NACE CORROSION 2014
March 9–13, 2014
San Antonio, Texas, USA

Review and Assessment of Techniques for Monitoring Environmental Conditions and Stress Corrosion Cracking of Stainless Steel Canisters

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ABSTRACT

Spent nuclear fuel at a number of U.S. locations is stored at independent spent fuel storage installations in dry cask storage systems (DCSSs), which commonly consist of a welded austenitic stainless steel canister within a larger concrete vault or overpack. Stress corrosion cracking of welded stainless steel is considered a high-priority technical issue and functional monitoring has been identified as one of the top crosscutting issues concerning performance of various dry cask components.

The work presented in this paper reviews and assesses the current state of technology for directly monitoring stress corrosion cracking, as well as the important environmental conditions—including temperature, humidity, and chloride concentration—that could affect this degradation mechanism. A variety of techniques were identified to be potentially suitable for application to extended storage, ranging from detecting crack initiation and measuring propagation from stress corrosion cracking to measuring the chloride concentration in deliquescent solutions. Some techniques are well developed and commercially available, but some require significant advancement to overcome limitations. Overall, because of geometry, space limitations, and the high ionizing radiation of DCSSs, all the monitoring methods must be modified and tailored for this application.

Keywords: Stress corrosion cracking, temperature, humidity, and chloride concentration

INTRODUCTION

Spent nuclear fuel at a number of U.S. locations is stored at independent spent fuel storage installations in dry cask storage systems (DCSSs), which commonly consist of a welded austenitic stainless steel canister within a larger concrete vault or overpack.[1] The majority of canister-based designs emplace the canister vertically within the overpack structure, as shown in one example in Figure 1. Some canister-based designs load and store the canister in a horizontal storage module, similar to that depicted in the generic schematic in Figure 2 for the TN NUHOMS System®.[2]

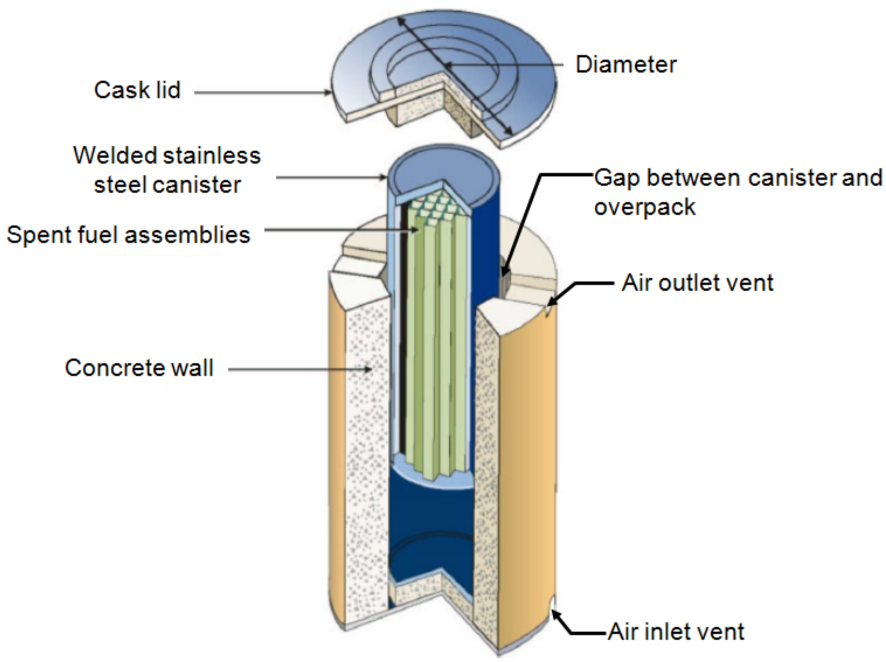


Figure 1. Schematics of Vertical Canister-Based System[2]

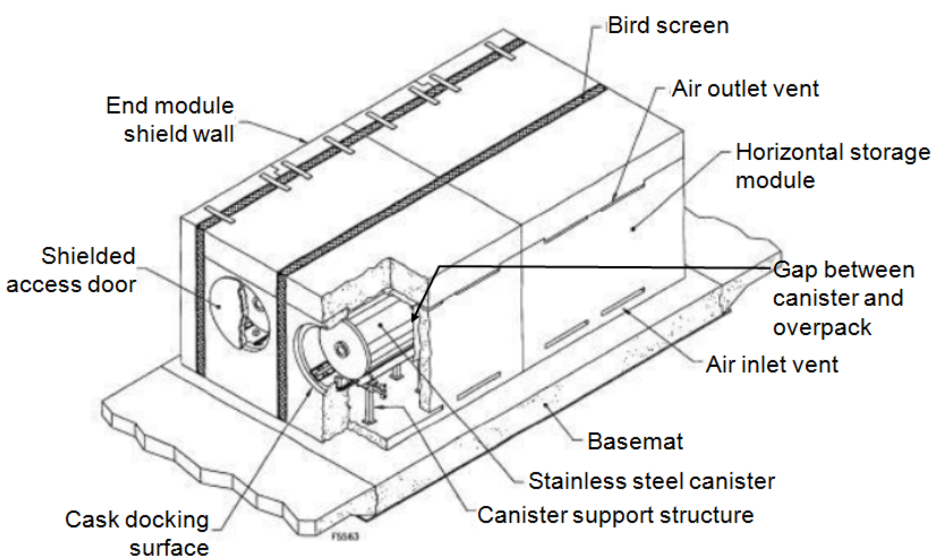


Figure 2. Schematics of Horizontal Canister-Based System[2]

