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Subject: Davis-Besse; Exponent Report Sections 2 and 10

Eric,
Per your request, attached are advanced copies of Sections 2 and 10 of the Exponent report "Review and Analysis of the Davis-Besse March 2002 Reactor Pressure Vessel Head Wastage Event", 12/15/06 which are the principal subject of our teleconference scheduled for Thursday afternoon. The full report was mailed to NRC this afternoon.
Jim

(See attached file: Section 2 - 12.17.pdf)(See attached file: Section 10 - 12.17.pdf)

The FENOC participants on the teleconference will be:

Jim Powers - Director, Fleet Engineering
Greg Kammerdeiner - Principal Consultant, Materials Programs
Dave Jenkins - Corporate Counsel
Dan Bullen - Exponent
Ron Latanision - Exponent
Dave Taylor - Exponent

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2. Principal Conclusions and Opinions

We have reached the following overall conclusion based on the work described in detail in the subsequent sections of this report.

The large wastage cavity discovered in March 2002 at control rod drive mechanism (CRDM) Nozzle 3 in the Davis-Besse reactor pressure vessel (RPV) head was caused by a unique, unexpected, and unforeseeable combination of high nozzle material susceptibility to primary-water stress corrosion cracking (PWSCC), high residual stresses from welding, rapid and non-linear crack growth, and development of thermal hydraulic conditions that resulted in accelerated attack of the RPV head alloy steel material. This event of the moment occurred around October/November 2001 when the leak rate from an existing J-groove weld crack combined with the leak rate from the CRDM Nozzle 3 crack to raise the total leakage rate to 0.16 gpm (84,000 gallons /year). This leak rate caused rapid catastrophic material removal from the RPV head. This event was not only unexpected, but was not foreseen or predicted by any of the extensive prior experience with boric acid corrosion, or from any of the inspection and analysis of CRDM cracking in nuclear plants worldwide from 1991 through 2002. It was the first occurrence of its kind, ever.

This conclusion is supported by the additional conclusions and opinions presented below, the bases for which are presented in Sections 4 through 10 of this report.

2.1 The discovery of the wastage cavity in the Davis-Besse RPV head and the subsequent industry response both show that this event was totally unexpected, unanticipated and unforeseeable (Section 4).

1. The NDE inspection performed on the Davis-Besse CRDM nozzles at the beginning of 13RFO in February 2002 pursuant to NRC Bulletin 2001-01 found five nozzles with cracks. Several of the cracks at Nozzles 2 and 3 were longer than had been predicted by prior analysis and experience. In particular, one crack

at Nozzle 3 was much longer than any crack previously detected in CRDM nozzles worldwide.

2. Nonetheless, plans were made to repair CRDM Nozzles 2 and 3, where the most significant cracks were detected. The large wastage cavity in the RPV head at Nozzle 3 was unknown and was not discovered until Nozzle 3 unexpectedly moved towards Nozzle 11 during the removal of the bottom section of the nozzle containing the cracks. Subsequent careful examination of the Nozzle 2 borehole revealed a smaller wastage cavity at that location also.

3. The size and extent of the wastage cavity at CRDM Nozzle 3 was totally unexpected and unpredictable, and was much larger than any of the "worst case" scenarios analyzed by industry experts in the decade prior to 2002.

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

2.2 The nuclear industry and regulatory focus of concern, both US and worldwide, for CRDM nozzle cracking, was on the safety issue of circumferential cracks and possible ejection of a CRDM nozzle, which results in a breach of the reactor coolant pressure boundary and a loss-of-coolant accident (LOCA). Significant CRDM nozzle axial cracking leading to RPV head wastage was not foreseen and was not considered either plausible or a safety issue until the Davis-Besse event (Section 5).

1. Cracking of Alloy 600 CRDM nozzles was first detected in the French plant Bugey-3 in 1991, when a very small leak was discovered during a high-pressure hydrotest. Non-destructive examination (NDE) and other inspections of CRDM

nozzles at French, other European, and Japanese plants from 1991 on, identified significant cracking of CRDM nozzles. Subsequent experience with CRDM nozzle cracking prompted utilities in France, Sweden, Belgium, Spain and Japan to institute RPV head replacement programs. In both France and Sweden, an enhanced leakage detection system capable of detecting extremely small leaks was also installed at operating plants.

2. Only a few US plants, and only one B&W plant, performed NDE inspections of a limited number of CRDM nozzles from 1994 through 1999. The US industry and regulatory approach was to wait until nozzles had developed through-wall cracks and began leaking before performing inspections. When extensive cracking was discovered in several B&W designed plants in late 2000 and early 2001, the NRC began to develop rules requiring 100% NDE of CRDM nozzles.

3. The primary focus of the US PWR industry and the NRC from the discovery of cracking at Bugey-3 through to early 2001 was on the potential for CRDM nozzle failure and nozzle ejection, and on the critical axial and circumferential crack sizes that would be required before such failures would occur, and not on any potentially significant wastage of the RPV head. While the potential for boric acid corrosion of the RPV head was considered, it was not regarded as a safety issue. As the Davis-Besse event illustrates, the critical crack size at which boric acid leakage becomes large enough to cause thermal hydraulic conditions such that extremely high rates of metal removal from the RPV head occur, is well below the critical crack size at which nozzle failure might occur.

4. Evaluation and analysis of the experience with CRDM nozzle cracking at B&W plants in late 2000 and early 2001, led to the ranking by the EPRI Materials Reliability Program (MRP) of all US PWR plants by predicted cracking susceptibility. Davis-Besse in particular was predicted in March 2001 to be 3.1 EFPY away from developing cracks similar in size to those discovered at Oconee-3, the most seriously affected US plant at the time where, again, no significant wastage of the RPV head had been reported. In fact, rather than 3.1 EFPY away

from a 0.6-inch crack similar to Oconee-3, Davis-Besse was only a few months away from the development of a fast-growing, 1.23-inch, through-wall CRDM nozzle crack that quickly caused significant RPV head wastage.

5. The worldwide and US experience of actual CRDM cracking, the projected limited extent of CRDM nozzle cracking at Davis-Besse, and the total lack of any identified wastage of the RPV head at any of the plants affected by CRDM cracking all demonstrate that the serious Davis-Besse wastage discovered at CRDM nozzle 3 in March 2002 was unexpected, unanticipated and unforeseeable. I corrected the margin.

2.3 The industry and regulatory focus of concern, both US and worldwide, for boric acid leakage was on the wastage of external components and fittings due to boric acid corrosion, and most of the industry research and effort was directed towards the detection and quantification of this type of corrosion, which was readily detectable by means of visual inspection at refueling outages. Significant RPV head wastage was not foreseen and had not occurred until the Davis-Besse event (Section 6).

1. The majority of the boric acid corrosion that occurred in plants worldwide was the result of dripping and/or impingement of boric acid leakage onto external components such as piping, bolting and fittings in the reactor coolant system. RPV head wastage had been observed at only a few plants, and then only to a limited, shallow extent that was not considered significant.

2. Following the issuance of Generic Letter 88-05 by the NRC in 1988, the US nuclear industry led by Owners Groups and EPRI developed "Boric Acid Corrosion Control (BACC) programs and procedures to detect boric acid leakage before significant wastage occurred. However, it became apparent in 2001 that these inspection techniques and programs were possibly inadequate to detect very small leaks in the narrow annuli around CRDM nozzles. This was especially the case in plants where boric acid from known CRDM flange leakage above the RPV head accumulated on top of the head, thereby masking any minor leakage

from small nozzle cracks, thus making detection by visual inspection virtually impossible.

3. The NRC specifically implemented its own procedure in August 1991 to provide guidance to NRC resident inspectors in their evaluation of the effectiveness of PWR licensees' boric acid corrosion control (BACC) programs, and their compliance with the requirements of GL 88-05. However, the NRC procedure was apparently never performed at Davis-Besse by the NRC resident inspectors assigned to the plant, and was so "infrequently implemented" by NRC resident inspectors at other PWR plants that it was cancelled in September 2001. This occurred at the very time that the NRC and the industry were grappling with the discovery of CRDM nozzle cracks and leaks in the B&W Oconee units, for which BACC programs were then the primary means of identification.

4. The NRC and the industry recognized the limitations of existing leakage detection methods, but did nothing to require either more sensitive leak detection systems such as those which were installed at French and Swedish plants, or NDE inspections of CRDM nozzles at refueling outages to detect cracks before they began to leak.

5. Assessments of potential RPV head wastage from leaking CRDM nozzles by the US industry and accepted by the NRC were erroneous. Maximum metal removal rates of approximately 1.0 cubic inch per year were assumed to be very conservative, whereas actual metal removal rates at Davis-Besse are estimated to have occurred at least 100 times this rate.

6. While extensive testing of boric acid corrosion of low alloy steel components had been performed prior to 2002, the focus of most of this testing was on external leaks, drips and impingement tests on bolting, piping and other components, and not on tests for boric acid leakage into tight annular crevices such as those present around the CRDM nozzles. While some of these tests showed that boric acid could cause rapid corrosion of low alloy steel under certain conditions of concentration and temperature, it was not considered that these conditions could

be achieved in the annular CRDM crevice. The prevailing industry direction prior to the Davis-Besse event was that leaks into nozzle crevices would rapidly cause evaporation of the water, and result in dry boric acid which was widely believed to be non-corrosive to the RPV head steel.

7. Several major corrosion test programs have been undertaken by the NRC and EPRI since the Davis-Besse event in attempts to provide more detailed understanding of the environments that can develop in CRDM crevices due to boric acid leakage from cracked nozzles. Some of these results are available, and provide information about potential corrosion rates under conditions that had not previously been investigated.

8. The extensive wastage cavity discovered at Davis-Besse CRDM nozzle 3 in March 2002 was therefore not considered plausible, and was unforeseen, unpredictable, and unexpected.

2.4 FENOC's response to industry and regulatory concerns about both CRDM nozzle cracking and boric acid corrosion was both responsible and was in accordance with industry recommendations and regulatory requirements (Section 7).

1. FENOC implemented the inspection and monitoring programs developed by both US industry groups and required by the US NRC, for CRDM nozzles and for external boric acid leakage and potential wastage corrosion of external reactor coolant system components.

2. The NCR required and the industry implemented inspection and monitoring programs that could not detect incipient boric acid crevice corrosion in the annulus around the CRDM nozzles, especially where significant boric acid was present from CRDM flange leakage. Experience at the B&W Oconee units in 2000 and 2001 showed that the leakage of boric acid from through wall cracks was in fact very small, and could easily be missed or obscured during visual inspections of the RPV head by deposits from CRDM flange leakage.

3. Two resident NRC inspectors at the Davis-Besse plant monitored FENOC's plant operations, maintenance, and repair activities. No negative findings were documented by the NRC resident inspectors, who were present at the refueling outages in 1996, 1998 and 2000, with respect to CRDM nozzle and RPV head inspections during the inspections conducted as part of FENOC's BACC program mandated by NRC GL 88-05.

4. Nothing in the prior worldwide industry experience with boric acid corrosion of RCS components alerted the B&W plant designers, the PWR industry, the US NRC, or FENOC to the potential for development of the extensive wastage cavity in the RPV head that was found at CRDM nozzle 3 in March 2002.

5. The NRC Inspection Reports for the inspections that occurred during 11RFO and 12RFO made no mention of the inability to fully inspect the RPV head due to boric acid remaining after the cleaning. The report for 12RFO also did not comment on the amount and location of boric acid left on the RPV head.

