6. Boric Acid Wastage of Carbon Steel Components in US PWR Plants

The large wastage cavity discovered at Davis-Besse CRDM Nozzle 3 in March 2002 was an a unique and singular event that was totally unexpected and unanticipated either from the prior three decades of operating experience, or from the large body of boric acid corrosion research that had been conducted over that same time period.

The purpose of this section is to provide an overview of the wastage events that have been documented in the US nuclear industry, the regulatory response to these events and to review the current and prior experimental efforts to quantify the effects of boric acid corrosion on carbon steel. Although significant metal penetration rates have been observed under certain experimental conditions, the rapid formation of the wastage cavity on the Davis-Besse RPV head under high-temperature reactor operating conditions was completely unexpected and unforeseen. In addition, the formation of the wastage cavity was not due to ordinary “wear and tear.”

There are approximately 155 operating PWR plants worldwide, and prior to the Davis-Besse event, only minor boric acid wastage of the RPV head had been reported in a few isolated events over a 32-year time period from 1970 through 2002.

In the three prior RPV head wastage events that had been reported (Beznau-1 in 1970, Turkey Point-4 and Salem-2 in 1987), considerable quantities of boric acid had been deposited on the RPV head that were, in both volume and quantity, similar to or greater than the 900 lbs of boric acid estimated to be on the Davis-Besse RPV head in 2002. Yet in none of those three events was significant boric acid wastage of the RPV head found under the deposits, all three RPV heads were returned to service, and are still in service today. At these three plants, the boric acid leakage occurred from leaking connections above the RPV head.

Similarly, in the seven B&W-designed US plants, leakage from the CRDM flanges[a] resulted in boric acid deposits on the RPV head on numerous occasions over the 30 or so years these plants have been operating, none of which caused any significant or reported wastage of the head.

In addition to this limited experience with RPV head wastage, despite the large number of cracks found in CRDM nozzles in PWR plants from 1991 through 2002, many of which (almost all in US plants) had resulted in leakage, not a single leak had resulted in any wastage of the top surface of the RPV head, and not a single leak had resulted in any sub-surface wastage cavity formation.

The large wastage cavity at Davis-Besse CRDM Nozzle 3, and even the smaller sub-surface cavity at CRDM Nozzle 2, remain the only reported instances of significant RPV head wastage caused by boric acid leakage from cracked CRDM nozzles.

It is clear from our review of this thirty-year history that the Davis-Besse RPV head wastage event was not the result of ordinary “wear and tear” to the reactor vessel head. Rather, it was an extraordinary, one-of-a-kind event 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 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.

The overwhelming focus of the industry until the Davis-Besse event in 2002 was on leakage from mechanical closures such as bolted and gasketed flanges on pumps, valves and vessel nozzles, from valve packings, and from welded/threaded pipe fittings. In all of these cases, the concern was over wastage degradation of carbon steel piping and bolted fasteners resulting from the boric acid leakage.

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[a] The seven operating B&W plants were the only ones to use a flanged CRDM design, which had a history of leakage that took the seven plants a number of years to correct. At Davis-Besse, the last leaking CRDM flanges were repaired at 12RFO in April-May 2000. Other PWR designs used welded designs.

Given the industry experience, there was an understandable lack of focus by the industry and the NRC on boric acid corrosion of the carbon steel RPV head at leaking Alloy 600 penetration nozzles. The key safety issue was seen as potential nozzle failure of CRDMs and instrument connections due to Alloy 600 circumferential cracking, and not on carbon steel vessel shell or head wastage due to the boric acid leakage from cracked nozzles.

The reasons for the lack of corrosion of carbon steel pressure vessel shells (RPV, pressurizer and steam generators) given the many cracked and leaking Alloy 600 nozzles found were summarized in the comprehensive 1995 EPRI Guidebook on the issue of boric acid corrosion as follows[1]:

> "The main reasons for the general lack of significant corrosion damage are that the amount of leakage is typically very small, there is little oxygen in the crevice between the nozzle and the clearance hole in the vessel shell, and the small amount of water which does reach the surface of the vessel shell quickly evaporates."

We have reviewed the key reports prepared by EPRI, by the NRC, and by the BWOG and other PWR owners groups (WOG and CEOG) which document the plant incidents from the mid-1970's that involve boric acid leakage and wastage of carbon steel components..We provide a brief summary of the US plant experience with boric acid corrosion of both pressure vessels such as the RPV and pressurizer, as well as other RCS components in Section 6.1 below.

In Section 6.2, we review the US NRC regulatory response to the ongoing problem of boric acid wastage of carbon steel components in PWR plants, as well as the parallel industry work both independent of and in response to the concerns and issues in NRC Information Notices and Bulletins.

In Section 6.3, we review the large body of research that was conducted on boric acid wastage of carbon steel in a variety of geometries, and we note here that most of this work was focused on immersion, drip and impingement testing, representative of the vast majority of the reported plant events.

Finally, in Section 6.4 we review the recent research sponsored by both EPRI and the NRC that has been specifically focused on replicating the thermal hydraulic and boric acid wastage conditions that are thought to have been present in the Davis-Besse 2 and 3 CRDM nozzle annular crevices. This recent work both reinforces some of the earlier pre-2002 corrosion research that is relevant to the Davis-Besse event, but in addition provides significant new information that we have used in Sections 9 and 10 of this report to develop our understanding of the progression of the wastage cavities at the two nozzles.

6.1 Review of US Experience with Boric Acid Corrosion of Carbon Steel Components Prior to 2002

We divide the review of the US experience with boric acid corrosion of carbon steel components prior to 2002 into two parts. Section 6.1.1 provides a brief summary of the US experience with wastage of RCS carbon steel components other than the shells and heads of the RPV, pressurizer, and steam generators which comprised the bulk of the corrosion experience and therefore commanded most of the industry and regulatory attention. Section 6.1.2 summarizes the few instances of wastage of the RPV and pressurizer heads caused by boric acid leakage that have been reported prior to the 2002 Davis-Besse event.

6.1.1 Boric Acid Corrosion of Components Other than the RPV Head

Boric acid corrosion of carbon and alloy steel bolting in PWRs has been an ongoing problem from the mid-1970s. Information regarding some of the more significant events related to wastage of bolts and fasteners in the RCS was disseminated by the NRC in Information Notices between 1980 and 1982, and eventually the NRC issued a Bulletin on this issue in 1982 that required written responses and commitments from PWR operators (see Section 6.2).

One of the earliest surveys of US plant experience was presented in a NRC report that was published in July 1982[2]. The operating experience of seven US plants was reviewed to identify instances of corrosion and wastage cause by exposure to boric acid, and to relate the observed rate of corrosion from field experience to corrosion data from laboratory tests.

The documented events involved corrosion of reactor coolant pump casing studs and nuts from leaking gaskets and seal piping, and corrosion of various valves and valve bolting from leaks in the valves themselves. Review of laboratory test corrosion data showed that corrosion of carbon steel in boric acid at various concentrations increased rapidly with temperature, reaching a maximum of up to 0.13 inches per year at 212 deg. F, then decreasing to about 50% of this rate as the temperature was increased to 352 deg. F. Recommendations for inspection intervals of the RCS for component leakage were based on these data and on the field experience.

In August 1988, EPRI published a report containing an updated review of US plant experiences through 1987 with boric acid wastage of RCS components[3]. Again the field experiences were mostly related to wastage of bolting, fasteners, and piping caused by leaks of boric acid from leaking valves and flanges. The EPRI report documents 32 boric acid “corrosion events” between 1968 and 1987 involving over 250 “fasteners” of various types[4].

The report does present some published data from laboratory “drip” tests to determine boric acid corrosion rates of carbon steel, noting that these had been found to be as high as 4.8 inches/year in short term (6 hour) tests. CE conducted additional tests for the EPRI report at 220 deg. F for various boric acid concentrations. The results indicated that the corrosion rates for short term tests of 4 to 96 hour duration, ranged from 0.2 inches/year for the 96 hour test up to 7.2 inches/year for the 4 hour test[5].

Various recommendations were made to evaluate boric acid containing systems where carbon steel components were present, conduct system walkdowns, identify and correct leakage indicated by boric acid accumulations, and generally heighten awareness of plant personnel of the potential for accelerated wastage of carbon steel components by boric acid where leakage could contact hot metal surfaces and become concentrated[6].

In addition to the large number of bolting and fastener events, the EPRI report does contain descriptions of the RPV head wastage events at Turkey Point-4 and Salem-2, and of the pressurizer at ANO-2, all of which were discovered in 1987, and we discuss these in Section 6.1.2.

A survey report prepared for the US NRC by Brookhaven National Laboratory (BNL) in 1990[b] provides an update on the earlier 1982 NRC report discussed above[7]. The 1990 report lists 17 "major recorded events of boric acid wastage corrosion on both threaded fasteners and other carbon steel components since 1977."[8] The majority (14) of these events involved bolts, studs, piping and valves, but the list includes the two RPV head wastage events at Turkey Point-4 and Salem-2 in 1987, as well as the pressurizer head wastage at ANO-2 in 1987.[9]

The NRC report did not present any new data on boric acid corrosion rates derived from laboratory tests, except for a brief mention of some French laboratory tests which reportedly showed corrosion rates of up to 0.75 inches/year, with the caveat from the French citation of this work that[10]:

> "Real life experience has almost never shown such a high corrosion rate, which may be attributed to boric acid crystals creating a solid, far less corrosive blanket around the stud…."

The NRC report concluded by noting that this French observation was "consistent with US-PWR experience."

The EPRI Boric Acid Corrosion Guidebook published in 1995 provides a comprehensive review of US experience with boric acid corrosion of carbon steel RCS components to

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[b] The major focus of this 1990 NRC report is on a review of utility responses to NRC Bulletin 88-05, which we discuss in Section 6.2.

that point in time[11]. In Chapter 2 and Appendix A, the report documents 123 reported instances of boric acid wastage of carbon steel components from 1969 through to 1992[c].

Of these 123 events, only 18 are listed as having involved the RPV itself. Of these 18 events, a total of 11 resulted from leaks above the RPV head at flanges or seal welds with 7 events occurring at CRDM nozzles and 4 at instrument nozzles. However, of these 11 leaks, only 2 – the Turkey Point-4 and Salem-2 events in 1987 (see Section 6.1.2 below) – resulted in actual wastage of the RPV head, and none involved wastage in the CRDM nozzle crevice. All of the other reported 105 events involved other RCS components such as bolts, studs, flanges, valves and piping, where boric acid wastage occurred as a result of a leak dripping or impinging on the component. Thus again, field experience resulted in industry and NRC attention being focused on component leaks other than CRDMs..

The rationale given in the 1995 EPRI Boric Acid Corrosion Guidebook for the lack of pressure vessel wastage at leaking nozzles was described in the introduction to this Section 6 and is worth repeating here - very small leak rates, little oxygen in the crevice, and rapid evaporation of the leakage due to the hot metal surface.

In addition, the EPRI report hypothesized that accumulated boric acid deposits could protect carbon steel vessel heads from boric acid wastage by keeping moisture away from the head and excluding oxygen[12]. The 1987 Turkey Point-4 experience, where "minor 0.25 inch corrosion depth on the vessel head" rather than the 5 to 10 inches/year expected from laboratory tests was cited as support for this hypothesis. Figure 6-2 (taken from the 1995 EPRI report) illustrates the mechanism by which this was thought to occur.

The 1995 EPRI Boric Acid Corrosion Guidebook also contains:

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[c] Only two non-US events are included, both for the Beznau-1 plant in Switzerland in 1969 and 1973. Curiously, even though these were reported as RPV related events, neither appears to be the RPV head wastage event that occurred in 1970 that we discuss in Section 6.1.2.

- An extensive discussion and summary of boric acid corrosion mechanisms (Chapter 3) and laboratory test data (Chapter 4) that we summarize in Section 6.3;

- A review of the regulatory requirements (Chapter 5) that we review in Section 6.2; and

- Methods for detecting leakage (Chapter 6), especially leakage less than 0.1 gpm for which the installed plant leakage detection systems were inadequate, that we discuss later in Section 7.2.

In summary, while the 1995 EPRI Boric Acid Corrosion Guidebook provided Davis-Besse and other US PWR operators with a "state-of-the-art" report on all aspects of boric acid corrosion of carbon steel components, it essentially de-emphasized and relegated the potential issue of RPV head wastage due to crevice corrosion caused by leaking CRDM and other vessel nozzles to one of minor importance that was unlikely to occur.

Given the lack of field experience of any crevice corrosion caused by leaking nozzles in over 25 years of worldwide PWR operation, the prevailing industry view in 1995 was certainly understandable.

In November 2001, EPRI published an updated revision to the Boric Acid Corrosion Guidebook[13]. In Chapter 2 and Appendix A, this revision to the report documents an additional 18 reported instances of boric acid wastage of carbon steel components from 1993 through 2000, 141 events total from 1969 through 2000[d]. Of the additional 18 events, only 4 are listed as having involved the RPV itself, and again only the Turkey Point-4 and Salem-2 events in 1987 resulted in actual wastage of the RPV head, and none involved wastage in the CRDM nozzle crevice as found at Davis-Besse.

The section addressing stress corrosion cracking of Alloy 600 materials was expanded to incorporate more recent plant experiences of this type. Whereas the 1995 report described only the 1987 ANO-2 pressurizer carbon steel head corrosion caused by leakage from a cracked Alloy 600 heater sleeve (see Section 6.1.2 below), the 2001 revision to the report added a number additional events of leaking through wall cracks[14]:

- Cracking and leakage in pressurizer and hot leg piping instrument nozzles at numerous CE plants, where it was noted that "in none of the cases has there been any significant corrosion of the pressure boundary base metal."

