Aging Management Program for Stainless Steel Dry Storage System Canisters

Darrell S. Dunn[1], Bruce Lin[1], Ryan M. Meyer[2], and Michael T. Anderson[2],
[1]*Nuclear Regulatory Commission, Washington, DC, darrell.dunn@nrc.gov*
[2]*Pacific Northwest National Laboratory, P.O. Box 999, Richland, WA 99352;*

ABSTRACT

Welded stainless steel canisters are used in the majority of the dry storage systems for spent nuclear fuel from commercial power reactors in the U.S. These systems were originally licensed for 20 years. Current Nuclear Regulatory Commission (NRC) regulations allow relicensing for periods up to an additional 40 years. A review of aging effects that could affect structures, systems, and components (SSCs) is required in license renewal applications and licensees are required to address aging effects using either a time-limited aging analysis (TLAA) or an aging management program (AMP).

Operational experience with stainless steel in nuclear reactor applications has shown that chloride induced stress corrosion cracking (CISCC) can occur in welded stainless steel components as a result of atmospheric deposition and deliquescence of chloride containing salts. Laboratory and natural exposure tests suggest that CISCC can occur with sufficient surface chloride concentrations and that crack propagation rates can be of engineering significance during continued storage. As a result, an AMP for welded stainless steel canisters used in dry storage systems is needed to address localized corrosion and stress corrosion cracking. An AMP for welded stainless steel canisters developed by the NRC staff is summarized in this paper and provides an example to be considered for future license renewal applications.

INTRODUCTION

The U.S. has more than 70 Independent Spent Fuel Storage Installations (ISFSIs) including both site specific and general licensed facilities. These ISFSIs have systems for the dry storage of commercial nuclear power reactor spent fuel. Storage systems in use in the U.S. include several designs but about 90 percent of the systems use welded stainless steel canisters as the primary containment boundary. When originally licensed, the dry storage systems that are currently in use were intended to provide a near-term solution to spent fuel storage needs and were often necessary at operating commercial nuclear power reactors to maintain full core offload capability when space in storage pools became limited. Several site specific ISFSI licenses have received renewed licenses after being in operation for 20 years. Current NRC regulations allow for relicensing of site specific ISFSI licenses as well as Certificate of Compliance (CoC) for storage systems for use at a generally licensed ISFSI for periods of up to 40 years.

Per NRC regulations outlined in 10 CFR 72.42(a), 72.240(c) [1], NRC licensees are required to have conducted an aging management review of the SSCs that are important to safety (ITS) or that may affect the operation of an ITS SSCs. Aging effects that may affect SSCs within the scope of the review must be addressed with either a TLAA that demonstrate an important to safety SSC will continue to perform their intended function for the period of extended operation or an AMP for management of issues associated with aging that could adversely affect ITS SSCs. TLAAs have been used to assess the effects of fatigue on important to safety SSCs. Environmentally induced aging effects such as degradation of concrete and corrosion of containment SSCs that cannot be managed using a TLAA are required to be addressed with an AMP.

CISCC of Stainless Steels

Stress corrosion cracking (SCC) requires a combination of a tensile stress, a corrosive environment, and a susceptible material or microstructure. The combination of conditions necessary for SCC is represented in a Venn diagram shown in Figure 1.

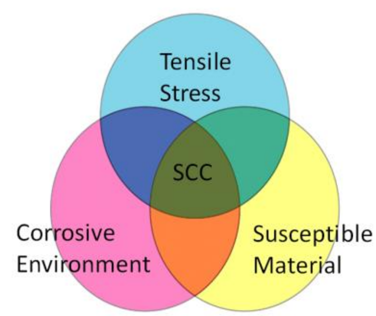

Figure 1. Venn Diagram showing the necessary components for stress corrosion cracking.

Austenitic stainless steels were first patented in 1912 and extensively developed by the mid-1930s. Widespread use of stainless steels in domestic, transportation, aviation, civil engineering applications had occurred by 1940s. The effects of alloy composition on CISCC susceptibility was developed from the late 1950s to early 1980s. These investigations identified chloride as an aggressive species that can promote SCC, a strong dependence of temperature on SCC susceptibility, and confirmed that tensile residual stresses from welding are sufficient to initiate and propagate SCC. Reports of atmospheric CISCC occurred in the late 1970s and initial testing of stainless steels under conditions relevant to atmospheric CISCC occurred in the mid-1980s.

