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Abstract *– In 2003, representatives from the Central Research Institute of Electric Power Industry (CRIEPI) requested development of a project with the objective of determining the performance of a concrete spent nuclear fuel storage cask. Radiation and environmental effects may cause chemical alteration of the concrete that could result in excessive cracking, spalling, and loss of compressive strength. The Idaho National Laboratory (INL) project team and CRIEPI representatives identified the Ventilated Storage Cask (VSC-17) spent nuclear fuel storage cask as a candidate to study cask performance, because it had been used to store fuel as part of a dry cask storage demonstration project for more than 15 years. The project involved investigating the properties of the concrete shield. INL performed a survey of the cask in the summers of 2003 and 2004. Preliminary cask evaluations performed in 2003 indicated that the cask has no visual degradation. However, a 4-5 mrem/hr step-change in the radiation levels about halfway up the cask and a localized hot spot beneath an upper air vent indicate that there may be variability in the density of the concrete or localized cracking. In 2005, INL and CRIEPI scientists performed additional surveys on the VSC-17 cask. This document summarizes the methods used on the VSC-17 to evaluate the cask for compressive strength, concrete cracking, concrete thickness, and temperature distribution.*

I. INTRODUCTION

Durability of the concrete shielding on a concrete spent nuclear fuel (SNF) storage cask is a key design attribute that dictates the usability of these casks for long-term storage. Radiation and environmental effects may cause chemical alteration of the concrete and could result in excessive cracking, spalling, and loss of compressive strength. The Idaho National Laboratory (INL) and the Central Research Institute of Electric Power Industry (CRIEPI) have been studying the concrete shield performance of the Pacific Sierra Nuclear ventilated SNF storage cask, VSC-17, because it has been storing SNF for over 15 years as part of a dry cask storage demonstration project.

The VSC-17 is a concrete-shielded SNF storage cask system that was designed to contain 17 pressurized water reactor (PWR) fuel assemblies. The VSC-17 is a product of the Pacific Sierra Nuclear Company, which was assimilated into the British Nuclear Fuel Limited (BNFL), BNFL Solutions Division. The design is unique in that it was scaled down from the commercially produced VSC-24 units to be compatible with the INL cask mover that was used to move casks from the cask storage pad to the hot shop. It consists of a central steel container and the multi-element sealed basket (MSB). The MSB is surrounded by a vertical right circular annulus, known as the Ventilated Concrete Cask (VCC), which has a concrete wall thickness of 51 cm (20 in.). The inner liner of the VCC annulus is A-36 steel that is 89 mm (3.5 in.) thick, which provides structural support and additional shielding. The annular gap between the steel liner and the MSB is 76 mm (3 in.). Transfer of decay heat from the MSB occurs by convective airflow through vents in the concrete shielding component. The VSC-17 is one of several casks stored at INL as a demonstration project to show the feasibility of dry storage of commercial SNF. The VCC concrete performance was the focus of this study.

The fuel stored in the VSC-17 came from the Florida Power & Light Turkey Point and Virginia Electric Power Company Surry Plants. The fuel was originally configured as a 15 × 15-rod array in PWR assemblies. The fuel was repackaged as a part of the Dry Rod Consolidation Technology project into canisters that have the same external dimensions as a PWR assembly (4.3 m [14 ft] × 21.6 cm [8.5 in.] square), but contain 410 rods from derodded assemblies, slightly greater than a two to one consolidation ratio for spent fuel rods. The fuel had a nominal heat load of 398 to 685 W (26.8 to 30.5 GWd/tU) per assembly in 1987, prior to derodding.[1]

Preliminary cask evaluations performed in 2003 indicated that the cask has no visual degradation. However, a 4-5 mrem/hr step-change in the radiation levels about halfway up the cask and a localized hot spot beneath an upper air vent indicate that there may be variability in the density of the concrete or localized cracking. Ultrasonic testing on a one-eighth scale model of the cask suggested that achieving uniform concrete placement underneath the metal vent structure was difficult and that variations in radiological shielding may be more a function of manufacturing quality than aging degradation. To determine the reason for these variable radiation readings, the project team performed follow-on nondestructive examination measurements on the VSC-17.

