e3

From: "RLS4@NRC.GOV" <rls4@nrc.gov>
To: "BLB@NRC.GOV" <blb@nrc.gov>, "TJW2@NRC.GOV" <tjw2@nrc.gov>, "GCW@NRC.GOV" <gcw@nrc.gov>
Date: Tue, Jun 19, 2007 9:06 AM
Subject: Additional information about the CR I sent in yesterday.

CC: "JER7@NRC.GOV" <jer7@nrc.gov>, "RLS4@NRC.GOV" <rls4@nrc.gov>

F-257

Site: G201

CONDITION REPORT

CR Number 07-21815

TITLE: EXPONENT FAILURE ANALYSIS REPORT CLARIFICATIONS REQUIRE FENOC TECHNICAL REVIEW

ORIGINATION

DISCOVERY DATE	TIME	EVENT DATE	TIME	SYSTEM / ASSET#
6/7/2007	1600 hours	6/7/07	1600 hours	

EQUIPMENT DESCRIPTION N/A

FLOC System | **FLOC**

DESCRIPTION OF CONDITION and PROBABLE CAUSE (if known) Summarize any attachments. Identify what, when, where, why, how.

Exponent Failure Analysis Associates submitted an electronic document to provide clarification for questions raised by FENOC related to the Exponent Report (reference CR G201 07-17452) submitted to FENOC and reviewed under CRs G201 07-15077, G201 07-17452, and G298 07-20722. The clarifications provided by the vendor, Exponent Failure Analysis Associates, document responses to discussions held between FENOC and Exponent on Wednesday June 6, 2007 and Thursday June 7, 2007 regarding technical questions associated with the original Exponent Report submitted to FENOC in December 2006.

This CR is being written to track the technical reviews of the clarifications provided in the Exponent submittal. Review should include possible effects on Davis Besse and Beaver Valley Units.

Responsibility for review coordination and compilation is being assigned to Fleet Engineering, FDEN.

PDF file containing clarification submittal is being attached to this CR for reference purposes.

IMMEDIATE ACTIONS TAKEN / SUPV COMMENTS (Discuss CORRECTIVE ACTIONS completed, basis for closure.)

Directed to write CR to ensure comprehensive review task is assigned and tracked to completion. Clarifications are related to history of deposits on old reactor head removed from Davis Besse and do not apply to current RPV head in service. SRO Review Required block checked yes to provide information to Control Room Staff; operability issue does not exist since old head has been removed from the station. Initial review of the contents shows the clarification document to include explanations and rationale for conclusions contained in the previously submitted formal report. Submitted to control room at Davis-Besse for information.

QUALITY ORGANIZATION USE ONLY
Quality Org. Initiated ☐ Yes
Quality Org. Follow-up ☐ Yes ☐ No

IDENTIFIED BY (Check one)
☑ Individual/Work Group
☐ Supervision/Management
☐ Self-Revealed
☐ Internal Oversight
☐ External Oversight

ATTACHMENTS
☑ Yes ☐ No

ORIGINATOR	ORGANIZATION	DATE	SUPERVISOR	DATE	PHONE EXT.
KLINE, W	FMEN	6/8/2007	LOEHLEIN, S	6/8/2007	825-5779

Site: G201

CONDITION REPORT

CR Number 07-21815

TITLE: EXPONENT FAILURE ANALYSIS REPORT CLARIFICATIONS REQUIRE FENOC TECHNICAL REVIEW

PLANT OPERATIONS

SRO REVIEW	EQUIPMENT OPERABLE	OPERABILITY ASSESSMENT REQUIRED	ORG. NOTIFIED	IMMEDIATE INVESTIGATION REQUIRED	ORG. NOTIFIED	MODE CHANGE RESTRAINT
☑ Yes ☐ No	☐ Yes ☐ No ☑ N/	☐ Yes ☑ No		☐ Yes ☑ No		☐ Yes ☑ No

MODE	ASSOCIATED TECH SPEC NUMBER(S)	ASSOCIATED LCO ACTION STATEMENT(S)
N/A	N/A	#1 N/A
		#2
		#3

DECLARED INOPERABLE (Date / Time)	REPORTABLE?		APPLICABLE UNIT(S)
N/A	☐ Yes ☑ No ☐ Eval Required	One Hour N/A Four Hour N/A Eight Hour N/A Other N/A	☑ U1 ☐ U2 ☐ Both

COMMENTS

This condition report was written to track the technical reviews of the document submitted by Exponent Failure Analysis Associates. As stated in the Supervisor comments, the report provides clarifying information having to do with the old reactor vessel head corrosion event. The head has been replaced and there is no Operability impact to any installed plant equipment; therefore, Equipment Operable is N/A. This is not a reportable condition.

Current Mode - Unit 1	Power Level - Unit 1	Current Mode - Unit 2	Power Level - Unit 2	
1	100	N/A	N/A	

SRO - UNIT 1	SRO - UNIT 2	DATE
Boissoneault, P	Baldwin, J	6/8/2007

CRPA / SUPV / MRB

CATEGORY / EVAL	ASSIGNED ORGANIZATION	DUE DATE
CF	FDEN	7/23/2007

TREND CODES

Process / Activity / Cause Code(s)			Comp Type / ID (If Cause T or W)		Cause Org
LP2	2600				

REGULATORY

REPORTABLE? ☐ Yes ☑ No ☐ LER No:

REPORTABILITY REVIEWER

Wolf, G

DATE

06/12/07

INVESTIGATION OPTIONS	CLOSED BY	DATE
☐ Maint Rule ☐ OE Evaluation		

Site: G201

INVESTIGATION SUMMARY

NOP-LP-2001-06

CR Number: 07-21815

Category / Eval: CF   Assigned Organization: FDEN   Quality Followup Req'd: ☐ Yes ☑ No

For Fix Investigations Only:
☐ Hardware / Degraded Condition Resolution Required? ☐ Yes ☐ No If Yes: ☐ Repair ☐ Scrap ☐ Rework ☐ Use-As-Is

☐ Acceptance of the CR Investigation signifies acceptance of the following items, as applicable:

	Originator Identification	Date
Corrective Actions (listed below)	(listed below, if any)	(listed below, if any)
Cause Analysis		
Generic Implications		
10 CFR 21 Decision Checklist		

Acceptance of Investigation: Date: Quality Approval: Date:

Site-VP Acceptance: Date:

Closure Comments:

Quality Comments:

CORRECTIVE ACTIONS

CA Number:	Sched Type:	CA Type:	Cause Code:	Resp Org. Codes:	CA Acceptance:	Accept Date:	Due Date:	Completed Date:

Clarifications of the Exponent Report

1.0 Statements concerning the accumulation of boric acid from the Nozzle 3 leak at 12FRO

In section 5.3.2 at page 5-19, the Exponent Report states:

> "For Davis-Besse, we conclude that the accumulation of boric acid from the long axial crack at Nozzle 3 at 12RFO in April-May 2000 was no more than 6 cubic inches (Section 10.2.3), and may have been much less than even this minute amount."

The "6 cubic inches" cited in this statement is statement was an error and was missed in final quality assurance checking. The cited paragraph also contains a second error in the reference to Section 10.2.3 which was changed in the re-numbering of the sections of Section 10 in the final version of the report.

Final checking of calculations and cracking/leak rate timelines resulted in a volume of less than 1 cubic inch, as cited in Section 10.2.1, page 10-8:

> "The maximum boric acid accumulation due to this small leak rate in the last four months of the fuel cycle from December 1999 to April 2000 would have been no more than 1 cubic inch (0.05 lb), even assuming all of the leaking boric acid collected on the RPV head and was not ejected above the mirror insulation and out into the containment building."

The correct volume of 1 cubic inch of boric acid was also cited in Section 2.7.1, page 2-13, which referred to Section 10 for its basis:

> "It is possible that an incipient sub-surface wastage cavity formation had already begun by 12RFO above the crack at CRDM Nozzle 3......Any boric acid deposits from this small leak would have been correspondingly small, no more than 1 cubic inch, similar to those found at Oconee-1 in November 2000."

