Dry Storage Canister Inspections to Inform Aging Management Efforts

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The Electric Power Research Institute (EPRI) has completed the initial set of inspections of loaded stainless steel dry storage canisters at three operational dry storage facilities. The goals of these inspections were to demonstrate the accessibility of the canister surface and to collect information on the environmental conditions experienced by the canisters over decades of storage. Stress corrosion cracking (SCC) has been identified as a potential degradation mechanism for stainless steel dry storage canisters. While laboratory studies indicate that SCC can occur in the materials used for dry storage canisters when exposed to a marine atmosphere, data from in-service canisters are needed to evaluate such behavior in real-world conditions. Conditions important for atmospheric-related SCC include temperature, humidity, distance and elevation from salt water, air flow, and the concentration of chlorides and other particulates in the air. Hence, to provide the information on the canister conditions the inspections included: visual inspection for signs of corrosion, canister surface temperature distribution, and salt and dust deposition on the canister surfaces (amounts and composition). To gather the data, EPRI collaborated with utilities and cask vendors to obtain visuals, temperature measurements, and surface samples from canisters at three in-service Independent Spent Fuel Storage Installations (ISFSIs).

I. INTRODUCTION

With no clear path for its ultimate disposition, spent fuel will remain in dry storage containers for an extended period of time, likely well beyond the current license period of 60 years. Aging management plans for dry storage license renewal need to address potential degradation mechanisms to ensure the continued integrity of stainless steel spent fuel containers. One such degradation mechanism is stress corrosion cracking (SCC) of welded stainless steel dry storage canisters which may potentially impact systems exposed to corrosive atmospheric elements, such as those occurring near salt water bodies. The Electric Power Research Institute (EPRI) identified the potential for SCC of welded stainless steel canisters exposed to a marine atmosphere as being the only high priority data gap for extended storage[1].

Several studies have shown that the materials used for dry storage canisters can in fact undergo SCC under the right conditions[2,3,4,5], however, the experiments have been performed under extreme conditions such that the results may not be indicative of actual, in-service conditions. What is not well understood are the actual conditions of the canisters in service.

Conditions important for atmospheric-related SCC include temperature, humidity, distance and elevation from salt water, air flow, and the concentration of chlorides and other particulates in the air. Hence, the data to be acquired through in-service inspections will include: visuals for signs of corrosion, canister surface temperature distribution, and salt and dust deposition on the canister surfaces (amounts and composition).

EPRI initiated a project to perform a series of voluntary inspections of dry storage canisters at operating independent spent fuel storage installations (ISFSIs) to collect the first data on the actual conditions of the canisters that had been in service. EPRI worked collaboratively with the utilities, cask vendors and national laboratories to conduct inspections at Calvert Cliffs, Hope Creek and Diablo Canyon. The sites were all located near saline or brackish bodies of water, but their selection was primarily driven by their willingness to volunteer for the inspection.

By collecting data on the actual in-service conditions of stainless steel canisters—and combining that data with information on the conditions required for SCC—the susceptibility of canisters to SCC will be better understood. This will aid in the development of aging management plans to better inform the need and frequency of inspections.

II. SYSTEMS INSPECTED

The three inspections included both horizontal and vertical dry storage systems. Calvert Cliffs uses the AREVA TN NUHOMS-24P design (Figure 1), while Hope Creek uses the HOLTEC HI-STORM-100S Version B design (Figure 2) and Diablo Canyon uses a similar vertical system that is a site specific version of the HOLTEC HI-STORM-100SA design.

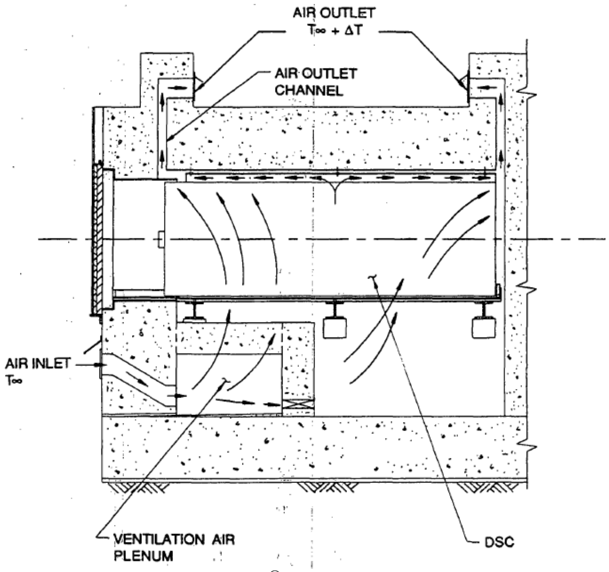

Figure 1. NUHOMS® Dry Cask Storage System Showing Air Flow[6]