CISCC of welded stainless steel components including water piping and storage tanks has been observed in operating commercial nuclear power reactors. NRC Information Notice 2012-20 [2] documents previous cases of atmospheric CISCC of welded stainless steel piping systems and tanks at operating reactor locations. Table 1 includes a summary operating experience for reactors where CISCC was observed as a result of atmospheric deposition and deliquescence of chloride containing salts. All of these cases involve welded stainless steel components in reactors that were located close to an open ocean or bay. All of these instances involve components that are exposed at near ambient temperatures, although the actual temperatures of these components are also unknown and are expected to be dependent on a number of factors including location, and seasonal variations.

Laboratory Testing and Analyses

Operational experience shows that CISCC can occur as a result of atmospheric transport, deposition and deliquescence of chloride containing salts. However, there is insufficient information to determine the conditions under which atmospheric CISCC can occur or actual crack propagation rates.

The NRC has recently published the results of a completed investigation of CISCC testing of type 304, 304L and 316L stainless steel and welds in NUREG/CR-7170 [3]. These tests showed that atmospheric CISCC was possible when temperatures are low enough to allow the relative humidity at a heated surface to increase to the point where deliquescence of the some of the chloride containing components of deposited sea salts can occur (Figure 2). Based on deliquescence data for the major chloride containing components of sea salt and assuming an absolute humidity of 30 g/m^3, deliquescence of calcium chloride ($CaCl_2$) is expected at temperatures below 65°C and deliquescence of magnesium chloride ($MgCl_2$) is expected at temperatures below 52°C. Deliquescence of sodium chloride (NaCl) would not occur until temperatures fall below 36°C. The appearances of the specimens during testing also suggest partial deliquescence of the deposited sea salt. Thus, at temperatures above approximately 36°C, CISCC of the specimens is primarily due to the formation of a chloride containing solution as a result of deliquescence of $MgCl_2$ and $CaCl_2$.

In the NRC sponsored study, testing was conducted above and below the critical chloride surface concentration reported by Shirai et al. [4]. However, the results reported in NUREG/CR-7170 clearly indicate that SCC was observed at surface salt concentrations of 100 mg/m^2 which were approximately an order of magnitude lower than the critical surface concentration reported by Shirai et al. [4]. The relatively quick initiation of CISCC for type 304 stainless steel at surface concentrations of 100 mg/m^2 reported in NUREG/CR-7170 suggests that SCC could occur at lower surface concentrations.

While the test results reported in NUREG/CR-7170 did not establish or confirm the minimum sea salt (or chloride) surface concentration necessary for CISCC, previous testing by Tokiwai et al. [5] showed that the critical stress necessary to initiate SCC was dependent on surface chloride concentration. Using only NaCl salt, Tokiwai et al. [5] reported CISCC of sensitized 304 stainless steel was observed with surface chloride concentrations of 8 mg/m^2. It should be noted that the conditions used by Tokiwai et al. [5] resulted in deliquescence of all of the deposited NaCl.

The critical sea salt concentration for CISCC it may be estimated using the results of previous studies. Some assumptions regarding the speciation of deposited sea salts are necessary to compare the results reported by Tokiwai et al. [5] to the results reported by He et al. [3]. Using a simulated sea salt composition [6] and assuming that the relative humidity at temperatures above 40°C are too low for the deliquescence of the NaCl component of sea salt, the critical deposited surface sea salt concentration for CISCC is estimated to be 65 mg/m^2.

The Electrical Power Research Institute (EPRI) also has an ongoing effort to develop susceptibility assessment criteria for welded stainless steel canisters. In addition, several recent reports have been published by the EPRI that address the potential for CISCC of welded stainless steel spent fuel storage canisters including an analysis of the effects of CISCC on welded stainless steel canisters [7], a literature review of CISCC that summarizes the results of many previous laboratory investigations [8], and a flaw tolerance and growth assessment for CISCC of welded stainless steel canisters for dry storage of spent nuclear fuel [9]. It should be noted that the EPRI flaw tolerance and growth assessment does not evaluate the time necessary for conditions for CISCC of the canisters to develop. The EPRI assessment is focused on CISCC growth and the EPRI calculations indicate that CISCC penetration of welded stainless steel canisters may range from 26 to more than 100 years depending on environmental conditions.

