7. FENOC/Davis-Besse Response to CRDM Cracking and Boric Acid Corrosion Issues

In this section of the report, we summarize our review in three areas that are relevant to the key technical issues of CRDM nozzle cracking and leakage. The purpose of this review is to provide a detailed summary of the events and conditions leading to the formation and discovery of the wastage cavity near CRDM Nozzle 3 in the Davis-Besse RPV head in March 2002.

The unexpected and unforeseen nature of this event is highlighted by the fact that, prior to the Davis-Besse event, the primary focus of the industry and regulatory effort was on the potential for CRDM circumferential cracking and control rod ejection. This effort focused on predicting, detecting and repairing cracks before CRDN nozzle failure could occur as a result of the cracking.

While the potential for boric acid corrosion of the RPV head was considered, it was not regarded as a significant or a safety issue until the 2002 Davis-Besse event. The history of CRDM flange leaks as noted in Section 7.3, and the response of the industry (and Davis-Besse) to the boric acid corrosion issues raised by the NRC, show that the magnitude of the CRDM crack in Nozzle 3 and the wastage that resulted from that crack were both unanticipated and unforeseeable.

First, in Section 7.1, we briefly review the responses by FENOC and Toledo Edison, the prior owner and licensee of the Davis-Besse plant, to the industry issues of CRDM nozzle cracking and boric acid corrosion, in particular NRC Bulletin 88-05, Generic Letter 97-01, and Bulletin 2001-01, which addressed these issues.

In Section 7.2, we review the installed methods of RCS leak detection at the Davis-Besse plant. In conjunction with the implementation of a boric acid control program and visual inspections for leaks that could only be carried out during plant shutdowns, the leak detection systems were the primary means – mandated by the NRC Technical Specifications for the plant - by which Davis-Besse and the US PWR industry monitored the RCS for primary coolant leakage during operation.

In Section 7.3, we present the results of our review of documentation describing the refueling outage activities from 8RFO in March/April 1993 through 13RFO, which began in February 2002, and during which the large wastage cavity in the RPV head at CRDM nozzle 3 was discovered. Our focus in this review was on the video inspections of the RPV head, CRDM flange and other RCS leakage, and the

NRC's and Framatome's awareness of these activities. We also review the available data and information from the leak detection and other systems for the operational periods between refueling outages in order to extract quantitative estimates and qualitative indications of possible leakage from CRDM nozzles.

7.1 Davis-Besse Actions and Responses to Key US NRC and Industry Initiatives

Here we briefly review the responses by Toledo Edison, FENOC and the Davis-Besse plant to the major industry and NRC initiatives that are relevant to the detection of boric acid corrosion and CRDM cracking and nozzle leakage. We have already covered much of this at the generic industry level in Sections 5 and 6 of this report, where we described the BWOG support and input in these two critical areas.

Toledo Edison and FENOC, like most US PWR licensee owners and operators, relied heavily on the major vendors – B&W, Westinghouse and CE – not only for technical support in addressing industry wide issues, but also in providing plant specific responses to NRC imposed Bulletins, Orders and other NRC information requests.

Until the establishment of the EPRI MRP in 1998, US utilities and their NSSS vendors organized "Owners Groups" to coordinate actions and programs to respond to generic issues such as those related to Alloy 600 and other materials. This approach allowed for the sharing of information and experience between individual utilities, established a common technical basis to address issues that affected all plants, and allowed the costs of major programs to be shared.

In 1998, since many of the issues related to materials – particularly those related to Alloy 600 cracking - were common to all three US vendors, these individual Owners Group efforts were combined under the EPRI Materials Reliability Program (MRP).

While there were many industry materials issues that arose over the 1990 to 2002 time frame, we focus here just on the two issues of CRDM nozzle cracking and boric acid corrosion of carbon and low alloy steel components.

7.1.1 Davis-Besse Response to NRC Bulletin 88-05 and the Implementation of a Boric Acid Corrosion Control Program

As we discussed in Section 6.2, the primary industry response to the requirements imposed by NRC GL 88-05 was the implementation of formal boric acid corrosion control programs and procedures.

At Davis-Besse, this requirement was met through the development and implementation of a “Boric Acid Corrosion Control” (BACC) plant procedure NG-EN-00324, which was first issued and made effective on September 8, 1989[1]. The “Commitment” section of the procedure notes that the procedure was being implemented in response to GL 88-05[2].

The “Purpose” Section of the procedure repeats the four key requirements imposed by GL 88-05 (see Section 6.2)[3]:

- Identification of principal locations where leaks can cause degradation of the primary pressure boundary by boric acid corrosion;
- Procedures for locating small coolant leaks;
- Methods for conducting examinations and performing engineering evaluations to establish the impact on the reactor coolant pressure boundary when leakage is located; and
- Corrective actions to prevent recurrences of detected boric acid leaks.

The “References” section[4] includes a number of the key industry reports and events that were available at the time which were discussed in Section 6.2 of this report, such as EPRI NP-5985[5], NUREG/CR-2827[6], and NUREG-1095, the NRC evaluation of responses by utilities to Bulletin 82-02[7].

In the “Responsibilities” section, the procedure defines the appropriate Toledo Edison personnel responsible for the identification, reporting, evaluation, and implementation of corrective actions in the event a boric acid leak was found[8]:

- The Shift Supervisor in the Plant Operations group for determining plant operating response to the identification of a leak;

- The Systems Engineering group for performing the necessary inspections, removal of boric acid, and determining the root cause of any identified leakage;
- The Design Engineering group for determining the extent of any corrosion damage, performing appropriate engineering evaluations and analyses, and the determining the appropriate immediate and long term actions required to prevent a recurrence of the leakage.

Section 6.0 of the Toledo Edison procedure provides detailed guidance for the above actions:

Leak Locations: The procedure stresses that boric acid leaks can occur from any systems or components containing reactor coolant under pressure, and provides a list of "principal locations" for probable leakage[9]. The lack of industry attention in 1989 to the potential for CRDM nozzle cracks (the 1991 Bugey-3 leak was yet to occur) is evidenced by the inclusion of "CRDM flanges" – already a problem with the B&W CDRM design - on the list of "principal locations" but not the actual nozzles.

Leak Detection: The procedure emphasizes the need for vigilance in identifying small leaks from boric acid deposits in the reactor containment building during routine operation, during special plant operations such as pressure tests, startup, shutdown, and preventive maintenance, as a result of actions triggered by the plant leak detection systems[10].

Inspection and Evaluation: The procedure requires the Toledo Edison Systems Engineering group to perform a thorough inspection of the leak location to determine and document the components affected by the leak, evaluate any immediate or long term safety concerns, clean-up the boric acid deposits, document the cause of the leakage, issue a "Maintenance Work Order (MWO)" for component repair if the leak was straightforward, or a "Potential Condition Adverse to Quality (PCAQ)" report if the leak required engineering evaluation and possibly plant modifications to provide the appropriate long term corrective action[11].

Corrective Action: If a PCAQ had been issued, the procedure provides for the engineering evaluation of the condition to assess component damage, determine the corrosion rate, take into account industry experience as documented in the industry reports listed in the "References" section, and develop design changes where appropriate[12]. MWOs and PCAQs were to be processed in accordance with the relevant Toledo Edison quality assurance management procedures[13].

Overall, the initial issue of the procedure provides an appropriate framework and guidance for meeting the requirements imposed by NRC GL 88-05.

We discussed the review of the Toledo Edison BACC procedure by both B&W and the NRC in Section 6.2 of this report, and so here we summarize just the main points:

- As part of the response to GL 88-05 by the BWOG, B&W reviewed the Toledo Edison procedure, along with the procedures submitted to the NRC by other B&W plant licensees. B&W concluded in 1990 that "each of these procedures has a good approach to reducing the degree of leakage and resulting corrosive damage."

- Toledo Edison, the licensee of the Davis-Besse plant at the time, submitted this procedure to the NRC in September 1989, and the NRC apparently closed out this response by Toledo Edison to GL 88-05 as being satisfactory.

- The BNL/NRC team conducted an on-site audit of the boric acid corrosion control program at Davis-Besse in 1989, along with the programs at nine other selected plants, and found that it met the intent and requirements of GL-88-05.

Changes to the procedure were implemented between the initial issue in September 1989 and August 1991 to expand the guidance in the "Examination and Evaluation" section of the procedure to ensure that:[14]

- The amount of boric acid residue on each component affected by a leak was determined;

- The full extent of all areas and components potentially affected by the leak was identified to ensure that any boric acid leakage had not spread to locations not readily visible;

- Affected areas be inspected for signs of corrosion such as "red rust or red/brown stained boron;"

- The amount of corrosion and corrosion products was estimated if corrosion was found to be present;

- Personnel were aware that corrosion rates of carbon steel of “up to one third of an inch per month under ideal conditions” could occur, and that “accelerated corrosion” could occur at temperatures near 200 deg. F;

- Metal temperatures were determined for existing conditions and other conditions that may occur, e.g. high temperatures during normal operation and lower temperatures during shutdown, to assess the potential for corrosion.

These were appropriate changes and typical of the incremental changes that are usually made to new procedures as experience is gained in their use.

The BACC procedure was re-written to “incorporate lessons learned”, and Revision 1 was issued with an effective date of February 22, 1994[15], but the changes did not significantly alter the defined responsibilities or actions that were to be taken in the event of boric acid leaks from the previous version (Revision 0 plus Procedure Changes C-1 and C-2). Procedure Changes C-1[16] and C-2[17] made only minor changes to the Revision 1 issue, but in April 1999, Procedure Change C-3 implemented several significant updates[18]:

- The separate “Responsibilities” section was eliminated and incorporated into the body of the procedure where the various required actions were defined.

- Additional industry reference documents that had been published since the 1994 versions of the procedure were added to the “References” section[19]. These included the important 1995 EPRI Boric Acid Corrosion Guidebook[20], and the initial issue of the 1994 BWOG report on boric acid corrosion testing[21].

- GL 88-05 was also included directly in the “References” section.

- Attachment 1, a two page “Boric Acid Corrosion Control Inspection Checklist” was added to “provide guidance for performing an inspection and a means to document the inspection.”[22]

- The previous requirement to issue a PCAQ if the leakage problem was significant and required engineering evaluation was changed to require the issue of a Condition Report (CR)[23]. Functionally, the CR was to be processed and resolved by the Design Engineering group in the same manner as the previous PCAQ in accordance with the relevant Toledo Edison quality assurance management procedures.

Later in 1999, the procedure was completely revised, and Revision 2 was issued on September 30, 1999[24]. This revision implemented a number of significant changes.

First, the "Definitions" section was expanded to differentiate between "minor", "moderate", and "substantial" leakage; and between "dry" and "active" boric acid leakage[25]:

- "Minor leakage" was defined as "dry boric acid leakage which is small and limited to the immediate vicinity of the pressure retaining component", and where "no corrosion has occurred."

- "Moderate leakage" was defined as being "limited to the immediate area of the leaking component", or where "corrosion may have occurred but does not affect pressure boundary components."

- "Substantial leakage" was defined as leakage that "has gone beyond the immediate area of the component to affect other components" or where "significant corrosion has occurred that has affected the pressure boundary bolting," or where there may be components with "degraded parts due to corrosion" that "have a strong potential to cause an unplanned outage."

- "Dry" boric acid leakage was defined as being "accumulation of dry boric acid crystals and no moisture" which was noted to generally be a "housekeeping concern only."

- "Active boric acid leakage" was defined as leakage that results in "the accumulation of moist boric acid crystals or visible moisture or fluid."

These changes clearly were intended to assist in the classification of boric acid leakage and its potential to cause corrosion of components.

