An Evaluation of Flow-Accelerated Corrosion in the Bottom Head Drain Lines of Boiling Water Reactors

Technical Report

An Evaluation of Flow-Accelerated Corrosion in the Bottom Head Drain Lines of Boiling Water Reactors

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REPORT SUMMARY

The lower vessel drain line of boiling water reactors (BWRs) is susceptible to damage caused by flow-accelerated corrosion (FAC). It is difficult to inspect this line because of the presence of obstructions, and available inspection approaches result in high radiation dose rates. A leak or rupture in the piping under the vessel could not be isolated and would result in a small break loss-of-coolant accident. This report describes an investigation into the susceptibility of the bottom head drain line in U.S. BWRs to damage caused by FAC.

Background

Although the lower vessel drain line has been included in many utility FAC inspection programs, a condition report written by one U.S. BWR licensee who encountered inspection difficulties led to increased utility and regulatory attention to this issue.

Objective

To determine the status and health of the U.S. BWR fleet with respect to FAC in the bottom head vessel drain line.

Approach

The research team, under CHECWORKS™ Users Group (CHUG) sponsorship, performed a survey to determine geometry, operating conditions, and inspection history of bottom head vessel drain lines in the United States and in a limited number of international BWRs. They used the results of this study as input parameters for a series of analyses performed using the CHECWORKS™ Steam/Feedwater Application. In addition, researchers obtained and summarized inspection results from several operating BWR plants.

Results

Parametric analysis demonstrated that water chemistry, particularly the amount of oxidant in the bottom head vessel drain line, is the most important parameter with respect to the susceptibility of a specific reactor unit to FAC damage. Flow rate is also important. Using the analytical results obtained, investigators divided the U.S. units into three categories based on predicted FAC susceptibility. Inspection results showed that very little wear has been occurring in lower vessel drain lines, even in units with the highest predicted susceptibility.

EPRI Perspective

Although the bottom head vessel drain line has been included in the FAC inspection program at many plants, this issue is receiving increased attention due to the importance of the line. FAC in this line is not an emergent issue, but it remains an important one. CHUG has notified all FAC coordinators from the most susceptible units and will continue to follow this issue, obtain and analyze new inspection data, and report back to the BWR community. Inspection techniques to provide line thickness measurements in areas under the BWR vessel are also under development.

Keywords

Flow-Accelerated Corrosion
FAC
Bottom Head Drain Line
Boiling Water Reactor
Water Chemistry
Nondestructive Examination Data

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INTRODUCTION

Flow-accelerated corrosion (FAC) is the name given to the process by which iron oxides on a steel surface dissolve into a flowing stream of water or steam-water mixture. The resulting material loss has caused leaks and failures in pipes and pressure vessels. See reference 1 for a comprehensive treatment of the subject.

Since the late 1980s, US nuclear utilities have implemented extensive programs to protect against failures caused by FAC. Recently, attention has been focused on the possibility of FAC-caused degradation in the bottom head drain line found in boiling water reactors (BWRs) (reference 2). This line is important because it is unisolatable and a failure would result in a small break loss-of-coolant accident (Small Break LOCA). Inspecting the portion of this line underneath the reactor vessel is very difficult – at least from the outside – due to the presence of control rod drives, insulation, instrumentation, shielding, and shoot-out steel. Additionally, inspections downstream (i.e., away from the reactor vessel) are expensive because of the high radiation fields typically encountered; and in some plants, the inspection results may not be representative of the piping underneath of the vessel because of changes to the material, line size, and/or type of fittings used.

This report describes an investigation into this issue. The investigation included:

- A survey to determine geometry and operating conditions found in the line as well as available inspection data.
- Parametric analyses using the CHECWORKS™ Steam/Feedwater Application (reference 11) to identify the most important variables affecting piping degradation susceptibility.
- Identification and plant specific analyses of the most susceptible units.
- Recommendations for future activities.

The report is organized as follows:

Section 2 presents a description of the CHECWORKS Users Group’s (CHUG) survey.

Section 3 presents the CHECWORKS™ analyses performed.

Section 4 presents the available inspection data.

Section 5 discusses the results of the analyses and the available inspection data.

Section 6 presents the implications to the operating units.

Section 7 presents the recommendations and conclusions of this work.

Two appendices furnish additional information.

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CHUG SURVEY

To obtain input data for the evaluation, CHUG conducted a survey to determine the geometry, inspection history, operating conditions and water chemistry in US and several foreign BWRs. The survey form is presented in Appendix A. A total of 39 units including all 35 US units and 4 foreign units responded to the survey. Some of the important results are summarized in the remainder of this section.

2.1 Drain Geometry

In general, the bottom head drain is a 2-inch, Schedule 160[1] , SA-106 Grade B carbon steel pipe extending downward from the center of the bottom head. In most cases, there is a 90º elbow located approximately one foot below the head. The drain line continues radially outward until it exits the area of the control rod drives (CRDs), and, depending on the plant design, can make several additional changes of direction before exiting the reactor pedestal area. Ultimately, it connects to other portions of the reactor water clean-up system. There are many differences in details between different units. For example:

- Some lines continue as 2 inch while others expand to 2.5-, 4- or 6-inch pipe.
- Some lines continue as carbon steel while others change to stainless steel.
- Most units (~ 2/3) have socket-welded fittings while others have butt-welded fittings.
- One unit has the elbow welded to the vessel while all other units have a pipe before the first elbow. Reported pipe lengths varied from about 1.5 inches to 26 inches.

2.2 Inspection History

Twelve units reported that inspections had been performed on the line. These inspections were usually performed in areas away from the reactor vessel – typically outside the reactor pedestal region. This is the most accessible area. With a few exceptions, most of the available data are very limited – one or two components that have been inspected once. It should be noted that some of the reported inspection data were on downstream pipe and fittings larger than 2-inch nominal diameter. FAC wear rates in larger diameter pipe will be lower due to the lower flow velocity.[2] The inspection data are summarized and discussed in more detail in Section 4 of this report.

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[1] 2 inch, Schedule 160 pipe, has an outside diameter of 2.375 and a nominal wall thickness of 0.344 inch.

[2] CHECWORKS™ calculations indicate that the predicted ratio of wear rates of 2.5-, 3-, 4- and 6-inch pipe to 2-inch pipe are 65%, 44%, 24%, and 11% respectively.

2.3 Operating Conditions

With the exception of flow rates, the operating conditions of the surveyed units were basically similar. This is important in that flow rates varied widely and fluid velocity is an important parameter in determining the rate of FAC. The reported flow rates varied from a maximum of 240 gpm to a plugged condition (zero flow) reported by a few units. It should be noted that a flow rate of 70 gpm through a 2-inch, Schedule 160 pipe at about 530ºF corresponds to a liquid velocity of 10 feet per second.