- A cracked and leaking nozzle safe end weld at V.C. Summer in 2000, where it was reported that "there was some visible evidence of boric acid corrosion on the carbon steel nozzle material, but it was not measurable."

- A cracked and leaking CRDM nozzle weld at Oconee-1 in 2000, where it was reported that the quantity of boric acid accumulated on the RPV head was about 0.5 cubic inch, but that "there was no evidence of boric acid corrosion."

- Several cracked and leaking CRDM nozzle welds at Oconee-3 in 2001, where "leakage was detected from the annulus between several CRDM nozzles and the reactor vessel head" from boric acid deposits but that "no corrosion of the low-alloy vessel head material was detected."

The rationale given in the 2001 revision to the EPRI Boric Acid Corrosion Guidebook for the "general lack of significant corrosion damage" at these leaking nozzles was identical to that given six years previously in the 1995 version, i.e. a combination of very small leak rates, little oxygen in the crevice, and rapid evaporation of the leakage due to the hot metal surface[15]. It was noted in the section of the revised Guidebook dealing with leaking CRDM flanges in B&W plants that the Oconee-1 and Oconee-3 CRDM

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[d] As for the 1995 edition of the EPRI Boric Acid Corrosion Guidebook, only two non-US events are included, again both for the Beznau-1 plant in Switzerland in 1969 and 1973.

nozzle leaks “would not have been detected had there been significant boric acid residue on the vessel head.”[16]

Thus, even as late as November 2001, the industry consensus was that leaks from cracked CRDM and other nozzles did not pose any risk of significant wastage of the RPV head.

6.1.2 Boric Acid Corrosion of RPV and Pressurizer Heads Prior to the 2002 Davis-Besse Event

Prior to the discovery of the wastage cavity at CRDM Nozzle 3 at Davis-Besse in 2002, we are aware of only three reported and isolated instances of wastage of the RPV head caused by boric acid leakage. In all three of these wastage events, the wastage was caused by boric acid dripping onto the RPV head from leaks in instrument connections above the head. In one further relevant event, minor wastage of the lower head of the pressurizer at the ANO-2 CE plant occurred due to boric acid leakage from a cracked Alloy 600 heater sleeve. None of these minor events involved a situation similar to what occurred at Davis-Besse.

The following are brief summaries of these four events based on published reports and information.

Beznau-1, 1970: A canopy seal weld leak caused containment air cooler fouling, and two months later RPV head wastage was found. The wastage area was 2 inches (40mm) wide by 1.6 inches (40mm) deep, and the estimated leak rate was 0.02 gpm[17]. MRP-110 reports that this leak resulted in the accumulation of 35 to 70 cubic feet (1 to 2 cubic meter) of boric acid on the RPV head, and that the wastage area under this boric acid accumulation had a maximum depth of 1.6 inches[18]. MRP-110 further notes that “the volume of boric acid deposits reported for the Beznau incident indicates a leak rate during the corrosion progression likely greater than 0.1 gpm[e].

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[e] The volume of boric acid accumulated as a result of the 2 month leak during the 1970 Beznau-1event cited in the MRP-110 report converts into 3150 to 6300 lbs of boric acid using a density of 0.052 lbs/cubic inch. This is an astounding quantity for the cited leak rate of 0.02 to 0.1 gpm. According to Figure 7-5 of MRP-110, even a 0.1 gpm leak would have to persist for a full 18 month fuel cycle to

Turkey Point-4, 1987: Prior to the 2002 Davis-Besse incident, this was the most significant boric acid wastage event associated with leakage in the RPV head area. Descriptions are presented in a number of reports, the most detailed being the 1988 EPRI report on boric acid corrosion of carbon steel components in nuclear plants[19].

As described in the EPRI report, boric acid crystal deposits were first noted on the RPV head during an outage in August 1986. The origin of this accumulation was determined to be from a “small leak” from a Conoseal joint leak on thermocouple Nozzle 53. No specific leak rate was reported at that time, although the description of this event in a December 1990 B&W report states that the Conoseal leak rate was believed to be an “insignificant fraction” of the prevailing 0.45 gpm total RCS unidentified leak rate[20].

During a second outage in October 1986 unrelated to this leak, an accumulation of about one cubic foot (approximately 60-80 lbs) of boric acid deposits was found and removed, but the leakage was judged to be acceptable for continued operation for a six-month period. By the time of the next shutdown on March 13, 1987, over 500 lbs of boric acid crystals had accumulated on the RPV head, and the leakage had run down the head, past the vent shroud support ring, as far as the head closure flange, studs and nuts.

After the boric acid deposits were removed and the head was cleaned, two general areas of wastage of the RPV head were noted. The first was on the RPV closure flange where two small areas of wastage of less than 4 sq. inches were found with a maximum depth of 1/16 inch around several closure head studs[21]. Three of the closure studs had experienced wastage to the point where they had to be replaced, as had several other carbon steel components in the path of the leakage flow, such as components of the instrumentation assembly itself, and a section of the vent shroud[22].

The second area of RPV head wastage was a “boomerang-shaped” area over 8 inches long with a maximum depth of 0.25 inches close to the penetration 53[23]. Evaluation showed that the RPV head wastage was acceptable because the minimum remaining

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result in the cited accumulation. We have not been able to resolve this discrepancy, but clearly the 1970 Beznau-1 event did deposit a significant volume of boric acid on the RPV head, possibly well in excess of the 500 lbs estimated for the 1987 Turkey Point-4 event, the 900 to 1200 lbs for the 1987 Salem-2 event, and the 900 lbs for the 2002 Davis-Besse event.

thickness of the head was in excess of minimum ASME Code requirements in both areas. Figure 6-1 (from the 1990 EPRI report) shows the areas of wastage of the RPV head and associated carbon steel components resulting from this event.

This event was also described in the June 1990 NRC/BNL report on boric acid corrosion of carbon steel components in nuclear plants[24], and more specifically in NRC Information Notice (IN) 86-108 Supplement 1, which was issued on April 20, 1987 to all operating PWR plants to advise them of the potential for small boric acid leaks to cause wastage of the RPV head and other carbon steel components[25]. This Information Notice also noted that the leak was a fraction (less than 0.25 gpm) of the total RCS unidentified leakage of around 0.45 gpm.

The most significant observation from this event was that despite the act that the leak was allowed to continue for over seven months and 500 lbs of solid boric acid was allowed to accumulate on the RPV head, the resultant head wastage was insignificant, requiring no repairs to the RPV head.

Salem-2 1987: Later that year, during an unplanned shutdown on August 7, 1987 to investigate a suspected RCS leak, boric acid crystals were found on a joint seam in the ventilation system cowling around the RPV head area. Removal of the cowling revealed a “rust covered pile of boric acid” 3 feet by 5 feet by 1 foot in height (900 to 1200 lbs) on the RPV head, as well as a “thin film of white boric acid residue” in several areas of the head as well as 1 to 2 feet up some of the CRDM nozzles.

The leak was determined to be from three pinhole leaks in a seal weld at the base of a Conoseal connection on thermocouple nozzle assembly. Nine corrosion “pits” were found on the RPV head underneath the boric acid deposit, these pitted areas were 1 inch to 3 inches in diameter with a maximum depth of 0.4 inches. Evaluation showed that the head thickness in this area still met the ASME Code requirements. The estimated leak rate was not reported in this case. This event is described in the 1988 EPRI report[26], the 1990 NRC/BNL report[27], and in the second Supplement to NRC Information Notice 86-108 that was issued on November 19, 1987[28].

As for the earlier Turkey Point-4 event, the most significant observation from this event at Salem-2 was that despite the fact that the leak had obviously existed for some period of time resulting in a large (over 900 lbs) accumulation of boric acid on the RPV head, the resultant head wastage was again minimal.

ANO-2 1987: One additional relevant instance of carbon steel vessel head wastage due to leaking boric acid should be mentioned here. At the CE ANO-2 plant in April 1987, leakage of boric acid at a rate estimated to have been around 0.002 gpm (60 drops per minute) occurred from a downward facing cracked Alloy 600 heater sleeve in the lower head of the pressurizer[29]. The leak had not been detected at an outage in October 1986, and so had existed for no more than six months. Although this leakage was well below the detectable limits for RCS pressure boundary leakage, it resulted in a wastage area at the nozzle exit of approximately 1.5 inches in diameter by 0.75 inches deep on the outside head surface. This plant experience prompted the CE tests of boric acid wastage for the pressurizer nozzle configuration that we discuss below in Section 6.3.1.

Other Pressurizer Shell Wastage: At the 1991 EPRI PWSCC workshop, there were two instances of pressurizer shell wastage mentioned. The first was buried in the extensive discussions and presentations concerning the Calvert Cliffs pressurizer heater Alloy 600 nozzle cracking problem, where it was reported that[30]:

> "There was very little corrosion (<0.03 inches (<0.76 mm)) on the inside of the hole in the pressurizer shell opposite the crack."

This implies some very minor wastage deep in the annulus near the crack due to boric acid leakage, but we have found no further discussion of this observation, either in the workshop proceedings or in the several utility and CE presentations related to the Calvert Cliffs problem.

The second was a note in the "Introduction and Update" to the 1991 workshop proceedings that subsequent to the actual workshop, with respect to San Onofre-3 that[31]:

> “In early 1992, boric acid deposits and indications of corrosion were found on the pressurizer shell near one of the vapor space nozzles which had been replaced in 1987….”

There is no additional information reported at the 1991 workshop concerning this reported finding, but it is implied in the above statement that whatever wastage was found was on the external surface of the shell, and not in any crevice that may have been present at the nozzle.

Other than the above, we have found little additional information concerning wastage of the carbon steel shell of the pressurizer as a result of cracked and leaking Alloy 600 heater sleeves and other pressurizer nozzles at CE plants, other than the ANO-2, Calvert Cliffs-2, and San Onofre-3 experiences described above.

The NRC “Lessons Learned Task Force” report on the Davis-Besse RPV head wastage event does briefly note that pressurizer vessel carbon steel wastage occurred at ANO-2, San Onofre-2, San Onofre-3, and Calvert Cliffs-2 (all CE plants) as a result of Alloy 600 heater sleeve cracking and boric acid leakage[32], but we have found no information about the San Onofre-2 event, and only the information discussed above for the other occurrences of wastage in these CE plants.

6.2 NRC Regulatory and US Industry Responses to Boric Acid Corrosion Issues 1980-2001

Between 1979 and 1988, the US NRC issued five Information Notices (INs) and one Bulletin to disseminate information concerning significant US plant events where boric acid corrosion of carbon steel components had been reported:

IN 80-27: This was issued on June 11, 1980[33] to describe the corrosion that occurred on reactor coolant pump casing closure studs at the Fort Calhoun-1 CE plant. Wastage of approximately 50% of the diameter of some of these low alloy carbon steel studs had occurred.

IN 82-06: This was issued on March 12, 1982[34] to describe failure due to boric acid wastage of 6 out of 20 studs on a steam generator manway at the CE Maine Yankee plant.

Bulletin 82-02: This was issued on March 12, 1982[35] to summarize the occurrences of boric acid wastage of threaded studs and fasteners that had occurred to that point in time, including the Fort Calhoun-1 and Maine Yankee events described in Information Notices 80-27 and 82-06. NRC staff review of operating experience had resulted in the identification of 44 incidents of degradation of threaded fasteners since 1964, with 15 of these from 1977 on being related to reactor coolant pressure boundary degradation. Amongst the actions required by the NRC Bulletin were the development and implementation of plant level procedures for the correct installation of bolted fasteners to eliminate leakage, identification by each plant of bolted closures where leakage and/or degradation had been observed, and the results of examinations performed on any leaking and/or degraded fasteners.

IN 86-108: This was issued on December 29, 1986[36] to describe the discovery in October 1986 of severe wastage (75% through wall) of a carbon steel high-pressure injection nozzle and associated wastage on the cold leg main coolant piping at the B&W ANO-1 plant. This had been caused by a leak from a high-pressure injection valve of approximately 0.8 to 0.9 gpm that had persisted for around 6 months during the time period from August 1985 through February 1986. A similar but less severe cold leg main coolant piping wastage event at the CE Calvert Cliffs-2 plant in 1981 was also described.

IN 86-108 Supplement 1: This was issued on April 20, 1987[37] to describe the Turkey Point RPV head wastage that was discovered on March 13, 1987, that we previously described in some detail in Section 6.1.2.

IN 86-108 Supplement 2: This was issued on November 19, 1987[38] to describe both the Salem-2 RPV head wastage that was discovered on August 7, 1987 (see Section 6.1.2 again), and an event at the San Onofre-2 plant in August 1987 where the packing hold down bolts failed due to boric acid wastage and the consequential ejection of the valve packing resulted in a major coolant release into the containment building.

Supplement 2 to IN 86-108 also contained a report of corrosion tests by Westinghouse that showed boric acid corrosion rates of up to 400 mils/month (4.8 inches/year) in both immersion tests of carbon steel in aerated boric acid solutions at 200 deg. F, and in tests where 15% boric acid at 200 deg. F was dripped onto carbon steel surfaces at 210 deg. F. With respect to testing of the CRDM geometry, it was reported that[39]:

> "In one series of Westinghouse tests relating to leakage of boric acid, a mock up of the Inconel CRDM head weld with a typical crevice geometry was exposed to dripping 15% boric acid at 210 deg. F. Extensive general corrosion of the steel occurred (to approximately 400 mils/month) but there was no preferential attack in the crevice of the on the Inconel."