2.5 PWSCC crack growth rates (CGRs) assumed in the FENOC Root Cause Report were apparently based on the EPRI industry averaged curve. CGR measured in recent tests for the NRC by Argonne National Laboratory (ANL) on samples of actual Alloy 600 from Davis-Besse CRDM Nozzle 3 are three to four times faster than the industry curve predicts. The fact that the CGR for the Nozzle-3 Alloy 600 material is nearly four times that assumed by FENOC for the Davis-Besse event analyses means that the crack growth and the development of the large wastage cavity at CRDM Nozzle 3 occurred over a much shorter period of time than previously estimated (Section 8).

1. Crack growth rates (CGRs) in Alloy 600 (nozzles) and Alloy 182 (welds) can be highly variable and unpredictable. The general scatter in CGR data for both Alloy 600 and 182 spans roughly two orders of magnitude, or a factor of 100. Variations in cracking performance of apparently identical Alloy 600 CRDM nozzles and Alloy 182 welds at other PWR plants also show that the process is highly variable. We attribute this variable performance primarily to the process by which the nozzles are manufactured and installed, in particular the manual

welding process, which can result in highly variable residual stress levels from nozzle to nozzle.

2. In addition, data on crack initiation and growth for both Alloy 600 and Alloy 182 weld metal indicate that the PWSCC process is generally one of initiation of multiple cracks followed by a growth and linkup process as multiple small cracks grow into each other and coalesce to form large cracks. Analysis of the effect of this process, as well as observations in the field, indicate that rapid increases in crack growth can occur when several small cracks, growing relatively slowly, link up in a relatively short time to form a larger crack.

3. The variability in CGR is self evident from the cracking behavior of CRDM Nozzles 2, 3, 4, and 5 at Davis-Besse, all of which are located in the same geometric position on the RPV head, were fabricated from the same heat of Alloy 600 using the same manufacturing processes, were installed using the same manufacturing and welding procedures, and experienced the same operating stress and temperature histories. Yet Nozzle 4 exhibited no cracking, Nozzle 5 was found to have only one very short non-through-wall crack, Nozzle 2 had seven leaking axial cracks (six of which were through wall) plus one circumferential crack, and Nozzle 3 had two through wall axial cracks, one of which was the longest axial crack ever found in a CRDM nozzle, as well as a very large weld crack extending almost completely across the J-groove weld.

4. NRC/ANL test results recently reported (November 2006) for CGRs in actual Davis-Besse CRDM Nozzle 3 Alloy 600 material show that the CGRs for this material are at roughly the 95th percentile of the Alloy 600 database. This CGR is three to four times that assumed in the 2002 FENOC event analysis and root cause report, which was based on the Alloy 600 CGR data generally used by the industry at the time, and which was believed to be conservative.

5. This recent NRC/ANL test data is highly relevant to the analysis of the progression of events at Davis-Besse Nozzle 3, because it implies that the nozzle crack growth, leakage, and wastage cavity formation and growth all occurred over

a much shorter time frame than was previously concluded. Consequently, the previous analyses project time frames for through wall crack growth, leakage, and wastage cavity development that are around three to four years earlier in time than they could possibly have occurred.

6. Similarly, analyses by B&W, EPRI, and others prior to 2002 of the relative susceptibility of the Davis-Besse plant to CRDM nozzle cracking effectively assumed that the Davis-Besse CRDM nozzles would exhibit the same CGR as Oconee-3. It was that assumption that led to the prediction in March 2001 by the EPRI MRP that Davis-Besse was 3.1 EFPY away from experiencing cracking to a similar extent as Oconee-3. That conclusion proved to be incorrect, because the Davis-Besse CGR's were in fact much higher than had been assumed. Our analysis shows that by March 2001, the large crack at Davis-Besse Nozzle 3 had already grown through-wall above the weld, was already leaking significantly, and that the wastage cavity was already established and growing at an accelerating rate.

7. Under the high tensile hoop stresses in the J-groove weld and adjacent nozzle wall, determined from our finite element stress analysis, our analysis shows that the crack driving force for the upper tip of Crack 1 in Nozzle 3 as it grew past the top of the J-groove weld was in excess of 50 ksi-in$^{1/2}$. Subsequent growth of the crack above the weld exhibited decreasing crack driving force, estimated to be at least 24 ksi-in$^{1/2}$ in the latter stages of growth.

8. The NRC/ANL experimental data for Nozzle 3 indicates that at a crack driving force of 50 ksi-in$^{1/2}$, the CGR for the nozzle crack would have been about 0.8 inch per year, and about a quarter-inch per year at 24 ksi-in$^{1/2}$. Based on the crack growth studies we have performed, we conclude that the long axial Crack 1 discovered on the downhill side of Nozzle 3 in 2002, which was responsible for the initial cavity formation and growth, just reached above the top of the weld around the time of the mid-Cycle 12 outage in April-May 1999.

9. Our analysis further shows that this same crack had reached a point far enough above the top of the weld to begin leaking at a very low rate around the time of the 12RFO in April-May 2000, and that the crack had grown to a size sufficient to cause substantial head wastage a year later, in May 2001. This crack would then have reached the measured length, 1.23 inches above the weld, by February 2002.

2.6 Detailed modeling and analysis of the thermal hydraulic conditions in the CRDM annulus has been performed by means of a Computational Fluid Dynamics (CFD) code. CFD analyses have been performed for a range of flows, crack sizes and wastage cavity sizes that cover the range of possible conditions from very low leakage rates into the initially tight cavity, through the crack sizes and leak rates existing at Nozzle 2 in 2002, up to the final large cavity, crack size, and leak rate that existed for the crack at Nozzle 3 in March 2002 crack. These analyses show that thermal hydraulic conditions of velocity, temperature, and wetness develop that can result in extremely high metal wastage rates in the cavity (Section 9).

1. CFD modeling and other calculations show that very high velocities, well over 2000 feet per second, are generated downstream of a leaking nozzle crack. These velocities are high enough to result in aggressive metal removal. The point at which the velocity is at a maximum is generally at the point where the leak flow first encounters an enlarged cross sectional area for flow.

2. For an initially tight annulus, this expansion point would be expected at the exit of the annulus at the top surface of the RPV head. However, the CRDM nozzles in the B&W design are installed with a shrink fit, and the nozzles in question at Davis-Besse (2, 3) had metal-to-metal interference fits that were calculated to remain closed at operating conditions. Thus, the expansion point for the initial leakage, where the crack first begins to leak at a very low flow rate, could occur anywhere along the annulus length wherever the interference fit happened to be relaxed somewhat.

3. The extremely high maximum fluid velocities (up to 2,700 fps) predicted by the CFD modeling near the cracks and in the bottom of the wastage cavity once it

developed imply that material removal by mechanical means was likely at these locations. The momentum of the water droplets traveling at these velocities is sufficient to cause material removal. In addition, both pre-2002 test data and recent (July 2006) data from an EPRI corrosion test program show that penetration rates of up to 8 to 11 inches per year can result from a high-temperature, high-pressure stream of reactor coolant impinging on an alloy steel specimen.

4. As the leak flow expands, water both flashes and is evaporated by heat transfer from the surrounding steel, causing the boric acid to concentrate. Under the initially very low leak rate flow conditions, the temperature rapidly rises to the point where most or all of the water has evaporated and a phase transition from orthoboric acid to metaboric acid occurs. In the absence of moisture, dry or molten boric acid is relatively non-corrosive, and metal removal in nozzle annulus would have occurred relatively slowly, principally due to the erosive action of the high velocity jet from the nozzle crack.

5. As the leak flow from the crack increases and the wastage cavity develops, the CFD model results show that significant changes in the thermal hydraulic conditions occur. The leak flow eventually becomes large enough that heat transfer from the RPV head can no longer evaporate all the water, and moisture persists into the lowest part of the previously slowly growing wastage cavity. However, due to the high metal wall temperatures, metaboric acid continues to be formed and deposited in the nozzle annulus and the wastage cavity from the evaporating coolant leakage. Recently reported data (July 2005) from corrosion tests specifically carried out by the NRC/ANL to investigate this condition show that extremely high steel corrosion rates are possible where moisture is present and wetting of molten metaboric acid occurs.

6. In conjunction with continued metal removal by the high velocity fluid from the nozzle crack, corrosion from wetted molten metaboric acid causes accelerated metal removal at the bottom of the wastage cavity. In addition, the high velocities

and the presence of corrosion product and boric acid particles can result in more rapid metal removal by abrasive water jet cutting. The combination of these metal removal processes results in more rapid metal removal at the bottom of the wastage cavity, so that once the cavity has formed and the leak rate has increased, the wastage cavity grows downward toward the upwardly advancing crack at an accelerating rate.

7. As the leak rate increases further and the cavity grows larger, the top of the nozzle crack eventually grows into the bottom of downward growing wastage cavity. For this condition, the CFD model results show that further significant changes in the thermal hydraulic conditions occur. The leak flow from the part of the crack that extends into the cavity is now directed radially onto the cavity wall at that location, resulting in more rapid metal removal by direct jet impingement. Metal removal at the bottom of the cavity also continues due to corrosion by wetted molten metaboric acid and by abrasive water jet cutting. In addition, significant moisture now persists all the way to the top of the wastage cavity and annulus, causing metal removal from the upper RPV head steel surface to begin due to corrosion under the layer of molten metaboric acid already present on the RPV head.

8. The downward growth of the wastage cavity at an increasing rate eventually uncovers the large, pre-existing weld crack, and the leak flow increases rapidly by an order of magnitude, from about 0.02 to around 0.16 gpm. The CFD model results using this magnitude of leak flow into the large wastage cavity ultimately found at Nozzle 3 show that the conditions for metal removal by jet impingement, abrasive water jet cutting, and corrosion due to wetted molten metaboric acid all persist, but at an increased volumetric rate due to the increased leak flow. As the wastage cavity grows out to its final size and the cavity walls move further away from the nozzle and weld cracks, the effects of direct jet impingement and abrasive water jet cutting decrease as the velocities near the cavity walls decrease. However, the velocities are still sufficient to cause flow assisted boric acid corrosion.

2.7 By April-May 2001, the nozzle crack had grown to the point where aggressive metal removal conditions developed at the bottom of the wastage cavity. Between May and October 2001, the downward growing wastage cavity intersected with the upward growing crack. This resulted in a significant change in the thermal hydraulic conditions in the wastage cavity such that extremely high rates of erosion/corrosion occurred, leading to the large cavity found in March 2002 (Section 10).

1. It is possible that an incipient sub-surface wastage cavity formation had already begun by 12RFO above the crack at CRDM Nozzle 3, this cavity would have been much smaller than the wastage cavity found at Nozzle 2 in 2002, and so would not have been visible by means of typical visual (i.e., remote video) inspections of the RPV head. 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. Such deposits would have been totally obscured by the large existing boric acid deposits resulting from the CRDM flange leakage problem even if the RPV head had been completely cleaned of boric acid at 12RFO. Finally, any incipient enlargement of the annulus at the RPV head surface had taken place at Nozzle 3 by 12RFO would have been much smaller than that discovered at the top of the Nozzle 2 annulus in March 2002, and it would not have been visible using visual video inspection techniques

2. Shortly prior to October 2001, the long crack at CRDM Nozzle 3 reached a critical length where the downward growing wastage cavity finally intersected with the upward growing crack. A significant change in the thermal hydraulic conditions occurred, particularly immediately opposite the crack exit at the bottom of the wastage cavity where the velocity was high and the leak flow was impinging directly on the wastage cavity wall.