II. WORK DESCRIPTION

Previous measurements taken in 2003 on the VSC-17 cask indicated a step-change in the radiation readings at a point approximately 2.5 m (8.2 ft) above the base of the cask. In addition, the cask showed radiation hot spots at the 52-degree location beneath one of the upper vents as shown in Figure 1.[2] The cause of the variable radiation readings was unknown. The project team focused on the possibility of variable concrete density or cracking. They also examined radiation and temperature test methods for the possibility of suspect data.

The nondestructive tests performed in 2005 were designed to evaluate the concrete density, thickness, and any potential weak spots to determine the reason for the variable radiation readings. The project team evaluated the concrete shield for compressive strength, cracking, and temperature distribution to determine if the aging effects of radiation and the environment have reduced the shield strength of the cask. The team performed thermocouple measurements, thermal imaging, concrete hammer tests, and ultrasonic testing.

To determine if the cask had any thermal hot spots or other measurable thermal characteristics, the project team performed temperature measurements using two different methods. First, a thermocouple ladder (a 5.5-m [18-ft] mast with thermocouples attached 30 cm [1 ft] apart) was used to obtain surface temperature measurements. Thermocouple measurements were planned for 41 radial positions, located 20 cm (8 in.) apart. Second, a thermal imaging camera was used to determine if the external temperature of the cask varied consistently with atmospheric conditions. Temperature variations could provide an indication of shield concrete nonuniformity.

Compressive strength of the cask was tested using a hammer rebound test. The Schmidt hammer test is an in situ method used for determining the strength of

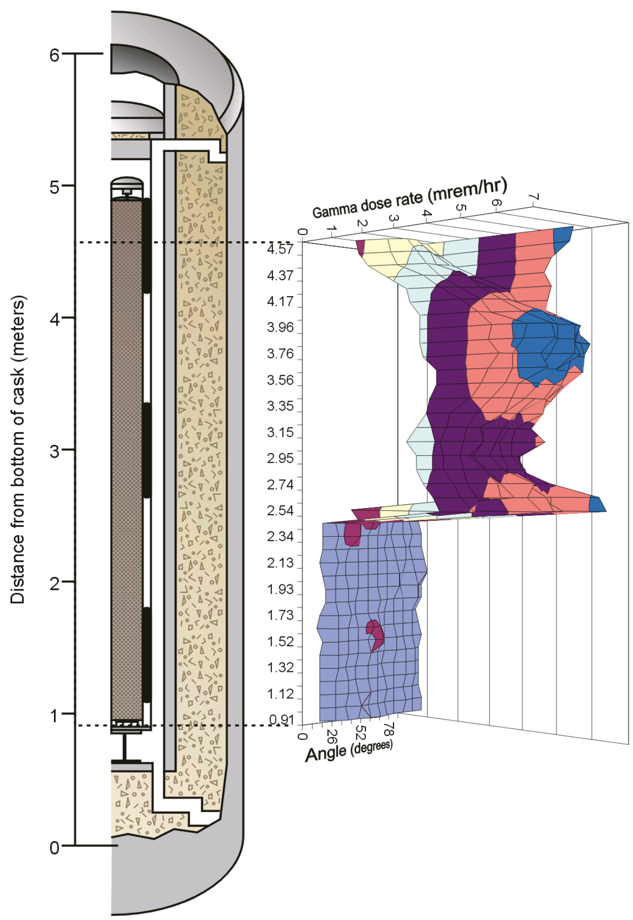


Fig. 1. Surface dose rate of the VSC-17 VCC from 0 to 90 degrees.

hardened concrete as specified by the American Society of Testing and Materials (ASTM) C805. The compressive strength (f_c') is established by measuring the hardness (rebound value) of the concrete surface and comparing this to a conversion curve. It can also be used to measure the relative quality of concrete by identifying variations over a region. Variation testing over a region can lead to the location of weak spots and flaws, but the results are relative. Ideally, the concrete should have a relatively smooth, flat surface, and results should be compared to compression and flexural tests from the same concrete mass.