Section 6 of the procedure was completely reorganized and expanded[26]:

- An "Initial Inspection" section was created to provide more detailed guidance for the location and classification of boric acid leakage, any associated corrosion, and the potential impact of the leakage and/or corrosion, according to the expanded definitions described above[27].
- The "Detailed Inspection" section also incorporated procedural steps from the prior version, and provided additional steps to be taken where follow-up inspections were required to fully assess wastage damage to components, corrective action, and to determine boric acid concentration and temperature where the situation could not be immediately corrected[28].
- A "Periodic Monitoring" section was added, together with a new checklist for "BACC Periodic Monitoring," for monitoring and documenting leaks that could not be repaired within 30 days of identification[29].

Section 6 of the procedure also added a designated "Boric Acid Control Coordinator" with responsibility for planning and oversight of the Davis-Besse BACC program. The coordinator was assigned major responsibility for all aspects of the program including[30]:

- Oversight and monitoring of all identified boric acid leaks and corrosion locations in the Davis-Besse plant.
- Reviewing periodic inspection program for compliance.
- Analyzing trends and failure mechanisms.
- Maintaining awareness of industry developments and experience with boric acid leakage and corrosion.
- Planning and coordinating all outage activities related to the BACC program.

A new section was also added to define the "Containment Walkdown and Inspection" that was to be followed during forced and refueling outages[31]. This new section of the procedure required a "BACC

Team" with members assigned from key plant departments to provide "timely identification, evaluation and correction of boric acid leaks."

Finally a new "Attachment 3: Inspection Guidelines" was added to provide clarification and assistance to personnel performing initial and detailed inspections for boric acid leakage and corrosion[32]. The guidelines discuss many aspects of boric acid leakage and corrosion of carbon steel components including:

- The visual signs of boric acid leakage and potential corrosion;
- The determination of the area and components affected by any identified boric acid leakage;
- The need to remove deposits to expose bare metal to determine if any underlying corrosion had occurred; and
- The potential for accelerated corrosion where concentrated boric acid was present at temperatures near 200 deg. F.

This revised and detailed procedure provided the framework for an effective BACC program that clearly went well beyond the requirements of GL 88-05. We discuss the implementation and use of this 1999 (and earlier) issues of the Toledo Edison BACC program procedure at the various refueling outages in Section 7.3 below.

The BACC programs at Davis-Besse and other US PWR plants for detecting boric acid leakage and corrosion that were instituted to satisfy the requirements of NRC GL 88-05 were also relied upon nine years later by the industry in response to NRC GL 97-01, which addressed potential leakage from cracks in CRDM nozzles[33]. We discussed the industry reliance on BACC programs for detecting leakage from cracked CRDM nozzles, as well as the NRC's acceptance of this approach, in Sections 5.3.4 and 5.3.3 respectively. We comment here only that the Davis-Besse BACC was already in effect in 1997, and did not undergo any changes to specifically address GL 97-01.

7.1.2 FENOC Responses to US NRC Bulletin 2001-01 and Subsequent Information Requests

We discussed the initial FENOC response to NRC Bulletin 2001-01 in Section 5.3.6. This initial response was based on the industry generic response developed by the EPRI MRP, the most important result being that, based on the plant operating temperature and CRDM material properties, Davis-Besse was 3.1 EFPY away from having CRDM cracks comparable to those discovered at Oconee-3 in February 2001.

Subsequent to this initial response based on the generic MRP submission, considerable correspondence and meetings between FENOC/Davis-Besse personnel and the NRC staff took place to expand the Davis-Besse submission and provide considerable plant specific information and analyses to show that the Davis-Besse plant could safely operate through to the next planned refueling outage in March 2002.

In the following summary of this interchange, we have extracted items that are relevant to the issues we have addressed in this report.

September 4, 2001: FENOC submitted its Davis-Besse plant specific response to Bulletin 2001-01 to the NRC. This letter re-iterated the conclusion from the generic EPRI MRP-48 report that Davis-Besse was 3.1 EFPY away from having CRDM cracks comparable to those discovered at Oconee-3 in February 2001[34].

The letter provided summary information about the visual inspections of the Davis-Besse RPV head at 11RFO in April 1998 and 12RFO in April 2000[35], which was supplemented in the October 17, 2001 letter as described below. Five CRDM nozzles were noted as having flange leaks and boric acid deposits, one of which was nozzle 3.

Information was provided about the expected annulus gap for the Davis-Besse CRDM nozzles based on the generic safety assessment performed by B&W in 1993 (see Section 5.3.2). Based on that assessment, it was expected that there would be a gap and a leak path for CRDM crack leakage to the top of the RPV head for the Davis-Besse CRDM nozzles[36].

October 17, 2001: FENOC submitted extensive supplemental information to the NRC[37], which included a generic Framatome-ANP[a] safety assessment for RPV head nozzles in B&W plants[38], and a Davis-Besse plant specific analysis of the CRDM nozzle/annulus gaps and leakage paths performed by Structural Integrity Associates (SIA)[39].

The FENOC letter first provided additional information about RPV head inspections at 10RFO (April-June, 1996), 11RFO (April-May 1998) and 12RFO (April-May, 2000)[40]. FENOC informed the NRC that 65 of 69 CRDM nozzles were inspected during 10RFO, 50 of 69 were inspected during 11RFO, and 45 of 69 were inspected during 12RFO[b].

FENOC further informed the NRC that of the 24 nozzles obscured by boric acid during 12RFO, 19 were those obscured by boric acid crystal deposits during the 11RFO inspection, and that the deposits were "clearly attributed to leaking motor tube flanges from the center CRDMs". Attachments 2 and 3 were provided to show the extent of the location of the leaking flanges, the extent of the boric acid deposits, and which nozzles were obscured and could not be inspected. The obscured nozzles included 1, 2 and 3, all of which were found in 2002 to have through wall cracks.

The Framatome-ANP safety assessment was used to demonstrate that, with a "worst case scenario", Davis-Besse could safely operate until November 2003 before the maximum allowable CRDM nozzle crack size would be reached[41]. The "worst case" scenario assumed that:

- A "visible nozzle axial crack leak developed immediately after start-up from 10RFO in May 1996," and occurred in a nozzle that could not be inspected because of boric acid deposits at 11RFO or 12RFO.

- The crack would grow circumferentially through wall in 3.5 years (range 3.5 to 10 years), and would take an additional 4 years to reach the maximum length allowed by the ASME Code.

We note here, as we have previously, that the entire focus of the NRC's concerns throughout the Bulletin 2000-01 response process with FENOC was on the potential for CRDM nozzle failure and

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[a] Framatome-ANP was the successor company that had taken over B&W's US PWR service division.

[b] See section 7.3 for a detailed discussion of the visual inspections of the RPV head at these three outages.

ejection, and not on the potential for RPV head wastage. It is not surprising therefore that this concern was also the focus of FENOC's responses, as well as the assessments and analyses performed by EPRI MRP, and FENOC's technical support vendors such as Framatome-ANP and SIA.

The Framatome-ANP safety assessment relied heavily on the prior assessment performed by B&W in 1993 (BAW-10190P), which we discussed in detail in section 5.3.2. Although not explicitly cited in FENOC's letter, the Framatome-ANP safety assessment included a leakage and RPV head wastage assessment, which were largely unchanged from the 1993 version[42].

The Framatome-ANP leakage assessment noted the Oconee-3 experience, where despite the large 165° circumferential crack (5.75 inches in length and through wall), the leaking CRDM nozzle only resulted in 0.5 cubic inches of boric acid deposits, while only 5 of the 8 leaking thermocouple nozzles exhibited boric acid deposits. It is also noted that the Oconee-3 crack leakage was so small that it may have been missed at prior outage visual inspections due to the masking effects of CRDM flange leakage[43].

The possible reason presented for the small amount of boric acid deposits followed the thinking that had prevailed for almost 10 years:[44]

> "It is reasoned that a small leak and narrow annulus can lead to "leak plugging" by the formation of less dense metal oxides in the annulus. Thermal cycling is anticipated to lead to starting or re-initiating a weeping type leak. Therefore, leakage is anticipated to be minimal until a long axial flaw (i.e. approximately the length of the RV head penetration) develops above the weld."

In other words, leakage from either axial or circumferential cracks above the weld would not be expected to be significant until an axial crack grew above the top surface of the RPV head to be clear of the restriction posed by the narrow annulus gap.

The Davis-Besse experience demonstrates how wrong this reasoning was, and we now know that the critical crack length above the weld before rapid carbon steel metal removal by boric acid wastage, erosion and other mechanisms is only of the order of 1 inch, not 5 or 6 inches.

The Framatome-ANP wastage assessment for the RPV head itself is unchanged from the 1993 assessment. The maximum metal loss rate from the RPV head due to boric acid wastage would be 1.07

cubic inches/year (based on the 1991 CE crevice tests, see section 6.3.2), and even after 6 years of wastage at this maximum rate, there would be no safety concern for the structural strength of the RPV head[45].

The SIA finite element gap analysis for the Davis-Besse CRDM nozzles produced a result in conflict with the earlier generic B&W assessment cited in FENOC's September 4, 2001 letter to the NRC. The SIA analysis showed that for the four center nozzles 1, 2, 3 and 4, there would still be a nominal interference fit even at operating conditions, and so it could not be assured that leakage from cracks in these four nozzles would be visible at the surface of the RPV head[46].

An issue that confronted the NRC was whether even large nozzle cracks could be detected at Davis-Besse by means of the expected miniscule leakage of boric acid similar to that observed at Oconee-3. Note that at Oconee-3 the nozzle annulus was open and not closed as it was predicted to be for the-- Davis-Besse center nozzles.

October 30, 2001: The October 17, 2001 letter to the NRC prompted a large number of NRC "requests for additional information (RAIs)", which FENOC responded to on October 30, 2001 with a lengthy written response and a large number of supporting and requested documents[47].

Five of the NRC RAIs addressed the lack of a nozzle annular gap for the four center nozzles[48], and another five questions related to the detectability of small leaks by means of boric acid deposits[49]. FENOC's responses to these RAIs noted that the industry had not experienced any circumferential cracking in the center CRDM nozzles due to lower stresses for nozzles in that location, but that in any event the four nozzles in question would be inspected by NDE at the next outage to determine of cracks were present. FENOC further stated that if any nozzle were obscured so as to prevent visual inspection for small leaks, those nozzles would also be inspected by NDE.

One RAI related to the environment in the annulus[50], to which the response was that ERPI had "recently convened a panel of experts to evaluate Alloy 600 material crack growth rates and to establish the nature of the environment in the annulus between a leaking CRDM nozzle and the RPV head environment." After describing the possible environments that a leak might produce in the annulus, the response noted that "none of these environments are expected to contribute to an accelerated crack growth rate."

Again, throughout this exchange, the focus is on the potential for leaks contributing to nozzle cracks reaching a critical size where failure might occur, and not on concerns for the possibility of accelerated wastage of the RPV head.

October 30, 2001: A second FENOC letter on this date[51] responded to a request by the NRC at meeting between FENOC and the NRC (on October 24, 2001) for "pictorial documentation" of the visual examinations conducted of the Davis-Besse RPV head at 10RFO, 11RFO and 12RFO. The requested photographs from the videotaped inspections were forwarded to the NRC by this letter, which also re-emphasized to the NRC numbers and locations of the nozzles that could not be inspected at these three outages due to boric acid deposits.

November 1, 2001: This letter forwarded a Davis-Besse plant specific risk assessment of CRDM nozzle cracks[52], which was based on the generic Framatome-ANP analysis submitted with the October 17, 2001 letter. Significantly, the risk assessment is again focused on the probability of large cracks causing CRDM nozzle failure and on the loss-of-coolant-accidents (LOCAs) that would result, and not on the potential for wastage of the RPV head.

The risk assessment assumes that leakage from CRDM nozzle cracks "could not be detected from any CRDM nozzles where boron deposits from flange leaks may have obscured indications of CRDM nozzle leakage."[53] The risk assessment reminds the NRC yet again that four nozzles in the center of the head were obscured by boric acid deposits and were not inspected at 10RFO in 1996, and that 19 nozzles in 1998 (11RFO) and 24 nozzles in 2000 (12RFO) were similarly obscured by boric acid deposits from CRDM flange leakage[54].