The rates calculated by Fuhr et al. [9] are comparable to rates estimated from operation experience in Table 1. Rates from these events back calculated from time of initial operation to time of detected failure for the thickness of the component range from 0.11 to 0.91 mm/year. However it should be noted that this calculation ignores the time for the accumulation of sufficient chloride containing salts for CISCC initiation.

TABLE 1. Summary of reactor operating experience with Atmospheric CISCC in welded stainless steel components

Plant	Distance to salt water, m	Material and Component	Thickness, or crack depth, mm	Time in Service, years	Average crack growth rate, mm/yr
Koeberg (South Africa)	100	304L refueling water storage tank	5.0 to 15.5	17	0.29 to 0.91
Ohi (Japan)	200	304L refueling water storage tank	1.5 to 7.5	30	0.17 to 0.25
St Lucie (FL, USA)	800	304 refueling water storage tank pipe	6.2	16	0.39
Turkey Point (FL, USA)	400	304 pipe	3.7	33	0.11
San Onofre (CA, USA)	150	304 pipe	3.4 to 6.2	25	0.14 to 0.25

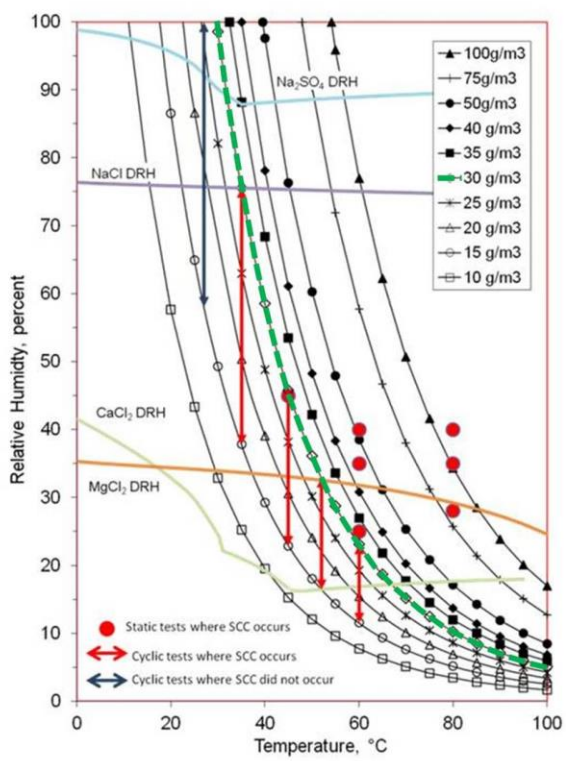

Figure 2. Relative humidity vs. temperature diagram for varying absolute humidity values. Deliquescence behavior of sea salt components and U-bend CISCC tests reported in NUREG/CR-7170 are shown as a function of temperature [3].

Kosaki [10] reported a median rate for CISCC propagation of 9.6×10^{-12} m/s (0.29 mm/yr) obtained in natural exposure tests of type 304 base metals and welds, type 304L welds and type 316LN welds. These rates were obtained from tests exposed under natural conditions on Miyakojima Island which is located about 350 km east of Taiwan with an average temperature of 23°C and typical minimum and maximum temperatures of 14°C to 31°C, respectively. Actual specimen temperatures were not measured and could have varied considerably compared to the ambient temperature as a result of heating from solar radiation during exposure. Nevertheless, the CISCC rates measured by Kosaki [10] on Miyakojima Island at ambient temperatures are comparable to atmospheric CISCC rates determined from operational experience at both domestic and foreign nuclear power plants listed in Table 1 including events at San Onofre, Turkey Point, St. Lucie, and Koeberg (South Africa).

CISCC propagation rates are known to be strongly temperature dependent. Fuhr et al. [9] noted that test results reported by Hayashibara et al. [11] support activation energies from 25 to 105 kJ/mol, with the greatest support for activation energy in the 30-40 kJ/mol range. The large range of activation energy values indicated that additional crack propagation rate data within the temperature range of interest would be beneficial to reducing uncertainty of CISCC models.