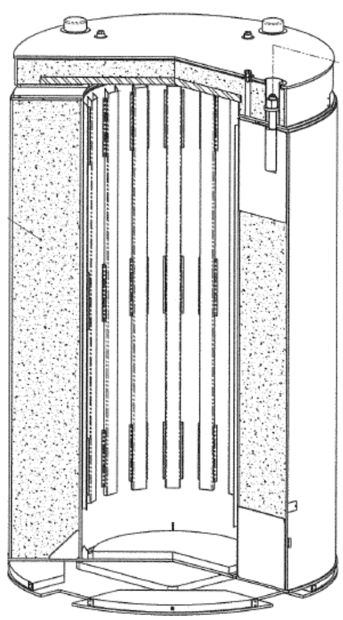

Figure 2. HOLTEC HI-STORM-100S Version B[7]

Two canisters at each site were selected for the inspection. The canisters selected considered several factors. It was desirable to select a canister that had been in service longer as it would have more time to accumulate salt deposits and would likely have higher surface salt concentrations. Similarly, a canister that had directly faced the body of salt water the longest would have been directly exposed to the wind carrying chlorides from the salt water the longest and potentially have higher accumulation of chloride. The expected canister surface temperature was desired to be in the range of deliquescence (<70°C) as that would have the greatest potential for initial signs of corrosion. Also, accessibility to the canisters was a factor in order to ensure personnel and equipment could access the systems to be inspected as well as keeping personnel doses as low as reasonably achievable (ALARA). The canisters selected for inspection are listed in Table I.

TABLE I. Canisters Selected for Inspection

Canister selected for inspection	Years in service	Heat Load at time of inspection (kW)
Calvert Cliffs		
DSC-6	16	7.6
DSC-11	18	4.2
Hope Creek		
MPC 144	7	9.3
MPC 145	7	9.2
Diablo Canyon		
MPC 170	3.7	13.9
MPC 123	1.9	17.0

III. DEVELOPMENT

The scope of the inspections included surface sample collection and analysis, temperature measurement and visuals. Before any inspection activities could begin, development efforts were needed to identify the inspection and measurement equipment to obtain the data, and a method to remotely deliver and operate the inspection tools at the canister surface. Although the horizontal and vertical systems have drastic design differences, the equipment used and even the general approach for deployment of the equipment wound up being very similar, with some changes needed to accommodate the different designs as noted.

For surface sample collection, both a wet and dry method were employed for all three inspections. The wet collection would dissolve and extract the surface deposits providing a thorough removal of all the surface deposits while the dry method would better collect the loose deposits of the dust and debris observed. The wet collection method used the commercially available SaltSmart™ device which, following extensive testing to qualify it for the specific conditions, was found to provide good collection efficiency. The dry collection method used an abrasive porous pad or Scotch-Brite™ type material to rub on the surface and collect as much loose surface dust and debris as possible for later analysis. There were some differences in the surface sample collection between the horizontal and vertical systems. The delivery of water for the wet method differed between the two designs. The dry method was manually operated for the horizontal system, while the vertical system used a mechanical actuation. The horizontal system used an additional felt paper behind the coarse abrasive pad with a vacuum assist for collection of the loose deposits, while this was not included in the vertical system due to space constraints.

Different temperature measurement instruments were evaluated and it was concluded that a contact thermocouple provided the best technique. Again, the horizontal system manually deployed the thermocouple while the vertical system used a mechanical actuation and was able to take advantage of the limited gap between the overpack and the canister, applying pressure to the inner wall of the overpack to provide more pressure for thermocouple contact against the canister surface.

