5. Worldwide Industry Response to CRDM and Other Alloy 600 Nozzle Cracking

There are almost 10,700 CRDM nozzles in 155 PWR plants (69 US, 86 non-US) around the world. Through the end of 2000 for non-US plants and through the end of 2003 for US plants, cracks have been found in only 414 (137 US, 277 non-US) of these 10,700 nozzles. Cracks have occurred in only 3.9 % of all CRDM nozzles. As reported by EPRI MRP-110, other than at Davis-Besse, none of these nozzle cracks found extended more than 0.6 inches above the weld, and none caused significant leakage. The one-of-a-kind Davis-Besse Nozzle 3 crack represents 0.00935% of all CRDM nozzles.

The one long axial crack discovered in the one Davis-Besse CRDM Nozzle 3 in February 2002 was 1.23 inches long. It resulted in a primary coolant leak that ultimately, through an unexpected and unforeseeable sequence of complex events, caused the large wastage cavity at Nozzle 3. While much work has been undertaken to investigate and understand the reasons for this crack at Davis-Besse Nozzle 3, it remains a unique and in many ways an unexplained event that can not be considered the result of any expected, ordinary, “wear and tear” process.

The purpose of this section is to present the worldwide experience with CRDM cracking, the inspection, analysis, and repair activities between 1991, when the first CRDM nozzle crack was found in a French plant, and 2002, when the Davis-Besse RPV head wastage was found, and the industry and regulatory responses to this issue. It is clear from our review of this experience that the one Davis-Besse Nozzle 3 crack was a unique, singular, “event of the moment”, not experienced in any other CRDM nozzle in any plant, and one that will likely never be repeated.

A second purpose of this section is highlight the fact that the primary focus of all the worldwide effort was on the potential for CRDM nozzle failure and nozzle ejection, and on the critical crack sizes that would be required before such failures would occur.

While the potential for boric acid corrosion of the RPV head was considered, it was not regarded as a significant or a safety issue until the 2002 Davis-Besse event.

In Section 5.1, we review the initial reports of cracking in Alloy 600 CRDM nozzles that were first found in the French 900 MWe ("CPO") plants operated by Electricité de France (EdF) that had the longest operating histories of the French plants, and the inspection activities and the subsequent discovery of similar Alloy 600 CRDM cracking in other French plants, and at other European plants in Sweden and Belgium. The European regulatory and industry approach to identifying and repairing cracked CRDM nozzles is then briefly described, together with the success of this approach in preventing any significant RPV head wastage corrosion due to boric acid leakage from nozzle cracks. The Japanese approach to the CRDM cracking issue is also briefly summarized.

In Section 5.2, we briefly review the US experience with Alloy 600 nozzle cracking in pressurizer nozzles, which was a precursor to CRDM nozzle cracking and was discovered first in the pressurizer nozzles in CE plants.

Section 5.3 then describes the US experience with CRDM nozzle cracking in B&W, Westinghouse, and CE plants, from 1994 through the 2002 Davis-Besse event and up to 2003. This section also describes in some detail the regulatory and industry responses to both the European and US experience with CRDM nozzle cracking over this time frame.

5.1 Non-US Experience and Responses to CRDM Nozzle Cracking

5.1.1 Bugey-3 and Subsequent EdF Experience

The first plant to discover and report cracks in CRDM nozzles was the EdF Bugey-3 plant in September 1991, and preliminary information concerning this discovery was first described in the U.S. at the October 1991 EPRI PWSCC workshop[1]. A leaking peripheral CRDM nozzle was found during hydrotest; inspection by ECT confirmed a through wall crack; and subsequent laboratory examination confirmed the cracking to be PWSCC.

This discovery prompted EdF to conduct inspections of CRDM nozzles at the six 900 MWe (CPO) plants with the longest operating histories. One additional cracked CRDM nozzle was found at Bugey-3, 8 out 65 CRDM nozzles were found cracked at Bugey-4, and 1 out of 26 inspected nozzles was found cracked at Fessenheim-1. All of the cracked nozzles were peripheral nozzles where the residual stresses from welding were determined to be highest, but only the nozzle at Bugey-3 was leaking due to through wall cracking above the weld. Even at this early stage of investigation of the CRDM nozzle cracking, EdF had decided to replace the RPV heads at the six 900 MWe (CPO) plants.

More detailed information on the Bugey-3 CDRM nozzle cracking was presented by the French at the December 1992 EPRI workshop on PWSCC of Alloy 600. As a result of the French report, as well as reports of subsequent inspections and reported cracks at Belgian and Swedish plants, the primary focus of this 1992 EPRI workshop was on CRDM nozzle cracking.

The Bugey-3 CRDM nozzle crack was discovered during the hydrotest of the RPV in September 1991 following the mandatory 10-year in-service inspection (ISI) of the plant.[2] At the time of this discovery, Bugey-3, one of the earlier (CPO class) 900 MWe units, had been operated for approximately 12 years (80,000 hours of service) since start-up in 1979, and was the sixth French plant to have conducted a 10 year ISI and hydrotest.

The CRDM crack was evidenced by visual observation of a small leak - less than 1 liter/hour or 0.004 gpm - in one of the outermost CRDM nozzles during the 3000 psi hydrotest. This prompted a non-destructive examination (NDE) of the 65 CRDM nozzles by means of eddy current (ECT) inspection techniques. This inspection resulted in the identification of several axial cracks in the lower (welded) region of the leaking nozzle, one of which was through wall and provided the leak path. One other outer CRDM nozzle was found to have a part depth axial crack.

Subsequent removal of the cracked nozzle and laboratory metallurgical examination revealed that the through wall leaking crack initiated on the inner diameter (ID) of the nozzle below the weld, and propagated through the nozzle wall to the outer diameter (OD) above the weld[3 4]. The crack was approximately 1 inch long on the ID and 0.08 inch long on the OD above the weld, with a maximum sub-surface length of about 2 inches. This crack profile provided a leak path, although the crack length available for leakage (0.08 inch) above the weld was small and resulted in the leakage being correspondingly small. Reportedly there was no boric acid accumulation on the RPV head as a result of this leak, indicating that the crack length was too small to allow coolant leakage during operation at normal pressure, but that it opened up under the hydrotest pressure to allow the observed leakage[5].

The metallurgical examination confirmed the cracking mechanism to be PWSCC. There were also two small OD circumferential cracks, one in the weld, and one in the nozzle which was connected to the leaking axial crack.

The discovery of these CRDM nozzle cracks in Bugey-3 in 1991 resulted in EdF embarking on a program of CRDM nozzle inspection at other 900 MWe CPO plants of the same vintage, as well as at some of the second generation 1300 MWe plants with similar RPV head temperatures (597-599 deg F).

The results of these inspections were reported in more detail by EdF at the 1992 EPRI workshop on PWSCC, and are summarized in Table 5-1[6]. A total of 696 CRDM nozzles at 15 plants had been inspected by the time of the workshop, with 29 nozzles being found to have cracks. Bugey-3 remained the only EdF plant found to have a through wall crack resulting in a leaking nozzle.

As summarized in Table 5-1, the French updated these inspection results at the 1994 EPRI PWSCC workshop[7], and a further update was presented at the 2000 EPRI

PWSCC workshop[8], although by that time many of the original RPV heads had been replaced. Although the incidence of CRDM nozzle cracking was low relative to the total number of CRDM nozzles in service (about 6.5% overall), the French plants continued to be the plants most affected by CRDM nozzle cracking. However, no leaks were reported from any of these cracked CRDM nozzles after the initial Bugey-3 leak, so in that respect the French approach to this problem was certainly successful.

5.1.2 Other Non-US Experience with CRDM Nozzle Cracking

The French report of CRDM nozzle cracking at Bugey-3 and other plants, prompted some of the national regulatory bodies to require and utilities in Sweden, Spain, Belgium, and Japan to institute inspection programs to identify cracked CRDM nozzles.

Sweden: In Sweden, where there were three PWRs operated by Vattenfall at Ringhals, the approach was similar to that adopted by EdF. The Swedish Nuclear Inspectorate (SKI) required either that the utility prove that CRDM cracking similar to that observed in the French units could not occur, or perform inspections at the next outage. Since the Three Ringhals units operated with a RPV head temperature of 606 deg. F, and had also operated for similar times to the early French units like Bugey-3, Vattenfall performed NDE inspections in 1992 at all three units using ECT, ultrasonic (UT), and dye penetrant (PT) techniques.

The results of these inspections were presented at the 1992 EPRI PWSCC workshop[9]. At Ringhals-2, initial inspection of twelve CRDM penetrations revealed axial crack indications[a] in four nozzles, the longest (in Nozzle 53) being 16 mm (0.63 inches) in length, located partly above the weld, and only 4 mm (0.16 inches, about 25% through wall) in depth by UT. In one of the four nozzles (Nozzle 19), PT subsequent to the ECT showed multiple close-spaced shallow cracks in several locations both above and

---

[a] Indications identified by Ultrasonic Testing (UT) include a range of sub-surface anomalies and metallurgical discontinuities that may or may not be representative of cracking. The size and location of these anomalies dictate whether or not repair (e.g., grinding and weld repair) is required.

below the weld area. The remaining 53 CRDM penetrations were then inspected, and one additional cracked nozzle was found.

At Ringhals-3, 60 out of the total 65 penetrations were inspected, and no cracks were found. At Ringhals-4, all 65 penetrations were inspected, with cracks being found in just two nozzles below the weld, neither requiring repair, but one with multiple small cracks detected by PT.

The above-weld crack in Nozzle 53 was repaired by machining out the crack by EDM, as were the multiple small cracks in Nozzle 19[b].

Vattenfall reported an update of the Ringhals CRDM nozzle inspections at the 1994 EPRI PWSCC workshop[10]. All of the nozzles with known cracks from the 1992 inspections were re-inspected in1993, with the result that three new indications were discovered in previously cracked nozzles (two in Ringhals-2 and one in Ringhals-4), and one of the pre-existing cracks in Ringhals-2 had increased in length by 4.3 mm (0.17 inch).

The islands of multiple small crack indications discovered by ECT and confirmed by PT in 1992 in Ringhals-2 Nozzle 19 had coalesced. A boat sample was cut from one of these areas below the weld in 1993, and laboratory metallurgical examination confirmed that the indications were PWSCC[11].