3. The rate of metal removal increased significantly due to the combination of mechanical processes and corrosion by wetted molten metaboric acid. This resulted in more rapid growth of the wastage cavity through the one-inch of steel that remained above the upper surface of the stainless steel cladding. In addition,

moisture was now carried all the way to the top of the wastage cavity and annulus. The presence of the boric acid deposits around Nozzle 3, which were likely molten metaboric acid due to the high head temperature, caused metal removal from the upper RPV head steel surface to begin.

4. Shortly after October/November 2001, the downward growing wastage cavity at CRDM Nozzle 3 reached the upper surface of the weld, and the large pre-existing weld crack was rapidly uncovered. The leak flow increased eightfold from about 0.02 gpm to around 0.16 gpm after the weld crack was fully uncovered, and the sub-surface wastage cavity in line with the cracks grew more rapidly both axially and radially.

5. Also at this time, the increased moisture content of the high leak flow from the combined nozzle and weld cracks caused the wastage rate due to wetted molten metaboric acid corrosion at the top surface of the RPV head around Nozzle 3 to increase. The accelerated metal removal both in the sub-surface cavity and at the RPV head surface resulted in the large wastage cavity found in March 2002.

Given the information cited above, we conclude that there was no sub-surface wastage cavity of significance present at Nozzle 3 at the time of 12RFO in April-May 2000, and therefore no available inspection methodology could have found it. Based on the results of our crack growth analysis and thermal hydraulic modeling, and on the factual observation of the spatial orientation of the cavity relative to the nozzle and weld cracks at Nozzle 3, the appearance of the walls of the wastage cavity and on the plant operating history, we have concluded that the large wastage cavity found during the 13RFO inspection in March 2002 at Nozzle 3 could have formed in as little as a few weeks in the extreme of complete fluid jet cutting of the head. The most likely cause of the wastage cavity includes both mechanical and chemical actions (including flow assisted corrosion), which began to occur at an accelerating rate after a critical point was reached shortly before October 2001. The event of the moment was reached when the large Nozzle 3 crack and the growing wastage crack intersected and quickly uncovered the large pre-existing weld crack at Nozzle 3. The resulting increase in leak

rate caused extremely aggressive conditions to develop at this time and resulted in the rapid removal of metal from the cavity in matter of a few months, forming the large wastage cavity found in March 2002.

10. The Unique Nature of the Davis-Besse Nozzle 3 Crack and the RPV Head Wastage Cavity

In the context of the nuclear industry, the cracks in Davis-Besse Nozzle 3 and its associated J-groove weld, and the unprecedented RPV head wastage that they caused, were not the result of ordinary "wear and tear." This unique combination of circumstances represented an unexpected, unforeseeable, and extraordinary event of the moment. It occurred in the October/November 2001 time period when the leakage rate increased rapidly from 0.02 gpm from the nozzle crack alone, to approximately 0.16 gpm (84,000 gallons per year). This rapid, eightfold increase in RCS leak rate was the result of the uncovering of the large, 0.7-inch-long J-groove weld crack near the same location as the nozzle crack. In turn, this created a unique thermal hydraulic environment in the wastage cavity that resulted in metal removal and cavity growth at not just an unusual, but at an unprecedented rate.

The Davis-Besse Nozzle 3 Crack 1 remains the longest axial CRDM nozzle crack ever found, over twice the length of any CRDM axial nozzle crack reported in ERPI MRP-110, and it grew at a rate four times greater than any previously observed CRDM nozzle crack. The wide radial/axial weld crack at CRDM Nozzle 3, in line with the axial crack and the wastage cavity at the 10° location, was the only weld crack reported to have been exposed by RPV head cavity wastage.

Our crack growth, CFD modeling, and analysis of the potential metal removal and wastage mechanisms lead us to conclude that the downward growth of the wastage cavity accelerated after the axial nozzle crack intersected the wastage cavity shortly before October/November 2001. At this point, there was only around 1 inch of RPV head steel remaining between the bottom of the wastage cavity and the upper surface of the stainless steel cladding. The aggressive metal removal processes in the bottom of the cavity would have removed this remaining metal in a relatively short period of time, as little as a few weeks.

The metal removal process significantly accelerated again after the downward growing wastage cavity reached the RPV stainless steel cladding, the large pre-existing weld crack was uncovered, and the leak rate increased by an order of magnitude. This sequence of events leads us to conclude that most of the wastage cavity formation occurred, from October/November 2001 through February 2002.

We further conclude that at 12RFO in April-May 2000, any incipient sub-surface wastage cavity at Nozzle 3 would have been insignificant in size and extent, and much smaller than the wastage cavity eventually found at Nozzle 2 in February 2002. It would not have been visible at 12RFO, even if the RPV head had been completely cleaned of boric acid deposits during the outage. Moreover, even had there been no pre-existing boric acid deposits on the RPV head from CRDM flange leakage at 12RFO, the sub-surface cavity that was present would not have been detectable from the very small enlargement of the nozzle annulus that may have been present at that time.

10.1 Wastage Cavities at Nozzles 3 and 2

10.1.1 Physical Appearance and Characteristics of the Wastage Cavity at Nozzle 3

The detailed physical examination of the large wastage cavity at CRDM Nozzle 3 after a portion of the RPV steel containing the cavity was removed from the RPV head and examined in the laboratory[1] shows the following principal characteristics (Figures 10-1 through 10-4):

- The cavity extends down to the upper surface of the stainless steel cladding, exposing both the cladding and the J-groove weld.
- The cavity extends approximately 8 inches towards nozzle 11, is a maximum of approximately 4 inches in lateral dimension, and extends back to approximately the 90° and 270° points on the nozzle bore.
- The total volume of alloy steel removed was approximately 195 cubic inches.

- The cavity is centered on the large axial/radial crack in the J-groove weld at CRDM Nozzle 3 at the 10° location.

- The axial Crack 1 in Nozzle 3, which extended 1.23 inch above the top of the J-groove weld, is also approximately centered on the wastage cavity.

- The cavity morphology is indicative of a combination of processes, including mechanical removal by impingement of high velocity fluid, flow assisted corrosion, and boric acid corrosion.

- The corrosion process is clearly more dominant in the upper region of the cavity. There is clear evidence of mechanical removal and/or flow-assisted corrosion in the lower region, where the wastage cavity is clearly undercut. This lower undercut region is indicative off a more rapid metal removal process than at the mid-elevation point of the cavity.

- General corrosion of the upper RPV head surface around the cavity is evident to a depth of 1 to 1.5 inches. This can be seen in the view of the top section of the cavity (Figure 10.4) and more clearly shown in the dental mold impressions (Figure 10.5).

10.1.2 Physical Appearance and Characteristics of the Wastage Cavity at Nozzle 2

Field examination of the much smaller wastage cavity at CRDM Nozzle 2 by means of a borescope camera revealed the following characteristics (Figures 10-6, 10-7):

- The wastage cavity was located above three of the through wall axial cracks in Nozzle 2, in the upper half of the nozzle bore, centered on the 270° location.

- The wastage area was located 180° away from the two longest axial cracks in Nozzle 2, which were either side of the 90° location.

- Enlargement of the annulus clearance at the upper surface of the RPV head was observed at approximately the 90° location.
- None of the axial cracks extended up into the wastage cavity.
- The wastage area extended approximately 3 ½ to 4 inches down from the upper surface of the RPV head and was 50° (1 ¾ inches) in circumferential extent.
- The maximum penetration of the cavity into the RPV head was approximately 3/8 inch in the radial direction away from the nozzle OD, and this maximum point was approximately 1 ¾ inches below the upper surface of the RPV head. This indicates that whatever processes of mechanical removal, corrosion, or flow-assisted corrosion were active; the cavity was growing at its maximum rate sub-surface.

10.1.3 Cracks in CRDM Alloy 600 Nozzle 3 and Alloy 182 Weld

The inspection data derived from the extensive UT examination of CRDM Nozzle 3 before the wastage cavity was discovered, as well as the later definition of the crack profile from the UT data, provide significant information about the long through-wall Crack 1 in CRDM Nozzle 3. Unfortunately, this crack was completely destroyed when the lower part of the nozzle was bored out for repair.

However, careful metallurgical examination of the portion of the J-groove weld that remained after the RPV head section containing the cavity was removed from the RPV head, together with the UT data, allowed us to build up a composite picture of the large nozzle and weld crack at CRDM Nozzle 3 that is shown in Figure 10.8 (See Section 8.4.2).

The large cracks at Nozzle 3 show the following characteristics (Figures 10-9 through 10-14):

- A large axial through-wall crack (Crack 1) at the 3° location at the top of the J-groove weld extended from almost the bottom of Nozzle 3 to 1.23 inches above the weld on the OD.
- This axial nozzle crack appears to have extended into and almost completely across the J-groove weld at Nozzle 3.
- The metallurgical examination of this weld crack showed that it was quite wide and extended approximately 0.75 inches across the weld in the radial direction at the 10° location (Figures 10.9 through 10.14).
- The weld crack was in line with the upward bulge and crack in the stainless steel cladding at the bottom of the wastage cavity. The bulge in the cladding may have contributed to opening of the weld crack.

The fact that the weld crack and to a lesser extent the nozzle crack at Nozzle 3 are in line with the centerline and "nose" of the wastage cavity at approximately the 10° location indicate that they are manifestations of the same crack. This crack, more likely than not, initiated on the nozzle OD below the weld, and then propagated axially up through the nozzle wall around the weld, radially towards the ID eventually reaching through-wall, and radially out through the weld. The possibility of multiple initiation sites on both the OD and ID of the nozzle cannot be ruled out, and this would have shortened the overall time for the crack to reach the top of the weld and begin leaking (see Section 8.1.1).

This process of crack growth resulted in the long axial crack that leaked initially from the nozzle into the annulus and wastage cavity, and later through the weld crack directly into the wastage cavity.

10.1.4 Metal Removal Processes by Corrosion, Erosion, Flow Assisted Corrosion (FAC), and Water Jet Cutting (WJC)

Data from extensive boric acid corrosion testing prior to 2002 shows that corrosion rates in concentrated aerated aqueous boric acid corrosion can be as high as 8 inches per year, and metal penetration rates due to jet impingement can be up to 11 inches per year (Section 6.3).

Recent data from EPRI (Section 6.4.1) and NRC/ANL (Section 6.4.2) corrosion test programs confirm these results. These corrosion tests all showed that the wastage process in highly dependent on temperature, pH and local flow velocity.

In addition the NRC/ANL corrosion test program also generated significant new data showing that re-wetting of high temperature molten metaboric acid – a condition previously thought to be relatively non-corrosive - can result in corrosion rates of up to 6 inches per year (Section 6.4.2).

These tests show that under the appropriate conditions, metal removal at high rates will occur. For impingement or flow-assisted corrosion (FAC) this can result in a highly localized penetration rate at low flow and high velocity, and a lower penetration rate but higher volumetric metal removal rate at higher leak flows. Superimposed on these flow assisted corrosion and metal removal mechanisms are the aggressive corrosion rates obtainable in both high temperature molten metaboric acid cooled to 300-340°F by the presence of moisture, and in concentrated aqueous boric acid at lower temperatures in the 200 to 230°F range. (see summary in Section 9.2).

The CFD modeling we have performed and reported in Section 9 support the conclusion that all of these aggressive metal removal processes can occur. In addition, metal removal by the purely mechanical action of the high velocity expanding fluid stream at the crack exit – known as water jet cutting (WJC) and Abrasive Water Jet (AWJ) cutting - provide additional mechanisms for significant material removal at a very rapid rate. (see Appendix E).