The number of potentially cracked and leaking nozzles that were present but were assumed to be not detectable because of boric acid deposits therefore increased with time in the analysis. Thus, the risk assessment includes undetected cracks that could have started leaking "as early as November 1994", after startup from 9RFO[55].

These obscured and un-inspected nozzles dominated the risk assessment because cracks in these nozzles could have remained undetected for several fuel cycles and could proceed to failure and a LOCA[56]. The risk assessment was specific to the 13th fuel cycle, i.e. from the May 2000 startup to the projected shutdown in March 2002, because the risk would be much lower after 13RFO "after a 100% inspection of all 69 CRDM nozzles is completed during 13RFO." [57]

The risk assessment takes note of the four nozzles (1, 2, 3 and 4) that did not have a demonstrable annular gap, and where leakage may not occur even if they were cracked. Further, these four nozzles were assessed as being "not prone to the circumferential cracking observed during recent inspections of other plants in the B&W fleet and consequently are not risk significant." Since they were deemed not to be prone to circumferential cracking, they were simply removed from the risk assessment as possible contributors to the LOCA frequency[58]. The irony of this of course is that three of these four nozzles (1, 2 and 3) were all found to have significant through wall axial cracks at 13RFO in February-March 2002, and one, CRDM nozzle 3, was the one that leaked sufficiently to cause the large wastage cavity that required the RPV head to be replaced.[c]

November 19, 2001: The NRC sent a letter to FENOC[59] summarizing a November 15, 2001, conference call that discussed the status of FENOC's response to Bulletin 2001-01 after all the correspondence, submittals and meetings on November 8, 9, and 14, 2001.

In the letter, the NRC noted that of thirteen PWRs categorized as having a "high susceptibility to PWSCC at RPV head penetration (VHP) nozzles", eleven had been inspected, and ten had found cracking. More significantly, the NRC noted that the six B&W plants other than Davis-Besse had already inspected their VHP nozzles, all six had found cracking in the nozzles and/or welds, and that three had found circumferential cracking in the nozzles.

The letter concluded that the NRC staff "believes there is more than a reasonable likelihood that the Davis-Besse facility currently has cracking in one or more VHP nozzles and/or the associated J-groove welds, the extent of which is unknown," and requested that "future discussions or submittals on this subject focus on how Davis-Besse is unique or can be distinguished from the other high susceptibility facilities." .

November 26, 2001: The NRC noted in this meeting summary[60] that the NRC staff had met with FENOC on November 8, 2001 to review "videotapes made during the refueling outages" in 1996 (10RFO), 1998 (11RFO) and 2000 (12RFO). The purpose of this review was to determine "whether an independent assessment of the reactor vessel penetrations could be made." The NRC meeting summary is silent as to the results of this assessment by the NRC staff, noting only that "the staff made

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[c] A further irony is that later that same month, a follow-up inspection at Oconee-3 revealed a 29% through wall circumferential crack in Nozzle 2.

various comments concerning the quality of the inspections and their results." Clearly, the NRC staff had the opportunity to review the videotapes from these three outages, and determine for themselves the extent of boric acid deposits on the RPV head at Davis-Besse in 1996, 1998 and 2000. We have not been able to locate any further information related to the NRC staff's conclusions from their review of the outage videotapes.

November 30, 2001: The final resolution of the long interchange between FENOC and the NRC concerning Bulletin 2001-01 is set forth in this letter from FENOC[61]. FENOC committed to a shutdown by February 16, 2002, to reduce hot leg temperature from 605 to 598 deg. F by December 16, 2001 to reduce the potential growth rate of any existing PWSCC cracks, and to "perform inspection of 100% of VHP nozzles, e.g. qualified visual examination or other non-destructive examination technique(s)."

Summary

In summary, this long interchange between FENOC and the NRC between the issuance of Bulletin 2001-01 on August 3, 2001 and November 30, 2001 serves only to highlight the NRC's - and in response the industry's - focused on the risk posed by CRDM nozzle failures due to circumferential PWSCC cracks. The risk posed by the accelerated wastage of the RPV head due to boric acid leakage from cracks much shorter than those that could cause actual nozzle failure was not even considered.

This was highlighted in a memorandum from the then NRC Chairman to the NRC Inspector General, in response to a December 30, 2002 report by the Office of the Inspector General (OIG)[62]. The OIG report was critical of the NRC staff's actions with respect to Davis-Besse and the FENOC response to Bulletin 2001-01, and the fact that the NRC had allowed FENOC to operate past the deadline of December 31, 2001 set in Bulletin 2001-01 for inspections of RPV head nozzles.

After noting that the OIG report "serves only to deflect attention from the real safety issue raised by the Davis-Besse episode, the unexpected head corrosion," the NRC Chairman's memorandum went on to say:

> "But, in our view, it is unfair to criticize the staff for its decision to allow a brief period of extended operation before inspection of the nozzles because of the subsequently discovered head corrosion. The staff did not know about the head corrosion at the time of its decision and,

> quite frankly, it is Monday-morning quarterbacking to question the decision on CRDM cracking in the false light of subsequent knowledge.
>
> In sum, we believe that the report is seriously inaccurate and misleading. You have done a significant disservice by your release of such an unfair analysis."

We fully agree with this perspective. Analysis of an unexpected and unpredictable accident or failure such as the Davis-Besse event is always a possible undertaking after the fact. Even with the benefit of hindsight, in the present case, it has already taken almost five years of ongoing effort by the industry to conduct research and analysis in an effort to understand how the accident occurred.

No-one predicted the significant Davis-Besse head corrosion. Not the technically experienced and highly capable engineers and scientists at vendors such as Westinghouse, CE, and B&W, nor the equally capable personnel at organizations such as EPRI and other industry organizations and consultants, nor the technical staff at the NRC, nor the scientists at the various national laboratories, all of whom contributed to the understanding of Alloy 600 cracking and boric acid corrosion in PWR's over the span of 15 to 30 years.

7.2 RCS Leakage Monitoring at Davis-Besse

The identification of reactor coolant system (RCS) leakage in operating nuclear power plants can be a challenging task due to the size of the RCS, the number of potential sites for both identified and unidentified leakage, and the dynamic response of the fluid in the RCS to changes in operating parameters (power level, temperature change or the fluid as it flows through the reactor core, localized boiling conditions within individual fuel channels, etc.). The evaluation of a RCS water inventory balance is the method employed to identify possible fluid leakage. This inventory balance is completed on a daily basis and the changes in RCS leakage are noted. The procedure that governs the water inventory balance at Davis-Besse is Surveillance Test Procedure DB-SP-03357, RCS Water Inventory Balance.[63]

7.2.1 RCS Inventory Balance

The development of methods to accurately determine the RCS leak rate include the completion of a baseline inventory of reactor coolant. At some later time, a second RCS inventory is completed. The difference between the inventories divided by the time between measurements is the total RCS leak rate. Once the total leak rate has been determined, the known sources of leakage are evaluated. These known leakage sources include reactor coolant pump seals, makeup pump seals, valve packing seals, and leakage through check valves to core flood tanks, coolant drain tanks, coolant quench tanks, spent resin storage tanks, etc.[64] This known leakage is subtracted from the total leakage leaving the unidentified leakage for that time period.

This unidentified leakage determination is a required part of the Technical Specifications and must be completed at least once per 72 hours during steady state operation in Modes 1 through 4. It should be conducted daily when possible.[65] The Technical Specifications for all nuclear power plants include limits on the RCS leak rates. These leak rates will fluctuate over the course of each cycle as reactor power and temperatures vary and as mechanical components such as seals and valve packing degrade with use. The RCS leakage rates allowed by the Davis-Besse Technical Specifications are listed below.[66]

Leakage Type	Tech Spec Limit
Pressure Boundary Leakage	0 gpm
Primary to Secondary Leakage	1 gpm or less
Unidentified Leakage	1 gpm or less
Pressure Isolation Valve Leakage	5 gpm or less
Identified Leakage	10 gpm or less
Controlled Leakage	10 gpm or less

Since there is a large range in the allowable leakage rates in the Technical Specifications, it can be challenging to determine the magnitude of relatively small leaks. In addition, there are significant day-to-day fluctuations in the calculated unidentified leak rates. Figure 7.1 shows a plot of the data for daily unidentified leak rates as a function of time for the final 15 months of Cycle 13.[67] Note the significant variation in the leak rate on a daily basis. Simple averaging of the same unidentified leak rate data over a 3-day averaging period provides somewhat less variability in the data as shown in Figure 7.2.[67] Note the reduction in the magnitude of the variation in the unidentified leak rate.

A significant reduction in the variation of the unidentified leak rate data is obtained by employing a running average over a longer period of time, such as the 30-day average unidentified leak rate data shown in Figure 7.3.[68] Although this averaging techniques allows for the evaluation of general trends in the variation of the unidentified leak rate, some of the details associated with daily changes or shorter-term (3-day) averaging are lost with this method. Similarly, the use of monthly average unidentified leak rates, as shown in Figure 7.4 for Cycles 10-13,[69] further reduces the ability to evaluate shorter term fluctuations in the unidentified leak rate.

Based upon our evaluation of the unidentified leak rate data for Cycle 13, we have determined that the unidentified leak rate at the end of Cycle 13 was about 0.20 gpm. Using the historical data for unidentified leak rates, we estimated that the historical unidentified leak rate was on the order of 0.03 gpm. These data allowed us to estimate the maximum total leak rate that could be attributed to all CRDM nozzle cracks at the end of Cycle 13 to be approximately 0.17 gpm, which is simply the difference between these values. This range of unidentified leak rates was used to determine the CRDM nozzle crack leak rates, which are presented in Section 9.4 and used as input parameters for our CFD fluid flow calculations presented in Section 9.6.

It should be noted that any evaluation of unidentified leakage represents an upper bound to the leakage considered in the present analyses. Since there are numerous sources of unidentified leakage within the RCS, all unidentified leakage is not necessarily pressure boundary leakage (e.g. from leaking CRDM nozzles). Hence, calculations presented in Chapters 8 and 9 of this report use leak rates for CRDM nozzle cracks that are only a fraction of the total unidentified leak rate.

7.2.2 Reactor Building (RB) Radiation Monitoring

Radiation monitors RE 4597AA and RE 4597BA are two identical containment air sample monitoring systems. These monitors provide a means to detect RCS leakage through particulate and noble gas activity detection. These detector systems draw a continuous sample from containment and pass this sample through a fixed particulate filter and an iodine cartridge through the use of a pump. The sample then passes through a noble gas chamber and is discharged back to containment atmosphere. The containment radioactive gas monitor is less sensitive than the containment air particulate. The location of radiation monitors RE 4597AA and RE 4597BA is shown in Figure 7.5.[70]

The containment airborne particulate monitor measures the buildup of particulates on a fixed filter. The particulate monitor consists of a fixed particulate filter in a 3 inch, spherical lead shield. A beta detector is inserted into the lead shield to detect the activity deposited on the filter paper. The filter paper is 99 percent efficient for 0.3 micrometer and larger particles. Although these detectors are effective in identification of a rapid change in leakage, they tend to constantly accumulate particulates in containment over the course of a fuel cycle, giving a continuously increasing detector response that is difficult to distinguish from subtle changes in leakage. The output also fluctuates with filter changes. Therefore, the particulate detector does not provide a good measure of possible long-term CRDM nozzle leakage. However, the potential for plugging the 0.3 micrometer filter paper can be a strong indication of the beginning of RPV head wastage due to the energetic process associated with RCS leakage as shown in Chapter 9 of this report.

