150	0.132	2.74E-08

a HFEF and LCC vaults are located in the same array.

4.4.1 Physical Investigation and Repair of Vault Component Cracks

Cracking exceeding the 0.01-in. width limit imposed by PLN-5460 and PLN-5077 was more frequently observed in the more massive concrete components (such as the vault plugs and interior void partition areas of the HFEF and FTC upper risers and bases) as indicated in Table 9. In some of these components, the width of the crack apparently increased from the time of initial inspection to the time of installation, which in some cases was several months, or were discovered during installation (i.e., see NCR-29). This phenomenon is explained in the attachment found in Appendix A. Simply, as reinforced concrete cures and hydrates, there is an enormous amount of heat generated that results in thermal expansion and contraction of the concrete components during the months-long curing process. In addition, there are local temperature changes that affect the surface temperature of the more massive components requiring very long time periods to cure. Per the Portland Cement Association Design and Control of Concrete Mixtures:

> "As the interior concrete increases in temperature and expands, the surface concrete may be cooling and contracting. This causes tensile stresses that may result in thermal cracks at the surface if the temperature differential between the surface and center is too great. The width and depth of cracks depends upon the temperature differential, physical properties of the concrete, and the reinforcing steel."

Therefore, for the more massive components, surface cracking and increase over time of crack widths is expected.

In standard practice, the depth of cracking is controlled by the depth of concrete covering the steel-reinforcing materials. Based on requirements of the RH-LLW Disposal Facility project, at least 2-in. of concrete cover was required for the plugs and riser sections, and prior to pouring the concrete, the rebar depth was inspected and verified to meet the requirements. The temperature environment was controlled during initial component curing and the physical properties of the concrete include high compressive (and, therefore, tensile) strength. The concrete mix design, pouring, and curing process limited cracking to very few components (as noted in Table 9).

Crack widths smaller than 0.01-in. are allowable in these inspection plans based on their potential to heal autogenously as discussed in Section 4.2. Potentially non-healing cracks (i.e., those exceeding the 0.01-in. width limit imposed by the project) were evaluated further based on the relative importance of concrete cracking to concrete strength and durability. In this evaluation, physical crack depths were investigated as reported in SNR-086, SNR-124, and SNR-45 with a letter of explanation provided as Appendix A. These investigations show that the depth of shrinkage cracks exceeding the 0.01-in. Level 3 crack width limit ranged from 3/8 to 5/8-in. for representative cracks in plug NP-P7 (see SNR-087), 0.448-in. for the longer 47-in. crack found in plug LC-P95 (see SNR-124), and 1/32-in. for the 48-in. long crack found in upper riser NP-U19. From these investigations, the maximum crack depth associated with shrinkage cracks in these reinforced concrete components are roughly equivalent to the 1/2-in. concrete loss allowable for honeycombing, bugholes, and spalling.

Cracks widths 0.01-in. or larger were repaired by the RH-LLW Disposal Facility project. Cracks were repaired in order to prevent water from entering them and possibly leading to premature component degradation over time. Repairs were made regardless of whether the components were installed above the freeze/thaw depth or below that depth. This determination was made in order to protect shield plugs installed above the freeze/thaw line that could be more susceptible to freeze/thaw expansion cracking and to protect the steel reinforcement from premature corrosion for components installed deeper.

5. CONCRETE TEST DATA AND ANALYSIS

The facility performance specification (SPC-1437) required the design-build contractor to provide the vault system concrete mix design and cured cylinder test plans and results. Concrete data resulting from specified analyses were recorded in either PLN-5077 or PLN-5460. Completed records are maintained in the INL Vendor Data System under Project 31055. Including specific requirements of SPC-1437, the following tests or data were specified in the *Vault Concrete Compliance Test Plan* (PLN-4956):

- Chemical Composition. These requirements were fulfilled through submittal of the *Vault Concrete Mix Design Report* (PLN-4953) and strict adherence to the concrete mix through vault fabrication as documented in the *Vault Component and Cask-To-Vault Adapting Structures (CVAS) Fabrication Quality Inspection/Test Plan* (PLN-5460 or PLN-5077) reports for each component produced at Oldcastle.
- Temperature, Unit Weight, and Yield of Fresh Concrete Samples. The minimum air-dried unit weight (density) was required to show compliance with the minimum 134 lb/ft^3 determined by the *Vault Plug Shielding Analysis* (ECAR+2747). Temperature was required for conformance to curing limitations and yield was recorded for completeness. Concrete samples were tested for density and yield in accordance with ASTM C138. Concrete samples were tested for temperature in accordance with ASTM C1064.
- Air Content. Two separate mix designs were used in fabricating the vault components as discussed in Section 3.2. Mix #2 contained an air-entraining admixture to provide freeze protection for the shield plugs and perimeter pieces installed above the frost line. Mix #3 did not contain an air-entraining admixture and was used for the vault upper risers and base sections because they were installed below the frost line. Tests were performed on fresh concrete samples in accordance with ASTM C231.
- Porosity. These requirements were fulfilled in accordance with the requirements of PLN-4956. In addition to porosity, density and absorption were provided. Porosity tests were performed on six random, hardened Mix #3 (i.e., the concrete mix used for the base and upper riser components installed below the frost line) concrete samples from each vault array (i.e., four arrays total) for a total of 24 samples. The tests were conducted to determine density, percent absorption, and percent voids in accordance with ASTM C642. Test data were collected on three of the samples at an age of 28 days and on the other three samples at an age of 90 days by Certified Testing Laboratories Inc.
- Permeability/Hydraulic Conductivity. These requirements were fulfilled in accordance with the requirements of PLN-4956. The permeability tests were performed on six random Mix #3 hardened concrete samples from each vault array (i.e., four total) for a total of 24 samples. The permeability was measured in accordance with American Petroleum Institute (API) RP 40, “Recommended Practices for Core Analysis,” at the Terra-Tek laboratories in Salt Lake City, Utah.
- Diffusivity (Chloride). Attachment 5 of PLN-4952 contains the chloride diffusivity results obtained during the concrete mix design process for both Mix #3 and Mix #2.
- Water Soluble Chloride Content. The water-soluble chloride ion content was tested to verify consistency with mix design testing according to ASTM C1218. The maximum water-soluble chloride ion content in concrete percent by weight was specified to be 0.15%.
- Compressive Strength. Concrete samples for strength tests were cured in accordance with ASTM C31, with testing performed in compliance with ASTM C39. Tests were performed at 7 days, 14 days, and 28 days. The minimum acceptable 28-day compressive strength specified by SPC-1437 was 5,000 psi.

5.1 Concrete Density, Absorption, and Porosity Data

Concrete density, absorption, and porosity were obtained for six hardened concrete samples taken from each of the four vault arrays destined to receive LLW. Data were collected according to ASTM C642. This test method provides the following:

- Oven Dried Sample Mass. Determined by placing the specimen in a forced draft oven and drying the sample at a temperature of 230 ±9°F (110 ±5°C) for no less than 24 hours, cooling in dry air to a temperature of 72 ±5°F (22 ±3°C), and determining the mass. If the specimen was comparatively dry when its mass was first determined and the second mass agrees with the first within 0.5%, consider it dry; otherwise, repeat the drying step. If the difference between values obtained from two successive values of mass exceeds 0.5% of the lesser value, return the specimens to the oven for an additional 24-hour drying period and repeat the procedure until the difference between any two successive values is less than 0.5 % of the lowest value obtained. Designate this last value to be the oven dry sample mass, which is designated value A.
- Surface Dry Mass in Air after Immersion. Determined by immersing the specimen on its edge in water at 72 ±5°F (22 ±3°C) and soaking the specimen in water for no less than 48 hours and until two successive mass values for the surface-dried sample at intervals of 24 hours show an increase in mass less than 0.5% of the larger value. Then the surface moisture is removed using a towel and the immersed surface mass is obtained, which is designated value B.
- Surface Dry Mass in Water after Immersion and Boiling. Determined by first placing the specimen in boiling water for at least 5 hours, followed by cooling through natural loss of heat for no less than 14 hours to a final temperature of 72 ±5°F (22 ±3°C). After these steps, the sample is suspended in water and weighed, which is designated value D.
- Surface Dry Mass in Air after Immersion and Boiling. Determined by first placing the specimen in boiling water for at least 5 hours, followed by cooling through natural loss of heat for no less than 14 hours to a final temperature of 72 ±5°F (22 ±3°C). After these steps, the sample is dried and weighed, which is designated value C.
- Absorption after immersion: $Absorption_i\ \% = \left[\frac{B-A}{A}\right] \times 100$
- Absorption after immersion and boiling: $Absorption_{ib}\ \% = \left[\frac{C-A}{A}\right] \times 100$
- Bulk density, dry: $\rho_{bulk} = \left[\frac{A}{C-D}\right] \times \rho_{water} \times 100$
- Bulk density after immersion: $\rho_i = \left[\frac{B}{C-D}\right] \times \rho_{water}$
- Bulk density after immersion and boiling: $\rho_{ib} = \left[\frac{C}{C-D}\right] \times \rho_{water}$
- Apparent density: $\rho_A = \left[\frac{A}{A-D}\right] \times \rho_{water}$
- Volume of permeable pore space (voids) = total porosity:

$$\phi_{total}\ \% = {(\rho_A - \rho_{bulk})}/{\rho_A} \times 100 = [(\mathrm{C}-\mathrm{A})/(\mathrm{C}-\mathrm{D})] \times 100$$

where:

ϕ_{total} = total porosity

A = mass of oven-dried sample in air

B = mass of surface-dry sample in air after immersion

C = mass of surface-dry sample in air after immersion and boiling

D = apparent mass of sample in water after immersion and boiling

ρ_{bulk} = bulk density, dry

ρ_A = apparent density

ρ_{water} = density of water.