A number of technical issues and research and data needs associated with extended spent fuel storage have emerged from recent gap assessments.[1] Stress corrosion cracking (SCC) of welded stainless steel was considered as one of the top priority technical issues and functional monitoring was identified as one of the top crosscutting issues concerning performance of various dry cask components. For canister-based systems, partial exposure to the external environment can lead to the formation of a salt solution on the canister surface through the following process. Aerosolized salts could enter the outer cask through air vents, as shown in Figures 1 and 2. Once various salts have deposited onto a canister surface, the salts may absorb moisture from the air and deliquesce under certain environmental conditions, which include RH and temperature. The reverse of deliquescence is efflorescence, which involves the loss of water from the salt solution and precipitation of salts. The deliquescence and efflorescence of a salt or salt mixture occur at a specific value of RH at the canister surface, which depends on the composition of the deposited salt mixture and temperature. Therefore, humidity and temperature at the canister surface are important parameters to monitor and are relevant to the technical information needs on degradation of the canister material. Experimental testings[3,4] have shown that chloride has a strong effect on SCC and SCC could occur when temperature at the canister surface is below 100 °C at some humidity values. Therefore, measurement of temperature, humidity, and chloride concentration is important for determining the integrity of a canister.

The work presented in this paper reviews and assesses the current state of technology for directly monitoring the important environmental conditions (temperature, humidity, and chloride) affecting SCC, as well as crack initiation and propagation. As the monitoring methods described in this paper are not routinely used in DCSSs, the information and assessment presented must be viewed as preliminary and it must be recognized that a number of technical issues must be evaluated prior to considering any senor or monitoring system for DCSS applications.

MONITORING TECHNIQUES FOR TEMPERATURE, RELATIVE HUMIDITY, AND CHLORIDE

Temperature Monitoring

The following temperature sensors were determined to be promising for this extended storage application based on many factors, including radiation susceptibility, physical size, and measurement range: (i) thermocouples, (ii) resistance temperature detectors (RTDs), (iii) radiation thermometers, (iv) ultrasonic temperature measurement, and (v) fiber optic temperature sensors. The main features of these techniques are described in Table 1. Other sensors such as silicon temperature sensors, thermistors, and Johnson noise thermometers may also be applicable, but these methods were not evaluated in this paper.

A thermocouple consists of a junction of two wires of dissimilar materials, usually metal alloys, that produces a voltage at its terminals proportional to the temperature of the junction.[5–7] The thermocouple is placed in physical thermal contact with the component or structure whose temperature is to be measured. Thermocouples have been widely used to measure temperature in industrial and nuclear settings for many years.

A RTD contains a wire of a single metallic material whose resistance varies in a predictable way with its temperature. A data acquisition device can apply a known voltage (V), measure the resulting current (I), and then calculate the equivalent resistance (R) using Ohm's Law ($V = I*R$). The conversion of measured resistance to temperature is straightforward because the resistance-temperature curve for an RTD is nearly linear and any non-linearities are highly predictable and repeatable.[6]

Table 1. Temperature Monitoring Techniques					
Features	**Thermocouples**	**Resistance temperature detectors**	**Radiation Thermometers**	**Ultrasonic Measurement**	**Fiber Optic Sensors**
Maturity	Field deployed for nuclear		Field deployed for non-nuclear	Field deployed for nuclear	Field deployed for non-nuclear
Temperature measurement range	Up to 1,700 °C	0 to 482 °C	>1,000 °C, maximum device temperature: 40–70 °C	>2,000 °C	>2,000 °C
Sensitivity	~ 1 °C		~ 0.1 °C	~ 0.001 °C	~ 0.1 °C
Radiation tolerance	300 Mrads total integrated dose		Unknown	Unknown, but generally low	Unknown, but likely high
Replacement difficulty	High if bonded or low if in air		Low (if accessible)	Moderate (if accessible)	Possibly moderate (if accessible)
Monitoring area	Contact		Direct field of view	Integral portion of the measuring medium	Direct thermal contact with the optical fiber
Space requirements	<5 cm^3; 0.1–6.5 mm D × 10 mm L		1,000 cm^3; 10 cm L × 10 cm W × 10 cm H	200–2,000 cm^3; diameter of measuring wire <1 mm	2,000 cm^3; diameter of optical fibers <5 mm
Power requirements	On the order of 10–20 watts		On the order of 20–100 watts	On the order of 20–100 watts	On the order of 20–100 watts
Longevity	Decades		Years	Unknown	Years—Decades
Data collection mode	Continuous or intermittent		Continuous or intermittent	Continuous or intermittent	Continuous or intermittent
Amount of data per measurement	Small, on the order of bits		Single image or video frame	Large intermediate data	Small; on the order of bits
Strengths	Mature, small size, high-temperature and radiation tolerance, long lifetime		Mature technique	Mature technique, high-temperature tolerance	Mature technique, high-temperature and radiation tolerance
Weaknesses	Requires signal cable, good thermal bonds are essential for surface temperature measurements		Low temperature range and radiation tolerance, emissivity of surface must be known	Low radiation tolerance	Potential fiber darkening and embrittlement