The measurement of noble gas activity by the RE 4597AA and RE 4597BA radiation monitors can also be an indication of RCS leakage. The noble gas radiation levels for the RE 4597AA and RE 4597BA radiation monitors for Cycles 10-13 are shown in Figure 7.6.[71] Note the significant increase in noble gas radiation levels associated with the pressurizer relief valve leakage in mid-Cycle 12 (May 1999). Noble gas detector output is particularly sensitive when RCS activity is high. Under this condition, noble gas activity may provide indication of very small RCS leakage. However, a representative combination of isotopes in the RCS is required to achieve the scaling factor needed to screen out the effects of RCS activity and determine the RCS leak rate. Even if this was accomplished, other RCS leakages could still mask the relatively small leakage expected from a CRDM nozzle leak. Therefore, these detectors are also of limited value for diagnosis of the low leak rates associated the early CRDM nozzle leakage.[72]

The iodine detector can detect radioactivity at concentrations as low as $7x10^{-7}$ µCi/cc of containment air. The primary iodine isotopes released with leaking RCS coolant are I-131 and I-133, which have half-lives of 8 days and 21 hours, respectively Output data from the detectors were manually recorded on a monthly basis from late 1992 through November 2001. These detectors frequently saturated during the fall of 2001 due to high Cycle 13 coolant activity and known increases in RCS leakage. This resulted in a loss of alarm function for the remaining channels.

The carbon filters were removed from the detectors in November 2001, which took the detectors out of service. Data prior to November 2001 is presented on Figure 7.6.[73] Although the output indicates a clearly increasing trend, the readings from the monitor show a significant amount of scatter. The cause of the scatter is not known. It could be related to non-equilibrium conditions in the detector or actual changes in CTMT atmosphere conditions (e.g. scrubbing of the iodine by condensate on the containment air coolers, or retention by condensate in the sample lines).[74] Although increased leakage is indicated, there is no means to easily distinguish CRDM nozzle leakage from any other RCS leakage. However, this increasing trend in levels of radiation detected coincides with our estimate of increased unidentified leak rate due to CRDM nozzle cracks, as noted in Section 7.2.1.

7.3 Review of Davis-Besse Plant Refueling Outages and History of Boric Acid Leakage

Pressurized water reactors designed by Babcock & Wilcox have a history of reactor coolant leaks at the flanges of the control rod drive mechanisms (CRDMs). The Davis-Besse reactor has experienced a series of CRDM flange leaks that resulted in significant deposits of boric acid crystals on the reactor pressure vessel head. These CRDM flange leaks contributed to the inventory of unidentified leakage. Numerous CRDM flange leaks during Cycle 7 (21 leaking flanges) and Cycle 8 (15 leaking flanges) resulted in significantly higher levels of unidentified leakage (approximately 0.3 gpm in Cycle 7 and 0.4 gpm in Cycle 8).[75] In addition, other significant leakage events, such as the pressurizer relief valve leakage event, which occurred early in Cycle 12 (early 1999), resulted in an unidentified leakage rate (0.8 gpm) approaching the technical specification limit of one gallon per minute (gpm). A summary of relevant CRDM flange leakage events with subsequent formation of boric acid deposits on the RPV head is provided in Table 7.1.

7.3.1 Pre-8RFO CRDM Flange Leakage

As early as 6RFO (January to July 1990), a large number (22 of 69) of CRDM flanges showed "evidence of leakage and therefore should be re-worked during 6RFO."[76] These flange leaks resulted in significant boric acid accumulation under the mirror insulation on the RPV head. The condition report stated that,

> "… inspection of the reactor vessel closure head below the insulation found three areas of boron deposits." "These areas were cleaned by RC personnel using wire brushes and a vacuum cleaner. After cleaning, these areas were visually re-inspected by Systems Engineering personnel to be sure the deposits were removed and there were no surface irregularities from the deposits. Deposits were removed and no surface irregularities were found."[77]

All 22 of the leaking CRDM flanges (see Table 7.1), were repaired with new split nut rings.

During 6RFO, erosion of the outer gasket groove in the flange on Nozzle 37 was identified. The flange was determined to be "acceptable to use as is".[78] Future inspections of this flange were required to support this determination.

Additional CRDM flange leaks were repaired during the next three refueling outages. During 7RFO in 1991, 21 CRDM flanges were identified as leaking and 15 were repaired. The remaining 6 CRDM flanges that exhibited leakage were justified for "use-as-is".[79] As summary of the nozzles that were repaired and those that were designated for "use-as-is" is presented in Table 7.1

7.3.2 8RFO Inspections and Events – March/April 1993

Significant deposits of boric acid on the RPV head were found during 8RFO in 1993, when boric acid from leaking CRDM flanges dripped through the gaps in the mirror insulation. These boric acid deposits are show in Figures 7.8 and 7.9.[80] Inspection of the CRDM flanges identified another 15 leaking flanges, which were subsequently repaired. These leaking flanges are noted in Table 7.1.

During a video inspection of the RPV head, these boric acid deposits were noted to be "reddish brown in color," as shown in Figure 7.10.[81] Cleaning of the reactor head and flange area "was performed such that essentially all boron was removed from the vicinity of the flange area. Because the head was installed on the vessel, an evaluation of the effectiveness of head cleaning could not be performed."[82]

7.3.3 9RFO Inspections and Events – October/November 1994

Video inspection of the CRDM flanges was completed during 9RFO in 1994. This inspection identified eight CRDM flanges that were leaking, all of which were repaired. A summary of the nozzles identified as leaking is provided in Table 7.1. The condition report for this nozzle repair noted,

> "The leakage identified is orders of magnitude less than has been seen in the past. Some leaks of greater magnitude were not repaired in past outages. There was no degradation to carbon steel components.".[83]

There are no records to indicate that a video inspection of the RPV head was completed during 9RFO.

7.3.4 10RFO Inspections – April/May 1996

A total of nine CRDM flanges were identified as leaking during 10RFO. These leaking flanges are documented in Table 7.1. The gasket materials in these nozzles were replaced with a new gasket material, which completed the upgrade of all CRDM nozzle flanges to the new gasket material.[84]

Video inspection of the RPV head was completed during the 1996 outage (10RFO). The condition report summarizing this inspection noted,

> "CRDM nozzle inspection (below the RV head insulation) show(ed) several patches of boric acid accumulation on the RV head. Also one of the CRDM nozzles, 67 (P6), show(ed) rust or brown stained boron on the bottom of nozzle where it meets the head. The head area in this vicinity also had rust or brown stained boron accumulation. The videotape of CRDM flange inspections was reviewed to determine the flange leakage. The inspection of the CRDM nozzle 67 flange did not show any leakage during cycle 10, which indicated that the leakage marks and boron accumulation on CRDM nozzle 67 was due to leakage from previous operating cycles."[85]

Figure 7.11 shows the boric acid accumulation behind the CRDM nozzles on the North side of the RPV head at 10 RFO.[86] A request for a modification to allow access to the RPV head was initiated to "allow for adequate access to the top surface of the head to clean/remove any accumulated boric acid buildup. The modification has been approved for implementation during 13RFO by both the PRC [Project Review Committee] and the WSC [Work Scope Committee]."[87]

7.3.5 11RFO Inspections – April/May 1998

One CRDM flange (D-10, Nozzle 31) was identified has having a minor flange leak during 11RFO. According to the Potential Condition Adverse to Quality Report,[88]

> "The leak from CRDM D-10 is considered minor. Using previously developed criteria, the leakage would be categorized as between a CAT 1 and a CAT 2 with Cat 5 being the worst. There were no stalagmites hanging from the flange and there was no boric acid bridging to adjacent flanges. There was no rust present on either the flange or the split nut rings and no degradation of the split rings was visible. Leaks of this magnitude have not always increased

> over time. There have been several occasions where leakage identified during one outage and not repaired, stopped leaking over the next cycle."

The report continued by noting,

> "A major concern of RCS leakage is boric acid corrosion of carbon steel components. Accumulation of boric acid on the reactor vessel caused by leaking CRDMs has not resulted in any boric acid corrosion. This was identified through inspection following reactor vessel head cleaning in past outages. Additionally, B&W documentation discussing CRDM nozzle cracking further stated that boron deposits on the head caused by leaking CRDM flanges would not result in head corrosion. The split nut rings are made of SA 320 Grade L43, a material considered to be a low-alloy steel. Although this material has some susceptibility to boric acid corrosion, inspection of the split nut rings removed on previously leaking flanges identified no corrosion regardless of the magnitude of the leak."[88]

This report also addressed previous unidentified leakage rates from the RCS system by stating,

> "Unidentified leakage data was reviewed for the past several cycles. With the numerous flange leaks present in both 7 RFO and 8 RFO, the highest unidentified leakage was approximately 0.3 gpm in Cycle 7 and 0.4 gpm in Cycle 8. The cycle 11 unidentified leakage averaged 0.05 gpm. No Technical Specifications were exceeded even when significant flange leakage was present. If greater leakage than expected occurs during Cycle 12, the Technical Specifications covering RCS leakage will ensure appropriate action is taken."[88]

The report concluded by stating,

> "Based on the above information, it is considered acceptable to defer any repairs to CRDM D-10 until 12RFO following re-inspection."[88]

Inspection of the reactor pressure vessel head identified the existence of boric acid residue, as shown in Figures 7.12, which shows the boric acid deposits near Nozzle 31 (D-10).[89] The condition report that summarized the review of the video taped inspection of boric acid on the reactor pressure vessel head noted,

> “that most of the head area was covered with an uneven layer of boric acid along with some large lumps of boric acid.”[90]

This report also noted that,

> “The color of the layer and the lumps varied from rust brown to white. The rust brown color is an indication of the old boric acid deposits. The above tape also showed white streaks on the OD of CRDM housing. This indicates leaking CRDM flanges. It appears that the leaking CRDM flanges contributed to the deposit of boric acid layer and lumps.”[91]

The condition report continued by stating,

> “The reactor vessel head was cleaned as best as we can. (Cleaning is recorded on videotape dated 5/5/98). The visual inspection did not show any significant pitting of the head surface. Base on engineering judgement, the head thickness (6 $^5/_8$”) will not be adversely impacted by very slight pitting. Also there were slight boron deposits left on the head after cleaning. These deposits will not create any corrosion since the head temperature is ≥ 550°F. This is based on the result of boric acid corrosion test performed by B&WOG (B&W document #51-1229638-1). The testing showed almost no corrosion occurred at temperature greater than 550°F and the highest corrosion rate for carbon steel occurred at approximately 300°F, at the interface where the dried boric acid crystals were re-wetted by the leakage. Lower levels of corrosion occurred at temp. approaching 500°F. The only time the higher corrosion rate can be encountered is during shutdown and heatup when the temperature of the head will be well below 550°F. Since this duration is very short, no impact on reactor vessel head is anticipated. Thus RCS pressure boundary is not impacted and the RV head will continue to perform its intended function.”[91]

The leak in the flange on Nozzle 31 was the only CRDM flange leakage identified during 11RFO. The justification for not repairing this flange leak and the justification for not completely removing the boric acid deposits from the RPV head, were documented in the Potential Condition Adverse to Quality Reports (PCAQR). Neither of these conditions was identified as a problem or finding in the NRC Inspection Report for the reporting period that included 11RFO.[92]

7.3.6 12RFO Inspections – April/May 2000

During cycle 12, a number of conditions developed within containment that significantly impacted the evaluation of leakage from the reactor coolant system (RCS). The most notable of these conditions was the significant increase in containment sump in-leakage due to the removal of the pressurizer code safety valve rupture disks and the severing of the drain line to the quench tank. This event was summarized in the Condition Report, which noted,

> "The increase in sump in-leakage is a result of leakage into the containment volume. A portion of this leakage is suspected to be originating from the Pressurizer Code Safety Relief Valves, which are known to be leaking. The code safety valve leakage was originally channeled to the Pressurizer Quench Tank and classified as identified leakage. Implementation of a temporary mod, that severed the discharge rupture disks and disconnected the drain lines allowed the leakage to escape into the containment atmosphere. This leakage also shifted from RCS identified leakage to unidentified leakage based on the fact that it could no longer be quantified or contained."[93]

The significant leakage associated with the severing of the discharge rupture disks resulted in a release of reactor coolant vapor into containment. The condensation of this vapor significantly increased the unidentified leakage and resulted in the deposition of significant quantities of boric acid on the condensing surfaces. Specifically, this leakage resulted in the deposition of solid boric acid on the cooling fins and in the ductwork of the containment air cooling (CAC) system. From November 19, 1998 to April 21, 1999, the CAC system was cleaned 17 times.[94] These cleanings resulted in the removal of significant quantities of wet boric acid deposits. A mid-cycle outage began on April 24, 1999, during which modifications were made to the Pressurizer Code Safety Relief Valves to eliminate the significant release of reactor coolant vapor into containment. Following the mid-cycle outage the CAC system was cleaned two more times, in June 1999[95] and July 1999,[96] to remove boric acid deposits from the fins and ductwork.

