Climatic Corrosion Considerations for Independent Spent Fuel Storage Installations in Marine Environments

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1013524
Technical Update, June 2006

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ABSTRACT

It has been clearly demonstrated in laboratory and field studies plus field experience with actual and simulated components that the stress corrosion cracking (SCC) of austenitic stainless steel can occur at ambient temperatures in marine-type environments. Therefore, the SCC concerns for spent fuel storage canisters identified in a November 2004 presentation by Nuclear and Industrial Safety Agency (NISA) and Central Research Institute of Electric Power Industry (CRIEPI) representatives are clearly warranted.

As discussed in detail in the first report in this series Effects of Marine Environments on Stress Corrosion Cracking of Austenitic Stainless Steels, EPRI, Palo Alto, CA: 2005. 1011820, the SCC propensity of austenitic stainless steels in marine environments is affected by many variables including the amount of moisture and time of wetness, airborne contaminants (e.g., chlorides, sulfur dioxide, carbon dioxide, etc.), distance, elevation, orientation and shelter, temperature, sunlight and wind.

This report evaluates the climatic differences among the various independent spent fuel storage installation (ISFSI) sites compared to the reference marine test site at Kure Beach, NC among the various reactor sites that have or plan to have spent fuel storage systems exposed to a marine environment. The typical surface temperature vs. time profiles of spent fuel canisters are also presented as is an evaluation of composition of airborne materials that could deposit on the spent fuel canisters exposed to a marine environment.

However, an attempt to evaluate corrosion data from the LaQue Center for Corrosion Technology at Kure Beach, NC, which is the LaQue Center’s marine atmospheric test facility, was unsuccessful due to a lack of data, communication, and the apparent future closure of the facility.
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1

CLIMATE COMPARISON CONSIDERATIONS

1.1 Introduction

It has been clearly demonstrated in laboratory and field studies plus field experience with actual and simulated components that the stress corrosion cracking (SCC) of austenitic stainless steel can occur at ambient temperatures in marine atmosphere environments. As discussed in detail in the first report in this series\(^1\), the SCC propensity of austenitic stainless steels in marine environments is affected by many variables including the amount of moisture and time of wetness (TOW), airborne contaminants (e.g., chlorides, sulfur dioxide, carbon dioxide, etc.), distance from the water, elevation from the water, orientation and shelter, temperature, etc.

To address overall corrosivity classification issues, it was considered prudent to first describe standard methodologies that are sometimes used to rank the corrosivity of atmospheric environments. For example, a comprehensive corrosivity program classification system was developed by the International Standards Organization (ISO)\(^2,3\). ISO 9224\(^2\) specifies guideline corrosion rate values and characteristics of corrosion for the corrosion categories defined in ISO 9223\(^3\). Verification and evolution of this system is continuing through the largest designed exposure program ever developed\(^4\). The ISO corrosivity classification is semi-quantitatively based on the simplifying assumption that the TOW, defined as the time when the relative humidity is >80% and the temperature is >0°C (>32°F), and the levels of only two airborne impurities (e.g., chloride and sulfur dioxide) determine the relative corrosivity of an atmospheric environment\(^2\). However, while this standard is widely accepted by some organizations, there are many indications that the ISO 9223 standard overstates its database. Extensive research on factors causing atmospheric corrosion has repeatedly indicated that the subtleties that make up a corrosive environment are simply factored in ISO 9223 while other parameters carry a disproportionate weight. (Appendix A provides some additional discussion on this subject.)

ASTM provides atmospheric classifications methodologies similar to those of ISO\(^5\). ASTM standards exist for site characterization, TOW monitoring and pollution monitoring. In addition, a fast and convenient method to compare atmospheric corrosivities is the CLIMAT (Classification of Industrial and Marine ATMospheres) test\(^5\). It consists of aluminum wires wound around threaded bolts of various metallic and nonmetallic materials.
Climate Comparison Considerations

Each of these methodologies could be used to rank the various independent spent fuel storage installation (ISFSI) environments versus the reference Kure Beach, NC environment\(^1\). However, it is critical to note that the most important material and atmospheric data are not those reported by ISO, ASTM or any other source, but those data that pertain to the specific application of interest\(^6\). Also, ISO has several inherent limitations such as lack of consideration for the effects of temperature, sheltering, etc., it covers only four standard materials (e.g., carbon steel, zinc, copper and aluminum) and the methodology does not consider localized corrosion such as pitting, crevice corrosion and, most importantly for this study, SCC.

1.2 Climatic Comparison Methodology

As noted in the first report of this investigation\(^1\), most of the marine atmosphere corrosion data has been generated at the soon to be razed La Que Center for Corrosion Technology at Kure Beach, N\(^7\). This location is considered one of the most severe marine environments in the US and is clearly the most well documented for the effects of marine corrosion on materials performance. To obtain a climatic comparison between Kure Beach and all the other ISFSI current and future locations, the respective climatic data was obtained from the Kure Beach website\(^8\), the National Oceanic and Atmospheric Administration (NOAA)\(^9\), Western Regional Climate Center\(^10\), Cornell University\(^11\), the Environmental Protection Agency (EPA)\(^12\) and the National Atmospheric Deposition Program (NADP)\(^13\). The first step in this climatological process is to identify the NOAA climate region for each ISFSI location as presented in Table 1-1. Note that the term “on” or “near” the ocean is used based on utility input, there is no climatic difference between these two location designations since only regional climatic data is available.

This NOAA climatographic data includes normals and standard deviations for the five 30 year normals periods and the 70 year period from 1931-2000 for each climate division\(^9\). A climate division represents a region within a state that is as climatically homogeneous as possible. There are 344 climate divisions in the conterminous U.S., with additional divisions in Alaska, Hawaii, Puerto Rico, the U.S. Virgin Islands and Pacific trust territories. Monthly divisional average temperature and total precipitation data are derived by giving equal weight to all stations reporting both temperature and precipitation within a climatological division.

Temperature values are corrected for time of observation in the conterminous U.S\(^9\). In the conterminous U.S., observers at National Weather Service cooperative stations often take one observation per day, where the ending time of the climatological day can vary from station-to-station as well as year-to-year. Differences of the 24 hour period over which maximum and minimum temperature (as well as average temperature) is reported impact the calculated monthly mean temperature. These potential biases are rectified by adjusting for varying observation times using a model to adjust the climate division averages such that all stations end their climatological day at midnight, i.e., climatological and calendar day coincide.
Monthly divisional temperature normals and 70 year averages are computed by adding the yearly values for a given month and then dividing by the number of years in the period. The annual normal and 70 year average are computed by adding all of the monthly normal or long-term average values and then dividing by 12. Precipitation normals and long-term means are computed in a similar manner, except for the annual, which is the sum of monthly values.

Table 1-1

<table>
<thead>
<tr>
<th>#</th>
<th>Plant</th>
<th>ISFSI Location</th>
<th>ISFSI Status</th>
<th>NOAA Climate Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>San Onofre</td>
<td>San Clemente, CA</td>
<td>Operating ISFSI on ocean</td>
<td>CA-06</td>
</tr>
<tr>
<td>2</td>
<td>Calvert Cliffs</td>
<td>Lusby, MD</td>
<td>Operating ISFSI near ocean</td>
<td>MD-03</td>
</tr>
<tr>
<td>3</td>
<td>Millstone</td>
<td>Waterford, CT</td>
<td>Operating ISFSI near ocean</td>
<td>CT-03</td>
</tr>
<tr>
<td>4</td>
<td>Oyster Creek</td>
<td>Forked River, NJ</td>
<td>Operating ISFSI near ocean</td>
<td>NJ-03</td>
</tr>
<tr>
<td>5</td>
<td>Connecticut Yankee</td>
<td>Haddam Neck, CT</td>
<td>Operating ISFSI near ocean</td>
<td>CT-02</td>
</tr>
<tr>
<td>6</td>
<td>Maine Yankee</td>
<td>Wiscasset, ME</td>
<td>Operating ISFSI near ocean</td>
<td>ME-03</td>
</tr>
<tr>
<td>7</td>
<td>Diablo Canyon</td>
<td>Avila Beach, CA</td>
<td>Contracted ISFSI on ocean</td>
<td>CA-04</td>
</tr>
<tr>
<td>8</td>
<td>Humboldt Bay</td>
<td>Eureka, CA</td>
<td>Contracted ISFSI on ocean</td>
<td>CA-01</td>
</tr>
<tr>
<td>9</td>
<td>Pilgrim</td>
<td>Plymouth, MA</td>
<td>Contracted ISFSI near ocean</td>
<td>MA-03</td>
</tr>
<tr>
<td>10</td>
<td>Hope Creek</td>
<td>Salem, NJ</td>
<td>Contracted ISFSI near ocean</td>
<td>NJ-02</td>
</tr>
<tr>
<td>11</td>
<td>Seabrook</td>
<td>Seabrook, NH</td>
<td>Contracted ISFSI near ocean</td>
<td>NH-02</td>
</tr>
<tr>
<td>12</td>
<td>Turkey Point</td>
<td>Florida City, FL</td>
<td>Contracted ISFSI near ocean</td>
<td>FL-06</td>
</tr>
<tr>
<td>13</td>
<td>St. Lucie</td>
<td>Hutchinson Island, FL</td>
<td>Contracted ISFSI near ocean</td>
<td>FL-06</td>
</tr>
<tr>
<td>Ref</td>
<td>Kure Beach</td>
<td>Kure Beach, NC</td>
<td>Reference Test Site</td>
<td>NC-06</td>
</tr>
</tbody>
</table>

Note that the term “on” or “near” the ocean is used based on utility input, there is no climatic difference between these two location designations since only regional climatic data is available.

Figures 1-1 through 1-14 present the geographic locations of the ISFSI plus reference Kure Beach, NC. Each figure also contains a small figure of the climatic region as identified by NOAA.
Climate Comparison Considerations

Figure 1-1
San Onofre, San Clemente, CA, NOAA Region CA-06

Figure 1-2
Calvert Cliffs, Lusby, MD, NOAA Region MD-03
Figure 1-3
Millstone, Waterford, CT, NOAA Region CT-03

Figure 1-4
Oyster Creek, Forked River, NJ, NOAA Region NJ-03
Climate Comparison Considerations

Figure 1-5
Connecticut Yankee, Haddam Neck, CT, NOAA Region CT-02

Figure 1-6
Maine Yankee, Wiscasset, ME, NOAA Region ME-03
Climate Comparison Considerations

Figure 1-7
Diablo Canyon, Avila Beach, CA, NOAA Region CA-04

Figure 1-8
Humboldt Bay, Eureka, CA, NOAA Region CA-01
Climate Comparison Considerations

Figure 1-9
Pilgrim, Plymouth, MA, NOAA Region MA-03

Figure 1-10
Hope Creek, Salem, NJ, NOAA Region NJ-02
Climate Comparison Considerations

Figure 1-11
Seabrook, Seabrook, NH, NOAA Region NH-02

Figure 1-12
Turkey Point, Florida City, FL, NOAA Region FL-06
Climate Comparison Considerations

Figure 1-13
St. Lucie, Hutchinson Island, FL, NOAA Region FL-06

Figure 1-14
Kure Beach, NC, NOAA Region NC-06
1.3 Climatic Evaluations

Unfortunately, climatic data for most ISFSI locations is not available and nearby or somewhat even distant locations must be used. Table 1-2 presents the locations that were used for the various climatic and air quality parameters evaluated in this section of this chapter.

1.3.1 Precipitation

Table 1-3 and Figure 1-15 present the 1931 to 2000 average precipitation for reference Kure Beach, NC and San Clemente, i.e., San Onofre, where an ISFSI is currently located on the ocean. This precipitation value typically includes the liquid water equivalent of frozen precipitation. Tables 1-4 and 1-5 and Figures 1-16 and 1-17 present the 1931 to 2000 average precipitation for reference Kure Beach and ISFSI facilities operating near the ocean and contracted ISFSIs on or near the ocean, respectively.

It is obvious from Table 1-3 and Figure 1-15 that Kure Beach is characterized by significantly higher precipitation than San Onofre, i.e., San Onofre is drier by a factor of three, than Kure Beach with a total of 425 mm (16.8 inches) of precipitation per year as opposed to NOAA NC-06’s 1285 mm (50.6 inches) of precipitation a year. Also, since most of the San Onofre’s precipitation occurs during lower temperature winter, the corrosion kinetics of the stainless steel (regardless of the form of corrosion) would be expected to be lower than stainless steel exposed to the Kure Beach environment where most of the precipitation occurs during the warmer summer.

Table 1-4 and Figure 1-16 indicate that Kure Beach also has greater precipitation than the sites with ISFSIs located near the ocean. Again, significantly higher precipitation occurs during the higher temperature summer, i.e., July through September, at Kure Beach. The average precipitation for Kure Beach is also higher than the other sites.

Table 1-5 and Figure 1-17 indicate that all the ISFSI sites in this contracted category, with the exception of Diablo Canyon, have significantly higher precipitation than Kure Beach during November and that Turkey Point and St. Lucie have higher total precipitation than all the other contracted ISFSI sites during the summer. As expected, Diablo Canyon is the driest of all these contracted ISFSI sites.
## Climate Comparison Considerations

### Table 1-2
Respective ISFSI Climate Data Reference Locations

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>San Onofre</td>
<td>San Clemente, CA</td>
<td>NOAA CA-06</td>
<td>San Clemente[10]</td>
<td>Orange and San Diego</td>
<td>CA42 Tanbark Flat</td>
</tr>
<tr>
<td>2</td>
<td>Calvert Cliffs</td>
<td>Lusby, MD</td>
<td>NOAA MD-03</td>
<td>Baltimore[11]</td>
<td>Baltimore and Calvert</td>
<td>MD13 Wye, MD</td>
</tr>
<tr>
<td>4</td>
<td>Oyster Creek</td>
<td>Forked River, NJ</td>
<td>NOAA NJ-03</td>
<td>Atlantic City[11]</td>
<td>Ocean</td>
<td>NJ00 Edwin B. Forsythe National Wildlife Refuge</td>
</tr>
<tr>
<td>7</td>
<td>Diablo Canyon</td>
<td>Avila Beach, CA</td>
<td>NOAA CA-04</td>
<td>Santa Maria[10]</td>
<td>San Luis Obispo</td>
<td>CA66 Pinnacles-Bear Valley</td>
</tr>
<tr>
<td>8</td>
<td>Humboldt Bay</td>
<td>Eureka, CA</td>
<td>NOAA CA-01</td>
<td>San Francisco[11]</td>
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<td>CA45 Hopland</td>
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<td>Boston[11]</td>
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<td>MA01 North Atlantic Coastal Laboratory</td>
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<td>NOAA NJ-02</td>
<td>Atlantic City[11]</td>
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<td>NJ00 Edwin B. Forsythe National Wildlife Refuge</td>
</tr>
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<td>MA13 Middlesex County</td>
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<td>St. Lucie</td>
<td>Hutchinson Is., FL</td>
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<td>Vero Beach[11]</td>
<td>St. Lucie</td>
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<td>NOAA NC-06</td>
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<td>NC06 Beaufort</td>
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Table 1-3
Comparison of Precipitation Between Reference Kure Beach, NC, and San Onofre

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<tr>
<td>February</td>
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<td>April</td>
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<td>3.16</td>
</tr>
<tr>
<td>May</td>
<td>96.27</td>
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Climate Comparison Considerations

Figure 1-15
Comparison of Precipitation Between Reference Kure Beach, NC, and San Onofre
## Table 1-4
Comparison of Precipitation Among Reference Kure Beach, NC, and Plants with ISFSIs Near the Ocean

<table>
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<th>Month</th>
<th>Kure Beach, NC</th>
<th>Calvert Cliffs</th>
<th>Millstone</th>
<th>Oyster Creek</th>
<th>Connecticut Yankee</th>
<th>Maine Yankee</th>
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Figure 1-16
Comparison of Precipitation Among Reference Kure Beach, NC, and Plants with ISFSIs Near the Ocean
Table 1-5
Comparison of Precipitation Among Reference Kure Beach, NC, and Plants with ISFSIs Contracted to be on or Near the Ocean

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<th>Month</th>
<th>Kure Beach, NC</th>
<th>Diablo Canyon</th>
<th>Humboldt Bay</th>
<th>Pilgrim</th>
<th>Hope Creek</th>
<th>Seabrook</th>
<th>Turkey Point/ St. Lucie</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm</td>
<td>in</td>
<td>mm</td>
<td>in</td>
<td>mm</td>
<td>in</td>
<td>mm</td>
</tr>
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<td>7.85</td>
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Climate Comparison Considerations

Figure 1-17
Comparison of Precipitation Among Reference Kure Beach, NC, and Plants with ISFSIs Contracted to be on or Near the Ocean
1.3.2 Temperature

Table 1-6 and Figure 1-18 present the 1931 to 2000 average temperatures for reference Kure Beach, NC and San Clemente/San Onofre. Although the average yearly temperature of Kure Beach is only slightly higher than San Onofre (16.4 versus 16.1ºC [61.5 vs. 61.0ºF]), Kure Beach is warmer than San Onofre during the summer.