Radiation thermometers measure a portion of the thermal radiation emitted by the object being measured.[7–9] Optical pyrometers, infrared thermometers, and radio-frequency-based thermal radiation measurement are examples of this class of instruments. Computing the temperature of a device under test conditions requires a line-of-sight measurement of the emitted thermal radiation and an estimated or known value of the object's emissivity. For some radiation thermometers, the emissivity of the object under examination is configured via keypad or user display. In these cases, the device internally calculates the conversion and provides a temperature readout of the object. The line-of-sight measurement capability, combined with large standoff distances and the availability of portable systems, makes these instruments potentially useful for temperature monitoring

Ultrasonic temperature measurement is based on the thermal dependence of the speed of sound in materials.[10,11] The time difference between the transmission of an ultrasonic pulse and the signal reflected from a calibrated location allows for calculation of the temperature of the material through which the pulse travels. In contrast with other devices that measure temperature at a single point, ultrasound measures the bulk mean temperature throughout the measuring medium.

Optical fibers can be used as sensors to measure strain, temperature, pressure, and other quantities by modifying a fiber so that the quantity to be measured modulates the intensity, phase, polarization, wavelength, or transit time of light in the fiber[10–12]. Sensors that vary the intensity of light are the simplest, because only a simple source and detector are required. Temperature can be measured by using a fiber that has evanescent loss that varies with temperature or by analyzing the Raman scattering of the optical fiber.

Humidity Monitoring

Humidity measurements have been widely used in industrial and non-industrial applications for more than 100 years.[13–15] The technologies that are commercially available for measuring humidity include capacitance-, chilled-mirror-, electrical-resistance-, electrolytic-, and psychrometer-based humidity sensors. There are approximately 500 vendors and close to 1,500 types of humidity sensors[16] available. This further highlights the need and availability of humidity sensors for industrial and non-industrial applications. Technologies such as acoustic-based[17] and hygrometric- and gravimetric-based humidity sensors,[13] while conceptually feasible, have not been sufficiently developed or demonstrated to be viable for long-term industrial and non-industrial applications. High-energy physics researchers have experimentally demonstrated the initial feasibility of fiber optic humidity sensors in a high-radiation environment up to 1 Mrad,[18] with space and access restrictions that are similar to those in potential SNF dry storage applications. Two commercially available leakage monitoring systems have been identified, both of which have already been deployed in nuclear power plants including the Areva Flüs system and the Westinghouse Leakage Monitoring System.[19–21] In this paper only commercially available technologies are evaluated.

The promising humidity sensors for this application are: (i) capacitance-based, (ii) chilled-mirror-based, and (iii) electrical-resistance-based humidity sensors. The main features of these techniques and the leakage monitoring system deployed in nuclear power plants are described in Table 2.

For capacitance-based humidity sensors, the effect of water concentration on the dielectric constant of a non-metallic sensing substance, such as ceramic (metal oxide) or polymer, is measured. The measured dielectric constant is correlated to RH using a calibration chart. The sensitivity and range of operating temperature of the capacitance-based sensors depend on the sensing substance. The capacitance-based humidity sensors are the most abundantly available and commercially used, based on information from Chen and Lu[14] and a survey of various vendors. Chen and Lu[14] provided detailed information on various polymeric materials used in capacitance-based humidity sensors.

Chilled-mirror-based sensors operate by measuring the dew point or frost point, which is the temperature at which a sample of air at constant pressure becomes saturated with water vapor. At this saturation temperature, further cooling of air results in condensation of water in a liquid or solid phase. The condensation is allowed to occur on a chilled-mirror surface. A light from a lamp is projected onto the chilled mirror and the reflection is received by a photo resistor, as schematically shown in Figure 3.