The unidentified leakage rate was significantly reduced following the mid-cycle outage in which the Pressurizer Code Safety Relief Valves were modified. Immediately prior to the mid-cycle outage, the unidentified leakage rate, as shown in Figure 7.4, was approaching the Technical Specification Limit of 1 gallon per minute. After the mid-cycle outage, the unidentified leakage rate dropped to between 0.2 gpm and 0.3 gpm.[97]

A number of CRDM nozzles exhibited flange leakage in the video inspection completed for 12RFO. The leaking flanges included flange 3, 6, 11, 31, and 51.[98] The Condition Report noted:

> "The main source of leakage was believed to be associated with D10 (Nozzle 31) and F10 (Nozzle 11) drives. Positive evidence existed that drives F8 (Nozzle 6), D10 (Nozzle 31), and C11 (Nozzle 51) have limited gasket leakage. Based on the available information, System Engineering recommend replacement of gaskets and repairs of flanges for Control Rod Drives located at F8 (Nozzle 6), G9 (Nozzle 3), F10 (Nozzle 11), D10 (Nozzle 31), and C11 (Nozzle 51)."[98]

It is important to note that the leaking CRDM flanges on Nozzles 3, 6, and 11 are in very close proximity to the wastage cavity discovered between Nozzle 3 and Nozzle 11 during 13RFO. The deposition of boric acid deposits on the RPV head from flange leaks immediately above the wastage cavity would have obscured the discovery of any boric acid deposits resulting from a small leak from the annulus around Nozzle 3 due to cracks in the Alloy 600 CRDM nozzle. A complete cleaning of the RPV head followed by an entire cycle of reactor operations with no additional CRDM flange leakage would be required to identify any boric acid deposits resulting from CRDM nozzle leakage. The results of our estimates of CRDM nozzle crack length and the resulting leakage rates are presented in Sections 8.3.1 and 9.3.4 of this report.

Video inspection of the RPV head was completed during 12 RFO. This inspection noted significant boric acid buildup near the center of the RPV head, as shown in Figure 7.[99] Some of this deposit of boric acid was the remnants of the boric acid that was not completely removed during previous outages. Additional boric acid deposits were the result of the CRDM flange leakage that occurred during Cycle 12. The Root Cause Report noted:

> "The RCS engineer acknowledges that the cleaning was not 100% successful and some boric acid deposits were left behind on the RPV head. The engineer stated that he was running out of time to continue cleaning the RPV head (the RPV head was scheduled to return to the RPV during the next shift). Outage management concurred that no additional time and dose should be spent because further attempts would not produce successful results and the results were believed to be acceptable. Radiation Work Permit (RWP) 2000-5132 package was written as a tool to control radiological exposure for cleaning boric acid from the RPV head on April 6,

> 2000. The RWP identified 30 man-hours and a 100 mRem dose was estimated for the work. There were 282.31 man-hours and 1611 mRem expended for cleaning the RPV head."[100]

> "No written evaluation was performed to allow the boric acid to remain on the RPV head. At this point in time, the modification to cut the openings in the service structure was scheduled for the next outage. With these openings and a more aggressive cleaning technique, the RPV head could be completely cleaned of the boric acid deposits and inspected. The amount of boric acid deposits left on the RPV head cannot be estimated."[100]

The location and amount of boric acid remaining on the RPV head at the beginning of Cycle 13 cannot be estimated. The report for the NRC inspection, which occurred during 12RFO made no mention of the inability to fully inspect the RPV head due to boric acid remaining after the cleaning. This report also did not comment on the amount and location of boric acid left on the RPV.[101]

7.3.7 13RFO Inspections – Started February 2002

A number of key observations were made during the course of RPV head inspections during 13RFO. These observations include a significant deposit of boric acid on the RPV head and the lack of any apparent RCS leakage from CRDM flanges, as previously noted in Section 4.1.1 of this report. In addition, ultrasonic testing of all CRDM nozzles was completed in response to NRC Bulleting 2001-01. Based upon these observations, a condition report noted,

> "Ultrasonic testing (UT) performed on the #3 Control Rod Drive Mechanism (CRDM nozzle (location G9) revealed indications of through-wall axial flaws in the weld region. CR 02-00891 was issued to document this condition. Response to the CR will evaluate crack size, location and other aspects of the failure. Boric acid found on the reactor head did not originate from CRDM flanges. This was verified by videotape examination of CRDM flanges performed by FTI/SYME on 2/25/02 and 2/26/02."[102]

Video examination of the RPV head beneath the mirror insulation was completed during 13RFO. The results of this initial examination, prior to cleaning the RPV head were noted in the Root Cause Report.

> "During the CRDM flange inspection, the camera again encountered a boron pile in the vicinity of nozzle 3 making the inspection of the underside of the flange difficult. No flange leakage was identified during this outage indicating that previous repairs were successful.
>
> The engineers responsible for inspecting the CRDM flanges reported boric acid deposits flowing out of the mouse holes and piled up to 4 inches high in the southeast quadrant on the RPV head flange and extending 360° around the RPV head flange. The boric acid deposits in the southeast quadrant were hard-baked, whereas the deposits around the remainder of the RPV head flange were loose. During the inspection of the RPV head under the insulation, significant boric acid was encountered in the southeast quadrant. In the remaining quadrants, significant piles of boric acid were encountered two to three nozzles in towards the center of the RPV head as shown in Figure 24. The deposits were hard, porous deposits and were a mixture of reddish brown and white deposits. The deposits were removed by hydrolasing, which operates at approximately 2,000 psi."[103]

Figure 7.14 shows the areas of boric acid buildup on the RPV head prior to cleaning by hydrolasing.[104] This figure shows significant boric acid deposits covering the center of the RPV head and extending outward toward the "mouse holes." Following the removal of boric acid, another video inspection was completed. Although a majority of the deposits on the RPV head were removed by the hydrolasing process, there were still significant deposits in and around the wastage cavity between Nozzle 3 and Nozzle 11. These deposits are shown in images captured from the post-cleaning inspection video. Figure 7.15 shows the deposits near Nozzle 3 from the 90-degree side (near Nozzle 7).[105] Figure 7.16 shows the deposits near Nozzle 3 from the 270-degree side (near Nozzle 6).[106] A closer inspection of the video shows that although the wastage cavity appears to be filled with metal oxides and boric acid, there was no significant pile of debris over the wastage cavity. A majority of the metal oxides and boric acid appear to have been deposited in the region between Nozzle 3 and Nozzle 1. Some of this deposit completely filled the gap between the mirror insulation and the RPV head. The location of these deposits is explained by the fluid flow calculations completed in Chapter 9 of this report.

Summary

In this chapter, we reviewed actions and responses by Davis-Besse to key industry and regulatory initiatives in order to document that the procedures employed for the detection of CRDM cracking, nozzle leakage, and boric acid corrosion control met the requirements of all regulations and industry standards. We also reviewed the RCS leakage program and the history of CRDM flange leakage during all relevant RFO's to document the efforts of Davis-Besse staff and management to address the boric acid leakage issue. The wastage discovered during the RPV head inspection at 13RFO was unanticipated and unexpected. As noted previously in this Chapter, no individual or organization in the nuclear utility industry, ranging from the reactor vendors, owner's groups, operators, or regulators, considered that significant RPV head wastage due to boric acid deposits would occur. None of these organizations identified the potential for cracking of the CRDM nozzles to lead to significant RCS leakage and resulting head wastage. The unexpected nature of this event is further emphasized by the accidental discovery of the wastage cavity due to an unexpected tool movement during the nozzle repair process, as noted in Chapter 4 of this report.

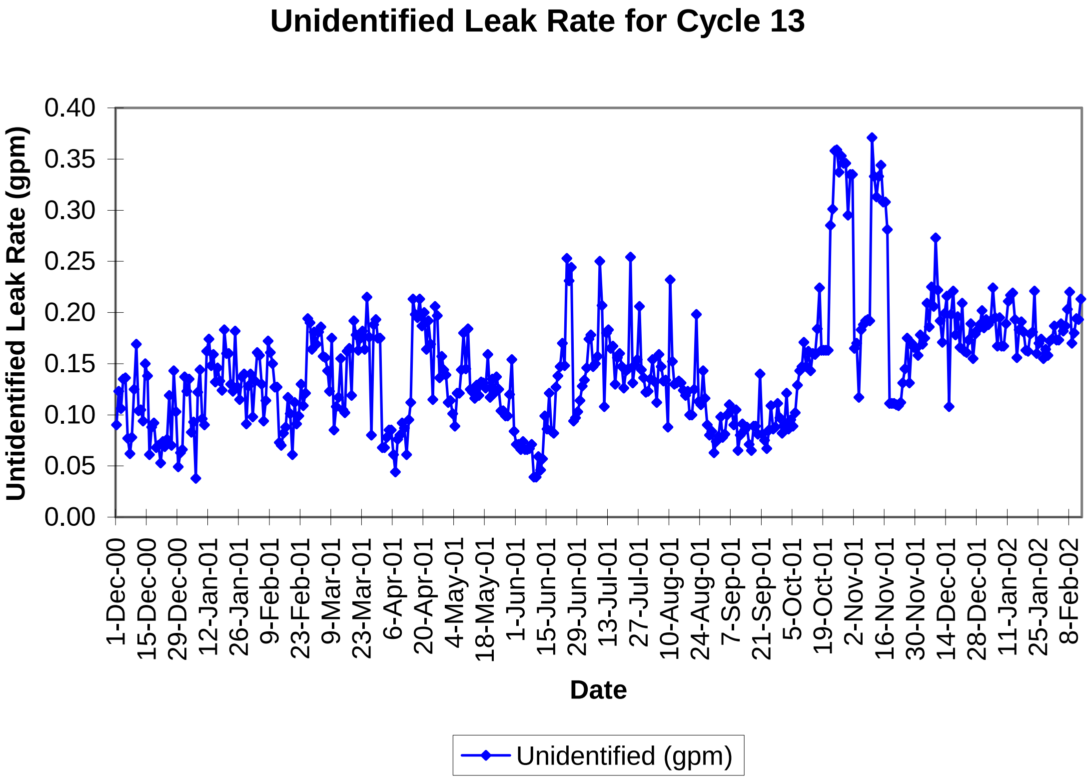


Figure 7.1 Daily average unidentified leak rate for Davis-Besse Cycle 13.[67]

