# 4. The Davis-Besse March 2002 Event

The purpose of this section is to describe the series of unexpected and unforeseeable events leading up to the formation and discovery during 13RFO of a large wastage cavity in the RPV head at Davis-Besse. The cavity, which formed as a result of the leakage of high-pressure, high-temperature reactor coolant from a unique CRDM nozzle crack (as described in Section 8), was not formed as the result of ordinary wear and tear.

Given the unexpected and unanticipated size and depth of the corrosion cavity at nozzle 3 and its safety significance, the industry and regulatory response was wide ranging and comprehensive, and is still on-going today, almost five years after the event. The very scope of this effort shows that it could not have been readily predicted or expected on the basis of pre-existing industry analysis and operating experience.

In Section 4.1, we first summarize the chronology of events and plant activities during the initial stages of 13RFO, including the visual inspections of the boric acid deposits on the RPV head and head cleaning operations preparatory to the UT inspections of the CRDM nozzles that were required by NRC Bulletin 2001-01, and the UT inspections that led to the identification and sizing of cracks in Nozzles 1, 2, 3, 5, and 47.

In Section 4.2, we describe the initial nozzle repair plans, and the surprising and unexpected discovery of minor boric acid wastage corrosion of the RPV head at CRDM Nozzle 2, and the large wastage cavity at CRDM Nozzle 3.

Finally, in Section 4.3, we summarize FENOC, industry and regulatory response to the discovery of the large wastage corrosion cavity at CRDM Nozzle 3.

## 4.1 Summary Chronology of the March 2002 Event

This section summarizes the events that lead to the discovery of the wastage cavity on the Davis-Besse reactor pressure vessel head at 13RFO. The specific results of ultrasonic, video and visual inspections of the wastage cavity are provided in Section 7 of this report.

### 4.1.1 RPV Head Video Inspections, CRDM Flange Leakage, Boric Acid Deposits, and Head Cleaning

The 13RFO for Davis-Besse began on February 16, 2002. As part of the Boric Acid Corrosion Control program, routine video inspections of the RPV head were completed on February 25, 2002. These inspections were completed using techniques similar to those employed in previous outages. A video camera was guided through the "mouse holes" around the RPV head using flexible plastic piping. Although difficult to complete, this method provided a video record of the condition of the top of the reactor pressure vessel head. During the performance of these video inspections of the RPV head, a greater amount of boron than expected was found on the top of the head.[1]

In addition to the video inspection of the RPV head, FENOC committed to complete inspection of the CRDM nozzles to evaluate possible circumferential cracking in response to NRC Bulletin 2001-01. This inspection included a 100% qualified visual inspection, non-destructive examination (NDE) of 100% of the CRDM nozzles, and characterization of flaws through NDE if cracks were detected. During the course of these inspections, significant wastage damage was discovered in the low-alloy steel portion of the RPV head.

During 12RFO, CRDM flange inspections indicated boric acid leakage from the flanges on Nozzles 3, 6, 11, 31, and 51. The most significant leakage was associated with the flange on CRDM F10 (Nozzle 11). The condition report that described this event stated,

> "Five leaking Control Rod Drives were identified at locations F10, D10, C11, F8, and G9 [Nozzle 3]. Main source of leakage can be associated with F-10 drive [Nozzle 11]. Positive evidence exists that drives F8, D10 and C11 have limited gasket leakage. This condition can propagate at any time and therefore these drives are considered as leaking. There are no boron deposits on the vertical faces of the flange of G9 drive [Nozzle 3]. The bottom of the flange of G9 [Nozzle 3] drive is inaccessible for inspection due to the boron buildup on the reactor head insulation, not allowing full camera insertion. Since the boron is evident only under the flange and not on the vertical surfaces, there is a high probability that G9 is a leaking CRD."[2]

This statement was further clarified by the sentence immediately following in the Condition Report, which stated,

> "Based on the available information, System Engineering recommends replacement of gaskets or repairs for control rod drives located at locations F10, D10, C11, F8, and G9."[3]

All boron deposits on the RPV head identified during 12RFO were attributed in the Condition Report to CDRM flange leakage.

Initial visual inspection of the reactor pressure vessel head flange during 13RFO in 2002 noted,

> "loose boron 1-2" deep around 75% of the circumference of the flange. On the other 25% from stud 16 to 30 (clockwise), the boron was hard baked 3-4" thick on southeast quadrant (x-y axis). The large boron accumulation is in the same region as seen in 12RFO, but not as deep".[4]

The boron accumulation from the previous outage (12RFO) is shown in Figure 4.1.[5] Video inspection of the RPV head during 13 RFO was completed on February 25, 2002. During this video inspection, "more boron than expected was found on the top of the head." Video inspection of CRDM flanges performed on February 25-26, 2002, indicated no flange leaks. However, boric acid was encountered in the vicinity of Nozzle 3, which made the inspection of the underside of the flange difficult.[6]

During inspection of the RPV head under the mirror insulation, boric acid deposits were encountered. The deposits ranged from hard-baked to porous in nature. Some deposits were a mixture of white and reddish brown in color. The deposits were removed by hydrolasing, which employed high-pressure (2,000 psi) water to remove the material.[7]

### 4.1.2 CRDM Nozzle UT Inspections

Ultrasonic testing (UT) of the CRDM nozzles was performed on February 27-28, 2002. The results of this testing at "#3 control rod drive mechanism (CRDM) nozzle (location G9) revealed indications of through-wall axial flaws on the weld region. These indications represent potential leakage paths. Further characterization will be performed per the reactor head nozzle action plan using the top-down UT tooling”.[8] Ultrasonic testing of all 69 CRDM nozzles using the “under-head” circumferential probe and subsequent confirmatory testing using the “top-down” tool revealed additional CRDM cracks in addition to those previously identified on Nozzle 3.

There were indications of cracking on five nozzles:

> “Nozzle 1 (location H8) – Axial cracks, some with pressure boundary leakage.
>
> Nozzle 2 (location G7) – Axial cracks, some with pressure boundary leakage, and a partial depth circumferential crack of approximately 30 degrees.
>
> Nozzle 3 (location G9) – Axial cracks, some with pressure boundary leakage.
>
> Nozzle 5 (location K7) – Small axial cracks, predominantly below the weld, no leakage but repairing require.
>
> Nozzle 47 (locationD12) - Small axial cracks, predominantly below the weld, no leakage but repairing require.”

The condition report summarizing this UT inspection noted that “UT results with the top-down tool also provide some evidence of carbon steel base metal corrosion at Nozzles 2 and 3”.[9] The extent of cracking noted in the UT tests, particularly Crack 1 in Nozzle 3, was significantly greater than expected for Davis-Besse, as discussed in Section 5.3.6 of this report.