Thus, the potential for crevice corrosion in the RPV head around leaking CRDM nozzles was again de-emphasized to the industry and PWR operators.

Faced with the mounting number of events involving boric acid wastage and degradation of RCS pressure boundary components that are described in Section 6.1 above, the NRC issued Generic Letter (GL) 88-05 on March 17, 1988 to address this issue and to require action by operators of US PWR plants[40].

This was a significant milestone in addressing boric acid wastage of carbon steel components (including RPV heads), since the actions taken by the industry to respond to GL 88-05 included the development and implementation of procedures for detecting boric acid leakage from primary system components that were later proposed by the industry (and accepted by the NRC) as being the primary means of detecting cracked and leaking CRDM nozzles.

GL 88-05 provided an overview of the 1987 Turkey Point-4 and Salem-2 RPV head wastage events, the 1987 San Onofre-2 and 1980 Fort Calhoun bolting failures, and the 1986 ANO-1 piping wastage, all of which had been previously described in the NRC INs and Bulletin discussed above.

GL 88-05 required PWR licensees todevelop and implement programs to ensure that:

> "…boric acid corrosion does not lead to degradation of the assurance that the reactor coolant pressure boundary will have an extremely low probability of abnormal leakage, rapidly propagating failure, or gross rupture."

The program was to include the following elements:

- Determination of locations where boric acid leaks could cause degradation of the primary pressure boundary and/or where conditions could exist that could result in high concentrations of boric acid;
- Procedures for locating small leaks of reactor coolant;
- Methods for conducting examinations and performing engineering evaluations to establish the impact on the reactor coolant pressure boundary when leakage was located, as well as the collection of evidence before boric acid deposits were removed.
- Corrective actions such as modifications to equipment and operating procedures to prevent recurrences of boric acid corrosion.

In January 1990, the NRC published the results of a review by BNL of the actions taken and programs implemented by 50 licensees in response to GL 88-05[41]. Section 2 of this NRC report reviews the more important plant experiences with boric acid corrosion of carbon steel components through 1988, and continues with a brief discussion of corrosion mechanisms and laboratory tests of boric acid corrosion rates (see Section 6.1.1 of this report)

The NRC report continues with a summary of the NRC efforts to address the problem of boric acid corrosion, which covers the various Information Notices and Bulletins issued between 1980 and 1988 that we discussed above[42]. The responses of 41 PWR licensees to NRC Bulletin 82-02 were evaluated by the NRC and closed out by May 1985 through the issuance of an NRC report[43]. Likewise, the responses of 50 PWR licensees to NRC Bulletin 88-05 were evaluated by the NRC, and “all were found satisfactory and met the intent of the Generic Letter.”[44]

The NRC report then describes the industry efforts to address the issue in a coordinated manner through EPRI sponsored programs, which were disseminated by means of reports and seminars[45]. Much of the EPRI work described in the NRC/BNL report was focused on the bolting and fastener wastage issues, which, as we discussed in section 6.1.1, had dominated the plant experience to that point in time.

BNL and NRC personnel selected ten plants as candidates for joint audit by means of site visits in 1989. The NRC report concludes that “all of the audited licensees satisfactorily addressed the four specified requirements of Generic Letter 88-05,” but that it would be prudent for “NRC resident inspectors to verify (at their plants) that a “documented and auditable program complying with Generic Letter 88-05 is in effect at each U.S. PWR plant.”[46]

At Davis-Besse, the GL 88-05 requirement for a boric acid corrosion control program was met through the development and implementation of boric acid leakage monitoring in accordance with plant procedure NG-EN-00324, which we review in Section 7.1.1. We note here that Toledo Edison, the licensee of the Davis-Besse plant at the time, submitted this procedure to the NRC in September 1989[47], and the NRC closed out this response by Toledo Edison to GL 88-05.

As part of the response to GL 88-05 by the BWOG, B&W also reviewed the Toledo Edison procedure, along with the procedures submitted to the NRC by other B&W plant licensees. B&W concluded that “each of these procedures has a good approach to reducing the degree of leakage and resulting corrosive damage.”[48]

According to the NRC’s September 2002 Lessons Learned Task Force (LLTF) report on the Davis-Besse event, one of the ten plants where the BNL/NRC team audited boric acid corrosion control programs in 1989 was in fact the Davis-Besse plant. While the LLTF report notes that the Davis-Besse boric acid control program was determined to be "satisfactory" in the 1989 audit by BNL/NRC, it also concludes (with the benefit of hindsight) that the program was in need of improvement[49].

The LLTF report notes that the NRC developed its own procedure[f] in August 1991 to evaluate the effectiveness of PWR licensees' boric acid corrosion control programs and their compliance with the requirements of GL 88-05. The apparent intent of the procedure was to provide guidance to NRC resident inspectors in their evaluation of the effectiveness of PWR licensees' boric acid corrosion control programs, and their compliance with the requirements of GL 88-05[50]. 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[51].

Subsequent to the issuance of GL 88-05, the industry implementation of the required programs and procedures, and the NRC's review and endorsement of the industry and licensee responses, the industry's attention was focused on the potential problem of CRDM nozzle cracking by the discovery of the first such instance of this cracking at Bugey-3 in 1991. The subsequent analysis of the CRDM cracking issue throughout the 1990s, first by the various Owners Groups and later by the EPRI MRP, all relied on the procedures and programs implemented by PWR operators in response to GL 88-05 in order to detect boric acid leakage from CRDM nozzle cracks.

We discussed the industry effort to respond to the issue of CRDM nozzle cracking in detail in Sections 5.3.2 and 5.3.4 of this report, and as we pointed out there, the Owners' Group (BWOG, WOG, CEOG) work and the follow-on EPRI MRP work was focused largely on the potential safety issues posed by nozzle cracking and failure. While the potential for RPV head wastage corrosion was not ignored by the industry, owner's group or the regulator, it was not given significant attention. Prior to the Davis-Besse experience, it was not known that a critical crack size can lead to serious and rapid boric acid corrosion of the RPV head. This critical crack size for RPV head wastage is much

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[f] NRC Inspection Procedure IP 62001, "Boric Acid Corrosion Prevention Program."

less than the critical crack size at which nozzle failure by circumferential cracking is likely to occur.

6.3 Boric Acid Corrosion Research and Testing Prior to 2002

The initial EPRI 1995 Boric Acid Corrosion Guidebook contains a comprehensive summary of the available boric acid corrosion research and testing that had been conducted to that point in time, and the 2001 revision to the Guidebook summarizes the additional corrosion research and test work between 1995 and 2000.

Since much of it is relevant to the corrosion rates one might expect as boric acid leakage concentrates on hot metal surfaces, we first review and summarize the large body of work reported by EPRI that was conducted using drip, immersion and impingement test set-ups in section 6.3.1 below. We follow this in section 6.3.2 with a more detailed discussion of the testing conducted by CE and EPRI where test set-ups more representative of the CRDM nozzle crevice geometry were utilized.

6.3.1 Non-Crevice Geometry Boric Acid Corrosion Testing

The 1995 EPRI Boric Acid Corrosion Guidebook reports the results of 13 different corrosion test programs conducted over the years prior to the report to measure corrosion rates of carbon and low alloy steels in boric acid solutions. The test programs were conducted by various organizations including Westinghouse, CE, B&W, BNL, Tennessee Valley Authority (TVA), and the Moscow Power Institute in Russia. The test programs covered a range of boric acid conditions as well as test configurations, and they were broken down in the EPRI Guidebook into five different basic conditions and/or configurations[52]:

- Immersion tests in de-aerated water containing boric acid at various concentrations and temperatures;
- Immersion tests in aerated water containing boric acid at various concentrations and temperatures;

- Tests in which water containing boric acid at various concentrations and temperatures was dripped onto hot metal surfaces;

- Impingement tests where a jet of water containing boric acid at various concentrations and temperatures was directed onto hot metal surfaces; and

- Tests where water containing boric acid at various concentrations and temperatures was injected through cracked alloy tubes into tight crevices in carbon steel blocks at various temperatures.

Figure 6-3, taken from the 1995 EPRI Guidebook, illustrates the various test program configurations and conditions.

All but one of the tests reported in the 1995 EPRI Guidebook fell into the first four categories. The one test of a crevice configuration reported in the 1995 Guidebook is discussed separately in Section 6.3.2 below.

Details of twelve additional boric acid corrosion test programs are provided in the 1995 EPRI Guidebook. Here we summarize the key results of these tests to provide some perspective on the range of carbon steel corrosion rates measured in the various programs:

- For immersion tests in de-aerated water containing boric acid, the measured corrosion rates were generally very low regardless of boric acid concentration or temperature.

- For immersion tests in aerated water containing boric acid, the corrosion rates were much higher than in the de-aerated tests, ranging from low rates at low (room) temperatures, but reaching up to a very high rate of 7.5 inches/year in concentrated boric acid solutions at 220 deg. F.

- For tests in which water containing boric acid was dripped onto hot metal surfaces (up to approximately 600 deg. F), the corrosion rates were high and generally in the range of 2 to 5 inches/year, with the highest rate measured at 7.8 inches/year. The corrosion rate was highest in tests where the flow rate was high enough to concentrate boric acid and reduce the metal temperature to the 200 to 300 deg. F range, and occurred at the interface between the wetted metal surfaces where boric acid crystals formed as the water evaporated. These high corrosion rates were consistent with immersion tests in aerated solutions at comparable concentrations and temperatures. The lowest corrosion rates in these drip tests were measured for low flow rates and high metal temperatures where the water evaporated quickly, leaving non-corrosive dry boric acid deposits.

- For tests in which water containing boric acid was allowed to impinge as a jet onto hot metal surfaces, the corrosion rates were again very high, ranging from about 0.2 inches/year all the way up to a maximum of 11.1 inches/year. In these tests borated water at 600 deg. F was forced through a capillary tube to impinge on a flat carbon steel plate that was heated to 650 deg. F in some tests and unheated in others. The highest corrosion/erosion rate of 11.1 inches/year was measured at the impingement location in a test where the "target" plate was 0.5 inches from the capillary jet. Moving the target plate out to 2 inches away from the capillary jet reduced the corrosion/erosion rate to a maximum of 3.9 inches/year. Away from the impingement location, the measured corrosion rates were 0.4 to 0.6 inches/year.

The common feature of these test results that is relevant to the Davis-Besse event is that the maximum corrosion rates of up to almost 8 inches/year were measured in immersion tests where concentrated boric acid solutions at 200 to 230 deg. F were used, as well as in drip and impingement tests where the flow rate of water containing boric acid was high enough to allow both concentration of the boric acid on the hot metal surface and localized cooling of the metal surface to the 200 to 230 deg. F range. The added effect of material removal by an impinging jet can increase this already high wastage rate to over 11 inches/year.

A useful presentation of all of the results summarized above is provided in Figure 6.4, which is taken from the 2001 Revision to the EPRI Boric Acid Corrosion Guidebook[53]. The tests reported in the 1995 Guidebook are labeled A through M in this figure, with additional tests in the five categories conducted for EPRI by SWRI between 1996 and 1998 being labeled EPRI-1 through EPRI-7[54].

Prior to their publication in the EPRI Boric Acid Corrosion Guidebook in 1995, some of the tests programs conducted by B&W on behalf of the BWOG were provided directly to the BWOG members (including Toledo Edison, the licensee of the Davis-Besse plant at the time) in detailed reports in 1990[55] and 1994[56]. While the focus of the two reports was on the B&W test programs, they also include a survey of other available industry test data on boric acid corrosion of carbon steel.

In these B&W tests, water containing boric acid was dripped onto hot metal surfaces. The measured wastage rates were not sensitive to either the flow rate (in the range of low flow rates used) or the initial boric acid concentration. The highest levels of corrosion (up to 5.1 inches/year) were measured at the interface between the flowing coolant and the dry boric acid crystals at metal temperatures of 300 to 350 deg. F, where dry boric acid crystals were continually being re-wetted by the boric acid solution. Rust-colored deposits were observed wherever carbon steel corrosion occurred. Lower wastage rates (1.3 to 4.1 inches/year) were measured as metal temperatures were increased to 500 deg. F, and above 530 deg. F, wastage rates were minimal and a “glassy residue” was observed on the steel[57]. Although the results of these tests are included in the composite Figure 6-4 (tests I and J), Figure 6.5 is included here to show the clear temperature dependency.

These B&W tests showed that at high metal temperature where wetting of dry boric acid deposits could not take place, there was minimal to no wastage. This was an important result, since it confirmed the prevailing view that dry boric acid deposits on the RPV head did not pose any risk of wastage.

6.3.2 Crevice Geometry Boric Acid Corrosion Testing Prior to 2002

CE presented the results of this first test of a leaking nozzle/crevice geometry at the 1991 EPRI PWSCC workshop[58]. It was included as the only test of a leaking nozzle in a crevice configuration in the 1995 EPRI Boric Acid Corrosion Guidebook[59], and was also likewise included in the 2001 Revision to the Guidebook[60].

This test program was conducted by CE in 1991 as part of the investigation into the observed corrosion at the cracked Alloy 600 pressurizer heater sleeve at ANO-2 in 1987[g]. The test configuration is shown in Figure 6.6, and was such that the nozzle faced down (with the weld at the top and the crevice exit at the bottom) to simulate a nozzle in the bottom head of a pressurizer[61].