In 1994, Vattenfall re-inspected the nozzles in Ringhals-2 and Ringhals-4 that had previously identified indications, and found only minor changes in ECT signals. It was concluded from the 1993 and 1994 inspection that the crack growth rates were low[12].

---

[b] At the presentations at the 1992 EPRI PWSCC workshop, the Swedish utility Vattenfall reported that the Swedish regulatory authority SKI in Sweden had concerns over boric acid corrosion rates for carbon steel of up to 10 mm/month (4.7 inches/year), and that this resulted in a zero tolerance for leakage from cracked CRDMs, which had to be located and repaired before the cracks reached through wall and above the weld region.

Three welds in Ringhals-2 had previously been inspected in 1992 by PT with no indications found. In 1993, in addition to re-inspecting the known nozzle cracks, Vattenfall also inspected all of the J-groove welds by PT to determine if there were any surface breaking cracks in the welds. At the Nozzle 62 weld, a circumferential indication was found that extended approximately 40% of the way around the nozzle at the interface between the base RPV carbon steel material and the J-groove weld buttering[13]. Two boat samples approximately 1 inch deep were cut, and laboratory examination established that the cracks penetrated the full depth of the samples. Although the defect had been exposed to primary water, PWSCC was not evident, and the crack was attributed to a manufacturing defect. This discovery played a major role in the decision to plan for the replacement of the Ringhals-2 RPV head in 1996.

Spain: In Spain, four plants were inspected for CRDM cracks in 1994 – Almaraz-2, Asco-2, Vandellos-2 and Jose Cabrera (Zorita), and the results of these inspections were reported at the 1994 EPRI PWSCC workshop[14]. No cracks were found at the first three plants (606, 610 and 595 Deg. F head temperatures respectively), but 18 of the 37 inspected penetrations at Jose Cabrera had cracks, which were eventually attributed to demineralizer resin incursions into the primary system and resultant sulfur/sulfate induced IGA/SCC rather than PWSCC[15].

Belgium: In Belgium, 435 CRDM penetrations at the seven Belgian plants at Doel and Tihange (60,000 to 140,000 hours of operation and head temperature 549 to 604 deg F) were reported to have been inspected, with no indications found[16]. At the 1994 EPRI PWSCC workshop, the report of a single indication (5 mm long, 1mm deep below the weld) identified during the 1992 inspection of the CRDM nozzles at Tihange-1[17] was now dispositioned as a “scratch” that would be monitored in future inspections.

The Belgian inspection experience was updated at the 2000 EPRI PWSCC workshop[18]. In the 1998 inspections, indications and cracks were detected at Tihange-1, Doel-1, and Tihange-3. No indications were found at Doel-3 or Tihange-2, both of which operated at lower head temperatures (549 deg. F).

At Tihange-1 (604 deg. F head temperature), cracks were found in four nozzles in 1998 after about 170,000 EFPH of operation. These findings prompted replacement of the RPV head, and three of the four nozzles were re-inspected after the RPV head was replaced in October 1999. These 1999 inspections showed that one crack had grown from 26 mm to 36 mm in length and 6 mm to 10 mm in depth (38% to 63% through wall) in one 17 month fuel cycle of 12,000 EFPH.

At Doel-1 (585 deg. F head temperature), shallow indications about 1 mm deep were detected by ECT and UT on 11 penetrations in August 1998, re-inspection of these 11 in August 1999 identified one crack 36 mm long and 4 mm deep, and crack length growth rates were determined to be around 7.7 mm/EFPY (0.30 inches/EFPY).

At Tihange-3 (604 deg. F head temperature), one indication was found in December 1996 after 85,000 EFPH of operation, and this indication was re-confirmed in June 1998 after 97,000 EFPH of operation.

Japan: In Japan, eleven of the oldest RPV heads with about 100,000 hours of operation had been visually inspected at the time of the 1992 EPRI PWSCC workshop with no visible leaks being found, and a nationwide ECT inspection of CRDM nozzles was being planned for 1994[19].

At the 1994 EPRI PWSCC workshop, the results of this inspection program were reported. 17 out of 24 plants and 887 CRDM nozzles out of the total of 977 nozzles had been inspected by ECT in 1993 and 1994, with no indications being reported[20].

5.2 Alloy 600 Pressurizer Nozzle Cracking

PWSCC of Alloy 600 steam generator tubes had been an issue that the PWR industry had been deeply involved in for almost ten years prior to 1990. The cracking occurred at welded connections where the combination of susceptible Alloy 600 material, high residual stress from fabrication and welding, and high operating temperature caused initiation and propagation of PWSCC cracks.

Some of the earliest non-steam generator Alloy 600 cracking was discovered in Alloy 600 pressurizer nozzles such as heater penetrations and instrument connections in CE plants. The pressurizer is the highest temperature location in the RCS (around 650 deg F) since it operates at the saturation temperature corresponding to the RCS pressure.

As more cracking incidents began to surface, EPRI organized a workshop in October 1990 to share experience, inspection approaches, remedial measures and strategic planning to address the growing problem of PWSCC of welded Alloy 600 connections in PWRs[21]. The Alloy 600 pressurizer heater sleeve and nozzle cracking was not a trivial problem – at the Calvert Cliffs CE plant, the one of the first to experience the problem, resolution of the heater sleeve cracking problem extended the refueling outage by one year, cost over $20 million in direct costs, and loss of plant output during the outage[22].

Although the US focus of this meeting was on Alloy 600 connections such as the pressurizer nozzles and not CRDM nozzles where cracking had not yet been found in US plants, it was at this meeting where the initial report of CRDM cracking at Bugey-3 and other French 900 MWe (CPO) plants was reported (see Section 5.1.1).

At the workshop, representatives from EPRI and the three US PWR owners groups, Combustion Engineering (CEOG), Westinghouse (WOG) and Babcock and Wilcox (BWOG), described programs that were being developed to address the growing problem of PWSCC of Alloy 600 nozzles and components.

The US NRC issued an Information Notice (IN 90-10) on February 23, 1990 to ensure all PWR utilities were aware of the field experience[23]. An Information Notice is the lowest level of notification used by the NRC and does not require individual utility or industry response or action commitment. The focus of IN 90-10 was on the Alloy 600 PWSCC problem in pressurizer and instrument connections in US and French plants, and did not mention the potential for Alloy 600 cracking in CRDM nozzles.

5.3 US Experience and Responses to CRDM Nozzle Cracking

In contrast to the significant problem of Alloy 600 CRDM nozzle cracking in the French plants which clearly required immediate attention, there was almost no CRDM nozzle cracking found in the 1994 to 2000 time period in US PWR plants. Therefore, the US response, both by the industry and the NRC, was more measured.

5.3.1 Initial Experience of CRDM Nozzle Inspections and Cracking in US Plants 1994-2000

The initial inspections of CRDM nozzles in US plants were at Point Beach-1, D.C. Cook-2 and Oconee-2 in 1994.[c] Point Beach-1 was the first US plant to be inspected in April 1994, where 49 CRDM nozzles were inspected by ECT, and no indications were found. [24] [25]

At D.C. Cook-2, 71 of 78 RPV head penetrations were inspected by ECT, 66 of which were CRDM nozzles, the remaining 5 nozzles being instrument nozzles[26]. D.C. Cook-2 head temperature was 604 deg. F and the plant had operated for 9.9 EFPYs. Three axial ID cracks were detected in one of the instrument nozzles in the outermost row below the weld, the longest being 47 mm (1.77 inches) long reaching just into the weld region, with a maximum depth of 6.8 mm (0.27 inches or 43% through wall). Based on analysis that showed the crack would not exceed 75% through wall in the next fuel cycle (18 effective full power months), the nozzle was left in service un-repaired, to be inspected at the next refueling outage.

At Oconee-2, the first B&W plant to be inspected, all 69 CRDM nozzles were examined by ECT in October 1994. Oconee-2 head temperature was 602 deg. F and the plant had operated for 140,000 hours. No indications were found in 68 of the nozzles, but indications were found in Nozzle 23, and subsequent PT identified the indications as consisting of about 20 small cracks, the longest being 9.4 mm (0.37

[c] Point Beach-1 and D.C. Cook-2 are Westinghouse designed plants, while Oconee-2 is a B&W designed plant.

inches) in length. UT could not identify or size these indications, so it was concluded that the depth of the largest indication was less than 2 mm (0.08 inches) deep[27].

Nozzle 23 at Oconee-2 was inspected again in 1996 and 1999, and the results of these inspections, which were reported at the 2000 EPRI PWSCC workshop, showed that there was no significant change in the ECT signal from the 1994 inspection at either the 1996 or 1999 inspections, the 1996 ECT finding being confirmed with PT[28]. At this 2000 workshop, a second nozzle (63) was reported to have had ECT indications at the 1994 inspection that were not at the time confirmed by PT. Like Nozzle 23, Nozzle 63 was reported to have shown no change in ECT signal at the 1996 and 1999 inspections, but the 1996 inspection did confirm the ECT result by PT. Six additional CRDM nozzles were inspected in 1999, and the ECT signals showed no change from the inspection of the same nozzles five years earlier in 1994.

The Duke Power and Framatome representatives at the 2000 EPRI PWSCC workshop concluded that these results showed that crack growth rates were low, and that the probability of through wall cracks and leakage developing at Oconee-2 was low. On the basis of the Oconee-2 inspection findings, ECT inspections of Oconee-1 and Oconee-3 were deferred[29].

CRDM nozzle inspections were also reported at the 2000 EPRI PWSCC workshop for Ginna, a Westinghouse designed plant[30]. Thirty eight penetrations were inspected by ECT in 1999, and indications were reported at only one nozzle. Inspection by UT did not show any depth to the indications, and they were concluded to be less than 2 mm in depth. Crack growth analysis was reported to show that from a 2 mm depth, a crack would not grow to 75% through wall before the end of licensed plant life in 2009.

The only other US plant CRDM inspection reported at the 2000 EPRI PWSCC workshop was for the Millstone-2 plant, where 69 CRDM and 8 instrument nozzles were inspected by ECT and UT[31]. A cluster of shallow axial crack indications was reported at one CRDM nozzle, with crack lengths ranging from 0.16 to 0.44 inches, and crack depths less than 0.022 inches. The cracks were removed by grinding.

