# **ENCLOSURE 8**

Calvert Cliffs Nuclear Power Plant (CCNPP) ISFSI: Canister Cask Stress

**Corrosion Cracking Review for License Renewal – Non-Proprietary** 

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TN PROJECT NO: 10955	PROJECT NAME:	Calvert Cliffs Nucle	ear Power Plant
CLIENT CONTRACT NO: PO #439518	CLIENT:	CENG	
ENGINEERING EVALUATION TITLE: Calvert Cliffs Nuclear Power Plant (CCN License Renewal.	PP) ISFSI: Canister Cask Str	ess Corrosion Crack	ing Review for
SUMMARY DESCRIPTION:			
Engineering Evaluation Summary			
the Welded Austenitic Stainless Steel Ca	nister		
Engineering Evaluation Preparation:			
Originator Name and Signature: Hundal	(Andy) Jung Juny Hu	nda	Date: 6/10/2013
Engineering Evaluation Verification (E completeness, and correctness): Verifier Name and Signature: William Br	Whas been checked for co acey Willim /	nsistency, Drout	Date: 6/10/2013
Engineering Evaluation Approval:	Similar	f	06 /11 /2013 Date:
Project Engineer Name and Signature: 0	Sirish Patel		

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Rev.		Description		Affected Pages
0	Initial Iss	ue .		All
1	Revised	to address the client's comment and an ed	ditorial change	Pages 20 and 24

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# 1.0 INTRODUCTION/PURPOSE: INITIATION OF CHLORIDE-INDUCED STRESS CORROSION CRACKING (CISCC)

Stress corrosion cracking (SCC) of austenitic stainless steel such as AISI 304, 316, and the corresponding L grades can occur when three critical conditions are present to initiate SCC. These conditions are (i) susceptible material, (ii) relatively high residual tensile stress present on the metal surface, and (iii) corrosive environment.

It is known that austenitic stainless steel under tensile stress from welding is susceptible to chloride-induced stress corrosion cracking (CISCC) when exposed to a relatively high concentration of chloride in a marine atmosphere [Ref 1, 2, 3]. Similar to the failure of austenitic stainless steel components due to CISCC observed in power plants near the ocean [Ref. 4], stainless steel dry storage canisters located in coastal areas such as Calvert Cliffs (CCNPP) ISFSI could also be susceptible to CISCC due to the exposure of airborne chloride salts.

The chloride content in the air can depend on multiple variables such as distance from the sea, altitude above sea level, prevailing winds, wave action, and shelter [Ref. 5]. Sheltering has showed a benefit to reduce chloride deposition and decrease atmospheric corrosion rate of iron [Ref. 5]. As the distance from the sea and altitude increases, the chloride content generally decreases: Increasing distance from the sea resulted in a lower corrosion rate as shown for carbon steel corrosion testing at Kure Beach as summarized in Ref. 5. According to the precipitation monitoring data from the National Atmospheric Deposition Program (NADP), the precipitation from rain, snow, or sleet at the monitoring location MD 13 site near the Chesapeake Bay in Maryland presented a relatively low concentration of chlorides compared to the location near the Ocean such as MD 18 site from 1993 to 2011 (See Appendix Figures A-1 and A-2). An inland location of MD 99 site presented further decrease in chloride concentration (See Appendix Figure A-3). The three years survey result of the airborne chloride concentration in the coastal areas in Japan shows a reduction in airborne chlorides by a factor about 50 at 0.8 km distance inland [Ref. 6, Fig.8].

For spent fuel dry storage systems, in marine environments, airborne salts from the seawater can deposit and accumulate on the canister surface via the external vent. The moisture required to support the electrochemical reactions associated with CISCC can be obtained from deliquescence of the salts, wherein dry salt absorbs moisture from the air to form a saturated solution. As addressed in NUREG/CR-7030 [Ref. 1], CISCC is closely related to deliquescence behavior of the deposited chloride salts. Deliquescence of the salts depends on relative humidity (RH) and temperature. Each salt has a characteristic relative humidity for deliquescence (called to as deliquescence relative humidity, DRH) as shown in Figure 2-1. If ambient RH is above the DRHs for the chloride salts, chloride-rich brine can be produced which may corrode the metal canister.