## 4.2 March 2002 13RFO Discovery of Large Head Corrosion Cavity at CRDM Nozzle 3 and Minor Crevice Corrosion at CRDM Nozzle 2 in the RPV Head

On March 5, 2002, a large wastage cavity was discovered on the Davis-Besse RPV head between Nozzle 3 and Nozzle 11. This discovery, which was not part of the ordinary wear and tear expected for this component, was identified due to an unexpected tool movement that occurred during the repair of the cracked nozzles identified during the NDE examinations. Subsequent investigation revealed an additional small area of RPV head wastage adjacent to Nozzle 2.

### 4.2.1 Initial Discovery of the Corrosion Cavity in the Reactor Pressure Vessel Head

Nozzle repairs were initiated following the identification of cracks in Nozzles 1, 2, 3, 5, and 47 that were detected by non-destructive examination in response to NRC Bulletin 2001-01. During the course of these repairs on March 5, 2002, an unexpected movement of the nozzle boring tool of approximately 15 degrees occurred.[10] Evaluation of the bottom-up ultrasonic test data in the area of Nozzle 3 indicated significant, unexpected degradation of the reactor pressure vessel head pressure boundary.[11] Following the removal of Nozzle 3, a wastage cavity was discovered in the low-alloy steel RPV head on the down hill side of Nozzle 3 above the J-groove weld. The wastage cavity is shown in Figure 4.2.[12] The occurrence and the magnitude of the wastage of the RPV head was completely unanticipated. The relative location and size of the wastage cavity (with respect to the RPV head) is shown in Figure 4.3. This figure is a computer-generated image of the cavity on the RPV head.

The top portion of Nozzle 3 was removed and the RPV head was cleaned by hydrolasing. Subsequent video inspection of the wastage in the low-alloy steel near Nozzle 3 revealed material missing from the RPV head. The preliminary estimates of the dimensions of the cavity were that it was about 6-7 inches long and approximately 4-5 inches wide. The total volume of material removed is estimated to be about 200 cubic inches (approximately 3,000 cubic cm). These estimates are based on measurements taken from the dental mold images in the BWXT Services, Inc. report.[13]

A small area of wastage (annulus enlargement) was observed via video inspection of the RPV head near Nozzle 2. The crevice associated with this wastage is shown in Figure 4.4. This annulus enlargement, which was relatively minor, was found using hand-held video inspection techniques that were undertaken through access holes cut through the mirror insulation above the RPV head. Using a boroscope, subsequent video inspection of the interior of the small wastage area adjacent to Nozzle 2 was completed on March 9, 2002.[14] This video inspection showed that a majority of the material removal occurred below the surface of the RPV head and was not readily observable by video inspection of the top of the RPV head This observation is significant and will be addressed in detail in subsequent Sections 9 and 10 of this report.

### 4.2.2 Inspection and Metallurgical Analysis of the Nozzles and Corrosion Cavity

Detailed metallurgical analyses of the remaining portion of Nozzle 3 and the low-alloy steel and cladding material removed from the Davis-Besse RPV head were completed following the removal of a 17-inch diameter section of the head that encompassed the entire wastage area between Nozzle 3 and Nozzle 11 (Figure 4.2). These analyses were completed by BWXT Services, Inc. and summarized in a report dated June 2003.[12] The BWXT report provided the first detailed metallurgical analyses of Nozzle 3 material, the J-groove weld, and the low-alloy steel RPV head materials. One of the more significant findings associated with these analyses was the determination that the crack in Nozzle 3 had progressed into the J-groove weld, as shown in Figures 4.5 and 4.6.[15-16] This cracking of the J-groove weld resulted in an unexpected and significantly greater crack length (1.8 inch vs. 1.2 inch) than was initially identified by UT examination and reported in the Root Cause Report. The longer final crack length resulted in a much higher leak rate for Nozzle 3 than was anticipated by any previous analyses of CRDM nozzle leakage. The significance of this longer crack length will be discussed in detail in subsequent sections (Sections 8, 9 & 10) of this expert report.

Detailed examination of the wastage cavity was also completed as part of the BWXT Services analyses. Some of the most significant indications of various material removal mechanisms that resulted in the formation of the wastage cavity are found in the images of the cavity (Figures 4.5, 4.6, and 4.7).[17-19] These images show the surface morphologies at the final stage of cavity formation. These morphologies suggest a range of material removal mechanisms that range from mechanical removal (flow impingement) and flow-enhanced corrosion (corrosion/erosion) to general boric acid corrosion and molten metaboric acid corrosion. These mechanisms will be discussed in detail in subsequent sections (Sections 9 & 10) of this report.

## 4.3 Responses to the March 2002 Davis-Besse RPV Head Corrosion Cavity Discovery

Given the unexpected and unanticipated size and depth of the corrosion cavity at Nozzle 3 and its safety significance, the industry and regulatory response was wide ranging and comprehensive, and is still on-going today, almost five years after the event. The very scope of this effort speaks to the unexpected and unanticipated nature of the Davis-Besse RPV head wastage event and the complex factors that led to it. If the extent of the cracking and wastage could have been readily predicted or expected on the basis of pre-existing industry analysis and operating experience, clearly the event would never have happened.

We briefly review these responses to the Davis-Besse event and their relevance to the issues covered in this report in Sections 4.3.1 through 4.3.4 below.

### 4.3.1 FENOC Responses

The discovery of the large wastage cavity at CRDM Nozzle 3 was documented in a FENOC "Condition Report (CR)", which was issued on March 8, 2002[20]. The initial technical response by FENOC was the organization of a investigation team to determine the root cause and contributing factors for the major wastage damage at CRDM nozzle 3 and the minor wastage at Nozzle 2. The team was comprised of technical personnel from Davis-Besse and Beaver Valley[a], and consultants from Dominion Engineering, Framatome-ANP, and the EPRI MRP.

The team issued a four page preliminary "Probable Cause" report just two weeks later on March 22, 2002[21]. This preliminary report presented the "collective judgment of the team based on the data and evidence that has been characterized at this time (current to 3/22/02)." The team concluded that PWSCC of the Alloy 600 CRDM nozzle 3 had resulted in through wall cracks and boric acid wastage of the head. The team made the following prescient observation[22]:

> "**Probable Cause:** The factors that cause corrosion of the RPV head in the regions of Nozzles 2 and 3 are the CRDM nozzle leakage associated with through wall cracking, followed by boric acid corrosion of the RPV low-alloy steel….Since PWSCC of CRDM nozzles is a known damage mechanism of Alloy 600 materials, and similar corrosion as experienced near Nozzle 3 has not been reported from this cause at other nuclear plants, the "probable cause" does not provide the explanation for the extent of damage that occurred in the evolution of this incident."