Table 2. Humidity Monitoring Techniques					
Features	**Capacitance-Based**		**Chilled-Mirror-Based**	**Electrical-Resistance-Based**	**Leakage Monitoring**
	Ceramic	**Polymeric**			
Maturity	Commercially available	Commercially available	Commercially available	Commercially available	Field deployed for nuclear
Temperature tolerance, °C	−30 to 70	−70 to 180	−60 to 115	25 to 200; −40 to 125 Xeritron	-15 to 85
Sensitivity	± 5%	± 1.5%	± 0.1%	± 10%, up to ± 3% for Xeritron	± 1.5%
Radiation tolerance	Unknown	Unknown	Unknown	100 Mrad for Xeritron; unknown for others	High
Replacement difficulty	Low	Low	High	Low	Moderate
Monitoring area	Immediate vicinity of the probe	Immediate vicinity of the probe	Various locations where humidity determined	Various locations where humidity determined	Various locations where deliquescence occurs
Space requirements, cm^3	5–10 cm L × 2–4 cm D* for probe	10–15 cm L × 1–3 cm D based on VAISALA probe	13 cm L × 5 cm D from The Kahn Company, 25 cm L × 12 cm D from others	2 cm L × 3 cm D for the probe	100 cm L × 1 cm D
Power requirements	1 watt	1 watt	20–60 watts	1 watt	Several watts
Longevity	5–10 years	5–10 years	Decades	5–10 years	Years
Data collection mode	Continuous or intermittent	Continuous or intermittent	Continuous or intermittent	Continuous or intermittent	Intermittent when deliquescence occurs
Amount of data per measurement	Small; on the order of bits	Small; on the order of bits	Small; on the order of bits	Small; on the order of bits	Small, alarm log
Strengths	Small-size	Small-size, wide temperature range, high precision, no hysteresis effects	High accuracy, expandable temperature range, long life, no hysteresis effects	Small-size, wide temperature range, temperature range can be increased, no hysteresis effects	Small size of sensing lines, Multi-location monitoring, deployed for nuclear
Weaknesses	May require frequent calibration, low precision, exhibits hysteresis effects	Low radiation resistance, frequent calibration due to radiation environment	Large size, requires large power, potential periodic cleaning of chilled mirror	Low precision, require simultaneous measurement of temperature	Need for sizable monitoring station through which the sensing lines are routed
L = length; D = diameter					

If water condenses on the mirror, the photo resistor picks up the optical signal and records the change in intensity of the reflected light from the mirror. The mirror temperature is recorded when the change in the intensity of the light occurs. The temperature of the mirror is controlled by electronic feedback to maintain a dynamic equilibrium between evaporation and condensation on the mirror, thus closely measuring the dew point temperature. The measured dew or frost point temperature values are used to estimate saturation vapor pressure and, in turn, to estimate water concentration in air. Chen and Lu[14] reported that recent improvements have increased precision of the sensors. These recent improvements include use of fiber optics for projecting and receiving the light on the mirror surface, and use of a laser source for light.

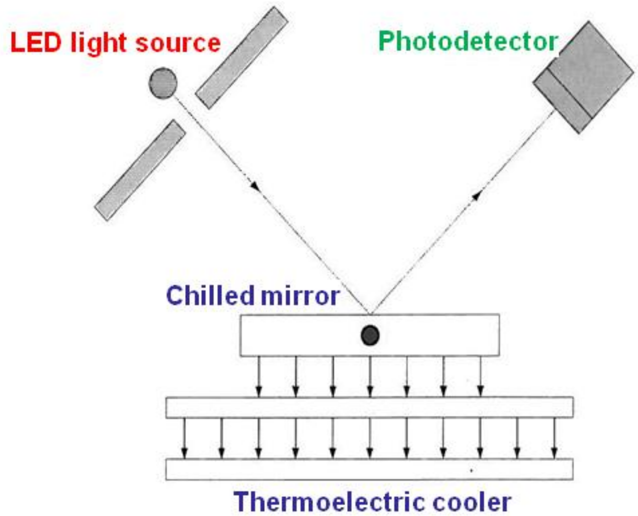


Figure 3. Measurement Principle of a Chilled-Mirror-Based Sensor

The electrical-resistance (ER)-based humidity measurement technology measures the change in ER of a material due to humidity. The measured change in the ER is correlated to absolute humidity using a calibration chart. Specifically, the resistance-based sensors contain two matched resistors. One resistor is hermetically sealed (glass encapsulated) in an inert gas (i.e., nitrogen or helium) while the second resistor is exposed to the environment. The two resistors are energized by passing electrical charge through them. As the resistors are energized, the heat dissipated from the sealed resistor is different from the exposed resistor due to the difference in thermal conductivity of nitrogen or helium with respect to air containing moisture. As a result, the two resistors are at different temperatures. The difference in the resistors' temperatures is directly proportional to the absolute humidity of the environment.

Chloride Ion Monitoring

There are some commercially available single use conductivity-based devices for measuring concentrations of soluble salts such as chloride, nitrate, and other species. There is also an extensive literature on technologies for specifically detecting and measuring chloride ions using sensors. Some of these devices and sensors can be used to measure the chloride concentration of brines that could form as a result of the deliquescence of salts that are present in atmospheric particulate matter and deposit on the dry cask storage canister outer surface. To be useful for measuring chloride ion concentration, most of the sensors must be immersed in the solution to be analyzed, meaning that a horizontally positioned sample cell or container is necessary to collect the deposited salts and to contain the deliquescence brine that forms.