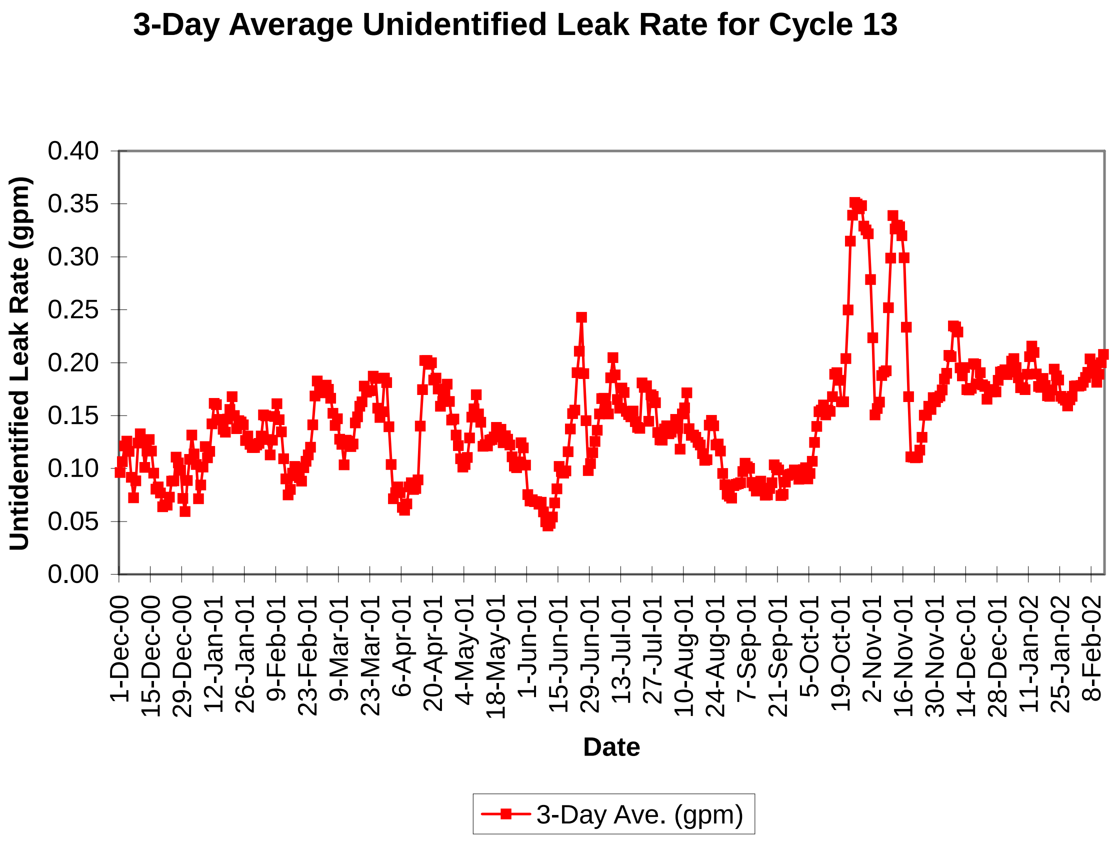


Figure 7.2 Three-day average unidentified leak rate for Davis-Besse Cycle 13.[67]

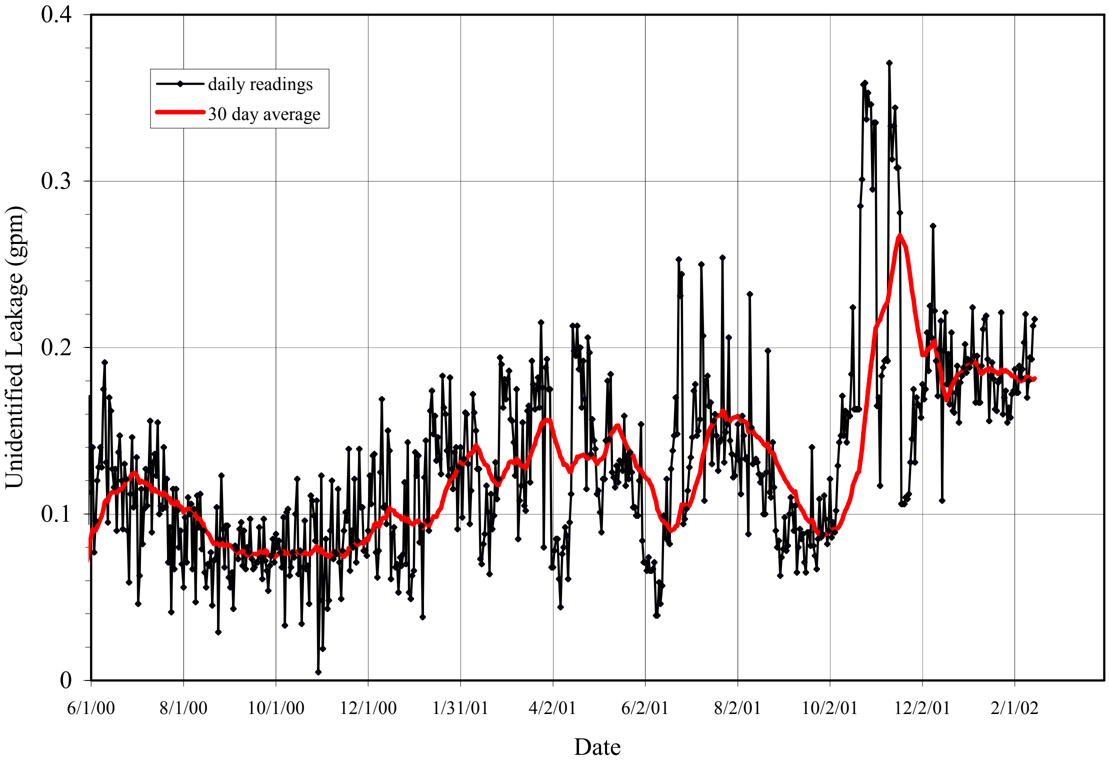


Figure 7.3 Thirty-day average unidentified leak rate for Davis-Besse Cycle 13.[68]

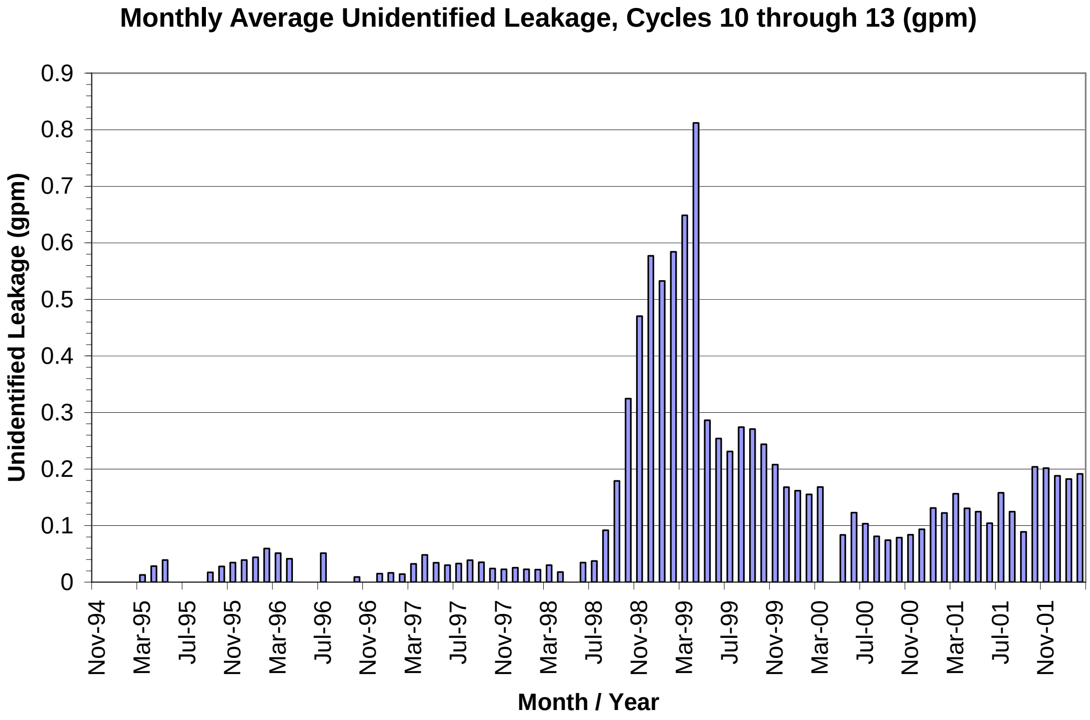
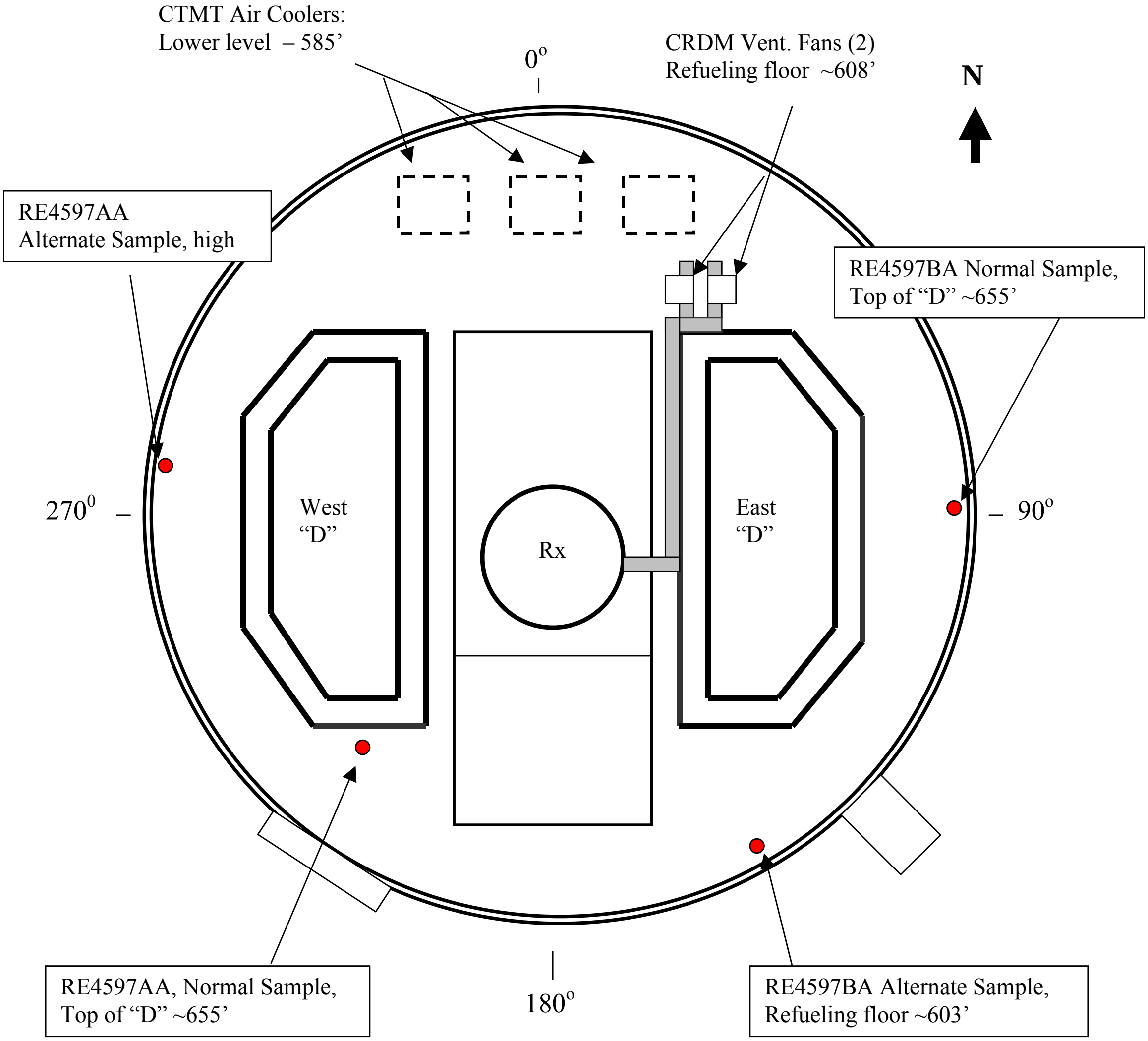


Figure 7.4 Monthly average unidentified leak rate for Davis-Besse Cycles 10 through 13.[69]



(not to scale)

Figure 7.5 Location of radiation monitors RE 4597AA and RE 4597BA.[70]