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#### 2.0 DESIGN EVALUATION

#### 2.1 Critical Environmental Conditions for CISCC Initiation

Figure 2-1 presents the DRH lines for the three major chloride sea salts, NaCl, MgCl<sub>2</sub>, and CaCl<sub>2</sub> as a function of RH and temperature with constant absolute humidity. Absolute humidity is a mass of water vapor per unit volume in air. Relative humidity is the ratio of the partial pressure of the water vapor in an air-water mixture to the saturated vapor pressure at the conditions expressed as percent. Absolute humidity can increase with temperature; approximately 15 g/m<sup>3</sup> and 30 g/m<sup>3</sup> when the air is saturated with water vapor at 16°C and 30°C, respectively [Ref. 7].

As shown in Figure 2-1, DRH of chloride salts depends on RH rather than temperature and the DRH of the salt decreases in the order of NaCl, MgCl<sub>2</sub>, and CaCl<sub>2</sub>. In Figure 2-1, the circle, square, diamond and red arrows represent the experimental conditions of temperature and humidity where CISCC of austenitic stainless steel has been observed under laboratory or natural exposure to chlorides [Ref. 1, 2, 3, 8, 9, 10, 11, 12, 13, 14]. Although NaCl is the most abundant constituent in sea salt, SCC occurred at RH levels below its DRH of 65% to 75% at the temperatures 90°C to 30°C. Most CISCC occurred in the RH range close to DRH of MgCl<sub>2</sub> (25% to 35% in the temperature range of interest), indicating deliquescent MgCl<sub>2</sub> could be a significant contributor in CISCC. At the RH below DRH of MgCl<sub>2</sub>, however CISCC still occurred with the relatively high concentration of chloride deposition such as 1 g/m<sup>2</sup> of synthetic sea salt at 52°C [Ref. 10] or 10 g/m<sup>2</sup> of sea salt at 70°C and 80°C [Ref. 12]. The minimum concentration of chloride to initiate SCC was reported to be as low as 0.1 g/m<sup>2</sup> at the temperatures of 35°C and 45°C after 4 months exposure using cyclic humidity tests [Ref. 10]. In [Ref. 15], a minimum concentration of chloride content was also reported as 0.1 g/m<sup>2</sup> for SCC of AISI 304 SS tested at 80°C using a pressurized humidity chamber.





Figure 2-1: DRH lines for NaCl, MgCl<sub>2</sub>, and CaCl<sub>2</sub> as a function of temperature and relative humidity with the constant absolute humidity at 15 g/m<sup>3</sup> and 30 g/m<sup>3</sup>. Circles, squares, diamonds and red arrows represent the experimental conditions of temperature and humidity where CISCC of austenitic SS has been observed.

Based on the information as presented in Figure 2-1, Table 2-1 summarizes the identified critical conditions of environmental parameters of temperature, relative humidity, and chloride concentration for CISCC initiation and these conditions are used in this report for analysis.

Parameter	Critical Condition
Temperature	30°C – 80°C
RH	≥ 15% *
Chloride Concentration	≥ 0.1 g/m <sup>2</sup>

Table 2-1: Critical Conditions of Temperature, Relative Humidity, and Chloride Concentration for CISCC Initiation

Note: \* The critical RH is assumed to be 15% corresponding to the lowest RH for CaCl<sub>2</sub> DRH to be conservative. Most CISCC of SS has been observed above the DRH of MgCl<sub>2</sub> which is close to ~30 % RH.

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Stress analysis results of the welded areas of the NUHOMS<sup>®</sup> 24P and 32P DSCs revealed tensile residual stress sufficiently high ( $\geq 0.5 \text{ Y.S}$ ) to initiate SCC as presented in AREVA Document No 86-9203390 (Stress Analysis) [Ref. 16]. Therefore, this report will evaluate the environmental conditions of temperature, relative humidity, and chloride concentration deposited on the canister surface at the Calvert Cliffs ISFSI by comparison with their required critical conditions as shown in Table 2-1. The results of the comparison will also be applied to predict an approximate timeframe that can initiate CISCC for the NUHOMS<sup>®</sup> 24P and 32P DSCs.

