U.S. NUCLEAR WASTE TECHNICAL REVIEW BOARD

CHLORIDE-INDUCED STRESS CORROSION CRACKING POTENTIAL IN DRY-STORAGE CANISTERS FOR SPENT NUCLEAR FUEL

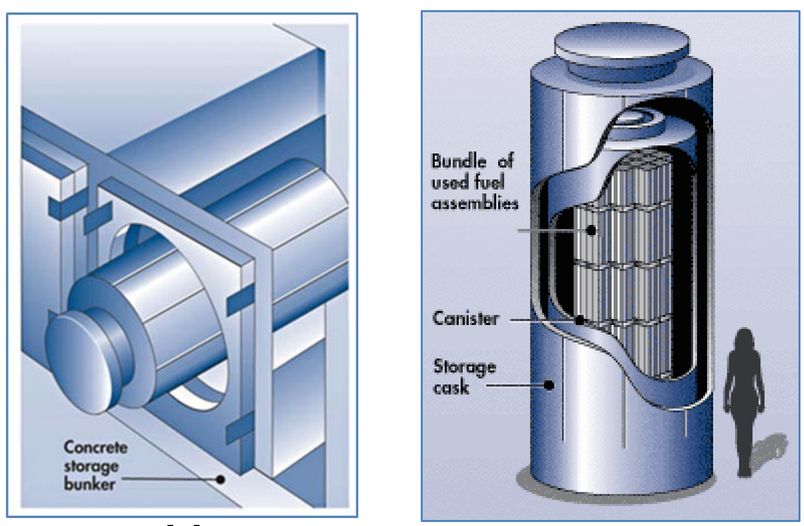
SUMMARY

Chloride-induced stress corrosion cracking (CISCC) is a type of degradation that leads to cracks in certain stainless steel materials. While known to be common in submerged water environments, CISCC can affect components in open-air locations if certain environmental conditions exist (as discussed below). CISCC occurring in open-air settings is often called atmospheric CISCC.[1] Because many of the stainless steel canisters holding commercial spent nuclear fuel (SNF) are stored in outdoor environments that may be conducive to CISCC, these canisters may be susceptible to degradation from CISCC. The Electric Power Research Institute (EPRI), the Nuclear Regulatory Commission (NRC), and the Department of Energy (DOE) are undertaking research to increase their understanding of the CISCC mechanism and to develop techniques for detecting CISCC in SNF canisters as a high priority.

SPENT NUCLEAR FUEL DRY CASK STORAGE SYSTEMS

At commercial nuclear power plant sites in the United States, SNF removed from nuclear reactors is cooled in spent fuel pools and, when sufficiently cool, may be loaded into SNF dry cask storage systems. As of January 2017, most nuclear power plant sites loading SNF into dry cask storage systems seal the SNF inside stainless steel canisters with welded lids (Ux Consulting Company, LLC (UxC) 2017). Five nuclear power plant sites have loaded SNF into bolted-lid casks that are not susceptible to CISCC although only two of those plants are still loading bolted lid storage casks: the Peach Bottom plant and the Prairie Island plant.

The steel SNF canisters with welded lids are the components that are susceptible to CISCC. The canisters are loaded into storage modules or overpacks (see Figure 1); these combined canister/overpack units are called dry cask storage systems. The systems are located above-ground or below-ground at concrete pads called Independent Spent Fuel Storage Installations



[A] [B]

Figure 1. Dry Cask Storage Systems for Commercial SNF.
[A] SNF canister in a horizontal storage module (or bunker);
[B] SNF canister in a vertical storage cask (or overpack). (NRC 2016)

[1] In the nuclear industry, cracks caused by atmospheric CISCC have been documented by the Nuclear Regulatory Commission in outdoor piping and tank systems not related to spent nuclear fuel storage (NRC 2012).

(ISFSI). As of January 2017, approximately 90 percent of all commercial SNF in dry storage was contained in systems with welded canisters (UxC 2017). Few of the dry cask storage systems with welded SNF canisters have been inspected while in service. However, a few nuclear power plant sites have completed a small number of canister inspections with no indications of CISCC. For example, two horizontally-stored welded canisters were inspected at the Calvert Cliffs Nuclear Power Plant in 2012, after more than fifteen years in storage. Video inspections of the canisters showed an accumulation of windblown dust and other particulate material on the top surfaces of the canisters but the canister surface was found to be "in good condition with no signs of gross degradation" (Calvert Cliffs Nuclear Power Plant 2012; EPRI 2014a).

THE MECHANISM OF ATMOSPHERIC CISCC

Three conditions must exist before CISCC can be initiated and sustained on the outside surface of an SNF canister[2]:

- First, the canister must be fabricated from a material with metallurgical properties that make it susceptible to CISCC, such as type 304 and type 316 stainless steels, which are both used in fabricating SNF canisters.
- Second, there must be tensile stress[3] acting on the canister. In the case of welded SNF canisters, residual tensile stresses have been confirmed to exist near welds in the canister body (Enos and Bryan 2016).
- Third, the canister must be located in an environment that is conducive to CISCC. The environmental factors that may lead to CISCC are the presence of chloride salts (*e.g.*, sodium chloride, magnesium chloride, or calcium chloride), a favorable temperature range, and a favorable relative humidity range.

Once the three basic conditions are met, it is possible for CISCC to start on the surface of an SNF canister as follows. Chloride salts can absorb moisture from the air to form an aqueous chloride-rich solution (a process called deliquescence). For a given salt type, the absorption of moisture can occur only in specific ranges of temperature and relative humidity, and those ranges are different for each salt type. Results of research to determine the ranges of temperature and relative humidity that may support deliquescence in chloride salts can be found in EPRI (2014b) and He *et al*. (2014). The chloride-rich solution chemically attacks the steel material in regions of high tensile stress.