Inspection of Welded Stainless Steel Canisters

Inspections of dry storage canisters in service have been conducted at a few ISFSI sites. Details of the inspection conducted at the Calvert Cliffs nuclear power plant ISFSI was reported by Waldrop et al. [12]. The inspection was conducted as part of a lead system inspection associated with the site specific license renewal. Inspections consisted of remote visual inspections using equipment specifically designed to operate in radiation environments. In addition, collection methods were developed to obtain surface samples from canisters that had been in service for 16+ years. The remote visual inspection methods were limited in coverage due to access restrictions. For areas that were examined, no evidence of localized corrosion was identified. Red rust colored patched were observed and were assessed to be iron containing corrosion products from related to surface iron contamination in the stainless steel canister. Samples collected contained a variety of components with some amount of chloride containing salts (5.2 mg/m^2) on the canister surfaces.

EXAMPLE AGING MANAGEMENT PROGRAM FOR WELDED STAINLESS STEEL CANISTERS

Results of laboratory and field testing conducted in the past 30 years has provided a better understanding of the factors that influence atmospheric CISCC susceptibility of welded stainless steel components. Although it remains unclear if the conditions necessary for localized corrosion and CISCC to occur will develop on spent fuel storage canisters, CISCC has been observed on welded stainless steel components at operating commercial power reactors. Because it is possible that in certain environments CISCC may be potential aging mechanism for welded stainless steel spent fuel storage canisters, an inspection based example AMP using guidance from consensus codes and standards to assess the condition of canisters after many years in service was developed. This AMP, which will be included in the NRC's revision to regulatory guidance on license renewal of dry storage systems NUREG-1927 [13], is presented in this paper along with a discussion of the potential technical challenges.

Scope

The scope of this AMP is the inspection of welded stainless steel dry storage canisters for the presence of atmospheric deposits, localized corrosion, and stress corrosion cracking. Examination of the canisters should focus on the canister fabrication welds, closure welds, and the associated weld heat affected zones. In addition, several other areas should be included in the scope of the AMP including areas of the canister to which temporary supports or attachments were attached by welding and subsequently removed, areas immediately adjacent to locations on the canister where a crevice is formed, canister surfaces where atmospheric deposits accumulate, and areas of the canister surface that are at lower temperatures.

Preventative Actions

It should be noted that there are generally two types of AMPs: (1) condition or performance monitoring, and (2) preventative actions. This AMP is for condition monitoring of existing systems where preventative actions are not presently incorporated into the existing dry storage canister design. It is recognized that future designs or amendments could include preventative actions such as surface modification methods to impart compressive residual stresses on the canister in the welds and weld heat affected zones or materials that are resistant to CISCC. Such features will be considered if they are included in future designs.

Parameters Monitored or Inspected

Parameters Monitored or Inspected should include canister surfaces identified in the scope for discontinuities and imperfections as well as the appearance and location of deposits on the canister surfaces. This includes visual evidence of localized corrosion including pitting corrosion and crevice corrosion and stress corrosion cracking and the size and location of any indications identified.

Detection of Aging Effects

Remote visual inspections for indications of corrosion products associated with localized corrosion or direct detection of pitting and crevice corrosion that is open to the surface can potentially be detected by visual testing [14]. In order to ensure that inspections methods are consistently applied and the results of the inspection are comparable, the procedures for remote visual examination should be demonstrated and the procedure attributes including equipment resolution, lighting requirements, etc., should reference applicable standards, such as BWRVIP-03 [15] for EVT-1 examinations or the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code Section XI, Article IWA-2200 [16] for VT-1 and VT-3 examinations.

Augmented inspection may be necessary to characterize localized corrosion or stress corrosion cracking when evidence of localized attack is identified. In these cases, the severity of degradation must be assessed including the dimensions of the affected area and the depth of penetration with respect to the thickness of the canister. For accessible areas where adequate cleaning can be performed, it may be possible to use remote visual inspection meeting the requirements for VT-1 examination in ASME Section XI, IWA-2211 [16] to determine the type of degradation. Examinations to characterize the extent and severity of localized corrosion and/or stress corrosion cracking will likely require the use of surface and/or volumetric inspection techniques such as those consistent with the requirements of ASME Section XI, IWB-2500 for category B-J components [16].

The sample size for initial inspection should include at least one canister at each site with preference given to the canisters with the greatest susceptibility for localized corrosion or CISCC. Factors to be considered include older and colder canisters with the greatest potential for the accumulation and deliquescence of deposited salts that may promote localized corrosion and stress corrosion cracking. Initial inspections should be completed prior to entering the period of extended operation at each site and subsequent inspections should occur every 5 years.