#### 2.2 Canister Surface Temperature and Relative Humidity (RH)

The canister surface temperature will decrease with time and can vary with the initial heat load and ambient temperature. The annual ambient temperature at CCNPP was reported to be from 1.5 to 24.6°C [Ref. 17, Table 1-7]. The temperature transient data used in the analysis are for the ambient temperature of 21°C [70°F] as presented in TN Calculation No 10955-0401 (Thermal Analysis) [Ref. 18].

#### 24P DSC

Figures 2-2(a), (b), (c) and (d) present the canister surface temperature and the corresponding RH as a function of storage time for the 24P DSC with the heat loads of 15 kW, 10.5 kW, 6 kW, and 4 kW, respectively. As a result of radioactive decay, the heat load and canister temperature decrease with time and the corresponding RH increases. Note that the absolute humidity used for RH calculation is 30 g/m<sup>3</sup> in order to be conservative. In Figure 2-2 (a) to (d), the critical RH (15%) and the DRH for MgCl<sub>2</sub> (30%) are also plotted for comparison with the corresponding RH.

In Figure 2-2(a), for the case of 15 kW, the corresponding RH for the maximum temperature case (e.g., upper part of horizontal canister) can reach a critical RH of 15% after 30 years and then increases with time. Meanwhile, the RH for the minimum temperature case for the welded area of DSC bottom as presented in TN Calculation No. 10955-0401 (Thermal Analysis) [Ref. 18] exceeds the critical RH at the beginning (0 year) and then increases up to 90% after 120 years. A similar trend is observed for the 10.5 and 6 kW cases with the exception of a little earlier time to reach 15% RH after 25 and 10 years for the maximum temperature with 10.5 and 6 kW, respectively (Figure 2-2(b) and 2-3(c)). For the case of 4 kW (Figure 2-2(c)), the corresponding RHs for both maximum and minimum temperature cases show a relatively high RH compared to that for the 15 kW and 10.5 kW cases due to its lower surface temperature and the RH exceeds a critical RH at the beginning of storage. Therefore, as the next step for checking the critical condition of chloride concentration, all four cases are further considered.

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Figure 2-2 (b)

Figures 2-2 (a), (b), (c) and (d): Canister surface temperature and corresponding RH of 24P DSC with (a) 15 kW, (b) 10.5 kW, (c) 6 kW and (c) 4 kW heat load.

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#### <u>32P DSC</u>

Figure 2-3 presents the temperature transient with time and corresponding RH for the 32P DSC with an initial heat load of 19 kW. For the maximum temperature case, RH can reach a critical RH of 15% after ~55 years and then increases with time. RH for the minimum temperature exceeds the critical RH at the beginning (0 year) and then increases up to 80% after 120 years.

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#### Figures 2-3

Figures 2-3: Canister surface temperature and corresponding RH of 32P DSC with an initial heat load of 19 kW.

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#### 2.3 Amount of Chloride Salt Deposit

As presented in Table 2-1, the chloride concentration deposited on the canister surface should be higher than the critical concentration of 0.1  $g/m^2$  (=100 mg/m<sup>2</sup>) to initiate CISCC of austenitic SS. Shirai et al. [Ref. 12] reported the salt deposition rate to estimate the accumulated salt amount on the canister side wall in a vertical concrete cask based on the laboratory and field test results and the rate, Q is

 $Q = \{5.07 - 0.022(T-30)\} \times (1.55 \text{ t} \times \text{C}/10000)^{1/2}$  Eq. (2-1)

where Q is the amount of chloride salt deposit in mg/m<sup>2</sup>, T is the temperature of canister surface in  ${}^{\circ}C$ , t is time in hours, and C is the airborne salt concentration as chloride in  $\mu g/m^3$ .

Assuming that the salt deposition rate at CCNPP ISFSI follows Eq. (2-1), the amount of salt deposition on the 24P DSC surface is estimated with time at different airborne salt concentrations. Note that in calculating chloride deposition using Eq. (2-1), temperature is changed with time to reflect heat decay over time as presented in Table B-4 for 24 P DSC and Table B-5 for 32P DSC in TN Calculation No. 10955-0401 (Thermal Analysis) [Ref. 18].

#### 24P DSC

The calculated chloride deposition for the 24P DSC is presented in Figures 2-4 (a) & (b), 2-4 (c) & (d), 2-4 (e) & (f), and 2-4 (g) & (h) for 15 kW, 10.5 kW, 6 kW, and 4 kW heat load, respectively.