Resulting data are given in Table 11 for concrete samples held for either 28 or 90 days. In Table 11, there are two samples with results for hold times at 34 and 40 days. The difference in hold time was an error by the design-build subcontractor and data are provided for information.

Data important to concrete performance include the following:

- Total Porosity. This is important to concrete durability because it can influence the penetration time for water and air to reach the steel reinforcement although the effective porosity is a more representative value to use to describe this process. The average value for total porosity was determined to be 14.3%, with a standard deviation of 1.2% and coefficient of variation of 8.7%. The porosity data are shown in Figure 9 as a function of time the test cylinder concrete was held after pouring the test cylinders prior to conducting the porosity test (i.e., the hold time). This figure shows the variability in porosity decreases with increasing hold times, with the average value equal to 14.3%, the standard deviation equal to 0.7%, and the coefficient of variation equal to 4.7% for longer hold times. This trend is typical of test data for concrete with a smaller porosity and coefficient of variation occurring as the concrete continues to cure.
- Bulk Density. This is important to the shielding function of the upper portion of the vault risers. The data shown in this table were not obtained for the shield plugs. Bulk density as reported using the methods in ASTM C642 represents a completely dry environment because the data are obtained after oven drying the samples. The average value for bulk density was determined to be 134 lb/ft^3, with a standard deviation of 3 lb/ft^3 and coefficient of variation of 2%.

For both data sets, the low coefficients of variation provide an indication that concrete components are uniform and exhibit little overall variability.

Table13 provides the statistical correlation between total porosity and other measured parameters obtained using the ASTM C642 methods. The P-value less than 0.15 for dry bulk density, wet density, apparent density, and wet absorption indicates a relatively high degree of correlation for these parameters to total porosity. As substantiated by the similarity in average value and standard deviation, total porosity is less strongly correlated to the number of days the samples were held prior to taking the test data.

Table 14 provides concrete batch ticket (i.e., mix ticket) data for each of the tested samples. This table contains the amount of aggregate (i.e., gravel and sand) added to the cement, the pozzolan (i.e., flyash) amounts, and the water/cement ratio given in Column 8. The amounts of admixtures used in each of the tested concrete batches are provided in Columns 9 through 11. Summary statistics for concrete components indicate the water/cement ratio is within specifications and the highest variability in concrete component quantities occurs with the accelerator with a coefficient of variation equal to 14%. Variability in water added is accounted for in the water/cement ratio, which accounts for moisture content of the aggregate.

The variation in porosity could partially be accounted for by variation in the NC534 accelerator shown by the low P-value in Table 14. However, there is little correlation with porosity and water/cement ratio or with the Glenium superplasticizer.

Table 11. Concrete density, absorption, and porosity data.

Sample Name	Batch ID	Dates (2016)			Mass (g)				Density (lb/ft^3)				Absorption %		Total Porosity % (ϕ_{total})
		Poured	Tested	Held Days	Oven Dry	Surface Dry in Air after Immersion	Surface Dry in Air after Immersion and Boiling	Apparent in Water after Immersion and Boiling	Dry Bulk (ρ_{bulk})	After Immersion	After Immersion and Boiling	Apparent (ρ_A)	Dry	Wet	
PorNuPac1	51958	2/9	3/14	34	1,134	1,188.5	1,188.4	676.4	137.9	144.8	144.8	154.8	4.8	4.8	10.9
PorNuPac2	51958	2/9	5/9	90	1,093.8	1,177.1	1,178.5	644.6	127.9	137.3	137.9	152.3	7.6	7.7	16
PorNuPac3	52148	2/19	3/18	28	1,019.2	1,099.5	1,102.6	600.8	126.7	136.7	137.3	152.3	7.9	8.2	16.8
PorNuPac4	52148	2/19	5/19	90	1,094.1	1,165.3	1,165.1	654.9	133.5	142.3	142.3	155.4	6.5	6.5	14.1
PorNuPac5	52948	3/23	6/21	90	1,320.5	1,412.3	1,411.2	790.4	132.9	141.6	141.6	155.4	7	6.9	14.5
PorNuPac6	53325	4/4	5/2	28	1,150	1,216.8	1,218.2	697.2	137.9	146	146	158.5	5.8	5.9	13
Por-HFEF/LCC-1	53374	4/5	5/3	28	1,128.4	1,206.9	1,207.5	676.7	132.9	141.6	141.6	156	7	7	14.8
Por - HFEF/LCC-2	53441	4/7/	7/6	90	1,337	1,418.4	1,421.5	808.3	136	144.1	144.8	157.9	6.1	6.3	13.8
Por - HFEF/LCC-3	53572	4/12	5/10	28	1,103.2	1,183.5	1,183.2	659.3	131.7	141	141	155.4	7.3	7.2	15.3
Por-HFEF/LCC-4	55073	5/24	8/22	90	1,120.5	1,189.7	1,189.8	674.3	135.4	144.1	144.1	156.6	6.2	6.2	13.5
Por-HFEF/LCC-5	56103	6/22/	9/20	90	1,106	1,177.6	1,180.6	669.4	134.8	143.5	144.1	157.9	6.5	6.7	14.6
Por-HFEF/LCC-6	56430	7/1	8/3	28	1,347	1,437	1,440.9	614.3	134.2	142.9	143.5	157.9	6.7	7	15
Por-55T-1	53408	4/6	5/4	28	1,135.4	1,200.5	1,199.8	685.5	137.9	145.4	145.4	157.2	5.7	5.7	12.3
Por-55T-2	53485	4/8	7/7	90	1,353.3	1,438.7	1,441.7	814.6	134.8	142.9	143.5	156.6	6.3	6.5	13.9
Por-55T-3	54115	4/27	7/26	90	1,339.1	1,422.6	1,422.8	803.9	134.8	143.5	143.5	156	6.2	6.3	13.6

Table 11. (continued).

Sample Name	Batch ID	Dates (2016)			Mass (g)				Density (lb/ft^3)				Absorption %		Total Porosity % (ϕ_{total})
		Poured	Tested	Held Days	Oven Dry	Surface Dry in Air after Immersion	Surface Dry in Air after Immersion and Boiling	Apparent in Water after Immersion and Boiling	Dry Bulk (ρ_{bulk})	After Immersion	After Immersion and Boiling	Apparent (ρ_A)	Dry	Wet	
Por-55T-4	55077	5/24	8/22	90	1,123.3	1,197.2	1,197.4	676.1	134.2	143.5	143.5	156.6	6.6	6.6	14.3
Por-55T-5	55446	6/3	7/13	40	1,331.9	1,419.8	1,423.9	804.8	134.2	142.9	143.5	157.9	6.6	6.9	15
Por-55T-6	55604	6/8	7/6	28	1,304.1	1,396.6	1,403	788.2	132.3	141.6	142.3	157.9	7.2	7.6	16.2
Por-MFTC-1	53516	4/11	5/9	28	1,078.7	1,150.6	1,150.5	646.4	133.5	142.3	142.3	156	6.7	6.7	14.4
Por-MFTC-2	53762	4/18	5/16	28	1,130.5	1,202.6	1,204.9	681.6	134.8	143.5	143.5	157.2	6.4	6.6	14.3
Por-MFTC-3	54593	5/11	8/9	90	1,381	1,469.7	1,472.3	832.3	134.8	143.5	143.5	157.2	6.4	6.6	14.3
Por-MFTC-4	54968	5/20	8/18	90	1,348.4	1,434.3	1,434.7	810.6	134.8	143.5	143.5	156.6	6.4	6.4	13.9
Por-MFTC-5	55840	6/15	9/13	90	1,123.3	1,197.9	1,201.1	677.5	134.2	142.9	142.9	157.2	6.6	6.9	14.7
Por-MFTC-6	54968	6/29	7/27	28	1,338.7	1,427	1,430.4	808.9	134.2	143.5	143.5	157.9	6.6	6.8	15
Minimum					1,019	1,100	1,103	601	127	137	137	152	5	5	10.9
Maximum					1,381	1,470	1,472	832	138	146	146	159	8	8	16.8
Average					1,200	1,278	1,280	713	134	143	143	156	7	7	14.3
Standard Deviation					118	125	126	74	3	2	2	2	1	1	1.2
Coefficent of Variation %					10	10	10	10	2	2	1	1	10	10	8.7