We concur with this observation, since not only had wastage not been observed as a result of cracked CRDM nozzles at other plants, but a detailed and plausible explanation of the extent of

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[a] Beaver Valley was another two-unit PWR nuclear station operated by FENOC.

wastage at Davis-Besse CRDM Nozzle 3 is still the subject of considerable ongoing experimental and analytical work.

Notwithstanding this caveat, the team had already developed a "most probable timeline of key events" that directly led to the development of the wastage[23]:

- 1990 (+/- 3 years): CRDM nozzle crack initiated at Nozzle 3;
- 1994-1996: CRDM Nozzle 3 crack propagates through wall of nozzle;
- 1998 and 1999: Nozzle leakage not identified and boric acid not successfully removed from Nozzle 3 region;
- 1999: Noteworthy corrosion at Nozzle 3 of the RPV head initiated, as evidenced by iron oxide in the containment atmosphere;
- 2002: Significant corrosion discovered on RPV head at Nozzle 3, relatively minor damage discovered at Nozzle 2."

The event timeline was based "primarily on the video and photographic evidence of conditions on the head" from the various refueling outage records. The rate of corrosion progression was presented as follows[24]:

- 4 years of significant corrosion rates, based on evidence of boric acid accumulation on the head and other visual evidence, such as discoloration of the boric acid deposits, and increasing accumulation on the RPV flange;
- Up to 8 inches, maximum progression of corrosion area (from Nozzle 3 toward Nozzle 11), based on measurements of the cavity region;
- Average rate of 2 inches per year along line from Nozzle 3 toward 11;
- For the purposes of bounding rate assumptions, a linearly increasing rate results in a maximum rate of 4 inches per year;
- Rate in lateral direction is about ½ of that in axial direction.

This estimate for how long wastage had been developing on the RPV head was noted to be compatible with test results reported in the EPRI Boric Acid Corrosion Guidebook, and was also “consistent with the video, photographic and other plant data, that show that significant corrosion was occurring by the 1996 to 1998 timeframe.”

The team published the initial version of the full Root Cause Report Analysis Report two weeks later on April 8, 2002[25]. This report was a commendable and thorough technical effort given the short time that had elapsed since the discovery of the wastage cavity at CRDM Nozzle 3. Although considerable detailed discussion was added, both the event timeline and the estimate of wastage progression remained the same as presented in the preliminary March report [26].

Revision 1 to the Root Cause Analysis Report was issued as the final report on August 27, 2002[27]. This revision was issued to incorporate the results of investigations and analyses that were still not complete in April, 2002. The principal technical change was the addition of a section describing the analyses of boric acid and corrosion product samples recovered from the RPV head. Some discussion was added to the qualitative description of the four postulated stages in the development of the wastage cavity, but other changes were relatively minor[b]. Again, both the event timeline for the development and growth of the CRDM nozzle crack and the development of the wastage cavity were unchanged from the initial March version[28].

The root cause report first contains an “Event Narrative” (Section 2) that presents a detailed sequence of relevant plant and industry events from 1980 through 2002. The “Data Analysis” (Section 3) is organized into a number of major sections, each of which addresses important technical areas relevant to the event.

**Section 3.1** presents the results of non-destructive examination (NDE) of the RPV head (visual) and CRDM nozzles (UT), and the results of analyses of boric acid and corrosion product samples from the RPV head.

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[b] A major organizational change in Revision 1 of the root cause report in August was the removal of the sections dealing with “management and human performance”, which were being published in a second root cause report. Here we are concerned principally with the technical analysis of the plant data and other evidence related to the wastage cavity development.

**Section 3.2.1** presents a summary of CRDM cracking experience and RPV head wastage at other plants, the factors involved in PWSCC, a comparison of the Davis-Besse CRDM nozzle material properties and cracking to these data.

**Section 3.2.2** discusses leakage rates through CRDM nozzle cracks, calculated crack leakage vs. crack length, and the possible contribution of CRDM nozzle crack leakage to the measured unidentified leak rate at Davis-Besse between November 1994 and February 2002.

**Section 3.2.3** discusses the sources and volume of boric acid on the Davis-Besse RPV head and summarizes the Davis-Besse plant experience with leaking CRDM flanges.

**Section 3.2.4** is a key section of the report, which presents the root cause team's qualitative description of the development of the crack, leakage and wastage cavity at CRDM Nozzle 3. As the report points out[29]:

> "Given the current limited experimental data applicable to the observed degradation and a the lack of existing detailed analytical calculations of the thermal-hydraulic and thermo-chemical environment along the nozzle leak path, it is not possible to definitely state the exact progression of mechanisms that led to the observed material loss."

After describing the many complex thermal hydraulic processes involved, the report goes on to outline a "viable" progression of events in four postulated stages for the development of the wastage cavity[30]. We address these in detail in Section 6.4.1, where we describe the EPRI test program that was undertaken as a result of the Davis-Besse event, and which adopted the same qualitative description of the cavity development as the FENOC root cause report. We also examine them further in Section 9, where we describe the modeling work that we undertook for this report to develop a better understanding of the thermal hydraulic conditions, both in the initially tight annular crevice and in the wastage cavity as it developed, and in Section 10, where we present our own timeline for the wastage cavity development and growth.

**Section 3.3.1** presents the graphical timeline of key events relevant to the cavity formation from 1995 through 2002.

**Section 3.3.2** is a detailed tabular sequence of relevant plant events from 1980 through 2002 on which the timeline was based.

**Section 3.3.3** presents a detailed history of CRDM flange leakage, repair and the video and photographic evidence of boric acid accumulations on the RPV head at refueling outages between 1990 and 2000.

**Section 3.3.4** describes the containment air cooler cleanings that were required between 1992 and 2002 as a result of boric acid fouling.

**Section 3.3.5** discusses the indications from the containment building radiation monitors and plugging of the monitor filter.

**Section 3.3.6** discusses the possible contribution from failure of the containment fans to iron in the containment atmosphere.

**Section 3.4.1** presents a summary overview of industry and regulatory responses to the major issue of PWSCC of Alloy 600 and the associated problem of CRDM nozzle cracking.

**Section 3.4.2** presents a summary overview of industry and regulatory responses to the major issue of boric acid corrosion (BAC) of carbon steel components, and the Davis-Besse BACC program.