Most of the one-time soluble salt measurement devices are conductivity-based, which measure the total concentration of soluble salts. Chloride ion-specific sensors can be broadly classified into four types: (i) optical, (ii) electrochemical, (iii) electromechanical, and (iv) electrical. Optical methods can be further subdivided into techniques based on the following technologies: (i) long-period grating, (ii) fluorescence spectroscopy, (iii) absorption spectroscopy, and (iv) quantum dots. Electrochemical methods include technologies that use silver/silver-chloride (Ag/AgCl) electrodes and all-solid-state chloride electrodes. The reviewed and assessed chloride ion-specific sensors are: (i) long-period grating optical-based, (ii) fluorescence optical-based, (iii) high electron mobility transistor electrical-based. The features of the conductivity-based salt meter and the chloride ion-specific monitoring techniques are summarized in Table 3.

Table 3. Chloride Concentration Monitoring

Features	Conductivity-Based SaltSmart™ Meter	Long-Period Grating-Based Optical Sensor	Fluorescence-Based Optical Sensor	High Electron Mobility Transistor-Based Sensor
Maturity	Field deployed in nuclear	Tested in laboratory	Tested in laboratory	Tested in laboratory
Temperature tolerance	0–50 °C	Maximum is ~100 °C due to solution evaporation	Maximum is ~100 °C due to solution evaporation	Maximum is ~100 °C due to solution evaporation
Sensitivity, g/cm^2	1×10^{-7}	4×10^{-4} to 3.2×10^{-2}	4×10^{-4} to 5.8×10^{-4}	4×10^{-4} to 5.8×10^{-10}
Radiation tolerance	Up to 10 Mrad	~1 Mrad†	~1 Mrad†	Less than 0.1 Mrad
Replacement difficulty	External one-time use with low difficulty	Medium	Medium	Medium
Monitoring area	$3\ cm^2$	Surfaces external to canister	Surfaces external to canister	Surfaces external to canister
Space requirements	$10 \times 1.5 \times 1\ cm^3$	$2.5 \times 2 \times 2\ cm^3$	$2.5 \times 2 \times 2\ cm^3$	Less than $1 \times 1 \times 1\ cm^3$
Power requirements	Several watts	Tens to hundreds of watts	Tens to hundreds of watts	Tens to hundreds of watts
Longevity	One-time use device	~1 year†	~1 year†	Less than 1 year
Data collection mode	Intermittent	Continuous or intermittent	Continuous or intermittent	Continuous or intermittent
Amount of data per measurement	Several bytes	A few kilobytes	A few kilobytes	A few bytes
Calibration requirements	Not required	Required weekly	Required weekly	Required weekly
Strengths	Fast and automated method, no sealing to the substrate necessary allowing testing of curved or irregular surfaces	Simple fabrication; easy interrogation using fiber optics; potential for onsite, real-time, and remote sensing	Easy interrogation using fiber optics; potential for onsite, real-time, and remote sensing	Small sample volume; potential for onsite, real-time, and remote sensing
Weaknesses	One-time use. The highest working temperature is only 50 °C. Measure total concentration	Sensitive response to temperature changes; unknown thermal and radiation stability; possible interference by other ions and signal attenuation with increased fiber cable length	Other halide ions and oxygen may interfere; thermal and radiation stability is unknown	Temperature could affect measurement; thermal and radiation stability is unknown; possible signal attenuation with increased electrical cable length
†Based on general practice.				

Various conductivity-based devices and meters were developed to assess the level of soluble salt ions (e.g. chlorides, sulfates, and nitrates) deposited on substrate and in air, in which the conductivity is mainly directly proportional to the concentration of dissolved salts in the solution. In coastal regions, it is very likely that the soluble salts are from sea salt. Assuming seawater ion assemblage and using known molar conductivities for the ions, a chloride ion concentration can thus be inferred from the conductivity measurement results. There are manual and automated, dry and wet devices available in the market, mainly differing in the sampling means. Although their detailed procedures vary depending on the sampling device, all of them operate using the following basic steps: (i) collect and dissolve the salts, (ii) measure the conductivity of the soluble salt, and (iii) convert the measured conductivity to salt concentration. Most of the dry methods use mechanical means (i.e., scraping, brushing, and vacuum) to collect the salts.

The long-period, grating-based optical sensor is a fiber optic method. A long-period grating is a periodic perturbation, typically on the order of several hundreds of micrometers, of the refractive index along the core of a fiber optic cable that is created when the fiber is exposed to ultraviolet light.[22] The transmission spectrum of a typical long-period grating comprises a number of attenuation bands in an optical fiber. When there is a concentration change (e.g., in chloride concentration) that causes a refractive index change in the surrounding medium, the center wavelengths of an attenuation band also change. A measuring system that uses a long-period grating sensor requires a broadband amplified spontaneous emission (ASE) fiber source, a sensing long-period grating fiber, a sample cell that contains the solution to be measured, and an optical spectrum analyzer (OSA).[23] The ASE and OSA, which are coupled to the long-period grating sensor through a fiber optic cable, can be placed remotely but the sample cell must be placed in the area to be monitored. .