Figure 2-4 (a) & (b): Estimated chloride salt amount deposited on the 24P DSC surface (15 kW heat load) at different airborne salt concentration as chloride with time

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Figure 2-4 (f)

Figure 2-4 (e) & (f): Estimated chloride salt amount deposited on the 24P DSC surface (6 kW heat load) at different airborne salt concentration as chloride with time

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Figure 2-4 (h)

Figure 2-4 (g) & (h): Estimated chloride salt amount deposited on the 24P DSC surface (4 kW heat load) at different airborne salt concentration as chloride with time

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For the 15 kW DSC with the maximum temperature (Figure 2-4(a)), the amount of salt can reach the critical concentration after ~38, 22 and 12 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively. Even if the chloride concentration in the salt can reach the critical concentration (100 mg/m<sup>2</sup>) before 30 years, CISCC will not initiate until after 30 years due to a RH limitation (i.e., less than 15% before 30 years). However, for the minimum temperature case (Figure 2-4(b)), CISCC can initiate when the chloride concentration reaches the critical concentration without RH limitation (i.e., greater than 15% RH at the beginning). Thus, CISCC can initiate after ~30, 16 and 8 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively. At the airborne salt concentration < 2  $\mu$ g/m<sup>3</sup>, for both maximum and minimum temperature cases, the accumulated salt amount will not reach the critical concentration up to 120 years, and there is no CISCC occurrence with such a low airborne salt concentration.

With the heat of 10.5 kW and maximum temperature, the salt amount deposited on the 24P DSC surface can reach the critical concentration after ~37, 21, and 12 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively (Figure 2-4(c)). Similar to the 15 kW, however, CISCC can initiate after 25 years due to a RH limitation (i.e., less than 15% before 25 years) at the airborne salt concentrations of 20 and 40  $\mu$ g/m<sup>3</sup>. The minimum temperature case shows the years to reach the critical concentration at 30, 17, and 9 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively (Figure 2-4(d)).

Similarly, the salt amount for the 6 kW case can reach the critical concentration after 40, 20, and 12 years at the airborne salt concentration of 10, 20, and 40  $\mu$ g/m<sup>3</sup>, respectively (Figure 2-4(e)). The minimum temperature case shows the years to reach the critical concentration at 30, 17, and 9 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively (Figure 2-4(f)).

For the 4 kW case with the maximum temperature (Figure 2-4 (g)), the time to reach critical concentration is further extended up to approximately 37, 20 and 12 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively. The minimum temperature case can reach the critical value a little earlier for CISCC initiation (28, 18 and 10 years for the airborne chloride salt concentration at 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively) (Figure 2-4(h)).

#### 32P DSC

Figure 2-5 (a) & (b) present the calculated salt deposition for 32P DSC with the initial heat load of 19 kW.

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	Figure 2-5 (a)		
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	Figure 2-5 (b)		

Figure 2-5 (a) & (b): Estimated chloride salt amount deposited on the 32P DSC surface (19 kW heat load) at different airborne salt concentration as chloride with time

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For the maximum temperature case, the amount of salt can reach the critical concentration after 42, 25 and 17 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively. However, even though the chloride concentration can reach the critical concentration before ~55 years, CISCC will not initiate until after ~55 years due to a RH limitation. For the minimum temperature case (Figure 2-5(b)), CISCC can initiate when the chloride concentration reaches the critical concentration without RH limitation (i.e., greater than 15% RH at the beginning). Thus, CISCC can initiate after ~32, 18 and 8 years at the airborne salt concentration of 10, 20 and 40  $\mu$ g/m<sup>3</sup>, respectively.