2.4 Water Chemistry

Relatively few respondents included dissolved oxygen in their survey responses. The values reported varied from over 200 ppb to essentially 0 ppb. This variation in oxygen reflects the fact that there are three different water chemistry regimes that have been or are being used in operating BWRs. Briefly, these are:

- Normal Water Chemistry (NWC) – this is the chemistry originally used in all BWRs. No hydrogen or other additives are used.[3] This chemistry results in the highest concentration of oxidants in the drain line (i.e., oxygen and hydrogen peroxide). Currently, there are no US BWRs using Normal Water Chemistry.
- Hydrogen Water Chemistry – hydrogen is injected into the feedwater to lower the oxygen concentration (or more properly the electrochemical corrosion potential – ECP) in the recirculation lines and in the reactor vessel. Note that different units inject different amounts of hydrogen.

  Conventionally, feedwater hydrogen addition in the range of 1.0 to 2.0 ppm is known as Moderate Hydrogen Water Chemistry (MHWC). See reference 8. Of the water treatments used, this chemistry results in the lowest concentration of oxidants.
- Noble Metal Chemical Addition (NMCA)[4] – in addition to hydrogen injection, the reactor vessel internals are treated with a solution containing the noble metals platinum and rhodium. These metals are plated out on surfaces within the vessel. The presence of these metals on the reactor surfaces catalyzes the recombination of hydrogen and oxygen into water, and thus lowering the oxidant concentration. This approach requires a much lower concentration of injected hydrogen to achieve essentially zero oxidant at metal surfaces (see reference 3 for more information). This chemistry results in an intermediate concentration of oxidants in the free stream.

Note that the oxidant concentration is extremely important because the rate of FAC has been shown to vary inversely with oxidant concentration. In other words, the higher the oxidant, the lower the rate of FAC. See, for example, reference 1.

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[3] This discussion ignores zinc addition. Zinc addition has been used at many BWRs and the presence of deposited zinc has been shown to lower the rate of FAC. However, due to lack of specific knowledge concerning surface zinc concentrations, the impact of zinc will be conservatively ignored.

[4] Also known as NobleChem™, a trademark of General Electric.

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ANALYSIS PERFORMED

In order to evaluate plant susceptibility associated with differing conditions, several types of analyses were performed using CHECWORKS™. A complete range of conditions, as determined by the survey, was explored in this work.

3.1 Principal Assumptions

In view of the limited amount of inspection data available, and the fact that the data available showed only small amounts of degradation, a CHECWORKS™ Pass 1 analysis was performed.[5] In a Pass 1 analysis, the program predicts the rate of FAC based only on input conditions. Inspection results are not used to refine the predictions.

In a Pass 1 analysis, the assumptions made are very important, as the predictions do not have the check of a comparison with measured inspection data. Some of the most important assumptions made were:

- The pipe material was assumed to be carbon steel with no trace chromium present (this assumption is conservative as it results in the maximum rate of FAC).
- The geometric representation of the drain line was a pipe downstream of a nozzle (geometry code 61), followed by a butt-welded 90º elbow (geometry code 2), and followed by a pipe downstream of a butt-welded elbow (geometry code 52). Note that the program uses the geometry codes to choose the appropriate geometry factors.[6]
- While the geometry factors for the elbow and the pipe downstream of the elbow are believed accurate for butt-welded fittings, the geometry factors for a socket-welded elbow and the pipe downstream of a socket-welded elbow are not known. There is much anecdotal experience that suggests that with a large fit-up gap, the geometry factor for a socket-welded elbow would be larger than for comparable butt-welded fitting. Until such factors are available, the geometry factor was assumed to be bounded by 1 to 2 times the geometry factor for a butt-welded elbow.
- Temperature factor at 530ºF. The CHECWORKS predictive model is empirical. The temperature factor is based on plant and laboratory data up to ~450ºF. It was assumed that the temperature factor at temperatures above 450ºF was the same as that at 450ºF. This is believed to be conservative as the temperature factor peaks at ~300-350ºF.

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[5] Small amounts of degradation imply an imprecise estimation of the amount of wear that has occurred. As most of the available data were for units operating with NWC with very low predicted wear rates, it was decided that the use of Pass 2, i.e., using the measured wear to alter the predictions, was not prudent.

[6] A geometry factor is defined as the peak rate of thinning in a fitting divided by the rate of thinning in a straight pipe remote from flow disturbances, and having the same operating conditions.

- The CHECWORKS predictive model does not account for zinc. The effect of zinc injection on FAC has not been quantified, although it is believed to decrease the rate of damage.
- Values of oxygen and hydrogen peroxide obtained from the BWRVIA[7] program (reference 4) for typical units were used to determine the total oxidant. The total oxidant values were used as input into CHECWORKS™, as discussed below. As the BWRVIA does not calculate concentrations in the drain line, values calculated for the lower plenum were used.
- The chemistry was defined through the Advanced Run Definition form (i.e., a "Z-line"). The equivalent input oxygen value was determined using the following formula:

  Oxidant = Oxygen + 0.47 * Peroxide[8]

  where:

Oxidant =	the equivalent oxidizing potential in ppm (input as oxygen in CHECWORKS™)
Oxygen	the concentration of dissolved oxygen in ppm
Peroxide	the concentration of hydrogen peroxide (H_2O_2) in ppm

3.2 Cases Run

Three test series were run during the course of this work. These cases and their results are described below.

3.2.1 Parametric Runs

The first set of runs covered three parameters over the range of conditions of the plants surveyed. The three parameters examined were[9]:

- Oxygen – a range of 0 to 200 ppm oxygen (oxidant, as discussed above).
- Flow rate – as taken from the surveys, a range of 20 to 200 gpm was considered. Note that a flow rate of 70 gpm corresponds to a liquid velocity of 10 feet per second.
- Temperature as taken from the surveys; a range from 450 to 550 ºF was considered.

The results of the CHECWORKS™ calculations were plotted showing the variation of corrosion rate in mils per year in relation to flow rate and oxidant concentration. A separate chart was prepared for each temperature run. A sample of these charts is presented as Figure 3-1. The results of these calculations found oxidant to be the most important parameter and flow rate to be

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[7] The BWR Vessel & Internals Application predicts local chemistry, radiolysis and electro-chemical corrosion potential (ECP) in the reactor vessel and internals of BWR plants to identify conditions favorable for stress corrosion cracking.

[8] The factor, 0.47, in the equation comes from the fact that hydrogen peroxide decomposes to water releasing one-half of an oxygen molecule per molecule decomposing. Thus, the mass percentage of oxygen to peroxide would be 16 (the molecular weight of half an oxygen molecule) divided by 34 (the molecular weight of hydrogen peroxide) or 47%.

[9] The other parameters in the CHECWORKS™ wear rate model, alloy content and geometry, are constant across all of the plants.

the second most important parameter. Temperature variations were found to be relatively unimportant.