2.0 Statements concerning the detectability of the leak at CRDM Nozzle 3 at 12RFO

Various statements are made in the Exponent Report concerning the detectability of three conditions resulting from the leak at CRDM Nozzle 3 at 12RFO in April/May 2000:

- The maximum volume of boric acid accumulation around the nozzle resulting from the leakage prior to 12RFO;
- The incipient sub-surface wastage cavity;
- The annulus enlargement at Nozzle 3 at the top surface of the RPV head.

The most complete description of the Exponent's conclusions concerning the detectability of these three conditions at 12RFO in April/May 2000 is contained in Section 10.2.1 at pages 10-8 and 10-9:

- The maximum boric acid accumulation due to this small leak rate in the last four months of the fuel cycle from December 1999 to April 2000 would have been no more than 1 cubic inch (0.05 lb), even assuming all of the leaking boric acid collected on the RPV head and was not ejected above the mirror insulation and out into the containment building.
- The minute amount of boric acid would have been totally obscured by the boric acid accumulation from five leaking CRDM flanges above the RPV head, one of which was the CRDM Nozzle 3 flange. Complete cleaning of the boric acid accumulation from the RPV head at this time would also have removed the very small amount of boric acid that originated from the CRDM nozzle crack.
- A minor and insignificant sub-surface wastage volume at Nozzle 3 is likely present at this time, but due to the much lower leak rate, this would have been much smaller in axial and radial penetration, annular gap, and total wastage extent than that found at Nozzle 2 at 13RFO. This size of wastage cavity would not have been detectable by any visual or available NDE technique.
- Annulus enlargement at the RPV head surface may have been present, but this would also likely have been much less than that observed at Nozzle 2 at 13RFO in 2002. Annulus enlargement, if present, would not have been detectable with "through-the-mouse-hole" video

inspection techniques, even if the RPV head had been completely cleaned of boric acid at 12 RFO.

The basis for Exponent's conclusion that there was "likely present" a "minor and insignificant sub-surface wastage volume at Nozzle 3" at 12RFO was Exponent's estimate of the leak rate from the Nozzle 3 crack at that time. The estimated leak rate was only 0.0004 gpm, about 1/25th of the estimated leak rate at Nozzle 2 at 13RFO in 2002, where a small sub-surface wastage cavity was found. This conclusion is further supported by the very minor annulus enlargement and no sub-surface cavity found at Nozzle 1 at 13RFO, where the maximum axial crack length above the weld was comparable to that at CRDM Nozzle 3 at 12RFO in April/May 2000.

The basis for Exponent's conclusion regarding the detectability of a minor and insignificant sub-surface wastage volume or sub-surface annulus enlargement at CRDM Nozzle 3 at 12RFO, even if one existed, was Exponent's understandings of the capability of NDE inspection methods in 2002 to find such small wastage volumes.

The conclusion regarding the detectability of possible annulus enlargement the RPV head surface at 12RFO was based on Exponent's review of the video records at 13RFO. That video clearly showed the difficulties FENOC faced in finding minor annulus enlargement at CRDM Nozzle 2 in 2002, even after cutting an access hole through the insulation, and even with full knowledge that a small sub-surface cavity was actually present at Nozzle 2 at that time.

With respect to the detectability of the small boric acid accumulation at 12RFO, Section 7.3.6 at page 7-27 of the Exponent Report added an additional observation:

> "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."

Additional statements regarding the detectability of these three conditions appear in Section 1 at page 1-5, Section 2.7 at pages 2-13, 2-14, and Section 10 at page 10-2. These statements, while not as complete as those cited above, express the same conclusions.

3.0 Leak rate from the weld crack and leak rate vs. axial crack length above the weld

Exponent's work and conclusions with regard to the leak rate from the CRDM Nozzle 3 weld crack, and the dependence of the leak rate from the axial cracks on crack length above the CRDM nozzle weld are summarized in Section 9.4 and Appendix D of the Exponent Report.

That work showed that the attribution of the total leak rate of up to 0.15 gpm in the Root Cause Report solely to the 1.2 inch axial crack at CRDM Nozzle 3 in Figure 21 of the FENOC Root Cause Report was incorrect.

Exponent's work showed that the leak rate from a crack of this length was only around 0.02 gpm, and that it is impossible for a1.2 inch long axial PWSCC crack in a CRDM nozzle to leak at the 0.15 gpm rate that the Root Cause Report concluded it did. Thus, the conclusions of the Root Cause Report first, that an axial crack and leak of this magnitude existed at CRDM Nozzle 3 for a long period of time; and second, that this was the cause of most of the boric acid accumulation on the RPV head from 1996 on, are not consistent with our calculations.

At the time the Root Cause Report was finalized in August 2002, the existence of the weld crack at Nozzle 3 was not known, and only the existence of the axial nozzle crack was considered in the Root Cause Report. Exponent concluded that the leak rate from the large weld crack found in the CRDM Nozzle 3 weld accounted for the approximately 0.14 gpm increase in unidentified leak rate evident in the October/November 2001 time period.

Exponent's CFD analyses described in Section 9 of the Exponent Report show that for a leak rate of around 0.17 gpm, considerable moisture is carried up through the growing wastage cavity to the upper surface of the RPV head. Based on the thermal hydraulic conditions and the NRC/ANL work on boric acid corrosion, Exponent concluded that rapid "top down" corrosion of the RPV steel began in October/November 2001 as the weld crack uncovered, and that significant enlargement of the upper region of the cavity occurred in a few months.

Based on this, Exponent further concluded that had a leak rate of the magnitude of around 0.1 to 0.15 gpm existed from the Nozzle 3 cracks for the period of time that the Root Cause Report concluded it did – at least 4 years from 1998-2002, then the enlargement of the wastage cavity by boric acid corrosion processes, continuously fed by moisture from the leak, would have continued, and would have likely been limited only by the extent of the boric acid deposit in the SE quadrant. Therefore, based on the corrosion rates for the conditions at the upper head surface due to boric acid corrosion processes, cavity enlargement would have occurred to a much greater extent than that observed for the final cavity, perhaps as much as an order of magnitude greater, if the leakage began in 1998.

4.0 Exponent's consideration of plant operational data

Throughout Exponent's comprehensive and detailed failure analysis of the Davis-Besse RPV head wastage event, Exponent fully considered all of the available plant operational data, as well as the review and analysis of that same data contained in the FENOC Root Cause Report.

It is important to note that Exponent made no a priori "assumptions" about any of the plant operational experience data. Rather, Exponent first established a specific timeline of crack growth and leakage for the long axial crack at CRDM Nozzle 3, then examined the plant operational data to determine if it was consistent with that timeline, and if it was not, that it could be accounted for by other plant events. The relevant plant operational data considered by Exponent are discussed in detail in Attachment A, which has previously been forwarded to FENOC.

5.0 Initial Nozzle 3 Leakage and Iron Oxide Deposits

Exponent completed detailed computational analyses of the evolution of the axial nozzle crack in Nozzle 3 of the Davis-Besse reactor pressure vessel (RPV) head using the measured crack growth rate data published by Argonne National Laboratories (ANL). These crack growth rate data were derived from direct measurements completed on metal specimens extracted from Nozzle 3 following removal from the damaged RPV head. The analyses completed by Exponent provided the crack length estimates cited in the Exponent Report (pages 8-18, 10-7, 10-9).