The NRC assessment report published in 1994 (Section 5.3.3) presents a summary of the worldwide inspections of CRDM nozzles available at the time of the report publication[32]. The data summarized in the NRC report show that:

- 67 non-US plants in 7 countries had inspected 4,181 RPV head penetration nozzles, with indications being found in 101 penetrations.
- Of these, 45 plants were in France, where 3,095 penetrations had been inspected, with 89 nozzles being found with indications.
- Only 49 RPV penetrations had been inspected at one US plant (Point Beach-2), with no indications found.

Adding in the two US plants (D.C. Cook-2 and Oconee-2) and the 12 Japanese plants for which additional inspection data was reported at the November 1994 EPRI PWSCC workshop, by the end of 1994:

- 79 non-US plants in 7 countries had inspected 4,793 RPV head penetration nozzles, with indications being found in 101 penetrations.
- Only 189 RPV penetrations had been inspected at the three US plants, with two minor indications reported.

Over five years later, at the time of the February 2000 EPRI PWSCC workshop, the US situation with respect to CRDM nozzle inspections was not much changed. A summary of the worldwide inspection results was presented by US representatives, and shows the following[33]:

- 86 non-US plants in 10 countries had inspected 5,718 RPV head penetration nozzles, with indications being found in 271 penetrations.

- Of these, 47 plants were in France, where 3,752 penetrations had been inspected, with indications being found in 244 penetrations.

- Only 266 RPV penetrations had been inspected at 7 US plants, with only one penetration being listed as having an indication[d].

The US perspective on CRDM nozzle cracking was summarized in this same presentation, with the following key points being made:

- A large portion of detected indications were shallow surface cracks and never grew in depth.

- Only three through wall cracks had been found, and only one of these cracks leaked.

- Cracks were predominantly found in outermost row CRDM nozzles.

- The incidence of cracking in US plants inspected was only 1.5% of the nozzles inspected, compared with 6.5% in France and 4.5% worldwide.

- Analysis had showed that leakage from through wall cracks was unlikely except under full hydrotest pressures, and therefore the likelihood of a leak or damage from leakage was low.

- Because of the significant incidence of CRDM nozzle cracking in French PWR plants, replacement heads had already been installed or had been ordered for all 47 plants. Likewise, three plants each in Spain and Japan, and one each in Belgium and Sweden had installed or had ordered replacement RPV heads..

[d] It appears from the workshop summary (page S-2) that this is the indication at D.C. Cook-2, the shallow indications at Oconee-2, Ginna, and Millstone-2 being discounted. Inspections at Palisades and North Anna-1 were also mentioned as having been performed, with no indications being found.

It was noted in the summary to the 2000 EPRI PWSCC workshop that:

> "Eleven countries have now observed indications of reactor vessel closure head nozzle PWSCC, and new indications continue to be identified abroad. To date, approximately 4.5% of the nozzles inspected worldwide have been found with PWSCC indications or cracks.
>
> French plants are particularly affected by CRDM nozzle cracking considering relatively low operating temperatures reported for the French heads, as cracks or indications have been identified in approximately 6.5% of the French nozzles inspected to date.
>
> The more rapid cracking in these plants is believed to be the result of the use of more susceptible forged bar material and possibly from a greater degree of cold work of the inside surfaces of the nozzles (all CRDM nozzles are machined on the ID). EdF is currently in the process of replacing all their closure heads with new heads using Alloy 690 nozzles."

In summary, the European and Japanese response to the discovery of CRDM cracking at Bugey-3 and other EdF plants in France was to inspect virtually all CRDM nozzles, and repair or replace cracked nozzles as a temporary measure until the RPV heads could be replaced. In the US, by the time of the February 2000 EPRI PWSCC workshop, out of the 266 nozzle penetrations inspected at seven, only one minor indication had been found, and the issue of CRDM cracking was essentially regarded as mainly a French problem, at least in the near term.

5.3.2 Initial US Industry and NRC Regulatory Response to CRDM Nozzle Cracking

The initial US industry response to the discovery of PWSCC in French CRDM nozzles was through the owners groups for the three domestic vendors – the B&W Owners Group (BWOG), the Westinghouse Owners Group (WOG) and the Combustion

Engineering Owners Group (CEOG). Toledo Edison, the licensee for Davis-Besse at the time, was a member of the BWOG, and only the BWOG efforts are reviewed here.

On October 2, 1992, the BWOG issued a proprietary report for PWSCC of Alloy 600 materials in B&W designed plants[34]. This report presented a PWSCC susceptibility ranking model based on the material properties (carbon content and annealing temperature), operating/residual stresses and operating temperature. The report provided the susceptibility ranking of the Alloy 600 components on B&W designed plants. The Davis-Besse CRDM nozzles were of four different heat numbers, with heat M3935, from which CRDM Nozzles 1 through 5 were manufactured being ranked as 2-3, indicating a low probability of failure within 40 years.

In December 1992, the BWOG issued a second proprietary report addressing the issue of PWSCC of CRDM nozzles[35]. The fabrication and manufacturing processes for B&W designed CRDM nozzles were reviewed, and it was concluded that the B&W CRDM nozzle design was not immune to PWSCC. While 24 of the peripheral CRDM nozzles at Davis-Besse were rated as having "very high susceptibility" for PWSCC, CRDM Nozzles 1 through 5, all manufactured from heat number M3935, were again ranked as having the lowest susceptibility ranking of 2-3 on a scale of 1 to 5 with 2-3 being a low probability of failure in a 20 year time period.

The first comprehensive safety assessment of CRDM nozzle cracking for the operating B&W plants was reported in B&W report BAW-10190P, which was completed in May 1993[36]. The report presented a sequential analysis consisting of, in order:

1. A stress analysis;

2. A crack growth analysis;

3. A leakage assessment; and

4. A wastage assessment of both the RPV head and the nozzle crevice.

Each step of this complex analysis was highly dependent on the prior analysis step.

The report first notes that the BWOG had performed an evaluation of similarities and differences between French and B&W designed CRDM nozzles, and concluded that, since there were no substantial differences, the B&W nozzles were not inherently less susceptible to PWSCC[37].

The stress analysis showed that the residual stresses from welding were high on both the ID and OD of the nozzle, and that the hoop stresses that produce axial cracks were higher than the axial stresses which can lead to circumferential cracks. The stress analysis also showed that the initial interference fit of the nozzle in the annulus would "open up" under operating conditions on the "downhill" side of the nozzle[38].

The results of the stress analysis were then used to develop crack growth rates, using an industry standard crack growth rate model developed for Alloy 600 steam generator tubing, which was considered to be conservative, and applying temperature corrections to account for differences in operating temperatures.

The conclusions from this analysis were that it would take 6 years minimum for a postulated ID initiated axial crack above the weld to grow through wall to the OD, and a further 4 years for a 0.5 inch long OD axial crack to grow to a length of 2 inches, or 6 years for the crack to grow to a length of 2.5 inches[39].

The analysis then used these crack sizes to estimate leakage rates through the crack and nozzle annulus. Calculated leakage rates ranged from 0.00368 gpm for a 0.5 inch leaking crack in a tight (0.0001 inch clearance) nozzle annulus, to 0.559 gpm for a 2.0 inch leaking crack in a 0.003 inch clearance nozzle annulus. As crack lengths were increased above 2.0 inches in the high clearance annulus, calculated leakage rates increased dramatically to over 12 gpm[40].

The potential for corrosion of carbon steel by leaking boric acid containing coolant is a very complex issue that we discuss in detail in Sections 6 and 9 of this report. We simply note here that after reviewing available data that showed localized erosion/corrosion rates of up to 5.1 inches/year, the B&W analysis used a “worst case” metal removal rate derived from a (then) recent CE test simulating leakage from a cracked pressurizer nozzle. That CE test showed erosion/corrosion penetration at a maximum rate of about 2.0 inches/year, and a maximum material loss rate of 1.07 cubic inches/year[41].

The B&W analysis then assessed the possible corrosion damage to the RPV head, both on the surface and in the nozzle annulus, based on the calculated leakage rates and the available corrosion data. It was noted that CRDM flange leaks had been experienced at B&W plants, but that this type of leakage flashed to steam and that the resultant dry boric acid would not cause any RPV head corrosion[42].

The analysis continued by assessing the structural impact of various corrosion/erosion cavity geometries in the RPV head that could potentially result from leakage from a nozzle crack into the nozzle annulus. The analysis showed first, that all three defects were acceptable from a structural standpoint, and second, since each cavity had a volume of 6.42 cubic inches, that it would take 6 years for a cavity to reach this size using the 1.07 cubic inches/year metal removal rate derived from the CE tests[43].

The analysis concluded by estimating the boric acid accumulations that would result on the RPV head for the various calculated leak rates from CRDM cracks. These ranged from 55.3 pounds/year (0.62 cubic feet/year) at the lowest 0.00368 gpm leak rate calculated for a 0.5 inch long crack, to 8,403 pounds/year (93.9 cubic feet/year) at the 0.559 gpm leak rate calculated for a 2.0 inch long crack[44].

Since walk-down inspections for boric acid leakage were already being conducted at operating plants in accordance with NRC Generic Letter 88-05 (see Section 6.2), it was thought unlikely that accumulations of the size calculated to result from the crack sizes calculated to develop would be missed over the six years it was estimated the cavity would take to grow to the assumed size[45].

We have described this initial analysis in some detail because subsequent analyses and safety assessments for B&W plants through at least 2002 followed the same general approach and relied heavily on this 1993 BWOG safety assessment. A considerable amount of work has been conducted since the 2002 Davis-Besse event, and the above analysis is now known to be non-conservative in several respects.

First, the specific Davis-Besse CRDM Nozzle 3 Alloy 600 material has been shown to exhibit crack growth rates well in excess of the industry standard curves. Thus, under equivalent stresses, cracks in this material can grow much faster than calculated in the BAW-10190P analysis, and we discuss this in detail in Section 8 of this report. In addition, the CRDM nozzle cracks at the Oconee-1, Oconee-2 and Oconee-3 plants that were found in 2000/2001 also imply crack growth rates much higher than those calculated in BAW-10190P (see Section 5.3.2).

Second, the assumed material loss rate of 1.07 cubic inches/year assumed by the anlayis is clearly low by several orders of magnitude. The corrosion/erosion cavity at Davis-Besse CRDM Nozzle 3 was approximately 195 cubic inches in size[e] (see Section 9.7.1), and if the metal loss rate were only 1.07 cubic inches/year, it would have taken almost 200 years for the actual observed cavity to develop.