Calibration should best be done with cylinders of the same cement and aggregate as used on the structure being tested. This method is a quick way of obtaining an indication of strength, with accuracy of plus or minus 15 to 20% for specimens cast, cured, and tested under conditions for which calibration curves have been established. Results apply only to the surface and are only a measure of compressive strength. Crack and flaw location and extent are not measurable except when present as gross surface characteristics. Nothing at depth is determined. The results are affected by factors such as smoothness of surface, size and shape of specimen, moisture condition of the concrete, type of cement and aggregate, and extent of surface carbonation or deterioration.

Ultrasonic testing was performed over the surface of the VCC to find evidence of cracks not visible on the surface of the VCC concrete shield. Again, measurements were concentrated beneath the vent at 45 degrees. A crack and deterioration evaluation was made using a wave propagation velocity test. Comparison measurements were made at the 90-degree position, which has no vent structure to introduce concrete placement discontinuities.

III. REVIEW AND VERIFICATION OF PREVIOUS WORK

The 2004 VSC-17 annulus inspection[3] raised several questions about the actual versus expected radiation profile of the stored SNF. The loading of the SNF canister was researched to determine if it may be affecting the radiation readings of the VSC-17.

In addition, the external temperature measurements showed variability of up to 7°F. The project team revisited the process for obtaining surface temperature data from the cask. This section provides the results of further analysis and investigation on these topics.

III.A. Radiation Profile of Stored Spent Fuel

The fuel stored in the VSC-17 cask is repackaged PWR fuel of the 15 × 15 Westinghouse type from Florida Power & Light Turkey Point and Virginia Electric Power Company Surry 2 reactors. The repackaging amounted to removing the individual rods from the original end boxes (nozzles) and skeleton and putting 408 rods in a stainless steel shell that has the same dimensions as a PWR assembly containing 204 rods.

Because the stainless steel end boxes and skeleton were removed, the cobalt-60 activation product associated with those components is not present in the SNF assembly. The radiation profiles at the time of repackaging show the expected high plateau of activity (100,000 to 110,000 counts/sec) in the middle of the assembly, tapering off to the ends (50,000 to 75,000 counts/sec).

The radiation profile of the activity in the skeleton indicated that the highest activity was associated with the peak at the bottom nozzle and peaks at each of the spacer grids. The nozzles and spacer grids were constructed of stainless steel, which became activated with cobalt-60, with proportionally higher activity than the primary fission product cesium-137. Neither the skeleton profile nor the assembly profile suggested that there is a reason for a step-change in activity as was measured on the exterior of the VSC-17 cask in 2003.

III.B. Temperature Stability Testing

Temperature data measurements in 2004 were acquired by using a series of thermocouples mounted on an aluminum mast, resulting in substantial (5 to 7°F) variation during the measurements. This design was composed of a support structure constructed of 5-cm (2-in.) aluminum angle that supported 17 thermocouples that were used to measure temperature variations along the height of the cask wall. The Type J thermocouples were mounted on adhesive felt pads to prevent contact with the aluminum angle. The project team noted during data analysis that the values for 0/360 degrees were inconsistent, showing lower temperatures and a different gradient an hour following the initial measurement. Ambient temperatures during the period of testing had risen by 4°F. The project team immediately began to determine the source of the inconsistency. Stability and repeatability testing were performed to establish data acquisition error versus system error.