At the moment, within the authors' knowledge, the airborne salt concentration as chloride at the CCNPP ISFSI is not available. In Japan, the maximum airborne salt concentration as chloride was reported to be 22  $\mu$ g/m<sup>3</sup> for Tokai No. 2 NPP and ~38  $\mu$ g/m<sup>3</sup> for Fukusima Daiichi NPP [Ref. 12]. One important item to note though is that the Chesapeake Bay at CCNPP consists of brackish water and would not be as salty as the Atlantic or Pacific Ocean water at According to salinity data provided by the National Oceanic and the Japanese plants. Atmospheric Administration (NOAA), the areas close to CCNPP in the Chesapeake Bay is approximately one third to a half the salinity of the Atlantic Ocean through the years 1985 to 2013 (NOAA) (See Figures B-1, B-2, B-3 in Appendix B). Furthermore, global salinity data show a similar range of salinity in the sea water between the Atlantic Ocean and Pacific Ocean (See Figure B-4 in Appendix B). CCNPP ISFSI is located about 0.8 km away from the Chesapeake Bay shore and 114 feet above sea level (See Appendix Figure A-5). Accounting for at least a factor of 2 reduction in salinity at the location of CCNPP on the Chesapeake Bay in comparison to the Atlantic Ocean coast line as shown in Appendix B and a factor of about 50 reduction in airborne chlorides at 0.8 km distance inland based on the survey results for the coastal areas in Japan [Ref. 6, See Figure C-1], the maximum airborne chloride concentration at the CCNPP ISFSI would reduce to about 0.2 to 0.4 µg/m<sup>3</sup> with an average of about 0.3 µg/m<sup>3</sup> when compared to the maximum chloride concentrations at Tokai No.2 and Fukusima Daiichi NPPs.

#### 2.4 Approximation of CISCC Initiation Time

Considering such critical conditions, an approximate time required to initiate CISCC of austenitic SS (defined to as t<sub>initiation</sub>) is estimated at different airborne salt concentrations as summarized in Table 2-2 and Table 2-3 for 24P DSC (15 kW, 10.5 kW, 6 kW, and 4 kW heat loads) and 32P DSC (19 kW heat load), respectively.

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Table 2-2: Approximate time to CISCC initiation ( $t_{initiation}$ ) for 24P DSC considering critical conditions of temperature, RH, and chloride concentration

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Table 2-3: Approximate time to CISCC initiation ( $t_{initiation}$ ) for 32P DSC considering critical conditions of temperature, RH, and chloride concentration

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#### 2.5 Comparison With Actual Salt Analysis Data Collected From 24P DSC Surface

Most recent analysis results of the salts collected from the DSC-11 canister shell in HSM-1 at Calvert Cliffs indicates that the chloride concentration can be as low as 5.2 mg/m<sup>2</sup> as chloride obtained from x-ray fluorescence [Ref. 19]. As described in the RAI response for the Calvert Cliffs ISFSI license renewal application [Ref. 20], HSM-1 was loaded in 1993 and the heat load was estimated to be 4.2 kW in 2011. Using Eq. 2-1, the chloride concentration deposited on the DSC-11 canister in HSM-1 after 20 years exposure with the initial heat load of 6 kW is calculated to be 8.2 and 9.2 mg/m<sup>2</sup> for the maximum and minimum temperature, respectively, when the airborne salt concentration is  $0.3\mu g/m^3$  (that is the expected maximum airborne chloride concentration in average at the location of CCNPP ISFSI discussed in Section 2.3). At the same airborne salt concentration  $(0.3\mu g/m^3)$  and 20 years exposure, for the case of 4 kW, the calculated chloride concentrations can be 12.5 and 14.7 mg/m<sup>2</sup> for the maximum and minimum temperature, respectively. When compared to the concentration of 5.2  $mg/m^2$ obtained from the collected salts, the calculated concentrations are relatively high by a factor of about 2 to 3. Considering the maximum airborne chloride concentration used in the calculation based on the Japanese data, high values of the chloride concentration from the calculation should be reasonable. If the salt deposition rate using Eq. (2-1) is applicable to predict salt amounts on the 24P DSC at CCNPP ISFSI, the accumulated chloride salt concentration with the initial heat load of 4 kW can range from 22.1 to 24.8 mg/m<sup>2</sup> after 60 years of exposure. This concentration is still less than the critical chloride concentration of 100 mg/m<sup>2</sup>, thus no CISCC initiation will occur.