For the visuals, the horizontal system was able to take advantage of the large open area offered through the outlet vent to insert a 100mm pan-tilt-zoom camera. Once inserted, the camera was kept away from the highest dose rate near the side of the canister, and nearly the entire canister surface was observable using the pan/tilt/zoom capability. For the vertical design a smaller camera was required due to the significantly smaller open area in annular gap between the canister and concrete overpack. An articulating 8.4 mm borescope was mounted as an integral part of the inspection tool delivery system. It should be noted that a similar borescope was used on the tool for the horizontal system to provide visual aid during the surface sample collection and temperature measurement.

The inspection needed to be performed remotely, with the canisters remaining in the storage module, so tooling had to be developed for delivering the test equipment to the canister surface. For the horizontal system, a number of options were evaluated including remote operated vehicles, a robotic snake arm and a straight tool for direct access. The direct access method was chosen for surface sample and temperature measurements for the horizontal design due to cost and schedule. A long tool was inserted through a narrow gap between the canister and the storage module to access the canister from the front opening with the door removed and temporary shielding installed. However, for the visuals the larger outlet opening at the top was used to insert a camera for access to the area inside of the module. For the vertical system a number of access pathways and methods were considered including removing the lid for direct access from the top, through the inlet at the bottom, and through the outlet at the top. Access through the top outlet was chosen for the ease of access and minimizing the impact to the system. A tool delivery system was developed and fabricated to first slide the tool all the way in the outlet to reach the annular gap between the canister and concrete overpack, direct the tool downward 90°, push the tool down the annulus to a known height for the inspection, remotely activate the tool using pneumatics to deploy the tool to the canister surface and perform the inspection, then retract the tool and remove it from the overpack.

IV. INSPECTIONS

Following significant effort and planning in preparation, the inspections were completed in 4-5 days at each site.

Calvert Cliffs inspected canisters between June 25 and June 29, 2012. The ISFSI at Calvert Cliffs is approximately 0.5 miles from the Chesapeake Bay and approximately 75 miles from the Atlantic Ocean. Hope Creek inspected canisters between November 18 and November 22, 2013. The ISFSI at Hope Creek is approximately 0.2 miles from the Delaware River, approximately 55 miles from the Atlantic Ocean and approximately 0.1 miles to the site's large natural draft cooling towers. Diablo Canyon inspected canisters between January 13 and January 16, 2014. The ISFSI at Diablo Canyon is approximately 0.4 miles from the Pacific Ocean and is about 300 feet above the water.

The inspections successfully collected a number of samples from the canister surface, measured the temperature of the canister and obtained pictures of the canister from inside the overpack.

Due to good ALARA practice and planning the total dose received for each inspection was relatively low. The total dose received for all the inspection activities at Calvert Cliffs was 40 mrem, at Hope Creek was less than 20 mrem and at Diablo Canyon was 48 mrem. The higher dose at Diablo Canyon was due to the higher dose rate casks at this site as well as a temporary fence that was installed near the casks in preparation of site construction activities. This fence prevented the workers from getting farther away from the casks while not directly performing work as is the standard practice for using a low dose waiting area.

V. RESULTS

This first set of inspections focused specifically on the canister conditions relevant to SCC were successful at demonstrating the ability to access the canister surface, obtain visual evidence of the condition of the surface, take temperature measurements at numerous locations and collect samples of the contaminants deposited on the canister over years of service.

V.A. Calvert Cliffs

The visual results showed both canisters had substantial amounts of dust, particularly on the top surface, and a few small rust blooms were observed on DSC-6, however, the general condition of both canisters was good, with no signs of gross degradation. Significant amounts of dust were seen on the upper portions of the canisters and several small clumps of unknown material were observed (Figure 3). While there was significant dust and material on the top surface of the canister, the lower surface was still shiny and appeared the same as when it was loaded. On both canisters, there was evidence of what appeared to be dripping, possibly from wind driven rain, that left a mark on the canister surface by disturbing the dust in that area. A few areas of rust were observed on DSC-6. Some rust appeared to be associated with what was an initiating scratch that likely occurred during canister loading and transfer, yet other areas were small rust blooms, not clearly associated with any external factors, but may be attributed to free iron contamination during the fabrication process. Some of the painted surfaces on the inside of the storage overpack had some coating failure.