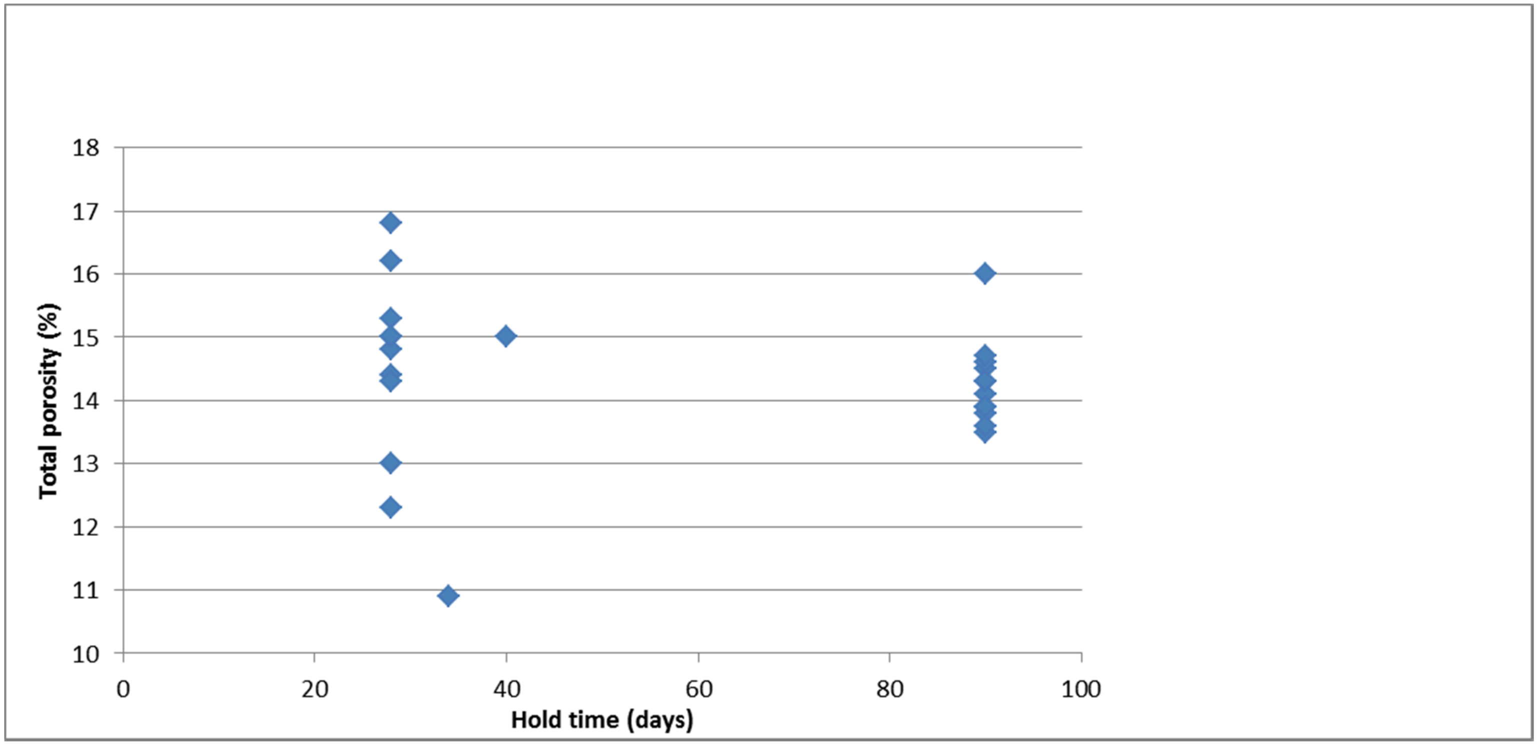


Figure 9. Total porosity as a function of hardened concrete hold time prior to testing.

Table 12. Correlation between total porosity and other measured values from ASTM C642 data.

Regression Statistics	
Multiple R	0.9999
R Square	0.9998
Adjusted R Square	0.9996
Standard Error	0.0247
Observations	24

ANOVA

	df	SS	MS	F	Significance F
Regression	11	3.47E+01	3.16E+00	5.17E+03	2.78E-20
Residual	11	7.32E-03	6.10E-04		
Total	22	3.47E+01			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	1.32E+01	1.78E+00	7.40E+00	8.23E-06	9.30E+00	1.71E+01	9.30E+00	1.71E+01
Held days	-6.49E-05	2.20E-04	-2.96E-01	7.73E-01	-5.43E-04	4.14E-04	-5.43E-04	4.14E-04
Oven dry mass	-1.71E-02	1.64E-02	-1.04E+00	3.18E-01	-5.28E-02	1.87E-02	-5.28E-02	1.87E-02
Surface dry mass in air after immersion	1.92E-02	2.31E-02	8.32E-01	4.22E-01	-3.10E-02	6.94E-02	-3.10E-02	6.94E-02
Surface dry mass in air after immersion and boiling	-3.21E-03	1.81E-02	-1.78E-01	8.62E-01	-4.26E-02	3.62E-02	-4.26E-02	3.62E-02
Apparent mass in water after immersion and boiling	8.88E-05	1.57E-04	5.67E-01	5.81E-01	-2.52E-04	4.30E-04	-2.52E-04	4.30E-04
Dry bulk density (ρ_{bulk})	-5.74E-01	2.89E-02	-1.98E+01	1.55E-10	-6.37E-01	-5.11E-01	-6.37E-01	-5.11E-01
Wet density (ρ_{wet})	8.37E-02	3.56E-02	2.35E+00	3.65E-02	6.18E-03	1.61E-01	6.18E-03	1.61E-01
Wet density after immersion and boiling	-6.60E-02	4.10E-02	-1.61E+00	1.34E-01	-1.55E-01	2.34E-02	-1.55E-01	2.34E-02
Apparent density (ρ_A)	4.80E-01	3.75E-02	1.28E+01	2.37E-08	3.98E-01	5.62E-01	3.98E-01	5.62E-01
Dry absorption	-3.31E-01	2.41E-01	-1.37E+00	1.94E-01	-8.55E-01	1.94E-01	-8.55E-01	1.94E-01
Wet absorption	3.98E-01	1.49E-01	2.67E+00	2.03E-02	7.36E-02	7.23E-01	7.36E-02	7.23E-01

Table 13. Concrete porosity and density versus batch ticket data.

Sample Name	Cement (lb)	Flyash (lb)	Gravel (lb)	Sand (lb)	Water (gal)	Prewater (gal)	Water/Cement Ratio (w/cm)	Glenium (oz) Superplasticizer	NC534 (oz) Accelerator	ASR 30 (oz) Lithium
PorNuPac1	1,162	320	2,870	2,770	32.8	24.8	0.3700	45	440	488
PorNuPac2	1,162	320	2,870	2,770	32.8	24.8	0.3700	45	440	488
PorNuPac3	1,162	320	2,780	2,830	45.8	24.3	0.3700	50	360	488
PorNuPac4	1,162	320	2,780	2,830	45.8	24.3	0.3700	50	360	488
PorNuPac5	1,160	320	2,810	2,785	37	24.3	0.3720	45	398	488
PorNuPac6	1,158	320	2,790	2,850	39.5	24.5	0.3710	45	400	488
Por-HFEF/LCC-1	1,164	320	2,800	2,920	34.3	24.5	0.3700	400	488	1,164
Por -HFEF/LCC-2	1,158	320	2,785	2,825	45.3	24.5	0.3740	300	488	1,158
Por -HFEF/LCC-3	1,160	320	2,790	2,790	43.8	24.3	0.3710	400	488	1,160
Por-HFEF/LCC-4	1,158	320	2,805	2,915	32	24.5	0.3710	400	488	1,158
Por-HFEF/LCC-5	1,158	320	2,785	2,825	45.3	24.5	0.3710	300	488	1,158
Por-HFEF/LCC-6	1,160	320	2,790	2,880	37.3	24.5	0.3700	250	488	1,160
Por-55T-1	1,158	320	2,785	2,880	41.8	24.5	0.3700	46	400	488
Por-55T-2	1,156	320	2,810	2,745	38	24.5	0.3720	44	400	488
Por-55T-3	1,156	320	2,785	2,885	40	24.3	0.3690	45	400	488
Por-55T-4	1,156	320	2,805	2,880	32	24.5	0.3700	45	400	488
Por-55T-5	1,162	320	2,790	2,866	37.8	24.5	0.3710	52	300	488
Por-55T-6	1,158	320	2,795	2,810	38.8	24.8	0.3710	47	300	488
Por-MFTC-1	1,160	320	2,795	2,800	45	24.5	0.3700	44	400	488
Por-MFTC-2	1,160	320	2,790	2,820	45.3	24.5	0.3700	45	400	488
Por-MFTC-3	1,160	320	2,800	2,805	43.3	24.5	0.3700	47	400	488
Por-MFTC-4	1,158	320	2,800	2,880	33.5	24.5	0.3720	47	400	488
Por-MFTC-5	1,160	320	2,780	2,875	37.5	24.5	0.3700	46	300	488
Por-MFTC-6	1,158	320	2,785	2,850	40.3	24.5	0.3690	250	488	1,158
Minimum	1,156	320	2,780	2,745	32	24.3	0.3690	43	250	488
Maximum	1,164	320	2,870	2,920	46	25	0.3740	52	440	488
Average	1,159	320	2,800	2,836	39	24	0.3706	46	372	488
Standard Deviation	2	0	24	48	5	0	0.0011	2	52	0
Coefficent of Variation %	0	0	1	2	13	1	0.2968	5	14	0

Table 14. Correlation data for concrete porosity as a function of concrete mix components.