In fact, the pre-existing research on boric acid corrosion/erosion, and the more relevant recent corrosion work designed specifically to investigate the specific Davis-Besse conditions that has been conducted by EPRI and the NRC all show that extremely high erosion/corrosion rates can occur under conditions that we conclude developed in the Davis-Besse CRDM Nozzle 3 annulus between 2000 and 2002. We discuss the corrosion research in Section 6.3, the rapid crack growth in Section 8, and the rapid development of the cavity in Sections 9 and 10 of this report.

---

[e] The Davis-Besse Root Cause Report estimates the cavity metal removal volume to have been approximately 125 cubic inches, our higher estimate in Section 4.2.2 results from a more detailed analysis of actual measurements of the cavity once it had been cut out and taken to the lab for metallurgical analysis.

Third, accumulations of boric acid on the RPV head from tight PWSCC cracks are much smaller than predicted by the B&W analysis. The Oconee-1 and Oconee-3 experience in 2000/2001 showed that even long cracks, up to 5.75 inches and through wall in the circumferential direction in the case of Oconee-3, can in fact result in very small accumulations of boric acid, again in the case of Oconee-3 of the order of 1 cubic inch (see Section 5.3.3). For Davis-Besse, we conclude that the accumulation of boric acid from the long axial crack at Nozzle 3 at 12RFO in April-May 2000 was no more than 6 cubic inches (Section 10.2.3), and may have been much less than even this minute amount. These actual boric acid accumulations are much smaller than predicted by the B&W analysis, and could easily be missed if there were only minor CRDM flange leakage. Thus, while reasonable at the time since there was no plant experience of leaks from CRDM nozzle PWSCC cracks, the assumption that CRDM through wall cracks would be readily detected by means of RPV head visual inspections was erroneous.

While the BAW-10190P report acknowledges the problem of CRDM flange leakage, which can easily be an order of magnitude larger than any leakage from an early stage PWSCC crack, it does not consider the possibility that boric acid deposits from such flange leakage could overwhelm the small amount of boric acid that would be deposited as a result of leakage from a PWSCC crack. Cleaning the RPV head would not only remove the boric acid from the flange leak, but also the evidence of leakage from a cracked CRDM nozzle. Thus the primary means by which US utilities monitored for leakage from CRDM nozzle cracks could be rendered ineffective, as it was at Davis-Besse.

Two addenda to the BAW-10190P were developed. First, as a result of the discovery of a circumferential crack above the weld in the cracked Bugey-3 CRDM nozzle, the potential implications of this occurring in a B&W plant were assessed. The first addendum to BAW-10190P concludes that it would take more than 40 years for such a circumferential crack to grow to the point where nozzle failure might occur[46]. The second addendum to BAW-10190P addressed the issue of cracking in the J-groove weld of the CRDM following the discovery of a weld manufacturing defect at Ringhals-2 in 1992. The addendum concludes that up to two thirds of the weld may be unsound and still meet the required weld structural requirements[47].

The NRC staff reviewed the BWOG submission of BAW-10190P, and issued a safety evaluation report to the industry organization NUMARC in November 1993, which concluded that the issue of CRDM nozzle cracking was not an "immediate or near term safety concern"[48] [49]. The bases for this conclusion were as presented in BAW-10190P[50]

- "…the cracks would be predominantly axial in orientation;"
- "…the cracks would result in detectable leakage before catastrophic failure;" and
- "…the leakage would be detected during visual examinations performed as part of surveillance walkdown inspections before significant damage to the reactor vessel closure head would occur."

However, the NRC staff safety evaluation also concluded that[51]:

- An integrated long term program was necessary to address the issue of CRDM cracking;
- NDE examinations should be performed to ensure there is no unexpected cracking;
- Surveillance walk-downs proposed by NUMARC are not intended for detecting small leaks;
- It is conceivable that some affected PWRs could potentially operate with small undetected leakage at CRDM/CEDM penetrations; and

- It is prudent for NUMARC to consider the implementation of an enhanced leakage detection method for detecting small leaks during plant operation.

As we noted previously (Section 5.1.4), in France and Sweden, N-13 leakage monitoring systems for the space between the RPV head and the head insulation had been developed and deployed that were capable of detecting very small leaks from CRDM nozzle cracks. In the U.S., because the NRC concluded that the issue of CRDM cracking was not an "immediate or near term safety concern", such leak detection systems were not required.   .

5.3.3 NRC/INEL/EG&G Assessment of CRDM Nozzle Cracking

In October 1994, the NRC published an assessment of PWR CRDM nozzle cracking prepared for the NRC by EG&G Idaho, under the auspices of the Idaho National Engineering Laboratory and the US Department of Energy. This report contained a comprehensive review of CRDM nozzle cracking inspection experience and its safety significance, the effects of nozzle design, materials, stress and environment on PWSCC, the potential for boric acid corrosion of the RPV head, leak detection, and repair, replacement and other mitigation options[52].

This report essentially reached similar conclusions as both the BWOG reached in the May 1993 BAW-10190P safety evaluation report and the NRC staff reached in its November 1993 safety evaluation of that BWOG report. Some of the key conclusions of the NRC/EG&G report were that:

- Cracks would be mostly axial and were unlikely to lead to CRDM nozzle rupture.

- Through wall axial cracks would not grow more than a few inches above the weld because stresses in the nozzle drop off rapidly above the weld;

- Axial crack propagation to through wall in the CRDM nozzle would take at least six years;

- Conservative estimates[f] of boric acid corrosion of the RPV head showed that it would take at least six to nine years from the time leakage started from a through wall crack above the weld for RPV head wastage to progress sufficiently to challenge the structural integrity of the RPV head;

- Existing leakage detection methods and programs instituted in response to NRC GL 88-05 to detect boric acid leakage were not adequate to detect small leaks such as that observed at the Bugey-3 cracked CRDM nozzle;

- Enhanced N-13 based leakage detection systems had been developed and deployed in Europe to detect very small leaks from RPV head penetration nozzles;

- European and Japanese utilizes had carried out inspections of most CRDM nozzles for cracks at almost all plants, whereas only one US plant had been inspected; and

- Replacement of RPV heads as a permanent solution to the CRDM cracking problem was already well under way at non-US plants.

It is worthy of note here that the primary focus of all of this work was on the potential for CRDM nozzle failure and nozzle ejection, and on the critical crack sizes that would be required before such failures would occur. While the potential for boric acid

---

[f] By Westinghouse and B&W, not the NRC

corrosion of the RPV head was considered, it was not regarded as the primary safety issue.

In fact, as the Davis-Besse event illustrates only too well, and as the analysis in Sections 8 and 9 of this report show, the critical crack size at which boric acid leakage becomes large enough to cause thermal-hydraulic conditions such that extremely high rates of wastage and metal removal occur, is well below the critical crack size needed to cause nozzle failure.

5.3.4 NRC Generic Letter GL 97-01 and Industry Response

On April 1, 1997, almost six years after the first report of the Bugey-3 CRDM nozzle crack and leakage, the NRC issued a Generic Letter dealing with the subject of CRDM nozzle cracking[53]. A Generic Letter requires written responses and commitments from licensees, and GL 97-01 allowed PWR licensees 30 days to provide an initial response and 120 days for a detailed report describing licensee plans to comply with the GL 97-01 requirements.

GL 97-01 reviewed the history of CRDM nozzle cracking and the results of inspections both in the US and overseas, as well as the 1993 US industry safety assessments, including BAW-10190P discussed above. Despite the NRC staff's endorsement of BAW-10190P in its own November 1993 safety evaluation and its conclusion that CRDM nozzle cracking was not an immediate safety concern, the NRC continued to believe that an integrated long term program was necessary. GL 97-01 went on to re-iterate the NRC staff's November 1993 conclusions (discussed above in section 5.3.3) that NDE examinations of CRDM nozzles were needed to ensure that cracking was not present, and that enhanced leak detection methods were needed to detect small leaks.

GL 97-01 concluded by requiring licensees to submit within 120 days a written report containing the following information, to allow the NRC to determine if augmented inspection requirements should be imposed to detect CRDM nozzle cracking:

- A description of all inspections of CRDM nozzles previously performed;
- A plan for periodic inspection of CRDM nozzles or justification for not conducting such an inspection;
- A description of any demineralizer resin intrusions into the RCS.

This last requirement was imposed as a result of the sulfate induced IGA/SCC that had occurred in 1994 at the Jose Cabrera (Zorita) plant in Spain.

The BWOG response to GL 97-01 was provided to the NRC on July 25, 1997 in topical report BAW-2301, which provided an integrated response and program applicable to all of the B&W operating plants[54 55]. BAW-2301 provided no new analysis, but simply noted that the safety assessment submitted to the NRC four years previously in BAW-10190P in May 1993 was still valid, as was the November 2003 NRC safety evaluation of the BWOG report.

The requested information on resin intrusion events and sulfur contamination of the RCS was provided as an attachment to BAW-2301 for each of the B&W operating plants. No "Zorita type" events had been identified, although elevated levels of sulfur species had occasionally been noted at each plant. For Davis-Besse, the data submitted show typical "hide-out" return of sulfur species during plant refueling shutdowns, at which times sulfate levels sometimes approached or exceeded the chemistry limits of 150 ppb, but which were appropriately reduced prior to restart of the plant[56].

With respect to the inspection program required by GL 97-01, BAW-2301 described the 1994 and 1996 inspections at Oconee-2 (see section 5.3.1), and committed the B&W plants to follow-on inspections at Oconee-2 and Crystal River-3 in 1999, because these two plants were noted to be "two of the plants most susceptible to PWSCC, as currently ranked" by the BWOG[57]. BAW-2301 also advised the NRC that inspections for the five other operating B&W plants (Oconee-1, Oconee-3, Davis-Besse, Arkansas

Nuclear-1 and Three Mile Island-1) were not planned in the near term, i.e. between 1998 and 2000[58]. Data on CRDM nozzle Alloy 600 properties were also provided for all the B&W plants[59].

Oconee-2 had already been inspected twice in 1994 and 1996 with only shallow indications being found that had not grown over the two year period of operation. The BAW-2301 report states that Oconee-2 "contains CRDM nozzles that are the most susceptible of the B&WOG plants."[60] Given the CRDM cracking experience at Oconee-1 and Oconee-3 in 2000/2001 that we describe below in Section 5.3.5, this was clearly not the case.