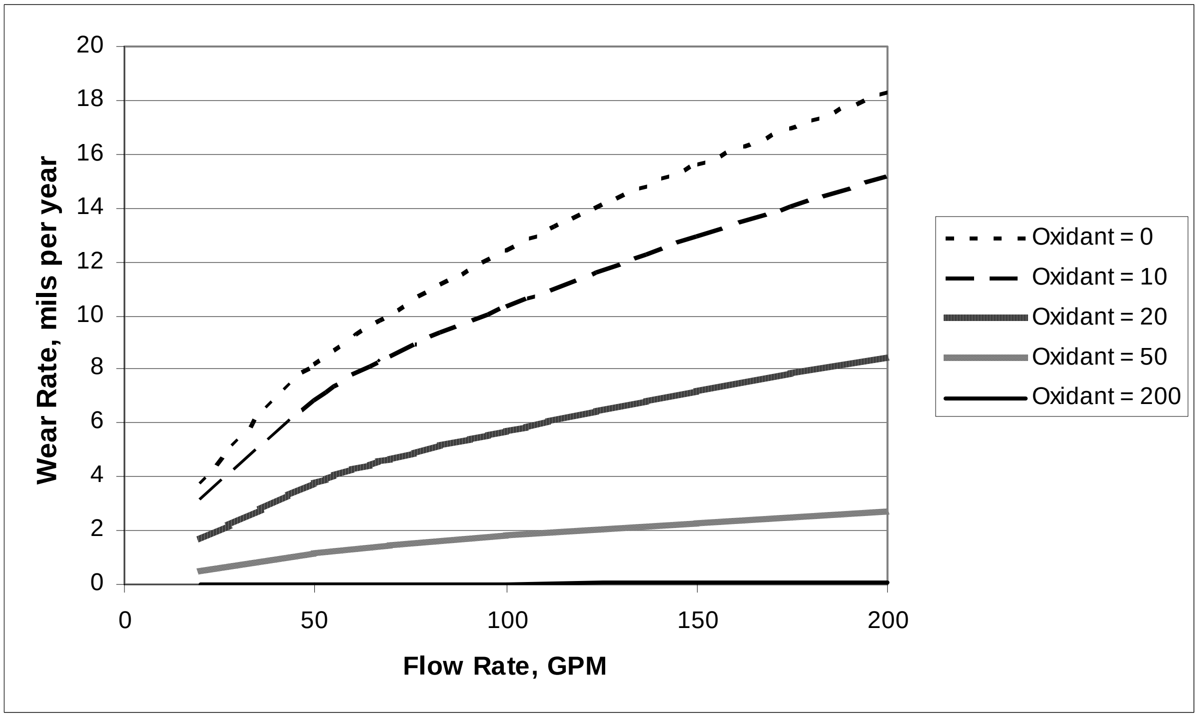

Figure 3-1
Sample of Parametric Calculations at 525 °F

3.2.2 Representative Cases

The second set of runs was designed to represent some typical cases likely to cover a large number of units. These cases were chosen to look at the realistic situation where a unit experiences more than one water chemistry treatment over the life of the plant. Each case was run using the assumptions described in Section 3.1, above. The cases were:

- Case 1 – a unit operates on NWC for 15 years and on NMCA for 25 years. A temperature of 530ºF and flow rates of 50 and 70 gpm were assumed (a temperature of 530ºF and flow rates of 50-70 gpm are typical values for the US BWRs). The results of these runs are presented in Table 3-1 as the total expected wear in inches for the life of the unit for each set of conditions. For convenience, the calculated wear rate for a butt-welded and a socket-welded elbow are presented in Table 3-2. The other fittings, i.e., the two pipes, have lower predicted wear rates than the elbow, and their results are not presented in this report.
- Case 2 – a unit operates on NWC for 15 years, for 18 years on NMCA, and for 7 years on MHWC. For this case, a temperature of 530º F, flow rates of 50 and 70 gpm, and two hydrogen injection rates (0.9 and 1.4 ppm) were assumed. The results of these runs are presented in Table 3-1 as the total expected wear in inches for the life of the unit.
- Case 3 – a unit operates for 8 years on NWC, for 18 years on NMCA, and for 14 years on MHWC. The operating conditions are the same as in Case 2. The results are presented in Table 3-1.

- Case 4 – a unit operates for 20 years on NWC, for 20 years on NMCA, and for 20 years on MHWC. The operating conditions are the same as in Case 2. The results are presented in Table 3-1.

The calculated results presented in Table 3-1 show again the predicted impact of changes in the water chemistry and flow rate. Once again, changes in flow rate are important, but tend to be dominated by changes in chemistry (i.e., total oxidant). Another important result is that plants that have operated (or plan to) only on NWC and NMCA probably do not have a problem (i.e., significant wear rates) even with a high flow rate[10]. Conversely, plants operating with MHWC at high levels of hydrogen may experience high wear rates.

3.2.3 Plant Specific Calculations

In reviewing the operating history of plants using MHWC, the following units were identified for plant specific evaluations (units listed alphabetically):

- Browns Ferry 2
- Brunswick 1 & 2
- Dresden 2 & 3
- Fermi
- Grand Gulf
- Hatch 1 & 2
- Hope Creek
- Monticello
- Pilgrim
- Quad Cities 1& 2
- Riverbend
- Susquehanna 1 & 2

A summary and discussion of the analyses results are presented in Section 5.

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[10] Results at 50 and 70 gpm were extended to higher flow rates using the CHECWORKS™ correlation for mass flow to reach this conclusion.

Table 3-1
Predicted Lifetime Wear in Elbows - Representative Cases

Case	Chemistry History (see Below)	Drain Flow Rate (gpm)	Butt - Welded Elbow - Lifetime Wear (inch)	Socket - Welded Elbow - Lifetime Wear (inch)
1	A	50	0.019	0.019 – 0.038
		70	0.024	0.024 – 0.048
2	B	50	0.027	0.027 – 0.054
		70	0.034	0.034 – 0.068
	BB	50	0.092	0.092 – 0.184
		70	0.115	0.115 – 0.230
3	C	50	0.040	0.040 – 0.080
		70	0.049	0.049 – 0.098
	CC	50	0.170	0.170 – 0.340
		70	0.212	0.212 – 0.424
4	D	50	0.053	0.053 – 0.106
		70	0.066	0.066 – 0.132
	DD	50	0.239	0.239 –0.478
		70	0.297	0.297 – 0.594

Chemistry History Codes

A = 15 Years on NWC + 25 years on MHWC (FW H_2 = 0.2)

B = 15 years on NWC + 18 years on NMCA (FW H_2 = 0.2) + 7 years on MHWC (FW H2 = 0.9)

BB = 15 years on NWC + 18 years on NMCA (FW H_2 = 0.2) + 7 years on MHWC (FW H2 = 1.4)

C = 8 years on NWC + 18 years on NMCA (FW H_2 = 0.2) + 14 years on MHWC (FW H2 = 0.9)

CC = 8 years on NWC + 18 years on NMCA (FW H_2 = 0.2) + 14 years on MHWC (FW H2 = 1.4)

D =20 years on NWC + 20 years on NMCA (FW H_2 = 0.2) + 20 years on MHWC (FW H2 = 0.9)

DD =20 years on NWC + 20 years on NMCA (FW H_2 = 0.2) + 20 years on MHWC (FW H2 = 1.4)

Table 3-2
Predicted Wear Rates for the Representative Cases

	Feedwater Hydrogen Concentration (ppm)	Drain Flow Rate (gpm)	Butt - Welded Elbow Wear Rate (mils/year)	Socket - Welded Elbow Wear Rate (mils/year)
Normal Water Chemistry	0.0	50	0.03	0.03 – 0.06
		70	0.04	0.04 – 0.08
Moderate Hydrogen Water Chemistry	0.9	50	1.85	1.85 – 3.70
		70	2.30	2.30 – 4.60
	1.4	50	11.18	11.18 – 22.36
		70	13.90	13.90 – 27.79
Noble Metal Chemical Addition	0.2	50	0.75	0.75 - 1.51
		70	0.94	0.94 – 1.87

4

INSPECTION DATA

As noted previously, there is only a limited amount of inspection data available. Most of the inspection data have been taken from outside the reactor pedestal area where the piping is more accessible and the radiation dose levels are lower. The inspection data are summarized in Table 4-1.