Table 1-7 and Figure 1-19 indicate that Kure Beach also has the highest monthly and average temperature, 16.4ºC (61.5ºF) than all the other the sites with ISFSIs near the ocean, while Table 1-8 and Figure 1-20 indicate that Turkey Point and St. Lucie have the highest average monthly, highest average temperature and highest temperatures during the summer than compared to all the other planned ISFSI sites.

<table>
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<tr>
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<th>San Onofre</th>
</tr>
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<td>ºF</td>
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Climate Comparison Considerations

Figure 1-18
Comparison of Temperature Between Reference Kure Beach, NC, and San Onofre
Table 1-7
Comparison of Temperatures Among Reference Kure Beach, NC, and Plants with ISFSIs Near the Ocean

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<th>Connecticut Yankee</th>
<th>Maine Yankee</th>
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<td>ºF</td>
<td>ºC</td>
<td>ºF</td>
<td>ºC</td>
<td>ºF</td>
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Figure 1-19
Comparison of Temperature Among References Kure Beach, NC, and Plants with ISFSIs Near the Ocean
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<th>Humboldt Bay</th>
<th>Pilgrim</th>
<th>Hope Creek</th>
<th>Seabrook</th>
<th>Turkey Point St. Lucie</th>
</tr>
</thead>
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<td>°C</td>
<td>°F</td>
<td>°C</td>
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<tr>
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</table>
Climate Comparison Considerations

Figure 1-20
Comparison of Temperatures Among Reference Kure Beach, NC, and Plants with ISFSIs Contracted to be on or Near the Ocean
1.3.3 Average Morning and Afternoon Humidity

The morning and afternoon humidity data was obtained from two sources, i.e., one that focused on the west coast of the US[8] and one that covered the entire country[9]. Table 1-9 plus Figures 1-21 and 1-22 present the average morning and afternoon humidity for Kure Beach and San Onofre, respectively. The relative humidity is expressed as a percentage measure of the amount of moisture in the air compared to the maximum amount of moisture the air can hold at the same temperature and pressure. Average humidity values are given for selected morning and afternoon observations. Maximum relative humidity values usually occur during morning hours.

Since the annual average values for morning and afternoon humidity for San Onofre (San Clemente, CA) are 85 and 72%, respectively, and Kure Beach (Wilmington, NC) are 85 and 56%, respectively, the relative morning humidity averages for the two sites are the same, but the afternoon average humidity is higher in San Onofre than Kure Beach.

Table 1-9
Average Morning and Afternoon Humidity for Kure Beach and San Onofre

<table>
<thead>
<tr>
<th>Month</th>
<th>Kure Beach, NC</th>
<th>San Onofre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Morning</td>
<td>Afternoon</td>
</tr>
<tr>
<td>January</td>
<td>81</td>
<td>56</td>
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<tr>
<td>February</td>
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<tr>
<td>March</td>
<td>82</td>
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</tr>
<tr>
<td>April</td>
<td>81</td>
<td>48</td>
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<td>May</td>
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</tr>
<tr>
<td>June</td>
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</tr>
<tr>
<td>July</td>
<td>87</td>
<td>63</td>
</tr>
<tr>
<td>August</td>
<td>90</td>
<td>64</td>
</tr>
<tr>
<td>September</td>
<td>90</td>
<td>62</td>
</tr>
<tr>
<td>October</td>
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<td>56</td>
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<tr>
<td>November</td>
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<td>53</td>
</tr>
<tr>
<td>December</td>
<td>82</td>
<td>56</td>
</tr>
<tr>
<td>Average</td>
<td>85</td>
<td>56</td>
</tr>
</tbody>
</table>
Climate Comparison Considerations

Figure 1-21
Average Morning Humidity for Kure Beach and San Onofre
Figure 1-22
Average Afternoon Humidity for Kure Beach and San Onofre
Climate Comparison Considerations

Table 1-10 plus Figures 1-23 and 1-24 present the average morning and afternoon humidity for Kure Beach and operating ISFSIs located near the ocean, respectively. While Kure Beach (Wilmington, NC) has the higher monthly and average morning humidity that the other ISFSIs, the average afternoon humidity for the various sites in this comparison are nearly equal. As was the case in the comparison between Kure Beach and San Onofre, Kure Beach has a lower afternoon humidity than three of the other ISFSI sites in this category.

Table 1-11 plus Figures 1-25 and 1-26 present the average morning and afternoon humidity for Kure Beach (Wilmington, NC) and contracted ISFSIs located on or near the ocean, respectively. Diablo Canyon (Santa Maria, CA) has the highest average morning humidity, followed by Kure Beach (Wilmington, NC). On a month to month comparison, Diablo Canyon has the highest monthly average morning humidity during the spring and summer. In the case of comparing the average afternoon humidity, Diablo Canyon (Santa Maria, CA), Humboldt Bay (Eureka, CA) and Turkey Point (Miami, FL) have the highest average afternoon humidity, while Kure Beach (Wilmington, NC) is the same as Hope Creek (Salem, NJ) with the lowest average afternoon humidity at 56%.
Table 1-10
Average Morning and Afternoon Humidity for Kure Beach and Operating ISFSIs Located Near the Ocean

<table>
<thead>
<tr>
<th>Month</th>
<th>Kure Beach, NC</th>
<th>Calvert Cliffs</th>
<th>Millstone</th>
<th>Oyster Creek</th>
<th>Connecticut Yankee</th>
<th>Maine Yankee</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Morning</td>
<td>Afternoon</td>
<td>Morning</td>
<td>Afternoon</td>
<td>Morning</td>
<td>Afternoon</td>
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<tr>
<td>January</td>
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<td>56</td>
<td>72</td>
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<tr>
<td>February</td>
<td>79</td>
<td>53</td>
<td>72</td>
<td>54</td>
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<td>56</td>
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<tr>
<td>March</td>
<td>82</td>
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<td>April</td>
<td>81</td>
<td>48</td>
<td>72</td>
<td>49</td>
<td>68</td>
<td>52</td>
</tr>
<tr>
<td>May</td>
<td>84</td>
<td>55</td>
<td>77</td>
<td>52</td>
<td>75</td>
<td>59</td>
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<td>85</td>
<td>59</td>
<td>77</td>
<td>51</td>
<td>78</td>
<td>61</td>
</tr>
<tr>
<td>July</td>
<td>87</td>
<td>63</td>
<td>80</td>
<td>53</td>
<td>78</td>
<td>61</td>
</tr>
<tr>
<td>August</td>
<td>90</td>
<td>64</td>
<td>84</td>
<td>55</td>
<td>79</td>
<td>61</td>
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<tr>
<td>September</td>
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<td>62</td>
<td>85</td>
<td>55</td>
<td>81</td>
<td>61</td>
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<tr>
<td>October</td>
<td>88</td>
<td>56</td>
<td>84</td>
<td>54</td>
<td>79</td>
<td>59</td>
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<tr>
<td>November</td>
<td>85</td>
<td>53</td>
<td>78</td>
<td>55</td>
<td>77</td>
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<tr>
<td>December</td>
<td>82</td>
<td>56</td>
<td>74</td>
<td>58</td>
<td>74</td>
<td>61</td>
</tr>
<tr>
<td>Average</td>
<td>85</td>
<td>56</td>
<td>77</td>
<td>54</td>
<td>75</td>
<td>59</td>
</tr>
</tbody>
</table>
Figure 1-23
Average Morning Humidity for Kure Beach and Operating ISFSIs Located Near the Ocean
Figure 1-24
Average Afternoon Humidity for Kure Beach and Operating ISFSIs Located Near the Ocean

Kure Beach, NC
Calvert Cliffs
Millstone
Oyster Creek
Connecticut Yankee
Maine Yankee
### Climate Comparison Considerations

**Table 1-11**

Average Morning and Afternoon Humidity for Kure Beach and Plants with ISFSIs Contracted to be on or Near the Ocean

<table>
<thead>
<tr>
<th>Month</th>
<th>Kure Beach, NC</th>
<th>Diablo Canyon</th>
<th>Humboldt Bay</th>
<th>Pilgrim/Seabrook</th>
<th>Hope Creek</th>
<th>Turkey Point</th>
<th>St. Lucie</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>A</td>
<td>M</td>
<td>A</td>
<td>M</td>
<td>A</td>
<td>M</td>
</tr>
<tr>
<td>Jan.</td>
<td>81</td>
<td>56</td>
<td>77</td>
<td>58</td>
<td>86</td>
<td>66</td>
<td>68</td>
</tr>
<tr>
<td>Feb.</td>
<td>79</td>
<td>53</td>
<td>83</td>
<td>61</td>
<td>84</td>
<td>64</td>
<td>68</td>
</tr>
<tr>
<td>March</td>
<td>82</td>
<td>52</td>
<td>88</td>
<td>63</td>
<td>81</td>
<td>62</td>
<td>69</td>
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<tr>
<td>April</td>
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<td>48</td>
<td>89</td>
<td>60</td>
<td>81</td>
<td>59</td>
<td>69</td>
</tr>
<tr>
<td>May</td>
<td>84</td>
<td>55</td>
<td>92</td>
<td>60</td>
<td>83</td>
<td>59</td>
<td>71</td>
</tr>
<tr>
<td>June</td>
<td>85</td>
<td>59</td>
<td>91</td>
<td>60</td>
<td>84</td>
<td>58</td>
<td>73</td>
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<tr>
<td>July</td>
<td>87</td>
<td>63</td>
<td>95</td>
<td>60</td>
<td>86</td>
<td>59</td>
<td>74</td>
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<tr>
<td>August</td>
<td>90</td>
<td>64</td>
<td>93</td>
<td>62</td>
<td>86</td>
<td>61</td>
<td>77</td>
</tr>
<tr>
<td>Sept.</td>
<td>90</td>
<td>62</td>
<td>92</td>
<td>62</td>
<td>83</td>
<td>58</td>
<td>79</td>
</tr>
<tr>
<td>Oct.</td>
<td>88</td>
<td>56</td>
<td>86</td>
<td>61</td>
<td>82</td>
<td>59</td>
<td>77</td>
</tr>
<tr>
<td>Nov.</td>
<td>85</td>
<td>53</td>
<td>81</td>
<td>61</td>
<td>84</td>
<td>63</td>
<td>74</td>
</tr>
<tr>
<td>Dec.</td>
<td>82</td>
<td>56</td>
<td>84</td>
<td>58</td>
<td>85</td>
<td>67</td>
<td>70</td>
</tr>
<tr>
<td>Ave.</td>
<td>85</td>
<td>56</td>
<td>88</td>
<td>61</td>
<td>84</td>
<td>61</td>
<td>72</td>
</tr>
</tbody>
</table>
Figure 1-25
Average Morning Humidity for Kure Beach and Plants with ISFSIs Contracted to be on or Near the Ocean
Figure 1-26
Average Afternoon Humidity for Kure Beach and Plants with ISFSIs Contracted to be on or Near the Ocean
1.4 Air Quality Data

The Environmental Protection Agency (EPA) AirData Monitor Values Report displays air pollution measurements recorded by thousands of monitoring sites throughout the United States\(^{12}\). The report presents a yearly summary of the measurements at individual monitoring sites and descriptive information about the sites. The EPA uses air pollution values to determine attainment or non-attainment of national air quality standards. Although only sulfur dioxide, nitrogen dioxide and ozone have been correlated with atmospheric corrosion\(^{14}\), carbon monoxide data is also included for information only. It should be noted that this data set is incomplete. Table 1-12 and Figure 1-27 summarize this air quality data for reference Kure Beach and all the other categories of ISFSI locations.

1.4.1 SO\(_2\) - Sulfur Dioxide

The US air quality standards for sulfur dioxide are:

- Three hour average concentration - 0.5 ppm that may not be exceeded more than once per year. (This is a secondary standard that pertains to societal welfare rather than health.)
- 24 hour average concentration - 0.14 ppm that may not be exceeded more than one day per year.
- Annual average concentration - 0.030 ppm

The plotted annual mean values are computed by Air Quality System (AQS) software from the 1-hour values reported in each calendar year is the arithmetic average of one hour SO\(_2\) concentration values for the year, in ppm by volume.

1.4.2 NO\(_2\) - Nitrogen Dioxide

The US air quality standards for nitrogen dioxide are:

- Annual average concentration - 0.053 ppm

The plotted annual values are computed by AQS software from the one hour values reported in each calendar year. The mean is the arithmetic average of one hour values for the year, in ppm by volume.

1.4.3 O\(_3\) - Ozone

The US air quality standards for ozone are:

- One hour average concentration - 0.12 ppm that may not be exceeded more than one day per year, after compensating for missing data (estimated number of exceedances).
- Eight hour average concentration - 0.08 ppm where the fourth highest value in a year, rounded to the nearest 0.01, may not exceed this level.
Climate Comparison Considerations

The plotted eight hour values are computed by AQS software for each hour of the day as a moving average of eight 1-hour values. The maximum value is the highest 8-hour value of each day in ppm by volume.

1.4.4 CO - Carbon Monoxide

The US air quality standards for carbon monoxide are:

- One hour average concentration - 35 ppm
- Eight hour average concentration - 9 ppm

The presented eight hour values for carbon monoxide are computed by AQS software for each hour of the day as a moving average of eight one hour values. The maximum carbon monoxide value is the highest non-overlapping eight hour value in the year, in ppm by volume.

1.4.5 Air Quality Summary

Due to the paucity and fragmentary nature of the available air quality data for reference Kure Beach and the other ISFSI sites, it is difficult to create any definitive comments. While the average sulfur dioxide concentrations of Kure Beach is slightly lower than the average of Kure Beach and all the ISHSI sites (e.g., 0.0025 versus 0.0029 ppm), the average ozone concentration of Kure Beach is slightly higher than the average of all the ISFSI sites and Kure Beach (e.g., 0.0840 versus 0.0808 ppm). Since no nitrogen dioxide data is available for Kure Beach, no comparisons can be made with the ISFSI sites.