Date	Crack Location/Length
Mid-1999	CRDM Nozzle 3 crack reached top of J-groove weld
April/May 2000 (12RFO)	Crack was 0.5 inches above J-groove weld
October 2001	Crack was 1.1 inches above J-groove weld

Following the development of this crack growth timeline, Exponent reviewed Davis-Besse plant operational data to determine if all observations agreed with the Exponent timeline. One of the most significant of these plant observations was the appearance of iron oxide deposits in radiation monitor filters in May 1999. The Root Cause Report noted that 83 radiation monitor filter changes occurred over the course of a 2 to 3 month time span. The Exponent report considered this information and noted (page 7-20),

> "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 extremely low leak rates associated with the initial flow of fluid through very short cracks in thick-walled nozzles at high temperatures and internal pressures dictate that the initial leakage from the CRDM Nozzle 3 crack after it reached the top of the J-groove weld in mid-1999 would not produce conditions conducive to the energetic process (fluid jet cutting) cited in the Exponent Report. However, this extremely low leak rate would result in conditions where the leaking fluid would flash to steam (either within the CRDM nozzle crack or within the annulus between the nozzle and the RPV head) and would begin the corrosion (albeit slight) of the alloy steel RPV head material. Basic thermodynamic analyses showed that the phase change associated with formation of the steam from the leaking high-pressure reactor coolant provided the mechanism for the alloy steel corrosion products (iron oxide) to be transported up the annulus, above the mirror insulation and be swept into containment by the ventilation system for the CRDMs.

Although this leakage and corrosion mechanisms represented the initiation of material removal from the RPV head, it did not mean that significant subsurface wastage had begun. As noted in the Exponent report (page 10-7), the leak rate for the 0.5-inch-long axial crack in Nozzle 3 at 12RFO was estimated to be approximately 0.0004 gpm (210 gal/year). While this leak rate caused corrosion within the annular gap at Nozzle 3 and the deposition of fine iron oxide particulates throughout containment, the flow rate was too small to produce the energetic processes that began the formation of subsurface wastage cavity as described in detail in the Exponent Report (Sections 9 and 10).

6.0 10RFO, 11RFO and 12RFO Flange Leakage Summary

The Root Cause Report conclusion that an axial crack in Nozzle 3 began leaking in the 1994 to 1996 time frame was derived from among other things, a number of plant observations. Some of these observations included:

1. Assumption that the RPV head was clean after 9RFO (1994)
2. Observation of an expanding area of coverage of boric acid at 10RFO (1996), 11RFO (1998) and 12RFO (2000)
3. Assertion that no significant CRDM flange leaks occurred in Cycles 10 and 11
4. Assertion that Nozzle 31 flange leaks would not have resulted in extensive deposits found at 12RFO (2000)

Exponent considered all of these assumptions/observations/assertions and concluded that the Nozzle 3 crack did not begin leaking until mid-cycle 12 in 1999. The information identified by Exponent to support this conclusion is provided below.

6.1 RPV Head Was Clean After 9RFO (1994)

The Root Cause Report noted (page 31) that for 8RFO (1993

> "Based on the results of head inspection, the RPV head and flange was cleaned with deionized water. The effectiveness of the cleaning could not be verified in that the RPV head had already been returned to the RPV. A cleaning effectiveness inspection was recommended as a follow-up activity for the next outage."

However, at the next outage in 1994 (9RFO) the Root Cause Report (page 31) also noted that

> "In 1994 (9RFO), the CRDM flanges were inspected; however, no records have been identified indicating a visual inspection of the RPV head was completed."

Since the effectiveness of the RPV head cleaning during 8FRO was not verified and since no visual inspection of the RPV head was completed during 9RFO, it is impossible to conclude that the RPV head was clean following 9RFO.

Further evidence of the lack of complete cleaning in 1993 is provided by outer row CRDM Nozzle 67. This nozzle had a leaking flange in 1991 but was not repaired at that time. It was still leaking in 1993 when it was finally repaired and when the head cleaning operation was performed. In 1996, the Root Cause Report notes (Att.2 page 142):

> "Video tape of CRDM nozzle inspection shows several patches of boric acid accumulation on the RV head. CRDM nozzle 67 shows rust or brown

stained boron at the bottom of the nozzle at the head. The head area in the vicinity also has rust or brown stained boron accumulation."

Exponent concluded from the plant records that boric acid was left on the head after the 8RFO cleaning in 1993, not just in the center region around Nozzles 1-5 as found in 1996 and shown in the Root Cause Figure 20, but also at least in the outer region near Nozzle 67.

6.2 Expanding Area of Boric Acid Coverage with No Significant CRDM Flange Leakage

The Root Cause Report noted an expanding area of boric acid coverage on the RPV head (Figure 20) from 10RFO (1996) through 13RFO (2002). Since the Root Cause Report also concluded that "there were no significant gasket leaks prior to 11 RFO," this expansion in boric acid coverage was considered to be evidence of CRDM nozzle leakage. Exponent concluded that the plant evidence does not support this conclusion. Hence, Exponent disagreed with this conclusion of the Root Cause Report.

As noted in the Exponent Report (Table 7.1), PCAQ 96-0580, and MWO 1-95-0613-03 for 10 RFO

> "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 PCAQs 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."

Since one leaking flange at an unknown location was noted at 10RFO and one of those flanges that was "repaired" was the flange on Nozzle 3, Exponent concludes that flange leakage resulted in the increase in boric acid coverage on the RPV head during Cycle 10.

There was one documented flange leakage during Cycle 11 as noted in Table 7.1 of the Exponent Report and in PCAQ 98-0649. The leaking flange was located on Nozzle 31. The repair of Nozzle 31 was deferred to 12RFO "due to the fact that the leak was of such little magnitude." It should be noted that even a leak of "little magnitude" can deposit a significant amount of boric acid over the course of an entire fuel cycle. Exponent completed calculations to evaluate the amount of boric acid contained in the volume of water for various leak rates over the course of an entire reactor fuel cycle including the effects of the variation in boric acid concentration in the reactor coolant system during the cycle. These calculations showed that even a leak of "little magnitude" on the order of 0.001 gpm, which is three orders of magnitude below the Tech Spec limit for unidentified leak rate (.1 gpm), results in the deposition of about 40 pounds of boric acid. Exponent concludes that flange leakage of even "little magnitude" resulted in the increase in boric acid coverage on the RPV head during Cycle 11.

During Cycle 12, the Root Cause Report and the Exponent Report note that significant CRDM flange leakage occurred at Flanges 31 and 11. Table 7.1 in the Exponent Report noted

> "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."

A total of 5 flanges were repaired during 12RFO, including the flange on Nozzle 3. Since all 5 flanges including flanges 3, 11 and 31 are located directly within the region of expanding boric acid coverage of the RPV head, Exponent concludes that flange leakage contributed to the increase in boric acid coverage on the RPV head during Cycle 12

6.3 Limited Flange Leakage from Nozzle 31 in Cycle 12

The Nozzle 31 flange was known to have been leaking for more that one entire fuel cycle ("little magnitude" at 11RFO and "found to have extensive pitting and was consequently machined" at 12RFO). Since the unidentified leak rate at the end of Cycle 12 was noted to be about 0.16 gpm and 0.08 gpm at the beginning of Cycle 12 (Root Cause Report, Figure 26, page 113) and since the Nozzle 31 flange was the only identified (and repaired) leaking flange at 12RFO, Exponent concludes that a majority of the change in unidentified leakage from the end of Cycle 12 to the beginning of Cycle 13 can be attributed to the repair of this flange leak. This provides an estimate of the leak rate due to Nozzle 31 during Cycle 12. Following the same methodology cited above and assuming that only 50% of the unidentified leakage change (0.04 gpm) was due to the repair of the Nozzle 31 flange, the leak from Nozzle 31 alone would deposit over 1,600 pounds of boric acid on the RPV head during Cycle 12. Exponent concluded that this would have resulted in extensive deposits on the vessel head at 12RFO.

Based on the results provided above, Exponent concludes that flange leakage and not nozzle cracks that caused the expansion of boric acid coverage on the RPV head during Cycles 10, 11, and 12.

In addition, the boric acid found on the RPV head at 12RFO in 2000 was noted in the Root Cause Report to be "solid rock hard deposits" (Root Cause Report Att.2 page 147). Exponent concluded that this description was consistent with a phase change to metaboric acid, with subsequent melting at RPV head operating temperature and solidification during shutdown. Since molten metaboric acid will "flow" on the RPV head, Exponent concluded that part of the expanding footprint shown in Root Cause Report Figure 20 was a result of this phenomenon. Since no estimates of the volume of the boric acid deposits on the RPV head were ever made prior to 13RFO in 2000, it is not possible from the available data to equate an expanding deposit footprint to an expanding volume of deposits.