In this CE test, the tube was a thin-walled Alloy 600 steam generator tube that had an actual through-wall crack[62]. The tube was inserted into a heated (600 to 650 deg. F) low alloy steel block with an annular clearance gap of between 0.002 and 0.008 inches (2 to 8 mils). Primary water at 600 deg. F containing boric acid (1000 ppm as boron) was supplied to the inside of the tube and leaked into the annulus at a rate of between 0.002 and 0.05 gpm. The test results reported by EPRI in the 1995/2001 Guidebooks were conducted for time periods from 12 to 27 days[63]. Table 6-1 presents the summary of some of the CE test results as presented in the 1995/2001 EPRI Guidebooks.

The key observations from these CE crevice tests were as follows[64]:

- The location of maximum wastage was at the exit (bottom) of the annulus rather than at the point where fluid exited the crack in the Alloy tube. This is shown in Figure 6.7, which is an “unfolded” view of the alloy steel crevice surface[65]. This was hypothesized to have occurred because the oxygen level was low deep in the crevice and

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[g] See Section 6.1.2 for a description of this event.

high at the crevice exit. The 2001 EPRI Guidebook summary notes that the location of maximum wastage at the annulus exit was "at a point that is typically available for visual inspection".

- Wastage rates increased as leak flow decreased. Again this was attributed to lower oxygen concentrations as the higher flow rates purged air from the annulus.

- Leak rates decreased with time, an observation attributed to the annulus becoming plugged with boric acid deposits.

- Maximum wastage rates of 0.64 to 2.15 inches/year were measured, localized both axially at the crevice exit and circumferentially (see Figure 6-7). The maximum wastage rate was noted to be equivalent to a material volume loss of 1.07 cubic inches/year.

This last observation is important, because it formed the sole foundation for the wastage assessment due to boric acid leakage from CRDM cracks, which was an integral part of the safety evaluation for CRDM nozzle cracking performed by B&W for the BWOG in 1993 that we discussed in detail in Section 5.3.2 of this report.

The EPRI Boric Acid Corrosion Guidebook (both the 2001 revision and the earlier 1995 version) notes that[66]":

> "The volume loss is not necessarily conservative because the exposed area increases as the corrosion depth increases and the rate of volume loss may also increase."

Notwithstanding this important caveat, the maximum 1.07 cubic inch/year material volume loss was adopted in the 1993 B&W safety analysis as a "worst case" scenario, accepted by the NRC in its 1993 safety evaluation of the BWOG safety assessment, continued in the 1997 BWOG response to GL 07-01 where the earlier 1993 B&W analysis was adopted without change, and was again accepted by the NRC in its close-out of that response. We repeat our earlier comment (in Section 5.3.2) here that the extrapolation of this short term test material volume loss rate to the event at Davis-Besse is not appropriate, since it would have taken around 200 years for the 195 cubic inch wastage cavity at Davis-Besse CRDM Nozzle 3 to develop at this rate.

A second crevice test conducted by SWRI for EPRI in 1998 was reported in the 2001 Revision to the EPRI Boric Acid Corrosion Guidebook[67]. As shown in Figure 6.8, the configuration in this test program had an upward facing nozzle (with the weld at the bottom and the annular crevice exit at the top) to simulate the orientation of RPV upper head nozzles such as CRDMs[68].

In the EPRI test program, high temperature water at 600 deg. F containing boric acid (2000 ppm boron) was injected through a nozzle at flow rates of 0.01 and 0.1 gpm into an annular gap of 0.005 inch (5 mil) around a 1.21 inch OD stainless steel insert in a low alloy steel block that was heated to 600 deg. F[69]. Note that the injected flow in these tests impinges on the OD of the cylindrical insert, which is different from the real situation (and the CE test) where the leakage is from the inside of the nozzle tube and impinges on the low alloy steel wall of the annulus. The tests were reportedly run for 50 days[70].

Table 6-2 presents the summary of some of the EPRI test results presented in the 2001 EPRI Guidebook[71]. The maximum wastage rates observed in the EPRI tests of 0.89 to 2.37 inches/year were comparable to those observed in the earlier CE tests, and the trend of increasing maximum wastage rate with decreasing leak rate is evident in the EPRI test results similar to the CE test results, as shown in Figure 6-9.[72]

The key difference in the EPRI tests was that the maximum wastage was always observed to have occurred deep within the annulus near the point of injection, in contrast to the CE test where the maximum wastage was observed at the annulus exit[73]. The location of the wastage in the EPRI tests can clearly be seen in Figure 6-10[74], which shows one of the EPRI steel test blocks after sectioning to view the two halves of the annulus and permit wastage measurements[h]. The 2001 EPRI Guidebook offers a possible explanation for the difference in location of the observed wastage[75]:

> "The most likely explanation for the difference in results is the orientation of the nozzles. In the CE tests, the nozzles were oriented down, and in the EPRI tests, the nozzles were oriented up. It is possible that steam blanketing in the annulus for the case of the downward-facing nozzle explains the inability of oxygen to penetrate to the injection location. However, this hypothesis has not been validated by test"

The 2001 EPRI Guidebook states that greater ingress of oxygen in *both* tests was responsible for the higher wastage observed at lower leak flows, since as in the CE tests, the wastage rate in the EPRI tests were higher at the lower flow rate. Whether higher oxygen concentrations were responsible for the increased wastage in both the CE and EPRI tests at lower leakage flows or not, it did not change the location of the observed wastage.

We believe that the difference in wastage location is more likely to have resulted from the differences in test configurations such as gap clearance and method of leak injection, which could significantly affect the local fluid velocities, thermal hydraulic conditions, boric acid concentrations.

Finally, with respect to the location of the wastage deep in the crevice for the EPRI tests, the 2001 EPRI Boric Acid Corrosion Guidebook noted that the "corrosion occurring at this location would not be seen during a visual inspection of the vessel surface, although boric acid deposits on the metal surface would indicate that there has been a leak."[76]. There was no discussion of the volume of boric acid accumulation that might be expected from a small leak flow, nor of the potential to miss the small quantities of boric acid that would result from leakage through a CRDM nozzle crack in the event that there were boric acid leaks above the RPV head.

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[h] We note that the wastage in Figure 6-10 occurred preferentially on one half of the annulus, although we do not attach too much significance to this since it could for example be an artifact of the injection point being slightly off-center.

6.4 Recent Research on Boric Acid Corrosion of RPV Head Resulting from the Davis-Besse Event

Since the Davis-Besse event, both EPRI and the NRC have sponsored research into boric acid corrosion in crevice environments. These environments were selected to simulate the thermal hydraulic conditions that are thought to have been present in the nozzle annulus from the point in time where leakage first began from a crack that reached the top of the weld, through to the final large cavity that was found in March 2002. The replication of the conditions that produced the significant RPV head wastage near CRDM Nozzle 3 has proven to be a very difficult task. The multi-phase EPRI program has systematically developed environmental conditions similar to those that existed at operating conditions on the Davis-Besse RPV head in an attempt to understand the mechanisms that caused the rapid wastage. With significant resources expended to date, the EPRI program has been unsuccessful in replicating the wastage rates necessary to explain the formation of the Davis-Besse RPV cavity. Initial high-temperature, sub-scale impingement and corrosion tests have yielded material removal rates that would require hundreds of years to produce the Davis-Besse wastage cavity. Planned full-scale tests may be the only way to replicate the Davis-Besse event.

We discuss these recent tests, the relevance of the conditions they were designed to simulate, and the results available to date in Sections 6.4.1 and 6.4.2 below.

6.4.1 EPRI Boric Acid Corrosion Testing to Replicate the Davis-Besse RPV Head Wastage Event

Subsequent to the discovery of the large wastage cavity at Davis-Besse CRDM Nozzle 3, FENOC instituted a root cause investigation to document and analyze the Davis-Besse inspection findings and operational history, review industry experience with CRDM nozzle cracking and boric acid corrosion, and develop a root cause explanation for the wastage.[i]

FENOC's root cause report documents the results of this initial investigation[77]. In the section of the report where a description of the development of the wastage cavity is presented[78], the report comments that “it is not possible within current knowledge to definitively identify a progression of corrosion mechanisms”,[79] and notes that “further effort is ongoing to better define the corrosion rates based on the final measured size of the cavity and thermal-hydraulic modeling being performed by the MRP.”[80]

The root cause report goes on to provide a qualitative description that the root cause investigation team had developed of the sequence of four “stages” that were considered in the development of the initial wastage cavity Davis-Besse Nozzle 3 and its progression to the final state discovered in 2002.[81]

The EPRI MRP effort apparently adopted this probable sequence of stages, since an identical description is provided in the MRP “Statement of Work” for RPV head boric acid corrosion testing[82]. This descriptive document defines the scope for the MRP to develop an understanding of the various corrosion mechanisms that were thought to be involved, and for which experimental data was lacking.

The four stages are shown in Figure 6-11, and are described as follows:

- Stage 1: Stagnant/low flow, where the crack has just started leaking into the nozzle annulus and corrosion begins to enlarge the annulus;
- Stage 2: Single and two-phase flow develop as the crack grows longer, the leak flow increases, and various corrosion/erosion mechanisms are possible;
- Stage 3: Deep annulus corrosion/erosion as crack grows and leak flow increases to the point where localized cooling of the RPV head steel occurs, resulting in more aggressive corrosion from a concentrated, aerated boric acid solution; and
- Stage 4: Full scale general boric acid corrosion in a large wastage cavity filled by a concentrated boiling boric acid solution, and rapid wastage caused by a variety of corrosion/erosion mechanisms occurs.

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[i] We briefly discussed the development of the FENOC root cause report in Section 4.3.1.

We defer further discussion of the development and progression of the wastage cavity until Section 9 of this report, where we present the results of our modeling of the thermal hydraulic and corrosion/erosion conditions in the Nozzle 3 crevice and wastage cavity.

We note here only that the MRP qualitative description above does not explain a number of the features of the wastage cavities at Davis-Besse Nozzles 2 and 3, such as the lack of erosion/corrosion deep in the Nozzle 2 annulus where the leakage emerged from multiple cracks, the axial and circumferential location of the relatively minor wastage cavity at Nozzle 2, the transition from zero leakage to annulus enlargement, and the morphology of the large wastage cavity at Nozzle 3.

The initial results of this EPRI MRP corrosion testing program were presented at the conference in Fontevraud, France in July 2006[83]. The results of three "separate effect" experimental corrosion test programs designed to investigate the first three stages described above were presented, with testing of full scale mock-ups of CRDM nozzles and crevices still to be undertaken.

The Stage 1 testing was conducted with an Alloy 600 tube in an annular steel crevice, with simulated primary water solutions (2000 ppm boron, 3.5 ppm lithium), under both static and low flow (less than 0.005 gpm) conditions, and at temperatures ranging from 392 deg F to 536 deg F. Corrosion rates were found to be negligible, with a maximum corrosion rate of 0.005 inches/year (5 mils/year) being reported[84]. In our opinion, these rates are insufficient to explain how the annulus wastage process begins, and as discussed in Section 9.2, we are convinced that other mechanisms for annulus enlargement are involved that were not operable during these tests.

The Stage 2 testing consisted of impingement tests of short duration (typically 5 days), again using simulated primary water solutions (1500 ppm boron, 1.1 to 3.7 ppm lithium), at 2250 psi directed through an orifice at right angles to a steel target specimen. Orifice sizes ranged from 3.5 mils to 10 mils (0.09 mm to 0.26 mm), flow rates from 0.009 gpm to 0.05 gpm, jet velocities from 250 to 650 ft/sec, and the separation between the orifice and the specimen surface (termed "jet length") was typically 79 mils (2 mm or 0.079

inches)[j]. Average penetration rates ranging from 2 mm/year to 200 mm/year (0.08 to 7.9 inches/year) were measured in these short term 5 day tests, with the highest penetration rate of 200 mm/year being obtained with the highest jet velocity used of 140 meter/sec (460 ft/sec). Penetration rates were higher at higher velocities, but volumetric metal removal rates increased at higher volumetric flows despite the lower jet velocities at the higher flows[85]. We note that these penetration rates are comparable to the rates for impingement tests reported in the 1995/2001 EPRI Boric Acid Corrosion Guidebooks that we summarized in Section 6.3.1.

The Stage 3 testing consisted of autoclave tests of steel specimens immersed in simulated primary water solutions (from 2000 ppm boron up to a liquid slurry of saturated boric acid, with lithium/boron ratios of 0.002 to 0.05), at temperatures ranging from 212 to 600 deg F, with either oxygen or inert gas overpressures, and using a variety of configurations ranging from uncoupled (free), creviced (with Teflon), and galvanically coupled to Alloy 600.

Actual measured corrosion rates were presented as a “single effect of at-temperature pH”, which makes comparison with other published data difficult[86]. However, the plotted results range from very low rates of around 0.02 inches year at low pH up to a maximum of around 5 inches/year at high pH, and this is consistent with other data on corrosion rates in concentrated, aearated boric acid solutions reported in the 1995/2001 EPRI Boric Acid Corrosion Guidebooks that we summarized in Section 6.3.1.