1.5 Kure Beach Chloride Deposition

The LaQue Center for Corrosion Technology at Kure Beach, NC measures the monthly chloride accumulation in mg/m$^2$/day for locations on the ocean front and also at a “near-ocean” lot$^{[15]}$. Table 1-13 and Figure 2-28 present this data for 2004, i.e., the most recent (and now only available) full-year data. The amount of chloride accumulated on the surface per day is very high at both test locations (e.g., an average of 8.3 grams of chloride/m$^2$/day in September 2004).
<table>
<thead>
<tr>
<th></th>
<th>Kure Beach</th>
<th>San Onofre</th>
<th>Calvert Cliffs</th>
<th>Millstone</th>
<th>Oyster Creek</th>
<th>Conn. Yankee</th>
<th>Maine Yankee</th>
<th>Diablo Canyon</th>
<th>Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Mean SO2, ppm</td>
<td>0.0025</td>
<td>0.0030</td>
<td>0.0050</td>
<td>0.0020</td>
<td>0.0045</td>
<td>0.0040</td>
<td>0.0020</td>
<td>0.0029</td>
<td></td>
</tr>
<tr>
<td>Annual Mean NO2, ppm</td>
<td>0.0162</td>
<td>0.0140</td>
<td>0.0140</td>
<td></td>
<td>0.0150</td>
<td>0.0160</td>
<td>0.0056</td>
<td>0.0125</td>
<td></td>
</tr>
<tr>
<td>Ave. Max 8-Hr O3, ppm</td>
<td>0.0840</td>
<td>0.0742</td>
<td>0.0857</td>
<td>0.0880</td>
<td>0.0905</td>
<td>0.0938</td>
<td>0.0785</td>
<td>0.0693</td>
<td>0.0808</td>
</tr>
<tr>
<td>Ave. Max. 8-Hr CO, ppm</td>
<td>3.0330</td>
<td>1.1000</td>
<td></td>
<td>2.5000</td>
<td>0.5000</td>
<td>1.3000</td>
<td></td>
<td>1.7958</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Kure Beach</th>
<th>Pilgrim</th>
<th>Humbolt Bay</th>
<th>Hope Creek</th>
<th>Seabrook</th>
<th>Turkey Point</th>
<th>St. Lucie</th>
<th>Ave.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Mean SO2, ppm</td>
<td>0.0025</td>
<td>0.0043</td>
<td>0.0015</td>
<td>0.0020</td>
<td>0.0030</td>
<td>0.0010</td>
<td></td>
<td>0.0029</td>
</tr>
<tr>
<td>Annual Mean NO2, ppm</td>
<td>0.0178</td>
<td>0.0130</td>
<td>0.007</td>
<td>0.0100</td>
<td>0.0100</td>
<td>0.0125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ave. Max 8-Hr O3, ppm</td>
<td>0.0840</td>
<td>0.0915</td>
<td>0.0545</td>
<td>0.0950</td>
<td>0.0800</td>
<td>0.0725</td>
<td>0.0740</td>
<td>0.0808</td>
</tr>
<tr>
<td>Ave. Max. 8-Hr CO, ppm</td>
<td>2.0000</td>
<td>1.9330</td>
<td>2.0000</td>
<td>2.0000</td>
<td></td>
<td></td>
<td></td>
<td>1.7958</td>
</tr>
</tbody>
</table>
Figure 1-27
EPA Air Quality Values for All ISFSI Sites
## Table 1-13
2004 Monthly Chloride Accumulation at Kure Beach, NC (mg/m²/day)

<table>
<thead>
<tr>
<th>Month</th>
<th>Ocean Front Lot</th>
<th>Near- Ocean Lot</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>130.7</td>
<td>70.7</td>
</tr>
<tr>
<td>February</td>
<td>277.1</td>
<td>150.4</td>
</tr>
<tr>
<td>March</td>
<td>170.3</td>
<td>74.8</td>
</tr>
<tr>
<td>April</td>
<td>206.4</td>
<td>104.5</td>
</tr>
<tr>
<td>May</td>
<td>78.9</td>
<td>45.0</td>
</tr>
<tr>
<td>June</td>
<td>183.3</td>
<td>64.8</td>
</tr>
<tr>
<td>July</td>
<td>110.9</td>
<td>93.9</td>
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<tr>
<td>August</td>
<td>469.0</td>
<td>244.0</td>
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<tr>
<td>September</td>
<td>8333.3</td>
<td>3075</td>
</tr>
<tr>
<td>October</td>
<td>154.8</td>
<td>46.1</td>
</tr>
<tr>
<td>November</td>
<td>107.8</td>
<td>38.8</td>
</tr>
<tr>
<td>December</td>
<td>42.2</td>
<td>19.0</td>
</tr>
<tr>
<td>Total</td>
<td>10264.7</td>
<td>4027.0</td>
</tr>
</tbody>
</table>
Figure 1-28
2004 Monthly Chloride Accumulation at Kure Beach, NC (mg/m²/day)
1.6 Atmospheric Deposition

The National Atmospheric Deposition Program (NADP) is a nationwide network of precipitation monitoring sites\[13\]. The network is a cooperative effort among many different groups, including the State Agricultural Experiment Stations, U.S. Geological Survey, U.S. Department of Agriculture and numerous other governmental and private entities. The purpose of the network is to collect data on the chemistry of precipitation for monitoring of geographical and temporal long-term trends. The precipitation at each station is collected weekly and subsequently sent to the Central Analytical Laboratory where it is analyzed for hydrogen (acidity as pH), sulfate, nitrate, ammonium, chloride and base cations, i.e., calcium, magnesium, potassium and sodium.

Tables 1-14 through 1-25 present the 2004 deposition data, which is the most recent year with a complete year data set, for the various NADP monitoring sites that are located nearest to ISFSI facilities. This data is presented for information only and is used in the next section of this report.

Table 1-14
Seasonal Precipitation-Weighted Mean Concentrations for NADP Monitoring Station Near San Onofre (CA-42 Tanbark Flat, CA) in 2004

<table>
<thead>
<tr>
<th>Month</th>
<th>Ca, ppm</th>
<th>Mg, ppm</th>
<th>K, ppm</th>
<th>Na, ppm</th>
<th>NH₄, ppm</th>
<th>NO₃, ppm</th>
<th>Cl, ppm</th>
<th>SO₄, ppm</th>
<th>Lab pH</th>
<th>Lab Cond., µS/cm</th>
<th>Field pH</th>
<th>Field Cond., µS/cm</th>
<th>Cation /Anion Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.04</td>
<td>0.009</td>
<td>0.005</td>
<td>0.064</td>
<td>0.12</td>
<td>0.7</td>
<td>0.11</td>
<td>0.14</td>
<td>5.21</td>
<td>4.94</td>
<td>5.7</td>
<td>4.2</td>
<td>1.07</td>
</tr>
<tr>
<td>Feb</td>
<td>0.02</td>
<td>0.008</td>
<td>0.004</td>
<td>0.055</td>
<td>0.08</td>
<td>0.3</td>
<td>0.09</td>
<td>0.16</td>
<td>5.36</td>
<td>3.5</td>
<td>5.98</td>
<td>5.8</td>
<td>1.21</td>
</tr>
<tr>
<td>Mar</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
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<td>--</td>
<td>--</td>
<td>--</td>
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</tr>
<tr>
<td>Apr</td>
<td>0.24</td>
<td>0.088</td>
<td>0.051</td>
<td>0.705</td>
<td>0.63</td>
<td>2.83</td>
<td>1.09</td>
<td>1.48</td>
<td>4.74</td>
<td>21.17</td>
<td>4.72</td>
<td>18.3</td>
<td>0.97</td>
</tr>
<tr>
<td>May</td>
<td>1.03</td>
<td>0.852</td>
<td>0.322</td>
<td>6.408</td>
<td>2.64</td>
<td>14.5</td>
<td>8.81</td>
<td>7.21</td>
<td>4.31</td>
<td>99.8</td>
<td>--</td>
<td>--</td>
<td>0.95</td>
</tr>
<tr>
<td>Jun</td>
<td>1.01</td>
<td>0.317</td>
<td>0.486</td>
<td>1.963</td>
<td>5.97</td>
<td>28.51</td>
<td>2.7</td>
<td>6.4</td>
<td>3.86</td>
<td>145.4</td>
<td>--</td>
<td>--</td>
<td>0.96</td>
</tr>
<tr>
<td>Jul</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
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Seasonal Precipitation-Weighted Mean Concentrations for NADP Monitoring Station Near Calvert Cliffs (MD-13 Wye, MD) in 2004

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<th>Field Cond., μS/cm</th>
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Table 1-16
Seasonal Precipitation-Weighted Mean Concentrations for NADP Monitoring Station Near Millstone and Connecticut Yankee (NY-96 Cedar Beach, NY) in 2004

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<th>Na, ppm</th>
<th>NH₄, ppm</th>
<th>NO₃, ppm</th>
<th>Cl, ppm</th>
<th>SO₄, ppm</th>
<th>Lab pH</th>
<th>Lab Cond., μS/cm</th>
<th>Field pH</th>
<th>Field Cond., μS/cm</th>
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### Climate Comparison Considerations

**Table 1-17**
Seasonal Precipitation-Weighted Mean Concentration for NADP Monitoring Station Near Oyster Creek and Hope Creek (NJ-00 Edwin B. Forsythe National Wildlife Refuge, NJ) in 2004

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<th>Lab Cond., μS/cm</th>
<th>Field pH</th>
<th>Field Cond., μS/cm</th>
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Table 1-18
Seasonal Precipitation-Weighted Mean Concentrations for NADP Monitoring Station Near Maine Yankee (ME-96 Casco Bay, ME) in 2004

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<th>Na, ppm</th>
<th>NH₄, ppm</th>
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<th>SO₄, ppm</th>
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<th>Lab Cond., μS/cm</th>
<th>Field pH</th>
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Seasonal Precipitation-Weighted Mean Concentrations for NAP Monitoring Station Near Diablo Canyon (CA-66 Pinnacles-Bear Valley, CA) in 2004

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<th>SO₄, ppm</th>
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### Table 1-20
Seasonal Precipitation-Weighted Mean Concentrations for NADP Monitoring Station Near Humboldt Bay (CA-15 Hopland, CA) in 2004

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<th>Lab Cond., μS/cm</th>
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## Table 1-21
Seasonal Precipitation-Weighted Mean Concentrations for NADP Monitoring Station Near Pilgrim (MA-01 North Atlantic Coastal Lab, MA) in 2004

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<th>SO₄, ppm</th>
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<th>Lab Cond., μS/cm</th>
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Climate Comparison Considerations

Table 1-23
Seasonal Precipitation-Weighted Mean Concentrations for NADP Monitoring Station Near Turkey Point (FL-11 Everglades National Park, FL) in 2004

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<th>Na, ppm</th>
<th>NH₄, ppm</th>
<th>NO₃, ppm</th>
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<th>Cation /Anion Ratio</th>
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### Table 1-24
Seasonal Precipitation-Weighted Mean Concentration for NADP Monitoring Station Near St. Lucie (FL-99 Kennedy Space Center, FL) in 2004

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<th>SO₄, ppm</th>
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<th>Lab Cond., μS/cm</th>
<th>Field pH</th>
<th>Field Cond., μS/cm</th>
<th>Cation/Anion Ratio</th>
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Climate Comparison Considerations

Table 1-25
Seasonal Precipitation-Weighted Mean Concentration for NADP Monitoring Station Near Kure Beach (NC Beaufort, NC) in 2004

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<th>NH₄, ppm</th>
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<th>SO₄, ppm</th>
<th>Lab pH Cond., μS/cm</th>
<th>Field pH Cond., μS/cm</th>
<th>Field pH</th>
<th>Cation /Anion Ratio</th>
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<td>0.915</td>
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<td>1.057</td>
<td>0.17</td>
<td>0.84</td>
<td>1.87</td>
<td>1.27</td>
<td>4.68</td>
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<td>4.58</td>
<td>19.9</td>
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<td>0.018</td>
<td>0.217</td>
<td>0.23</td>
<td>1.08</td>
<td>0.41</td>
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<td>0.013</td>
<td>0.219</td>
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<td>0.76</td>
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<td>0.034</td>
<td>0.667</td>
<td>0.08</td>
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<td>5.22</td>
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<td>0.121</td>
<td>0.052</td>
<td>1.039</td>
<td>0.13</td>
<td>0.57</td>
<td>1.88</td>
<td>0.82</td>
<td>4.93</td>
<td>14.2</td>
<td>4.91</td>
<td>14.5</td>
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<td>0.514</td>
<td>0.13</td>
<td>0.41</td>
<td>0.95</td>
<td>0.98</td>
<td>4.84</td>
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<td>4.73</td>
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<td>0.023</td>
<td>0.546</td>
<td>0.09</td>
<td>0.31</td>
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<td>0.1</td>
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<td>1.032</td>
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Laboratory precipitation weighted mean concentrations are reported in ppm for the various ions. In cases where the weekly ion concentration was below the analytical detection limit, one half the detection limit value (or, in the case of a diluted sample, one half of the product of the detection limit value and the dilution factor) was used in computing the mean.

Field precipitation weighted means are computed using measurements made on valid weekly samples by the site operator in the field laboratory. A set of screening criteria have been approved by the NADP for use in assessing the validity of individual field chemistry measurements. Only those field chemistry measurements which meet all of the screening criteria are selected for use in calculating the field means.
The cation/anion equivalence ratio is calculated as the sum of the weighted-mean cation concentrations, in micro-equivalents per liter, divided by the sum of the weighted-mean anion concentrations, in micro-equivalents per liter. Orthophosphate and bicarbonate are not included in these ratios. Hydrogen concentrations used are those computed from the laboratory measurements of pH.

1.7 Discussion

As summarized in Table 1-26, all of the above climatic results suggest that due to its relative precipitation and temperature histories, Kure Beach’s climate with 107 mm (4.22 in) average monthly precipitation, with 151.7 mm (5.97 in) average summer (July, August and September) monthly precipitation and average temperature of 16.4ºC (61.5ºF) and average summer temperature of 24.9ºC (76.8ºF) is not quite as severe as Turkey Point’s and St. Lucie’s climate with 127 mm (4.98 in) average monthly precipitation, with 188 mm (7.40 in) average summer monthly precipitation and average temperature of 23.8ºC (74.8ºF) and average summer temperature of 27.6ºC (81.7ºF). Also, based on average morning humidity histories, Kure Beach is only slightly more humid at 88% than St. Lucie at 84% and Turkey Point at 83%. Similar humidity results are obtained for average morning summer humidity. Kure Beach’s average afternoon humidity is lower than most of the other ISFSI locations.