Attachment A

Response to NRC 5/14/07 DFI Letter Request B

The DFI requests "a detailed discussion of the differences in assumptions, analyses, conclusions, and other related information of the Exponent Report and previous technical and programmatic root cause reports, developed following the 2002 Davis-Besse reactor pressure vessel head degradation event."

The August 2002 FENOC Root Cause Report states that "based on the visual inspections of the DB RPV head, containment air cooler cleaning frequency, interviews, etc., a reasonable time frame for the appearance of leakage on the RPV head was approximately 1994-1996." With respect to the crack initiation and growth of the long axial crack at CRDM Nozzle 3, the Root Cause Report concluded that the PWSCC crack at Nozzle 3 initiated in 1990 (+/- 3 years), and grew to through wall at a rate of approximately 4 mm/year (0.16 inch/year) to above the weld in this 1994 to 1996 time period (Root Cause Report, Section 3.2.1, page 18).

At this same crack growth rate (CGR), the crack would then have reached the observed point 1.23 inches above the weld by 13RFO in February 2002. The CGR assumed in the Root Cause Report was noted to be "consistent with industry data" (Root Cause Report Section 3.2.4, page 26) and "a reasonable approximation to the more detailed type of calculations performed by the B&WOG safety assessment" (Root Cause Report Section 3.2.1, page 18).

Based on a "review of the sequence of relevant events" including 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, the Root Cause Report further concluded that the "corrosion rate began to increase significantly starting at about April-May 11RFO (1998) and acted for a four-year period of time." This implied an average corrosion rate of about 2.0 inches/year, with a maximum corrosion rate near the end of Cycle 13 of about 4.0 inches/year (Root Cause Report page 24).

Thus the Root Cause Report based its timeline for the wastage cavity development on the assumption that plant indications of boric acid leakage not only marked the beginning of leakage from a through wall crack at CRDM Nozzle 3 just reaching the top of the weld in the 1994-1996 time period, but also marked the onset of a significant increase in corrosion rate around 1998. This timeline fitted the crack growth development assumed by the Root Cause Report based on industry accepted CGRs.

In contrast, the Exponent Report made no a priori assumptions about any of the plant operational experience data. Rather, the Exponent Report first established the specific timeline for crack growth for the long axial crack at CRDM Nozzle 3, which was measured by UT to be 1.23 inches above the weld in February 2002 (Exponent Report Section 8). The timeline for the development of the wastage cavity was then based on a fundamental analysis of leakage through the axial crack, leakage through the weld crack (discussed below), a state-of-the-art CFD analysis to determine the thermal hydraulic conditions in the developing cavity, and the identification of potential metal removal mechanisms based on these conditions (Exponent Report Sections 9 and 10).

With this timeline as a basis, the Exponent approach was then to examine the plant operational data to determine if it was consistent with the timeline, and if it was not, that it could be accounted for by other plant events. Exponent evaluated plant operational data that included boric acid deposits on the RPV head, unidentified leakage rate for the reactor coolant system, radiation monitor data, containment air cooler cleaning rates, and the chemical analyses of boric acid and iron deposits removed from the RPV head. None of the plant operational data available to Exponent for analysis were ignored or omitted. In addition, Exponent reviewed RPV head inspection video and CRDM flange inspection video from 8RFO (1993) to 13RFO (2002), with the exception of 9RFO (1994) for which no RPV head inspection video was taken.

The Exponent Report relied upon new data, not known at the time the FENOC Root Cause Report was finalized in August 2002, that was either developed by or made available to the NRC subsequent to that time. The most significant of the new data was the metallurgical examination of the Davis-Besse CRDM Nozzle 3 nozzle, weld and cavity[1], the NRC/ANL crack growth measurements on the Davis-Besse Nozzle 3 Alloy 600 CRDM material[2], and the NRC/ANL data on the corrosion of low alloy steels in

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[1] "Final Report: Examination of the Reactor Vessel (RV) Head Degradation at Davis-Besse," Report No. 1140-025-02-24, BWXT Services, Inc., June 2003, transmitted to the NRC by FENOC letter Serial No. 2968 dated August 13, 2003 (ADAMS Accession Nos. ML032310045, ML032310058, ML032310060).

[2] B. Alexandreanu et al., "Crack Growth Rates in a PWR Environment of Nickel Alloys from the Davis-

molten metaboric acid[3]. The NRC was already aware of all of this information, which, with the exception of the metallurgical report on the nozzle, weld and cavity, was also publicly available as conference proceedings or published reports.

The specific timeline developed for the axial crack growth at Nozzle 3 was based on detailed stress and fracture mechanics analyses which are described in detail in the Exponent Report in Section 8 and Appendices A and B. The Exponent stress analysis produced results similar to an NRC sponsored stress analysis that was published in 2005[4], and the Exponent fracture mechanics analysis was based on the specific crack growth rates for the Nozzle 3 Alloy 600 material that were experimentally determined under the NRC sponsored program at ANL (referred to above) that was published in 2006.

As pointed out in the Exponent Report (Section 8.5.2), the long axial crack at Davis-Besse CDRM Nozzle 3 which precipitated the chain of events that eventually led to the wastage cavity was unique in the worldwide history of CRDM nozzle cracks. This crack was measured by UT in 2002 to be 1.23 inches above the weld, much longer above the weld than any CRDM axial crack previously reported at any plant worldwide.

While the Root Cause Report could not and did not offer any explanation for this, the reason was conclusively established by the NRC/ANL work reported in 2006 (referred to above). That work showed that the specific Davis-Besse CRDM Nozzle 3 Alloy 600 Heat M3935 material exhibited CGRs that were at the 95th percentile of the EPRI industry data base, around three to four times that previously used in industry safety assessments and assumed in the Root Cause Report.

Based on this CGR data and the detailed stress and fracture mechanics analyses, the Exponent Report shows that this crack did not reach the top of the weld until mid-1999, in contrast to the Root Cause Report which, using a much slower CGR, placed this key

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Besse and V.C. Summer Power Plants," NUREG/CR-6921, U.S. Nuclear Regulatory Commission, November 2006 (manuscript completed in November 2005).

[3] "Boric Acid Corrosion of Light Water Reactor Pressure Vessel Materials", Argonne National Laboratory, NRC/ ANL report NUREG/CR-6875, ANL-04/08, July 2005 (manuscript completed in May 2004).

[4] D. Rudland et al., "Analysis of Weld Residual Stresses and Circumferential Through-Wall Crack K-solutions for CRDM Nozzles," *Proceedings of the Conference on Vessel Penetration Inspection, Crack Growth and Repair*, NUREG/CP-0191, U.S. Nuclear Regulatory Commission, September 2005.

event around 1994-1996.

At 12RFO in 2000, the Exponent Report shows that this crack was only around 0.5 inches above the weld and was leaking at only a minuscule rate (0.0004 gpm). At the very low leakage rate that existed in the few months leading up to 12RFO in 2000 and the low end-of-cycle boron concentration in the RCS, the Exponent Report further concluded that less than 1 cubic inch (0.05 lbs) of boric acid accumulation would have been present (Exponent Report Section 10). Given the very low leak rate, the Exponent Report concluded that there could have been minimal wastage cavity and no observable annulus enlargement at CRDM Nozzle 3 at 12RFO, in contrast to the conclusions reached in the FENOC Root Cause Report.

By mid-cycle 13 in April-May 2001, the Exponent Report shows that the leak rate from the crack at CRDM Nozzle 3 had reached around 0.01 gpm, equivalent to the total leakage from all leaking cracks combined at CRDM Nozzle 2 in February 2002. Since this level of leakage at Nozzle 2 had caused only a minor amount of wastage and annulus enlargement, the Exponent Report concluded that a similar minor wastage situation likely existed at CRDM Nozzle 3 in April-May 2001, and therefore that virtually all of the cavity formation occurred subsequent to that point in time (Exponent Report Section 10). This is in contrast to the Root Cause Report, which placed the onset of significant corrosion three years earlier in 1998.