In the "Summary and Conclusions" of BAW-2301, after discussing prior inspections of CRDM nozzles at B&W plants and the planned inspections at Oconee-2 and Crystal River-3 in 1999, the report noted that[61]:

> "In addition, the B&WOG plants perform visual inspections of the RV head for potential leakage at each refueling outage, if not more often, in accordance with the B&WOG utility responses to Generic Letter 88-05."

The NRC apparently accepted this inspection approach, despite on-going concerns about the ability of visual inspections and other existing leak detection programs to detect small leaks from cracked CRDM nozzles expressed in the NRC's own 1993 safety assessment and October 1994 report (Sections 5.3.2/5.3.3).

The major reliance by the US PWR industry on visual inspection for boric acid leakage from CRDM nozzles continued until the discovery of extensive cracking at the three B&W Oconee plants in 2000/2001. It was not until then that the NRC began requiring and the US industry began performing 100% NDE inspections of CRDM nozzles for cracks.

Finally, the BAW-2301 response to GL 97-01 concluded that, as a result of the activities and evaluations performed by the BWOG[62]:

> "Inspections are not necessary from a safety perspective….The time frame for future B&WOG plant inspections, other than those discussed in this document [Oconee-2 and Crystal River-3 planned for 1999], will be dependent upon results of the B&WOG planned inspections, other planned U.S. industry inspections, worldwide industry experience, and economic factors."

The interchange of information between the NRC and the US utility industry stretched into 1999. In September 1998, the NRC forwarded a "Request for Additional Information" (RAI) to Toledo Edison (at that time the operating licensee for Davis-Besse) concerning the information submitted in BAW-2301 in July 1997. The response was provided to the NRC in December 1998 in the form of a generic response applicable to all B&W plants, and was specifically submitted again by FirstEnergy in January 1999[63].

Most of the NRC's RAI was directed at the industry model for PWSCC susceptibility. With respect to this critical issue, in the industry response Davis-Besse was ranked in the "5-15 EFPYs Intermediate Susceptibility Group", meaning that Davis-Besse was judged to have the same probability of having a 75% through wall crack in 5 to 15 EFPYs (from January 1, 1997) as the probability that D.C. Cook-2 had of having the same 75% through wall crack[g] at the time of its 1994 inspection[64].

This is significant, since it gave both FirstEnergy and the NRC assurance that, as of January 1997 (when the ranking was first performed), Davis-Besse was well removed – in fact 5 to 15 EFPY removed - from having a 75% through wall crack similar to D.C. Cook-2 in a CRDM nozzle. Even the minimum 5 EFPY would carry Davis-Besse well into 2002 or even 2003 before such a 75% through wall CRDM nozzle crack would be expected to develop.

---

[g] In fact, the CRDM nozzle crack at D.C. Cook-2, was only 43% through wall (see section 5.31.), and the probability that Davis-Besse would have a crack at 43% through wall within 5 to 15 EFPYs was greater than the probability for a 75% through wall crack. The industry response used the 75% through wall as a criterion for ranking plants because 75% was the established repair limit.

This assessment, like other assessments of the probability of CRDM nozzle cracks at Davis-Besse and other plants, eventually proved to be erroneous, but it was the best assessment that the industry and the NRC could make at the time on the basis of the available data and information. The ranking table provided to the NRC showed that Davis-Besse, within its “5 to 15 EFPY Intermediate Susceptibility Group.”

We note here that the B&W plants at Oconee-1 and Oconee-3 were ranked in the “High Susceptibility <5 EFPY” group in the industry response to the NRC’s RAI related to GL 07-01[65]. Despite this ranking, inspection of the RPV head penetration nozzles at both Oconee-1 and Oconee-3 was not judged necessary and was not even planned because both had a lower calculated susceptibility to PWSCC in the CRDM nozzles than their “sister” plant Oconee-2.

A summary of the industry response to GL 97-01 was presented at the 2000 EPRI PWSCC workshop, and noted that the NRC had closed out GL 97-01 based on the satisfactory industry responses to the RAIs in late 1998/early 1999[66]. This presentation (as well as others at the same workshop) also noted that the industry had created the PWR Materials Reliability Program (MRP), coordinated by EPRI, to focus on various materials issues including the ongoing issue of CRDM nozzle cracking.

5.3.5 Experience of CRDM Nozzle Cracking in US Plants 2000-2001

The measured and long term response developed and implemented by the U.S. industry and the NRC in the 1994 to 1999 time period to address the issue of CRDM nozzle cracking at US plants was short lived. In the short time span of five months, four B&W plants were found to have leaking CRDM nozzles through routine RPV head visual examinations., All four of the plants required significant additional inspections and repairs[h].

---

[h] Most of the information in this and following sections on inspections and other information related to cracks and leaks from CRDM and other RPV head penetration nozzles through approximately the end

Oconee-1: In November 2000, small boric acid accumulations (less than 1 cubic inch total) indicative of leaking nozzles were discovered at Oconee-1 (a B&W plant) during a visual inspection of the RPV head. One leak was from a CRDM nozzle and five (out of eight) were located at thermocouple nozzles, which were smaller but had a similar Alloy 600 design[67]. ECT and UT inspections of the nozzle ID showed through wall axial cracks in all eight thermocouple nozzles, which were confirmed by laboratory examination to be PWSCC.

ECT inspection of the ID of the leaking CRDM nozzle and seven other CRDM nozzles showed “craze-type” indications on the up-hill side of the nozzles, both above and below the weld, but no cracks were found. UT inspection of the ID of the leaking nozzle, the seven inspected by ECT, and ten other nozzles was performed, but again no cracks were found. PT inspection of the weld region of the leaking nozzle identified some crack indications, and after grinding this region and performing another PT examination, an axial/radial PWSCC crack was found that appeared to have originated in the nozzle weld and then propagated in an axial/radial direction both through the weld and 0.4 inch into the nozzle from the OD. This was in contrast to previous industry experience, which showed most cracks to be ID initiated. The crack in this one leaking CRDM nozzle and weld was removed by grinding and the nozzle was weld repaired, while the thermocouple nozzles were removed and the holes in the PRV head were plugged[68 69].

In the next inspection in March 2002, a second CRDM nozzle was found leaking at the weld and had to be repaired, along with a third CRDM nozzle that was cracked but not leaking. By the September 2003 outage, Oconee-1 had developed leaks at two additional nozzles which were not inspected by ECT or UT because the RPV head was replaced at that outage[70].

---

of 2003 is taken from the EPRI MRP-110 report, which is the most recent and up-to-date compilation of data we have reviewed for this report.

Oconee-3: In February 2001 nine leaking CRDM nozzles were discovered at Oconee-3, again by visual inspection and evidence of boric acid leakage from the nozzle annuli. Inspection by ECT, UT, and PT confirmed the presence of through wall and part through wall axial cracks, originating again on the nozzle OD. In addition, several part depth circumferential cracks were found on the nozzle OD below the welds for four of the CRDM nozzles[71]. A total of 47 "recordable crack indications" in these nine nozzles were recorded as a result of the inspections[72].

Most significantly, during repair of these nozzles, circumferential cracks above the weld were also found on the OD of three CRDM nozzles. In two of these nozzles, the circumferential cracks extended almost half way (165º) around the nozzle, with one a through wall crack and the other with several pin-hole leaks. The third nozzle had a 35% through wall crack extending 66º around the nozzle. All three also had one or more significant circumferential cracks on the OD below the weld. A fourth nozzle had two significant circumferential cracks at the weld elevation, one 57% (extending 153º) and one 40% (extending 113º) through wall. These significant circumferential cracks had not been identified until the repair process was underway. UT inspection of nine additional CRDM nozzles showed that one additional nozzle had shallow axial indications on the nozzle ID. ECT inspection of these same nine nozzles showed "craze-type" indications (similar to those found on the ID at Oconee-1) distributed around the entire ID circumference of four of them[73] [74].

Circumferential cracks of this significance had not been seen before in CRDM nozzles in the U.S., and the NRC issued Information Notice IN 2001-05 on April 30, 2001 to disseminate information regarding these findings[75].

In November 2001, an additional five CRDM nozzles were found leaking at Oconee-3, all five were found to have axial through wall cracks, and two had circumferential cracks, one above the weld and one at the weld, 29% and 11% through wall respectively[i]. At the next outage in April 2003, the RPV head at Oconee-3 was replaced[76].

As we discussed in Section 5.3.4, although both Oconee-1 and Oconee-3 had been ranked in the "High Susceptibility <5 EFPY" group in the BAW-2301 response to GL 97-01 in July 1997, inspection of the RPV head penetration nozzles at these two plants was not judged necessary or even planned in 2000 and 2001 because both had a lower calculated susceptibility to PWSCC in the nozzles than their "sister" plant Oconee-2.

ANO-1: In March 2001, a month after the Oconee-3 discovery of significant CRDM nozzle cracking, a visual inspection of the RPV head at the B&W plant at ANO-1 revealed boric acid deposits, which were determined to have originated from a part depth axial crack on a CRDM nozzle that again initiated on the nozzle OD below the weld[77]. The crack had grown through the nozzle wall to a point 1.3 inches above the weld, thereby providing a leak path around the weld even though the crack was not through wall. The crack branched into two circumferentially oriented cracks just below the weld[78] [79].

At the next outage in October 2002, the same nozzle was again found leaking and was re-repaired, and seven additional CRDM nozzles were also found with cracks, one involving the weld. The ANO-1 RPV head was scheduled for replacement at the Fall 2005 outage[80].

We should note here that ANO-1 was ranked in the "Low Susceptibility >15 EFPY" group in the BWOG July 1997 response to GL 07-01 (section 5.3.4), and so in 2001, inspection of the RPV head CRDM nozzles at ANO-1 was likely regarded as an issue to be addressed in the future.

---

[i] The nozzle with the 29% through wall circumferential crack was Nozzle 2, one of the center nozzles where circumferential cracking was not anticipated due to the lower axial stresses predicted for that location as compared with the peripheral nozzle locations.