The following chronology summarizes the important features of the crack and wastage cavity development at Nozzle 3 at key points in time from late 1998 through to February 2002.

10.2 Cavity Development at Nozzles 3

In order to reach conclusions about the sequence of events that lead to the rapid development of the wastage cavity near Nozzle 3, we have used and taken into account the following:

- The CGR for crack growth in the nozzle above the weld that we developed in Section 8.5.1;
- The weld CGR of 0.7 to 1.0 inches/year that we also developed in section 8.5.1;
- The correlations between leak rate and "effective crack length for leakage" that we developed in Section 9.4 for the nozzle axial cracks and the radial/axial J-groove weld crack;
- The CFD modeling results for Cases 1 through 5 that we developed in Sections 9.5, 9.6 and 9.7;
- The corrosion test data that we described and summarized in Sections 6.3, 6.4 and 9.2;
- The history of RCS unidentified leakage as measured by the RCS inventory balance test and radiation monitoring that we described in Section 7.2;
- The review of plant outage information and CRDM flange leakage that we described in Section 7.3.

10.2.1 12 RFO: Nozzle 3 Crack is Leaking at a Low Rate and a Minor Wastage Cavity Begins to Form at Nozzle 3

- The Nozzle 3 CRDM axial Crack 1 extends to around 0.5 inches above the J-groove weld. The estimated leak rate from this axial nozzle crack is approximately 0.0004 gpm (210 gal/year). This is only 5% of the leak rate estimated for all seven cracks combined at Nozzle 2 in February 2002.

- The metal removal processes likely acting at this time to promote sub-surface cavity growth downward towards the crack were high velocity/low flow mechanical erosion from the fluid exiting the crack and flowing up the annulus. While conditions conducive to the formation of molten metaboric acid existed in the cavity, the low leak flow rapidly dries out and so there is no moisture present to promote boric acid corrosion.
- 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.

10.2.2 October- November 2001 - Weld Crack Uncovers, Leak Rate Dramatically Increases, Cavity Growth Accelerates, and Significant Damage to the RPV Head Occurs

- By October 2001, the leak rate and the cavity size have increased to a critical point after which rapid RPV head metal removal occurs.

- The upward growing Nozzle 3 CRDM axial crack is predicted to be approximately 1.1 inches above the J-groove weld, and extends well into the bottom of the rapidly downward growing wastage cavity. The leak rate at this time is estimated to be 0.02 gpm (10,500 gals/year). This leak rate has increased by a factor of 500 since 12 RFO (May 2000).

- The rate of metal removal at the very bottom of the cavity increases further due to direct impingement of the jet from the crack on the cavity wall, and abrasive water jet cutting is likely due to the extremely high velocities and entrainment of boric acid and corrosion product particles. The removal of the final one-inch of steel remaining above the stainless steel cladding due to these accelerated processes likely occurs in a very short period of time, possibly just a few weeks. In addition, the cavity starts to become undercut due to the more rapid metal removal at the bottom where the crack is located.

- Also by October 2001, in addition to the accelerated corrosion due to wetted molten metaboric acid at the bottom of the wastage cavity, moisture persists all the way through the wastage cavity to the upper RPV head surface. Wastage corrosion due to re-wetting of the molten metaboric acid accumulation on the RPV head begins to cause "top down" corrosion of the head in the region of CRDM Nozzle 3.

- The wide, pre-existing crack in the weld of 0.7 inches in length uncovers and the remaining steel above the weld is quickly removed by the continued jet impingement and abrasive water jet cutting effects of the high fluid velocities, as well as continued corrosion due to wetted molten metaboric acid.

- The total leak rate increases rapidly from the previous 0.02 gpm (10,500 gal/year) to approximately 0.16 gpm (84,000 gal/year) when the weld crack is completely uncovered.

- The rapid increase in leak flow predicted in the October-November time frame as the weld crack uncovered is supported by the plant data. The unidentified leak rate shows an increase of around 0.15 gpm, and both the noble gas and iodine radiation monitors likewise show responses indicative of an increased flow of reactor coolant in the containment building atmosphere.

- This leak flow is now high enough that the fluid stream still contains significant moisture all the way to the top of the wastage cavity and to the underside of the boric acid deposit on the RPV head, which is mostly molten metaboric at the prevailing 550 °F temperature. Wetting of the underside of this deposit over a wider area by the leak flow causes wastage both of the upper portion of the cavity and of the upper RPV head steel around the cavity, leading to the smooth wastage appearance evidenced by the photographs and the dental mold of the cavity.

- The significant increase in the rate of growth of the wastage cavity in this time period is due to the following metal removal processes:

- Abrasive water jet cutting due to entrained boric acid and corrosion product particles due to the extremely high velocities once the crack and wastage cavity intersect
- Mechanical erosion by direct jet impingement of the high velocity boric acid liquid stream once the crack and wastage cavity intersect.
- Accelerated corrosion due to wetted molten metaboric acid.
- Flow Assisted Corrosion (FAC).

- The wastage cavity grows rapidly as a result of these processes after the weld crack uncovers, causing significant damage to the RPV head in a relatively short period of time, a matter of a few weeks.
- As the cavity grows to its final observed size in March 2002, abrasive cutting slows significantly as the wastage cavity grows and the wastage cavity size becomes too large for efficient material removal by AWJ processes. Fluid velocity at the cavity wall is also significantly reduced due to the increased distance from crack.
- Cavity wastage continues at a significant rate due to flow-assisted corrosion at the bottom of the cavity and wetted molten metaboric acid both throughout the wastage cavity, and "top down" corrosion on the RPV head surface around the cavity continues at a significant rate due the moisture from the crack leak flow.

10.3 Postscript

In a risk assessment of the Davis-Besse event performed in December 2002, the NRC staff reached a similar conclusion. 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 report goes on to discuss the EPRI reported tests of aqueous and molten boric acid corrosion,[a] the various containment indicators of boric acid leakage, and the physical shape of the wastage cavity. The NRC report then concludes, much as we have, that:[2]

> "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.
>
> 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."

The large wastage cavity formed in the Davis-Besse RPV head at CRDM Nozzle 3 remains the only event of its kind ever experienced at any PWR. According to EPRI MRP-110, no significant wastage of the RPV head has been reported at any other US or non-US PWR as a result of cracked and leaking CRDM cracks per MRP-110.

The Davis-Besse RPV head wastage event was therefore not the result of ordinary "wear and tear". It was an unanticipated, unforeseeable, and extraordinary "event of the moment" that was brought about by a unique combination of a large, rapidly growing crack in CRDM Nozzle 3, leakage from that crack at a rate and at a location that caused a

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[a] The NRC report written in December 2002, noted that "there are no physical test results available for a situation like the postulated pool of molten orthoboric acid hydrated by a low rate of water leakage into the pool." The results recently reported by the NRC/ANL test program were designed to at least partially fill this knowledge gap, and showed corrosion rates for this condition of up to 6 inches per year. (Section 6.4.2)

unique thermal hydraulic environment to develop in the nozzle annulus, that in turn caused the wastage cavity to develop at not just an unusual, but at an unprecedented rate.

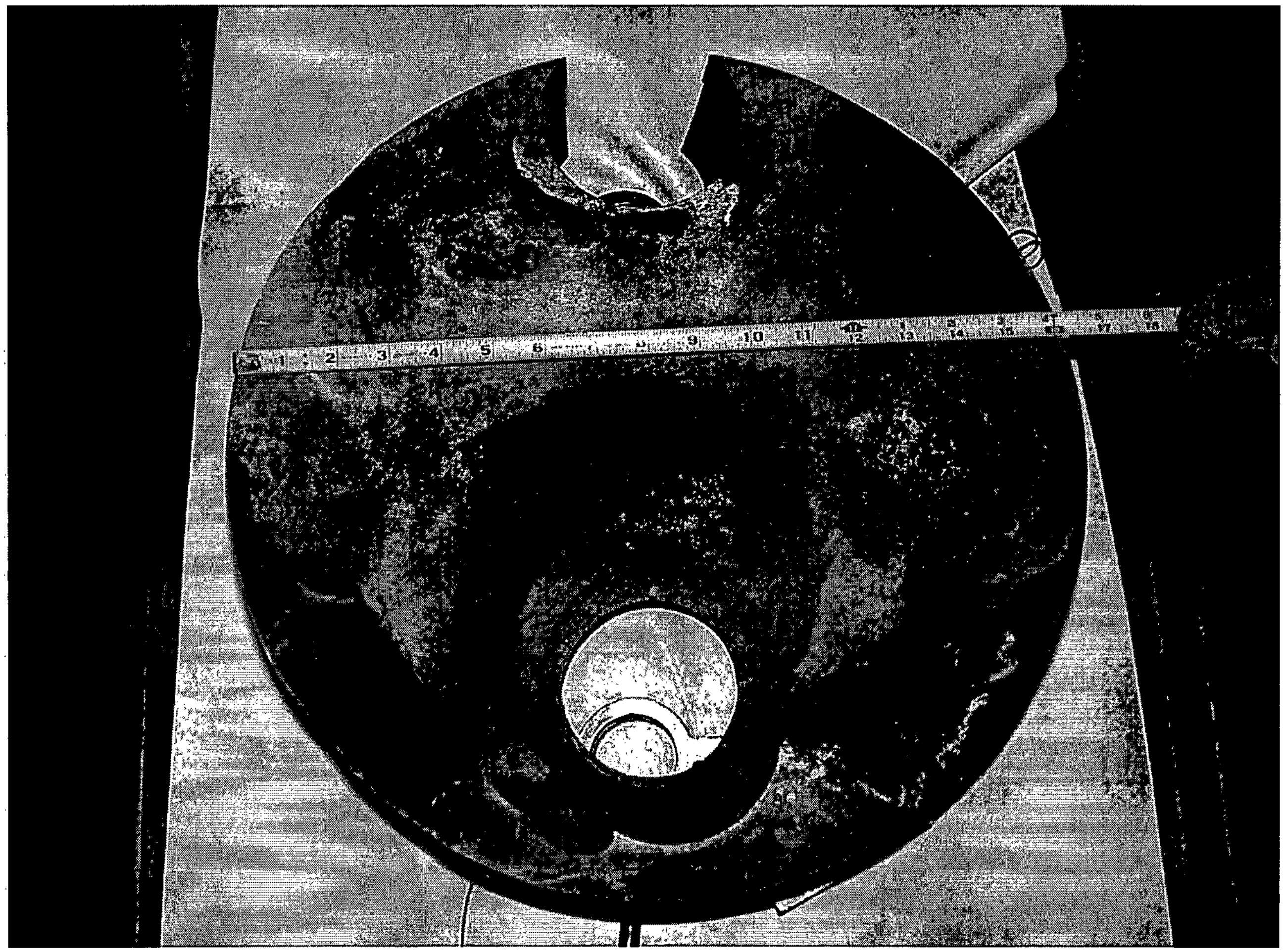


Figure 10.1 Top view of wastage cavity.