The project team removed the thermocouples from the aluminum support and mounted them on a square fiberglass tube. The modified thermocouple rake consisted of mounted thermocouples in closed cell foam. The support mast was surrounded by additional insulation. A cross section of the rake is shown in Figure 2. The closed cell foam enveloping the thermocouples conformed to surface variations and provided spring pressure to maintain contact with the surface. The external closed cell foam provided an additional barrier to airflow between the thermocouple and the surface.

This modification resulted in an improvement in data stability. The largest max-min delta was 4°F. Temperature comparison using a Raytek Minitemp MT4 noncontact infrared thermometer showed consistency within 0.1°F and confirmed that temperature variations on the test surface due to wind convection were indicated by both instruments.

IV. 2005 TEMPERATURE MEASUREMENTS

Thermocouple measurements were performed in a counterclockwise direction at nominal 20-cm (8-in.) radial positions, which correspond to approximately

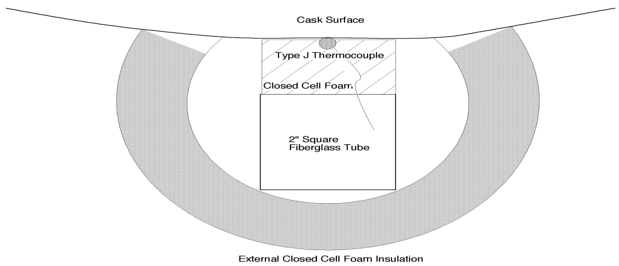


Fig. 2. Cross section of thermocouple rake.

8.8-degree intervals. The zero point corresponds to the south lifting lug, and 90 degrees corresponds to the nameplate position on the cask. The data acquisition system recorded values every second and reported the maximum and minimum value for that period. Data were taken as three sets of 30-second periods for each radial position. The test was performed operationally as shown in Figure 3. This image shows the thermocouple rake being supported against the cask surface by extension poles.

Since performing nondestructive examination in 2003, the cask was fitted with a conduit support structure that extended out sufficiently to interfere with making thermocouple contact readings between 210 degrees to 340 degrees. See Figure 4. Therefore, only 27 of the planned 41 radial positions were accessible. The test indicated limited variation in temperature on the cask surface.

One thermocouple located at the top of the mast and a second one located approximately 180 cm (6 ft) from the ground were not embedded in foam or shielded from the sun or wind. The temperature data from these two thermocouples showed a substantial variation from the temperature data obtained from the insulated thermocouples as well as the ambient temperatures recorded at the nearest weather station. The temperature variance was most notable for the measurements obtained when the ambient thermocouples were in the sun. Because of the low mass of the thermocouple, it is suspected that radiant heating from solar input created a 10 to 30°F offset between the thermocouples contacting the cask surface and the ambient exposed thermocouples. Average thermocouple rake readings are shown in Table 1. Graphical representation of the temperature data is shown in Figure 5.

Upper air vent at the 45-degree
radial position

Fig. 3. Thermocouple measurements were taken using a thermocouple ladder.

Instrument conduit
support structure

Fig. 4. Electrical conduit is visible from behind the VSC-17 cask.

TABLE 1. 2005 Average Thermocouple Measurements

	Degrees (F)
Radial Average Temperature	87.787
Radial Rake Maximum Average	91.797
Radial Rake Minimum Average	83.483
Radial Rake Max-Min Average Delta	8.314
Standard Deviation	0.478

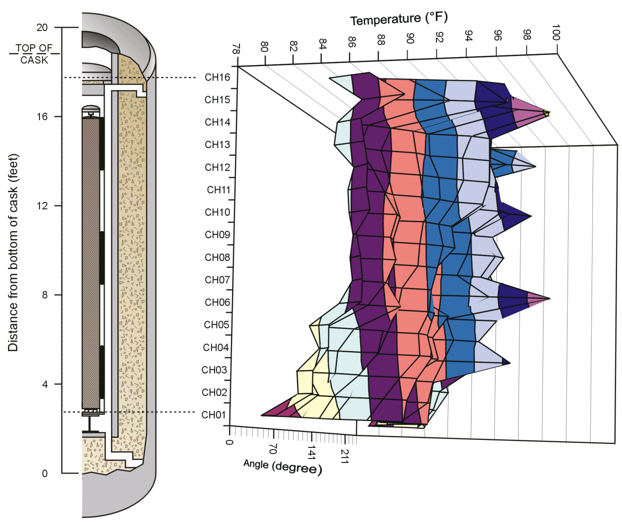


Fig. 5. Temperature readings for the 0 degree to 210 degree positions.