Oconee-2: The next month, in April 2001, during a visual examination of the RPV head at Oconee-2, boric acid deposits were found near four CRDM nozzles. Subsequent UT and PT examination identified all four nozzles as having OD axial cracks below the weld, none of which were through wall. Also, one CRDM was found to have an OD initiated circumferential crack above the weld around approximately 10% of the circumference and about 11% through wall. As for Oconee-1 and Oconee-3, subsequent ECT inspections of the ID the four leaking nozzles revealed shallow “craze-type flaw clusters” in all four nozzles, distributed around the entire ID circumference. It was concluded from the inspections that the leak path for the four leaking nozzles was through the interface between the nozzle and the weld from cracks originating on the OD below the weld[81].

During the inspections at the October 2002 outage, Oconee-2 was found to have ten additional CRDM nozzles with leaks, seven of which were leaking through the nozzle wall and three of which were leaking through the weld. Eight other CRDM nozzles with cracks required repair, three with cracks at welds. The Oconee-2 RPV head was replaced at the next outage in Spring 2004[82].

As we described in Section 5.3.1, Oconee-2 was the lead B&W plant to have CRDM nozzles inspected by ECT in 1994 (69 nozzles), 1996 (2 nozzles) and 1999 (8 nozzles). Only two minor indications had been found in Nozzles 23 and 63 in 1994, for which the ECT signals showed no change through the 1996 and 1999 inspections. Six other nozzles inspected in 1994 were re-inspected in 1999, with again no change in ECT signals being noted.

Clearly, and contrary to both the BWOG analysis and the NRC’s expectation, a number of nozzles had developed cracks and significant crack growth had occurred between the 1999 and the 2001/2002 inspections. Also noteworthy is the fact that by the October 2002 outage, one of the two nozzles (63) that had been tracked through three successive inspections in 1994, 1996 and 1999 required repair, as did one of the six other nozzles that had been inspected in 1994 and 1999 without significant indications being found.

MRP-110 reports that, subsequent to the cracked CRDM nozzles being discovered successively over the short time interval of five months at Oconee-1, Oconee-3, ANO-1, and Oconee-2[83]:

- "Over the next 15 months, leaks were discovered from CRDM nozzles at all seven B&W plants, and between 2000 and 2003, 53 CRDM nozzles were discovered to be leaking in 10 of the 69 U.S. PWRs and were subsequently repaired. These plants are among the top 15 of the highest susceptibility ranked units based on EDY calculations. The "high susceptibility" group defined by the NRC currently contains 28 units."

- "Most of the PWSCC cracks have been detected in the tube (predominantly axial cracks, on the ID or OD of the nozzle), but six units have experienced leaks due to weld cracking. At North Anna-2, six nozzles were found to be leaking in 2002, and the NDE results showed that most of the 65 CRDM J-groove welds had cracks requiring repair; the head was then replaced during the outage."

- "Leaks were discovered on small-bore thermocouple nozzles at Oconee-1 and TMI-1 in 2000 and 2001 respectively as previously noted (all 16 T/C nozzles were cracked at both units)."

- "Through-wall circumferential cracks above the J-groove weld were discovered first at Oconee-3 in 2001, and then at Oconee-2 (2001), Crystal River-3 (2001), North Anna-2 (close to the top of the weld, 2002) and Davis-Besse (2002)."

Overall, the B&W plants have experienced more leaks and cracks than any other vendor design worldwide, including the French units. This is clear from the overall statistics of CRDM nozzle cracks and leaks in the seven B&W plants:

- All seven operating B&W plants have experienced significant CRDM nozzle cracking;

- Cracking has occurred in 60 out of the 483 (12.4%) CRDM nozzles in the seven B&W plants;

- Of the 137 cracked nozzles that have occurred in the US fleet of 69 PWRs, 60 cracked nozzles (44% of the total) have been found in the seven B&W plants; and

- 42 of the 53 leaks that have occurred in the US fleet of 69 PWRs have occurred at the seven B&W plants.

Clearly, for the B&W plants, some combination of nozzle and weld design and manufacture, Alloy 600 material susceptibility, high residual and possibly high operating stresses, and high operating temperature, combined to produce this experience.

5.3.6 US Industry and NRC Regulatory Response to CRDM Nozzle Cracking 2000-2001

The experience of CRDM cracking at Oconee-1, Oconee-3 and ANO-1 in late 2000 and early 2001 described above in Section 5.3.2 prompted the NRC to issue Bulletin 2001-01 in August 2001 to address the problem[84].

Bulletin 2001-01 described the CRDM nozzle cracking at Oconee-1, Oconee-3, and ANO-1. While the NRC noted that the axial cracking discovered was "deemed to be of limited safety concern in the NRC staff's safety evaluation on the cracking of VHP nozzles dated November 18, 1993", the NRC now concluded that the circumferential cracking discovered at Oconee-3 in February 2001 and at Oconee-2 in April 2001 raised significant safety concerns. Among the NRC's concerns were[85]:

- The occurrence of cracking at the three B&W plants called into question the susceptibility model submitted in response to GL 97-01, since ANO-1 was judged to be a "low susceptibility" plant more than 15 EFPY away from any significant cracking.

- Through wall circumferential cracking of the extent found at Oconee-3 was not predicted or expected.

- Cracking of the weld metal prior to nozzle cracking had not previously been considered.

- Initiation of cracking from the OD raised questions about the effects of coolant leakage into the CRDM nozzle annulus.

- The Oconee-3 RPV head had been cleaned at the previous outage and no leakage had been experienced except from the CRDM nozzle cracks. The very small amount of boric acid deposits observed at Oconee-3 (less than 1 cubic inch) from leaking nozzles could easily be masked by pre-existing boric acid deposits, by leakage from other sources, be undetectable due to interferences from insulation, small clearances, or simply not be evident due to tight interference fits.

Licensees were required to submit the information requested by Bulletin 2001-01 within 30 days. Relevant to Davis-Besse, the key items were[86]:

- A plant specific susceptibility ranking with respect to Oconee-3.

- For "high susceptibility" plants within 5 EFPY of the operating time of Oconee-3, inspections were to be performed before December 31, 2001 to determine if CRDM cracking was present.

- If qualified visual inspections of the RPV head were proposed:

  - A qualified visual inspection of the 100% of the CRDM nozzles was to be performed before December 31, 2001.

- For the visual inspection, a plant specific demonstration was required to show that any nozzle with through wall cracks would provide sufficient leakage to the RPV head to allow detection based on the as-built nozzle configurations and clearances.

- The visual inspection should not be compromised by the presence of insulation, existing boric acid deposits, or other factors that could interfere with leakage detection.

• Absent the use of a qualified visual inspection meeting these criteria, a qualified volumetric examination (i.e. ECT or UT) of 100% of the nozzles was required to be performed by December 31, 2001.

An interim safety assessment of the newly discovered CRDM nozzle cracking at Oconee-1, Oconee-3 and ANO-1 was prepared by the EPRI MRP and is presented in MRP-44[87], and a final report to be used by individual utilities in responding to the plant specific requirements of NRC Bulletin 2001-01 was completed by August 2001 and presented in MRP-48[88].

The MRP-48 assessment showed that Davis-Besse was ranked in the "high susceptibility" category as a plant within 5 EFPY of the Oconee-3 operating time, with remaining EFPYs to reach an equivalent operating time to Oconee-3 of 3.1 EFPY calculated from March 1, 2001[89]. This was communicated by FirstEnergy to the NRC on September 4, 2001[90]. The MRP-48 assessment is significant because it gave FENOC assurance that Davis-Besse would not expect to find CRDM cracks such as those found at Oconee-3 until sometime in 2004 at the earliest, i.e. at the end of Cycle 14. Certainly on the basis of MRP-48, there would have been no expectation of finding significant cracks at 13RFO in March 2002.

It is significant here that the NRC's focus was on the risks posed by circumferential cracking and potential failure of CRDM nozzles, and not on RPV head wastage – in fact the issue of head wastage as a safety issue is not even raised in Bulletin 2001-01 or in the EPRI MRP responses. The only discussion in Bulletin 2001-01 about the crevice environment resulting from boric acid leakage concerns the potential effects of such leakage on the rate of cracking of the Alloy 600 nozzle material, and not on potential wastage of the RPV head.

Similarly the NRC staff's technical assessment as late as November/December 2001, focused on the effect of the CRDM crevice environment resulting from boric acid leakage to accelerate Alloy 600 crack growth rates, and not on the safety issue of accelerated RPV head wastage[91].

5.3.7 US CRDM Nozzle Cracks, Repairs, and RPV Head Replacements Since 2000

Table 5.2 shows RPV head nozzle design data[j] for all 69 operating US PWRs, 7 of which are B&W designed plants[92]. As this table shows, there are a total of 4,961 CRDM nozzles in these 69 plants[k].

Table 5.2 provides a summary of the 14 US plants where RPV head CRDM nozzle and/or weld cracking has been found. Cracking has occurred at a total of 137 (2.8%) of the 4,961 nozzles, in 14 plants (20%) out of 69 plants, with some nozzles experiencing cracking in both the nozzle and the weld. Half of the 14 plants where CRDM cracks have been found were the 7 B&W plants.

Table 5.3 provides a summary of the crack orientation and location for all detected CRDM nozzle cracks in US plants, with a total of 386 detected cracks in the 137 affected nozzles, of which approximately 30% occurred on the ID and 70% on the OD. Only 35 of the 386 cracks were circumferential cracks that required repair, and of the

---

[j] All data in this section are taken from MRP-110. Inspection data are current through approximately the end of 2003.

[k] The term Control Element Drive Mechanism (CEDM) is used for CE plants, we use the term "CRDM' throughout this report to describe both CRDMs and CEDMs.

19 circumferential cracks that were above or near the top of the weld, only two were through wall.

Table 5.4 provides a summary of inspections of US plant RPV head nozzle J-groove welds together with the number of cracked and leaking welds. Cracks and leaks have been found only in plants with greater than 12 EDYs of operation, but this may be partly because around 86% of the inspected welds were in these higher susceptibility plants.

Table 5.5 provides a summary of the 53 CRDM nozzles in the 10 US plants in which leakage due to nozzle or weld cracks has been detected. Of these 53 nozzle leaks, 42 occurred in the 7 B&W plants. Leakage in approximately 38% of the 53 leaking nozzles was attributable to cracking initiated in the weld. Also, for these 53 leaking nozzles, MRP-110 notes that[93]:

> "Over 50% of the nozzles were repaired with a method that would likely have detected significant wastage if had occurred. Little or no wastage has been detected in these units except for Davis-Besse."