**Sections 3.4.3 and 3.4.4** briefly discuss respectively the Davis-Besse In-Service Inspection (ISI) program and some of the relevant Condition Reports (CRs) relevant to the finding of boric acid on the RPV head.

**Section 3.5** is brief summary of RPV head inspection requirements and restart readiness after refueling outages at Davis-Besse.

**Section 3.6** presents the final summary of the causal factors and conclusions concerning the wastage, based on the prior detailed sections of the root cause report.

While we relied upon the root cause report both as an invaluable account of the factual evidence, and as a reference to the extensive documentation that was collected, we have conducted our own independent analysis of many of the same issues. These are presented in Sections 4 through 10 of this report.

We highlight here two principal areas where our analysis results differ from those presented in the root cause report.

**Crack Growth Rates:** In arriving at the timeline of the Nozzle 3 crack initiation (1990 +/- 3 years) and progression to through wall leakage 1995 +/- 1 year), the root cause report used a crack growth rate (CGR) of 4 mm/year derived from industry median curves for Alloy 600 developed by EPRI and others[31].

We disagree with this assumption for two reasons. First the Alloy 600 heat M3935 from which Davis-Besse Nozzles 1 through 5 were manufactured was the same heat from which 68 of the 69 CRDM nozzles at Oconee-3 were manufactured, and Oconee-3 experienced the most severe CRDM nozzle cracking of any of the B&W plants, which in turn, as a group, experienced more serious CRDM cracking than Westinghouse or CE designed plants.

Second, recently published work by the NRC and ANL reports actual measurements of metallurgical properties, including CGRs, for samples of Alloy 600 material specifically from Davis-Besse Nozzle 3. These data show that Nozzle 3 exhibits crack growth rates at the 95th percentile of the measured CGRs for Alloy 600 samples. In simple terms, the Nozzle 3 Alloy 600 material has higher crack growth rates at the same stress levels than other heats of Alloy 600. The CGR aspect of our work is described in detail in Section 8 of this report.

**Thermal Hydraulic Conditions:** The technical root cause report develops only a qualitative analysis and description of the progression of the wastage cavity from the initial tight annulus condition to the final state of the large wastage cavity at CRDM Nozzle 3. To explain the final cavity size, an “average” boric acid wastage rate of 2 inches per year over 4 years is used, with a maximum wastage rate of 4 inches per year. For the initially “tight” annular crevice, the root cause report cites wastage rates in the 0.02 to 0.08 inches per year for “similar geometry”, and up to 2.5 inches per year for a 50 mil annulus gap.

Again, we disagree with these assumed corrosion rates, and again for two reasons. First, while we agree that these various assumed rates of wastage are within the range of measured test results reported in the EPRI Boric Acid Corrosion Guidebook, we note that wastage rates in the same EPRI Guidebook are reported as being as high as 8 inches per year for concentrated, aerated boric acid solutions where the temperature is in the 200 to 230 deg. F range, and up to 11 inches per year in impingement tests in the same temperature range where erosion/corrosion is the prevalent mechanism metal removal (see Section 6.3) .

The CFD modeling of the thermal hydraulic conditions in the initial annular crevice and the developing cavity that we have undertaken shed considerable light on the range and direction of fluid velocities, as well as the temperature, moisture/dryout, and other thermal hydraulic conditions in the crevice and wastage cavity as it developed.  These results, which we describe in detail in Section 9 of this report, have allowed us to make more informed judgments as to the possible metal removal rates by mechanical, erosion/corrosion, and boric acid wastage as the annulus enlarges and the wastage cavity develops, which we believe to be much higher than those assumed in the root cause report.  We describe the CFD work we have undertaken in Section 9 of this report.

Second, the results of corrosion tests have recently been reported by the NRC and ANL for three sets of conditions that are considered to be relevant to the Davis-Besse wastage cavity growth (see Section 6.4.2).  One of the sets of conditions investigated was molten boric acid re-wetted by moisture, a condition for which there was previously no published data, and for which the NRC/ANL test data show wastage rates of up to 6 inches per year.  Based on our modeling results, these recent test data are relevant to conditions in the annulus and the wastage cavity.

These differences – Davis-Besse Nozzle 3 specific Alloy 600 CGRs much higher than assumed in the root cause report, a better understanding of the thermal hydraulic conditions in the crevice and cavity, and higher metal removal rates under certain thermal hydraulic conditions, lead us to the conclusion that the development of the large crack at Davis-Besse Nozzle 3 and the subsequent wastage cavity development occurred in a much shorter time frame than the root cause report concluded.  We provide a detailed discussion of our conclusions about the Nozzle 3 crack and wastage cavity development in Section 10 of this report.

### 4.3.2 EPRI Materials Reliability Program (MRP) Response

The principal response to the Davis-Besse event by the industry was organized by the EPRI Materials Reliability Program (MRP). One of the major efforts undertaken by EPRI was the totally revised safety assessment -MRP-110 report[32] - that we have relied on heavily for inspection data from US PWR plants, which is presented in Section 5.3. We do not have access to the individual plant data for proprietary reasons, and MRP-110 contains the most complete summary of inspection data through 2003 that we have found.

MRP-110 also contains the updated safety assessment of RPV head penetration nozzles for US plants that was prepared to replace the prior safety assessments performed first by the various owners groups such as BWOG, and after about 1998, by the EPRI MRP. The MRP-110 report is the “top level” document for the industry safety assessment, and replaced the interim safety assessment report (MRP-44, Part 2), which was issued in May 2001 (see Section 5.3.6)

MRP-110 covers inspection experience, Failure Mode and Effects Analysis (FMEA), stress analysis, allowable crack sizes and wastage volumes, nozzle ejection analysis, consequential damage assessment for failed nozzles, various modeling studies, and RPV head replacements.

This safety assessment includes, for the first time, a detailed assessment and preliminary model of the RPV head wastage process that can result due to leakage from cracked head penetration nozzles, and this again provided us with much valuable information, analysis and data for our modeling efforts.

Underlying MRP-110 are a large number of proprietary EPRI MRP reports dealing with various aspects of the MRP-110 safety assessment, including the nozzle ejection assessments for B&W, Westinghouse, and CE plants (MRP-103, MRP-104, and MRP-105), crack growth rate evaluation (MRP-55, MRP-21), PWSCC in Alloy 600 (MRP-77), inspection guidance and demonstration reports (MRP-95, EPRI 1007842 and MRP-89), and MRP-111, which evaluates the expected performance of the replacement head materials such as Alloy 690 nozzles and Alloy 52 welds.