Regression Statistics	
Multiple R	0.41
R Square	0.17
Adjusted R Square	0.04
Standard Error	1.20
Observations	24

ANOVA

	df	SS	MS	F	Significance F
Regression	3	5.81	1.94	1.34	0.29
Residual	20	28.91	1.45		
Total	23	34.72			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	6.34E+01	8.66E+01	7.33E-01	4.72E-01	-1.17E+02	2.44E+02	-1.17E+02	2.44E+02
Water/cement ratio (w/cm)	-1.32E+02	2.37E+02	-5.57E-01	5.84E-01	-6.25E+02	3.62E+02	-6.25E+02	3.62E+02
Glenium superplasticizer	5.92E-02	1.06E-01	5.57E-01	5.84E-01	-1.62E-01	2.81E-01	-1.62E-01	2.81E-01
NC534 accelerator	-8.16E-03	4.43E-03	-1.84E+00	8.02E-02	-1.74E-02	1.08E-03	-1.74E-02	1.08E-03

5.2 Permeability Test Data

Air-saturated permeability tests were obtained for six random Mix #3 hardened concrete samples from each vault array. Tests were performed by TerraTek, a subsidiary of Schlumberger, using methods recommended by API RP-40. The following test methods were applied to samples dried at 104ºC until the weights were stable:

- Helium Porosimetry. Helium expansion was used to determine grain volume, using the Boyles' Law technique. Gas porosimetry (for grain volume) is based on Boyle's Law, which holds that for an ideal gas, at constant temperature, the volume of the gas will vary inversely with pressure according to: $\frac{P_1}{P_2} = \frac{V_2}{V_1}$, where P_1 is the initial pressure in the initial volume V_1 and P_2 is the final pressure at volume V_2. The porosimeter consists of a steel vessel connected to a gas reservoir through high-pressure tubing. The porosimeter is calibrated by placing a series of steel billets of known volume into a gas expansion chamber. Calibration consists of sequentially increasing volume V_2 by known amounts. As V_2 increases, the ratio P1/P2 also increases. Linear regression is performed to determine the relationship between the measured ratio, P_1/P_2, and the sample volume such that: $V_s = m \times \frac{P_1}{P_2} + b$. The experimentally determined slope, *m*, thus gives the proportionality between the sample volume and the pressure ratio; whereas the Vs intercept, *b*, represents the zero offset (i.e., due to the dead volume in the porosimeter). These values of *m* and *b* are used in subsequent measurements of grain volume. To determine grain density, the billets are replaced by the sample, and the resultant pressure is measured, allowing calculation of V_g.
  - Bulk volume V_b was determined from the fluid volume displaced by the submerged test sample.
  - Sample masses were determined using electronic balances.
  - Effective porosity was calculated as: $= 1 - \frac{\rho_d}{\rho_g}$, where ρ_d is the dry bulk density and ρ_g is the grain density.
  - Grain density was determined as: $\rho_g = \frac{m_d}{V_g}$, where md is the mass of the dry sample and V_g is the corresponding grain volume.
  - Grain volume, Vg was determined using the Boyle's Law double cell technique. The specimens were not subject to confining stress during the tests.
- Single-Phase Gas Permeability (Nitrogen). Gas-phase permeability was measured at four different hydrostatic-confining pressures using the pressure fall off method (API RP 40 6.4.1.1, Pressure-Falloff, Axial Gas Flow). During the tests, the pore fluid was nitrogen gas and the samples were jacketed in Viton tubing to prevent fluid bypassing the sample. Gas permeability k_g was calculated using the Darcy equation modified for a compressible gas:

$$k_g = -\frac{Q_2}{A}\left[\frac{2P_2L}{P_2^2 - P_1^2}\right]\mu = v_2\left(\frac{P_2}{P_m}\right)\left(\frac{L}{\Delta P}\right)\mu$$

  where $v_2 = Q_2/A$ and Q_2 is the volumetric flow rate (or "discharge rate") at the downstream end, A is the cross-sectional area of the sample, P_1 and P_2 are the gas pressures at the upstream and downstream reservoirs, μ is the gas viscosity, L is the length of the sample in the macroscopic flow direction, and $P_m = ½(P_1+P_2)$.

Resultant data are given in Table 16 for the 24 hardened concrete samples. Table 16, Column 1 contains the sample designator and Column 2 contains the concrete batch ticket number. Columns 3 through 5 contain the dates the test cylinders were poured, the dates the permeability data were measured, and the hold time between the two dates. Columns 6 through 8 contain the as-received concrete sample density, the dry density after oven drying, and the calculated grain density used to determine effective porosity. Column 9 contains effective porosity that can be compared to total porosity given in Table 11. Gas-phase (nitrogen) permeability is given in milliDarcies in Columns 10 through 13 at increasing confining pressures as indicated in the table header.

Data important to concrete performance include the following:

- Dry Bulk Density. This is important to the shielding function of the upper portion of the vault risers. The data shown in Table 16 were not obtained for the shield plugs. The dry density reported in Table 16 can be compared to the bulk density reported using the methods in ASTM C642 in Table 11. The average value for bulk density using the ASTM C642 method for concrete samples with hold times of 28 to 90 days was determined to be 134 lb/ft^3 with a standard deviation of 3 lb/ft^3 and a coefficient of variation of 2%. Using the AP RP-40 method, the average dry bulk density for concrete samples ranging in hold times of 15 to 104 days is 135 lb/ft^3, with a standard deviation of 3 lb/ft^3 and a coefficient of variation of 2.1%. Therefore, the dry bulk density using both methods is equivalent.

- Effective Porosity. Effective porosity is more useful than total porosity provided in Section 5.1 because it gives a measure of the interconnected pore space influencing travel times for chemicals, air, and water. The average effective porosity was determined to be 11.9% compared to a total porosity of 14.3%, with a standard deviation of 1.2 % (compared to 1.2% for total porosity) and coefficient of variation of 10.2%. While the average effective porosity is smaller than the average total porosity, the standard deviations and coefficient of variation for effective porosity is equivalent or higher. This is attributable to the wider range in hold times prior to sample testing as explained in Section 5.1. For comparison, Figure 10 provides effective porosity versus total porosity for samples having the same batch ticket number. While this figure is somewhat informative, note that sample hold times where not equivalent for each measured value, making direct use of the data problematic.

  During the concrete mix-design selection process, four cured concrete samples were tested using the same procedure by TerraTek. The reported values are shown in Figure 11. The range of effective porosity values was 9.73 to 11.76%, which is lower than the values measured on the cured concrete cylinders tested during production of the prefabricated concrete components.

- Gas-Phase Permeability at Low Confining Pressures. Gas-phase permeability is important to concrete durability because it determines the flow rate of gases through concrete under given pressure gradients and can be scaled to determine the water-phase flow rate through concrete. Gas-phase permeability for all confining pressures is given in Figure 12. As shown in the figure, the gas-phase permeability decreases with increasing confining pressure as the confining pressure exerts a higher stress field on the core sample. Gas-phase permeability under low confining pressures is more appropriate for the vault component than under high confining pressures because of the shallow burial and relatively loose fill around the vaults during operations and after the final engineered cover is emplaced. At 500-psi confining pressure, the average gas-phase permeability was reported to be 0.083 mDarcy with a standard deviation of 0.014 mDarcy and coefficient of variation of 16.76%. The range of gas-phase permeability was 0.045 to 0.1 mDarcy, which is quite small.

  During the concrete mix-design selection process, four cured concrete samples were tested using the same procedure by TerraTek. The reported values are shown in Figure 11. At a confining pressure of 500 psi, the range of values was 0.031 to 0.045 mDarcy, which is lower than the values measured on the cured concrete cylinders tested during production of the prefabricated concrete components.

Given that the range in hold times is quite large for these data, the relatively small coefficient of variation for dry bulk density, and effective porosity shows that concrete component properties are uniform with very little overall variability.

Table 17 provides the statistical correlation between the gas-phase permeability at 500-psi confining pressure and other measured parameters obtained using the API RP-40 methods. The P-value less than 0.1 for dry bulk density, grain density, and effective porosity indicates a relatively high degree of correlation for these parameters to gas-phase permeability, although a linear relationship between gas-phase permeability and effective porosity is not apparent (see Figure 13).

Table 18 provides the concrete batch ticket (i.e., mix ticket data) for each of the tested samples. This table contains the amount of aggregate (i.e., gravel and sand) added to the cement, the pozzolan (i.e., flyash) amounts, and the water/cement ratio given in Column 8. The amounts of admixtures used in each of the tested concrete batches are provided in Columns 9 through 11. Summary statistics for the concrete components indicate that the water/cement ratio is within specifications and the highest variability in concrete component quantities occurs with the accelerator with a coefficient of variation equal to 15%. Variability in the water added is accounted for in the water/cement ratio, which accounts for the moisture content of the aggregate.

Variation in gas-phase permeability is not attributable to variation in the NC534 accelerator as shown by the low P-value in Table 19. Additionally, there is little correlation between permeability and water/cement ratio or with the Glenium superplasticizer.

5.3 Chloride Diffusion Coefficient

The apparent diffusion coefficient for chloride was obtained during the concrete mix design process for Mix #2 and Mix #3 using ASTM C1556-11a, "Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion." Results are shown in Figures 14 and 15 and are reproduced from PLN-4952. The diffusion coefficient for Mix #2 was determined to be 1.6E-12 m^2/sec and 1.7E-12 m^2/sec for Mix #3.