The NRC sponsored corrosion test program at ANL reported in 2005 (referred to above) provided new data that showed that wetted molten metaboric acid could result in high corrosion rates of low alloy steel, and hypothesized that such conditions may have been present in the developing wastage cavity at Davis-Besse CRDM Nozzle 3. The Computational Fluid Dynamic (CFD) analyses described in Section 9 of the Exponent Report showed that thermal hydraulic conditions developed in the latter half of Cycle 13 (after April-May 2001) such that molten metaboric acid would form on the hot metal surfaces of the developing cavity, and that the increasing leak rate from the growing axial crack at CRDM Nozzle 3 would result in moisture penetrating into the bottom of the cavity. These are the very conditions identified in the NRC/ANL work that caused accelerated corrosion of RPV low alloy steel by re-wetted molten metaboric acid.

Even prior to the completion in 2005 of the NRC/ANL experimental programs on CGRs in the specific DB CRDM Nozzle 3 Alloy 600 material and corrosion rates in molten metaboric acid referred to above, the NRC itself had already recognized the inherent limitations of the analysis and timeline presented in the FENOC RCR. In its evaluation NRR noted that:[5]

> "The Root Cause Report does not encompass all possibilities, partially because much of the data necessary to support alternate hypotheses simply does not exist. Wastage of low alloy steel in molten boric acid species, or in concentrated, aqueous solutions is not well-described or quantified in the literature, and especially not under the temperature, flow or stirring rates, and concentration of species that may have been present on the Davis-Besse head. The electrochemical potentials of the alloys and aqueous solutions involved are not known. Crack initiation times may have been short, and the stress-corrosion crack growth rate for the Alloy 182 in the J-groove weld and the Alloy 600 in the CRDM nozzles may have been atypically high, due perhaps to the thermo-mechanical processing of these materials. In short, the degree of uncertainty and the number of unknowns regarding the progression of events that led to the development of the cavity at Davis-Besse limits the ability to qualify the technical root cause report beyond "plausible" at this time."

A further critical piece of evidence that was not available at the time of the Root Cause Report was the June 2003 detailed report of the metallurgical examination of the material removed from around Davis-Besse CRDM Nozzle 3 (referred to above). This examination identified a very wide and long weld crack running radially across the weld at the 10° location, in line with the wastage cavity (Exponent Report Sections 4 and 10).

The crack growth analysis presented in the Exponent Report (Section 8.5.1, page 8-19, and Appendix B) showed that, due to the very high stresses in the weld region, a crack originating at the bottom of the weld on the nozzle OD would grow more rapidly in the Alloy 182 J-groove weld than in the Alloy 600 nozzle wall. The Exponent Report further concluded that, by the time the J-groove weld crack identified by the metallurgical examination was uncovered by the downward growing wastage cavity in October-November 2001, the crack had grown through the weld to a point close to the final

[5] "Davis-Besse Nuclear Power Station Degradation of Reactor Pressure Vessel Head Technical Sequence of Events, Docket No. 50-346", Office of Nuclear Reactor Regulation, Section 3.0 of Attachment 1 to NRC Integrated Inspection Report 50-346/03-04, May 9, 2003.

observed size in February 2002.

The analysis described in the Exponent Report (Section 9.4 and Appendix D) established that this weld crack, once fully uncovered, would leak at a rate that was about eight times greater than the pre-existing leak rate from the nozzle crack. No other plant had ever experienced the combination of circumstances that led to the high leak rate that resulted from the uncovering of this weld crack at Nozzle 3.

Neither the existence of the weld crack nor the large leakage through it were known at the time the Root Cause Report was finalized. However, given the existence of the weld crack, clearly at some point in the evolution of the wastage cavity at CRDM Nozzle 3, the RPV head steel above this weld crack was removed and the weld crack began to leak at an increasing rate. Further, given the Exponent Report conclusion (noted above) that there was only a minor cavity and annulus enlargement at Nozzle 3 in April-May 2001, the uncovery of the weld crack and the substantial increase in leak rate that resulted had to have occurred subsequent to this point in time.

The Exponent Report concluded (section 10.2.2) that the time at which this occurred was in October-November 2001, when plant operational data, principally the unidentified leak rate and iodine/noble gas radiation readings, indicate that a significant increase in leak rate into containment occurred. The Exponent Report further concluded that the large increase in leak rate then resulted in accelerated metal removal in the cavity by high velocity mechanical erosion, accelerated corrosion due to molten metaboric acid in the presence of increased moisture, flow assisted corrosion. Also at this time, rapid "top down" corrosion began due to moisture penetrating to the top of the cavity under the pre-existing accumulation of boric acid, which was molten metaboric acid at the prevailing temperature of the upper RPV head surface.

It is relevant to note that the NRC itself had recognized in a December 6, 2002 attachment[6] to the "Preliminary Significance Assessment" forwarded to FENOC by the NRC on February 25, 2003[7] that the FENOC Root Cause Report conclusions with respect

[6] "Response to Request for Technical Assistance - Risk Assessment of Davis-Besse Reactor Head Degradation (TIA 2002-01)", Davis-Besse SERP Attachment 2, December 6, 2002, Attachment A at pages 8, 9.

[7] "Davis-Besse Control Rod Drive Mechanism Penetration Cracking and Reactor Pressure Vessel Head

to the time period over which the wastage cavity at CRDM Nozzle 3 developed may have been incorrect.

After citing the FENOC root cause report conclusion that the wastage cavity at CRDM Nozzle 3 grew at an average rate of 2 inches/year over the 4-year period of the last two operating cycles, with a maximum corrosion rate near the end of about 4.0 inches/year, the NRC assessment goes on to discuss the EPRI reported tests of aqueous and molten boric acid corrosion, the various containment indicators of boric acid leakage, and the physical shape of the wastage cavity. Based on these data, the NRC assessment then notes that:

> "Therefore, it seems prudent to consider the possibility that the last stages of cavity growth on the Davis-Besse RPV head may have experienced corrosion rates on the order of 7-inches/year. At that rate, the football-shaped portion of the cavity could have begun developing in the latter half of the last operating cycle and reached its observed size by February 2002, when the cavity was discovered."

This is precisely the conclusion reached in the Exponent Report.

Degradation Preliminary Significance Assessment (Report No. 50-346/2002-08(DRS))", February 25, 2003 letter from J.E. Dyer, NRC Regional Administrator Response to Lew Myers, Chief Operating Officer, FENOC.

The DFI also requests that FENOC's response "address, among other matters you believe warranted, differences between the operational experience data, such as the origin and presence of boric acid deposits and corrosion products on air coolers, radiation filters, the reactor vessel head, and other components in the containment, and the Exponent Report assumptions for these items."

The most important point to note in this response is to repeat that the Exponent Report made no a priori "assumptions" about any of the plant operational experience data. Rather, the Exponent Report first established a specific timeline of crack growth and leakage for the long axial crack at CRDM Nozzle 3. The Exponent approach was then to examine the plant operational data to determine if it was consistent with the timeline, and if it was not, that it could be accounted for by other plant events. The relevant plant operational data considered by Exponent are discussed below.

Boric Acid Deposits on the RPV Head

Both the Root Cause Report (Section 3.3.3) and the Exponent Report (Section 7.3) discuss in detail the boric acid deposits on the RPV head from leaks at CRDM flanges at refueling outages prior to 1996 through to 2002, and reference is made to the two reports for these detailed discussions.

The Root Cause Report notes that boric acid deposits were observed flowing from the RPV head service structure mouse holes down the outside surface of the reactor vessel head to the RPV flange area at both 11RFO in 1998 and 12RFO in 2000. The Root Cause Report further notes that the boric acid was a "reddish rusty color", indicative of corrosion of the RPV head. A photo of the deposits at 12RFO is included in both the Root Cause Report and the Exponent Report (attached here as Figure 1).