In summary, while these initial results are a useful addition to the body of published data on boric acid erosion/corrosion rates, they do not provide much additional insight into the actual mechanisms by which the Davis-Besse wastage cavities developed over time. There is little information in the July 2006 Fontevraud presentation concerning the planned series of full scale mock-up tests. However, a recent NRC report describes the EPRI test program, and notes that the full scale mock-up tests will be designed to determine corrosion rates under representative nozzle leakage conditions including leak

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[j] We note that the orifice sizes used were large compared with typical PWSCC crack dimensions, and that the 79 mil separation between the orifice and the specimen in most of the tests was also large compared with initial nozzle annulus clearances.

rates ranging from 0.0001 to 0.3 gpm, controlled thermal conditions, full size nozzles, simulated crack geometries, and interference fits[87].

6.4.2 NRC/ANL Corrosion Test Programs to Replicate the Davis-Besse Wastage Conditions

Recognizing the unexpected and unanticipated nature of the Davis-Besse RPV head wastage, the NRC and ANL undertook a major corrosion test program to provide additional corrosion data over a wide range of temperatures and boric acid concentrations. The results of this test program were described in a report in July 2005[88].

In the foreword to the NRC/ANL report, the Director of the NRC's Office of Nuclear Reactor Regulation (NRR) noted[89]:

> "In the aftermath of the discovery of a corrosion cavity in the vessel head at the Davis-Besse Nuclear Power Station in March 2002, the U.S. Nuclear Regulatory Commission (NRC) renewed its effort to understand the mechanics and chemistry that occur during the corrosion process. Based on the results of corrosion testing over the preceding 15 or so years, the prevailing thinking at that time was that corrosion in an aqueous-based solution could not occur at an elevated temperature, because water would evaporate and dry boric acid salts were "known" to be non-corrosive. However, such thinking did not account for the corrosion rates that had prevailed on the Davis-Besse reactor head."

As previously stated, the "prevailing thinking" in the industry prior to the Davis-Besse event that any leakage of boric acid would not result in significant wastage of the RPV head. The NRR Director then describes how ongoing analysis of the Davis-Besse event had suggested one possible reason that the "prevailing thinking" before 2002 was erroneous[90]:

> As part of the investigation of the Davis-Besse reactor head corrosion event, industry analysts developed a model that suggested that the evaporative cooling effect would reduce the temperature of the pool of accumulating liquid to about 93 °C (200 °F) as the leak rate approached and exceeded about 0.4 liter (0.1

> gallon) per minute. This finding is important because this temperature is significantly cooler than assumed in earlier testing, and does not support the thinking that an aqueous-based boric acid solution would not exist because the water would evaporate.

In the "Executive Summary" of the NRC/ANL report, the NRC further acknowledged the "unanticipated" nature of the Davis-Besse RPV head wastage event[91]:

> Although cracking of Alloy 600 CRDM nozzles by primary water stress corrosion cracking (PWSCC) is a known degradation mechanism and has been observed at other nuclear power plants, damage of this magnitude to the RPV head caused by boric acid corrosion had not been anticipated….. At low leak rates (~10^{-6} to 10^{-5} gpm), the leaking flow completely vaporizes to steam immediately downstream from the principal flashing location resulting in a dry annulus and no loss of material. The Davis-Besse experience demonstrates that this is not always the case.

The introduction to the NRC/ANL report describes the qualitative scenario that the FENOC root cause investigation team had developed for the sequence of "stages" that were considered in the development of the wastage cavity at Davis-Besse Nozzle 3, and the progression of the cavity to the final state discovered in 2002. Noting the time limitations imposed on the root cause report analysis and the lack of supporting data for the major stages of the cavity development scenario described therein, the NRC/ANL report notes that[92]:

> "The Davis-Besse root cause report provides a scenario that attempts to explain the progression, but the differences between the Davis-Besse case and the other CRDM cracking instances are still unclear. The root cause report is incomplete in many regards, partially because much of the data necessary to support the hypotheses simply do not exist. Wastage of low-alloy steel in concentrated boric acid solutions is not well described or quantified in the literature, and especially not under the temperature, flow, and concentration of species that may have existed on the Davis-Besse head."

The NRC/ANL report then describes the rationale for the test program that was undertaken, as well as its relevance to the stages of corrosion/erosion and wastage cavity development[93]. Corrosion in three different sets of environmental conditions relevant to the various postulated "stages" of wastage in the CRDM annulus and subsequent cavity development were investigated:

- High-temperature, high-pressure aqueous environment with a range of boric acid solution concentrations, corresponding to the postulated condition of low leakage through the nozzle crack with the nozzle/head annulus plugged either by boric acid deposits or corrosion products.

- High-temperature 257 to 572 deg. F (150 to 300°C) boric acid powder and molten boric acid at atmospheric pressure with and without addition of water, corresponding to the postulated condition of low leakage through the nozzle crack and the nozzle/head annulus open.

- Both deaerated and aerated low-temperature concentrated boric acid solutions at approximately 203 deg. F (95°C), corresponding to the postulated condition where significant cooling is taking place due to high leakage through the nozzle crack with the nozzle/head annulus opened further by erosion and/or corrosion.

In the series of tests designed to investigate the first set of conditions, low alloy steel specimens were exposed to 4,000 ppm and 9,090 ppm boron (saturated solution at room temperature) at a pressure of 1800 psi and temperatures ranging from 212 to 601 deg. F. Measured corrosion rates increased with decreasing temperature from a low of around 0.005 inches/year at 601 deg. F up to 0.3 inches/year at 212 deg. F.[94] The results show that corrosion rates would be expected to be low if the annulus were plugged, but that with some build up of boric acid deposits and cooling in the annulus, increased corrosion and enlargement of the annulus could take place.

In the second series of tests, three dry or molten boric acid environments were first investigated, corresponding to the phase transitions that boric acid undergoes as temperature is increased and moisture is removed.

As boric acid (HBO_3) is heated, it first loses moisture and transforms into metaboric acid (HBO_2) at around 336 deg. F (169 deg. C). Metaboric acid melts at around 457 deg. F (236 deg. C), and as temperature is increased further and moisture is removed, transforms into dry boric oxide (B_2O_3) at around 572 deg. F (300 deg. C). Given the Davis-Besse RPV head temperature of 605 deg. F, all of these states are possible in the annular crevice environment depending on thermal hydraulic conditions such as leak flow rate, velocity, crevice dimensions, and heat transfer from the steel. In addition, it is evident that solid boric acid crystals deposited on the RPV head by evaporation of a primary coolant leak would eventually transform at least into metaboric acid, which would be molten at the head temperature.

The NRC/ANL test results show that negligible corrosion occurred either with a dry powder of boric acid/metaboric acid at 302 deg. F, with molten metaboric acid at 500 deg. F, or with dry powder of metaboric acid and boric oxide at 572 deg. F.[95] Based upon these results, the "prevailing thinking" prior to the Davis-Besse event that the high temperatures on the RPV head would lead to dry boric acid deposits that could not result in RPV head corrosion was icorrect.

However, further tests were run in which boric acid was first heated to 500 deg. F (260 deg. C) to obtain molten metaboric acid, and where water was then added to the melt. This resulted in cooling to between 302 deg. F (150 deg. C) and 338 deg F (170 deg. C) and very high corrosion rates up to 5.7 inches/year at the lower temperature[96]. As the NRC/ANL report points out, these were the first reported tests of carbon steel corrosion caused a re-wetted boric acid "melt", and the measured corrosion rates were comparable to the highest corrosion rates obtained in aerated concentrated boric acid in the 200 to 220 deg. F range[k].

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[k] The NRC/ANL test results of re-wetted molten metaboric acid provide quantitative support for the B&W qualitative "drip" tests reported by B&W (see Section 6.3.1) where the maximum corrosion was

The third series of tests were conducted in saturated (37,000 ppm boron) and half-saturated (18,500 ppm boron) in both deaerated and aerated low-temperature boric acid solutions at 208 deg F (97.5 deg. C). Corrosion rates measured in these tests were generally in agreement with other published data, with rates of up to about 5 inches /year being measured after the longest (411 hour) exposure times. Corrosion rates were generally higher at shorter exposure times; doubling the boric acid concentration roughly doubled the corrosion rate; and aerated solutions were more aggressive than deaearated solutions[97].

In summary, these recent NRC/ANL tests:

- Confirm the existing body of data on high wastage rates of carbon steel in aerated, concentrated boric acid solutions at low (208 deg. F) temperatures;
- Confirm that low wastage rates prevail in high temperature, high pressure boric acid solutions even when concentrated, but that moderate wastage rates are possible if the temperature is reduced by flashing;
- Confirm that dry solid boric acid in any of its forms is non-corrosive; and
- Provide new evidence that re-wetting of solid or molten boric acid deposits resulting in cooling to around 300 deg. F causes in high wastage rates of carbon steel.

We discuss these data further in Section 10, where we assess the possible corrosion rates at various points in the development of the wastage cavity at Davis-Besse Nozzle 3 under thermal hydraulic conditions developed in modeling work described in Section 9.

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observed at the interface between the aqueous solution and dry boric acid deposits where the deposits were alternately dry and wetted.

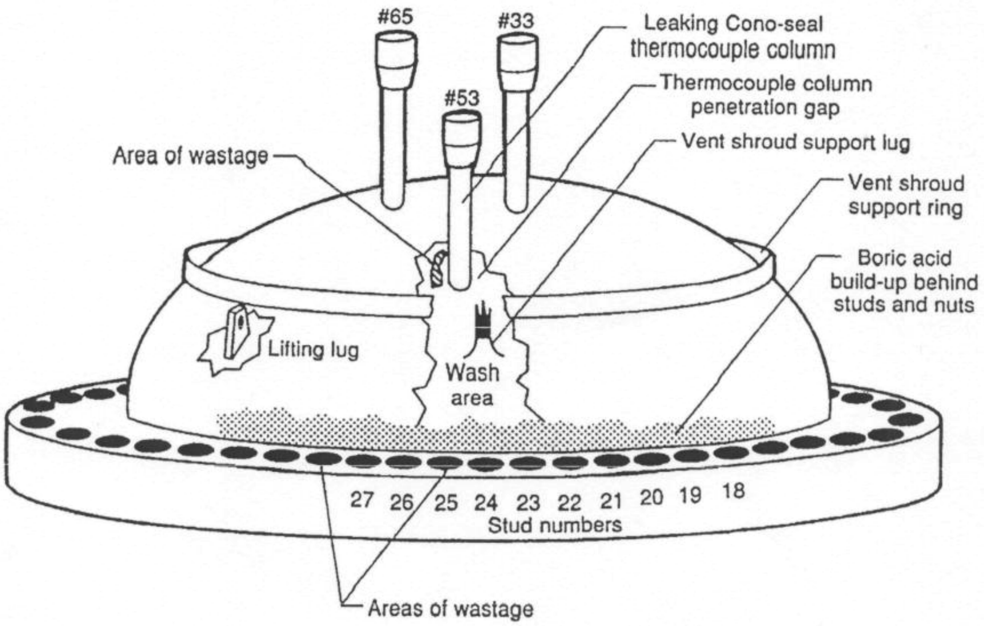


Figure 6.1 Areas on the RPV Head at Turkey Point-4 Affected by Boric Acid Wastage in 1987 (from EPRI Boric Acid Corrosion Guidebook, April 1995)

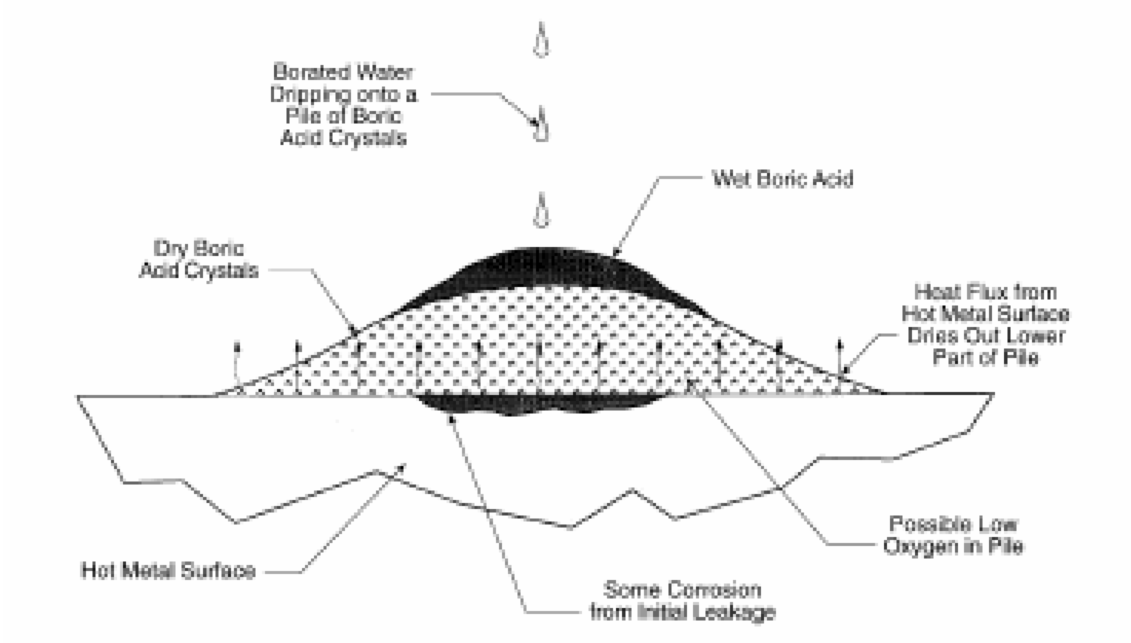
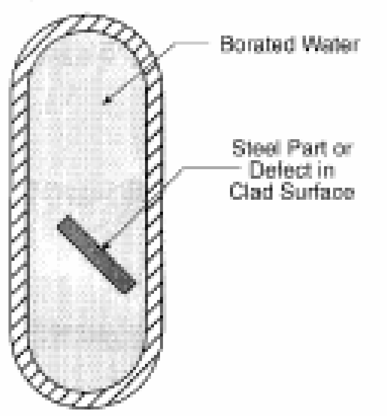
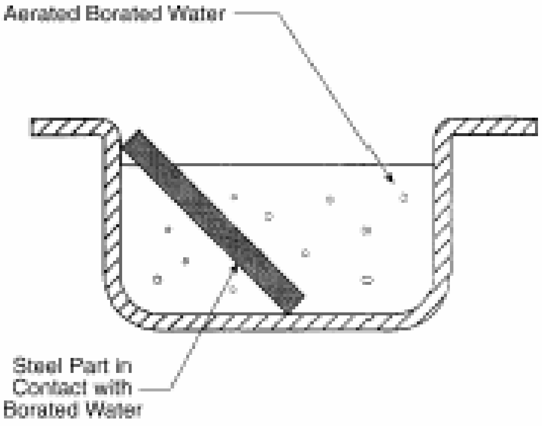