Taking a more conservative approach to account for any reversely affected uncertainties in predicting chloride deposition rate on the actual canister surface inside HSM due to mainly lack of empirical data for airborne chloride measurement at CCNPP ISFSI and uncertainties related to only single actual measurement of the salt concentration, the annual airborne salt concentration could be increased, for example 10  $\mu$ g/m<sup>3</sup>. At the airborne salt concentration of 10  $\mu$ g/m<sup>3</sup> (with a safety factor of 33.3 compared to 0.3  $\mu$ g/m<sup>3</sup>), the required duration for CISCC initiation is longer than ~30 years for the 24P DSC for the initial heat load of 15 kW, 10.5 kW, 6 kW and 4 kW. Because the chloride concentrations deposited on the actual canister in HSM-1 could vary with the local position and air flow around the canister, more data collected from the other positions on the canister are needed to represent a spatial variation of chloride concentration on the actual canister surface.

#### 2.6 Conservatism in Assessing CISCC Initiation

Following conservative approaches are applied in assessing CISCC in this report;

- Consideration of relatively high absolute humidity of 30 g/m<sup>3</sup>, resulting in a relatively high RH. For example, at the absolute humidity of 15 g/m<sup>3</sup>, the calculated RH is 12% at 60°C, which is lower than the critical RH of 15%.
- Consideration of lowest DRH for CaCl<sub>2</sub>. Most CISCC of SS in marine environment observed with respect to MgCl<sub>2</sub> deliquescence (close to DRH of 30%).

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#### 3.0 RESULTS/CONCLUSION

From this study, the following conclusions can be drawn:

- An initiation of CISCC for austenitic SS is affected by three major environmental parameters including temperature, humidity, and chloride salt concentration deposited on the canister surface.
- Literature survey results indicate that critical conditions of these parameters for CISCC initiation can be defined as: temperature of 30-80 °C, ≥ 15% RH, and 100 mg/m<sup>2</sup>.
- Based on linear extrapolation of a surface salt measurement performed at CCNPP in 2012, the critical concentration would not be reached until 120 years from the beginning of storage.
- Although chloride aerosol measurements at CCNPP ISFSI are not available, comparing with the Japanese measurement data and considering the CCNPP's location and local salinity in the Chesapeake Bay, the maximum chloride concentration can range from 0.2 to 0.4  $\mu$ g/m<sup>3</sup> with an average of 0.3  $\mu$ g/m<sup>3</sup>. Using this best estimate and the deposition equation 2-1, the CISCC threshold of 100 mg/m<sup>2</sup> would be not reached on CCNPP's until 120 years.
- Taking a more conservative approach assuming the airborne chloride salt concentration of  $10 \ \mu g/m^3$ , the combination of surface temperature, 15% RH, and surface chloride concentration would be at earliest reached ~30 years after storage to meet all critical environmental conditions for CISCC initiation.

Following uncertainties are noted:

- Airborne chloride salt concentration at the CCNPP ISFSI.
- Actual or effective absolute humidity in the HSM that can affect RH and DRH of the chloride salts on the canister surface.
- Application of the deposition rate equation for the vertical type canister to the case of the horizontal type NUHOMS<sup>®</sup> system
- Accuracy and range of the chloride deposition on the actual canister based on only a single measurement
- Extraction efficiency of the salt collection device was confirmed for clean mill-finished stainless steel, but not for the surface conditions containing dust, dirt, etc.

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# 4.0 APPLICATION OF A VERTICAL CANISTER SALT DEPOSITION MODEL TO THE HORIZONTAL NUHOMS® SYSTEM RECOMMENDATIONS:

- As presented in Table 2-1, CISCC initiation time is strongly dependent on the airborne salt concentration. Field measurements of salt aerosols at CCNPP and development of a salt deposition model for horizontal canisters would reduce the uncertainties in the prediction of CISCC initiation.
- More data for the deposited salt collected from different positions on the canister surface to represent a spatial variation of the chloride concentration is necessary to validate the relation between temperature, time, and chloride aerosol concentration in equation 2-1.
- From an aging management perspective concerning CISCC, an inspection (or monitoring) interval should consider the approximate time to initiate CISCC for each heat load case.

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Figure A-5. Geographical location of CCNPP ISFSI (marked as "A" in the left figure) and the magnified aerial view (in the right figure)







Figure B-2: Chesapeake Bay Mean Surface Salinity from 1985-2006 (http://www.chesapeakebay.net/maps/map/chesapeake\_bay\_mean\_surface\_salinity\_spring\_1\_ 985\_2006)





Figure C-1. Survey results for region B show the relationship between measured airborne chloride and the distance from coastline. (from Fig.8 in Ref. 6)