The Root Cause Report apparently interprets these "red" colored boric acid deposits as being indicative of iron oxide from RPV head corrosion due to leakage from CRDM nozzle cracks at Nozzle 3. However, Exponent concluded that the unqualified assumption that the "reddish rusty color" of the deposits shown in the 12RFO photo was the result of corrosion due to boric acid leakage from a CRDM nozzle crack is unwarranted. First, as discussed earlier, the Exponent analysis shows that at 12RFO in April-May, there was no significant leakage and no extensive boric acid deposits resulting from the axial crack at CDRM Nozzle 3 prior to 12RFO. Therefore, the "red" colored boric acid shown in the 12RFO photo could not have come from this crack, and neither could the "red" colored boric acid reported at 11RFO in 1998, when the Exponent CGR analysis showed that the crack at Nozzle 3 had not even reached the top of the weld.

Second, "red" boric acid deposits were noted on numerous occasions during the inspection of the RPV head at Davis-Besse. CRDM flange leaks resulting in boric acid deposits on the RPV head were identified by video inspection during 8RFO (1993), 10RFO (1996), 11RFO (1998), 12RFO (2000) and 13RFO (2002). Some of these boric acid deposits were "white" in appearance, while some appeared "red" (Exponent Report Sections 7.3.1 to 7.3.7)

The "red" appearance was first noted during 8RFO (Exponent Report Section 7.3.1, Figure 7.10; Root Cause Report Section 3.3.3, Figure 31), well before even the Root Cause Report concluded that CRDM axial crack leakage had begun; and so the "red" color at 8RFO was likely the result of RPV head steel corrosion due to existing boric acid deposits from CRDM flange leaks above the head. Following a reportedly complete cleaning of boric acid deposits from the head at 9RFO in 1994, "red" boric acid deposits were again noted at 10RFO, 12RFO and 13RFO. There was only one CRDM flange leak (Nozzle #31) noted during 11RFO, and repair of this flange leak was deferred to 12RFO, during which the Nozzle 31 flange leak and four other leaking flanges were repaired.

After 9RFO in 1994, difficulty was experienced at 10RFO, 11RFO and 12RFO in completely cleaning boric acid deposits from the RPV head, especially near the center nozzles where the clearance between the RPV head and the insulation was small. Thus throughout this time period, boric acid deposits were continually present on the Davis-Besse RPV head. Any boric acid deposits remaining on the RPV head at the completion of an outage would become molten when heated to reactor operating temperatures, and would flow slowly down the head and out of the mouse holes during normal operation, thereby resulting in the deposits observed at 12RFO shown in the Figure 1 photo.

There is no question that the "red" deposits resulted from the incorporation of iron corrosion products into the boric acid. The likely cause of this at Davis-Besse prior to

Cycle 13 was due to corrosion of the RPV head under existing and new boric acid deposits from CRDM flange leakage.

Several instances of boric acid corrosion of the RPV head steel under deposits resulting from leakage from above the head are described in the Exponent Report (Section 6.1.2), notably at Beznau-1 in 1970, and at Turkey Point-4 and Salem-2 in 1987. At the EPRI Boric Acid Workshop that was held in 2002 after the Davis-Besse event, photos of the 1987 Salem-2 event were presented showing the "rust colored" pile of boric acid that resulted from a canopy seal weld leak above the RPV head (attached as Figures 2, 3). The "pile" of boric acid was estimated to be 900 to 1200 lbs, similar to that found at Davis-Besse in 2002, but the under-deposit head corrosion was restricted to nine corrosion "pits" on the RPV head, which were 1 inch to 3 inches in diameter with a maximum depth of 0.4 inches. Clearly, even minor RPV head corrosion under boric acid deposits can result in the "red" or "rusty" appearance of the boric acid deposits.

The "red" deposits noted on the underside of CRDM nozzle flange #3 during 12RFO and 13RFO (Root Cause Report Section 3.3.3 and Figure 38) most likely resulted from the ejection of RPV head corrosion/erosion products within the annular gap. The deposits were characterized as consisting of mostly iron borate.

The Exponent Report showed (Sections 8 and 10) that the CRDM nozzle crack reached the top of the J-groove weld during the latter part of Cycle 12 (May 1999) and grew to a length of about 0.5 inches above the J-groove weld by 12RFO (May 2000). Although the estimated leak rate at this time was small (0.0004 gpm), the velocity of the fluid exiting the nozzle crack within the annulus was calculated by CFD modeling (Section 9) to be very high (~2,000 ft/sec). This velocity was sufficient to result in mechanical removal of the RPV low alloy steel head material and the ejection of this material out of the annulus along the axis of the nozzle. This material was likely carried above the mirror insulation and deposited on the underside of the CRDM flange.

The Root Cause Report estimated that approximately 900 lbs of boric acid had accumulated on the RPV head by the end of Cycle 13 (Root Cause Report section 3.2.2 page 21. Based on the calculated leak rates from the nozzle and weld cracks at CRDM

Nozzle 3 and the Cycle 13 boron concentrations, Exponent calculated the integrated boric acid discharge over Cycle 13 at approximately 450 to 550 lbs, with around 50% of this coming from the weld crack in the last three to four months of Cycle 13 and 50% coming from the axial crack which leaked throughout Cycle 13. This quantity is less than the estimated 900 lbs on the RPV head at 13RFO, and suggests that 350 to 450 lbs of boric acid was not removed by the 12RFO cleaning efforts.

Unidentified Leak Rate

Both the Root Cause Report (Section 3.2.2) and the Exponent Report (Section 7.2.1) considered the unidentified leak rate data from 1994 through 2002. The Root Cause Report noted that after the pressurizer safety valve leakage problem was corrected in April 1999 during the mid-cycle outage, the unidentified leak rate remained in the 0.15 to 0.25 gpm range, some of this being attributable to CRDM flange leakage and some to CRDM nozzle cracks. The Root Cause Report further noted that late in Cycle 13 there was an increase of 0.10 to 0.15 gpm in unidentified leak rate starting in October 2001, and that it was possible that this was "related to changing conditions at the crack in Nozzle 3." However, there was no discussion in the Root Cause Report of what these "changing conditions" might be, or how they could cause such a marked increase in unidentified leak rate.

In the Exponent Report, the unidentified leak rate was used only to estimate the "upper bound" of approximately 0.17 gpm that could be attributed to all CRDM leaks at the end of Cycle 13 (Sections 7 and 9). It is recognized that there are many possible sources that could contribute to unidentified leakage, however neither the Exponent Report nor the Root Cause Report undertook a comprehensive evaluation of plant records to establish what other contributors to unidentified leakage in containment might have existed over time.

The crack leak rate analysis described in Section 9 and Appendix D of the Exponent Report resulted in a total leak rate of 0.03 gpm from all leaking CRDM cracks towards the end of Cycle 13 in February 2002. The analysis further showed that 0.14 gpm was entirely consistent with a fundamental analysis of the leak rate through the weld crack given its dimensions. Since the maximum CRDM crack leak rate at the end of Cycle 13 was limited to the 0.17 gpm established by the unidentified leak rate, the crack leak rate analysis and the measured unidentified leak rate are in agreement.

It is clear that the large weld crack at CRDM Nozzle 3 was not leaking significantly as long as RPV head steel existed above it, but it is equally clear that at the end of Cycle 13 in February 2002, the weld crack was not only fully uncovered and leaking, it was the major contributor to leakage into the growing wastage cavity at CRDM Nozzle 3. The average trend line plots of unidentified leak rate discussed in both the Exponent Report (Section 7.2.1) and the Root Cause Report (Section 3.2.2) establish that the only point in time where this could have happened was in the October-November 2001 time frame.

Radiation Monitors

Both the Root Cause Report (Section 3.3.5) and the Exponent Report (Section 7.2.2) discussed the noble gas and iodine radiation monitor readings inside containment in the October-November 2001 time frame. Both reports recognize the limitations of these monitors for identifying and quantifying low level leakage from CRDM nozzle cracks, and the fact that the readings can not be used to discriminate between leakage from nozzle cracks and leakage from other sources.

However, as discussed above, the increase in leak rate of about 0.14 gpm that the Exponent Report concluded resulted from the uncovering of the weld crack was based on a fundamental analysis of leakage through cracks of the observed dimensions. Also, an increase in unidentified leak rate consistent with this calculated weld crack leak rate occurred in the October-November timeframe.