V. OPTICAL THERMAL MEASUREMENTS

The image and data in Figure 6 were produced using a FLIR Systems digital thermal imaging unit. The person in the center of the Figure 6 image is holding the thermocouple rake against the cask at the nominal 90-degree position.

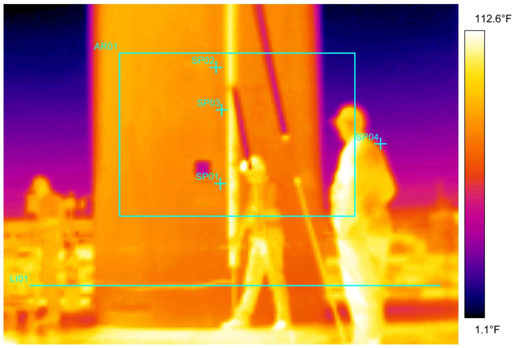
Emissivity has been adjusted to correlate the indicated value at SP02 (88.9°F) with the measured value reported on the second 30-second data segment of the correlating thermocouple on the thermocouple rake. A second image was taken to provide a reference with an unadjusted emissivity value and lower ambient temperature. The images showed that the external temperature of the cask varied consistently with atmospheric conditions.

VI. SCHMIDT HAMMER TEST

The INL project team performed hammer testing of the VSC-17 on October 5 and 10, 2005, following removal of paint from selected radial and vertical

FLIR Systems AB 7/27/2005

IR-Image File Name	Date



Comments:	
Section:	
Equipment:	
Additional Info.:	
Fault:	
Recommendation:	

IR information	Value	
Date of creation	7/27/2005	-
Time of creation	1:39:53 PM	-
Object parameter	**Value**	
Emissivity	0.95	-
Object distance	6.6 ft	-
Ambient temperature	68.0°F	-
Atmospheric	68.0°F	-
Transmission	0.99	-
Label	**Value**	**Diff**
SP01	87.4°F	19.4°F
SP02	88.9°F	20.9°F
SP03	87.7°F	19.7°F
SP04	54.9°F	-13.1°F
LI01 : max	115.6°F	47.6°F
LI01 : min	81.4°F	13.4°F

Description

Place for individual description.

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SP02 Position

Fig. 6. Thermocouple rake measurements and corresponding adjusted emissivity.

locations. Figure 7 shows testing being performed at the 270-degree position. What may appear to be residual paint in the work areas is actually exposed aggregate. The 90 and 270-degree radial locations have flat areas that were ground off to provide space for nameplate installation. Grinding the 30-cm (1-ft)-wide × 90-cm (3-ft)-high flats exposed the larger gravel aggregate.

Schmidt rebound hammer testing was performed at 70 locations on the concrete exterior surface of the VSC-17 VCC. Test interval spacing was at 20 cm (8 in.) for 10 positions below the 45-degree upper air vent where greater porosity was expected to be found. A test interval of 20 cm (8 in.) was also used at 90 degrees for 12 positions below the top of the cask because this portion of the cask was expected to have good porosity. The smaller test intervals used at the 45 and 90-degree positions provided a set of values to compare to the ultrasonic testing performed in these same locations. Twenty hammer impacts were performed at each location (twice the minimum required by the ASTM C805-02 method).

Fig. 7. Schmidt rebound hammer testing on the VSC-17 cask.