Hence it appears that Kure Beach is a suitable reference environment for all ISFSI locations with the exception of the two Florida locations and that corrosion data obtained from Kure Beach testing could be used as a worst case bench mark for all the non-Florida ISFSI locations. However, since the Kure Beach data is obtained from specimens openly exposed to the marine environment and the ISFSI materials are sheltered, the Kure Beach corrosion data may still be applicable and, in fact, conservative for all ISFSI locations.
### Table 1-26
Relative Climate Rankings of Kure Beach and ISFSI Locations

<table>
<thead>
<tr>
<th>Average or Total Precip.</th>
<th>Summer Average or Total Precip.</th>
<th>Average Temp.</th>
<th>Summer Average Temp.</th>
<th>Average Morning Humidity</th>
<th>Average Summer Morning Humidity</th>
<th>Average Afternoon Humidity</th>
<th>Average Summer Afternoon Humidity</th>
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<tr>
<td>Turkey Point</td>
<td>Turkey Point</td>
<td>Turkey Point</td>
<td>Turkey Point</td>
<td>Diablo Canyon</td>
<td>Diablo Canyon</td>
<td>San Onofre</td>
<td>San Onofre</td>
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<td>St. Lucie</td>
<td>St. Lucie</td>
<td>St. Lucie</td>
<td>St. Lucie</td>
<td>Kure Beach</td>
<td>Kure Beach</td>
<td>Diablo Canyon</td>
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</tr>
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<td>Kure Beach</td>
<td>Kure Beach</td>
<td>Kure Beach</td>
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<td>Hope Creek</td>
<td>Humboldt Bay</td>
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<td>Calvert Cliffs</td>
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<td>Oyster Creek</td>
<td>Turkey Point</td>
<td>Conn. Yankee</td>
</tr>
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<td>Hope Creek</td>
<td>Diablo Canyon</td>
<td>Oyster Creek</td>
<td>St. Lucie</td>
<td>San Onofre</td>
<td>Conn. Yankee</td>
<td>Diablo Canyon</td>
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<td>Conn. Yankee</td>
<td>Calvert Cliffs</td>
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<td>Turkey Point</td>
<td>Humboldt Bay</td>
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<td>Millstone</td>
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<td>Pilgrim</td>
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<td>Turkey Point</td>
<td>Millstone</td>
<td>St. Lucie</td>
</tr>
<tr>
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<td>Oyster Creek</td>
<td>Millstone</td>
<td>St. Lucie</td>
<td>Pilgrim</td>
<td>Humboldt Bay</td>
<td></td>
</tr>
<tr>
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<td>Millstone</td>
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<td>Maine Yankee</td>
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<td>Hope Creek</td>
</tr>
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<td>Seabrook</td>
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<td>Humboldt Bay</td>
<td>Conn. Yankee</td>
<td>Conn. Yankee</td>
<td>Hope Creek</td>
<td>Oyster Creek</td>
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<tr>
<td>Humboldt Bay</td>
<td>Humboldt Bay</td>
<td>Conn. Yankee</td>
<td>Diablo Canyon</td>
<td>Millstone</td>
<td>Millstone</td>
<td>Kure Beach</td>
<td>Pilgrim</td>
</tr>
<tr>
<td>Diablo Canyon</td>
<td>San Onofre</td>
<td>Seabrook</td>
<td>Seabrook</td>
<td>Pilgrim</td>
<td>Pilgrim</td>
<td>Oyster Creek</td>
<td>Seabrook</td>
</tr>
<tr>
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<td>Diablo Canyon</td>
<td>Maine Yankee</td>
<td>Maine Yankee</td>
<td>Seabrook</td>
<td>Seabrook</td>
<td>Calvert Cliffs</td>
<td>Calvert Cliffs</td>
</tr>
</tbody>
</table>
2
CORROSIVITY OF AQUEOUS AEROSOLS AT SPENT FUEL STORAGE CANISTER INSTALLATIONS

2.1 Introduction

The approach discussed in Section 1 does not account for the chemistry of aqueous solutions that could come into contact with container surfaces. Whether such considerations are needed is open to question because the ISFSI facilities are ostensibly dry to the extent that spent fuel storage canisters are sheltered by concrete casks or vaults from direct contact by rain or snow. It is possible, however, that liquids could impinge on container surfaces as aqueous aerosols, i.e., as moisture, entrained in air that is allowed to circulate through the casks/vaults for the purpose of dissipating radiogenic heat. Subsequent evaporation of these initially dilute solutions at elevated temperatures on the spent fuel storage canister’s surface could conceivably generate solutions having high concentrations of certain constituents (most notably chloride) that are known to strongly promote SCC of austenitic stainless steels.

The chapter addresses this possibility. The specific objectives of Section 2 are to:

1. Compile data characterizing the chemistry of aqueous aerosols at ISFSI sites;
2. Apply geochemical modeling techniques to simulate the chemical evolution of these solutions as they evaporate on container surfaces, and
3. Assess modeling results to obtain insights as to whether the initial/evaporated solutions would be aggressive or benign with respect to SCC of spent fuel storage canisters.

It is important to note that this “reconnaissance study” does not consider other types of aqueous solutions that could be generated by the deliquescence of solid aerosol particles that may come into contact with container surfaces, i.e., as “dry deposition.” These solutions could be evaluated using a similar modeling approach to that described below, however, provided data characterizing the mineralogy of such particles are available.

2.2 Model Description

This section describes conceptual and numerical aspects of the geochemical model used to simulate the evaporative evolution of aqueous solutions on container surfaces at U.S. ISFSI sites. The locations of these sites were presented in Table 1-1. Figures 2-1 through 2-7 present the ISFSI locations plus cloudwater and fogwater locations. An example spent fuel storage canister design that could be used at these sites is shown in Figures 2-8 and 2-9. Although variations in this basic design may be adopted among the various ISFSI facilities, they are likely to have
several key features in common. For present purposes it is assumed that these features include the provision for cooling air to circulate through the concrete casks/shelters.

Figure 2-1
Map of the U.S. West Coast Showing Locations of Operating and Contracted ISFSI Sites (square symbols), Cloud Water and Fog Water Sampling Locations (filled circles). The Latter Locations in the Los Angeles Basin include Sites at Lennox (1), San Pedro Hill (2), Long Beach (3), Henninger Flats (4), Riverside (5) and Corona del Mar (6)
Figure 2-2
Map of Florida Showing Locations of the Turkey Point and St Lucie NPP/ISFSI Sites and NADP Sampling Sites at Everglades National Park and the Kennedy Space Center

Figure 2-3
Map Showing the Location of the Kure Beach Reference Site and Selected NADP Sampling Sites in North Carolina and South Carolina
Figure 2-4
Map of Maryland Showing the Location of the Operating ISFSI Site at Calvert Cliffs and the NADP Sampling Site at Wye

Figure 2-5
Map of New Jersey Showing the Location of ISFSI Sites at Hope Creek and Oyster Creek and the NADP Sampling Site at Forsythe National Wildlife Refuge
Figure 2-6
Location Map of Operating ISFSI Sites in Connecticut and the NADP Sampling Site at Cedar Beach, New York

Figure 2-7
Map of Maine, New Hampshire, and Massachusetts Showing the Locations of ISFSI Sites, NADP Sampling Sites at Casco Bay, East and the North Atlantic Coastal Laboratory, and the Fog Water Sampling Site at Rye Beach
Corrosivity of Aqueous Aerosols at Spent Fuel Storage Canister Installations

Figure 2-8
Diagram of a Dry Nuclear-Fuel Storage Cask Showing Details of the Multi-Assembly Sealed Basket

Figure 2-9
Photograph of the Dry Fuel Storage Facility at Connecticut Yankee
2.2.1 Conceptual Model

The conceptual model considers the evaporative chemical evolution of moisture impinging on container surfaces, Figure 2-8, at each of the ISFSI locations noted in Table 1-1. Evaporation will occur in this scenario because the container’s surface is hotter than the air that is advecting through the spent fuel storage canisters. The equilibrium vapor pressure of moisture on the container’s surface must consequently be higher than the partial pressure of H\textsubscript{2}O(g) in the gas phase and this will cause H\textsubscript{2}O to exsolve from the liquid in an effort to establish phase equilibrium. Continuous evaporation of H\textsubscript{2}O causes the initial solution composition to follow a trajectory governed by the progressive concentration of residual solutes, mineral precipitation/dissolution and gas mass transfer. This compositional trajectory and its attendant evolution of precipitated (or dissolved) minerals are referred to below as a “reaction path.”

Key constraints on the present conceptual model include:

1. Moisture chemistry;
2. Container surface temperature; and
3. Gas phase composition

Each of these constraints is considered further in the following paragraphs.

*Moisture chemistry.* Since data on the chemistry of aqueous aerosols at specific ISFSI facilities are not available, a literature survey was performed to collect data that may be representative of aerosol compositions at these sites. The collected data come from two primary sources: 1) published studies characterizing the chemistry of fog waters and cloud waters at coastal sites across the U.S., and 2) data collected by the U.S. National Atmospheric Deposition Program (NADP) on the chemistry of rain waters and snowmelt at sampling sites on the east coast.

The data collected in this study include micronormal (μN) concentrations of major cations (Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, K\textsuperscript{+}, Na\textsuperscript{+}, NH\textsubscript{4}\textsuperscript{+}), major anions (Cl\textsuperscript{−}, NO\textsubscript{3}\textsuperscript{−}, SO\textsubscript{4}\textsuperscript{2−}) and pH (Table 2-1). The locations of the respective sampling sites and their proximity to operating and contracted ISFSI facilities are shown in Figures 2-1 - 2-7. Rainwater data are represented as seasonal averages for 2004, which is the most recent full-year dataset available. Fogwater and cloudwater data are for bulk samples, which include the entire spectrum of water-droplet sizes in a given sample volume of cloud or fog (see below). Important details regarding sampling procedures and analytical techniques are included in the cited references. These details are given for rainwater samples in documentation provided by the NADP website (http://nadp.sws.uiuc.edu). Organic constituents are not considered in the present study due to a lack of relevant data. It is worthwhile noting, however, that fogwaters, cloudwaters and rainwaters can contain detectable concentrations of organics (e.g., formaldehyde, glyoxal and organic acids such as formic and acetic acid) derived from natural and pollutant sources\textsuperscript{[16, 17]}. 
The quality of the data in Table 2-1 was assessed by calculating analytical charge imbalances. These values, shown in the penultimate column of the table, represent excesses of cationic or anionic charge resulting from analytical error and/or from a failure to analyze for important constituents. Individual analyses were not considered further if the calculated charge imbalance exceeds ±10%. One NADP analysis (sample 124, Table 2-1) and several fogwater and cloudwater analyses (samples 7, 17, 37, 40, 52-53, 54-56, 58-60, 62, 65, 83 and 85, Table 2-1) fail this test.

The representativeness of the data in Table 2-1 with respect to aqueous aerosol compositions at specific ISFSI sites is difficult to assess. Inspection of the data indicates, for example, that fogwaters and cloudwaters are generally more concentrated and more acidic than rainwaters\textsuperscript{[19, 20, 21]}. These differences do not simply reflect the effects of dilution because ionic ratios in fogwaters and cloudwaters also tend to differ significantly compared to their rainwater counterparts. Rather, the differences appear to be due to the fact that aqueous aerosols in fogs and clouds are highly reactive with respect to solid atmospheric particulates and soluble gases\textsuperscript{[18]}. This is evidenced by the observation that the compositions of fogwaters and cloudwaters tend to vary with droplet size\textsuperscript{[22, 16, 23]}. Aqueous chemistry and droplet size are correlated because droplet size appears to depend on the diameter of solid particulates acting as condensation nuclei. Thus, soil dusts and sea salts tend to control the chemistry of larger aqueous aerosols because their respective nuclei are relatively large, whereas NO\textsubscript{3}\textsuperscript{-} and SO\textsubscript{4}\textsuperscript{2-}, produced by the photooxidation of SO\textsubscript{2}(g), dimethylsulfide and NO\textsubscript{x}(g), tend to dominate the chemistry of smaller aqueous aerosols precipitating onto secondary solids such as (NH\textsubscript{4})\textsubscript{2}SO\textsubscript{4} and NH\textsubscript{4}NO\textsubscript{3}\textsuperscript{[22]}. In contrast, rainwaters tend to be more dilute and less acidic because the liquid-water content of precipitating clouds tends to be higher than in fogs and non-precipitating clouds and because condensation nuclei tend be washed out of the atmosphere with increasing amounts of precipitation.

For these reasons the chemistry of fogwaters, cloudwaters and rainwaters can be highly variable over minutes-to-days time frames at a given site\textsuperscript{[20]}. This variability may be strongly influenced by external environmental factors such as long-range transport and mixing of regional air masses, and by regional and local gas and particulate emission sources\textsuperscript{[24, 20]}. This suggests that the representativeness of the analytical data in Table 2-1 cannot be assessed simply on the basis of geographic proximity to a given ISFSI site.

With these important caveats in mind, Table 2-2 attempts to categorize the individual analyses in Table 2-1 into groups that may be considered, as a first approximation, to be representative of ambient aqueous aerosol compositions at each of the ISFSI coastal sites considered in this study. It is important to emphasize that these categories are determined in part on the basis of geographic proximity and may therefore be suspect for the reasons stated above. Note that most of the fogwater and cloudwater data are for ISFSI facilities on the west coast, whereas the east-coast sites are represented mainly by rainwaters. Temperatures listed in this table are maximum monthly temperatures for each site estimated in this report and are used as ambient temperatures for the respective sites in the geochemical model. This selection of ambient temperatures is somewhat arbitrary but does not materially affect the main conclusions of this study.
Table 2-1
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States (All Concentrations in \( \mu \)equiv l\(^{-1} \); Charge Balance, c.b., in Percent)

<table>
<thead>
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<th>No.</th>
<th>Water Type</th>
<th>Location(^{†} )</th>
<th>Year(^{††} )</th>
<th>Collector(^{†††} )</th>
<th>T (°C)</th>
<th>Ca(^{2+} )</th>
<th>Mg(^{2+} )</th>
<th>K(^+ )</th>
<th>Na(^+ )</th>
<th>NH(_4)(^+ )</th>
<th>NO(_3)(^- )</th>
<th>CI(^- )</th>
<th>SO(_4)(^2- )</th>
<th>pH</th>
<th>c.b.</th>
<th>Ref. (^{††††} )</th>
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<td>15.1</td>
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<td>15.0</td>
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Table 2-1 (continued)
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States
(All Concentrations in \( \mu \text{equiv l}^{-1} \); Charge Balance, c.b., in Percent)

<table>
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<tr>
<th>No.</th>
<th>Water Type</th>
<th>Location†</th>
<th>Year††</th>
<th>Collector†††</th>
<th>T (°C)</th>
<th>Ca(^{2+})</th>
<th>Mg(^{2+})</th>
<th>K(^+)</th>
<th>Na(^+)</th>
<th>NH(_4)(^+)</th>
<th>NO(_3)(^-)</th>
<th>Cl(^-)</th>
<th>SO(_4)(^2-)</th>
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<th>c.b.</th>
<th>Ref.††††</th>
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Table 2-1 (continued)
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States
(All Concentrations in $\mu$equiv l$^{-1}$; Charge Balance, c.b., in Percent)

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<th>No.</th>
<th>Water Type</th>
<th>Location</th>
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<th>Collector</th>
<th>T (°C)</th>
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<th>Mg$^{2+}$</th>
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Corrosivity of Aqueous Aerosols at Spent Fuel Storage Canister Installations

Table 2-1 (continued)
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States
(All Concentrations in $\mu$equiv l$^{-1}$; Charge Balance, c.b., in Percent)

<table>
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<tr>
<th>No.</th>
<th>Water Type</th>
<th>Location†</th>
<th>Year‡</th>
<th>Collector††</th>
<th>T (°C)</th>
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<th>Mg$^{2+}$</th>
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<th>NH$_4^+$</th>
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Table 2-1 (continued)
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States
(All Concentrations in \(\mu\text{equiv l}^{-1}\); Charge Balance, c.b., in Percent)

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### Table 2-1 (continued)
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States
(All Concentrations in μequiv l⁻¹; Charge Balance, c.b., in Percent)

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<th>Water Type</th>
<th>Location†</th>
<th>Year ††</th>
<th>Collector†††</th>
<th>T (°C)</th>
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<th>Mg²⁺</th>
<th>K⁺</th>
<th>Na⁺</th>
<th>NH₄⁺</th>
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<th>SO₄²⁻</th>
<th>pH</th>
<th>c.b.</th>
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### Table 2-1 (continued)

**Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States**

(All Concentrations in μequiv l⁻¹; Charge Balance, c.b., in Percent)

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<th>Collector†††</th>
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**FLORIDA**