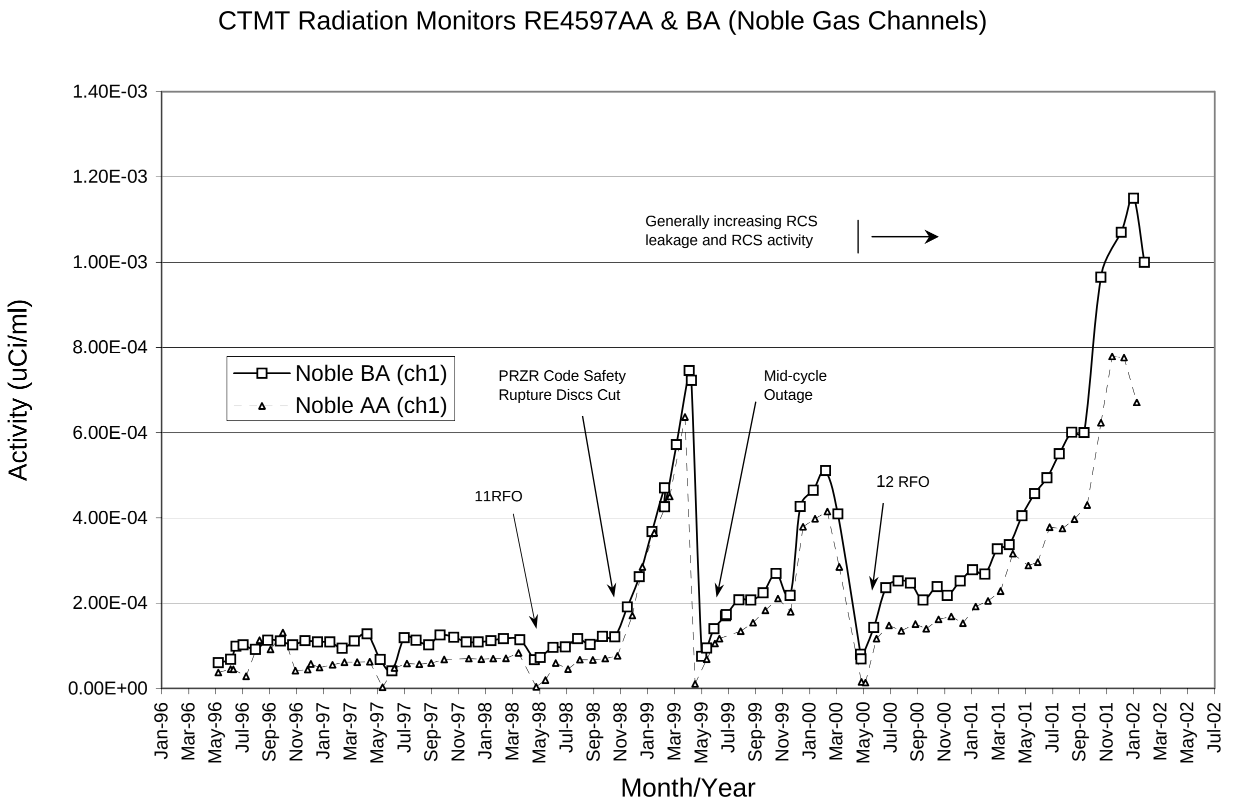


Figure 7.6 Noble gas activity for Cycles 10-13 for radiation monitors RE 4597AA and RE 4597BA.[71]

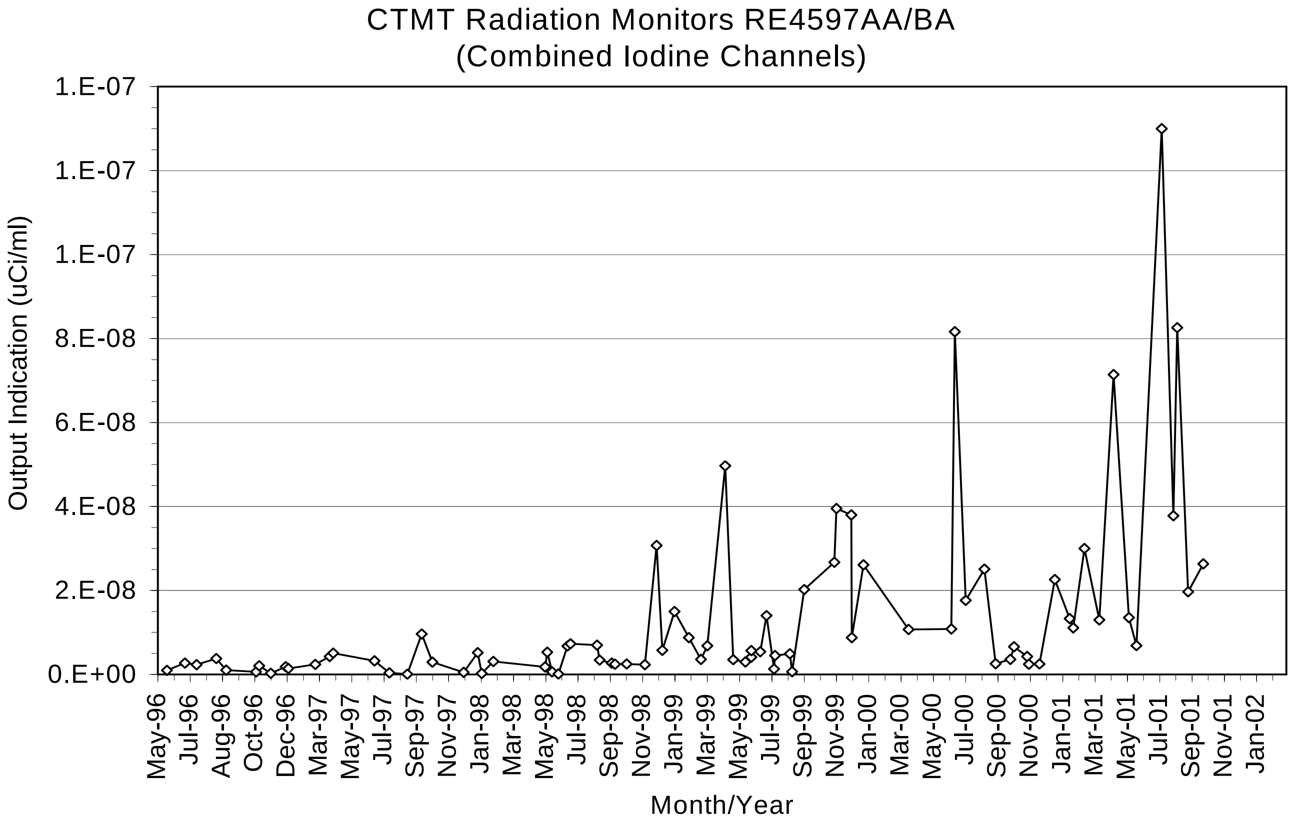


Figure 7.7 Iodine activity for Cycles 10-13 for radiation monitors RE 4597AA and RE 4597BA.[73]

Figure 7.8 Flange Leakage Showing Boric Acid Deposits Leaking Through the Mirror Insulation at 8RFO.[81]

Figure 7.9 Flange Leakage Showing Boric Acid Deposits On Side of Nozzles and Stalactites from Gaps in Insulation (8RFO).[81]

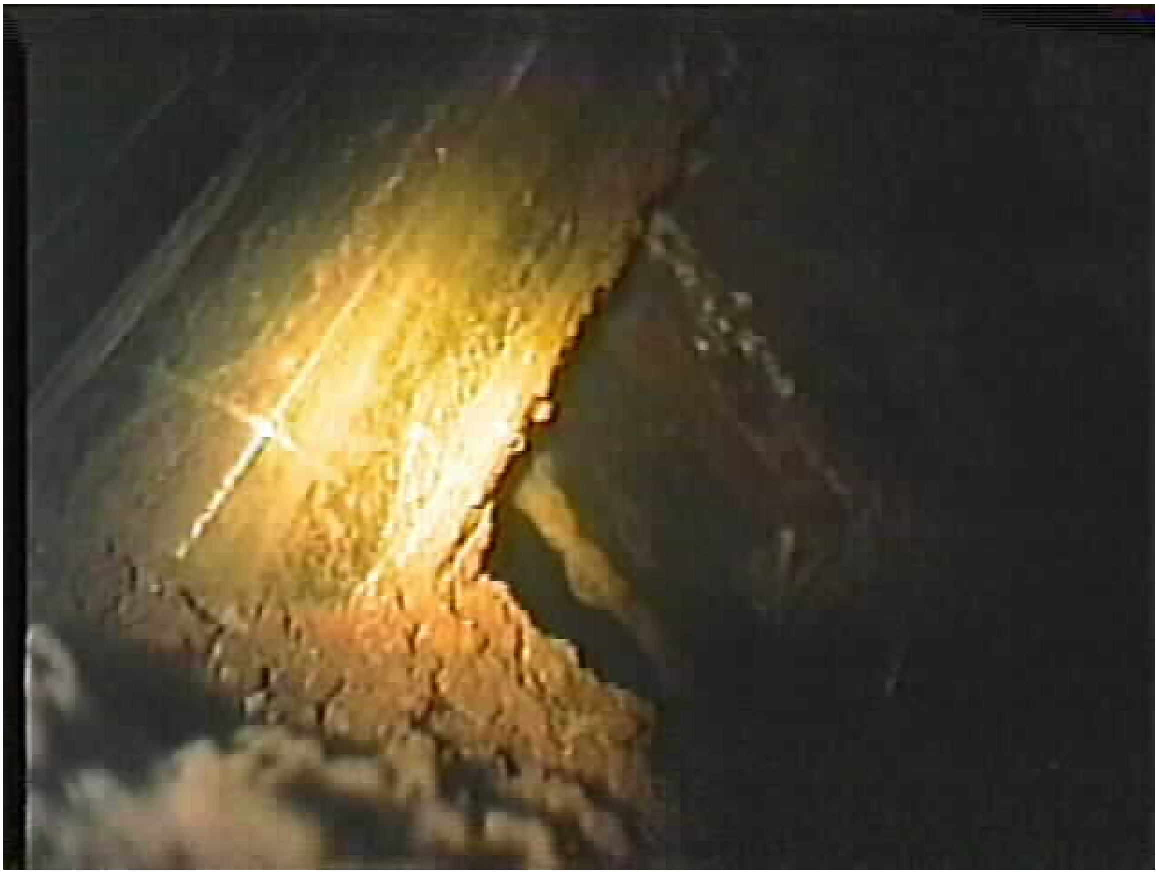


Figure 7.10 Reddish Brown Boron Deposits Crusted on Side of Nozzle (8RFO)[82]

Figure 7.11 Boric Acid Deposits Behind the CRDM Nozzles on the North Side of the Reactor Pressure Vessel Head at 10RFO.[86]

Figure 7.12 Boron Piled on Reactor Pressure Vessel Head Under the Mirror Insulation Near Nozzle 31 (11RFO).[89]

Figure 7.13 Boron Piled Up to the Mirror Insulation Near the Center of the RPV Head (12RFO).[99]