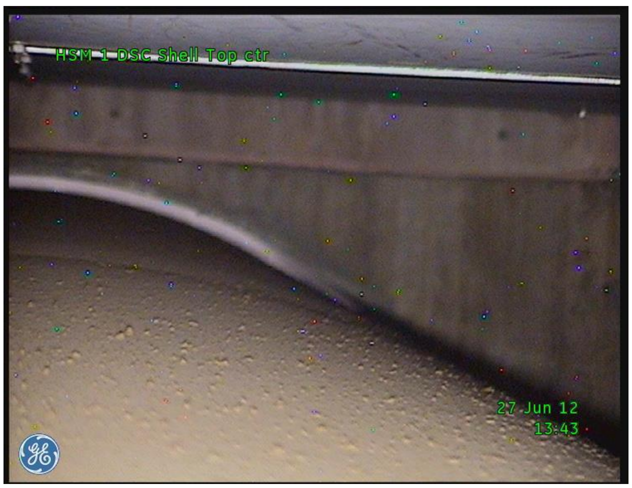

Figure 3. Dust on top of canister at Calvert Cliffs

Two sets of temperature measurements were taken. The first was using a thermocouple on the bottom of the DSC as soon as the door was partially raised. DSC-6 measured temperature was 51.1°C (124°F) and DSC-11 was 44.4°C (112°F). The predictions calculated 52.8°C (127°F) and 45.0°C (113°F) for DSC-6 and DSC-11, respectively, a difference of 0.6-1.7°C (1-3°F) (Ref. 8). A thermography gun was also used to take the temperature of the bottom of the DSC, however the thermography was greatly influenced by the overly bright conditions of the shiny steel surface and a sunny day, such that these results are too uncertain to be reported. The second set of temperature measurements were using the thermocouple tool inserted along the side of the canister and recorded at the 12, 3, 9, 5 and 7 o'clock radial positions and at axial positions in from the bottom of the canister approximately 10 cm (0.25 ft), 50 cm (20 inches) and 100 cm (40 inches). These temperature measurements were only taken on DSC-11. The temperatures ranged from a low of 40.0°C (104°F) to 48.3°C (119°F) and the temperature increase going from the bottom of the canister to as far in as the tool reached was only 2°C (4°F) maximum and as small as 0°C. This compares to model predictions ranging from 7 to 42°C (12 to 75°F) increase from the bottom of the canister to 102 cm (40 in.) from the bottom.

The surface samples collected had a suite of laboratory analyses performed[9]. The chemical analysis results found very low chloride concentrations, much less than 100 mg/m^2 by one or two orders of magnitude. The major anion species were sulfate and nitrate. The major cation species were Ca^{2+} with somewhat less amounts of K^+, Na^+, and Mg^{2+}. The iron is likely obtained from scraping some of the stainless steel canister itself. The high calcium is partially due to the high calcium content in the concrete overpack. Of particular interest was that the sample compositions resembled inland rainwater rather than seawater, indicating that the environment is more inland than marine.

V.B. Hope Creek

For Hope Creek, a borescope attached to the tool was used for the visuals. The borescope also provided good visual indication of the levelness and relative contact pressure of the surface sample collecting pads and thermocouple plate for each inspection. Due to the limited space, the field of view at the side of the canister was rather limited. The larger open area at the top, where more deposits collected, provided good access and visuals of the lid. The canister top lid and closure weld showed no signs of degradation and a thick layer of dust on the MPC surface with some organic matter (pollen). The walls of the concrete overpack were observed to be white and discolored. Some dust and organic matter was even observed in the annulus of MPC 144. On the top lid a "freckling" was noticed on the canister top lid surface which upon closer examination was found to be small piles of dust.

Temperature measurements were taken on the side and top of both canisters. The measured temperatures ranged from 22°C (71°F) to 57°C (134°F) on the side (Figure 4) and 54°C (129°F) to 79°C (174°F) on the lid. The lowest measured temperature corresponded to the area of the canister closest to the bottom, which is expected to be the coolest. The highest measured temperature corresponded to the area in the center of the lid. The measured temperature profile for the side of the MPC was similar for both canisters showing a non-linear shape increasing from bottom to top. The measured temperatures were roughly the same for the two canisters, due to the similar decay heats, although MPC 144 was slightly higher. On the first day of the inspection while performing temperature measurements on MPC 145, high winds were observed and likely affected the circulation of the natural convective air flow. It is not believed that this disturbance of the natural cooling air flow affected the results because the measured temperatures do not seem abnormal compared to other measured temperatures for this inspection.