5.4 Density and Compressive Strength Test Data

Fresh concrete density and compressive strength were measured for each component fabricated (a total of 448 bases, risers, and plugs; two CVASs, and 247 perimeter blocks). Dry density at 14 and 28-days was also measured for all plugs, perimeter blocks, and CVASs. Individual measurements are recorded on either PLN-5077 or PLN-5460. Completed records are maintained in the INL Vendor Data System under Project 31055. Summary statistical analyses are provided in Table 15.

Design criteria for dry density was determined via calculation for radiation shielding performance (ECAR-2747). It was determined that plugs and CVASs should have a minimum dry density of 134 pounds per cubic foot (pcf); no minimum dry density requirement was established for the vault bases and risers. Design criteria for compressive strength is identified in SPC-1437 as a minimum 28-day compressive strength of 5,000 psi for all concrete components.

As shown in Table 15, the as-fabricated concrete vault components meet or exceed the design criteria. The as-constructed density and compressive strength data have been incorporated into the analyses supporting the updated PA.

5.5 Alkali-Silica Reaction Test Data

As determined in the RP-212 report and confirmed in concrete mix design trials for RH-LLW vault components, the aggregate sources used are subject to ASR with concrete. To mitigate the ASR potential, the concrete mix designs for vault components shown in the Vault Concrete Mix Design Report (PLN-4953) (i.e., a low-alkali cement, a pozzolan [fly ash], and a lithium-based chemical admixture) were used as recommended by ACI 318-11. With the specific admixtures identified in PLN-4952, the potential for ASR was reduced to 0.02% average length change. The admixture dosage specified in PLN-4952 is identified in batch tickets that are included in component fabrication quality control records. Completed quality control records are maintained in the INL Vendor Data System under Project 31055. Review of the batch tickets confirms that the admixture dosage met design specifications.

Table 15. Concrete density and compressive strength summary statistics by component type.

	Plug	CVAS	Base	Upper	Perimeter
Wet Density					
Mean (pcf)	137.1	138.5	142.6	142.6	136.9
Standard Deviation (pcf)	0.1	NA	NA	0.0	0.1
Minimum (pcf)	134.3	138.5	139.9	139.9	134.3
Maximum (pcf)	141.0	138.5	145.0	145.0	141.0
Number	448	2	448	448	247
Dry Density (28-day)					
Mean (pcf)	136.2	137.8	NA	NA	NA
Standard Deviation (pcf)	0.1	NA	NA	NA	NA
Minimum (pcf)	132.5[a]	137.8	NA	NA	NA
Maximum (pcf)	140.3	137.8	NA	NA	NA
Number	448	2	NA	NA	NA
Compressive Strength (28-day)					
Mean (psi)	6,467.8	7,680.0	7,878.4	7,871.8	6,419.2
Standard Deviation (psi)	15.8	0.0	24.4	24.5	18.4
Minimum (psi)	5,700.0	7,680.0	6,450.0	6,450.0	5,700.0
Maximum (psi)	7,700.0	7,680.0	10,940.0	10,940.0	7,150.0
Number	448	2	448	448	247

a. Seven plugs were determined to have a 28-day dry density less than 134 pcf. These plugs were accepted via the nonconformance process.

6. CONCLUSIONS

This report summarizes the concrete component testing process, including the quality assurance process imposed during vault fabrication, and data necessary to support quantitative assessment of concrete durability. The vault quality assurance program resulted in components with insignificant defects and damage during the fabrication stage and vault installation stage. The test data summarized in this report are within the expected variation for each concrete parameter, with the exception of gas-phase permeability and effective proposity in the cured concrete, which are slightly higher than data used to select the concrete mix designs. These differences are evaluated in Appendix D of the PA (DOE-ID 2017). The PA demonstrates, based on the combined influence of hydrologic and concrete performance, that the vault system is expected to exceed the 500 year concrete longevity requirement specified in SPC-1437.

Table 16. Concrete permeability, porosity, and density data using API RP-40 methods.

Sample Name	Batch ID	Dates (2016)			Density (lb/ft^3)			Effective (Ambient) Porosity (ϕ_{eff})	Gas Permeability (mD)			
		Poured	Tested	Held Days	As Received (ρ_{ar})	Dry Bulk (ρ_{bulk})	Grain (ρ_{grain})		500 psi Confining Stress	750 psi Confining Stress	1,000 psi Confining Stress	1,250 psi Confining Stress
PorNuPac1	51598	2/9	6/2	114	140.0	131.9	150.3	12.3	0.111	0.103	0.095	0.089
PorNuPac2	52148	2/19	6/2	104	145.5	138.7	153.4	9.6	0.045	0.041	0.038	0.035
PorNuPac3	52948	3/23	6/2	71	142.5	134.5	151.3	11.1	0.072	0.065	0.061	0.057
PorNuPac4	53325	4/4	6/2	59	147.0	140.7	155.3	9.4	0.08	0.074	0.069	0.064
PorNuPac5	53368	4/5	6/2	58	139.7	130.5	149.7	12.8	0.096	0.088	0.082	0.077
PorNuPac6	53405	4/6	6/3	58	143.8	136.5	152.9	10.8	0.069	0.062	0.056	0.052
Por-HFEF/LCC-1	53441	4/7	6/3	57	144.0	135.8	152.4	10.9	0.08	0.073	0.068	0.064
Por-HFEF/LCC-2	53572	4/12	6/3	52	140.7	132.1	151.5	12.8	0.093	0.086	0.081	0.078
Por-HFEF/LCC-3	54498	5/9	6/3	25	142.4	133.7	152.7	12.5	0.092	0.083	0.077	0.072
Por-HFEF/LCC-4	55127	5/25	6/9	15	141.0	132.3	153.3	13.7	0.088	0.079	0.072	0.067
Por-HFEF/LCC-5	56103	6/22	7/29	37	143.0	135.5	153.9	12.0	0.098	0.089	0.08	0.075
Por-HFEF/LCC-6	57100	7/26	8/16	21	142.1	133.9	152.5	12.2	0.083	0.077	0.072	0.068
Por-55T-1	53485	4/8	6/3	56	143.3	135.1	152.8	11.6	0.084	0.077	0.071	0.066
Por-55T-2	53485	4/18	6/3	46	144.3	136.8	154.5	11.5	0.098	0.09	0.081	0.075
Por-55T-3	53770	5/9	6/3	25	140.3	131.7	152.1	13.4	0.079	0.073	0.068	0.063
Por-55T-4	54500	5/25	6/9	15	144.8	137.5	156.1	11.9	0.084	0.075	0.07	0.066
Por-55T-5	55077	6/3	7/15	42	147.6	141.2	157.2	10.2	0.086	0.073	0.068	0.063
Por-55T-6	55446	6/8	7/15	37	144.6	137.2	155.8	11.9	0.076	0.065	0.06	0.056
Por-MFTC-1	55604	4/11	6/3	53	142.3	134.5	152.0	11.6	0.1	0.092	0.085	0.081
Por-MFTC-2	53516	4/18	6/3	46	143.1	135.2	152.7	11.5	0.065	0.059	0.054	0.05
Por-MFTC-3	53762	5/11	6/9	29	142.8	135.0	153.9	12.3	0.079	0.072	0.066	0.063
Por-MFTC-4	54593	5/20	6/9	20	143.1	135.2	154.4	12.5	0.083	0.074	0.068	0.064
Por-MFTC-5	54968	6/15	7/15	30	140.4	131.2	153.4	14.5	0.077	0.07	0.066	0.063
Por-MFTC-6	55840	7/6	7/29	23	143.8	136.2	155.4	12.4	0.066	0.06	0.055	0.052
Minimum					139.7	130.5	149.7	9.4	0.05	0.04	0.04	0.04
Maximum					147.6	141.2	157.2	14.5	0.10	0.09	0.09	0.08
Average					143.0	135.1	153.3	11.9	0.08	0.08	0.07	0.07
Std. Dev.					2.1	2.8	1.8	1.2	0.01	0.01	0.01	0.01
Coefficent of Variation %					1.5	2.1	1.2	10.2	16.76	17.42	17.32	17.68