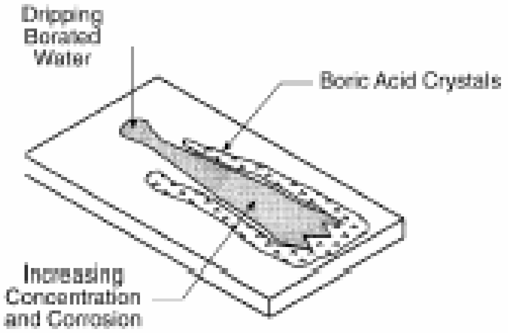
Figure 6.2 Effect of Boric Acid Deposits in Protecting Surfaces from Corrosion (from EPRI Boric Acid Corrosion Guidebook, April 1995)



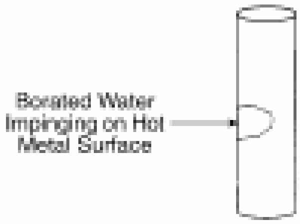
Immersion in Deaerated Water



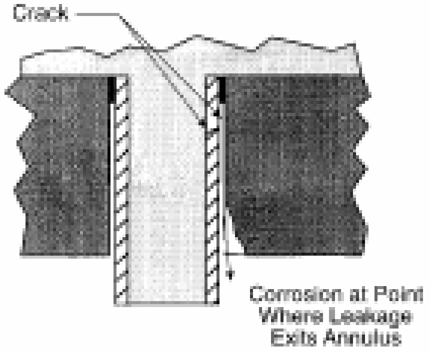
Immersion in Aerated Water



Dripping onto Hot Metal Surfaces



Impingement onto Hot Metal Surfaces



Leakage into Annular Gap

Figure 6.3 Boric Acid Corrosion Test Program Configurations and Conditions (from EPRI Boric Acid Corrosion Guidebook, April 1995)

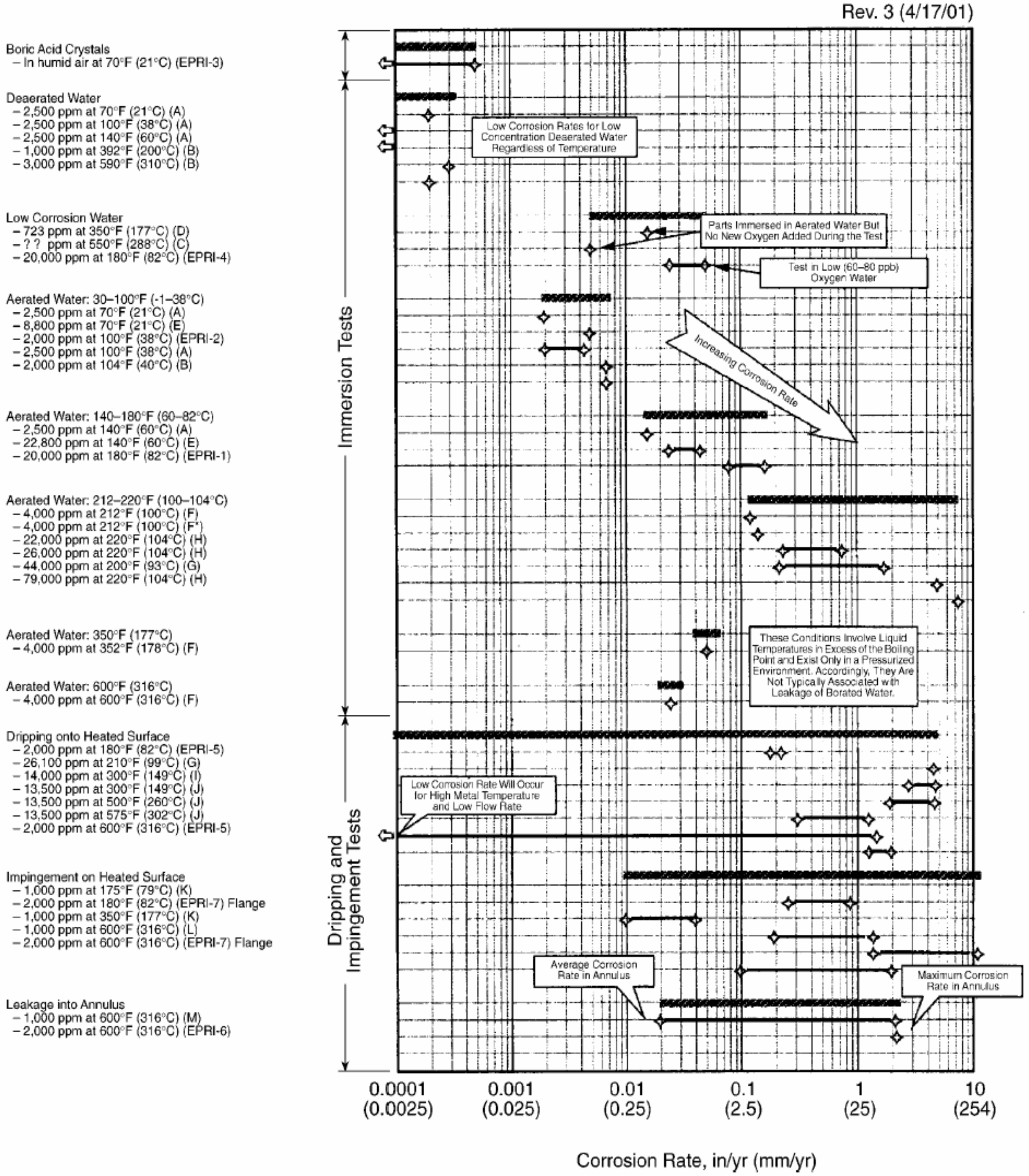


Figure 6.4 Summary of Boric Acid Corrosion Test Results (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)

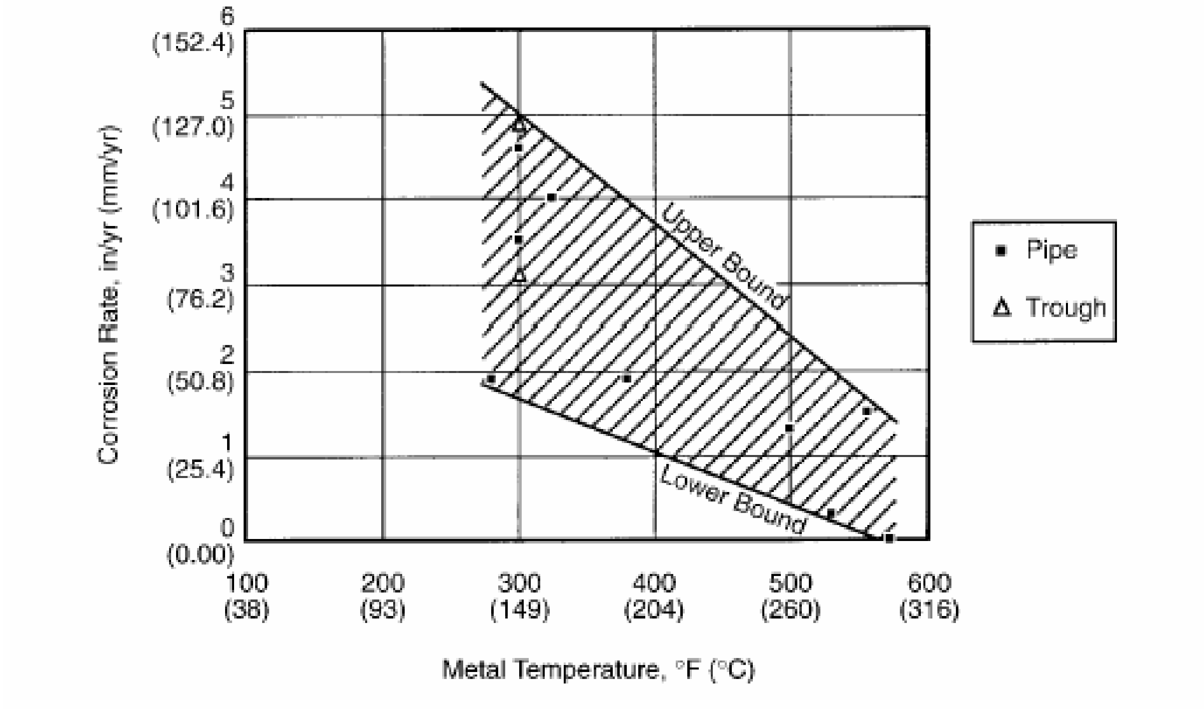


Figure 6.5 Temperature Dependency of Corrosion Rate in B& W Tests of Water Containing Boric Acid Dripping onto Pipes (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)

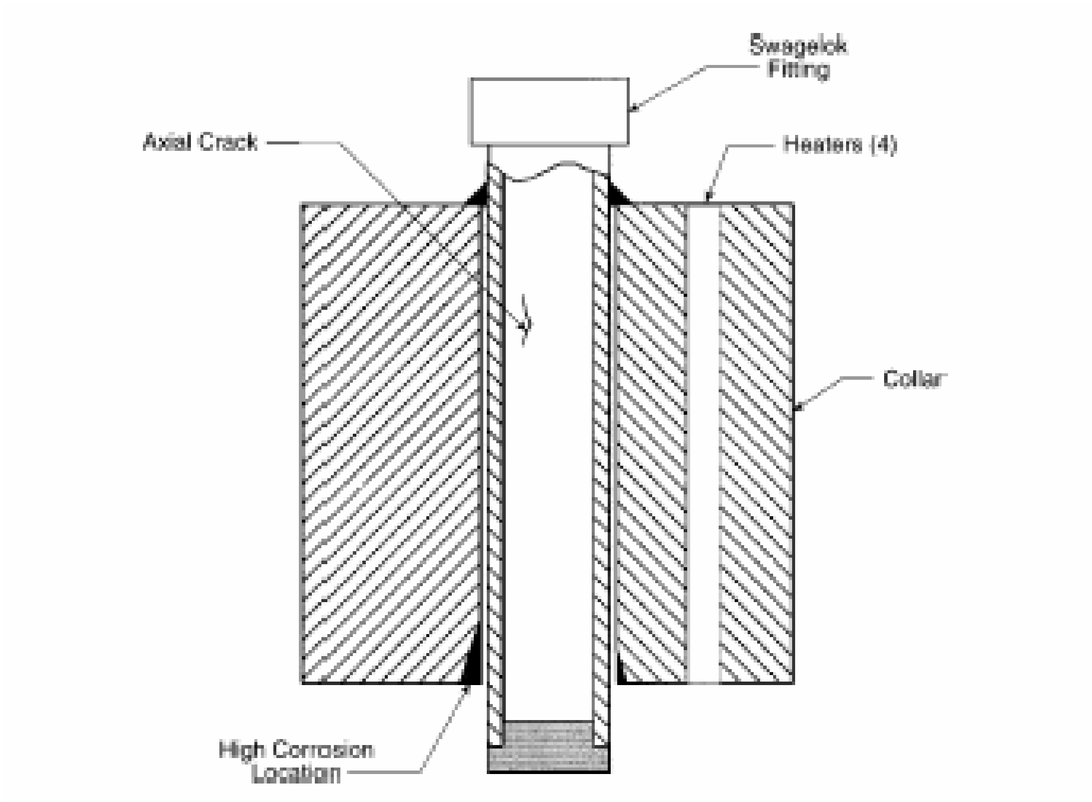


Figure 6.6 CE Crevice Test Configuration for Boric Acid Leakage into an Annular Crevice (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)