Very little wear was measured for plants that had never been on MHWC (Clinton, Columbia, LaSalle 1 & 2, Nine Mile Point 2, and Peach Bottom 2). This was consistent with the CHECWORKS™ analysis.

Five units have inspection data and have operated on MHWC for significant periods of time. Based on this study, they are the units that should show the most degradation. The units are Dresden Unit 2, Monticello, Susquehanna Units 1 and 2, and Pilgrim.

- **Dresden Unit 2 –** this unit has unique data in that the measurements were made under the reactor vessel on the horizontal pipe through the use of a crawler. A total of 24 inspection points were measured. Of these, only one point was below the nominal thickness, and it was above the manufacturer's minimum thickness.
- **Monticello –** this plant has performed inspections since 1993. A total of nine components have been inspected. Only limited thicknesses below nominal have been found (see Table B-2 and Figure B-1 for locations that have been inspected). One component was re-inspected after a 9-year interval. It was found to have increased in thickness (due to measurement inaccuracy, it is not uncommon the see components increase in thickness in cases where the wear rates are low).
- **Pilgrim –** four sets of inspection data indicate very little measured wear. The locations inspected were outside of the reactor pedestal area and downstream of an isolation valve.
- **Susquehanna Units 1 & 2 –** data indicate very little, if any, measured wear at Susquehanna 1 & 2 over a total of five inspections. These measurements were made in 6-inch pipe downstream from the 2-inch piping attached to the reactor vessel.

The inspection results from the above five units are presented in greater detail in Appendix B.

These data and their implications to the operating BWRs are discussed in the next two sections.

Table 4-1
Summary of Inspection Results

Unit	Years Inspected	HWC?	Diameter	Number of Components	Results
Clinton	2000	No	2-inch	1	No damage found
Columbia	1994 2001	No	2 & 4 in.	2	Very little changes seen <4mils/yr
Dresden, Unit 2	1995	Yes	2-inch	1	Inspection on horizontal pipe, little wear seen
LaSalle, Unit 1	2004	No	2 & 4 in.	2	$T_{minmeas} \sim T_{nom}$
LaSalle, Unit 2	2003	No	2 & 4 in.	2	$T_{minmeas} \sim T_{nom}$
Monticello[11]	1993 1994 2005	Yes	2-inch	9	No significant wear seen
Nine Mile Point 2	1993 1995 1996 2002	No	2.5-inch	1	No significant wear over 4 inspections
Peach Bottom, Unit 2	2002	No	2-inch	1	No wear seen
Perry	1997 1999 2001	No	4 & 6 in	3	No significant wear
Pilgrim	1993 2001 2003 2005	Yes	2-inch	2	One measurement within pedestal. One outside. Little degradation seen.
Susquehanna Unit 1	1996 2004	Partial	6-inch	1	Very little wear, if any, observed
Susquehanna Unit 2	1997 1999 2003	Partial	6-inch	1	Very little wear, if any, observed

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[11] Inspection results are discussed in Appendix B.

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DISCUSSION OF RESULTS

Predicted values of measured wear were determined for the 17 units identified in Section 3.2.3, which had run on MHWC.

Among these units, Monticello was identified as having the operating conditions and length of time operating under MHWC, which would result in the largest amount of predicted wear. It had operated on MHWC for the longest time, has a socket-welded elbow underneath the vessel, and quoted an unusually high flow rate (92 gpm ~ 13 feet per second). The conditions used for the Monticello analysis were:

- Temperature = 542ºF.
- Flow Rate = 92 gpm.
- Time on MHWC = 13.12 years.
- Socket-welded fittings.
- Feedwater hydrogen = 1.4 ppm.

With these assumptions, the predicted wear of the socket-welded elbow for the time on MHWC was calculated to be between 0.210 and 0.420 inch. This corresponds to a wear rate between 16 and 32 mils per year. Note that the nominal thickness of the attached pipe is 0.344 inches. Also, note that catalog wall[12] thickness of the socket portion of a 2-inch 3000 # elbow is 0.313 inch.

Other plants that stood out as having high predicted wear were Fermi (98-196 mils), Susquehanna Units 1 (137 mils) & 2 (138 mils), and Brunswick Units 1 & 2 (56 – 113 mils).

5.1 Comparison of Predictions with Inspection Results

For plants that have never operated on MHWC, both predicted and measured levels of degradation are quite small. The remainder of this section examines the several units with high predicted wear that have inspection data. They are: Monticello, Pilgrim, and both Susquehanna units. The detailed inspection results for these units are presented in Appendix B.

At Monticello, there was very little wear apparent in the components inspected. Of the 9 components that had been inspected, there was only one component found to be less than the manufacturer's minimum thickness and that one barely so (0.300" versus 0.301").[13] This component (E9 – see Figure B-1) was originally inspected in 1994 and re-inspected in 2005. The latest inspection showed a minimum thickness of 0.328". Note that the lifetime wear predicted for the first elbow was 0.219 – 0.421 inch.

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[12] Data found at www.capitolcamco/cap_sw_90elbow.htm

[13] The nominal thickness of 2 inch, Schedule 160 pipe is 0.344 inch. 87.5% of this value is 0.301 inch.

At Pilgrim, there is little wear apparent when the scatter of the data is considered. This is true in all of the components examined (an elbow, a tee, and their attached pipes for a total of seven components in all). The predicted wear for the first elbow was 43-86 mils.

The measured values of wear for the Susquehanna elbows were quite small, whereas the predicted wear was ~140 mils.

A discussion of reasons for the conservative predictions is provided in the next Section.

5.2 Sources of Conservatism in the Analysis

It is believed that the predictions made in this report are conservative for the following reasons:

- **High temperature** – the temperatures in the drains are about ~ 525ºF. Available data indicate that the peak rate of FAC occurs at temperatures of ~300-350ºF (reference 1). The temperatures used in the calculations in this report are greater than most of the data in the CHECWORKS™ laboratory database. In fact, there are scant data available above about 450ºF. Thus the temperature factor at 450ºF was used for the predictions. This is believed to be conservative and adds some uncertainty to the accuracy of the calculations. However, it is important to note that FAC damage has been reported to occur to the internals of a number of steam generators. See references 5 & 6. These steam generators operate at ~550ºF, so the possibility of FAC damage in the drain lines can not be ruled out due to high temperature alone.

  Also note that FAC degradation has also been observed in the outlet feeders of CANDU reactors (reference 1). These lines operate at about 600º F and have experienced FAC.