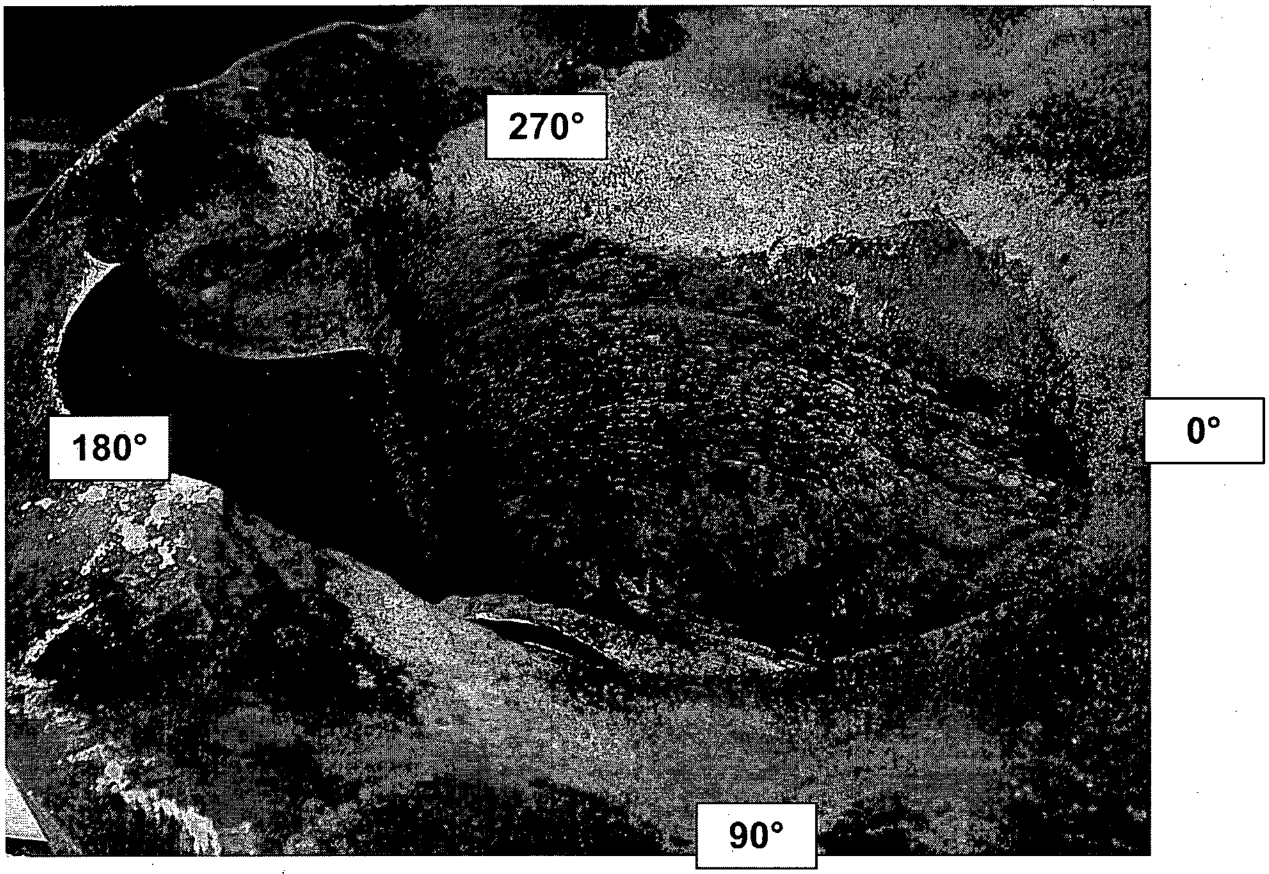


Figure 10.2 View of cavity looking toward 270°

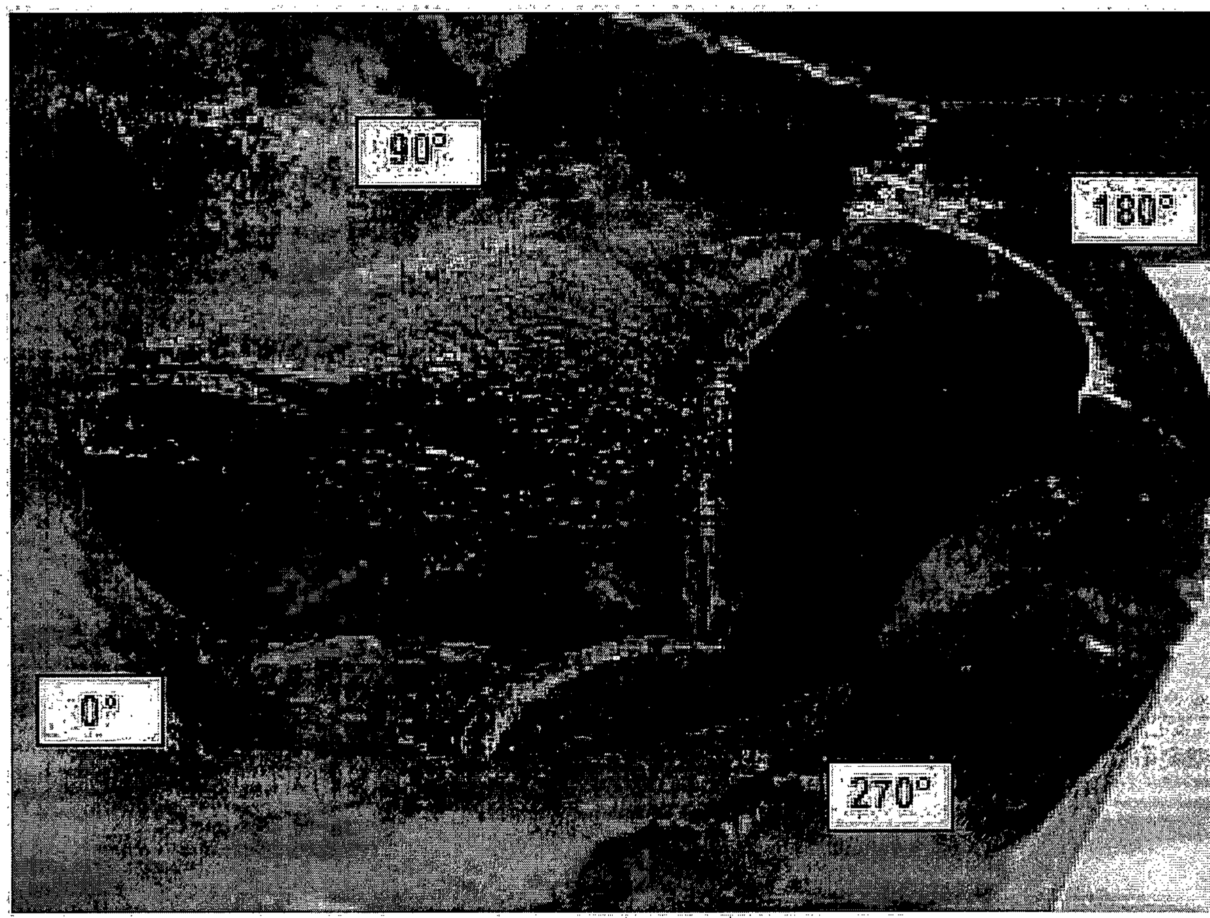
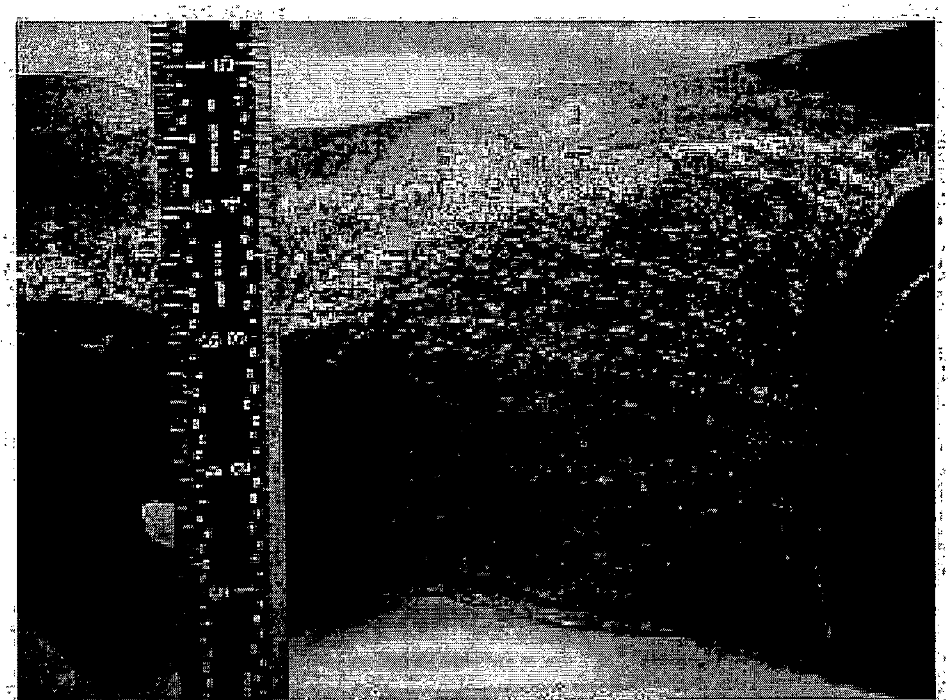