Research has shown that CISCC is more likely to be initiated in a pre-existing crevice, crack, or flaw, such as a pit caused by localized corrosion (Parrott and Pitts 2011). Once a crack has started, it will continue to advance through the crystalline structure of the stainless steel as long as the necessary conditions of temperature, tensile stress, and presence of a chloride-rich solution remain. Other factors affecting the initiation and progression of CISCC are the type of stainless steel used in fabricating the canister and the fabrication technique itself (*e.g.*, amount of cold working, annealing).

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[2] A more detailed description of the molecular, electro-chemical nature of stress corrosion cracking can be found in Jones (1992).

[3] A tensile stress is a force acting in a direction that tends to stretch the material.

RESEARCH AND DEVELOPMENT ON ATMOSPHERIC CISCC

The NRC, DOE, and EPRI have sponsored and continue to support several domestic research and development (R&D) efforts on CISCC. Related R&D is also being conducted in countries such as the United Kingdom, France, Japan, and Korea. All important aspects of CISCC are under investigation, including the following:

- the atmospheric deposition of chloride salts onto canister surfaces (*e.g.*, Central Research Institute of Electric Power Industry (CRIEPI) 2015; Tran *et al*. 2015)
- temperature profiles of loaded SNF canisters (*e.g.*, Suffield *et al*. 2012)
- tensile stresses in the walls of SNF canisters (*e.g.*, NRC 2013; Enos and Bryan 2016)
- crack initiation and growth rates under a variety of conditions (*e.g.*, Tani *et al*. 2008; Prosek *et al*. 2009; Caseres and Mintz 2010; He *et al*. 2014).

DOE and EPRI are also conducting research on robotic systems and instruments that can be used remotely to inspect loaded SNF canisters in dry cask storage systems. EPRI efforts to develop robotic inspection systems (see Figure 2) are documented in EPRI (2016). A summary of the results from a broad range of domestic and international R&D efforts on CISCC is provided by EPRI (2014b).

IMPLICATIONS OF CISCC

No evidence of CISCC in SNF canisters has been found, although very few canister inspections have been conducted (none with rigorous inspection criteria and mature inspection techniques). However, if CISCC is found, especially if it leads to through-wall cracks in a canister wall, there could be an impact on the storage, transportation, and disposal of the affected SNF.

Figure 2. Robot Demonstration on a Dry Cask Storage System at the Duke McGuire Nuclear Station. (photo courtesy of Duke Energy Corp.)

During storage, a through-wall crack could pose a problem because the NRC's SNF storage regulations[4] require that SNF storage systems be designed with structures and systems to confine radioactive material. In SNF storage systems with welded SNF canisters, the SNF canister is the system designed to confine radioactive material and a through-wall crack in the canister that could potentially release radioactive material is a condition that may not meet the licensing requirements.

[4] Title 10, Code of Federal Regulations, Part 72, *Licensing Requirements for the Independent Storage of Spent Nuclear Fuel, High-level Radioactive Waste, and Reactor-related Greater Than Class C Waste*.

During transportation, the SNF canister is loaded into a transportation cask (overpack). The transportation cask performs the functions of holding the canister securely for transport, preventing the release of radioactive materials during normal conditions and most transportation accidents, and providing radiation shielding. NRC regulations applicable to transporting SNF[5] do not require an SNF canister to remain leak-tight. However, if a canister were to leak radioactive material during transportation, the resulting radioactive contamination inside the transportation cask may possibly require cleanup and recovery actions after transportation. Furthermore, the affected SNF canister might not be accepted for storage at the destination storage site without remediation. Repairing the crack in the canister wall or placing the degraded but still loaded canister into a leak-tight overpack are possible remediation options.

Until the design of a deep geologic repository for SNF in the U.S. has been approved by the NRC, there is some uncertainty about the required robustness of the waste containers to be used. At a minimum, SNF canisters will have to meet the NRC requirements for storage and transportation, as these activities are expected to occur until the SNF canisters arrive at the final repository site. Depending on the repository design, and on the safety approach chosen for long-term protection against the release of radioactive material, the SNF canister may or may not be required to confine radioactive material for long periods of time (hundreds of years).

PREVENTING AND MITIGATING CISCC

In order to plan for the possible consequences of CISCC, if it is found to exist in SNF canisters, research groups such as EPRI in the United States and CRIEPI in Japan have begun to consider possible corrective actions. For example, in 2016, EPRI established a subcommittee within its SNF Extended Storage Collaboration Program to examine methods for preventing or mitigating CISCC in SNF canisters. One approach for preventing CISCC could be fabricating canisters from materials that are not susceptible to CISCC. Another approach could be using canister treatment techniques focused on reducing or eliminating tensile stresses. These techniques include annealing the whole canister or applying mechanical impulses (*e.g.*, peening) to the outside walls to replace the tensile stress at the surface with compressive stress. National and international R&D efforts remain focused on addressing the causes, detection, implications, and prevention of CISCC.

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[5] Title 10, Code of Federal Regulation, Part 71, *Packaging and Transportation of Radioactive Material*.

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The Board evaluates the technical and scientific validity of U.S. Department of Energy activities related to implementing the Nuclear Waste Policy Act. The Board also provides objective expert advice on nuclear waste management and disposal issues to Congress and the Secretary of Energy.

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