- **Iron Concentration** – although there is no known data supporting this claim, the bottom head drain should have a high concentration of dissolved iron. This claim is based on the fact that iron entering the reactor vessel in the feedwater is concentrated by the boiling process. The steam leaving the vessel contains very small amounts of iron, so most of the entering iron is deposited (e.g., on the fuel) or exits the vessel through the drain. To appreciate the effect of iron concentration in the free stream, the process of FAC must be understood.

  As described in reference 1, FAC is the dissolution of iron oxides into a flow stream. For dissolution to occur, there must be a difference between the solubility of the oxides at the surface and the free stream concentration: the larger the difference, the larger the rate of dissolution and rate of corrosion. Conversely, when the difference becomes smaller, the rate goes down. In most balance-of-plant cases of FAC, the effect of having a non-zero free stream iron is negligible. One exception is the blowdown piping in PWRs. Here, there is a situation analogous to the BWR bottom head drain. The blowdown piping contains a high concentration of iron and the rates of FAC in this system have normally been found to be very low.

- **Socket-Welded Fittings –** at this time there is no accepted geometry factor for socket-welded fittings**.** For the calculations performed in this report, the geometry factor for a socket-welded elbow was assumed to be bounded by 1 and 2 times the geometry factor of a butt-welded elbow. While the upper bound may be conservative, the use of the butt-welded elbow as a lower bound for the value should be reasonable.
- **Zinc Injection –** most BWRs inject zinc into the feedwater to reduce dose exposures caused by cobalt-60. Some testing has demonstrated that the presence of deposited zinc can lower the rate of FAC by at least a factor of 3 (reference 7). As this work is not well established and the amount of zinc deposited in the drain lines is unknown, this effect was conservatively neglected. All of the plants considered to be at highest risk for FAC in the bottom drain line (Category C in Section 6.1) use zinc injection. See reference 8.
- **NMCA –** there is some evidence that the presence of noble metals on carbon steel surfaces will reduce the rate of FAC (reference 9). Reference 9 describes two tests performed to demonstrate the increased corrosion resistance of carbon steel with a noble metal film. A palladium thickness of about 0.3 microns (~12 micro-inches) was used in these tests. The protected samples showed virtually no weight loss compared to uncoated samples. Since the amount of noble metals on the surface, the amount of time the noble metal remains on the surface, and the specific benefits are unknown, this effect was conservatively neglected.

  Note also that in cases where NMCA was used after MHWC, any long-term benefits of the noble metals would not have protected the surface from the low-oxidant environment previously experienced with MHWC.
- **Flow Rate –** in some units there seems to be some uncertainty concerning the flow rate through the drain lines. As mentioned previously, some units reported that the drain line was plugged and had been plugged for a number of years. Other units reported that the drain line was plugged for a while and then was cleared. In most units, the reported flow rates were estimates as most often the drain flow rates were not measured directly, but were inferred from the pressure drop data. These flow estimates were for all periods of operation, and credit was not taken for low-flow or no-flow situations.
- **Chromium –** all predictions made in this report have been based on the assumption that the components have no chromium. Chromium has been shown to be the alloying element that has the largest impact on reducing the rate of FAC. In fact, small amounts of chromium (e.g., 0.10%) have been shown to reduce the rate of FAC by more than a factor of 10 (see reference 10). None of the bottom head wall thickness measurements made to date (Section 4) has included chromium measurements.

6

IMPLICATIONS TO OPERATING UNITS

The information developed during the course of this work was applied to the 35 operating US BWRs. This was done to provide plant owners with information that can be used to help decide further action, if any, which they may wish to perform.

The approach taken was to divide the operating units into three bins or categories. These categories were defined using the results of the preceding sections.

6.1 Categories Used

All US BWRs were placed in one of three categories:

Category A – these units never operated on Moderate Hydrogen Water Chemistry. Rather, they operated on Normal Water Chemistry and possibly on Noble Metal Chemical Addition. As demonstrated in Case 1 (see Section 3.2.2), low rates of FAC were predicted. A total of 18 units fell in this category. These Units are listed in Table 6-1. They are viewed as having very limited susceptibility to damage from FAC in the bottom head drain line due to the high level of oxidant present.

Category B – these units either operated on MHWC for less than 7 years and had a flow rate of less than 70 gpm, or operated with a high enough oxidant concentration such as the predicted wear was consistent with the other Category B units.

The Category B units are viewed as having some susceptibility to FAC, but are bounded by the Category C plants. All of the Category B units have a predicted wear on the 2-inch elbow on MHWC of less than 40 mils. A total of 7 units were identified as Category B.

Category C – these units operated for more that 7 years on MHWC, or had a flow rate greater than 70 gpm and had chemistry yielding a high predicted wear. A total of 10 units were identified for this category and are presented in Table 6-3.

6.2 Disposition of Category C Units

The 10 units in Category C are viewed as being the most susceptible to FAC. A plant-specific analysis of each was performed with the bounding predictions for a socket-welded elbow, and is presented in Table 6-3.

Table 6-1
Category A Units

Units That Never Operated On Moderate Hydrogen Water Chemistry

Unit
Browns Ferry 1
Browns Ferry 3
Clinton
Columbia
Cooper
Duane Arnold
Fitzpatrick
LaSalle 1
LaSalle 2
Limerick 1
Limerick 2
Nine Mile Point 1
Nine Mile Point 2
Oyster Creek
Peach Bottom 2
Peach Bottom 3
Perry
Vermont Yankee

Table 6-2
Category B Units

Units That Operated For Limited Periods with High Susceptibility Conditions

Unit	Years on MHWC	Flow Rate GPM	Comments
Browns Ferry 2	1.25	?	Low operating time on MHWC
Dresden 2	12.76	80	High oxidant
Dresden 3	1.59	0 - 80	Low operating time on MHWC
Grand Gulf	5.78	33	Low flow and low operating time on MHWC
Quad Cities 1	8.5	37.9	High oxidant
Quad Cities 2	9.26	37.9	High oxidant
Riverbend	2.02	100	Low operating time on MHWC

Table 6-3
Category C Units

Units With the Highest Predicted Susceptibility to FAC

Unit	Years on MHWC[14]	Flow Rate (GPM)	Socket?	Inspection Data? Year?	Currently on MHWC?	Feedwater Hydrogen (ppm)	Equivalent Oxidant Concentration (ppb)[15]	Predicted Wear of Elbow for Years on MHWC (mils)	Minimum Measured Thickness (inch)[16]	Nominal Thickness (inch)
Brunswick 1	11.12	20-30	Yes	No	Yes	1.4	0 (A)	56 – 113	---	---
Brunswick 2	11.12	0 - plugged	Yes	No	Yes	1.4	0 (A)	<56 – 113	---	---
Fermi	7.45	63	Yes	No	Yes	1.1	1 (B)	98 - 196	---	---
Hatch 1	5.16	55	Yes	No	No	1.4	26 (B)	61 – 122	---	---
Hatch 2	5.17	55	Yes	No	No	1.4	26 (B)	61 - 122	---	---
Hope Creek	12.03	195.4	No	No	Yes	0.72	52 (C)	44	---	---
Monticello	13.12	92	Yes	1993, 1994 & 2005	Yes	1.4	3 (A)	210 - 421	0.300	0.344
Pilgrim	9.7	20 - 30[17]	Yes	1993, 2001 2003, 2005	Yes	1.2	15 (C)	43- 86	0.268 0.307	0.344 0.344
Susquehanna 1	6.11	200	No	1996 & 2004	Yes	> 2	0.1 (B)	137[18]	0.411	0.432
Susquehanna 2	5.53	240	No	1997, 1999 & 2003	Yes	> 2	0.1 (B)	138	0.468	0.432