Figure 10.3 View of cavity looking toward 90°



Looking toward 90° ~0.7X

Looking toward 270° ~0.5X

Figure 10.4 Low magnification photographs of cavity sidewalls

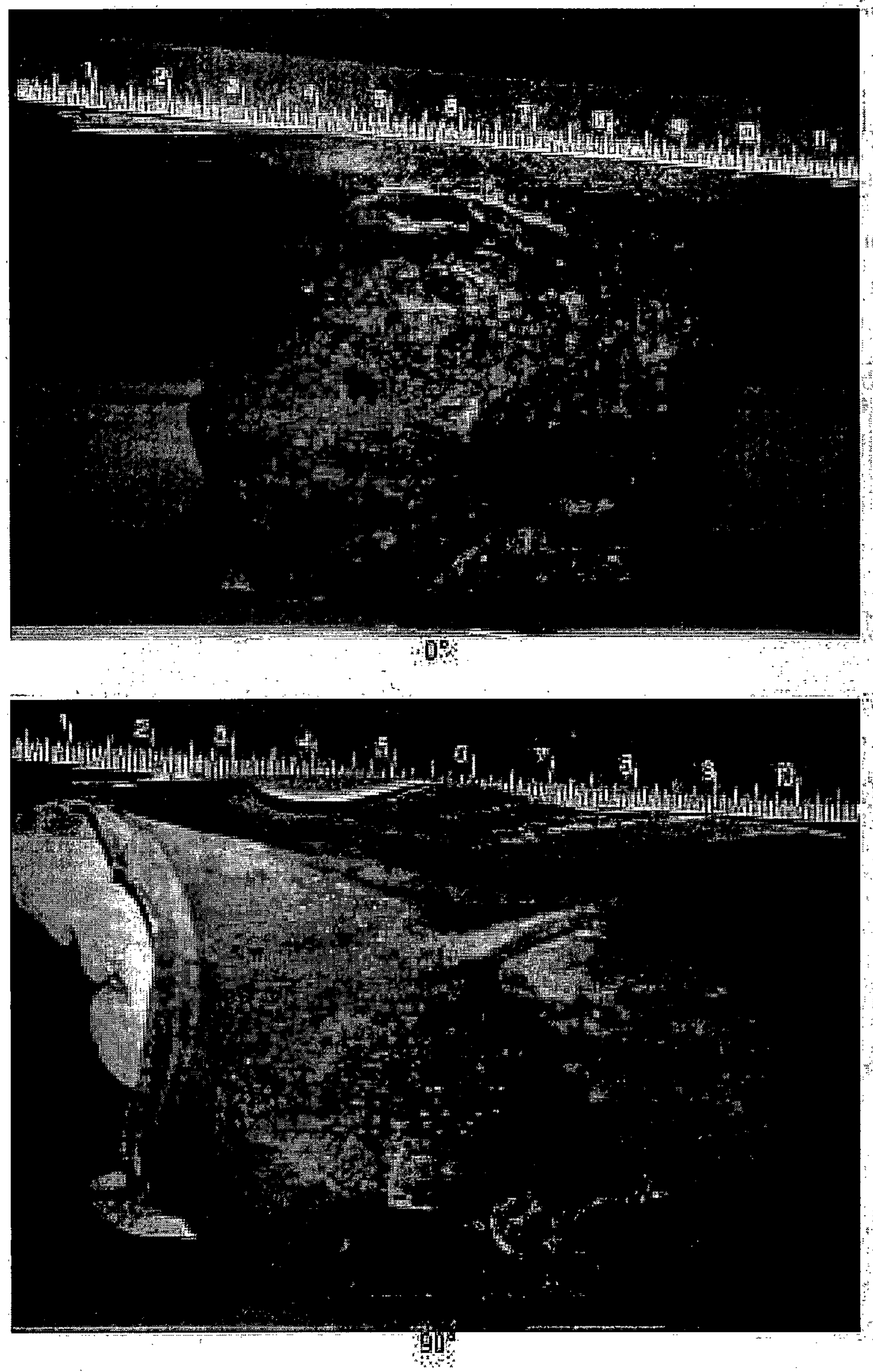
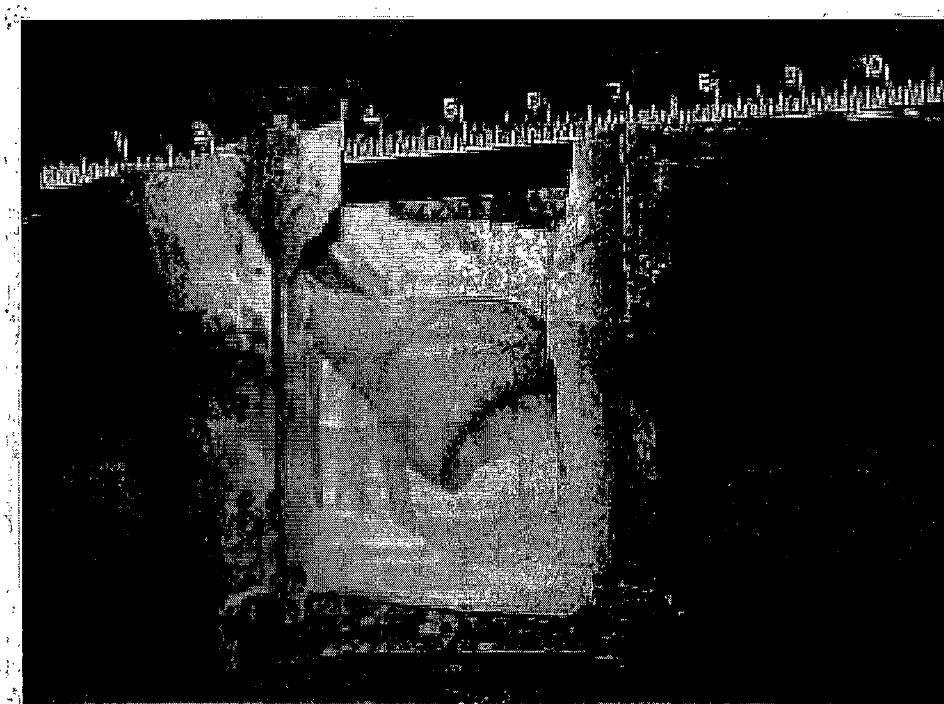
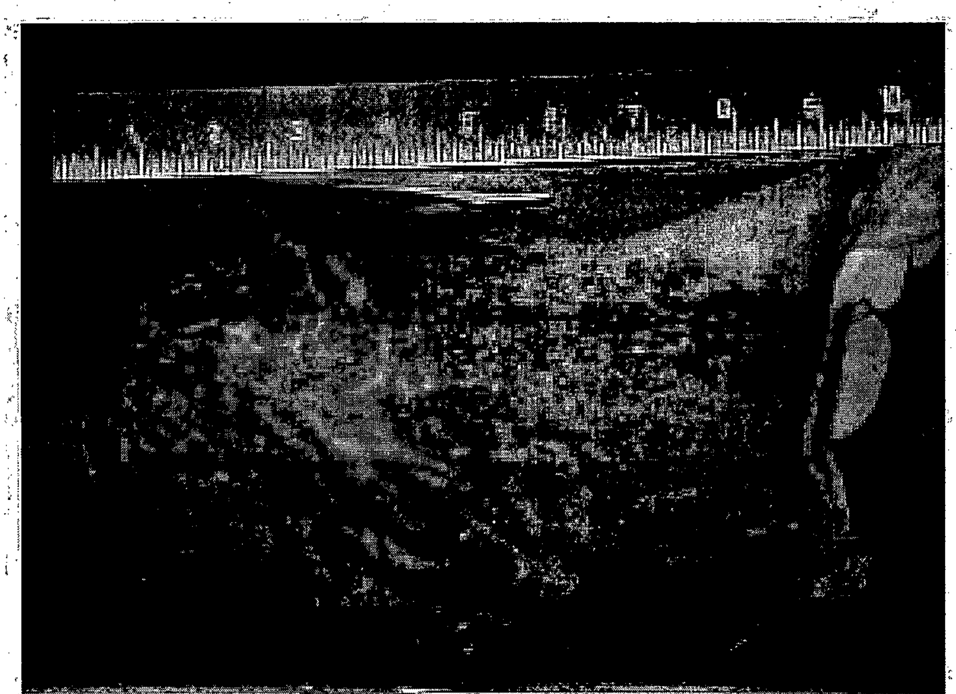