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**SOUTH CAROLINA**

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<th>Na⁺</th>
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**Corrosivity of Aqueous Aerosols at Spent Fuel Storage Canister Installations**

**Table 2-1 (continued)**
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States
(All Concentrations in μequiv l⁻¹; Charge Balance, c.b., in Percent)

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Table 2-1 (continued)

Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States
(All Concentrations in μequiv l⁻¹; Charge Balance, c.b., in Percent)

<table>
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<th>No.</th>
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<th>Collector†††</th>
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<th>Mg²⁺</th>
<th>K⁺</th>
<th>Na⁺</th>
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<th>NO₃⁻</th>
<th>Cl⁻</th>
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MARYLAND

| 108 | Rainwater | Wye (MD13) | 2004/W | NADP | N.R. | 2.0 | 2.9 | 0.4 | 13.7 | 5.5 | 10.9 | 16.6 | 20.0 | 4.65 | -0.7 | 6 |
| 109 | Rainwater | Wye (MD13) | 2004/S | NADP | N.R. | 6.2 | 2.5 | 2.0 | 5.8 | 23.5 | 25.2 | 7.4 | 48.2 | 4.39 | 0.0 | 6 |
| 110 | Rainwater | Wye (MD13) | 2004/S | NADP | N.R. | 3.4 | 1.2 | 0.3 | 3.6 | 15.7 | 17.7 | 5.8 | 50.6 | 4.31 | -0.6 | 6 |
| 111 | Rainwater | Wye (MD13) | 2004/F | NADP | N.R. | 1.9 | 1.9 | 0.3 | 8.7 | 10.2 | 11.8 | 11.1 | 19.3 | 4.73 | -0.7 | 6 |
# Table 2-1 (continued)

Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States

(All Concentrations in $\mu$equiv l$^{-1}$; Charge Balance, c.b., in Percent)

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<th>Location Type</th>
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<th>Collector</th>
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<th>$K^+$</th>
<th>$Na^+$</th>
<th>$NH_4^+$</th>
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<th>$Cl^-$</th>
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Table 2-1 (continued)  
Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States  
(All Concentrations in $\mu$equiv l$^{-1}$; Charge Balance, c.b., in Percent)

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<th>Na⁺</th>
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<tr>
<td>43</td>
<td>Fogwater</td>
<td>Rye</td>
<td>1990</td>
<td>CASCC</td>
<td>4</td>
<td>15.0</td>
<td>62.0</td>
<td>13.0</td>
<td>558.0</td>
<td>454.0</td>
<td>1149.0</td>
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<td>678.0</td>
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<td>94.0</td>
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<td>45</td>
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<td>CASCC</td>
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<td>53.0</td>
<td>345.0</td>
<td>49.0</td>
<td>1934.0</td>
<td>224.0</td>
<td>720.0</td>
<td>2437.0</td>
<td>428.0</td>
<td>3.04⁺</td>
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<td>46</td>
<td>Fogwater</td>
<td>Rye</td>
<td>1990</td>
<td>CASCC</td>
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<td>13.0</td>
<td>83.0</td>
<td>17.0</td>
<td>577.0</td>
<td>135.0</td>
<td>96.0</td>
<td>665.0</td>
<td>63.0</td>
<td>4.37⁺</td>
<td>2.6</td>
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<td>47</td>
<td>Fogwater</td>
<td>Rye</td>
<td>1990</td>
<td>CASCC</td>
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<td>12.0</td>
<td>39.0</td>
<td>16.0</td>
<td>318.0</td>
<td>782.0</td>
<td>615.0</td>
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<td>48</td>
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<td>Rye</td>
<td>1990</td>
<td>CASCC</td>
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<td>101.0</td>
<td>143.0</td>
<td>190.0</td>
<td>54.0</td>
<td>3.94⁺</td>
<td>-0.2</td>
<td>8</td>
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<td>NEW YORK</td>
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<tr>
<td>91</td>
<td>Orographic</td>
<td>Whiteface Mtn.</td>
<td>1993/1998</td>
<td>CASCC2</td>
<td>N.R.</td>
<td>49.7</td>
<td>13.8</td>
<td>4.6</td>
<td>3.4</td>
<td>256.1</td>
<td>213.2</td>
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<td>510.7</td>
<td>3.48⁺</td>
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<tr>
<td>104</td>
<td>Rainwater</td>
<td>Cedar Beach (NY96)</td>
<td>2004/W</td>
<td>NADP</td>
<td>N.R.</td>
<td>5.1</td>
<td>17.9</td>
<td>1.8</td>
<td>82.8</td>
<td>3.9</td>
<td>12.0</td>
<td>96.9</td>
<td>25.3</td>
<td>4.68⁺</td>
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</tr>
<tr>
<td>105</td>
<td>Rainwater</td>
<td>Cedar Beach (NY96)</td>
<td>2004/S</td>
<td>NADP</td>
<td>N.R.</td>
<td>6.6</td>
<td>11.7</td>
<td>1.7</td>
<td>51.9</td>
<td>11.6</td>
<td>17.0</td>
<td>60.0</td>
<td>31.8</td>
<td>4.60⁺</td>
<td>-0.1</td>
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<td>106</td>
<td>Rainwater</td>
<td>Cedar Beach (NY96)</td>
<td>2004/S</td>
<td>NADP</td>
<td>N.R.</td>
<td>3.6</td>
<td>9.6</td>
<td>1.0</td>
<td>43.1</td>
<td>4.3</td>
<td>9.9</td>
<td>52.3</td>
<td>21.3</td>
<td>4.69⁺</td>
<td>-0.9</td>
<td>6</td>
</tr>
<tr>
<td>107</td>
<td>Rainwater</td>
<td>Cedar Beach (NY96)</td>
<td>2004/F</td>
<td>NADP</td>
<td>N.R.</td>
<td>5.1</td>
<td>18.8</td>
<td>1.9</td>
<td>86.7</td>
<td>2.3</td>
<td>6.8</td>
<td>101.1</td>
<td>19.4</td>
<td>4.89⁺</td>
<td>0.2</td>
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</tr>
</tbody>
</table>
### Table 2-1 (continued)

**Chemistry of Cloudwater, Fogwater, and Rainwater Samples at Selected Coastal and Near-Coastal Sites Across the United States**

(All Concentrations in \(\text{µequiv l}^{-1}\); Charge Balance, c.b., in Percent)

<table>
<thead>
<tr>
<th>No.</th>
<th>Water Type</th>
<th>Location†</th>
<th>Year††</th>
<th>Collector†††</th>
<th>T (°C)</th>
<th>Ca(^{2+})</th>
<th>Mg(^{2+})</th>
<th>K(^+)</th>
<th>Na(^+)</th>
<th>NH(_4^+)</th>
<th>NO(_3^-)</th>
<th>Cl(^-)</th>
<th>SO(_4^{2-})</th>
<th>pH</th>
<th>c.b.</th>
<th>Ref. ††††</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MAINE</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>116</td>
<td>Rainwater</td>
<td>Casco Bay (ME96)</td>
<td>2004/W</td>
<td>NADP</td>
<td>N.R.</td>
<td>4.3</td>
<td>9.1</td>
<td>1.1</td>
<td>43.1</td>
<td>3.9</td>
<td>8.9</td>
<td>51.7</td>
<td>16.0</td>
<td>4.86(^b)</td>
<td>-0.9</td>
<td>6</td>
</tr>
<tr>
<td>117</td>
<td>Rainwater</td>
<td>Casco Bay (ME96)</td>
<td>2004/S</td>
<td>NADP</td>
<td>N.R.</td>
<td>2.9</td>
<td>2.9</td>
<td>0.5</td>
<td>12.0</td>
<td>17.8</td>
<td>17.5</td>
<td>13.9</td>
<td>26.7</td>
<td>4.67(^b)</td>
<td>-0.5</td>
<td>6</td>
</tr>
<tr>
<td>118</td>
<td>Rainwater</td>
<td>Casco Bay (ME96)</td>
<td>2004/S</td>
<td>NADP</td>
<td>N.R.</td>
<td>2.6</td>
<td>2.2</td>
<td>0.4</td>
<td>9.4</td>
<td>13.3</td>
<td>4.18</td>
<td>11.6</td>
<td>32.6</td>
<td>4.51(^b)</td>
<td>-0.2</td>
<td>6</td>
</tr>
<tr>
<td>119</td>
<td>Rainwater</td>
<td>Casco Bay (ME96)</td>
<td>2004/F</td>
<td>NADP</td>
<td>N.R.</td>
<td>2.0</td>
<td>3.1</td>
<td>0.4</td>
<td>14.8</td>
<td>4.2</td>
<td>11.5</td>
<td>17.3</td>
<td>17.7</td>
<td>4.68(^b)</td>
<td>-1.2</td>
<td>6</td>
</tr>
</tbody>
</table>

†- alphanumeric characters in parentheses refer to site descriptors used by the NADP. ††- Letters in descending order W, S, S and F denote Winter, Spring, Summer and Fall, respectively. †††- active - active cloudwater sampler; CASCC2 - Caltech Active Strand Cloudwater Collector, version 2; Rotating arm - rotating arm collector; CASCC - Caltech Active Strand Cloudwater Collector; NADP - standard rainwater collector used the NADP; ASRC - Atmospheric Sciences Research Center passive cloudwater collector. ††††- 1 – Reference 20; 2 – Reference 18; 3 – Reference 19; 4 – Reference 22; 5 – Reference 16; 6 - data retrieved from the NADP website at [http://nadp.sws.uiuc.edu](http://nadp.sws.uiuc.edu); 7 – Reference 25; 8 – Reference 24. \(^a\) - measured in the field. \(^b\) - measured in the laboratory.
Table 2-2
Selection of Representative Waters

<table>
<thead>
<tr>
<th>No.</th>
<th>ISFSI/Ref.</th>
<th>Maximum Ambient Temperature, °C (°F)</th>
<th>Representative waters (Table 2-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Humboldt Bay</td>
<td>19.4 (66.9) (July)</td>
<td>1,11,12-15,57</td>
</tr>
<tr>
<td>2</td>
<td>Diablo Canyon</td>
<td>18.8 (65.8) (August)</td>
<td>9,10 (also 61,63-64,66-78)</td>
</tr>
<tr>
<td>3</td>
<td>San Onofre</td>
<td>22.3 (72.1) (August)</td>
<td>2-6,8,16,18-36,38-39,41-42,61,63-64,66-78,79</td>
</tr>
<tr>
<td>4</td>
<td>Calvert Cliffs</td>
<td>24.6 (76.2) (July)</td>
<td>108-111</td>
</tr>
<tr>
<td>5</td>
<td>Oyster Creek</td>
<td>23.6 (74.5) (July)</td>
<td>100-103</td>
</tr>
<tr>
<td>6</td>
<td>Hope Creek</td>
<td>23.9 (75.0) (July)</td>
<td>100-103, 108-111</td>
</tr>
<tr>
<td>7</td>
<td>Millstone</td>
<td>22.6 (72.7) (July)</td>
<td>104-107</td>
</tr>
<tr>
<td>8</td>
<td>Connecticut Yankee</td>
<td>21.9 (71.4) (July)</td>
<td>104-107</td>
</tr>
<tr>
<td>9</td>
<td>Pilgrim</td>
<td>21.6 (70.9) (July)</td>
<td>112-115, 128-131</td>
</tr>
<tr>
<td>10</td>
<td>Maine Yankee</td>
<td>19.3 (66.7) (July)</td>
<td>116-119, 43-48</td>
</tr>
<tr>
<td>11</td>
<td>Seabrook</td>
<td>20.4 (68.7) (July)</td>
<td>128-131, 43-48</td>
</tr>
<tr>
<td>12</td>
<td>Turkey Point</td>
<td>27.8 (82.0) (August)</td>
<td>120-123</td>
</tr>
<tr>
<td>13</td>
<td>St. Lucie</td>
<td>27.8 (82.0) (August)</td>
<td>124-127, 120-123</td>
</tr>
<tr>
<td>---</td>
<td>Kure Beach</td>
<td>26.3 (79.3) (July)</td>
<td>92-95,96-99</td>
</tr>
</tbody>
</table>

Container surface temperature. Section 3 presents the estimated time-temperature evolution of container surfaces at ISFSI facilities. The primary variables controlling surface temperatures over time are the heat load from the spent fuel, the heat transfer rate from the fuel to the canister surface and the heat transfer rate from the canister surface to the atmosphere. The heat load from the spent fuel is primarily a function of the initial uranium loading in the fuel, power history in the reactor, time after discharge from the reactor and the number of spent fuel assemblies in the container.

Container surface temperatures were estimated versus fuel assembly decay times for various ambient temperatures (0.6, 21 and 40°C [33, 70 and 104°F]) and container locations (top, middle, bottom; see Figure 2-8). Assuming that 24 fuel assemblies decay for 13.5 years (decay heat load of approximately 600 watts per fuel assembly) before being placed in the storage container, the average surface temperature at the middle of the container between 13.5 and 100 years is estimated to be approximately 90°C (194°F), if an ambient temperature of 21°C (70°F) is assumed. Total ranges in surface temperature are from 149°C (300°F) (container top at 13.5
years with an ambient temperature of 40°C (104°F) to 41°C (106°F) (container bottom at 100 years with an ambient temperature of 0.6°C [33°F]).

The average surface temperature of 90°C (194°F) noted above is adopted in the geochemical model. Selection of alternative model temperatures from within the full estimated range of approximately 40 and 150°C (70 and 302°F) would not significantly affect the main conclusions of this study (see Section 2.3.3).

**Gas phase composition.** The spent fuel storage canister system is assumed to be an open thermodynamic system with respect to gas mass transfer between moisture evaporating on container surfaces and coolant air circulating through this system (Figure 2-8). The gases affected by this assumption include CO$_2$(g), HCl(g), NH$_3$(g) and HNO$_3$(g). This assumption constrains the partial pressure of any one of these gases within the storage cask and in the ambient air outside the storage cask to always be equal. This constraint can be justified because air is likely to advect rapidly through the storage casks and can thus be replenished by an essentially infinite volume of ambient air outside the casks. A bounding, but probably less realistic, alternative to this assumption would be to consider storage casks as closed systems, in which case the partial pressures of the model gases would be free to increase as moisture on container surfaces evaporates. This alternative assumption could significantly impact conclusions drawn from the present study for reasons discussed in Section 2.3.3, but is not considered further here.

### 2.2.2 Numerical Model

The conceptual model described above was evaluated using the EQ3/6 (version 8.0) geochemical modeling software package [26] and a supporting thermodynamic database (data0.ypf, version 1.0) that is compatible with the Pitzer formalism for calculation of activity coefficients in concentrated brines. The modeling approach used is essentially identical to the In-Drift Precipitates/Salts (IDPS) model developed by the U.S. Department of Energy to simulate the evaporative chemical evolution of seepage waters entering drifts at the proposed nuclear-waste repository at Yucca Mountain, Nevada. The IDPS model is described in detail [27] and the model results for seepage waters at Yucca Mountain are available [28, 29]. Key modifications to the IDPS model that were adopted in the present study are described below.

The water analyses in Table 2-1 include concentrations for nitrogen in two oxidation states: N(-3), as the ammonium ion NH$_4^+$, and N(+5), as NO$_3^-$. It is unlikely that these forms of dissolved N are in redox equilibrium, however, because the kinetics of the oxidation-reduction reaction appears to be too slow to reach equilibrium under conditions typical of most natural waters at relatively low temperatures [30, 31, 32].