Likewise, an increase in the readings from the noble gas and iodine radiation monitors occurred in this same October-November timeframe. Thus both the leakage timeline and the point in time of weld crack uncovering calculated as a result of the analyses presented in the Exponent Report (Section 7.2.2) are entirely consistent with the in-plant measurement of unidentified leakage and the radiation monitor readings.

The filter elements in the radiation monitors were subject to plugging by boric acid in the containment atmosphere when reactor coolant system leakage occurred and dispersed boric acid into the containment building, and this was particularly the case when the pressurizer safety valves were leaking in early 1999. Following the mid-cycle outage to replace these valves, filter plugging continued, but the boric acid deposits on the filters were now "brown" in color. Samples were analyzed and the discoloration was found to be predominantly due to iron oxide, indicative of steel corrosion somewhere in containment.

Since the crack at CRDM Nozzle 3 had reached the top of the weld by mid-1999 and a slow metal removal process had begun, it is possible that some of the iron oxide on the radiation monitor filters originated from head wastage and/or metal removal by the leak flow. However, other sources of iron oxide in containment cannot be ruled out.

Containment Air Cooler Cleaning

The containment air coolers are subject to fouling by boric acid entrained in the containment atmosphere whenever an RCS leak exists, and both the Root Cause Report (Section 3.3.4) and the Exponent Report (Section 7.3.6) discuss this. The containment air coolers were cleaned 17 times between November 1998 and April 1999 due to the pressurizer safety valve leakage, but only twice immediately after the safety valves were repaired during the mid-cycle 12 outage (Root Cause Report Attachment 2, pages 144-146).

After 12RFO in April-May 2000, containment air cooler fouling by boric acid was again evident, with four cleanings being required between June and December 2000, and four more in January through May 2001 (Root Cause Report Attachment 2, pages 148-149). Since there were no known CRDM flange leaks left un-repaired and none were found at 13RFO, the containment air cooler fouling was likely at least in part the result of the increasing leak rate from the CRDM nozzle cracks.

After May 2001, no further containment air cooler cleanings were required. The Root Cause Report speculates that, despite the increasing leak rate, this was due some change in the in the morphology of the nozzle crack leak. The Root Cause Report (Section 3.3.4) further provides a number of scenarios by which the containment air cooler fouling ceased:

"For example, if the corrosion cavity at CRDM nozzle 3 enlarged substantially during the last half of the fuel cycle (affecting exit velocity), or the boric acid cap contained the leakage differently, the nature and amount of particulate matter might have changed. Larger particles might settle and not be subject to ingestion by the CACs. (The later theory has some anecdotal support based on observations that the boric acid dust on horizontal CTMT surfaces was more granular in 13RFO, as opposed to fine powder in earlier outages)." These observations support the change in annular flow characteristics that were calculated to have occurred in the May 2001 timeframe in the Exponent Report (Section 9.6.3). However, as the Root Cause Report also notes, containment air cooler fouling by itself "could not be directly correlated with CRDM nozzle leakage."

In its December 2002 assessment of the Root Cause Report (cited previously) the NRC offered a similar explanation for the decrease in containment air cooler cleaning as the Root Cause Report:

"An interesting coincidence is that there was an abrupt decrease in the necessary rate for CAC cleaning in May of 2001, suggesting that something about the leakage path had changed at that time. The change may have been only in the path past the insulation that the airborne particles followed to reach the containment atmosphere, or it may signify that the leakage had been directed into the pool in the cavity at that time, starting the formation of the football-shaped portion. The containment radiation monitors showed continuing increases in the RCS leak rate until about December 2001."

Likely not coincidentally, the cessation in containment air cooler plugging occurred around the time the Exponent Report (Section 10.2.2) concludes that downward growing wastage cavity intersected with the upward growing axial nozzle crack, when the direction of the fluid flow in the annular region near the crack changed from upwards to more laterally oriented. This directional change in the fluid flow from the axial nozzle crack could well have markedly reduced the entrainment and carry over of boric acid into the containment atmosphere.

Chemical Analysis of Boric Acid and Iron Oxide Deposits

Both the Root Cause Report (Section 3.1.5) and the Exponent Report (Appendix E, Section E.5) discussed the chemical evaluation of boric acid and iron oxide deposits removed from the RPV head and wastage cavity near Nozzle 3, the results of which are contained in two reports (Root Cause Report References 8.2.14 and 8.2.15). The Root Cause Report noted that:

> "The samples taken from the reactor head were collected by scooping the material with a long handled tool. Due to the difficulty of collecting the field samples, the probability of cross contamination is fairly high and could lead to false or compromised results......although sample integrity is not assured, the sample results are consistent with other evidence that the material on the reactor head originated primarily at nozzle 3, and flowed or extruded away from that location."

One important conclusion of the analysis reports was that, "the most probable source of the iron is the carbon steel of the reactor vessel head."

The Exponent review of these same sample analysis reports (Exponent Report Appendix E, Section E.5, References 11 and 12) noted an additional observation that for these analyses, metallic fragments that could be readily isolated from the bulk deposit samples were removed from the samples before analysis. The exponent Report concludes that "the mechanical removal of metallic fragments was likely a result of water jet cutting or abrasive water jet cutting of the RPV head during periods of high nozzle leakage late in Cycle 13."

Although the Root Cause Report notes the possibility of "droplet and particle impingement erosion and potentially steam cutting" as metal removal mechanisms (Root Cause Report Section 3.2.4, page 25), there is no discussion of the presence of metallic fragments in the samples collected for analysis.

Summary

It should be noted in conclusion that the conventional wisdom prior to the 2002 Davis-Besse event was that it was conservative to use industry accepted CGRs for Alloy 600 in safety assessments of CRDM nozzle cracking, that any low level boric acid leakage from cracks would either rapidly evaporate leaving only dry boric acid which was thought to be non-corrosive to the low alloy steel RPV head, or that potential wastage rates from such low level leakage would be low.

Contrary to this, the Davis-Besse event showed that a unique set of unforeseeable factors combined to cause the accelerated wastage cavity formation in as little as 4 to 5 months. At CRDM Nozzle 3, these factors were:

- A very high CGR at the 95^{th} percentile of the industry data resulting in an axial crack growing at three to four times the expected rate;
- A very large weld crack that resulted in a rapid increase in leak rate as it was uncovered in the October-November 2001 time period;
- Previously undefined accelerated corrosion due to molten metaboric acid in the presence of moisture.

None of these factors were known at the time the FENOC Root Cause Report was completed in August 2002.