Figure 10.5(a) Photographs of cavity dental mold



180°



270°

Figure 10.5(b) Photographs of cavity dental mold

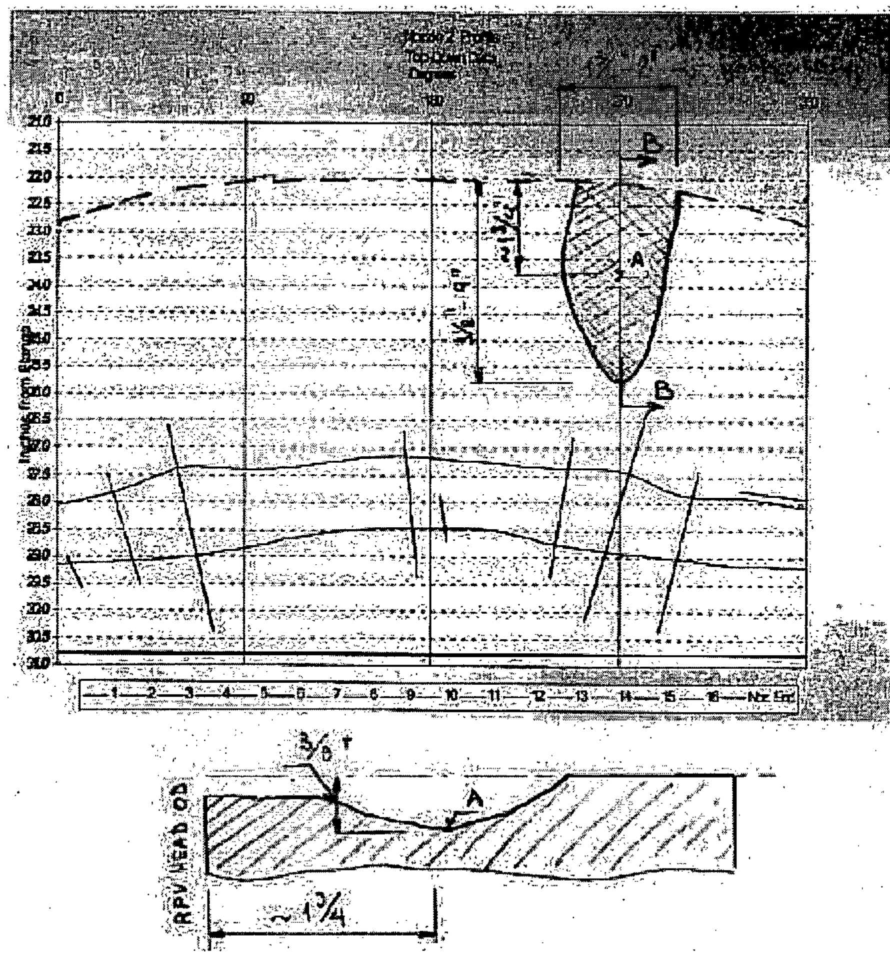


Figure 10-6 Wastage Cavity at CRDM Nozzle 2

Nozzle 2 Corrosion Profile

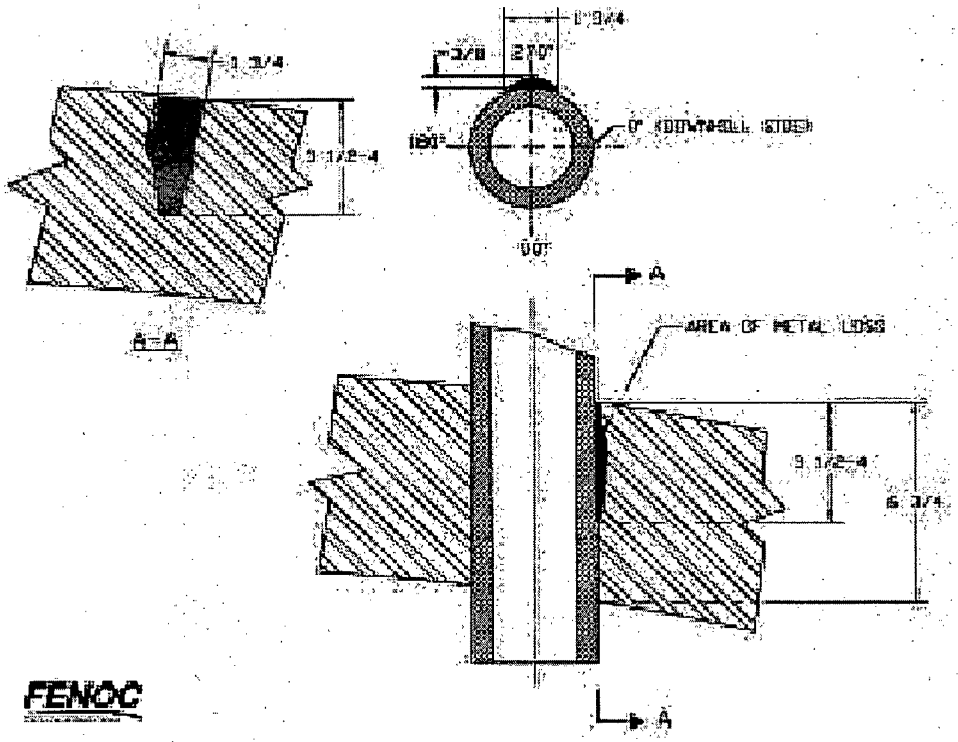


Figure 10-7 Wastage Cavity at CRDM Nozzle 2

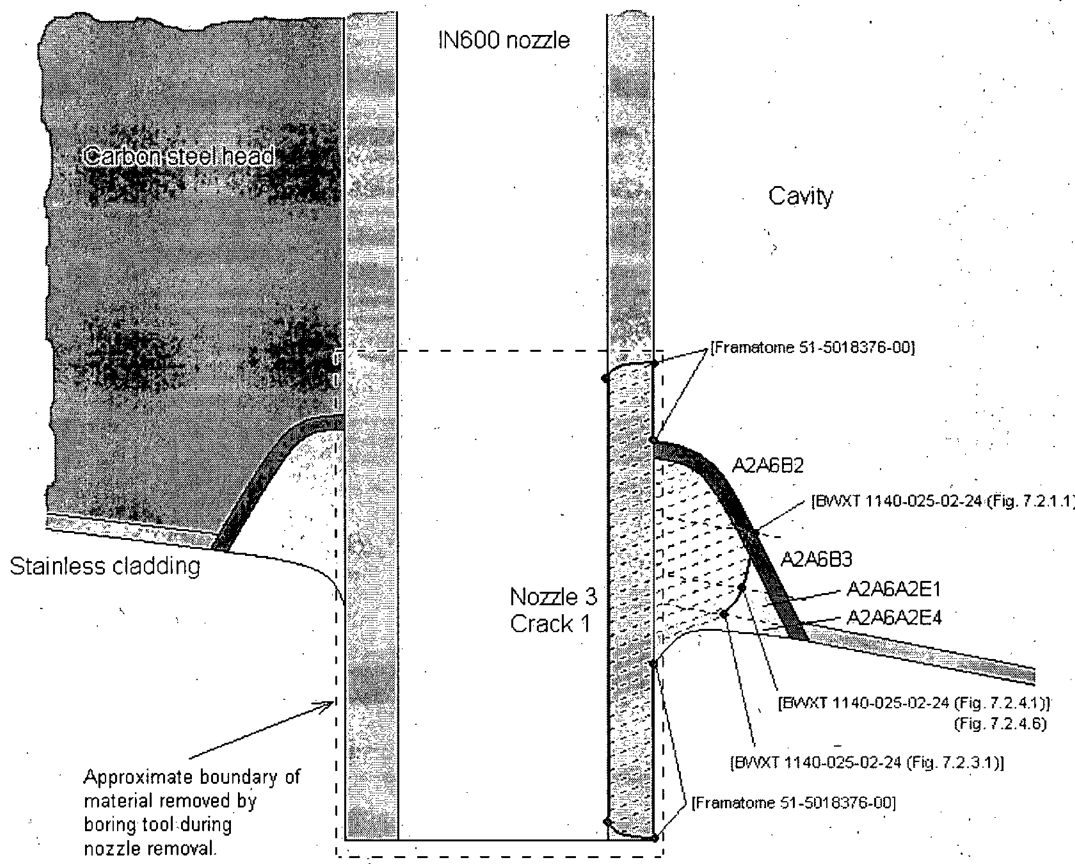


Figure 10.8 Schematic of final size and shape of Crack 1 in Davis-Besse CRDM Nozzle 3 (from Section 8, Figure 8-10)

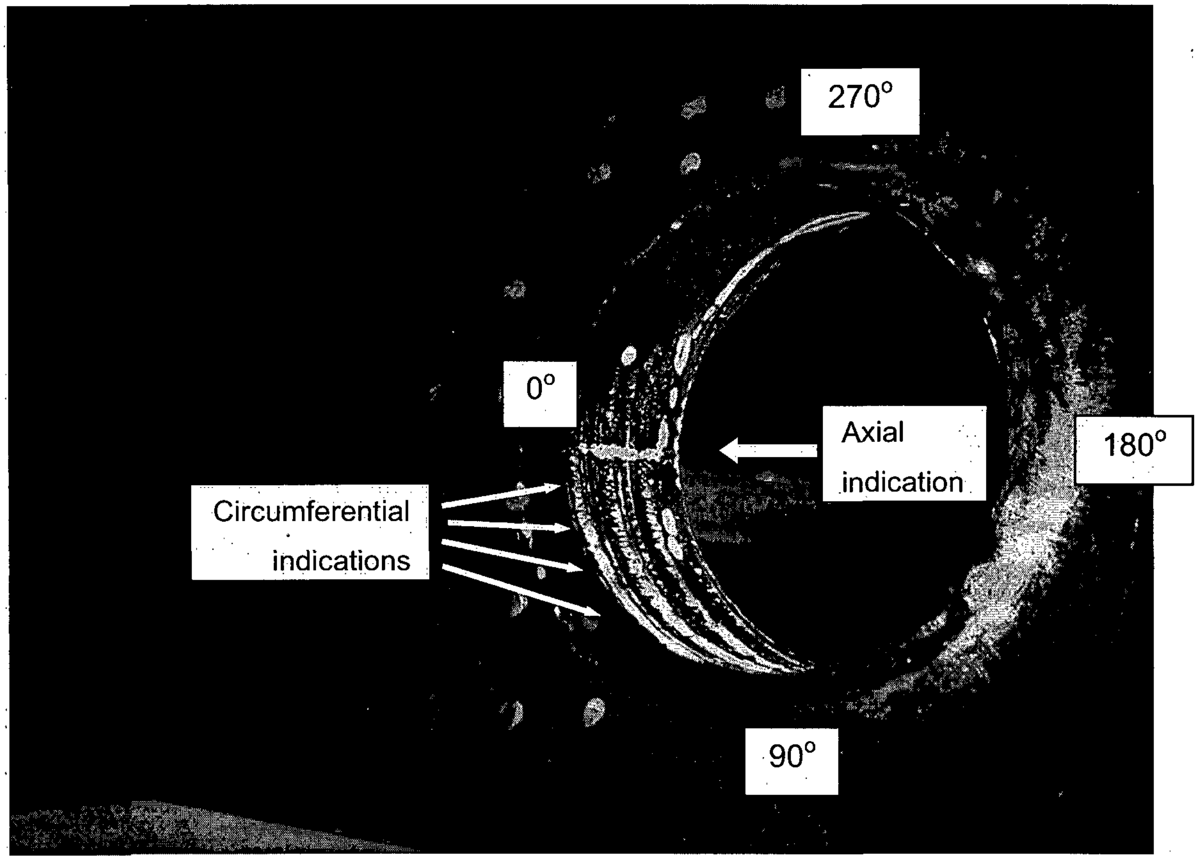
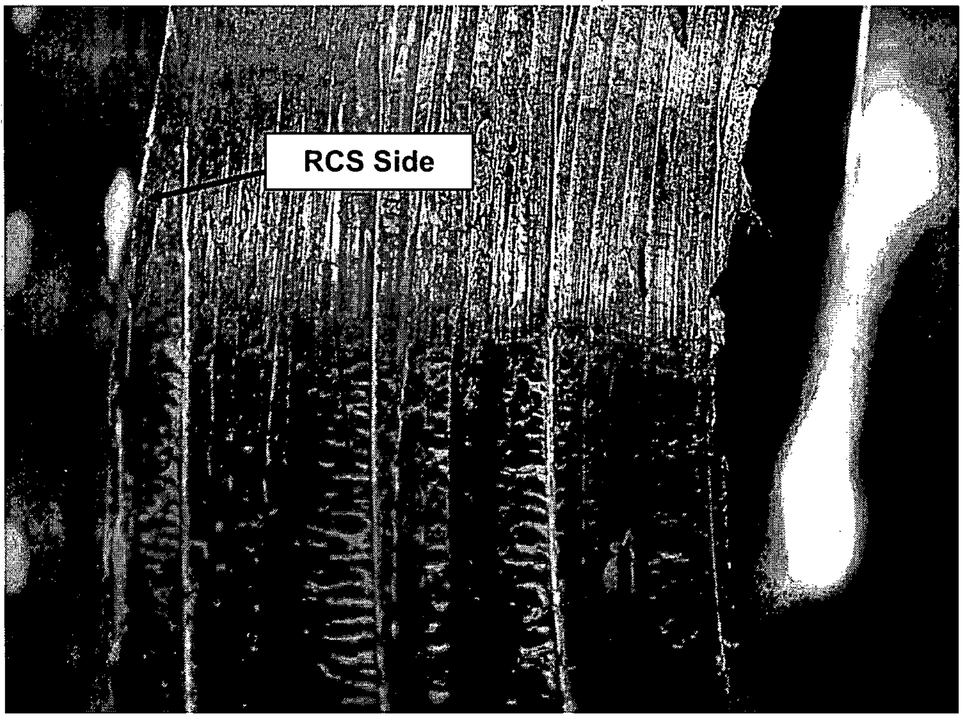
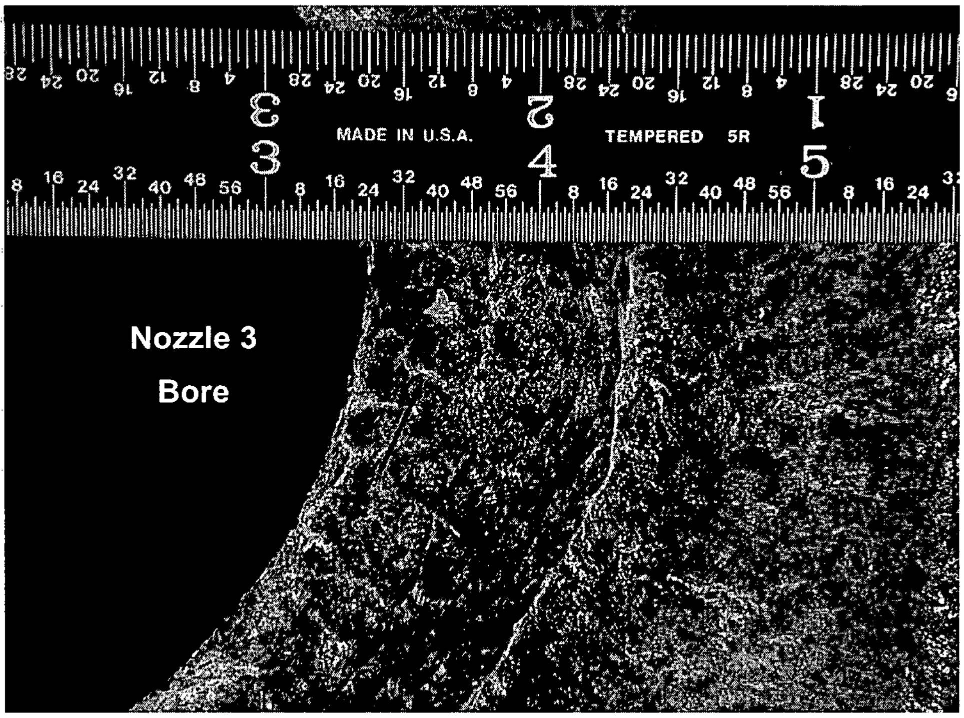


Figure 10.9 PT results for nozzle 3 J-groove weld bore and cladding underside. The J-groove weld contained an axial indication near 10° on the bore ID and circumferential indications on the RCS side from ~20° to ~45°.



Looking at J-groove weld bore near 10°. ~1.2X

Figure 10.10 Photograph showing the remaining portion of the axial crack near 10° in the CRDM Nozzle 3 J-groove weld. This is the portion remaining after the machining was completed for nozzle repair.



Top view of J-groove weld crack near 10°. ~1.4X

Figure 10.11 Photograph showing axial crack in CRDM nozzle 3 J-groove weld near 10°.