We would add that Davis-Besse remains the only plant where an extensive wastage cavity developed as a result of boric acid leakage from a cracked and leaking CRDM. All of the 53 leaks detected occurred in plants with more than 16 EDYs of operation, and 42 of the leaks occurred in the 7 B&W designed plants, representing almost 9% of the total number of nozzles installed in the B&W plants. The remaining leaks were in the three Westinghouse designed plants where the RPVs were manufactured by the Rotterdam Dockyard Company, and all the leaks in these three plants were associated with cracks in welds.

Finally, Table 5.6 provides a summary of US plants for which, as of January 2004, RPV head replacements had either been completed or announced, the total of 33 representing 48% of the 69 US PWRs in operation. Most of these are ranked in the "high susceptibility for PWSCC" category according to the MRP ranking method.

Table 5.1 EdF CRDM Inspection Results Reported at the 1992, 1994 and 2000 EPRI Workshops on PWSCC

December 1992 EPRI PWSCC Workshop

Plant Type	Number of Plants	Number of Plants Inspected	Total Number of CRDM Penetrations	Number of CRDM Penetrations Inspected	Number (%) of Inspected CRDM Penetrations With Cracks
CPO 900 MWe	6	6	390	304	19 (6.3)
CPY 900 MWe	28	0	1820	0	0
1300 MWe	20	9	1542	392	10 (2.6)

November 1994 EPRI PWSCC Workshop

Plant Type	Number of Plants	Number of Plants Inspected	Total Number of CRDM Penetrations	Number of CRDM Penetrations Inspected	Number (%) of Inspected CRDM Penetrations With Cracks
CPO 900 MWe	6	6	390	378	19 (5.0)
CPY 900 MWe	28	27	1820	1755	69 (3.9)
1300 MWe	20	14	1542	1080	20 (1.9)

February 2000 EPRI PWSCC Workshop

Plant Type	Number of Plants	Number of Plants Inspected	Total Number of CRDM Penetrations	Number of CRDM Penetrations Inspected	Number (%) of Inspected CRDM Penetrations With Cracks
CPO 900 MWe	6	6	390	390	23 (5.9)
CPY 900 MWe	28	27	1820	1820	126 (6.9)
1300 MWe	20	20	1542	1542	95 (6.2)

Table 5.2 Summary of US Plants with Detected RPV Head CRDM Nozzle and/or Weld Cracking (from MRP-110)

Number	Unit	EDYs thru Feb. 2001 (@ 600°F) (MRP-48)	Current Head Temp. (°F)	NSSS Supplier	Vessel Fabricator (Note 1)	Nozzle Material Supplier (Note 2)	No. of CRDM or CEDM Nozzles on Head	Number Cracked Penetrations Detected (Note 3)			Notes
								Total	Due to Tube Cracking	Due to Weld Cracking	
1	ANO 1	19.5	602.0	B&W	BW	B/H	69	8	7	2	
2	Beaver Valley 1	12.4	595.0	W	BW/CE	H/B	65	4	4	0	
3	Cook 2	13.0	600.7	W	CBI	W	78	3	3	0	
4	Crystal River 3	15.6	601.0	B&W	BW	B	69	1	1	1	
5	Davis-Besse	17.9	605.0	B&W	BW	B/H	69	5	5	0	
6	Millstone 2	10.5	593.9	CE	CE	H	69	14	14	0	
7	North Anna 1	19.4	600.1	W	RDM	S	65	6	6	1	
8	North Anna 2	18.3	600.1	W	RDM	S	65	42	8	42	
9	Oconee 1	22.1	602.0	B&W	BW	B	69	5	5	2	4
10	Oconee 2	22.0	602.0	B&W	BW	B	69	19	18	4	
11	Oconee 3	21.7	602.0	B&W	BW	B	69	14	14	2	
12	St. Lucie 2	12.3	595.6	CE	CE	SS/H	91	2	2	0	5
13	Surry 1	18.6	597.8	W	BW/RDM	H	65	6	0	6	
14	TMI 1	17.5	601.0	B&W	BW	B	69	8	7	4	4
							Unique Penetration Totals	137	94	64	

NOTES:

1. Key for Vessel Fabricators: BW = B&W, CBI = Chicago Bridge & Iron, CE = Combustion Engineering, RDM = Rotterdam Dockyard, CL = C.L. Imphy
2. Key for Material Suppliers: B = B&W Tubular Products, H = Huntington, S = Sandvik, SS = Standard Steel, W = Westinghouse, CL = C.L. Imphy, A = Aubert et Duval
3. The totals reflect CRDM and CEDM nozzles that were found to have cracks requiring repairs. In addition, the 8 small-diameter B&W thermocouple nozzles each at Oconee 1 and TMI 1 were found to be cracked. No other types of reactor vessel head penetrations have been reported to have PWSCC indications. Note that NDE of the welds is often not as complete as for the tubes, so some weld cracks may have not been found during inspections and thus not reflected in this table.
4. Also all 8 small-diameter B&W thermocouple nozzles were found to be cracked.
5. The CEDM nozzle material at this plant was supplied by Standard Steel, and the ICI nozzle material was supplied by Huntington Alloys.

Table 5.3 Orientation and Location of CRDM Nozzle Cracks in US Plant RPV Head CRDM Nozzles (from MRP-110)

Type / *Location*		No. of Indications on the Nozzle ID	No. of Indications on the Nozzle OD	*Total*
No. of Axial Tube Indications		112	239	*351*
No. of Circumferential Tube Indications	**Above Weld**	0	7	*7*
	Weld Elevation	0	12	*12*
	Below Weld	6	10	*16*
	Total	*118*	*268*	*386*

Note: Craze cracking and other shallow indications with no depth detectable by UT are not included.

Table 5.4 Summary of Inspections of US Plant RPV Head Nozzle J-Groove Welds (from MRP-110)

Inspection Number	Unit	NSSS Supplier	Approx. EDYs at Insp.	Insp. Date	No. of CRDM Nozzles on Head	Number Leaking Penetrations (Note 1) Total	Due to Tube Cracking	Due to Weld Cracking	Notes
1	ANO 1	B&W	19.6	Mar-2001	69	1	1	0	
2			21.1	Oct-2002	69	1	1	0	2
3	Crystal River 3	B&W	16.2	Oct-2001	69	1	1	0	
4	Davis-Besse	B&W	19.2	Apr-2002	69	3	3	0	3
5	North Anna 1	W	21.4	Mar-2003	65	1	0	1	
6	North Anna 2	W	19.0	Nov-2001	65	3	0	3	
7			19.7	Sep-2002	65	6	0	6	4, 5
8	Oconee 1	B&W	21.8	Nov-2000	69	1	0	1	6
9			23.2	Mar-2002	69	1	0	1	
10			24.7	Sep-2003	69	2	2	0	7, 8
11	Oconee 2	B&W	22.2	Apr-2001	69	4	4	0	
12			23.7	Oct-2002	69	10	7	3	
13	Oconee 3	B&W	21.7	Feb-2001	69	9	9	0	
14			22.5	Nov-2001	69	5	5	0	
15	Surry 1	W	19.1	Oct-2001	65	2	0	2	
16	TMI 1	B&W	18.1	Oct-2001	69	5	1	4	9
					Unique Penetration Totals	53	33	20	

NOTES:

1. No CEDM, ICI, or other types of reactor vessel head nozzles have been found to be leaking (other than the B&W thermocouple nozzles at the two units that have this type of nozzle). Note that NDE of the welds is often not as complete as for the tubes, so some leak path cracks through the weld metal from the wetted weld surface to the nozzle annulus may have not been found during inspections and thus not reflected in this table.
2. The leaking nozzle that was repaired in March 2001 was found to be leaking again in October 2002.
3. Detailed destructive examinations of the original Davis-Besse head have been performed to characterize the extent of wastage. The destructive examinations showed an axial crack through most of the weld cross section at the location of the long axial tube crack in Nozzle #3, which was adjacent to the large wastage cavity.
4. One of the leaking nozzles that was repaired in late 2001 was found to be leaking again in September 2002.
5. Several cracked nozzles have been extracted from the original North Anna 2 head for destructive testing including characterization of tube and weld cracks, among other tests.
6. Also 5 of the 8 small-diameter B&W thermocouple nozzles were found to be leaking.
7. It is assumed in the table that these two penetrations were found to be leaking due to base metal cracking although no inspections were performed to investigate before head replacement.
8. Also one small-diameter thermocouple penetration that was previously repaired with an Alloy 690 plug was found to be leaking. The cause of the leakage (incomplete weld coverage, cracking, etc.) was not determined as the head was replaced.
9. Also all 8 small-diameter B&W thermocouple nozzles were found to be leaking.

Table 5.5 Summary of US Plants with Detected RPV Head CRDM Nozzle Leakage (from MRP-110)

Inspection Number	Unit	NSSS Supplier	Approx. EDYs at Insp.	Insp. Date	No. of CRDM Nozzles on Head	Number Leaking Penetrations (Note 1): Total	Due to Tube Cracking	Due to Weld Cracking	Notes
1	ANO 1	B&W	19.6	Mar-2001	69	1	1	0	
2			21.1	Oct-2002	69	1	1	0	2
3	Crystal River 3	B&W	16.2	Oct-2001	69	1	1	0	
4	Davis-Besse	B&W	19.2	Apr-2002	69	3	3	0	3
5	North Anna 1	W	21.4	Mar-2003	65	1	0	1	
6	North Anna 2	W	19.0	Nov-2001	65	3	0	3	
7			19.7	Sep-2002	65	6	0	6	4, 5
8	Oconee 1	B&W	21.8	Nov-2000	69	1	0	1	6
9			23.2	Mar-2002	69	1	0	1	
10			24.7	Sep-2003	69	2	2	0	7, 8
11	Oconee 2	B&W	22.2	Apr-2001	69	4	4	0	
12			23.7	Oct-2002	69	10	7	3	
13	Oconee 3	B&W	21.7	Feb-2001	69	9	9	0	
14			22.5	Nov-2001	69	5	5	0	
15	Surry 1	W	19.1	Oct-2001	65	2	0	2	
16	TMI 1	B&W	18.1	Oct-2001	69	5	1	4	9
					Unique Penetration Totals	53	33	20	

NOTES:

1. No CEDM, ICI, or other types of reactor vessel head nozzles have been found to be leaking (other than the B&W thermocouple nozzles at the two units that have this type of nozzle). Note that NDE of the welds is often not as complete as for the tubes, so some leak path cracks through the weld metal from the wetted weld surface to the nozzle annulus may have not been found during inspections and thus not reflected in this table.
2. The leaking nozzle that was repaired in March 2001 was found to be leaking again in October 2002.
3. Detailed destructive examinations of the original Davis-Besse head have been performed to characterize the extent of wastage. The destructive examinations showed an axial crack through most of the weld cross section at the location of the long axial tube crack in Nozzle #3, which was adjacent to the large wastage cavity.
4. One of the leaking nozzles that was repaired in late 2001 was found to be leaking again in September 2002.
5. Several cracked nozzles have been extracted from the original North Anna 2 head for destructive testing including characterization of tube and weld cracks, among other tests.
6. Also 5 of the 8 small-diameter B&W thermocouple nozzles were found to be leaking.
7. It is assumed in the table that these two penetrations were found to be leaking due to base metal cracking although no inspections were performed to investigate before head replacement.
8. Also one small-diameter thermocouple penetration that was previously repaired with an Alloy 690 plug was found to be leaking. The cause of the leakage (incomplete weld coverage, cracking, etc.) was not determined as the head was replaced.
9. Also all 8 small-diameter B&W thermocouple nozzles were found to be leaking.