There were some small surface defects (approximately 2.5 mm [0.1 in.] diameter and depth) discovered when the paint was removed for impact testing. The degree of pitting seen here was not typical of other areas tested. By avoiding these as directed by the ASTM method, the relative compressive strength of concrete at this location was consistent with the remainder of the test areas. Figure 8 shows the surface of the cask concrete 10.2 cm (4 in.) below the upper vent following paint removal.

Of the 70 test areas, 28% had no data that departed from the mean by greater than six units, meaning that the high and low values were not removed from the average. The overall standard deviation among the 1400 data points was 3.37. This uniformity of rebound value was maintained even at the 45-degree location immediately below the upper vent, which was expected to have the greatest porosity based on radiation levels.

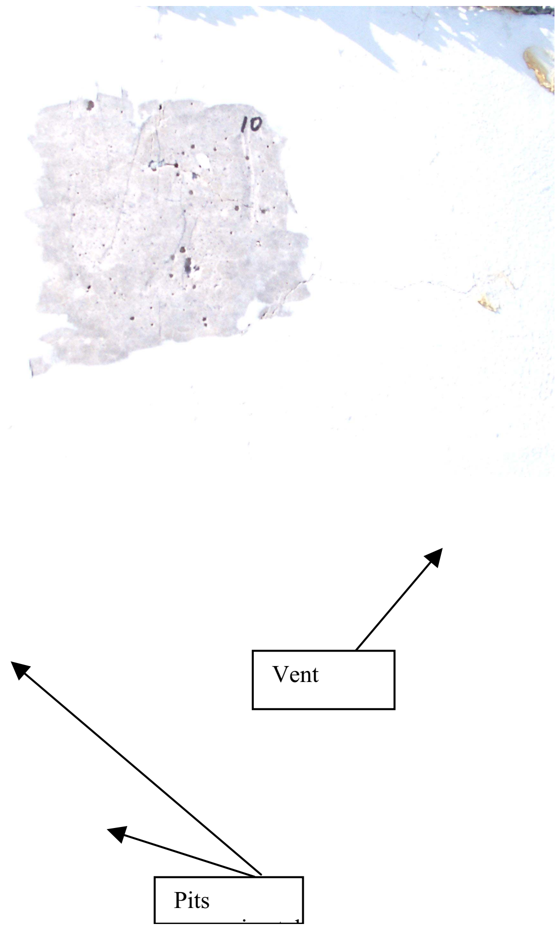


Fig. 8. Pits at position 10, below the 45-degree vent.

To gauge the readings received by hammer testing, a standard concrete test specimen was rebound tested and then broken at the INL Materials Testing Laboratory. The adjusted average rebound value for the first specimen was 37.1, while the second was 35.3. These specimens broke at 4,895 and 4,570 psi, respectively. When extrapolated, the average value indicated for compressive strength of the VSC-17 shield concrete is approximately 6,600 psi. In typical circumstances, concrete gains compressive strength as it ages, but the expected increase is typically about 20%. For the concrete used to construct the VSC-17 shield, that value should be on the order of 5,400 to 5,500 psi. In moist cured concrete, the value may increase by as much as 40%, which would project the 28-day average values from the cask fabrication pour from 4,509 psi to 6,312 psi at 5 years (Figure 9).

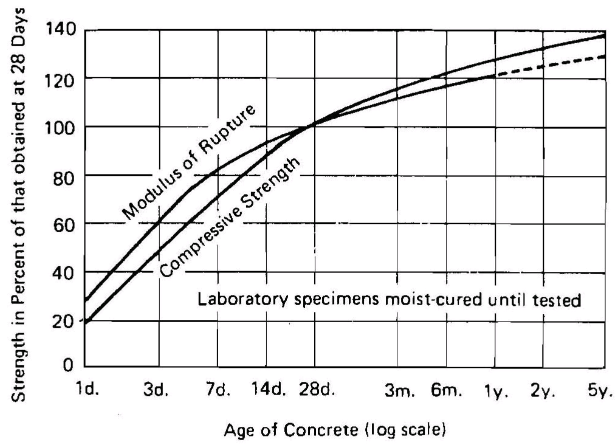


Fig. 9. Age-strength relationships for moist-cured concrete.[4]