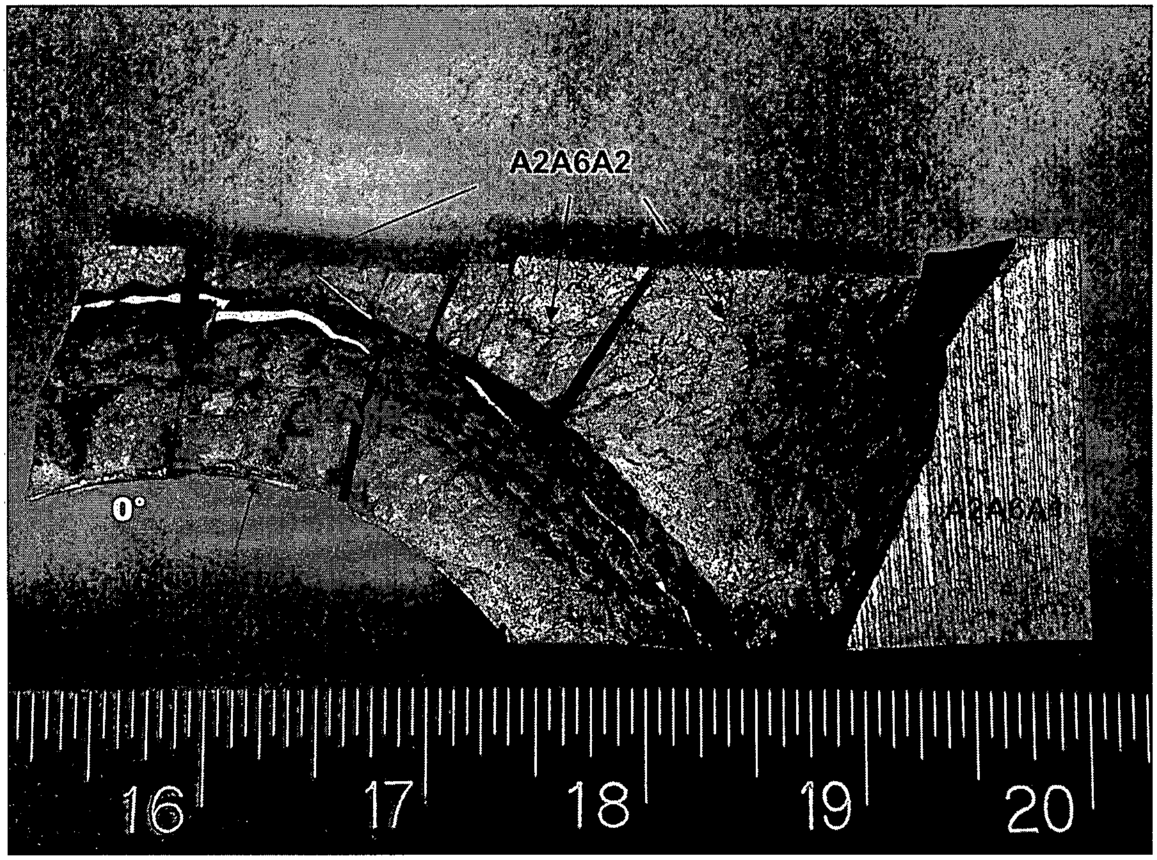


Figure 10.12 Piece A2A6 was first sectioned into Pieces A2A6A and A2A6B. Piece A2A6A was further sectioned into Pieces A2A6A1 and A2A6A2. Both cuts were made on the same plane, parallel to the paper. The first cut line is partially visible; Piece A2A6B is the upper portion of the weld. The second cut line between Pieces A2A6A1 and A2A6A2 is obscured by Piece A2A6A1

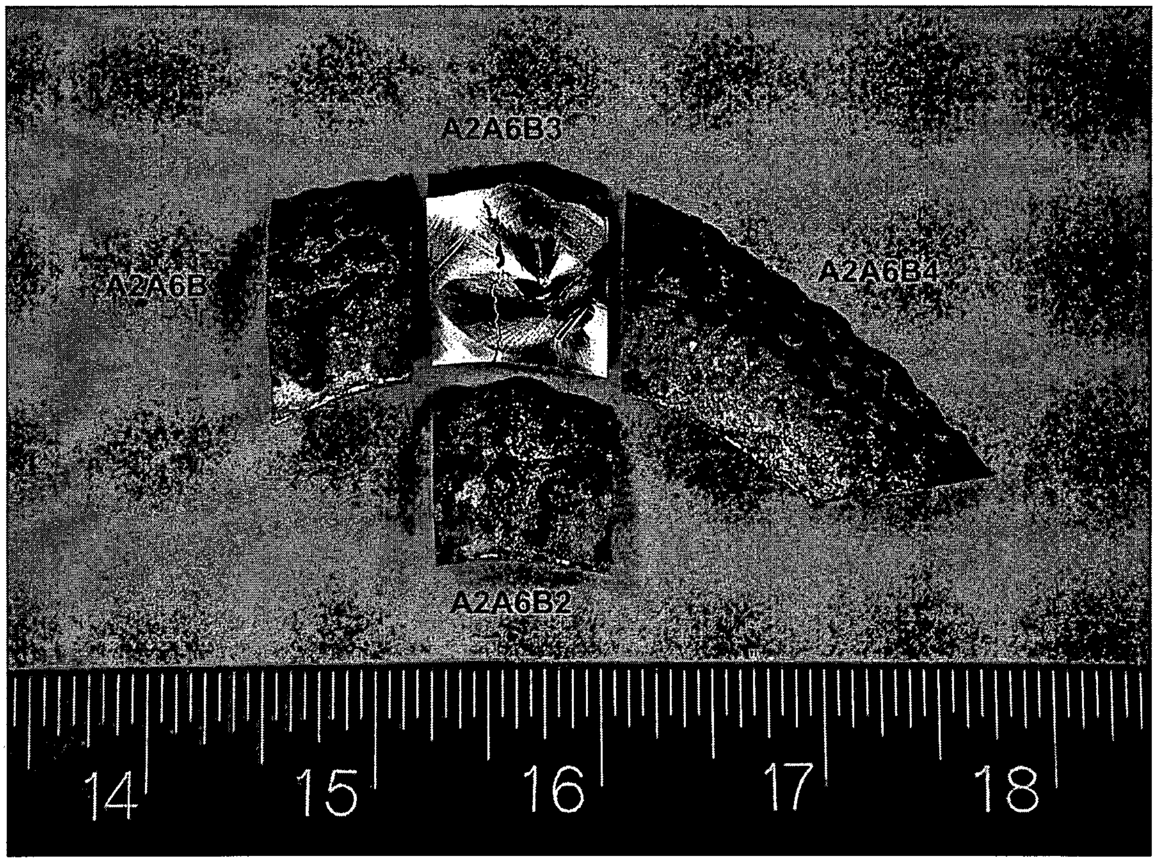
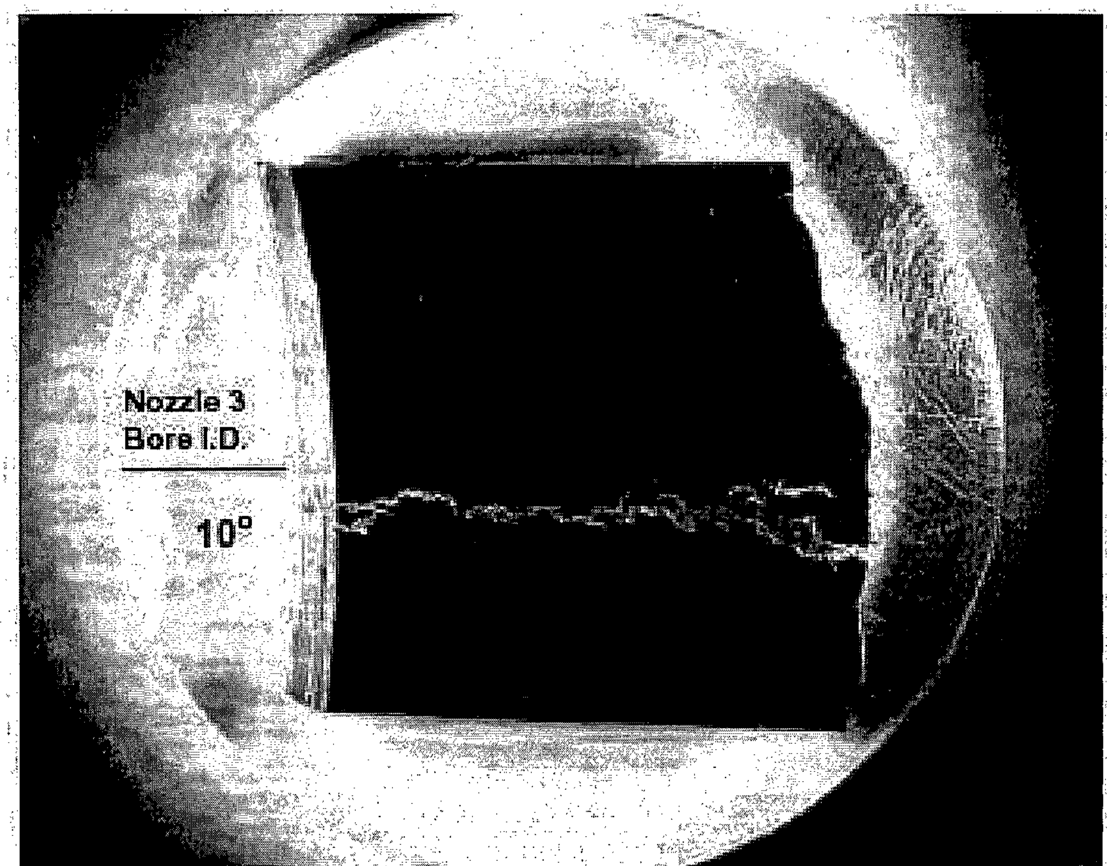
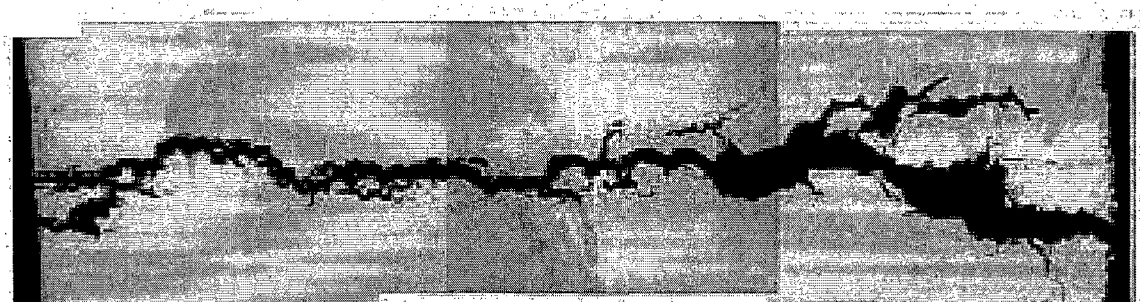


Figure 10.13 Piece A2A6B after sectioning. The bottom surface of A2A6B2 was mounted. The axial crack in A2A6B3 was opened up for SEM.



4X



Etched 8X

Figure 10.14 Macro photograph of metallographic mount sample A2A6B2 (see Figures 5.4 and 5.5 for the sample orientation). The axial cracking at ~10° is through the J-groove weld, in contrast to the cracking near 180°, which was partially through the weld. A slightly higher magnification micrograph is also provided

10.4 References

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.

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