The fluorescence-based optical sensor is also a fiber optic method. Typically, when ultraviolet light illuminates a fluorophore (a chemical compound that can reemit light upon light excitation), visible fluorescence is produced. Chloride ions can cause collisional quenching in certain fluorophores, which results in a reduced fluorescence intensity that is proportional to the log of chloride ion concentration. The decrease in fluorescence emission intensity can be measured and related directly to the chloride concentration. Several chloride ion-sensitive fluorophores are known, including SPQ (6-methoxy-N-3-sulfoproxyl-quinolinium), SPA (N-sulfopropylacridinium), Lucigenin (N,N'- dimethyl-9-9'-bisacridinium nitrate), MACA (N-methylacridinium-9-carboxamides), and MAMC (N-methylacridinium-9-methylcarboxylate). Fluorophores are immobilized ("trapped" or covalently linked) either to the surface or within organic or inorganic polymers. The sensor membranes or films that are produced then can be mounted on the tip of optical fibers to produce optrodes.[24] The system includes a light-emitting diode emitting at 365 nm that is coupled through a multi-mode fiber, using collimation and focusing lenses, into a 2 × 1 fiber coupler, with the sensor material located at the distal end of the fiber. The fluorescence from the material is collected by the other end of the fiber coupler, passed to a spectrometer, and then displayed on a computer screen.

The high-electron mobility transistor-based sensor uses an aluminum gallium nitride/gallium nitride (AlGaN/GaN) high electron mobility transistor. Positive countercharges at the high electron mobility transistor surface layer are induced by the two-dimensional electron gas located at the AlGaN/GaN interface. Any slight changes in the atmosphere can affect the surface charge of the high electron mobility transistor, thus changing the electron concentration in the channel at the AlGaN/GaN interface. The high electron mobility transistor structure consists of a 1–3 μm-thick undoped GaN buffer and a 250-A-thick undoped $Al_{0.25}Ga_{0.75}N$ cap layer deposited on 100 mm (111) silicon substrate. Depending on the gate area modification, AlGaN/GaN high electron mobility transistor sensors can be used for different applications (e.g. gas sensing) to detect hydrogen, carbon dioxide, and ammonium, and (e.g. liquid sensing) to detect protein, deoxyribonucleic acid, lactic acid, solution pH, glucose, chloride ion, and mercury ion.[24] For use as a chloride sensor, the gate area of the high electron mobility transistor structure is deposited with an idium nitride (InN) film.[25] The measured drain current of the InN-gated AlGaN/GaN high electron mobility transistor in chloride-containing solutions is linearly proportional to the logarithm of chloride concentration, consistent with the Nernst equation.

STRESS CORROSION CRACKING MONITORING

Several mature and novel non-destructive examination (NDE) technologies exist for detecting SCC degradation of stainless steels. Typical NDE methods used for SCC detection include ultrasonic, non-linear elastic wave spectroscopy; acoustic emission; guided wave; and eddy current. Because the use of these NDE approaches to detect SCC were detailed in the NRC-sponsored project at Pacific Northwest National Laboratory,[26] no further evaluation was pursued in this paper. Instead, the work presented here is devoted to reviewing and assessing technologies that are suitable for *in-situ* crack initiation and propagation monitoring but not based on NDE methods such as ultrasonic test methods.

The reviewed and assessed non-NDE techniques for monitoring SCC are listed here and described in the following sections: (i) fiber optic sensors, (ii) Luna crack growth sensor—self-contained mechanical test system designed to measure crack length, (iii) crack propagation sensor—gauge designed to measure the progress (length) of a crack and its rate of growth in a metal specimen. The features of these monitoring techniques are summarized in Table 4.

Fiber Optic Sensors

Fiber optic sensors measure the elongation or contraction of the fiber when it is bonded to a structure. The fiber structure consists of a core surrounded by a cladding with different indexes of refraction so that the light is concentrated around the core of the fiber. Optical fibers are made of a dielectric material and, as such, are chemically inert and popular for use in detecting changes in temperature, pressure, and strain. There are several types of materials for construction of optical fibers. Several pure silica core fibers have been successfully tested in nuclear environments, including the step-index polymer clad, grated-index fluorine-clad multi-mode, and pure silica single-mode fibers. Recently, photosensitive fibers (e.g., silica-based fibers doped with germanium dioxide) have shown promising results, including a long lifespan under harsh environments.[27–30]