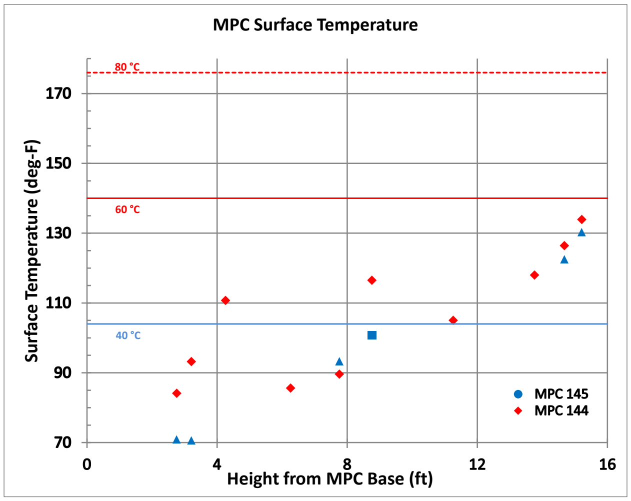

Figure 4. Hope Creek Canister Side Measured Temperatures

The surface samples collected had a detailed chemical analysis performed in the laboratory[10]. The chemical analysis results again found very low chloride concentrations, particularly on the canister side. The canister side found less than 8 mg/m^2 while the lid found as high as 60 mg/m^2. The major anion species were sulfate and nitrate. The major cation was calcium with an abundance of magnesium and sodium in the higher loaded samples. Sulfate was the dominant anion. Similar to Calvert Cliffs, the sample compositions resembled inland rainwater rather than seawater, indicating that the environment is more inland than marine.

V.C. Diablo Canyon

For Diablo Canyon, a special quartz fiber scope was used to better withstand the high radiation field instead of the normal scope used at Hope Creek that had some damage from the radiation levels. Again, the borescope provided good visual indication of the tool contact with the canister surface. The canister top lid and closure weld showed no signs degradation. Compared to other inspections, relatively small amounts of dust were observed on the horizontal MPC lid surface (Figure 5). This was likely due to the limited time in service. Some dark spots along the lid were observed and were determined to be small piles of dust. Some spotting on the upper portion of the inner wall surface of the concrete overpack was observed, which tapers off further down the overpack wall. Evidence of some streaking and possible corrosion was seen on the painted carbon steel surface of the inner wall of the concrete overpack. The side surfaces of both canisters showed no signs of degradation and little to no deposits, which is as expected due to the vertical orientation.

Figure 5. MPC 123 Top Surface and Lifting Hole

Temperature measurements were taken on the side and top of both canisters. The measured temperatures ranged from 49°C (120°F) to 118°C (245°F). Similar to Hope Creek, the lowest measured temperature was near the bottom, as expected, and a similar non-linear temperature profile was observed. The highest measured temperature corresponded to the area on the side of the canister very near the top. MPC 123 had consistently higher temperatures than MPC 170 as expected because the heat load for MPC 123 was about 20% higher.

The chemical analysis results for the surface samples collected again found very low chloride concentrations, particularly on the canister side, generally less than 5 mg/m^2 (Ref. 10). An abundance of sea salt aggregates were found in the dust samples at Diablo Canyon. Also, due to the higher canister temperatures, the collection efficiency of the SaltSmart™ is questionable. This is due to observations during the analysis of the samples that found less water in the reservoir and even that the outer wick had adhered to the silicone pad in some cases.

VI. CONCLUSIONS

These initial three inspections provided the first collection of data important to understanding the potential for SCC to occur on welded dry storage stainless steel canisters.

Generally, the canister surface appears in good condition with no signs of gross degradation. Limited surface corrosion was observed.