One of the MRP efforts is the experimental investigation of the boric acid corrosion processes that can occur under various thermal hydraulic and thermo-chemical environments that have been postulated to occur in the annular crevice around a CRDM nozzle (see Section 6.4.1). This work is intended to provide some definitive data and information from full size crevice mock-ups of the Davis-Besse Nozzle 3 annulus, to better explain how the wastage cavity developed over time and how fast it developed.

## 4.3.3 Regulatory Response

The US NRC response to the discovery of the large wastage cavity at Davis-Besse Nozzle 3 was also wide ranging. First, the NRC issued Information Notice 2002-11 on March 12, 2002, which simply provided the available factual information to PWR licensees concerning the event[33].

### NRC Bulletin 2002-01

The Information Notice was followed a week later on March 18, 2002 by NRC Bulletin 2002-01[34], which provided additional information about the size of the wastage cavity at CRDM Nozzle 3, and the preliminary conclusion that this resulted from boric acid corrosion from the cracked CRDM Nozzle 3. The bulletin noted that other plants that had experienced through wall cracking and leakage at CRDM nozzles had not reported RPV head wastage, but further noted that some of the inspection methods and techniques used would not have detected RPV head wastage even had it been present.

In discussing the boric acid corrosion programs instituted in response to Generic Letter 88-05, Bulletin 2002-01 clearly sets forth what the industry consensus was prior to the Davis-Besse event concerning the significance of boric acid leakage onto the RPV head:[35]

> “Historically, these programs have assumed that there is only a small potential for wastage of the reactor pressure vessel head attributable to leakage of primary coolant through the vessel head penetration nozzles. The supporting analyses assumed that coolant escaping from a penetration would flash to steam, leaving behind deposits of boric acid crystals.
>
> Typically, these crystals are assumed to accumulate on the reactor pressure vessel head; however, such deposits are assumed to cause minimal corrosion while the reactor is

> operating because the temperature of the reactor pressure vessel head is above 500 F during operation, and dry boric acid crystals are not very corrosive.
>
> Therefore, wastage is typically expected to occur only during outages when the boric acid could be in solution, such as when the temperature of the reactor pressure vessel head falls below 212 F. However, the findings at Davis-Besse bring into question the reliability of this model."

PWR licensees were required by Bulletin 2002-01 provide information within 15 days concerning RPV head inspections and any significant findings relevant to the Davis-Besse event findings, and projected plans and schedules for future RPV and CRDM nozzle inspections. Licensees were further required to submit all relevant inspection findings within 30 days after plant restart following these inspections, and the licensees' basis for concluding that the requirements of Generic Letter 88-05 concerning BACC programs were being met.

### NRC Augmented Inspection Team (AIT)

On March 12, 2002, the NRC dispatched an "Augmented Inspection Team (AIT)" [c] to the Davis-Besse plant site[d]. The charter of the AIT team was to[36]:

> "…..better understand the facts and circumstances related to the degradation of the reactor vessel head pressure boundary material. It is also to identify any precursor indications of this condition so that appropriate followup actions can be taken."

The AIT finished its onsite work on April 5, 2002, and completed a report of its "fact-finding" inspections which was forwarded to FENOC on May 3, 2002.[37]

The AIT report provided a description of the event, the nozzle cracking and wastage areas, a discussion of the "probable cause", a history both of inspections of the RPV head pursuant to the GL 88-05 BACC program and of the CRDM leakage problem at Davis-Besse, and a list of "opportunities for early detection of head degradation."

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[c] One of the two Davis-Besse resident inspectors who was in the process of conducting the February 16, 2002 through March 31, 2002 inspection was also assigned as a member of this team.

[d] This was apparently done in accordance with NRC Management Directive 8.3, "NRC Incident Investigation Program."

It is not our intent to critically examine all aspects of the AIT report, and our comments are focused those aspects of the AIT report that concern the nozzle crack and wastage cavity development at CRDM Nozzle 3, and the apparent basis for the conclusions reached by the AIT.

After presenting the results of the UT inspection of the CRDM nozzles and a summary of the cracks at Nozzles 1, 2, 3, 5, and 47[38], the AIT concluded that the cracks "which extend for the greatest distance above the J-groove weld are potentially the oldest cracks."[39] The AIT further noted that the longest crack discovered by the UT inspection was listed as being 1.3 inches above the weld at Nozzle 3, and that this was therefore likely to be the oldest crack in Nozzle 3.[40]

The AIT also noted that four of the cracked nozzles (1, 2, 3, 5) were manufactured by B&W from the same M3935 heat of Alloy 600 as the CRDM nozzles at Oconee-3, where 14 of 68 nozzles made from the same heat of material had experienced cracking, and that the nozzle cracking at Davis-Besse was "likely caused by PWSCC", as it was at Oconee-3.[41]

The AIT report does not mention the fact that the analysis performed by the EPRI MRP in response to NRC Bulletin 2001-01 (see Section 7.1.2) showed that as of March 1, 2001, Davis-Besse was 3.1 EFPY away from having CRDM cracks similar to those found at Oconee-3, and on that basis should not have had significant cracking in 2002. Neither does the AIT report mention the unexplained fact that the longest cracks in Davis-Besse Nozzles 3 and 2 were much longer than any found at Oconee-3.

The AIT report describes the FENOC March 22, 2002 preliminary root cause conclusions (see Section 4.3.1) that "the cracking initiated in Nozzle 3 in 1990 (+/- 3 years) and the crack had propagated through-wall between 1994 and 1996", but does not make any independent determination itself concerning this crack development timeline.[42]

With respect to the wastage cavity at Nozzle 3, the AIT noted that the longest of the two cracks in this nozzle "was on the downhill side of Nozzle 3 in direct alignment with the long dimension of the cavity," and therefore that "the cavity observed on Nozzle 3 was associated with boric acid corrosion from crack induced leakage at this nozzle." The AIT further concluded that “based on corrosion products observed on the head and in the containment air coolers and radiation element filters, the corrosion process had been in progress for at least 4 years.”[43]

In its discussion of the much smaller wastage cavity at Nozzle 2, the AIT report notes that detailed examination and characterization of this region was still underway, but concludes that “for Nozzle 2, the crack with the longest dimension above the J-weld was also located in the same area as the observed area of metal loss behind this nozzle”.[44] As we explain in Section 8.1, this conclusion is in fact erroneous.

The AIT report does not explain the lack of wastage adjacent to the other through wall cracks in Nozzle 2, neither does the AIT report address the fact that while Nozzle 2 had five through wall cracks, the largest being 1.0 and 0.8 inches above the weld, the wastage at this nozzle was insignificant compared with the wastage at Nozzle 3, which was centered on the single crack 1.3 inches in extent above the weld. Like the crack at Nozzle 3, these cracks at Nozzle 2 were much longer than any previously found at B&W plants.