To account for this likely state of redox disequilibrium involving nitrogen species, it is assumed in the modified IDPS model that disequilibrium is preserved during evaporation. This constraint is implemented in the model by fixing the partial pressures of NH$_3$(g) and HNO$_3$(g) at values in ambient air equilibrated with each initial water analysis. This in effect controls the partial pressure of O$_2$(g) through the NH$_4^+$/NO$_3^-$ half-cell reaction. Calculated $p_{O_2(g)}$ values using this
constraint generally vary during an evaporation simulation between about 10^{-20} to 10^{-25} bar. Although this is unrealistic given that the partial pressure of O_2(g) in ambient air is about 10^{-0.7} bar, the calculated \( p_{O_2(g)} \) values are still sufficiently oxidizing that other redox-sensitive species considered in the model, notably SO_4^{2-}, do not change oxidation state during the simulations.

The thermodynamic database supporting the IDPS model does not include data for NH_3(g).

Equilibrium constants for the reaction:

\[
\text{NH}_3(g) + H^+ = \text{NH}_4^+
\]

at temperatures between 0 and 300°C (32 and 572°F) were therefore included in a revised version of this database. These data are taken at face value from data0.ymp.R2, which is an alternative database included with the EQ3/6 software package^{33}.

The IDPS model considers a suite of minerals that are believed to be realistic and representative of solids that could precipitate from natural waters during evaporation. Three additional minerals are added to this set in the revised IDPS model: sal ammoniac (NH_4Cl), mascagnite [(NH_4)_2SO_4] and magnesite (MgCO_3). The first two minerals are considered because NH_4^+ is an important constituent of fogwaters, cloudwaters and rainwaters (Table 2-1). These minerals did not precipitate in any of the simulations, however. Magnesite is included because initial simulations indicated that this mineral would likely precipitate during evaporation of the waters considered in this study and because magnesite is commonly observed in mineral deposits formed by the evaporation of natural waters^{34}. Magnesium concentrations may more likely be controlled by sepiolite (a magnesium silicate), but this possibility cannot be evaluated in the present study because none of the analyses in Table 2-1 include data on dissolved Si concentrations. The minerals considered in the revised IDPS model are listed in Table 2-3.

The small charge imbalances in the selected water analyses noted in Section 2.1 were corrected by adjusting the concentration of Na⁺ until charge balance was achieved. In a few cases where this was not possible, i.e., because the Na⁺ concentrations could not be lowered sufficiently, charge balance was achieved by increasing the concentration of Cl⁻. This is a conservative assumption because it tends to increase Cl⁻ concentrations in evaporated solutions, and because Cl⁻ is expected to increase the susceptibility of steel containers to SCC.

The evaporation simulations were carried out for a reference starting mass (assumed in EQ3/6) of 1 kg H_2O for each solution considered. The reaction paths were terminated either when the solutions were evaporated essentially to complete dryness, i.e., when only about 1 – 10 mg of H_2O(l) remained, or when the calculations failed because the evaporated solutions became too concentrated (this usually occurs when total ionic concentrations are greater than about 15 – 20 molal).
## Table 2-3
Minerals Considered in the Revised IDPS Model

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Composition</th>
<th>Mineral Name</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite</td>
<td>CaCO₃</td>
<td>Anhydrite</td>
<td>CaSO₄</td>
</tr>
<tr>
<td>SiO₂(am)</td>
<td>SiO₂</td>
<td>Natrite</td>
<td>Na₂CO₃</td>
</tr>
<tr>
<td>Fluorite</td>
<td>CaF₂</td>
<td>Trona</td>
<td>Na₃(HCO₃)₂·2H₂O</td>
</tr>
<tr>
<td>Sepiolite</td>
<td>Mg₅Si₄O₁₅(OH)₆·6H₂O</td>
<td>Burkeite</td>
<td>Na₂CO₃(SO₄)₂</td>
</tr>
<tr>
<td>Celadonite</td>
<td>KMgAlSi₄O₁₀(OH)₂</td>
<td>Stellerite</td>
<td>Ca₂Al₄Si₁₄O₃₆·14H₂O</td>
</tr>
<tr>
<td>Thenardite</td>
<td>Na₂SO₄</td>
<td>Phillipsite</td>
<td>K₆Na₉Ca₅Al₄Si₁₃O₃₆·12.6H₂O</td>
</tr>
<tr>
<td>Halite</td>
<td>NaCl</td>
<td>Kieserite</td>
<td>MgSO₄·H₂O</td>
</tr>
<tr>
<td>Huntite</td>
<td>CaMg₃(CO₃)₄</td>
<td>Erionite</td>
<td>K₁₅Na₉Ca₅Al₄Si₁₃O₃₆·13H₂O</td>
</tr>
<tr>
<td>Sellaite</td>
<td>MgF₂</td>
<td>Ca(NO₃)₂</td>
<td>Ca(NO₃)₂</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO₄·2H₂O</td>
<td>Ca(NO₃)₂·3H₂O</td>
<td>Ca(NO₃)₂·3H₂O</td>
</tr>
<tr>
<td>Glauberite</td>
<td>Na₂Ca(SO₄)₂</td>
<td>Ca(NO₃)₂·4H₂O</td>
<td>Ca(NO₃)₂·4H₂O</td>
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<tr>
<td>Niter</td>
<td>KNO₃</td>
<td>Nahcolite</td>
<td>NaHCO₃</td>
</tr>
<tr>
<td>Sylvite</td>
<td>KCl</td>
<td>Pirssonite</td>
<td>Na₂Ca(CO₃)₂·2H₂O</td>
</tr>
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<td>Cryolite</td>
<td>Na₂AlF₆</td>
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<td>Soda Niter</td>
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<td>Carnallite</td>
<td>KMgCl₃·6H₂O</td>
<td>Mascagnite</td>
<td>(NH₄)₂SO₄</td>
</tr>
<tr>
<td>Pentasalt</td>
<td>K₂Ca₃(SO₄)₂·H₂O</td>
<td>Magnesite</td>
<td>MgCO₃</td>
</tr>
<tr>
<td>Syngenite</td>
<td>K₂Ca(SO₄)₂·H₂O</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2.2.3 Natural Analogues

It is not possible to test the reliability of the conceptual and numerical models discussed above because relevant experimental data appears to be unavailable. However, certain pedogenic salts in the Atacama Desert of northern Chile appear to form by processes that closely approximate those controlling the possible evaporative concentration of aqueous aerosols in ISFSI storage casks. The landscape of the Atacama is exceptionally stable and has not changed significantly since about the mid-Miocene (≈ 15 Ma)\textsuperscript{[35]} It is also the driest desert on Earth. These conditions are optimal for the accumulation and preservation of relatively thick deposits of highly soluble salts [including mainly gypsum (CaSO\textsubscript{4}·2H\textsubscript{2}O), anhydrite (CaSO\textsubscript{4}) and halite (NaCl)]. A recent study of sulfur- and strontium-isotope signatures in these minerals at locations within 90 km (56 miles) of the coast at elevations less than 1300 m (4265 ft) indicate a strong marine influence, suggesting that these minerals precipitate from marine fog as it penetrates inland and evaporates\textsuperscript{[36]}. The model described above could in principle be used to test this genetic model of soil-salt formation, provided reasonably detailed data are available characterizing salt mineralogy and the chemistry of local clouds and fogs\textsuperscript{[37]}. If successful, this would help build confidence that the model can be used to reliably predict changes in aerosol chemistry that could occur on the surfaces of spent-fuel containers.

2.3 Model Results

Results of the evaporation simulations for most of the starting water compositions in Table 2-1 are considered below with a focus on maximum Cl\textsuperscript{−} concentrations because of chlorides effect on the SCC of austenitic stainless steels\textsuperscript{1}. However, “threshold” SCC values for these parameters are somewhat uncertain.

2.3.1 Summary of Maximum Chloride Concentrations

Figure 2-10 shows a histogram of maximum Cl\textsuperscript{−} concentrations predicted in the evaporation simulations. The distribution is clearly bimodal with one group having relatively high-Cl\textsuperscript{−} concentrations between 10\textsuperscript{−6} and 10\textsuperscript{−2.5} molal and a second group having maximum Cl\textsuperscript{−} concentrations less than about 10\textsuperscript{−4} molal. The high-Cl waters are all highly evaporated. Chloride concentrations shown in the figure for these waters are produced at the final stages of evaporation when only a few mg of solution remain. In contrast, all of the low-Cl waters are completely unevaporated, i.e., Cl\textsuperscript{−} concentrations decrease continuously in these solutions as evaporation proceeds and initial concentrations are therefore equal to maximum concentrations.

\textsuperscript{1} Simulations were not attempted for North Carolina (Mt. Mitchell) samples 49-51, 80-82, 84 and 86-90 because the analyses are incomplete and/or because the authors of the respective studies from which these analyses were obtained concluded that the orographic cloudwaters were formed largely by polluted-continental, i.e., non-marine, air masses.
Figure 2-11 illustrates variations in pH with maximum Cl values in the high-Cl group of evaporated waters. As can be seen, these solutions are all near-neutral to moderately alkaline (neutral pH at the container’s surface temperature of 90°C [194°F] ≈ 5.6) The highest predicted Cl concentrations in this group are about 4 molal (≈ 141,000 mg/kg-H₂O), which is approximately 7.5 times the Cl content of seawater. Although there is some uncertainty in threshold values for Cl to induce SCC of austenitic stainless steels, there seems to be little doubt that at least some of these high-Cl waters would have sufficient Cl and would be sufficiently non-alkaline for this to occur. In contrast, none of the low-Cl waters would likely be capable of inducing such SCC of steel containers based on this criterion alone.

![Histogram of Maximum Cl Concentrations Predicted in the Evaporation Simulations](image)

**Figure 2-10**
Histogram of Maximum Cl Concentrations Predicted in the Evaporation Simulations (Hatched patterns indicate that the initial solution is rainwater; cross-hatched patterns indicate that the initial solution is fogwater or cloudwater.)
It is interesting to note that both rainwaters and fogwaters/cloudwaters fall into the high- and low-Cl groups shown in Figure 2-10. The most highly concentrated Cl solutions are generated only by evaporation of the latter solutions, however. This suggests that these aqueous aerosols are likely to be the most aggressive with respect to SCC of stainless steels because they tend to have higher initial Cl concentrations compared to rainwaters. The atmospheric-chemical processes controlling the local and regional compositions of fogs and clouds discussed in Section 2.1 may thus have an important influence on the SCC propensity of austenitic stainless steel spent fuel storage canisters at each ISFSI facility.

There are distinct trends in the geographic distribution of the high-Cl and low-Cl categories of evaporated solutions. All of the starting fogwaters and cloudwaters in Washington and Oregon evolve into high-Cl solutions. This is also true of rainwater samples from North and South Carolina, which may be representative of conditions at the Kure Beach reference site. All rainwaters from the selected NADP sites in Florida except sample 126 (Table 2-1) evolve into high-Cl solutions. Rainwaters from the northeastern NADP sites and fogwaters sampled at Rye, New Hampshire evolve either into high-Cl solutions (samples 44, 45, 46, 48, 100, 101, 103, 104-107, 112, 113, 115, 116, 119 and 128; Table 2-1) or low-Cl solutions (samples 43, 47, 102, 108-111, 114, 117, 118, and 129-131; Table 2-1) depending on the season, or, in the case of the fogwater samples, on time during the sampling day. All of the California fogwater and cloudwater samples evolve into low-Cl solutions, except samples 2, 3, 17, 19, 20, 27, 61, 49-51, 54-56 and 79 (Table 2-1). It is noteworthy that, as is the case for the Rye fogwaters, initial
solutions producing both high-Cl and low-Cl evaporated solutions are sampled from the same location at some of the California sites.

### 2.3.2 Description of Evaporation Reaction Paths

Both the high-Cl and low-Cl categories of evaporated solutions described in Section 2.3.1 evolve along distinctly different reaction pathways that are generally characteristic of each group. Representative examples of each of these reaction-path types are described below.

Cloudwater from Cheeka Peak, Washington (sample 1, Table 2-1) evolves into a high-Cl water. Figure 2-12 shows calculated variations in anion concentrations, cation concentrations and pH as this solution evaporates at 90°C (194°F). This reaction path ends when all but 3.5 mg of the original 1 kg mass of H$_2$O$_{(l)}$ remains unevaporated. At this stage, the water activity, $a_w$, which is equivalent to relative humidity, is about 80%. As can be seen in the figure, evaporation eventually causes the molalities of all the anions, especially HCO$_3$-$, CO_3^{2-}, SO_4^{2-}$ and Cl$^-$, to increase strongly. Carbonate concentrations increase because it is assumed in the model (Section 2.2.1) that the evaporating liquid remains in equilibrium with ambient air ($p_{CO_2(g)}$ ≈ 10$^{-3.5}$ bar) and because the evolving solution becomes steadily more alkaline. Sodium and K$^+$ concentrations also increase as evaporation proceeds, but those for Ca$^{2+}, Mg^{2+}, NH_4^+$ (not shown) and H$^+$ decrease. After 50.443 moles H$_2$O$_{(l)}$ evaporates, a sequence of minerals precipitates with continued evaporation in the order: 1) magnesite; 2) magnesite + calcite; 3) magnesite + calcite + natrite; 4) magnesite + calcite + nitrite + thenardite; 5) magnesite + calcite + natrite + thenardite + arcanite. The initially dilute Cheeka Peak cloudwater thus evolves into a concentrated Na-K-carbonate-SO$_4$-Cl brine.
Figure 2-12
Evolution of Anions (a), Cations (b) and pH (c) during Evaporation of Cheeka Peak Cloudwater (Sample No. 1, Table 2-1)
Fogwater from Rye Beach, New Hampshire (sample 43, Table 2-1) evolves into a low-Cl water. Figure 2-13 is analogous for this reaction path to that shown in Figure 2-11. The simulation fails when all but 1.7 mg of the original 1 kg mass of H₂O(l) remains unevaporated. At this stage \( a_w = 61\% \). Evaporation eventually causes \( \text{SO}_4^{2-} \) molalities to increase strongly while those for carbonate, \( \text{Cl}^- \) and \( \text{NO}_3^- \) (not shown) decrease. The latter anions are lost from solution as it becomes increasingly more acidic because this stimulates formation and exsolution of the corresponding acid gases \( \text{CO}_2(g) \), \( \text{HCl}(g) \) and \( \text{HNO}_3(g) \). Note that some caution is advised when interpreting the pH of concentrated, acidic brines [2-11], but that the evaporated fluid is acidic by any measure because \( \text{H}^+ \) molalities reach levels around 0.01 molal. Sodium and K⁺ concentrations increase monotonically as evaporation proceeds, while those for \( \text{Ca}^{2+}, \text{Mg}^{2+} \) and \( \text{NH}_4^+ \) either increase or decrease depending on the extent of evaporation. After evaporation of about 55.36 moles H₂O(l), a sequence of minerals precipitates with continued evaporation in the order: 1) anhydrite; 2) anhydrite + glauberite; 3) glauberite; 4) glauberite + thenardite; 5) glauberite + thenardite + kieserite. This sample of Rye Beach fogwater thus evolves into a concentrated Na-H-K-SO₄ brine.
Figure 2-13
Evolution of Anions (a), Cations (b) and pH (c) during Evaporation of Rye Beach Fogwater
(Sample No. 43, Table 2-1)
2.3.3 Interpretation: The HCl(g) Chemical Divide

The bimodal nature of the distribution noted in Section 2.3.1 between high-Cl and low-Cl waters suggests that these groupings are generated by a “chemical divide.” The chemical divide concept was proposed more than 30 years ago to generalize geochemical processes controlling the evaporation of natural waters\(^{38,39}\). It asserts that whenever a binary salt is precipitated during evaporation, and the ratio of the two ions in the salt differs from the concentration ratio of these ions in solution, further evaporation will result in an increase in the concentration of the ion present in greater relative concentration in solution, and a decrease in the concentration of the ion present in lower relative concentration\(^{40}\). Thus, of any two ions involved in the precipitation of a salt during evaporation, the concentration of one must increase and the concentration of the other must decrease. The only exception to this rule is when the concentration ratio of the ions in solution exactly matches their ratio in the salt. In such cases the concentrations of both ions in solution will decrease by an equivalent amount as evaporation proceeds and the salt precipitates. An instructive example of a classical chemical divide involving the evaporite mineral gypsum (CaSO\(_4\cdot2\)H\(_2\)O) is discussed below\(^{40}\).