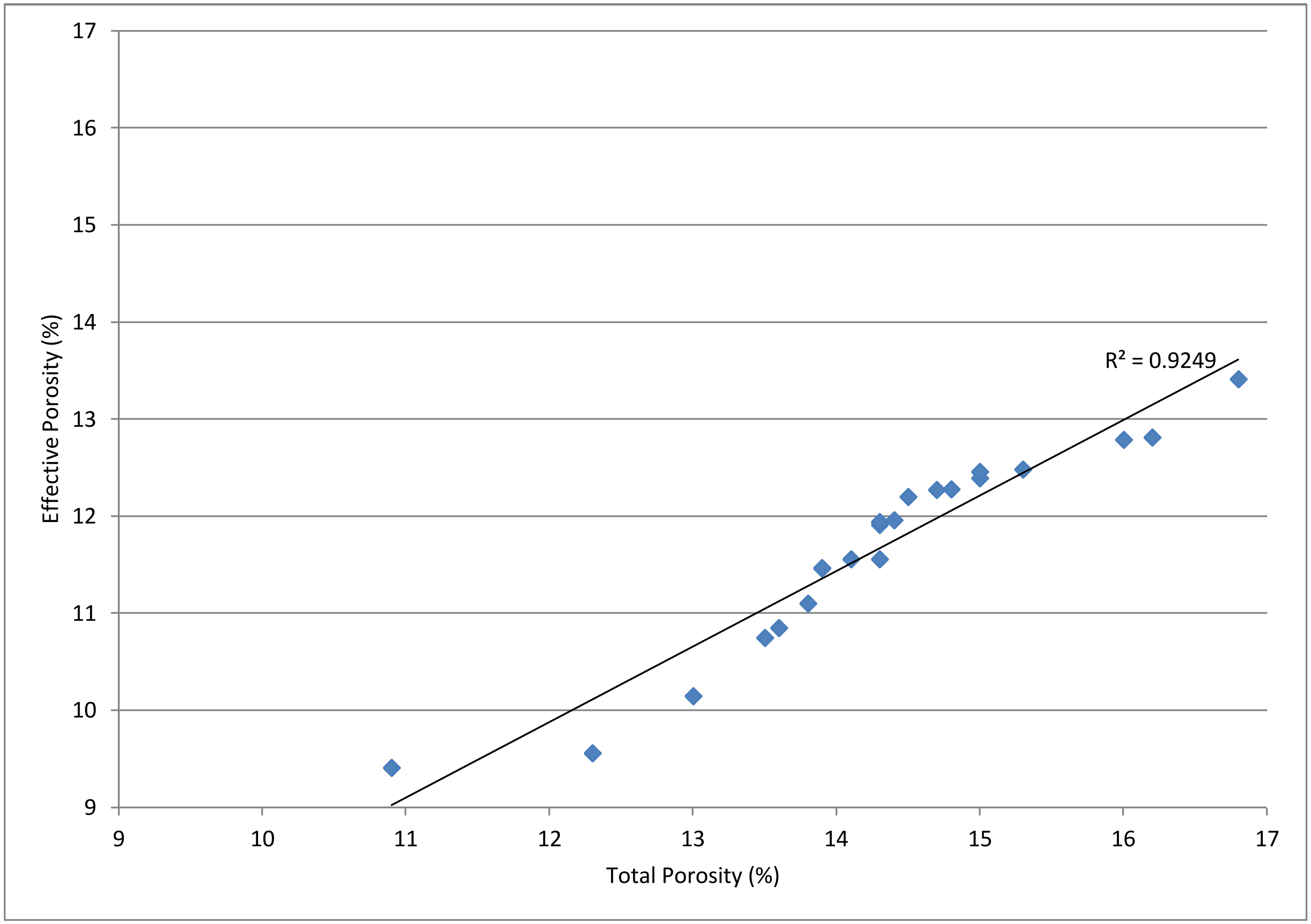


Figure 10. Effective porosity versus total porosity for samples having the same batch ticket number.

AREVA Federal Services LLC
Oldcastle Concrete
Routine Core Analysis Results Summary
504914
February 6, 2015

TerraTek
A Schlumberger company
Pioneer Business Park
1935 South Fremont Drive
Salt Lake City, Utah 84104

Sample ID	Sample Length (cm)	Sample Diameter (cm)	Dry Bulk Density (g/cc)	Grain Density (g/cc)	Ambient Porosity (%)	SS Gas Permeability (mD)	
3A - 500 psi	2.494	3.813	2.233	2.489	10.28	0.045	
750 psi						0.041	
1000 psi						0.038	
1250 psi						0.036	
3B - 500 psi	2.477	3.811	2.183	2.474	11.76	0.034	
750 psi						0.031	
1000 psi						0.029	
1250 psi						0.027	
4A - 500 psi	2.482	3.810	2.188	2.445	10.54	0.031	
750 psi						0.028	
1000 psi						0.026	
1250 psi						0.025	
4B - 500 psi	2.509	3.813	2.257	2.501	9.73	0.043	
750 psi						0.039	
1000 psi						0.037	
1250 psi						0.035	

Figure 11. Effective porosity and gas-phase permeability for test samples used to select the concrete mix designs from PLN-4952.

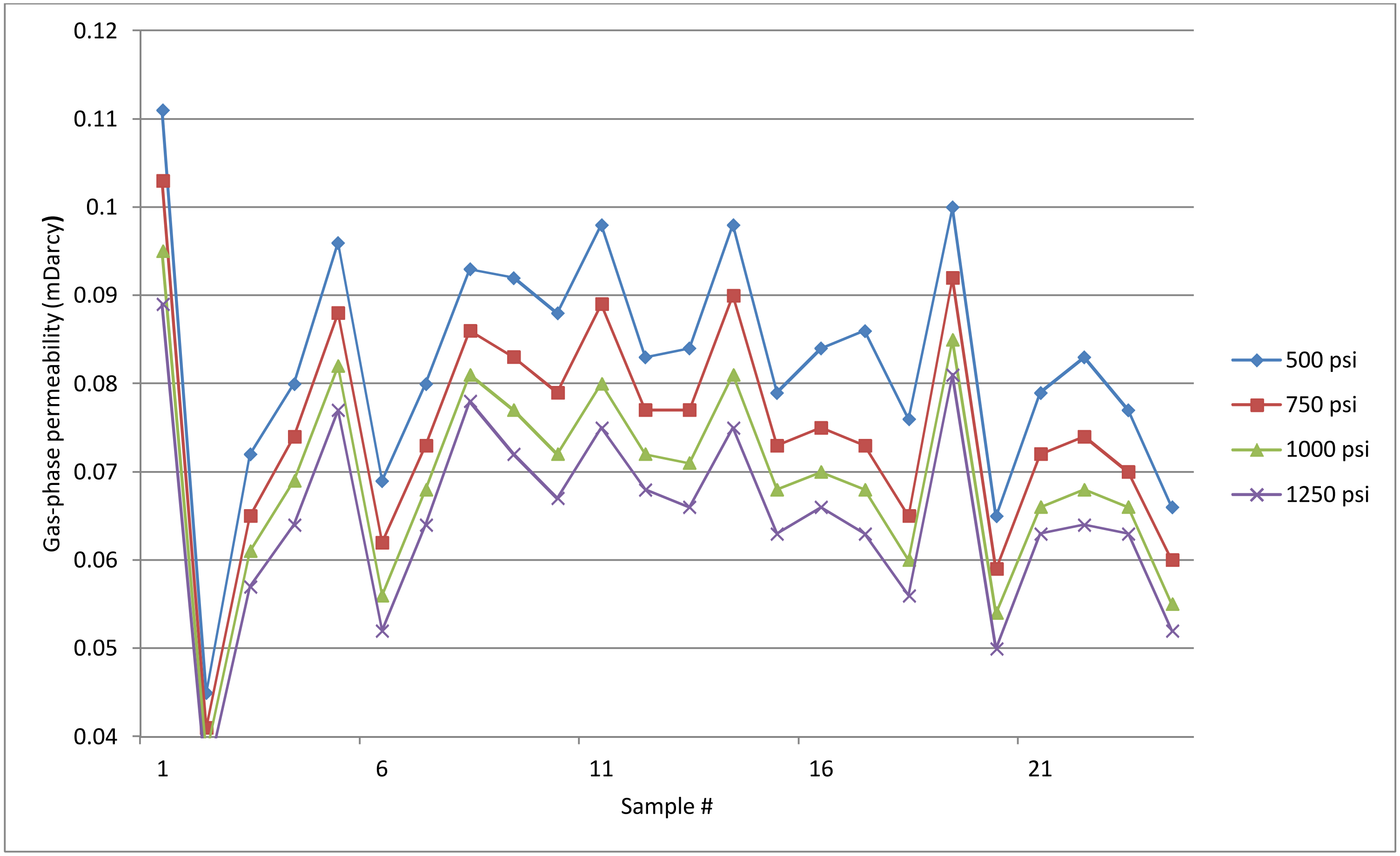


Figure 12. Gas-phase permeability at four different confining pressures.

Table 17. Correlation between measured values for the gas-phase permeability at 750-psi confining pressure and other API RP-40 data.