With respect to boric acid corrosion rates, the AIT report includes a brief summary of the published corrosion rate data, notes that corrosion rates ranged from 0.019 inches per year at 500 deg. F up to 4.8 inches per year at “lower temperatures”, but provides no discussion as to what rates are applicable to potential conditions in the annulus around the CRDM nozzles.[45]

The AIT report also briefly discusses the nozzle crevice tests conducted by CE and EPRI, which are reported in the 1995 and 2001 EPRI Boric Acid Corrosion Guidebooks.[46] We defer our own discussion of these tests and their applicability to the CRDM nozzle and annulus geometry to Section 6.3.2 of this report, but note here that there are a number of issues related to the test configurations and unexplained features of the test results that the AIT does not address.

The AIT simply states, without supporting rationale, that the EPRI crevice test “was performed utilizing a configuration, temperature, materials and leak rates which more closely matched the CRDM nozzle to vessel configuration” than the earlier CE test.[47] We disagree with this observation, since the CE test was performed with a pressurized tube containing an actual through wall leaking crack, whereas the EPRI test used a nozzle injection into the annulus to direct a jet of boric acid against the OD of a blank nozzle (see section 6.3.2).

After noting that the EPRI crevice test identified a corrosion rate of up to 2.37 inches per year, the AIT went on to note that the EPRI crevice test[48]:

> "…..also indicated that the maximum corrosion occurred at the location where the boric acid entered the annulus gap. The contour of the degradation observed at Nozzle 2 and Nozzle 3 appeared to support this test result."

This observation is erroneous, as is evident from our description (in Section 4.2 above) of the location of the wastage area at CRDM Nozzle 2. First, the small area of wastage lies above the upper end of the three nearest axial cracks. Second, there are seven cracks above the weld with leak paths (six of them through wall) that are distributed around the nozzle circumference, and only three of these are close to the wastage area. Third, the two cracks with the longest effective crack lengths for leakage are around 180° away from the wastage area.

After the section on "probable cause" of the nozzle cracking and head wastage discussed above, the AIT report goes on to present a detailed discussion of the history of CDRM flange leakage at Davis-Besse, and the significance the AIT attached to this chronology. This is followed by descriptions of the containment air cooler and radiation monitor filter fouling, and the AIT's conclusions as to the relevance of these to the wastage at CRDM Nozzle 3 and 2. We defer our discussion and analysis of these issues to Section 7.3 of this report.

In summary, the conclusions presented in the AIT report with respect to the causes and timing of the cracking at CRDM Nozzles 2 and 3 as well as the wastage at these two nozzles are essentially the same as those reached by FENOC's root cause team as early as March 22, 2002 that we discussed above in section 4.3.1.[e] As we have noted briefly above, the AIT does not reconcile its conclusions with some of the obvious facts, and it also does not provide the reasoning that led it to some of its more significant conclusions concerning the nozzle crack growth rate and the wastage cavity development.

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[e] We do not know if the AIT simply adopted the FENOC root cause team's conclusions, or whether the AIT independently reached the same conclusions with respect to the timeline of crack growth and wastage cavity development.

### NRC Lessons Learned Task Force (LLTF)

A longer-term effort was undertaken by the NRC's "Lessons Learned Task Force (LLTF)", which was established on May 15, 2002, and which published its report on September 30, 2002[49]. The overall objective and charter of the LLTF was to "independently evaluate the NRC's regulatory processes related to assuring RPV head integrity in order to identify and recommend areas for improvement that may be applicable to either the NRC or the nuclear industry."[50]

The LLTF report is a lengthy document that addresses many of the industry and regulatory aspects of the Davis-Besse event, and the NRC and industry approach to the problems posed by CRDM nozzle cracking and boric acid wastage. Much of this, particularly the regulatory aspects, is beyond the scope of our work, and we highlight here just two conclusions from the LLTF report with which we agree. First, with respect to the Alloy 600 CRDM nozzle cracking issue, the LLTF concluded that: [51]

> "Because the NRC and nuclear industry concluded that Alloy 600 VHP nozzle cracking was not an immediate safety concern, the NRC and the industry's efforts to further evaluate this issue became protracted. Also, the NRC and industry continued to rely on visual inspections of VHP nozzles. These inspections are incapable of characterizing the extent of nozzle cracking and damage. While the industry initiated actions to improve non-visual inspection capabilities, the requirements governing inspections remained unchanged."

Until the Oconee-3 discovery of circumferential cracking in 2001, the US approach was to wait until CRDM nozzle cracks became so large that they resulted in boric acid leakage, and only then inspect to determine the extent of the cracking.

Second, with respect to the issue of RPV head wastage due to boric acid leakage Alloy 600 CRDM nozzle cracking issue, the LLTF concluded that: [52]

> "The NRC and the industry regarded boric acid deposits on the RPV head as an issue that required attention; however, the NRC and industry did not regard the presence of the

> boric acid deposits on the RPV head as a significant safety concern because they expected that boric acid crystals would form from flashing steam and such crystals would not cause significant corrosion of RPV heads."

This is similar to the prevailing industry and NRC view of the low safety significance expressed in NRC Bulletin 2002-01. Until the Oconee-3 experience in 2001 showed that the leakage of boric acid from even large through wall CRDM cracks could be miniscule, could easily be masked by other leakage, and might even have been missed for a fuel cycle at Oconee-3, there was little attention paid to this aspect of leakage detection from cracked CRDM nozzles.

Like the AIT report, the LLTF report has a lengthy section describing the history of CDRM flange leakage at Davis-Besse and associated boric acid deposits on the RPV head, the containment air cooler and radiation monitor filter fouling, and the LLTF's conclusions as to the relevance of these plant indicators to the nozzle cracks and RPV head wastage at CRDM Nozzle 3 and 2[53].

We defer our detailed discussion and analysis of these issues to Section 7.3 of this report. However we note here that there is no support in the LLTF report for their inference that boric acid observed on the RPV head during 9RFO (1994)[54] and 10RFO (1996)[55] resulted from leakage through CRDM nozzle cracks. It is simply presented by the LLTF in its report without any substantiating discussion or analysis to show that through wall and leaking CRDM cracks were actually present at those two outages.