It is assumed in this example that a solution equilibrated with gypsum has \(m_{\text{Ca}^{2+}} = 2m_{\text{SO}_4^{2-}}\). Neglecting activity coefficients, the corresponding mass-action expression for the reaction CaSO\(_4\cdot2\)H\(_2\)O = Ca\(^{2+}\) + SO\(_4^{2-}\) + 2H\(_2\)O(l) is given by:

\[
K_{\text{sp}} = m_{\text{Ca}^{2+}} m_{\text{SO}_4^{2-}}
\]

where \(K_{\text{sp}}\) stands for the solubility product and where it is assumed that the activity of the solid and of H\(_2\)O(l) are equal to unity\(^2\). Assuming a value for \(K_{\text{sp}} = 10^{-4.61}\):

\[
m_{\text{Ca}^{2+}} = 7.0 \times 10^{-3}, \text{ and}
\]

\[
m_{\text{SO}_4^{2-}} = 3.5 \times 10^{-3}
\]

It is assumed that this initial solution evaporates until the mass of remaining water is equal to \(1/n\) of the original amount, where \(n\) represents a concentration factor\(^{40}\). During evaporation \(y\) moles of gypsum per kilogram of the initial water are assumed to precipitate. The concentrations of Ca\(^{2+}\) and SO\(_4^{2-}\) are then given by:

\[
m_{\text{Ca}^{2+}} = n(7.0 \times 10^{-3} - y), \text{ and}
\]

\[
m_{\text{SO}_4^{2-}} = n(3.5 \times 10^{-3} - y).
\]

\(^2\) This may not be a valid assumption for H\(_2\)O(l) in highly concentrated brines, but is adopted to simplify the discussion\(^{40}\).
Because the evaporated solution remains in equilibrium with gypsum, Equation (2-1) can be represented by:

$$K_{SP} = 10^{-4.61} = n^2 (7.0 \times 10^{-3} - y)(3.5 \times 10^{-3} - y).$$

This quadratic equation is then solved for $y$ as a function of $n$, and results are back-substituted into Equations (2-2) and (2-3) to solve for corresponding values of $m_{Ca^{2+}}$ and $m_{SO_4^{2-}}$. The results of these calculations are in accordance with the chemical divide concept and confirm that the concentration of $Ca^{2+}$, the ion in greater relative concentration in the initial solution, increases during evaporation and that the concentration of $SO_4^{-2}$ simultaneously decreases.$^{[40]}$

The results of the present study, summarized in Sections 2.3.1 and 2.3.2, can be interpreted in terms of the chemical-divide concept by considering the equilibrium mass transfer of HCl between an evaporating liquid and a coexisting gas phase. The relevant reaction is:

$$HCl(g) = H^+ + Cl^-,$$

for which the corresponding mass-action expression is given by

$$K = \frac{m_{H^+}m_{Cl^-}}{P_{HCl(g)}} \quad (2-4)$$

In this equation $K$ represents the equilibrium constant for the reaction and activity coefficients and fugacity coefficients are again neglected to simplify the discussion. Equation (2-4) can be rearranged to give:

$$Kp_{HCl(g)} = m_{H^+}m_{Cl^-} \quad (2-5)$$

The product on the left-hand side of this equation is fixed at a given temperature because it has been assumed in the geochemical model that the partial pressure of $HCl(g)$ is fixed at the value in ambient air at a given ISFSI facility (Section 2.2.1). Equation (2-5) is thus analogous to the example discussed above for gypsum (Equation 2-1) and is completely consistent with the chemical divide concept. This is because it represents the equilibrium mass transfer of two chemical constituents between two phases (in this case gas and liquid rather than mineral and liquid) and because the proportion of the constituents in one phase is fixed by stoichiometric constraints, i.e., $HCl(g)$ in this case rather than $CaSO_4\cdot 2H_2O$. This suggests that evaporating aqueous aerosols on container surfaces at ISFSI facilities will evolve either into high-Cl or low-Cl/high-$H^+$ solutions depending on the initial ratios of $H^+$ to $Cl^-$ in the initial solution.

This prediction is tested in Figure 2-14, where maximum $Cl^-$ concentrations (see Section 2.3.1) are plotted versus equivalent ratios of $H^+$ to $Cl^-$ in the starting fogwaters, cloudwaters and rainwaters shown in Table 2-1. The chemical-divide concept predicts that high-Cl waters should evolve from starting solutions in which the $H^+/Cl^-$ ratio is less than 1 because this value corresponds to the stoichiometric ratio of these ions in $HCl(g)$. This prediction is generally
confirmed in Figure 2-14, but there are a few exceptions. The exceptions occur because the H+/Cl\(^-\) ratios are computed from the initial solution compositions listed in Table 2-1 rather than from the corresponding ratios of these ions when the starting solutions are assumed to be initially heated to 90°C (194°F), i.e., when they are assumed to impinge on container surfaces. This initial heating step causes gas species to partially exsolve from the liquid into the gas phase and this affects the H+/Cl\(^-\) ratio in the heated solution prior to any evaporation. The fact that there are few exceptions to the chemical-divide prediction, as shown in Figure 2-14, suggests that these heating effects are generally small and that predictions using the HCl(g) chemical-divide model can be reasonably approximated based on the chemistry of fogwaters, cloudwaters and rainwaters at ambient temperatures.

![Figure 2-14](image)

**Figure 2-14**

Plot of Maximum Cl\(^-\) Concentrations in Evaporated Solutions versus Equivalent Ratios of H\(^+\) to Cl\(^-\) in Fogwaters, Cloudwaters and Rainwaters

This is a useful result because it can be used to gain some insights as to whether local environments at ISFSI facilities are likely to be corrosive or benign with respect to SCC of the steel containers. Figure 2-15 indicates, for example, that the acidity of solutions that are assumed here to be representative of aqueous aerosols at these sites is closely correlated with the concentrations of SO\(_4\)\(^2-\) and NO\(_3\)\(^-\). As noted in Section 2-1, high concentrations of these ions appear to result from the photooxidation of atmospheric pollutants, including primarily SO\(_2\)(g) and NO\(_x\)(g). This suggests that aqueous aerosols in polluted areas may be less likely to be corrosive with respect to Cl\(^-\) induced SCC of steel containers because these relatively acidic solutions are more likely to have H+/Cl\(^-\) equivalent ratios > 1, and because evaporation would therefore generate solutions having low Cl contents. However, pristine marine aerosols may be corrosive because they are more likely to be less acidic, to have higher proportions of sea-salt aerosols and, therefore, to have H+/Cl\(^-\) ratios < 1. Evaporation of these solutions would generate...
brines having high Cl contents, and could therefore induce SCC of the austenitic stainless steel spent fuel storage canisters.

![Figure 2-15]
**Figure 2-15**
Correlation between pH and Concentrations of SO₄²⁻ (open symbols) and NO₃⁻ (solid symbols) in Coastal Fogwaters, Cloudwaters and Rainwaters

### 2.4 Conclusions and Recommendations

A geochemical modeling approach has been used in this study to assess whether aqueous aerosols at operating and contracted ISFSI facilities in the United States could evolve into corrosive solutions as they evaporate on the surfaces of containers used to isolate spent nuclear fuel from the biosphere. Data characterizing the aqueous chemical compositions of fogs, clouds and rain in coastal regions of the country are assumed to be representative of the chemistry of aqueous aerosols that could exist at these ISFSI sites. Results are interpreted in terms of predicted chloride concentrations in the evaporated solutions because this anion is known to increase the propensity for SCC to occur in austenitic stainless steels that are used to fabricate the spent fuel storage canisters.

The conclusions of this study are as follows:

1. The initial fogwaters, cloudwaters and rainwaters evolve into two groups as they evaporate: 1) neutral-to-alkaline solutions containing high Cl⁻ concentrations \(10^{0.6} - 10^{-2.5} \text{ m}\), and 2) acidic solutions containing low Cl⁻ concentrations \(<10^{-2} \text{ m}\). It is possible that the high-Cl waters could induce SCC of spent-fuel containers. This seems unlikely for the low-Cl waters. The highest predicted Cl⁻ concentration is about 7.5 times that of seawater.
Corrosivity of Aqueous Aerosols at Spent Fuel Storage Canister Installations

2. The distinctly bimodal distribution of model results with respect to Cl is consistent with a chemical divide involving the equilibrium partitioning of HCl(g) between the evaporating liquid and coexisting gas phase. For this reason high-Cl waters tend to evolve from initial solutions having \( \text{H}^+/\text{Cl}^- \) equivalent ratios < 1. Low-Cl waters tend to evolve from initial solutions having \( \text{H}^+/\text{Cl}^- \) equivalent ratios > 1.

3. Aqueous aerosols in polluted air may be less corrosive with respect to SCC of steel containers than their counterparts in pristine marine air. This is because \textit{in-situ} oxidation of primary pollutants, including SO\(_2\)(g), dimethylsulfide and NO\(_x\)(g), tends to increase the acidity of these solutions and may thus cause them to have \( \text{H}^+/\text{Cl}^- > 1 \).

4. Based on current understanding of physical, transport/mixing and chemical processes controlling the chemistry of fogs and clouds, it is possible that the compositions of aqueous aerosols at a given ISFSI location could vary considerably over timescales as short as minutes to days. The present modeling results suggest that these variations could be of sufficient magnitude to cause the corresponding evaporated brines to vary in character between corrosive and non-corrosive conditions, i.e., by generating high-Cl versus low-Cl solutions. Such time-dependent chemical variations should be considered in any classification scheme assessing the corrosivity of these sites on the basis of climatic variables.

It should be emphasized that these results are based on a number of assumptions that are believed to be reasonable, but which are largely untested. It is therefore recommended that the modeling approach developed in this study be evaluated in relation to any existing and relevant experimental studies and observations from natural systems (e.g., Atacama pedogenic salts). Additional features and processes not presently considered in the model could also significantly affect the types of fluids produced by evaporation. The possible formation of deliquescence brines by particulate aerosols and the interaction of evaporating solutions with other minerals (e.g., carbonates and silicates) that could exist as dusts coating container surfaces should be considered with high priority in future revisions and refinements to the present modeling approach. It is also important to note that there is presently a complete lack of baseline data characterizing the chemistry of aqueous and particulate aerosols at any of the operating and contracted ISFSI sites. Field studies to obtain such data are recommended.
3
SURFACE TEMPERATURE VS. TIME PROFILES OF SPENT FUEL CANISTERS

3.1 Introduction

As discussed in Reference 1, the susceptibility of spent fuel canister stainless steel to SCC in a marine atmosphere environment is partially dependent on the surface temperature of the canister. The primary variables that determine canister surface temperature over time are the heat load from the spent fuel, the heat transfer rate from the fuel to the canister surface and the heat transfer rate from the canister surface to the atmosphere. The heat load from the spent fuel is primarily a function of the fuel initial uranium loading, power history in the reactor, time after discharge from the reactor and the number of spent fuel assemblies in the canister.

Two canister vendors were contacted to obtain canister surface temperature vs. time data for typical canister spent fuel loadings. Normally, the only surface temperature data required for the canister design and licensing are the maximum temperatures for various design conditions since the temperature will decrease over time and, therefore, result in a decreasing thermal design challenge over the life of the loaded canister. Thus, canister surface temperature vs. time data is not readily available from canister design calculations or in licensing reports. Such data has to be extracted from canister thermal calculations. Since extraction of such data is beyond the scope of this project, the only data available from the vendors was some example data that was extracted for other reasons. This section of the report presents the example data from one of vendors and some general information from the other vendor.

3.2 Canister Surface Temperature Data

Figure 3-1 is a plot of canister surface temperature vs. fuel assembly decay in years, for various ambient temperature conditions and locations on the canister. This data is based on an assumed decay heat load of 1000 watts per fuel assembly for 24 assemblies, corresponding to a decay time of 2.45 years. The initial surface temperature ranges from 192 to 145°C (377 to 293°F), depending on the assumed ambient temperature conditions. Assuming that the fuel assemblies decay for 13.5 years (decay heat load of approximately 600 watts per fuel assembly) before being placed in the storage canister, the initial surface temperature at the beginning of the storage period, in this example ranges from approximately 93 to 149°C (200 to 300°F), depending on the assumed ambient temperature conditions.
Surface Temperature vs. Time Profiles of Spent Fuel Canisters

Figure 3-1
Example of Canister Surface Temperature vs. Time
Information obtained from the second vendor is consistent with the above example in that the reported initial canister surface temperatures for design basis fuel are in the range of 177 to 235 ºC (351 to 455°F), depending on the canister design. The canister design heat loads have been increasing as the technology advances resulting in higher initial canister surface temperatures for the same atmospheric conditions.

The above example is more typical of earlier designs, however, it illustrates the type of surface temperature regime and temperature decay rates that can be expected for spent fuel storage canisters when evaluating their susceptibility for SCC in a marine atmosphere environment. Canister surface temperature vs. time data for specific applications would have to be determined using actual canister heat loads and atmospheric conditions.
4

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A

ATMOSPHERIC CORROSION MODELING

A.1 Introduction

Albeit this appendix provides no specific information relative to the possible SCC of austenitic stainless steel at ISFSIs, it does provide some background on modeling of atmospheric corrosion. These general corrosion models of basic materials of construction, which do not include stainless steels, include the effects of temperature, relative humidity, sulfur dioxide and chloride deposition.

The concern for atmospheric corrosion stimulated an ongoing need to better understand the kinetics of atmospheric corrosion for engineering metals. As a consequence of these concerns, the International Organization for Standardization (ISO) identified atmospheric corrosion as a priority action area at the organizational meeting of Technical Committee TC 156 in Riga, Latvia in 1976[A-1]. At the second plenary meeting of this committee in Boras, Sweden in 1978, it was decided to form a working group to develop standards addressing the classification of atmospheric corrosivity. This working group, under the leadership of the Czech delegation, produced four standards: ISO 9223, 9224, 9225, and 9226[A-1].

The system of atmospheric corrosivity classification was based on Czech national standards, and data used to develop this system came from a relatively small number of locations. Because the ISO standards are used worldwide, it was decided to conduct a worldwide exposure program to obtain atmospheric corrosion data together with pollution and weather data to verify the applicability of the ISO classification system. This exposure program was finalized in 1986 and titled the ISO CORRAG program. ASTM Committee g1 on the Corrosion of Metals assumed responsibility for this program in the USA with joint oversight responsibility in subcommittee G01.04 on Atmospheric Corrosion Testing and standing subcommittee g01.95, the TAG for ISO/TC156. A report on the initiation of exposures was published in ASTM STP 965[A-1, A-2].

A.2 International Atmospheric Corrosion Exposure Programs

Atmospheric corrosion site tests have been performed for many decades, either as tests on basic types of materials in a limited network of testing sites or as tests designed to define corrosion mitigation techniques[A-1]. More general application of the results of these studies have been limited because of comparability problems with the test materials, different methodologies of monitoring environmental factors and evaluation of corrosion rates and limited regional validity.