Regression Statistics	
Multiple R	0.519
R Square	0.270
Adjusted R Square	0.160
Standard Error	0.013
Observations	24

ANOVA

	df	SS	MS	F	Significance F
Regression	3	0.001	0.000	2.460	0.092
Residual	20	0.003	0.000		
Total	23	0.004			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-3.77	2.17	-1.73	0.10	-8.30	0.77	-8.30	0.77
Dry bulk density	0.21	0.11	1.87	0.08	-0.02	0.45	-0.02	0.45
Grain density	-0.19	0.10	-1.88	0.07	-0.39	0.02	-0.39	0.02
Effective porosity	0.33	0.17	1.88	0.07	-0.04	0.69	-0.04	0.69

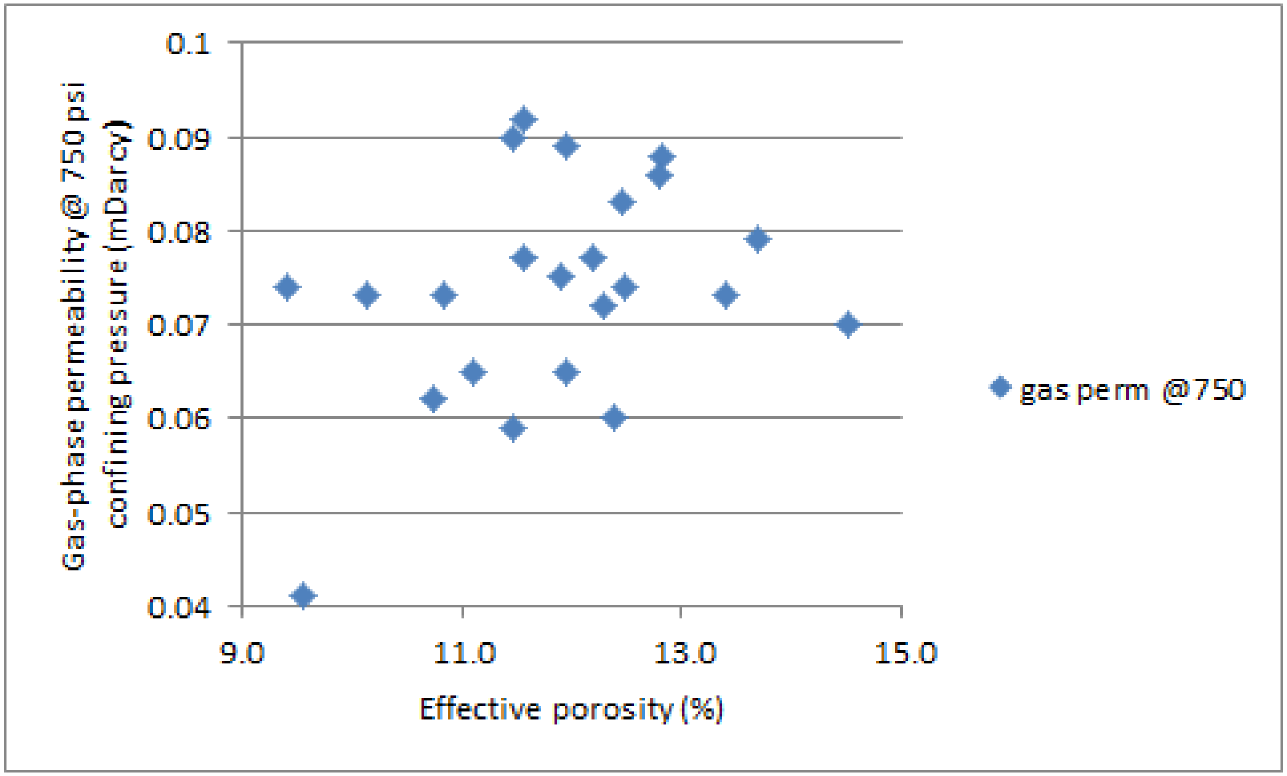


Figure 13. Gas-phase permeability versus effective porosity.

Table 18. Concrete permeability, porosity, and density sample batch ticket data.

Sample Name	Batch ID	Cement (lb)	Flyash (lb)	Gravel (lb)	Sand (lb)	Water (gal)	Prewater (gal)	Water/Cement Ratio (w/cm)	Glenium (oz) Superplasticizer	NC534 (oz) Accelerator	ASR 30 (oz) Lithium
PorNuPac1	51598	1,162	320	2,870	2,770	32.8	24.8	0.3700	45	440	488
PorNuPac2	52148	1,158	320	2,780	2,830	45.8	24.3	0.3700	50	360	488
PorNuPac3	52948	1,160	320	2,810	2,785	37	24.3	0.3720	45	398	488
PorNuPac4	53325	1,158	320	2,790	2,850	39.5	24.5	0.3710	45	400	488
PorNuPac5	53368	1,160	320	2,805	2,790	41	24.3	0.3700	47	400	488
PorNuPac6	53405	1,158	320	2,805	2,785	42.5	24.5	0.3700	45	400	488
Por-HFEF/LCC-1	53441	1,158	320	2,780	2,830	44.3	24.3	0.3740	46	400	488
Por -HFEF/LCC-2	53572	1,160	320	2,790	2,790	43.8	24.3	0.3710	43	400	488
Por -HFEF/LCC-3	54498	1,158	320	2,790	2,840	39.5	24.3	0.3710	46	400	488
Por-HFEF/LCC-4	55127	1,158	320	2,780	2,860	35.5	24.5	0.3700	45	400	488
Por-HFEF/LCC-5	56103	1,158	320	2,785	2,825	45.3	24.5	0.3710	48	300	488
Por-HFEF/LCC-6	57100	1,158	320	2,785	2,825	44.3	24.5	0.3700	51	250	488
Por-55T-1	53485	1,156	320	2,810	2,745	38	24.5	0.3720	44	400	488
Por-55T-2	53485	1,160	320	2,785	2,840	41.8	24.3	0.3720	45	400	488
Por-55T-3	53770	1,158	320	2,800	2,820	39.5	24.8	0.3710	45	400	488
Por-55T-4	54500	1,156	320	2,805	2,880	32	24.5	0.3710	45	400	488
Por-55T-5	55077	1,162	320	2,790	2,865	37.8	24.5	0.3700	52	300	488
Por-55T-6	55446	1,158	320	2,795	2,810	38.8	24.8	0.3710	47	300	488
Por-MFTC-1	55604	1,160	320	2,795	2,800	45	24.5	0.3710	44	400	488
Por-MFTC-2	53516	1,160	320	2,790	2,820	45.3	24.5	0.3700	45	400	488
Por-MFTC-3	53762	1,160	320	2,800	2,805	43.3	24.5	0.3700	47	400	488
Por-MFTC-4	54593	1,158	320	2,805	2,880	33.5	24.5	0.3700	47	400	488
Por-MFTC-5	54968	1,160	320	2,780	2,875	37.5	24.5	0.3720	46	300	488
Por-MFTC-6	55840	1,158	320	2,780	2,815	45	24.5	0.3700	42	250	488
Minimum		1,156	320	2,780	2,745	32	24	0.370	42	250	488
Maximum		1,162	320	2,810	2,880	46	25	0.374	52	400	488
Average		1,159	320	2,796	2,822	40	24	0.371	46	371	488
Standard Deviation		2	0	19	35	4	0	0.001	2	54	0
Coefficent of Variation %		0	0	1	1	11	1	0.272	5	15	0

Table 19. Correlation data for concrete gas-phase permeability at 500-psi confining pressure as a function of concrete mix components.

Regression Statistics	
Multiple R	0.266
R Square	0.071
Adjusted R Square	-0.069
Standard Error	0.014
Observations	24

ANOVA

	df	SS	MS	F	Significance F
Regression	3	0.0003	0.0001	0.5078	0.6814
Residual	20	0.0041	0.0002		
Total	23	0.0044			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.2234	1.1538	-0.1936	0.8484	-2.6301	2.1833	-2.6301	2.1833
Glenium superplasticizer	-0.0001	0.0014	-0.0654	0.9485	-0.0031	0.0029	-0.0031	0.0029
NC534 accelerator	0.0001	0.0001	1.0300	0.3153	-0.0001	0.0002	-0.0001	0.0002
Water/cement ratio (w/cm)	0.7746	3.0687	0.2524	0.8033	-5.6265	7.1758	-5.6265	7.1758

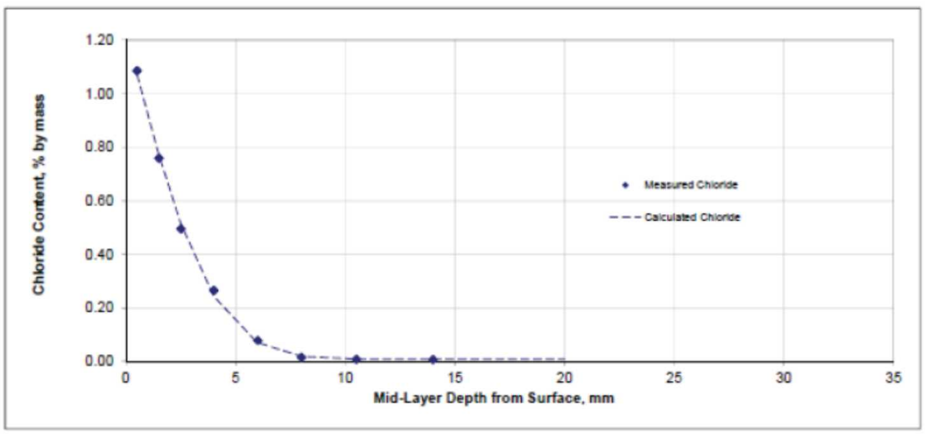
Client:	Applus RTD	**CTLGroup Project No:**	391202
Project:	AREVA RH LLW Project	**CTLGroup Project Mgr.:**	Joni Jones
		Analyst:	MS
Contact:	Jerry Harper	**Approved:**	Cyler Hayes
Submitter:	Jerry Harper	**Date Analyzed:**	December 30, 2014
Date Received:	November 5, 2014	**Date Reported:**	December 30, 2014

ASTM C1556 - 11a

Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion

Mix 2A, Cylinder 1 - CTLGroup Work Request 38558

Mid-Layer Depth	Measured Chloride	Calculated Chloride
mm	Cm, %	Cc, %
0.5	1.086	1.072
1.5	0.760	0.772
2.5	0.496	0.516
4	0.267	0.244
6	0.079	0.070
8	0.015	0.019
10.5	0.008	0.009
14	0.007	0.008
55.0	0.008	0.008
Exposure time, t, days	35	
Initial Chloride Content, Ci, %	0.008	
Surface Chloride Content, C_s, %	**1.23**	
Calculated Diffusion Coefficient, D_a ($x10^{-12}$)	**1.6**	