While the Toledo Edison Company response to GL 88-05 is a subject that we address in more detail later in section 6.2, with respect to the Toledo Edison/Davis-Besse BACC program, we note here that at the time of its initial development and implementation, the specific Davis-Besse procedure at issue was[f]:

- Submitted to the NRC in September 1989 as part of Toledo Edison's response to GL 88-05, and was reviewed and judged to be satisfactory by the NRC when it closed out the Toledo Edison response;

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[f] We discuss the development of the plant procedure NG-EN-00324 itself from its inception in September 1989 through to the October 1999 Revision in Section 7.1.1.

- Reviewed by a joint NRC/BNL team in late 1989 as one of ten plants selected for onsite audit for appropriate compliance with the requirements of GL 88-05, and determined to be "satisfactory".

- Reviewed and judged to be a "good approach to reducing the degree of leakage and resulting corrosive damage" by B&W in December 1990;

According to the LLTF report, the NRC specifically implemented its own procedure in August 1991[g].. The apparent intent of the procedure was to provide guidance to NRC resident inspectors in their evaluation of the effectiveness of PWR licensees' boric acid corrosion control programs, and their compliance with the requirements of GL 88-05[56].

However, the NRC procedure was apparently never performed at Davis-Besse by the NRC resident inspectors assigned to the plant, and was so "infrequently implemented" by NRC resident inspectors at other PWR plants that it was cancelled in September 2001[57]. At the very time this cancellation occurred, the NRC and the PWR industry were heavily involved in responding to the discovery of CRDM nozzle cracking at the Oconee plants, and to the requirements of NRC Bulletin 2001-01. At that time, the GL 88-05 BACC programs were the primary means relied upon by the NRC and the industry for the identification of CRDM cracks and leaks.

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[g] This was identified in the LLTF report as NRC Inspection Procedure IP 62001, "Boric Acid Corrosion Prevention Program", August 1991.

Figure 4.1 Boric acid and iron oxide flowing from mouse holes at 12RFO.[5]

Figure 4.2 Davis-Besse RPV head wastage cavity found adjacent to Nozzle 3.[12]

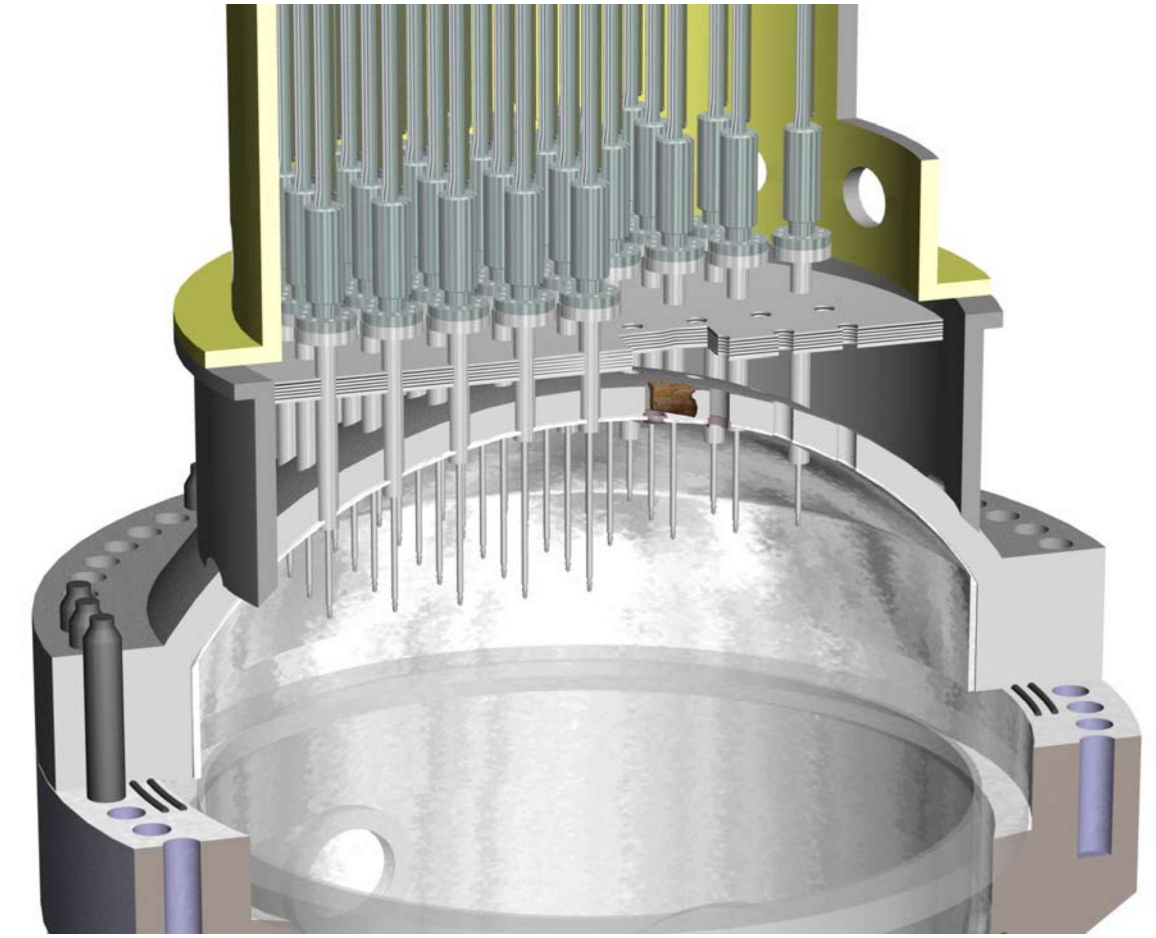

Figure 4.3 Location of RPV head wastage on the downhill side of Nozzle 3.