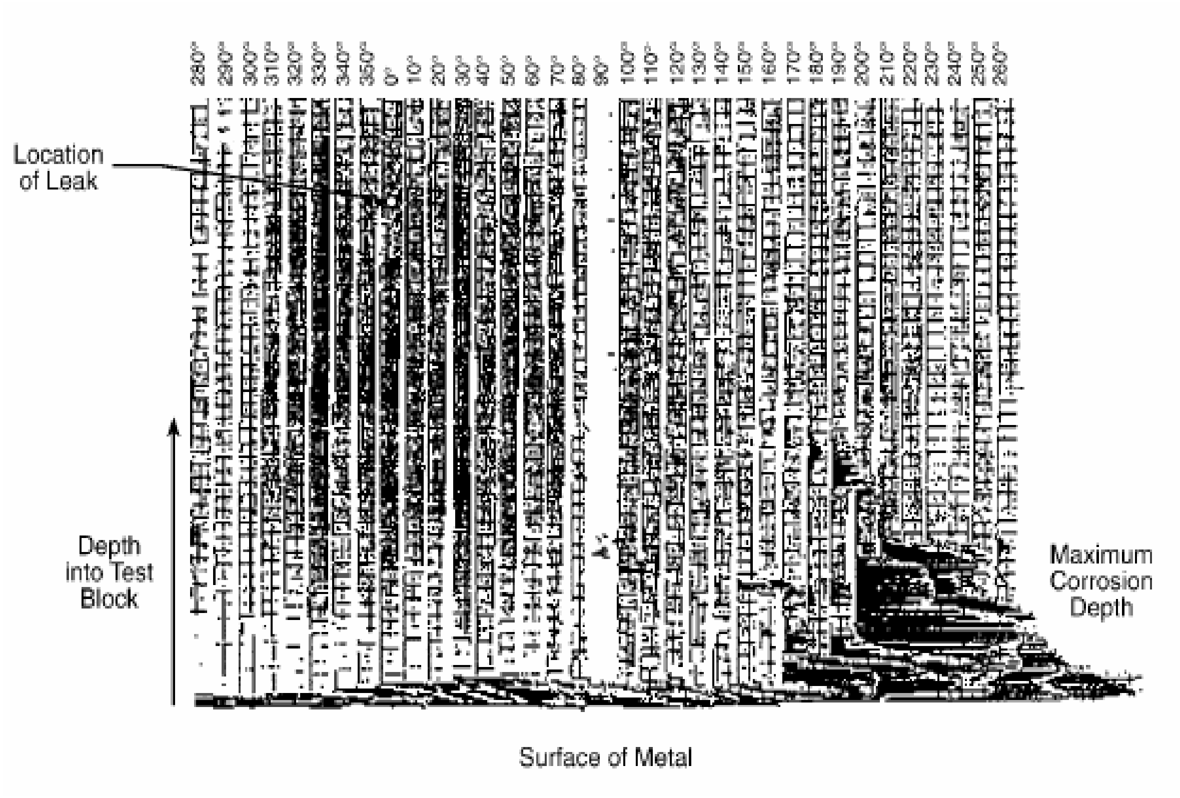


Figure 6.7 Location of Wastage in CE Crevice Test Configuration for Boric Acid Leakage into an Annular Crevice (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)

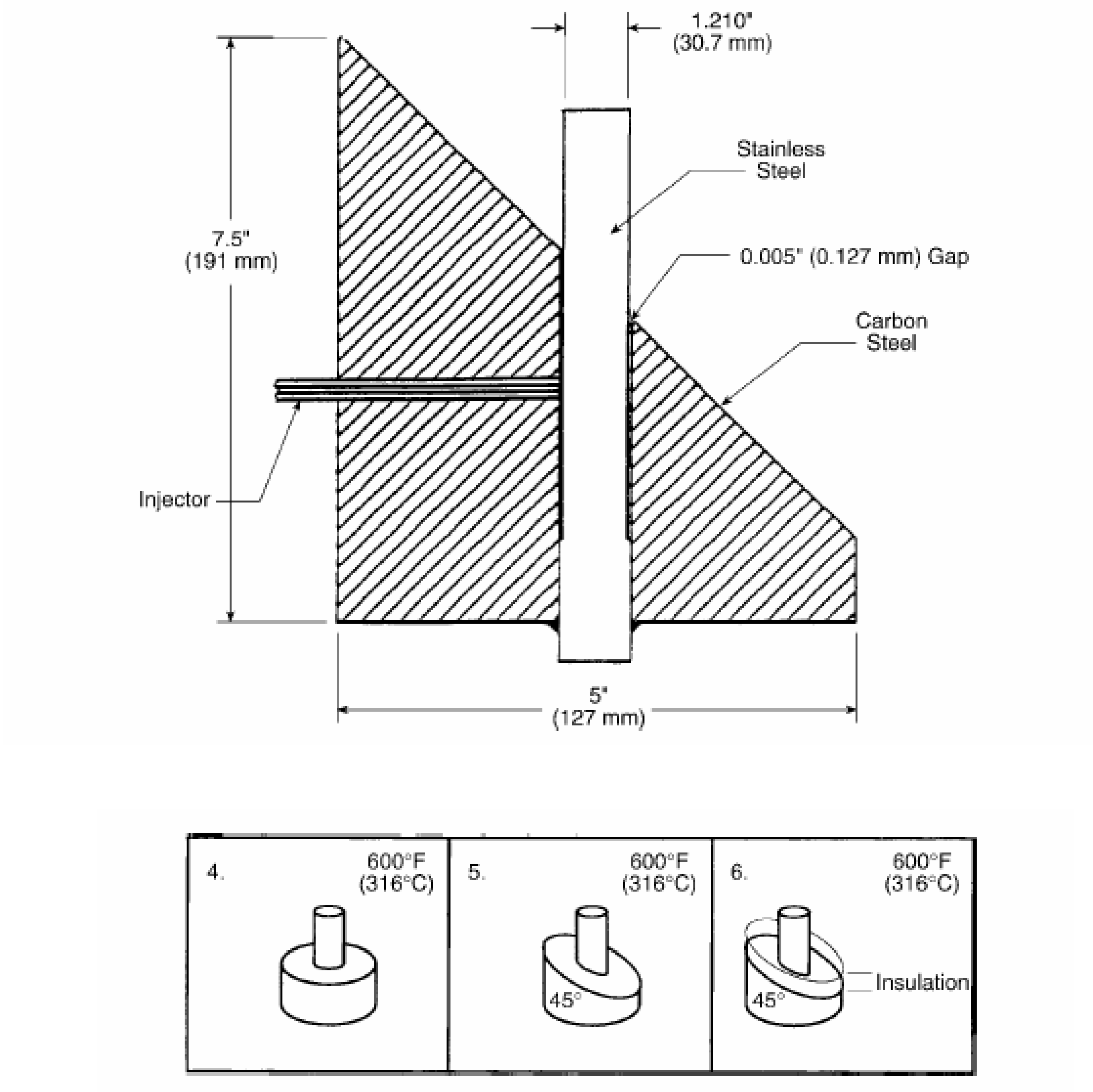


Figure 6.8 EPRI Crevice Test Configuration for Boric Acid Leakage into an Annular Crevice (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)

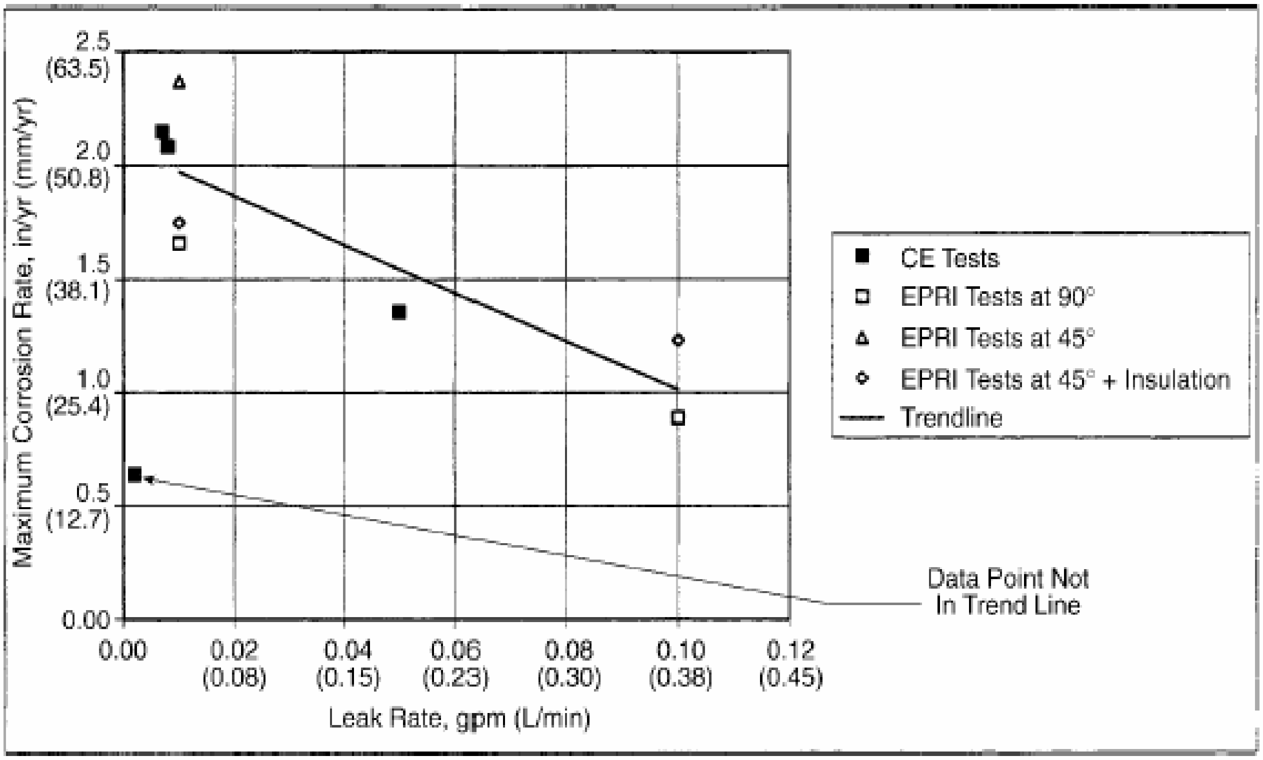


Figure 6.9 Maximum Wastage Rates from CE and EPRI Crevice Test Results (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)

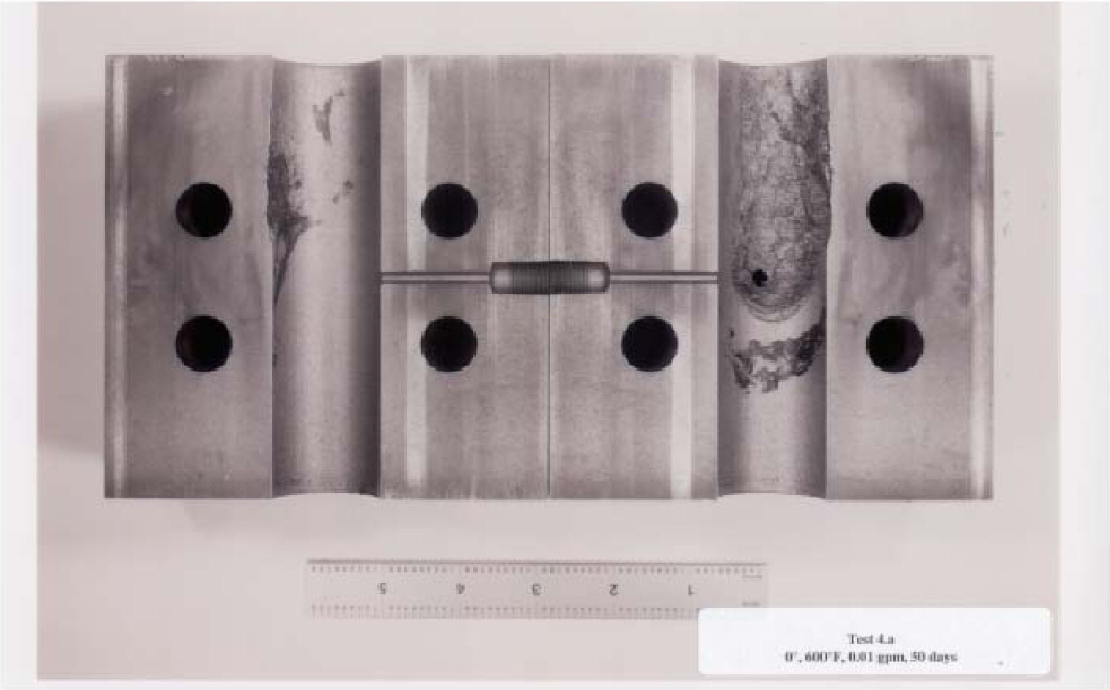
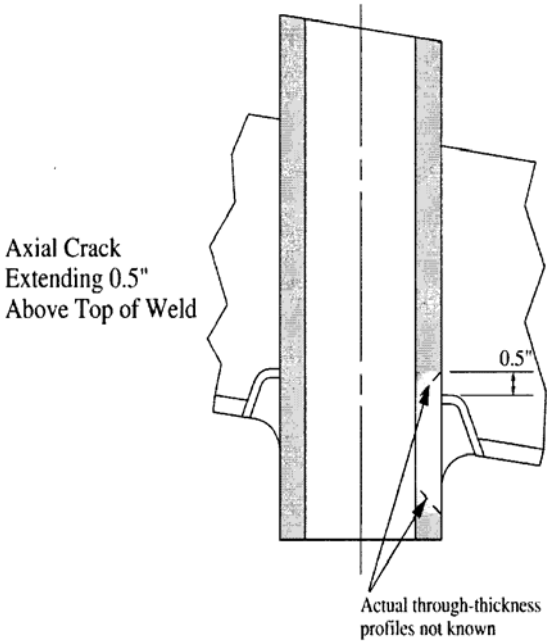
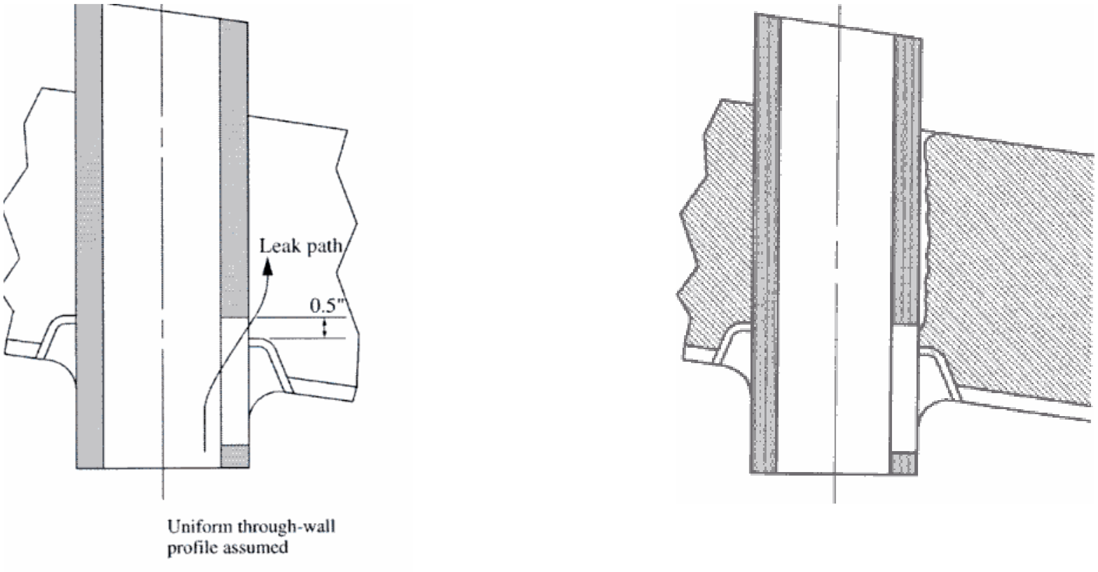