Oxidant Sources:
A = Value from BWRVIA Calculation
B = Value furnished by utility
C = Value estimated from BWRVIA results

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[14] As of February 2005
[15] Oxidant = Oxygen + 0.47*Hydrogen Peroxide
[16] See Appendix B for details.
[17] Line reported to be intermittently plugged. Flow rate range is probably maximum operating flow.
[18] The wear values for Susquehanna were based on 90% of the operating time on MHWC and the remaining 10% on NWC

7
CONCLUSIONS AND RECOMMENDATIONS

Based on the work performed, the following conclusions and recommendations are made:

- FAC in the bottom head drain is not an emergent issue for the fleet of US BWRs.
- The most important variables in estimating the amount of damage caused by FAC are the oxidant concentration in the lower plenum and the time the unit operated with the given oxidant concentration. Flow rate is also important.
- Regardless of the predictions, no plant has reported significant wear in the drain system.
- The Category C plants (highest susceptibility) have been identified and the owners of the plants have been notified.
- Plants are continuing to evaluate the need to inspect the drain piping.
- A commercially available tool exists to inspect one configuration of the first elbow and horizontal piping under the reactor vessel.
- A conceptual design of an inspection tool to measure the wall thickness of the first elbow under the vessel of all plant configurations has been developed in case it is needed.

8
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10. *Flow-Accelerated Corrosion Investigations of Trace Chromium*, EPRI, Palo Alto, CA, Report 1008047, December 2003.
11. CHECWORKS™ Steam/Feedwater Application, Version 2.1, EPRI Report 1009600, October 2004.

A
SURVEY FORM

A blank copy of the survey form is presented on the following page.

Survey - BWR Vessel Bottom Head Drain Piping

Plant: ____ Unit _____

BWR Model: 4 _____ 5 ______ 6 ______

Containment: Mark I ______ Mark II ______ Mark III _______

Vertical Drop: Material ________________ Diameter _______ Schedule ______

Insulated (Y/N): ______

1st Elbow: Material ________________ Diameter _______ Schedule ______

Weld (socket or butt): ____________ Insulated (Y/N): ______

Horizontal Pipe: Material ________________ Diameter _______ Schedule ______

Welds (socket or butt): ____________ Insulated (Y/N): ______

Inspected Vertical Drop (Y/N)? ____ When: ______ Results: ________________

Inspected 1st Elbow (Y/N)? ____ When: ______ Results: ________________

Inspected Horiz. Pipe (Y/N)? ____ When: ______ Results: ________________

Degree of Difficulty to Inspect Vertical Drop: __________________________________

Comments: ____

____

____

____

Completed by: ___________________________ Phone: ____________________

E-Mail: ___________________________

Return to Doug Munson by October 22, 2004:

E-mail: dmunson@epri.com Phone: 650-855-2573 Fax: 650-855-8588

B
INSPECTION RESULTS

This appendix presents the inspection results taken in the vessel drain piping near the reactor vessel of Dresden Unit 2, Monticello, Pilgrim, and Susquehanna Units 1 and 2. Inspection data from these five units are important as they are among the 11 units with the highest predicted rates of FAC.

B.1 Dresden Unit 2

The inspection data taken at Dresden Unit 2 are unique in that the data were taken on the horizontal pipe immediately downstream of the first elbow beneath the reactor vessel. A crawler operating on rails was used to access the inspection location. The data readings were obtained using four ultrasonic transducers positioned at 6 locations beginning near the elbow and proceeding downstream. These measurements were made in 1995 when the unit had operated for 8 ½ years on MHWC

A complete set of measurements is presented in Table B-1. The lowest reading on the 2 inch, Schedule 160 pipe, was 0.325” compared to a nominal thickness of 0.344.”

B.2 Monticello

Inspection data were taken in the vessel drain system in Monticello in 1993, 1994 and 2005. Seven components were inspected in 1993 and 1994, and four components, including a repeat inspection, were conducted in 2005.

The inspection locations are shown in Figure B-1 and the inspection results are provided in Table B-2. The repeat inspection of component “E9” is particularly revealing. Note that in the eleven years between inspections, the minimum measured thickness increased from 0.300” to 0.328.” This indicates that little, if any, wear is occurring, and illustrates the accuracy of the measurements. In the most recent inspection, the thinnest component measured (“P11”) at 0.312” (or 90.6% of nominal), and this is still greater than the manufacturers tolerance of 87.5% of nominal.

B.3 Pilgrim

Inspection data were taken in the vessel drain system in Pilgrim in 1992, 1993, 2001, 2003 and 2005. Two components and their attached pipes were inspected. One component, a socket-welded tee (Pt# 128.2, see Figure B-2) located outside the reactor pedestal area was inspected in 1992, 2003 and 2005. Another component, a socket-welded elbow (Pt# 346) located within the reactor pedestal area was inspected in 2001 and 2005.

The inspection locations are shown in Figure B-2. The results of these inspections are presented in Table B-3. In view of the fact that some components appear to be wearing, while others appear to be growing, it is safe to conclude that little wear is actually occurring.

B.4 Susquehanna

Inspection data from similar locations were taken at both Susquehanna units. These locations are shown schematically in Figure B-3.

B.4.1 Susquehanna Unit 1

Inspection readings were taken on a straight pipe downstream of a valve in the 6-inch portion of the drain line at Susquehanna Unit 1 in 1996 and 2004. A summary of the inspection data is presented in Table B-4. Note that in 1996 there were two low data points. These low readings were not found during the 2004 inspection and are regarded as spurious. It was concluded that no observable degradation is occurring.

B.4.2 Susquehanna Unit 2

Inspection data were taken on a 90° elbow downstream of a valve in the 6-inch portion of the drain system in 1997, 1999 and 2003. A summary of the results is presented in Table B-5. It was concluded that no observable degradation is occurring.

The Unit 2 data also allowed a point-to-point comparison between the 1999 and the 2003 inspections as the same grids were used. Looking at the differences between the grid points for the two inspections, it is again obvious that very little, if any, degradation is occurring.

B.5 General Discussion

Although thickness measurements of piping components using ultrasonic methods is a well developed technique, the measurement of components in the BWR drain system presents some challenges.

- ALARA – since the piping involved is either near or under the reactor vessel, the amount of occupational exposure to the NDE technicians is an important consideration. This limits the time available to perform the inspections.
- Pipe size - the large curvature of 2 inch pipe makes it difficult for the technician to properly position the transducer to get a good thickness reading. The expected accuracy is expected to be worse than the 5 – 8% of nominal reported in reference B-1.
- Socket geometry – the geometry of socket-welded fittings make measurements and interpretation of data difficult.
- Pipe finish, the rough as-forged surface of socket-welded fittings often makes it difficult to obtain accurate UT readings.