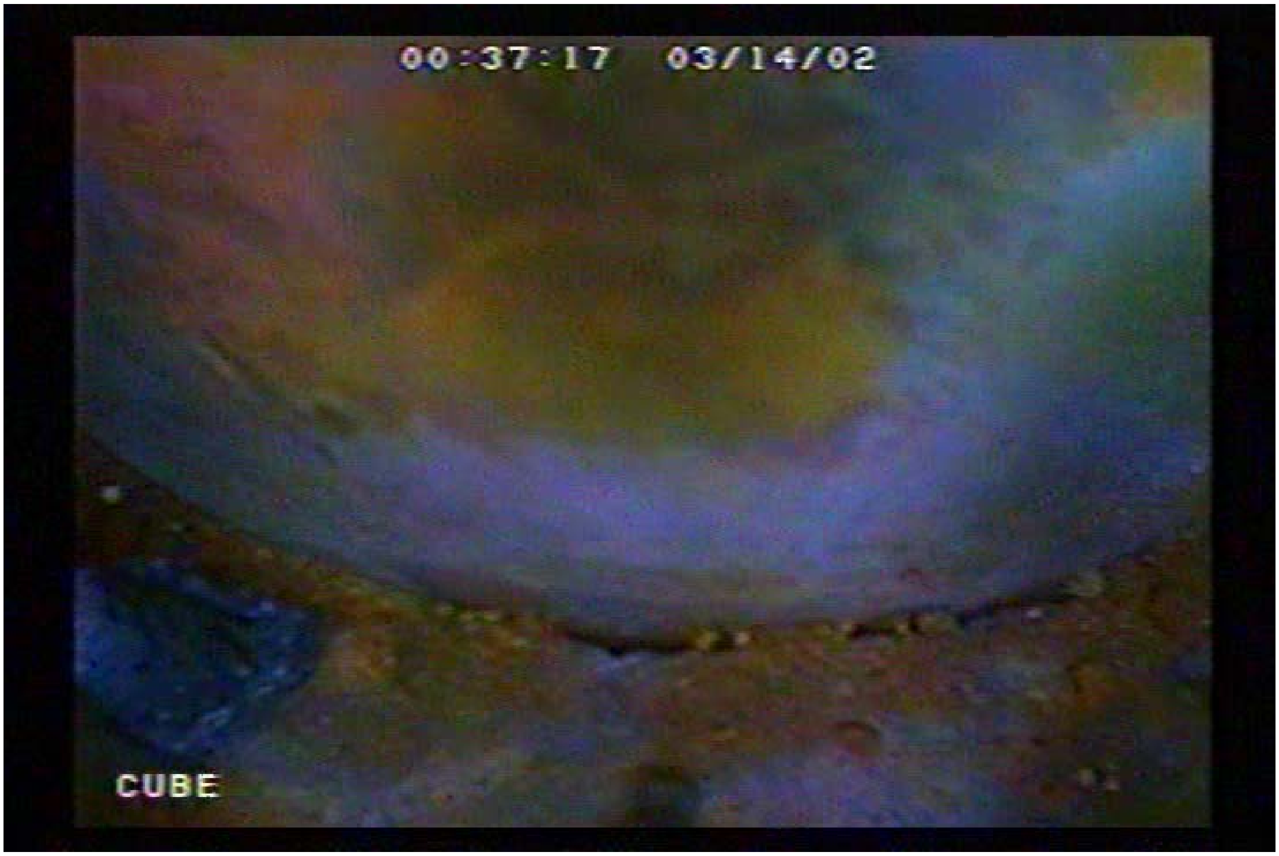

Figure 4.4 Crevice identified by inspection of Nozzle 2 with a hand-held video camera following the removal of a section of mirror insulation.[14]

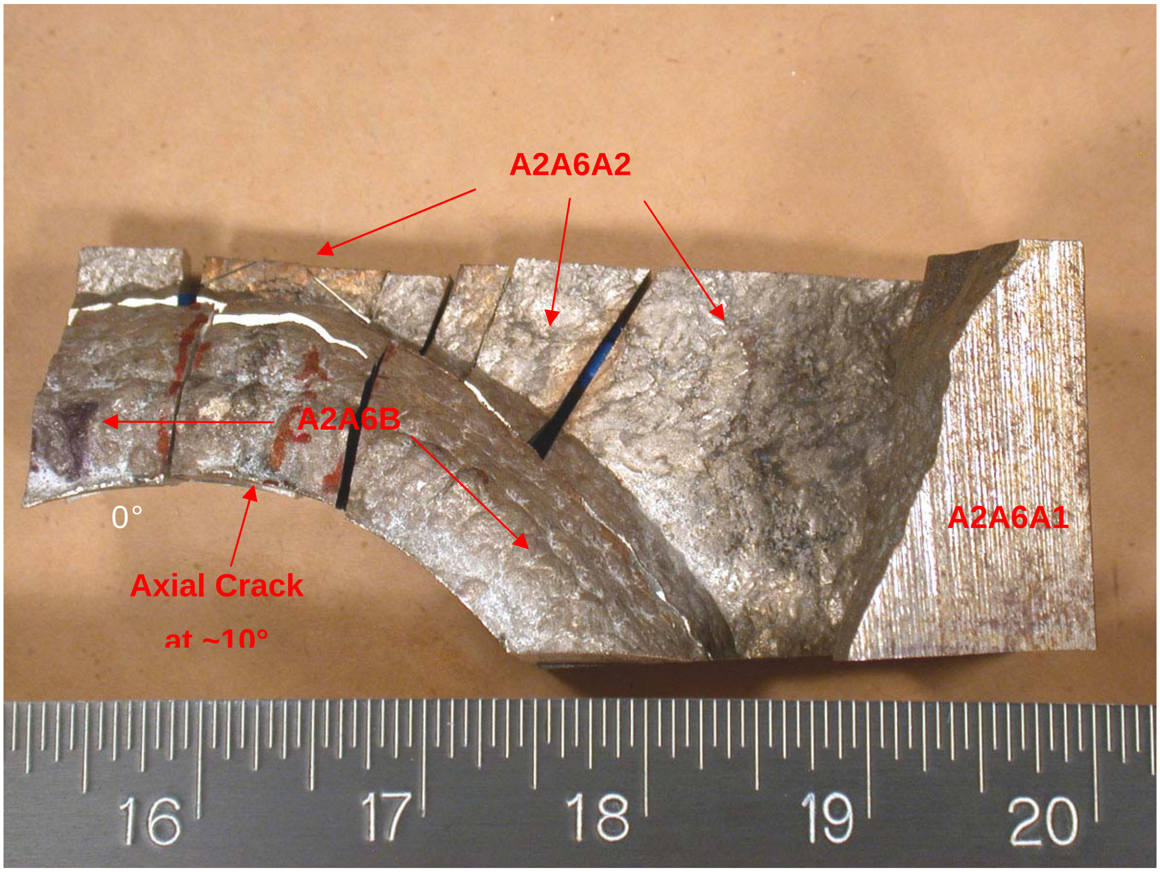

Figure 4.5 Portion of the J-groove weld with the 10-degree crack.[15]

Figure 4.6 J-groove weld with the 10-degree crack showing crack and flow channel.[16]

Figure 4.7 Surface morphology of the Davis-Besse RPV head wastage cavity looking toward the nose of the cavity (~10-degree).[17]

Figure 4.8 Surface morphology of the Davis-Besse RPV head wastage cavity looking toward the 90-degree side.[18]

Figure 4.9 Surface morphology of the Davis-Besse RPV head wastage cavity looking toward the 270-degree side.[19]

## 4.4 References

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