Notes:

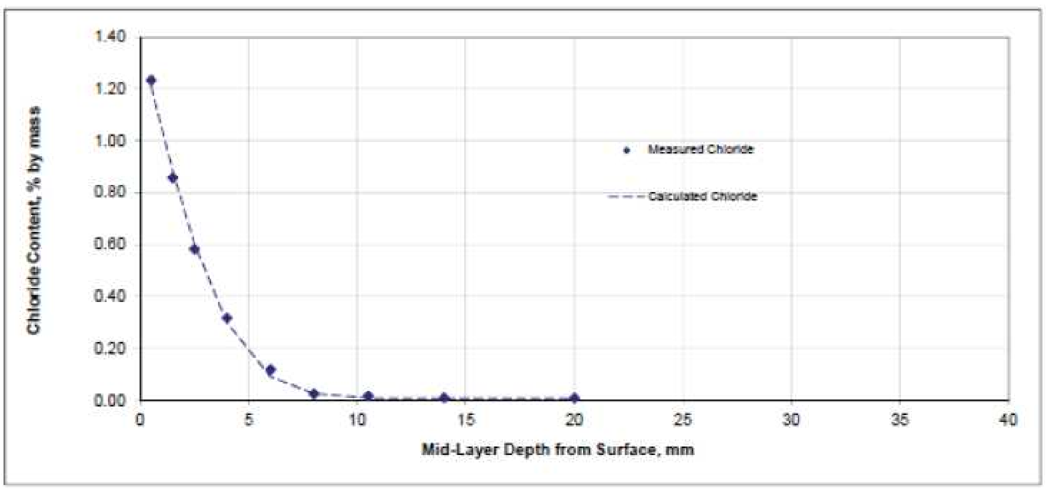
1. This report represents specifically the sample provided.
2. The sample was obtained, treated, prepared and calculations conducted following ASTM C1556 - 11a.
3. The chloride content was determined by ASTM C1152-04(2012)ε1.
4. This report may not be reproduced except in its entirety.

Figure 14. Apparent chloride diffusion test data for Mix #2A.

CTLGROUP

Client:	Applus RTD	**CTLGroup Project No:**	391202
Project:	AREVA RH LLW Project	**CTLGroup Project Mgr.:**	Joni Jones
		Analyst:	MS
Contact:	Jerry Harper	**Approved:**	Cyler Hayes
Submitter:	Jerry Harper	**Date Analyzed:**	December 30, 2014
Date Received:	November 5, 2014	**Date Reported:**	December 30, 2014

ASTM C1556 - 11a		
Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion		
Mix 2B, Cylinder 2 - CTLGroup Work Request 38558		
Mid-Layer Depth	Measured Chloride	Calculated Chloride
mm	Cm, %	Cc, %
0.5	1.234	1.210
1.5	0.857	0.885
2.5	0.583	0.604
4	0.316	0.297
6	0.118	0.091
8	0.025	0.025
10.5	0.016	0.009
14	0.009	0.008
55.0	0.008	0.008
Exposure time, t, days	35	
Initial Chloride Content, Ci, %	0.008	
Surface Chloride Content, C_s, %	1.38	
Calculated Diffusion Coefficient, D_a ($x10^{-12}$)	1.7	



Notes:
1. This report represents specifically the sample provided.
2. The sample was obtained, treated, prepared and calculations conducted following ASTM C1556 - 11a.
3. The chloride content was determined by ASTM C1152-04(2012)ε1.
4. This report may not be reproduced except in its entirety

Figure 15. Apparent chloride diffusion test data for Mix #3.

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Appendix A,
Evaluation of Crack Depth and Explanation of Shrinkage Crack Causes

Oldcastle Precast®

www.oldcastleprecast.com

To: Bob Ballard
From: Mike Blackham

Cause

The plugs are a large mass of concrete with reinforcing throughout to help prevent shrinkage/temperature type cracking. When pouring large mass concrete (minimum dimension in any direction is 5' thick) you always have the possibility and the reality that there will be cracking. As the concrete cures and hydrates there is an enourmous amount of heat that is generated and the product itself expands and contracts during the curing process. This expansion and contraction causes the product to crack. The reinforcing is spaced throughout the product per specification, but is held approximately 1.5" away from any surface. So the surface of the concrete is the area that is at risk of cracking and is usually the spot that the product does crack. These cracks are typically shallow cracks and do not extend beyond the reinforcing that is placed. In addition to the heat generated during the curing process with mass concrete, you also have the potential for temperature changes during the curing process. Any major change in the concrete temperature adds to the potential of the product expanding and contracting even more, and causes surface cracking. A perfect example of this is any slab on grade concrete. The requirements are to go in and put expansion joints/lines in the concrete at consistent intervals. This gives a relief point for the concrete to release built up stresses from the curing process and the possible temperature changes. It allows for a place for the concrete to crack so that you have a controlled cracking point. The following are descriptions of this process taken from the PCA (Portland Cement Association) Design and Control of Concrete Mixtures:

"Mass concrete is defined by ACI as any volume of concrete in which a combination of dimensions of the member being cast, the boundary conditions, the characterstics of the conrete mixture, and the ambient conditions can lead to undesirable thermal stresses, cracking, deleterious chemical reactions, or reduction in long term strength as a result of elevated concrete temperature due to heat from hydration. Mass concrete includes not only low-cementitous-content concrete in dams and other massive structures, but also moderate to high-cementitous-content concrete in structural members of bridges and buildings."

"As the interior concrete increases in temperature and expands, the surface concrete may be cooling and contracting. This causes tensile stresses that may result in thermal cracks at the surface if the temperature differential between the surface and center is too great. The width and depth of cracks depends upon the temperature differential, physical properties of the concrete, and the reinforcing steel."

"Temperature changes that result in shortening can crack concrete members that are highly restrained by another part of the structure or by ground friction. Consider a long restrained concrete member cast without joints that, after moist curing, is allowed to drop in temperature. As the temperature drops, the concrete wants to shorten, but can not because it is restrained longitudinally. The resulting tensile stresses cause the conrete to crack."

"Drying shrinkage is an inherent, unavoidable property of concrete, However, properly positioned reinforcing steel is used to reduce crack widths, or joints are used to predetermine and control the location of cracks. Thermal stress due to fluctuations in ambient temperature also can cause cracking, particularly at an early age."

Verification

Evaluation on the crack depth was conducted by MTI and Oldcastle. The cracks on component NP-P7 were ground down and the bottom of the cracks exposed. This piece was chosen because it appeared to have the worst cracks. The locations that were chosen were two CAR condition cracks and two others that represent over 90% of the cracks found on all the plugs. See attached pictures and report completed by Craig Reese. The results show that the cracks ranged from 3/8" deep to 5/8" deep. These were cracks that were measured to be up to 0.019" in width, which is worst case.

Solution

After evaluating the cracks and showing that they appear to be shallow type cracks as thought, it confirms that the cracks are more than likely an outcome of pouring mass concrete and temperature fluctuations within the concrete, curing, and yarding. As mentioned in PCA Design and Control of Concrete Mixtures these cracks typically form early in the curing/hydration process of concrete and are near the surface of the product.

The cracks are not structural in nature. All reinforcing was placed in the plug to help prevent and limit cracking per ACI code.

The cracks are not expected to affect the durability of the concrete. As shown, the cracks only go a maximum of 5/8" into the plug. All reinforcing has a minimum 1.5" clearance, so the reinforcing does not have exposure to any potential chemical or weathering attack.

NCHRP (National Cooperative Highway Research Program) 18-14 report "Evaluation and Repair Procedures for Precast/Prestressed Concrete Girders with Longitudinal Cracking in the Web" goes through the evaluation of cracking in bridge girders.

The report suggests the following:

"Cracks narrower than 0.012 in. may be left unrepaired. Cracks ranging from 0.012 to 0.025 in. should be repaired by filling the cracks with approved specialty cementitious materials and the end four feet of the girder side faces coated with an approved sealant."

All cracks noted in AFS RH LLW-SNR-086 are in the range of the mentioned tolerances above. Oldcastle proposes to follow this same criteria, with the exception that the 0.012 in. tolerance be reduced to 0.01 in. to stay consistent with current job specifications. This criteria would read that anything narrower than 0.01 in. may be left unrepaired, and cracks ranging from 0.01 in. to 0.025 in. would be repaired by filling the cracks with an approved repair material. The 0.01 in. compared to the listed 0.012 in. crack criteria is more conservative. This is an approved method for state highway girders that are a structural item exposed to the elements, so Oldcastle feels it is a sufficient guideline for the plugs which are also exposed to the elements. The sealant on the girder faces is not included in the recommendation for the plugs since it is not related to cracks in the concrete.

Based on a request by BEA during BEA's visit to the Oldcastle site to look at the plugs included in AFS' SNR-086, for all plugs included in the SNR, all cracks located on the tops of the plugs and any cracks extending from the top of the plug to 1 foot below the top edge along the sides will also be repaired no matter what width.

Oldcastle recommends that JetSet Smooth material be used as the cementitious material for the crack repairs.

Mike Blackham, PE
Oldcastle Precast Engineering Manager