Monitoring and Trending

Monitoring and trending should include the documentation of the examination of the canister, location and appearance of deposits and assessment of the suspect areas where corrosion products were observed. In particular this should address the appearance of the canister welds and documented with images and measurements that will allow comparison in subsequent examinations. Monitoring and trending should also document changes to the size and number of any rust colored stains as a result of iron contamination of the surface in subsequent inspections and the locations and size of any areas of localized corrosion and/or the stress corrosion cracking.

Acceptance Criteria

Acceptance criteria must be applicable to the methods used to detect aging effects. For remote visual inspections of welded stainless steel canisters, appropriate acceptance criteria where no additional actions are necessary is the absence of indications of localized corrosion pits, etching, crevice corrosion, stress corrosion cracking, red-orange colored corrosion products emanating from crevice locations, or red-orange colored corrosion products in the vicinity of canister fabrication welds, closure welds, and welds associated with temporary attachments during canister fabrication.

Indications subject to additional examination and disposition include localized corrosion pits, crevice corrosion, and stress corrosion cracking; locations with discrete red-orange colored corrosion products that are 1 mm in diameter or larger; linear appearance of corrosion products parallel to or traversing fabrication welds, closure welds, weld heat affected zones, and locations were temporary attachments may have been welded to and subsequently removed from the stainless steel dry storage canister; corrosion products present on canister surfaces that appear to be emanating from a crevice or occluded region that cannot be observed with visual inspection.

The acceptance criteria used in augmented inspections also will be dependent on the inspection method. For example, if the augmented inspections are limited to visual examinations such as VT-1 or EVT-1, appropriate acceptance criteria may be the requirements of ASME Section XI Table IWB-3514-2 for localized corrosion or linear indications. For volumetric inspections acceptance standards identified in ASME Section XI, IWB-3514.1 and the acceptance criteria identified in IWB-3640 may be appropriate [16].

Corrective Actions

Corrective actions are the response to an inspection finding that reveal conditions that are not in compliance with established acceptance criteria. Canisters with confirmed localized corrosion or stress corrosion cracking must be evaluated for continued service. Canisters with localized corrosion or stress corrosion cracking that do not meet the prescribed evaluation criteria must be repaired or replaced.

In addition, confirmation of localized corrosion and/or stress corrosion cracking requires assessment of the extent of condition. This includes inspection of additional canisters at the same location. Priority for additional inspections should be to canisters with similar time in service and initial loading.

Confirmation Process

The confirmation process will be in accordance with the specific or general licensee Quality Assurance Program consistent with 10 CFR 72 Subpart G [1] or 10 CFR 50 Appendix B [17]. The licensee QA program should ensure that inspections, evaluations, and corrective actions are completed in accordance with the Site Specific or General Licensees Corrective Action Program (CAP) including the extent of condition, evaluation for continued service, and actions necessary to either repair, replace, or mitigate SSCs that do not meet acceptance criteria

Administrative Controls

The site specific or general licensee corrective action program must be commensurate with 10 CFR 72 Subpart G, [1] or 10 CFR 50 Appendix B [17] and specifically address inspector requirements, record retention requirements, and the examination review process. In addition, administrative controls should address the frequency/methods for reporting inspection results to NRC and the frequency for updating the AMP based on industry-wide operational experience.

Operating Experience

Atmospheric CISCC of austenitic stainless steels is a known degradation mechanism for welded stainless steel SSCs and has been reported in a range of industries including welded stainless steel components and piping in operating nuclear power plants. Inspections of welded dry storage system canisters will directly add to the operating experience and will be beneficial for confirming the results of additional analysis and laboratory testing. It is expected that applicable operating experience including internal and industry-wide condition reports, licensee event reports, vendor-issued safety bulletins, NRC Generic Communications, and industry initiatives will be accumulated and evaluated along with operating experience from other ISFSIs with similar in-scope SSCs. The combination of these sources of information should be used to assess the adequacy of AMPs for welded stainless steel canisters and make necessary improvements to assure

CISCC does not result in unacceptable aging of the confinement boundary.