VII. GAMMA RADIATION MEASUREMENTS

Because of a need to reconcile the 2004 data with the 2003 measurements, collimated and uncollimated gamma ray measurements were made at the 52-degree radial position for vertical positions from 0.9 to 2.4 m (3 to 18 ft) The measurements made in 2005 suggest that the progressive increase of dose rate above 4 m (13.1 ft) is anomalous, the result of either incorrect recording or incorrect positioning of the detector during the 2003 measurements. Inconsistent values are believed to have been recorded due to problems getting all the equipment mounted on the lift platform to function simultaneously. The 2003 values from the 61-degree radial position appear to be consistent with the 2005 data. The comparisons are shown in Figure 10.

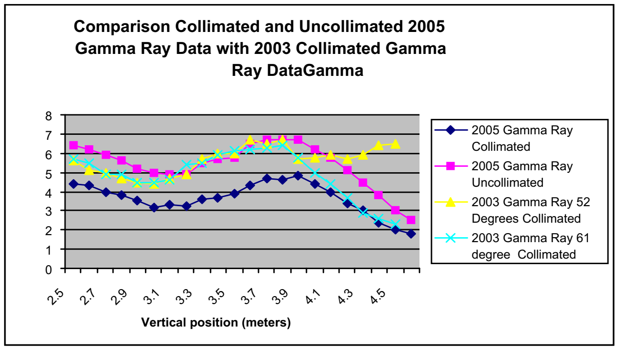


Fig. 10. Comparison of 2003 and 2005 collimated measurements.

Review of the 2003 log book for data acquisition indicated that inconsistent positioning of the detector with the value recorded resulted in the apparent increase in values above the 4-m (13.1-ft) position. On a less readily explained note, it appears that the 2005 measurements do not show the same step-change at 2.4-m (7.9 ft) vertical position as seen in all 41 measurements in 2003. Additional gamma reading would be required to further investigate this discrepancy; however, the classic radiation profile of the VSC-17 SNF suggests that there were likely anomalies in the 2003 data.

VIII. ULTRASONIC TESTING PROCESS

In August 2005 CRIEPI and their subcontract team from LAZOC Sensing Technology joined the INL project team to perform ultrasonic testing on the VSC-17. Figure 11 shows the CRIEPI team applying sensors to the VSC-17 and gathering data.

Figure 12 shows the ultrasonic sensor disposition for the transmitter and receiver. The project team used piezo-electric element type sensors with a resonance frequency

Fig. 11. CRIEPI and LAZOC Inc. representatives performed ultrasonic testing in August 2005.

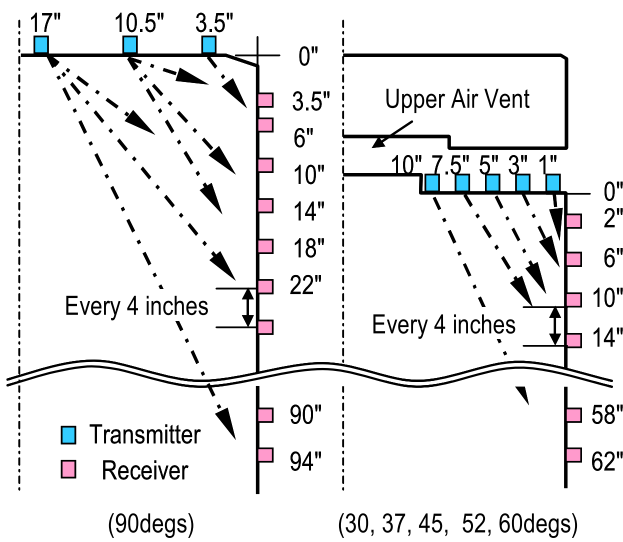
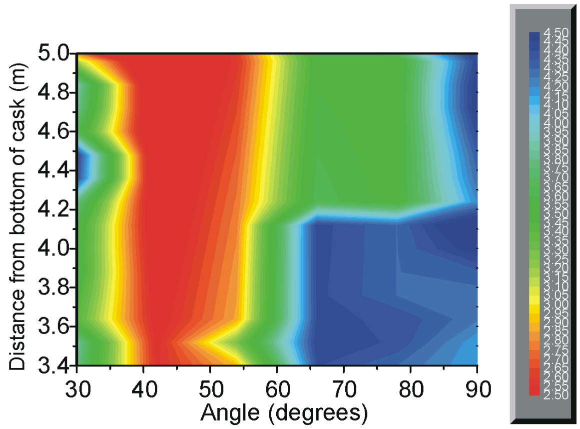