The first test site program of a global-scale was a 12-year program initiated in 1968 that focused on the assessment of general corrosion on basic structural metals, including monitoring climatic
Atmospheric Corrosion Modeling

factors and pollutions at 19 sites in the industrial area of Northern Bohemia\textsuperscript{[A-3, A-4]}. The regional spread of pollution and corrosion effects was worked into a corrosivity map, which also covered basic classification criteria of corrosivity. These were later established by an International Organization of Standardization (ISO) standard\textsuperscript{[A-3, A-5]}.

A.3 International Atmospheric Corrosion Programs – ISO CORRAG and MICAT

The development of international cooperation in the field of atmospheric corrosion was facilitated by the creation of ISO standards within the program ISO/TC 156/WG 4, “Classification of Atmospheric Corrosivity.” The goal of the ISO CORRAG program was to verify and further develop principles and methods for the derivation of atmospheric corrosivity as defined in ISO standards 9223 through 9226. At the same time the program was designed to provide data on atmospheric corrosivity in an extensive number of regions. This activity stimulated the foundation of another extensive international program called MICAT, the methodology of which is fully in accord with the ISO CORRAG program. The program was carried out in Iberoamerican countries (South America, Spain, Portugal, 72 sites, 14 countries). Databases of both programs were later unified and now provide a huge amount of information with a broad spectrum of climatic and pollution conditions.

Large databases of the ISO CORRAG and Iberoamerican Atmospheric Corrosion Map Project (MICAT) results were used for extensive statistical treatments performed in international cooperation. A few limited examples can illustrate this activity:

1. Characterization of the integrated ISO CORRAG/MICAT set of data
2. Regression analyses performed on one year results for flat and helix standard specimens
3. Derivation of “damage functions” (one year exposures) applicable for corrosivity estimation
4. Derivation of damage functions (long-term exposures) applicable for the calculation of steady state corrosion rates and guiding corrosion rates

Integrated data (six repeated one year exposures, eight years of exposure) conformed to most of the demands of the ISO corrosivity classification system. For derivation of dose/response (D/R) functions this database has been extended to include Russian sites from cold regions, which allowed the temperature effect on atmospheric corrosion to be expressed. Extensive statistical elaborations of the program results were aimed mainly at the evaluation of observed parameters for the kinetics of the corrosion process and lead to the derivation of the D/R functions.

The D/R functions are based on data (e.g., classification criteria, corrosion rates, time of wetness [TOW], deposition rates for sulfur dioxide and chloride) for one year exposures and can, therefore, only be used for corrosivity classification purposes. The R values are between 0.8 and 0.9, except for aluminum, in which case it is substantially lower. Aluminum experiences localized corrosion, but the corrosion attack is calculated as uniform corrosion.
For illustration purposes only, the D/R function for carbon steel is as follows:

\[ C_{ST} = 0.085 \times \text{SO}^{0.56} \times \text{TOW}^{0.53} \times \exp\{f_{ST}\} + 0.24 \times \text{Cl}^{0.47} \times \text{TOW}^{0.25} \times \exp\{0.049T\} \]

\[ f_{ST}(T) = 0.98(T-10) \] when \( T \geq 10^\circ C \), otherwise \( f_{ST}(T) = -0.087(T-10) \)

The D/R functions are derived for flat specimens only. The premise of comparable corrosion results received with the flat and helix standard specimens, Figure A-1, was not verified as valid within the ISO CORRAG program. The helix specimen corrosion rates are approximately twice as high as those for flat specimens\(^{[A-6]}\). The variability of evaluated corrosion rates of replicate helix specimens was also significantly higher.

The kinetic model widely used for atmospheric corrosion was applied for the calculation of long-term corrosion rates\(^{[A-3, A-7]}\):

\[ ML = aT^b \]

\[ \log(ML) = \log a + b \log T \]

where \( ML \) is the mass loss per unit area, \( T \) is exposure duration (years), \( a \) is the mass loss per unit area in one year, and \( b \) is the time exponent (usually less than one).

After “Convention on Long-Range Transboundary Air Pollution within United Nations/Economic Commission for Europe (UN ECE)” program was adopted in 1979, many international testing programs for the determination of effects of atmospheric pollution on various ecosystem components were initiated. The deterioration of materials is one of the significant effects of atmospheric pollution; therefore, the preparation of the International Cooperative Program (ICP) testing program, focused on the effects of air pollution on materials including historic and cultural monuments, was initiated in 1985. The program started in 1987 and is currently in its second stage (38 sites, mostly in Europe, the United States, Canada, and later in Israel).

The main objective of the program is to observe the effects of sulfurous atmospheric pollution with NOx and other pollutants and to observe their climatic effects on materials. Compared to a previous program, this program is based on more demanding methodology; the specimens are exposed both with and without shelter with a greater range of environmental parameters and are dependent on the interdisciplinary use of cooperative ECE programs [A-3, A-8].

The importance of factors was observed using a simple additive model and the contribution of individual environmental factors to experimentally determine corrosion loss was evaluated. The basic result, used within the context of the ICP UN ECE programs, is the derivation of the D/R functions based on an 8-year exposure. These functions, Table A-1, are used mainly for mapping regional effects and can be transformed into functions for the derivation of service life [A-3, A-9].

Table A-1
Summary of Initial Dose/Response Functions for Mapping Regional Effects [A-3, A-9]

<table>
<thead>
<tr>
<th>Material</th>
<th>Dose/Response Function</th>
</tr>
</thead>
</table>
| Weathering Steel | \( \ln(ML) = 3.5 + 0.33\ln(t) + 0.13\ln[SO_2] + 0.020\text{Rh} + f(T) \)  
\( f(T) = 0.059(T-10) \text{ when } T \leq 10\degree C, \quad f(T) = -0.036(T-10) \text{ when } T > 10\degree C \) |
| Zinc and Galvanized Steel | \( ML = 1.4[SO_2]^{0.22}e^{0.018\text{Rh}}e^{t^{0.85}} + 0.029\text{Rain[H]}t \)  
\( f(T) = 0.062(T-10) \text{ when } T \leq 10\degree C, \quad f(T) = -0.021(T-10) \text{ when } T > 10\degree C \) |
| Aluminum | \( ML = 0.0021[SO_2]^{0.23}\text{Rh}e^{t^{1.2}} + 0.000023\text{Rain[Cl]}t \)  
\( f(T) = 0.031(T-10) \text{ when } T \leq 10\degree C, \quad f(T) = -0.061(T-10) \text{ when } T > 10\degree C \) |
| Copper | \( ML = 0.0027[SO_2]^{0.32}[O_3]^{0.32}\text{Rh}e^{t^{0.78}} + 0.050\text{Rain[H]}t^{0.89} \)  
\( f(T) = 0.083(T-10) \text{ when } T \leq 10\degree C, \quad f(T) = -0.032(T-10) \text{ when } T > 10\degree C \) |
| Cast Bronze | \( ML = 0.026[SO_2]^{0.44}\text{Rh}e^{t^{0.88}} + (0.029\text{Rain[H]} + 0.00043\text{Rain[Cl]})t^{0.76} \)  
\( f(T) = 0.060(T-10) \text{ when } T \leq 10\degree C, \quad f(T) = -0.067(T-10) \text{ when } T > 10\degree C \) |

The corrosion attack is expressed as mass loss (ML in g/m²). The environmental parameters are expressed as annual mean averages and are time in years (t), temperature (T in °C), relative humidity (Rh in %), SO2, NO2 and O3 concentration (in μg/m³), amount of precipitation (rain in mm) and H⁺ and Cl⁻ concentration of precipitation (in mg/L).
The effectiveness of the European endeavor to decrease atmospheric pollution can be documented by a decrease in average corrosion rate values at selected sites. A significant decrease in selected regions was worked into maps for the period between 1991 and 2001.

### A.5 European Research Project MULTI-ASSESS

After a significant gradual decrease in sulfurous pollution in Europe, it was necessary to evaluate negative multi-pollutant effects on materials. Therefore, the MULTI-ASSESS project that is conducted within the framework of the programs supported by the European Union (EU) was initiated. This project covers extensive general station tests and targeted corrosion tests on selected important objects of cultural heritage. The model presented in Figure A-2 demonstrates complicated interactions of environmental factors in the process of the atmospheric corrosion of materials [A-3, A-10].

![Figure A-2: Interaction of Atmospheric Pollutants, Meteorological Conditions and Deposition Mechanisms in the Process of Atmospheric Corrosion](image)

Testing programs performed within the framework of the ICP UN ECE and MULTI-ASSESS projects should be evaluated in a context wider than the scope of atmospheric corrosion tests involving territories of countries or continents. Atmospheric environmental effects are assessed in a wide range of environments. The main objective of this program is to cover the quantitative aspects of the process of the atmospheric corrosion of metals and the atmospheric deterioration of other materials.
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D/R functions that quantify the effects of pollutants in combination with climatic parameters on the deterioration of different materials constitute an essential condition for the prediction of damage. The following three general models refer to the development of an approach to evaluate the complex action of the environment on materials:

The model of corrosion used in the ISO classification:

\[ K = K_{dry/wet}(T, RH, SO_2, Cl^-) \]

The present model of corrosion used in the UN ECE/ICP Effects on Materials:

\[ K = K_{dry}(T, RH, SO_2, NO_2, O_3) + K_{wet}(\text{Rain}, H^+) \]

The new model of corrosion used in MULTI-ASSESS

\[ K = K_{dry}(T, RH, SO_2, NO_2, O_3, HNO_3, \text{particulates}) + K_{wet}(\text{Rain}, H^+) \]

The program results and their further comprehensive elaborations broaden not only theoretical knowledge, but are also groundwork for various engineering bases that include European directives and EN and ISO standards.

A.6 Standardization in the Field of Atmospheric Testing and Corrosivity Classification

Atmospheric corrosivity classification is important for the selection of optimal protective systems or as a step in the process of choosing an adequate accelerated testing procedure. Atmospheric corrosivity classification should be based on the understanding of the corrosion process together with a reasonable engineering approach\[4-3\]. Even a well-established corrosivity classification system has some factors that provide limits in the corrosivity system application.

The category of “corrosivity” is related to properties of the corrosion system that can be very complex and involves metal and protective systems, atmospheric environment characterized by climatic and pollution parameters, technical parameters (construction design), conditions of operation, etc. A special working group, WG 4, for atmospheric corrosivity classification was established within ISO/TC 156 “Corrosion of Metals and Alloys,” right after the work on standardization began in 1978 and created in publishing of six international standards.

New, better elaborated D/R functions generally valid for wider regions were developed. The gradual introduction of these functions to the standardized classification system will remove or at least significantly lower the most often criticized disproportion in the derivation of corrosivity of atmospheres from the results of corrosion tests and the knowledge of environmental data.
D/R functions for the calculation of the year corrosion loss of structural metals are as follows:

**Carbon Steel**

\[
r_{\text{CORR}} = 1.77 \times [\text{SO}_2]^{0.52} \times \exp(0.020 \times \text{Rh}) \times \exp(f_{\text{St}}) + 0.102 \times [\text{Cl}]^{0.62} \times \exp(0.033 \times \text{Rh} + 0.040 \times T)
\]

\[f_{\text{St}} = 0.150 \times (T - 10) \text{ when } T \leq 10^\circ\text{C}, \text{ otherwise } = -0.054 \times (T - 10)\]

\[N = 128, \ R^2 = 0.85\]

**Zinc**

\[
r_{\text{CORR}} = 0.0129 \times [\text{SO}_2]^{0.44} \times \exp(0.046 \times \text{Rh}) \times \exp(f_{\text{Zn}}) + 0.0175 \times [\text{Cl}]^{0.57} \times \exp(0.008 \times \text{Rh} + 0.085 \times T)
\]

\[f_{\text{Zn}} = 0.038 \times (T - 10) \text{ when } T \leq 10^\circ\text{C}, \text{ otherwise } = -0.071 \times (T - 10)\]

\[N = 114, \ R^2 = 0.78\]

**Copper**

\[
r_{\text{CORR}} = 0.0053 \times [\text{SO}_2]^{0.26} \times \exp(0.059 \times \text{Rh}) \times \exp(f_{\text{Cu}}) + 0.0125 \times [\text{Cl}]^{0.27} \times \exp(0.036 \times \text{Rh} + 0.049 \times T)
\]

\[f_{\text{Cu}} = 0.126 \times (T - 10) \text{ when } T \leq 10^\circ\text{C}, \text{ otherwise } = -0.080 \times (T - 10)\]

\[N = 121, \ R^2 = 0.88\]

**Aluminum**

\[
r_{\text{CORR}} = 0.0042 \times [\text{SO}_2]^{0.73} \times \exp(0.025 \times \text{Rh}) \times \exp(f_{\text{Al}}) + 0.0018 \times [\text{Cl}]^{0.60} \times \exp(0.020 \times \text{Rh} + 0.094 \times T)
\]

\[f_{\text{Al}} = 0.009 \times (T - 10) \text{ when } T \leq 10^\circ\text{C}, \text{ otherwise } = -0.043 \times (T - 10)\]

\[N = 113, \ R^2 = 0.65\]

where \(r_{\text{CORR}}\) is the first-year corrosion rate of metal in µm/year. The remaining parameters are detailed in Table A-2, including parameter intervals.

Although the classification system will improve after these new D/R functions are introduced and will be easier to use, both methods cannot be fully equivalent due to fundamental problems. While direct corrosion tests cover the whole complex of environmental conditions during one specific year of exposure, the average conditions during expected service life of a component
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may be different. Using the D/R function, average values of environmental factors that are valid for given time periods and regions can be substituted. However, these functions involve only selected environmental factors and the calculated value of corrosion loss must be considered as a point determination of the value, which shows deviations that can be statistically determined, Table A-3.

Table A-2
Parameters Used in Dose/Response Functions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Interval</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Temperature</td>
<td>-17.1 to 28.7</td>
<td>°C</td>
</tr>
<tr>
<td>Rh</td>
<td>Relative Humidity</td>
<td>34 to 93 %</td>
<td>%</td>
</tr>
<tr>
<td>SO₂</td>
<td>SO₂ deposition</td>
<td>0.7 to 150.4</td>
<td>mg/m²/day</td>
</tr>
<tr>
<td>Cl⁻</td>
<td>Cl⁻ deposition</td>
<td>0.4 to 760.5</td>
<td>mg/m²/day</td>
</tr>
</tbody>
</table>

Table A-3
Estimated Levels of Uncertainty for the Assessment of Corrosivity Category Based on Determination (Exposure of Specimens) and Estimation (Dose/Response Function)

<table>
<thead>
<tr>
<th>Material</th>
<th>Determination</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Steel</td>
<td>±2%</td>
<td>-33 to 50%</td>
</tr>
<tr>
<td>Zinc</td>
<td>±5%</td>
<td>-33 to 50%</td>
</tr>
<tr>
<td>Copper</td>
<td>±2%</td>
<td>-33 to 50%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>±5%</td>
<td>-50 to 100%</td>
</tr>
</tbody>
</table>

ISO 9223 is the basic standard for corrosivity classification and will be subject to most changes when the ISO CORRAG program results and the results of other international testing programs are implemented. The adjustment of another three standards will lead to the following:

1. Introduction of a calculation model for the derivation of guiding corrosion values in ISO 9224
2. Updating of procedures for measuring atmospheric pollution in ISO 9225
3. Omission of helix specimens as standard specimens for the derivation of corrosivity and specification of pickling procedures in ISO 9226
A.7 Appendix A References

A-1 S. W. Dean, “Analysis of Eight Years of Exposure Data from the USA Contribution to the ISO CORRAG Program,” paper 11 presented at the 13th International Corrosion Congress, Melbourne, Australia, November 20-25, 1996, IV.


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