B.6 Reference

B-1 Bridgeman, J. & Shankar, R. ***Erosion/Corrosion Data Handling for Reliable NDE,*** presented at the post-SmiRT post-conference, Monterey, CA, 1989.

Table B-1
Dresden Unit 2 Inspection Data

Location	#1	#2	#3	#4
Elbow	0.375	0.375	0.365	0.365
↓	0.370	0.380	0.355	0.375
	0.375	0.375	0.375	0.375
Flow	0.380	0.360	0.380	0.365
	0.370	0.375	0.370	0.360
	0.375	0.375	0.370	0.325

Tabulated values are thicknesses in inches measured on the horizontal pipe.

Table B-2
Monticello Inspection Data

Year	Type/Name	Method	T_{nom}	$T_{minmeasured}$
1993	Elbow - E6	4 points	0.344	0.349
	Pipe - P6	8 points	0.344	0.345
	Pipe - P7	Grid	0.344	0.345
1994	Elbow - E9	2 points	0.344	0.300
	Pipe - P5	4 points	0.344	0.310
	Elbow - E4	2 points	0.344	0.530
	Elbow - E5	2 points	0.344	0.560
2005	Elbow - E10	Scan	0.344	0.545
	Elbow - E9	Scan	0.344	0.328
	Pipe - P10	Grid	0.344	0.321
	Pipe - P11	Grid	0.344	0.312
	Pipe - P9	Grid	0.344	0.330

Table B-3
Pilgrim Inspection Data

ID	Diameter	Tnom (inch)	Component Description	Date	Tmin (inch)
Pt# 128	2-inch	0.344	Socket-Welded Tee	1992	0.433
				2003	0.420
				2005	0.419
			Branch Pipe	1992	0.299
				2003	0.334
				2005	0.324
			Run Pipe	1992	0.299
				2003	0.268
				2005	0.273
			Run Pipe	1992	0.316
				2003	0.300
				2005	0.300
Pt# 346	2-inch	0.344	Upstream Pipe	2001	0.327
				2005	0.320
			Socket-Welded Elbow	2001	0.501
				2005	0.506
			Downstream Pipe	2001	0.307
				2005	0.311

Table B-4
Susquehanna Unit 1 Data Summary

Component	Date Inspected	Location	Minimum Measured Thickness (in.)	Comments
DBA1011-E1 (Pipe D/S of valve)	9/1996	Main	0.323	There are two low readings, 0.323” & 0.324”. Next lowest is 0.419”.
	3/2004	Main	0.411	Thin readings no longer apparent.

Table B-5
Susquehanna Unit 2 Data

Component	Date Inspected	Location	Minimum Measured Thickness (in.)	Comments
DBA2012-E2 90° Elbow downstream of valve	3/1997	Intrados	0.386	
		Extrados	0.353	
	4/1999	Intrados	0.393	
		Extrados	0.351	Inspector Comment: “Low readings due to localized grinding at weld toe area”.
		D/S Ext.	0.410	
	3/2003	Intrados	0.399	
		Extrados	0.356	
		D/S Ext.	0.413	