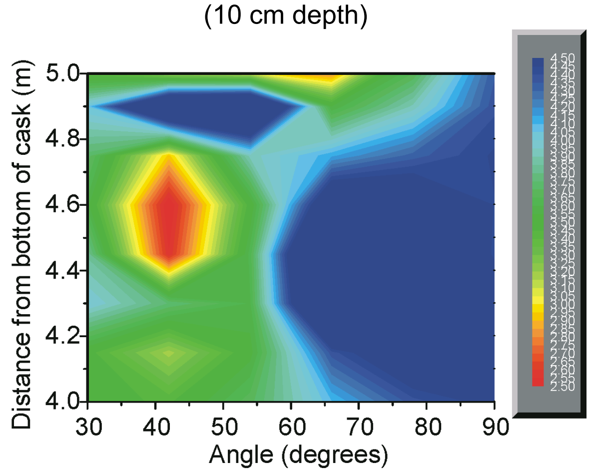
Fig. 12. Ultrasonic sensor disposition.

of 75 kHz and performed measurements at regular distances in the radial and gravitational directions.

Figure 13 shows the wave propagation velocity distribution at 10 cm (4 in.) and 20 cm (8 in.) depths on the upper part of VSC-17 cask in the 30 to 90 degrees radial positions. It appears that the concrete beneath the upper 45-degree air vent has a very low wave propagation velocity, indicating that there may be variability in its density or localized cracking. Because the Shmidt hammer test did not indicate surface damage in this area, it is likely that the concrete at 10 cm (4 in.) (reinforced concrete bars disposition) and 20 cm (8 in.) resulted in greater porosity due to the difficulty of curing or pouring concrete. The upper air vent structure could have complicated the fabrication of the shield just under the vent and has likely caused the localized radiation hot spot at the 52-degree radial position.



(10 cm depth)



(20 cm depth)

Fig. 13. Surface wave propagation distribution on upper part of VSC-17 cask (Sector 30-90 degrees).

IX. CONCLUSION

The temperature data from 2005 indicate that there is limited variation of temperature throughout the cask. This suggests that heat transfer is relatively uniform, and high temperatures occur at the vents as a result of hot airflow. There is no indication of temperature discontinuity that results from shield component material variability.

The Schmidt rebound hammer data show minimal variability among the data points on the cask. Substantial departures from the mean value occurred only where pits were approximately the diameter of the hammer impact point and in areas where the aggregate is exposed.

Variations in the radiation field between the lower and upper sections do not conclusively result from the construction of the cask. There is no indication that the lower material is denser or stronger based on ultrasonic and hammer testing. There is a substantial indication that the radiation hot spot identified under the 45 to 52-degree upper vent is a construction artifact. This is possibly a void underneath the metal vent shielding offset that was not completely filled in with concrete.

Ultrasonic testing indicated a flaw under the 45-degree vent that could be a product of either manufacturing or aging.

Overall, early analysis indicates that the VSC-17 VCC shield performance does not appear to have been significantly affected by the environment or radiation during its more that 15-year lifespan.

ACKNOWLEDGMENTS

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