The measured temperatures were generally as expected. Some measurement error is believed to be included due to insufficient contact pressure of the thermocouple, particularly for the manual contact at the end of a long pole for the horizontal system. It was found that best estimate thermal models can fairly accurately predict the canister surface temperatures, provided the models have the details on the actual system and fuel loaded in the specific canister. Of particular interest is that despite the wide range of decay heats for the canisters inspected (4 to 17 kW), some area of each canister is in the range of temperature for deliquescence to occur, which is the initiating condition for possible corrosion.

The chemical analysis revealed much less chloride than expected for all locations. For Calvert Cliffs and Hope Creek, the cation/anion composition was more like inland rainwater than seawater, indicating these sites are less “marine” sites.

The inspections also provided valuable lessons for improving the equipment and procedures for future inspections, either specific to the conditions related to SCC, or possibly more advanced inspection techniques for the detection of stress corrosion cracking.

The initial set of EPRI led canister inspections is complete. This has provided the first set of data on the actual conditions of the canisters in service, where we had none before. The next step is to use the data from the inspection results feed into an overall SCC plan[11]. Future inspections by vendors and utilities will likely be needed, particularly for license renewal and aging management plans. EPRI is willing to share lessons learned from the initial EPRI led inspections with others performing inspections. EPRI is also getting involved in development of advanced NDE techniques, delivery systems and qualification tools (such as mockups) and will be working collaboratively with industry toward demonstrating the capability for detection and sizing of SCC cracks. The final goal will be to develop and provide industry guidelines for an aging management plan of SCC for dry storage canisters.

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REFERENCES

1. *Extended Storage Collaboration Program (ESCP); Progress Report and Review of Gap Analyses*, EPRI, Palo Alto, CA: 1022914 (2011).
2. S. Koizumi, “Demonstration Program of Long-Term Storage (FY2004-2008) – SCC of MPC under the Condition of Sea Salt Deposition,” presentation to the US NRC, November 8-9, 2004, Washington, DC.
3. *Climactic Corrosion Considerations for Independent Spent Fuel Storage Installations in Marine Environments*, EPRI, Palo Alto, CA: 1013524 (2006).
4. *Atmospheric Stress Corrosion Cracking Susceptibility of Welded and Unwelded 304, 304L, and 316L Austenitic Stainless Steels Commonly Used for Dry Cask Storage Containers Exposed to Marine Environments*, U.S. NRC Office of Nuclear Regulatory Research, Washington, D.C.: NUREG/CR-7030 (2010).
5. NRC, Atmospheric Salt Fog Testing to Evaluate Chloride-Induced Stress Corrosion Cracking of Type 304 Stainless Steel, Corrosion 2012, NRC ADAMS Accession Number ML120720549, March 2012.
6. Pacific Nuclear, Topical Report for the Nutech Horizontal Modular Storage System for Irradiated Nuclear Fuel NUHOMS®-24P, NRC ADAMS Accession Number ML 110730769, April 1991.
7. Holtec International, Final Safety Analysis Report for the HI-STORM 100 Cask System, HI-2002444, Rev. 6, "Safety Significant," Chapter 1: General Description., NRC ADAMS Accession Number ML ML081350147, May 2, 2008.
8. S. R. Suffield, et.al, Thermal Modeling of NUHOMS HSM-15 and HSM-1 Storage Modules at Calvert Cliffs Nuclear Power Station ISFSI, PNNL-21788, Pacific Northwest National Laboratory, Richland, WA (2012).
9. D. G. Enos, C. R. Bryan, and K. M. Norman, *Data Report on Corrosion Testing of Stainless Steel SNF Storage Canisters*, SAND-2013-8314P, FCRD-UFD-2013-000324, Sandia National Laboratories, Albuquerque, NM (2013).
10. C. R. Bryan, and D. G. Enos, *Analysis of Dust Samples Collected from Spent Nuclear Fuel Interim Storage Containers at Hope Creek, Delaware, and Diablo Canyon, California*, SAND-2014-16383, Sandia National Laboratories, Albuquerque, NM (2014).
11. Letter to Aladar Csontos from Shannon Chu, EPRI, Subject: *Transmittal of Research & Development Roadmap to Address Potential Stress-Corrosion Cracking of Welded Stainless Steel Used Nuclear Fuel Dry Storage Canisters, Revision 1*, March 31. 2014, ML14238A020 (2014).