Luna Crack Growth Sensor

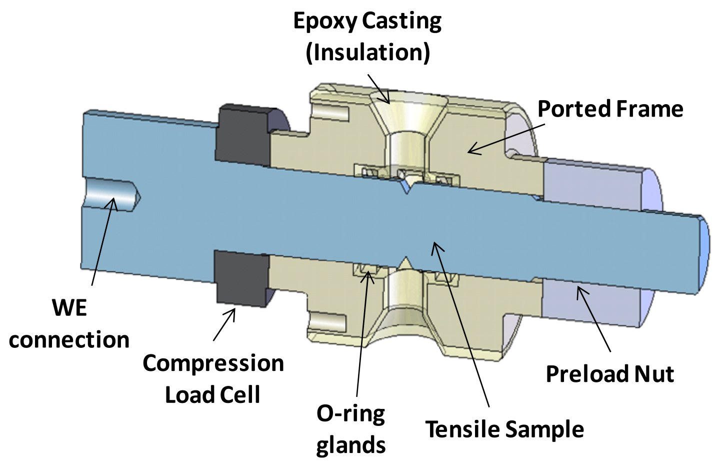
The Luna crack growth sensor was developed by Luna, Inc. It is a real-time *in-situ* crack growth sensor for atmospheric SCC monitoring of metallic components. The sensor design shown in Figure 4(a) consists of four major components: a tensile sample made of the same alloy as the structure under study, a ported frame, a compression load cell, and a pre-load nut. The load frame contains apertures that allow the external environment to be in contact with the stressed specimen. To facilitate field deployment, Luna, Inc. developed a single ruggedized package that contains the crack sensor along with signal processing and communication electronics, as shown in Figure 4(b).

The sensor functions while applying a tensile load to a cylindrical fracture mechanics sample that changes gradually, resulting in displacement as the sample is cracked. A hydraulic bolt tensioner is used to place the sample under a desired static tensile stress. The present sensor unit contains the dedicated electronics unit for data collection and post-processing capability. If the atmospheric conditions are such that SCC can develop, the strain gauge in the load cell can capture the change in displacement as cracks are initiating and propagating in the fracture specimen. For potential DCSS applications, the Luna crack growth sensor is a type of surrogate sensor (i.e., the sensor does not measure actual cracking events on the dry canister surface) that can be used to measure crack initiation and propagation with an expected nominal resolution on the order of a few microns. The actual resolution of the sensor is yet to be determined because no long-term studies have been conducted in nuclear environments, where radiation can pose challenges in the overall stability of the sensor.

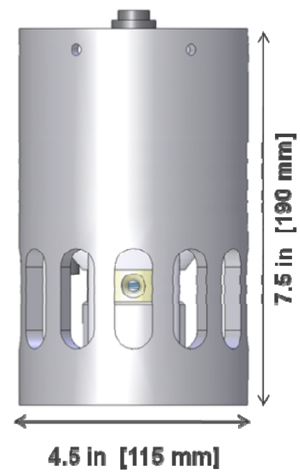
Table 4. Stress Corrosion Cracking Monitoring Techniques			
Features	**Fiber Optic Sensors**	**Luna Crack Growth Sensor**	**Crack Propagation Sensor**
Maturity	Field deployment started in 1980s	Field deployment started in 2009	Unknown
Temperature tolerance	>1,100 °C	~120 °C or greater	−269 to +230 °C
Sensitivity	Crack opening resolution of 40 µm	Crack depth resolution of 1 µm	Crack depth resolution of 250 µm
Radiation tolerance	Total gamma radiation up to 53 Mrad	Unknown	Total gamma radiation of ~10^2 Mrad
Replacement difficulty	High	High	High (if bonded to canister) or low (if placed on a pre-cracked sample)
Monitoring area	Local and general cracking	Local cracking	Local cracking
Space requirements	Gauge lengths 10 cm to more than 100 m with a 75–250 µm diameter	Cylindrical fracture specimen of 1.2 cm diameter and 10 cm long placed in the assembly of 11.5 cm in diameter and 19 cm in length	2.5 cm × 0.5 cm and 0.043 mm thick
Power requirements	Power consumption ranging from 90–300 watts	0.05 watts per measurement	Low. Less than 1 watt
Longevity	Unknown	~2 yr for a constant crack growth rate of 10^{-10} m/sec	~1.6 yr for a constant crack growth rate of 10^{-10} m/sec. Unknown under irradiation
Data collection mode	Continuous or intermittent	Continuous or intermittent	Continuous or intermittent
Amount of data per easurement	Medium, displacement, strain or signal loss measurement	Small, load measurement	Small, resistance or voltage measurement
Strengths	Electromagnetic immunity, small size, high-temperature tolerance, corrosion resistance, large area monitoring with single sensor, light weight, long record of field testing	Highly sensitive, sensor does not need bonding to canister	Simple to implement, wide operational temperature, sensor does not need bonding to canister, small size
Weaknesses	Gamma radiation interference, sensor deployment may be problematic, temperature calibration required	Large size, surrogate sensor (does not measure cracking of actual component), temperature compensation required, local cracking monitoring, limited field testing	Modest crack propagation resolution, unknown field testing, local cracking monitoring

Crack Propagation Sensor

The commercially available crack propagation gauge provides a simple method to indicate the propagation of a crack on a pre-cracked surrogate specimen or in an actual structure. The crack propagation sensor consists of a series of small strands (made of a high endurance alloy) connected in parallel and placed on a thin substrate in a ladder-like pattern. Typically, the sensor incorporates 10–20 resistor strands with a nominal thickness of 0.043 mm and a glass-fiber-reinforced epoxy matrix as sensor backing. The sensor can measure crack propagation in increments of 0.25 mm. The sensor is positioned in areas prone to cracking (e.g., welds) so that when a crack forms beneath the gauge, it will induce a sequential local fracture of the sensing strands of the sensor, causing successive open-circuiting of the strands and resulting in a stepped increase in the ER.