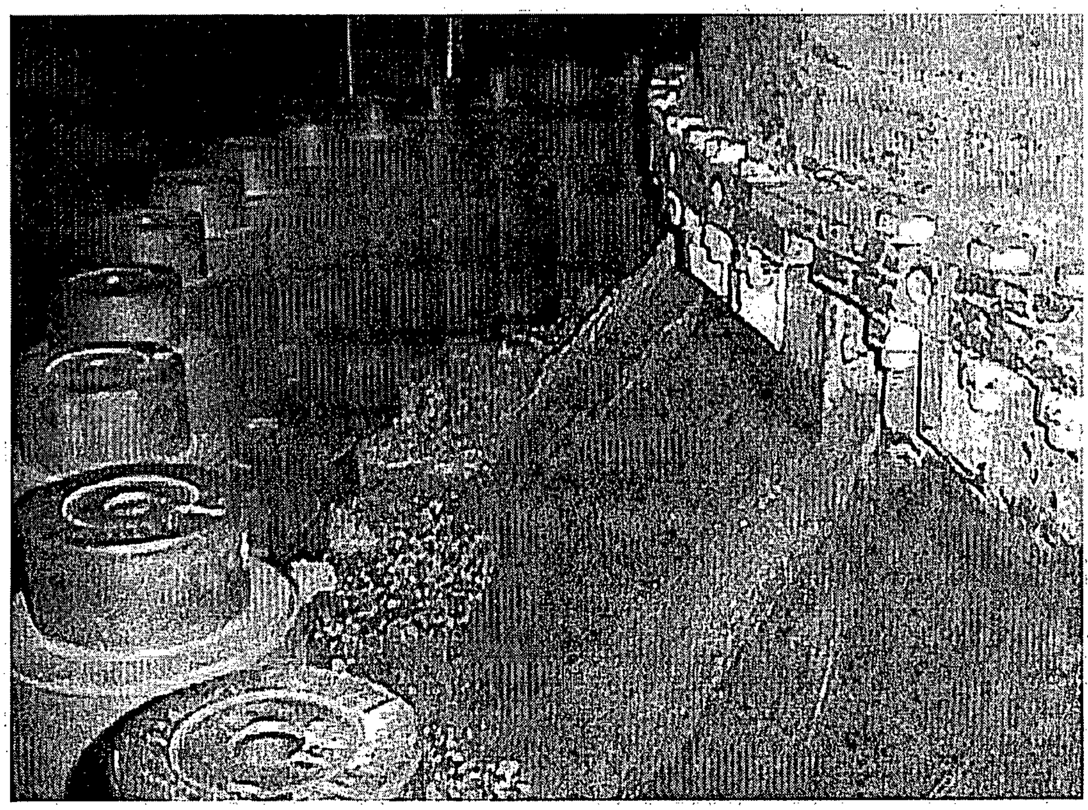

Figure 1. Boric acid and iron oxide deposits on Davis-Besse reactor pressure vessel flange at 12RFO. [Root Cause Report – Figure 4, page 91 and Exponent Report, Section 4, Figure 4.1, page 4-23]

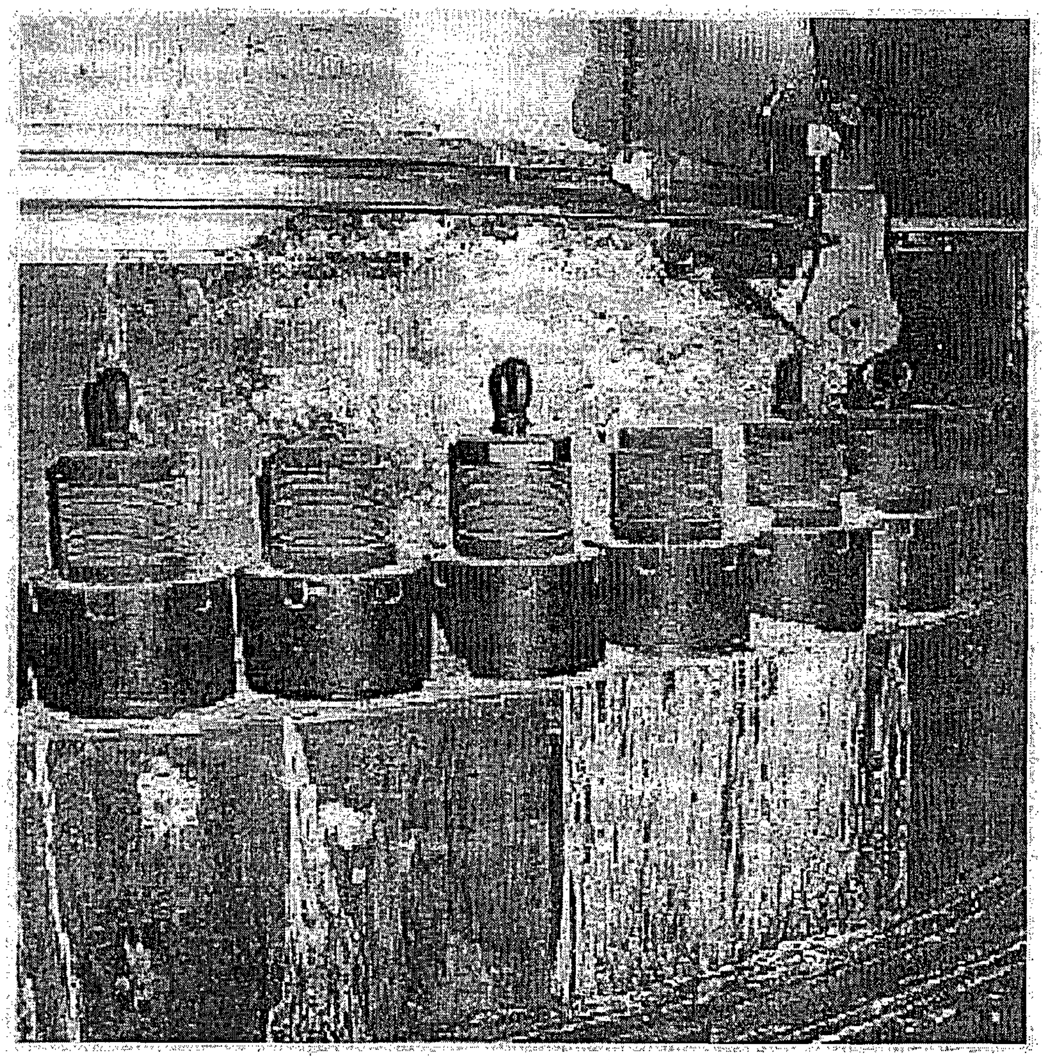

Figure 2. Boric acid and iron oxide deposits on Salem Unit 2 reactor pressure vessel head (August 1987). Reactor coolant system leakage was due to canopy seal weld leakage. [EPRI Boric Acid Corrosion Workshop, 2002 (MRP-77)]

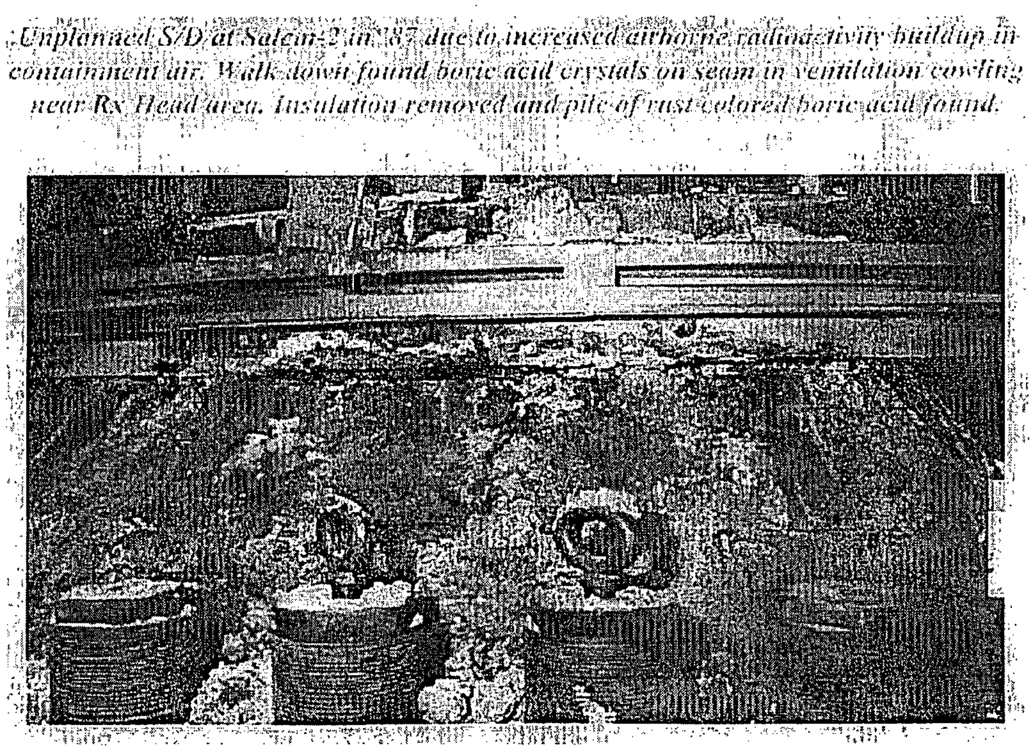

Figure 3. Boric acid and iron oxide deposits on Salem Unit 2 reactor pressure vessel head (August 1987). [EPRI Boric Acid Corrosion Workshop, 2002 (MRP-77)]