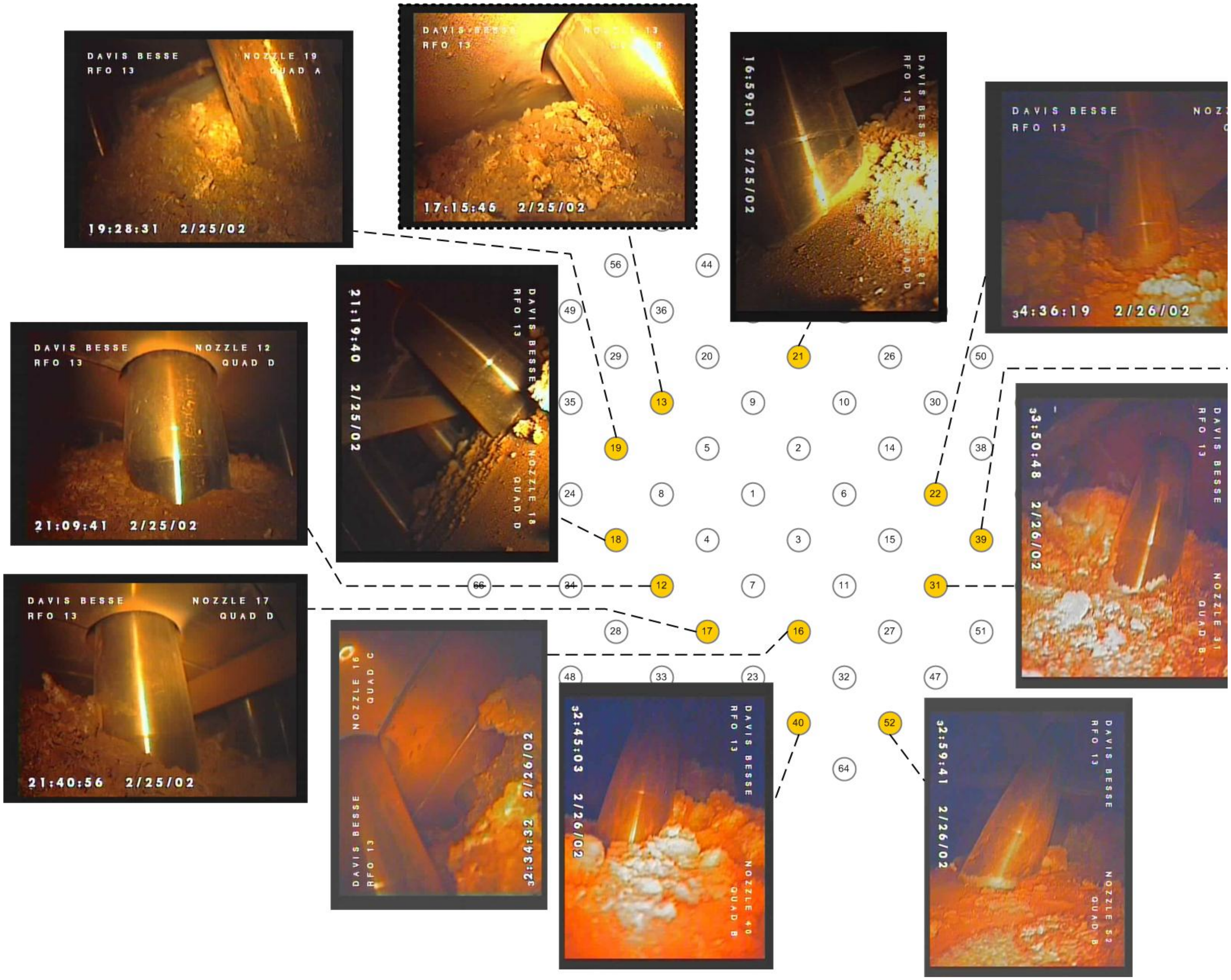


Figure 7.14 Boric Acid Deposits on RPV Head at 13 RFO. Note this is Figure 24 from the Root Cause Report.[104]

Figure 7.15 Corrosion Product/Boric Acid Deposits Adjacent to Nozzle 3 (90 Degree Side) after Hydrolasing.[105]

Figure 7.16 Corrosion Product/Boric Acid Deposits Adjacent to Nozzle 3 (270 Degree Side) after Hydrolasing.[106]

Table 7.1 Summary of Identified Leaking CRDM Flanges and Repairs for 6RFO to 12RFO

RFO	Date	Nozzles Identified	Nozzles Repaired*	Nozzles Not Repaired	Reference	Notes
6	1/29/90 - 7/5/90	1, 2, 6, 13, 17, 22, 23, 24, 33, 34, 37, 39, 40, 42, 43, 46, 50, 57, 59, 64, 68, 69	1, 2, 6, 13, 17, 22, 23, 24, 33, 34, 37, 39, 40, 42, 43, 46, 50, 57, 59, 64, 68, 69 (**See note)		PCAQ 90-0120, PCAQ 90-0221	Rework implemented FCR 82-0042 to install new split nut rings on the leaking nozzle flanges identified as being repaired. 69 had indications of errosion and 37 had indications of irregularities.
7	8/31/91 - 11/7/91	5, 8, 10, 11, 26, 29, 30, 31, 32, 35, 38, 44, 47, 49, 51, 53, 55, 58, 60, 63, 66, 67	5**, 8, 11**, 29**, 30, 32, 35**, 38, 49, 51, 55, 58, 60, 63, 66**	10, 26, 31, 44, 47, 53, 67	PCAQ 91-0353	Rework performed by MWO 1-91-0430-03. 5, 29, 35, 66, 11 identified as having indications of pitting.
8	03/01/93 - 04/30/93	4, 7, 9, 10, 15, 25, 26, 27, 31, 41, 47, 53, 65, 67	4, 7, 9, 10**, 15, 25, 26, 27, 31**, 41, 47, 53, 65, 67**		PCAQ 93-0132	31, 67 & 10 had some pitting and were used "as found".
9	10/01/94 - 11/15/94	18, 20, 21, 28, 22, 52, 54, 56	18, 20, 21, 28, 22, 52, 54, 56		PCAQ 94-0912	Rework performed by MWO 1-94-0169-01.
10	4/8/96 - 6/2/96	(See Note)	3, 12, 16, 17, 19, 36, 48, 61, 62 (**See note)		PCAQ 96-0580, MWO 1-95-0613-03	Two components of the CRDM on nozzle 48 were found in an unexpected material condition. This CRDM was disassembled to perform life extension. Gaskets to nozzles 62,3,16,61,17,36,12,19 were replaced under MWO 1-95-0613-03. The purpose of the MWO was to inspect for leakage and replace the gasket with a new material. No 10RFO PCAQRs were found to document any leakage for this outage. PCAQ 98-0649 indicates "The only flanges rebuilt in 10RFO were those without the new gasket material. Only one flange exhibited signs of leakage during this outage and it was already scheduled for repair." It is not evident which flange was leaking.
11	4-10/98 - 5/23/98	31		31**	PCAQ 98-0649	Repair of nozzle 31 was defered to RFO 12 due to the fact that the leak was of such little magnitude.
12	4/1/00 - 5/18/00	3, 6, 11, 31, 51	3, 6, 11**, 31**, 51		CR00-0995, CR00-0994	Nozzle 11 had indications of pitting and was used in the "as found" condition. Nozzle 31 was found to have extensive pitting and was consequently machined.

* Repair indicates a minimum of cleaning and replacing gasket. Additional work is noted in the notes.

** See notes for respective RFO

7.4 References

1. “Boric Acid Corrosion Control”, Toledo Edison Nuclear Group Procedure NG-EN-00324, Revision 00, September 8. 1989

2. *Ibid*, Section 8.0, “Commitments”, page 15.

3. *Ibid*, Section 1.0, “Purpose”, page 5.

4. *Ibid*, Section 3.0, “References”, page 6.

5. “Boric Acid Corrosion of Carbon and Low-Alloy Steel Pressure-Boundary Components in PWRs,” EPRI Research Project RP2006-18, Final Report NP-5985, August 1988.

6. “Boric Acid Corrosion of Ferritic Reactor Components”, NRC Report NUREG/CR-2827, BNL-NUREG-51561, July 1982.

7. “Degradation of Threaded Fasteners in the Reactor Coolant Pressure Boundary of PWR Plants”, NRC Bulletin 82-02, June 2, 1982.

8. “Boric Acid Corrosion Control”, Toledo Edison Nuclear Group Procedure NG-EN-00324, Revision 00, September 8. 1989, Section 5.0, “Responsibilities,” pages 6, 7.

9. *Ibid*, Section 6.1, “Principal Leak Locations”, page 8.

10. *Ibid*, Section 6.2, “Locating Small Coolant Leaks”, pages 8, 9.

11. *Ibid*, Sections 6.3.1 through 6.3.5, “Examination and Evaluation”, pages 9, 10, 11.

12. *Ibid*, Section 6.3.6, “Examination and Evaluation”, pages 11, 12.

13. *Ibid*, Section 7.0, “Records”, page 12.

14. “Boric Acid Corrosion Control”, Toledo Edison Nuclear Group Procedure NG-EN-00324, Procedure Change No. C-2, August 30, 1991, Section 6.3.1 at pages 10, 11.

15. “Boric Acid Corrosion Control”, Toledo Edison Nuclear Group Procedure NG-EN-00324, Revision 1, February 22, 1994.

16. *Ibid*, incorporating Procedure Change No. C-1, June 3, 1994.

17. *Ibid*, incorporating Procedure Change No. C-2, October 30, 1994.

18. *Ibid*, incorporating Procedure Change No. C-3, April 25, 1999.

19. *Ibid*, at pages 6, 14.

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21. “Boric Acid Corrosion Data – Summary and Evaluation”, B&W report 51-1229638-01, June 29 1994, prepared for the BWOG.

22. “Boric Acid Corrosion Control”, Toledo Edison Nuclear Group Procedure NG-EN-00324, Revision 1, incorporating Procedure Change No. C-3, April 25, 1999, at page 11.

23. *Ibid*, at pages 13, 14.

24. “Boric Acid Corrosion Control”, Toledo Edison Nuclear Group Procedure NG-EN-00324, Revision 2, September 30, 1999.

25. *Ibid*, section 4.0, at pages 7, 8.

26. *Ibid*, section 6.0, at pages 9 through 18.

27. *Ibid*, section 6.3, at pages 11, 12.

28. *Ibid*, section 6.4, at pages 13, 14.

29. *Ibid*, section 6.6, at page 15.

30. *Ibid*, section 6.7, at page 16.

31. *Ibid*, section 6.8, at page 17, 18.

32. *Ibid*, Attachment 3, at pages 22, 23.

33. BWOG materials Committee report BAW-2301, “B&WOG Integrated Response to Generic Letter 97-01: Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations”, July, 1997, ay page 4-1.

34. First Energy letter to the NRC, Serial Number 2731, September 4, 2001, response to item 1.a of NRC Bulletin 2001-01, Attachment 1 at page1.

35. *Ibid*, response to item 1.d of NRC Bulletin 2001-01, Attachment 1 at page 2.

36. *Ibid*, response to item 3.b of NRC Bulletin 2001-01, Attachment 1 at pages 5 through 7.

37. “Supplemental Information in Response to NRC Bulletin 2001-01”, FENOC letter to the NRC, Serial Number 2735, October 17, 2001.

38. “RV Head Nozzle and Weld Safety Assessment”, Framatome-ANP report 5012567-01, September 28, 2001, Attachment 4 to FENOC letter number 2735.

39. “Finite Element Gap Analysis of CRDM penetrations (Davis-Besse)”, Structural Integrity Associates Calculation Package W-ENTP-11Q-306, October 8, 2001, Attachment 5 to FENOC letter number 2735.

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41. “Supplemental Information in Response to NRC Bulletin 2001-01”, FENOC letter to the NRC, Serial Number 2735, October 17, 2001, Attachment 1 at pages 3, 4.

42. “RV Head Nozzle and Weld Safety Assessment”, Framatome-ANP report 5012567-01, September 28, 2001, Attachment 4 to FENOC letter number 2735, at pages 16, 17, Sections 5 and 6.

43. *Ibid*, at pages 22-29, Sections 9.2, 9.3.

44. *Ibid*, at page16 Section 5.

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47. “Responses to Requests for Additional Information Concerning NRC Bulletin 2001-01”, FENOC letter to the NRC, Serial Number 2741, October 30, 2001.

48. *Ibid*, RAIs BR-2, BR-3, SAI-4, FRA-10, FRA-11 and responses.

49. *Ibid*, RAIs FRA-2, FRA-2, FRA-7, FRA-8, FRA-12 and responses.

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55. *Ibid*, Attachment 1 at page 2.

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58. *Ibid*, Attachment 1 at pages 5, 6.

59. “Davis-Besse Nuclear Power Station, Unit 1, Documentation of Conference Call of November 15, 2001, re: Response to Bulletin 2001-01,” NRC letter to FENOC dated November 19, 2001.

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71. *Ibid,* page 129.

72. *Ibid,* page 39.

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