Figure 6.10 Typical Corrosion/Erosion Wastage Pattern Near Injection Point in EPRI Crevice Test for Boric Acid Leakage into an Annular Crevice (Slide 26 from the May 22, 2002 EPRI Meeting with the NRC; also in EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)



Phase 1

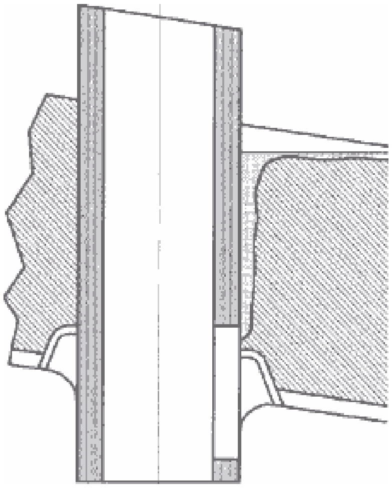
Stagnant/Low Flow



Phase 2

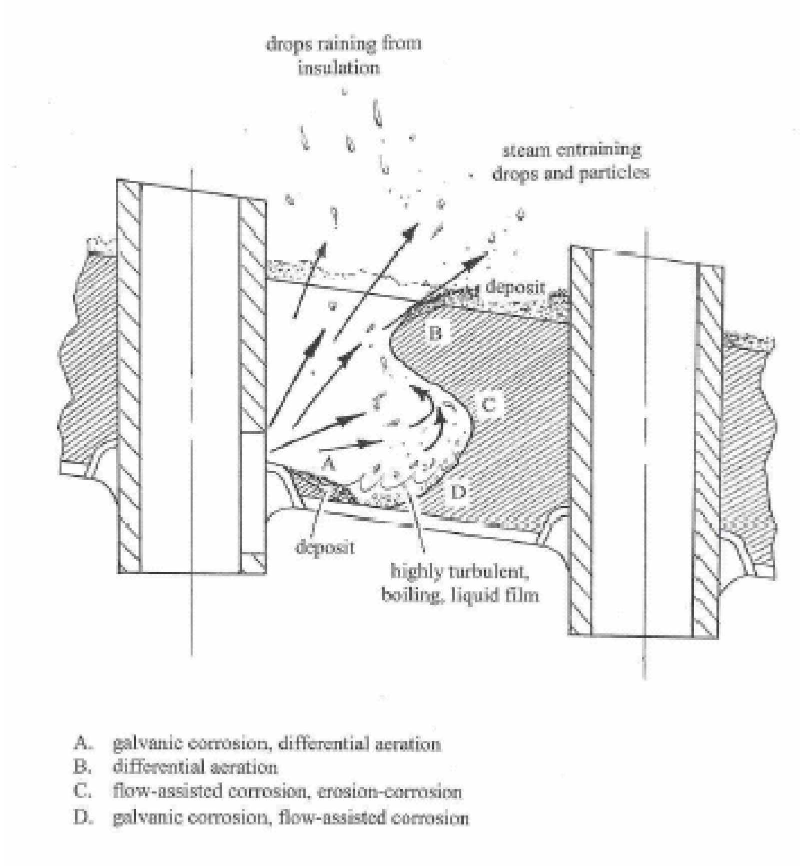
Bottom Up
Flowing/Impingement

Figure 6.11(a) EPRI MRP Corrosion Testing Wastage Model: Phase 1 and Phase 2



Phase 3

Top Down Concentrated
Boric Acid Corrosion

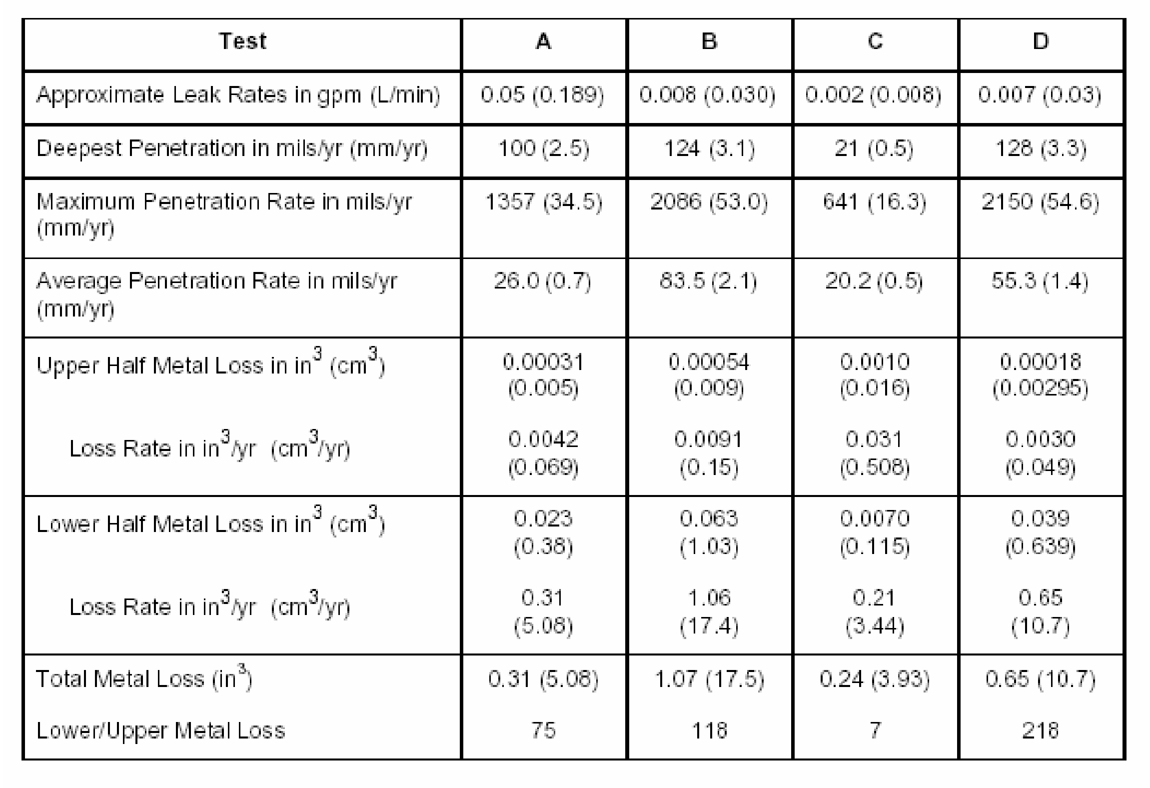


Phase 4

Full-Scale Corrosion
Consequences

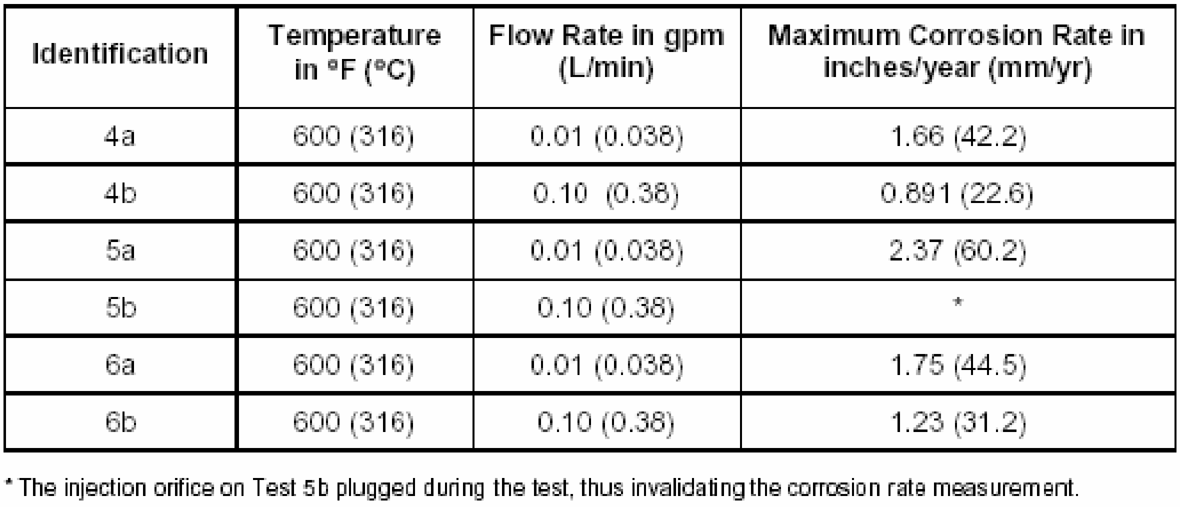
Figure 6.11(b) EPRI MRP Corrosion Testing Wastage Model: Phase 3 and Phase 4

Table 6.1 Test Parameters and Wastage Results from CE Crevice Test for Boric Acid Leakage into an Annular Crevice (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)



Test	A	B	C	D
Approximate Leak Rates in gpm (L/min)	0.05 (0.189)	0.008 (0.030)	0.002 (0.008)	0.007 (0.03)
Deepest Penetration in mils/yr (mm/yr)	100 (2.5)	124 (3.1)	21 (0.5)	128 (3.3)
Maximum Penetration Rate in mils/yr (mm/yr)	1357 (34.5)	2086 (53.0)	641 (16.3)	2150 (54.6)
Average Penetration Rate in mils/yr (mm/yr)	26.0 (0.7)	83.5 (2.1)	20.2 (0.5)	55.3 (1.4)
Upper Half Metal Loss in in^3 (cm^3)	0.00031 (0.005)	0.00054 (0.009)	0.0010 (0.016)	0.00018 (0.00295)
Loss Rate in in^3/yr (cm^3/yr)	0.0042 (0.069)	0.0091 (0.15)	0.031 (0.508)	0.0030 (0.049)
Lower Half Metal Loss in in^3 (cm^3)	0.023 (0.38)	0.063 (1.03)	0.0070 (0.115)	0.039 (0.639)
Loss Rate in in^3/yr (cm^3/yr)	0.31 (5.08)	1.06 (17.4)	0.21 (3.44)	0.65 (10.7)
Total Metal Loss (in^3)	0.31 (5.08)	1.07 (17.5)	0.24 (3.93)	0.65 (10.7)
Lower/Upper Metal Loss	75	118	7	218

Table 6.2 Test Parameters and Wastage Results from EPRI Crevice Test for Boric Acid Leakage into an Annular Crevice (from EPRI Boric Acid Corrosion Guidebook, Revision 1, November 2001)



Identification	Temperature in °F (°C)	Flow Rate in gpm (L/min)	Maximum Corrosion Rate in inches/year (mm/yr)
4a	600 (316)	0.01 (0.038)	1.66 (42.2)
4b	600 (316)	0.10 (0.38)	0.891 (22.6)
5a	600 (316)	0.01 (0.038)	2.37 (60.2)
5b	600 (316)	0.10 (0.38)	*
6a	600 (316)	0.01 (0.038)	1.75 (44.5)
6b	600 (316)	0.10 (0.38)	1.23 (31.2)

* The injection orifice on Test 5b plugged during the test, thus invalidating the corrosion rate measurement.

6.5 References

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5. *Ibid*, pages 2-13 through 2-14 and Table 2-2.
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22. *Ibid*, page 2-3 and Table 2-1 at page 2-5.

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44. *Ibid*, Section 3, page 16.

45. *Ibid*, Section 4, pages 16-18.

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62. *Ibid*, at page 4-54.

63. *Ibid*, Table 4-2 at page 4-17.

64. *Ibid*, at page 4-54.

65. *Ibid*, Figure 4-7(a) at page 4-24.

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71. *Ibid*, Table 4-23 at page 4-71.

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95. *Ibid*, at page 30, Table 8.

96. *Ibid*, at pages 30-32, Table 9, Figure 41.

97. *Ibid*, at pages 25-30, Tables 6-7, Figure 37.