(a)



(b)

Figure 4. (a) Schematic Representation of the Load Frame and (b) Stress Corrosion Cracking Sensor Assembly (Reproduced With Permission of Luna, Inc.)

For monitoring applications, because of its small size, the crack propagation sensor could be mounted directly on the component surface or a surrogate pre-cracked specimen made of the same material as the component to be monitored. For both cases, it is imperative that the sensor strands be placed perpendicular to the direction of the expected crack. The direct mounting of the sensor would be challenging for an existing DCSS, and special considerations for such a sensor deployment would need to be addressed. It is anticipated that for the case of a direct mounting on a canister, a significant number of sensors would necessary to enhance the probability of crack detection. This sensing approach is better suited for crack propagation monitoring than for crack initiation monitoring. The actual resolution of the sensor is yet to be determined because no long-term studies have been conducted in nuclear environments, where radiation can pose challenges to the overall stability of the sensor.

SUMMARY

A broad literature review of monitoring techniques was conducted, covering the important environmental conditions (temperature, humidity, and chloride concentration) affecting SCC of the welded stainless steel canister, as well as SCC initiation and propagation. The main features of the techniques are summarized in Table 5. Some monitoring methods for important environmental conditions are well developed and require little or no advancement, but may require dry cask system modifications. For example, thermocouples are rugged sensors that have been used for many years in industrial and nuclear applications with high-radiation tolerance and were used in the previous cask demonstration program.[29] Radiation thermometers, ultrasonic measurement, and fiber optic sensors for external temperature measurement are mature technologies that have been field deployed for temperature measurement. Capacitance-based, chilled-mirror-based, and electrical-resistance-based humidity sensors for external humidity monitoring have been widely used in industrial and non-industrial applications for more than 100 years, and they are commercially available. Conductivity-based soluble salt measurement techniques are widely used in industry and field deployed in extended storage applications. Fiber optic crack detection gauges and crack propagation sensors for SCC have been field deployed in other non-nuclear applications. They require little or no advancement for application to extended storage.

Table 5. Potential Monitoring Techniques for Environmental Conditions and Stress Corrosion Cracking

Parameter	Monitoring Method	Level of Development	Strengths	Weaknesses
Temperature	Thermocouples	Field deployed for nuclear	High T* and radiation tolerance	Calibration required
	Resistance temperature detectors			
	Radiation thermometers	Field deployed for non-nuclear	Noncontact	Low T and radiation tolerance
	Ultrasonic measurement	Field deployed for nuclear	Mature, high T tolerance	Low radiation tolerance
	Fiber optic sensors	Field deployed for non-nuclear	Mature, high T tolerance	Radiation-induced darkening
Relative humidity	Capacitance-based: Ceramic	Field deployed for non-nuclear	Small size	Frequent calibration
	Capacitance-based: Polymeric		High precision, no hysteresis	Radiation-induced damage
	Chilled-mirror-based		High accuracy	Size modification
	Electrical-resistance-based		Small size, broad T range	Low precision
	Leakage monitoring system	Field deployed for nuclear	Small size	Sizable monitoring station
Chloride	Conductivity-based SaltSmart™ Meter	Field deployed for nuclear	Automated, no sealing needed	Limited to T <50 °C, one-time use
	Long-period grating-based	Laboratory	Potential real time	Unknown thermal and radiation stability
	Fluorescence-based optical			
	High electron mobility transistor-based		Small size and sample volume	
Stress corrosion cracking initiation and propagation	Fiber optic sensors	Field deployed for non-nuclear	Small diameter	Unknown thermal and radiation stability
	Luna crack growth sensor		Sensitive to crack	Size modification
	Crack propagation sensor	Not field deployed	Small size	Highly localized

*T = temperature

Environmental monitoring methods that are not well developed and require significant advancement include some chloride-specific sensors. Long-period grating-based, fluorescence-based, and high electron mobility transistor-based sensors for external chloride ion monitoring have been tested only in the laboratory.

Overall, because of geometry, space limitations, and the high ionizing radiation of DCSS, all the monitoring methods must be modified for this application.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the reviews of T. Wilt and D. Pickett. Appreciation is due to B. Street for assistance in preparing this paper.

This paper describes work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC–HQ–12–C–02–0089. The views expressed in this paper are not necessarily those of the NRC.

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