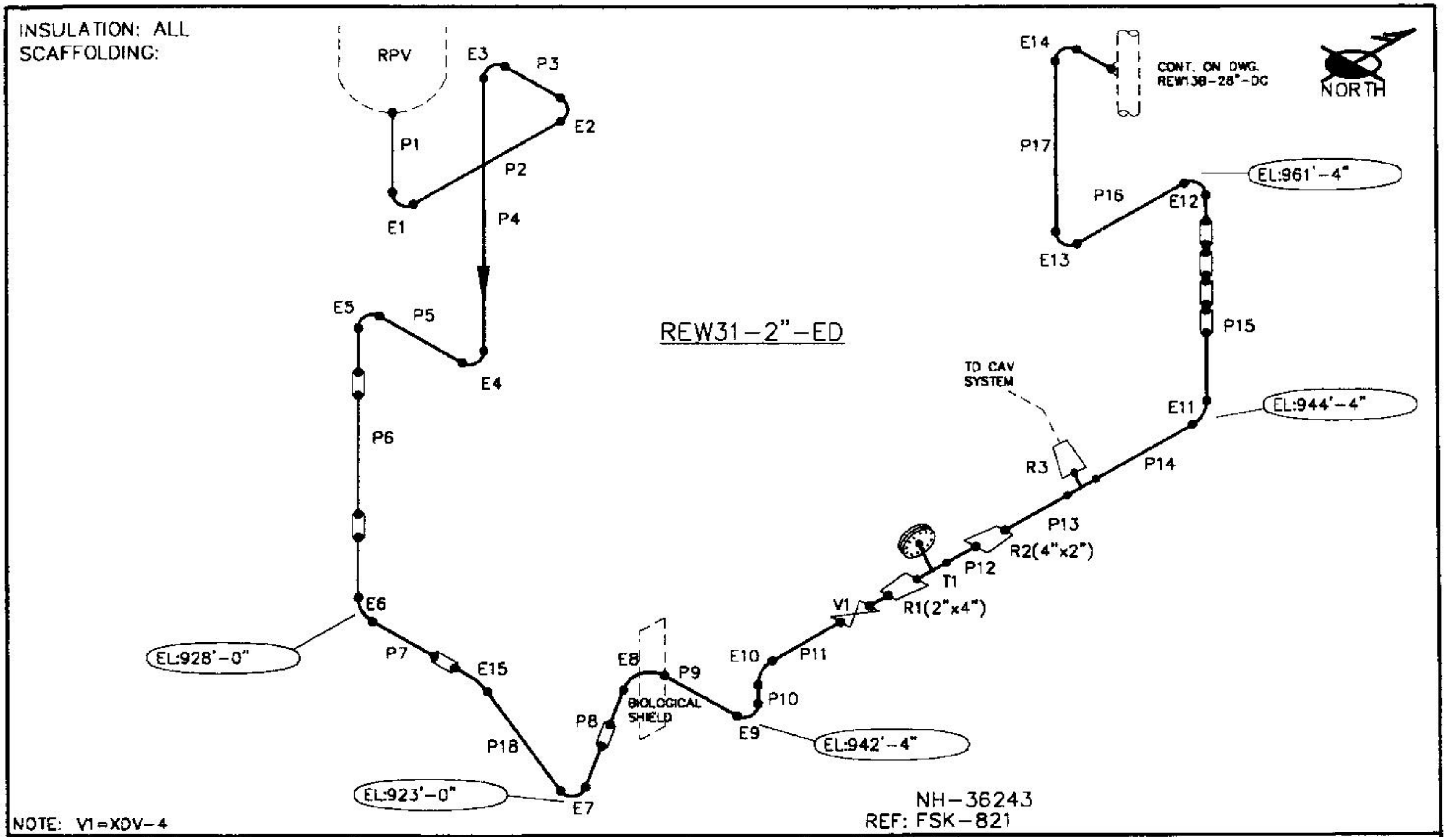


Figure B-1
Monticello Vessel Drain Arrangement

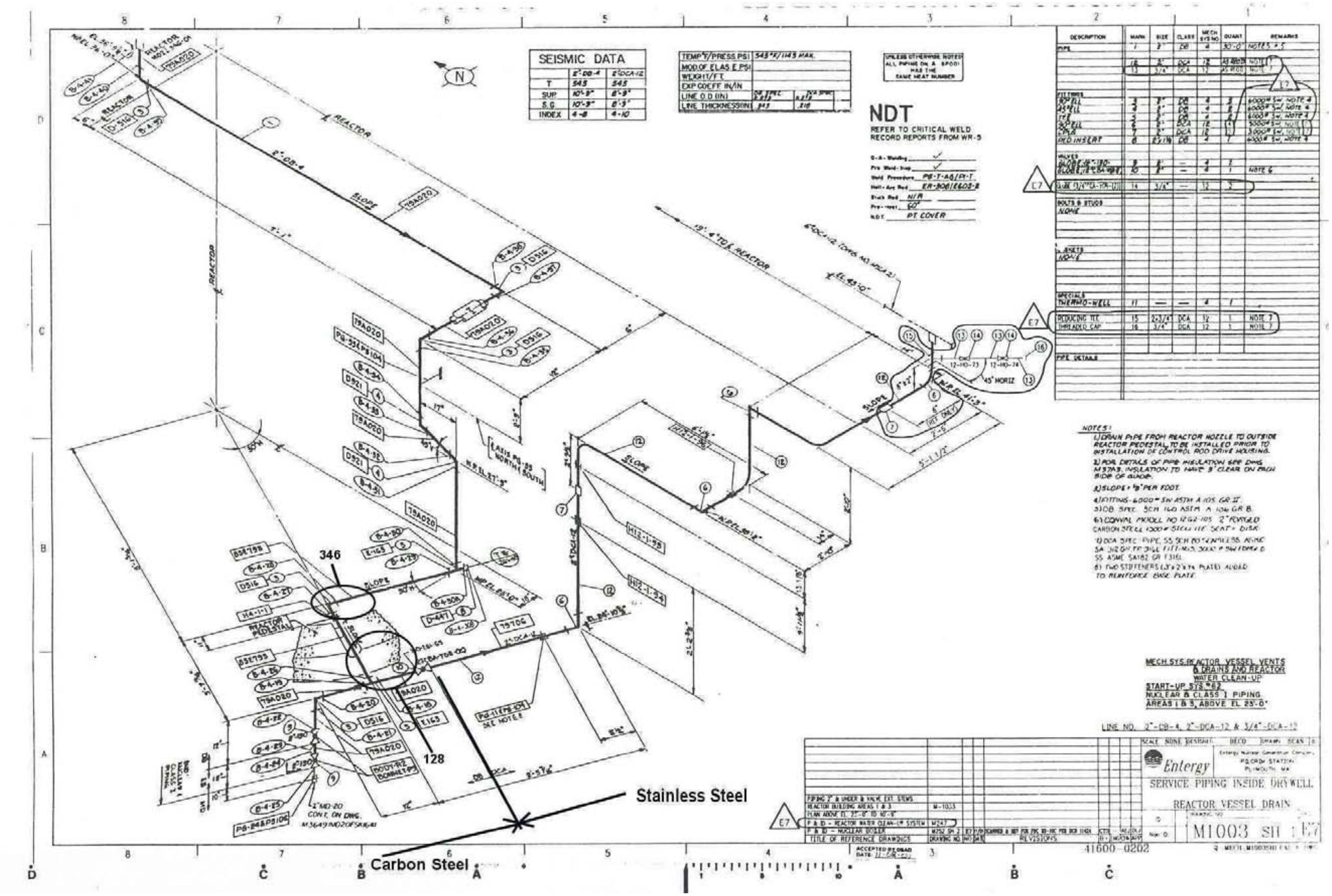
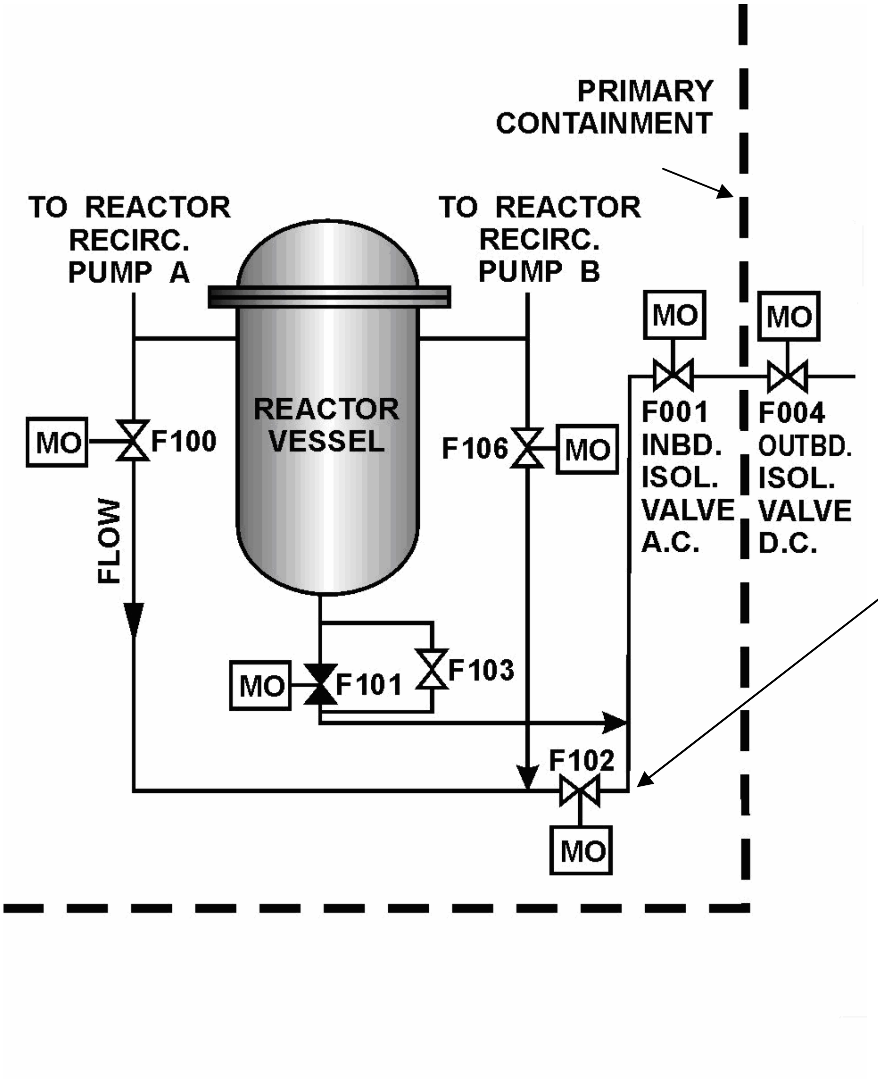


Figure B-2
Pilgrim Vessel Drain Arrangement



FAC Program inspection location, both Units.

Figure B-3
Schematic of Susquehanna Inspection Locations

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