DISCUSSION

The implementation of an AMP for welded stainless steel canisters such as this example that relies on inspection to assess the condition of the canisters will require detailed knowledge of the system design, access limitations, and the environment immediately adjacent to the canister (temperature, gamma and neutron radiation) in order to determine the type of inspection that can be conducted, the inspection instrumentation that can be accommodated, and the requirement of the inspection instrumentation delivery systems. While these are significant challenges, a discussion of the possible aging effects, inspection methods that may be utilized, and the expectation regarding discontinuities that can be detected is warranted.

The detection of aging effects on welded stainless steel canisters is under development and limited inspections have been conducted to date. Also, there is no spent fuel storage system equivalent for the ASME B&PV Code Section XI which addresses inspection requirements of operating commercial nuclear power plant systems. Previously conducted lead system inspections have used remote visual inspection to assess the condition of canisters. Although these inspections were not conducted in accordance with a consensus code or standard such was the ASME B&PV Code Section XI requirements, the remote visual inspections have shown that it is possible to obtain information to aid in the assessment of the canister condition after many years in service.

Based on testing and operating experience, pitting corrosion is a likely precursor to CISCC. However, detection of pitting corrosion may be more readily accomplished using remote visual methods compared to detection and characterization of CISCC. As previously indicated, the remote visual inspections conducted for lead system inspections identified red rust colored corrosion products on the canister surfaces [12]. Although these corrosion products were assessed to be a result of iron contamination rather than an indication of localized corrosion of the canister, the observation that corrosion products could be observed on a canister surface provides evidence that remote visual inspections may provide a semi-qualitative assessment of the canister condition.

Detection of stress corrosion cracks and in particular intergranular cracks which can result from CISCC can be challenging. Cumblidge et al. [18] noted that the crack opening dimension (COD) of service-induced cracks in nuclear components is one of the most important parameters affecting the reliability of visual tests. For stress corrosion cracks, the COD is related to the susceptibility of the material, stresses and crack history but COD is not strongly related to the crack depth. Subsequent studies by Cumblidge et al. [19] showed that cracks with CODs above 100 µm (0.004 in.) are generally detectable unless conditions are very unfavorable. Cracks with CODs less than 20 µm (0.0008 in.) were difficult to detect under all but the most favorable conditions. The quality of the examinations and camera systems was important for detecting cracks with CODs between 20-100 µm (0.0008-0.004 in.).

The limitations identified with visual inspection methods casts doubt on the use of remote visual inspection to assess the presence of CISCC, size cracks if they are present, and evaluate crack growth in subsequent inspections. After many years in service canister surfaces will likely have some accumulated deposits that may interfere with visual testing. Radiation levels and access restrictions may also be significant impediments to visual examination of the canisters. These potential limitations need to be evaluated in the development of an AMP to monitor the condition of welded stainless steel canisters.

This AMP is focused on evaluating the condition of the canisters rather than determining the environmental conditions on the canister surfaces. Waldrop et al. [12] reported analysis results of deposit samples collected from canisters at Calvert Cliffs ISFSI. The analysis was a first of a kind effort and challenges were noted in both the collection of the samples and the analyses. While it is recognized that analyzing deposits accumulated on the surface of the canisters could provide valuable information to determine whether the conditions necessary for localized corrosion and CISCC exist, much additional effort is needed to develop reliable methods to obtain samples of deposits from canister surfaces. Information from sample collection may be augmented with data that characterizes the conditions at an ISFSI location and standardized practices are available to obtain such information [20].

CONCLUSIONS

Welded stainless steel canisters are used in the majority of the dry storage systems for spent nuclear fuel from commercial power reactors in the U.S. Operational experience in commercial nuclear reactor applications has shown that CISCC can occur in welded stainless steel components as a result of atmospheric deposition and deliquescence of chloride containing salts. Laboratory and natural exposure tests suggest that CISCC can occur with sufficient surface chloride concentrations and that crack propagation rates can be of engineering significance during continued storage. To address this potential aging effect, an AMP for welded stainless steel canisters used in dry storage systems was developed by the NRC that relies on inservice inspection of canisters to detect localized corrosion that could promote CISCC. The AMP is based on existing inspection systems that have been utilized in lead system inspections. However, adaptation of existing inspection methods used for operating reactor pressure boundary components and development of instrument delivery systems for canister inspections are ongoing industry led activities. Advancements as a result of these ongoing efforts are expected to improve canister inspection capabilities.

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