Table 5.6 Summary of US Plant RPV Head Replacements (from MRP-110)

Status	Year	Season	No.	Unit Name
Already Replaced	2002	Fall	1	Davis-Besse
			2	North Anna 2
	2003	Spring	3	North Anna 1
			4	Oconee 3
			5	Surry 1
		Fall	6	Crystal River 3
			7	Ginna
			8	Oconee 1
			9	Surry 2
			10	TMI 1
Announced Plans	2004	Spring	11	Oconee 2
		Fall	12	Farley 1
			13	Kewaunee
			14	Turkey Point 3
	2005	Spring	15	Millstone 2
			16	Point Beach 2
			17	Prairie Island 2
			18	Turkey Point 4
			19	Salem 2
		Fall	20	ANO 1
			21	Farley 2
			22	Point Beach 1
			23	Robinson 2
			24	St. Lucie 1
			25	Salem 1
	2006	Spring	26	Beaver Valley 1
			27	Calvert Cliffs 1
			28	Prairie Island 1
		Fall	29	Cook 1
			30	Fort Calhoun
	2007	Spring	31	Calvert Cliffs 2
		Fall	32	St. Lucie 2
			33	Cook 2

5.4 References

1. “Proceedings: 1991 EPRI Workshop on PWSCC of Alloy 600 in PWRs”, EPRI Report TR-100852, July 1992 (workshop took place October 9-11, 1991), pages S-2, 1-2.

2. “Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs”, EPRI Report TR-103345, December 1993 (workshop took place December 1-3, 1992), pages 3-1 through 3-3 and presentation paper B1.

3. “Materials Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for US PWR Plants (MRP-110)”, EPRI report TR-1007830, March 2004, page 4-3.

4. “Assessment of Pressurized Water Reactor Control Rod Drive Mechanism Nozzle Cracking”, NRC report NUREG/CR-6245 (EGG-2715), October 1994, pages 4 through 6.

5. *Ibid*, page 5.

6. “Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs”, EPRI Report TR-103345, December 1993 (workshop took place December 1-3, 1992), pages 3-3 through 3-4 and presentation paper B2.

7. “Proceedings: 1994 EPRI Workshop on PWSCC of Alloy 600 in PWRs”, EPRI Report TR-105406, August 1995 (workshop took place November 15-17, 2004), pages 2-1 through 2-3 and presentation paper A1.

8. “Proceedings: 2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs (PWRMRP-27)”, EPRI Report 1000873, 2000 (workshop took place February 14-16, 2000), pages 3-1 through 3-2 and presentation paper B1.

9. “Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs”, EPRI Report TR-103345, December 1993 (workshop took place December 1-3, 1992), pages 3-4 through 3-7, 6-10 through 6-11, and presentation papers B3 and E6.

10. “Proceedings: 1994 EPRI Workshop on PWSCC of Alloy 600 in PWRs”, EPRI Report TR-105406, August 1995 (workshop took place November 15-17, 2004), pages 2-4 through 2-6 and presentation paper A3.

11. *Ibid*, presentation paper A3 at pages A3-4, 5, 18.

12. *Ibid*, presentation paper A3 at pages A3-5, 6, 19, 20, 24.

13. *Ibid*, pages 2-6 through 2-7 and presentation paper A4.

14. *Ibid*, pages 2-8 through 2-9 and presentation paper A5.

15. *Ibid*, page 5-11 and presentation paper D7.

16. *Ibid*, pages 2-13 through 2-14 and presentation paper A9.

17. "Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs", EPRI Report TR-103345, December 1993 (workshop took place December 1-3, 1992), page 3-16 and presentation paper B7.

18. "Proceedings: 2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs (PWRMRP-27)", EPRI Report 1000873, 2000 (workshop took place February 14-16, 2000), pages 3-4 through 3-5 and presentation paper B4.

19. "Proceedings: 1992 EPRI Workshop on PWSCC of Alloy 600 in PWRs", EPRI Report TR-103345, December 1993 (workshop took place December 1-3, 1992), pages 8-4 through 8-5 and presentation paper G5.

20. "Proceedings: 1994 EPRI Workshop on PWSCC of Alloy 600 in PWRs", EPRI Report TR-105406, August 1995 (workshop took place November 15-17, 2004), page 2-10 and presentation paper A6.

21. "Proceedings: 1991 EPRI Workshop on PWSCC of Alloy 600 in PWRs", EPRI Report TR-100852, July 1992 (workshop took place October 9-11, 1991).

22. *Ibid*, page B-1 and presentation paper B1.

23. US NRC Information Notice 90-19, "Primary Water Stress Corrosion Cracking of Inconel 600", February 23, 1990.

24. "Assessment of Pressurized Water Reactor Control Rod Drive Mechanism Nozzle Cracking", NRC report NUREG/CR-6245 (EGG-2715), October 1994, page 8.

25. "Proceedings: 1994 EPRI Workshop on PWSCC of Alloy 600 in PWRs", EPRI Report TR-105406, August 1995 (workshop took place November 15-17, 2004), page 2-15 and presentation paper A10.

26. *Ibid*, presentation paper A11.

27. *Ibid*, pages 2-3 through 2-4 and presentation paper A2.

28. "Proceedings: 2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs (PWRMRP-27)", EPRI Report 1000873, 2000 (workshop took place February 14-16, 2000), pages 3-7 through 3-8 and presentation paper B6.

29. "Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan", EPRI report (draft final) 1007830, March 2004, at page 4-4.

30. "Proceedings: 2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs (PWRMRP-27)", EPRI Report 1000873, 2000 (workshop took place February 14-16, 2000), pages 3-6 through 3-7 and presentation paper B5.

31. *Ibid*, page S-2 and presentation paper E2 at page E2-6.

32. "Assessment of Pressurized Water Reactor Control Rod Drive Mechanism Nozzle Cracking", NRC report NUREG/CR-6245 (EGG-2715), October 1994, Table 2 at page 9.

33. "Proceedings: 2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs (PWRMRP-27)", EPRI Report 1000873, 2000 (workshop took place February 14-16, 2000), pages 3-1 through 3-2 and presentation paper B1.

34. "Alloy PWSCC Time-to-Failure Models", B&W report 51-1218440-00, October 2, 1992.

35. "CRDM Nozzle Characterization", B&W report 51-1219143-00, December 1992.

36. "Safety Evaluation for B&W Design Reactor Vessel Head Control Rod Drive Mechanism Nozzle Cracking", BAW-10190P, May 1993.

37. *Ibid*, pages 1-2.

38. *Ibid*, pages 11-14.

39. *Ibid*, pages 15-17.

40. *Ibid*, pages 17-19.

41. *Ibid*, pages 19-21.

42. *Ibid*, pages 21-22.

43. *Ibid*, pages 21-24.

44. *Ibid*, pages 24-25.

45. *Ibid*, pages 25, 40.

46. "External Circumferential Crack Growth Analysis for B&W Design Reactor Vessel Head Control Rod Drive Mechanism Nozzles", BAW-10190P, Addendum 1, December 1993.

47. "Safety Evaluation for Control Rod Drive Mechanism Nozzle J-Groove Weld", BAW-10190P, Addendum 2, December 1997.

48. Letter from W.T. Russell (NRC) to W.H. Rasin (NEI) dated November 19, 1993.

49. NRC Generic Letter 97-01, "Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations", US NRC, Office of Nuclear Reactor Regulation, Washington, D.C., April 1, 1997, at pages 3, 5 of 10.

50. *Ibid*, at page 3 of 10.

51. *Ibid*, at page 6 of 10.

52. "Assessment of Pressurized Water Reactor Control Rod Drive Mechanism Nozzle Cracking", NRC report NUREG/CR-6245 (EGG-2715), October 1994.

53. NRC Generic Letter 97-01, "Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations", US NRC, Office of Nuclear Reactor Regulation, Washington, D.C., April 1, 1997

54. BWOG letter to the NRC dated July 25, 1997, transmitting BAW-2301.

55. BWOG materials Committee report BAW-2301, "B&WOG Integrated Response to Generic Letter 97-01: Degradation of Control Rod Drive Mechanism Nozzle and Other Vessel Closure Head Penetrations", July, 1997.

56. *Ibid*, Attachment C, pages C-8, C-9, C-19 through C-21.

57. *Ibid*, pages 2-5, 2-6, and Table 4 at page 2-13.

58. *Ibid*, at page 2-6.

59. *Ibid*, Table 1 at page 2-10.

60. *Ibid*, at page 2-5.

61. *Ibid*, at pages 4-1, 4-2.

62. *Ibid*, at pages 4-1, 4-2.

63. FirstEnergy letter to the NRC dated January 14, 1999, with Enclosures 1 through 7 (Enclosure 3, Items 1 through 4 contained information specifically applicable to all B&W plants including Davis-Besse).

64. *Ibid*, Enclosure 1, pages 1-6.

65. *Ibid*, Enclosure 1, pages 1-6.

66. "Proceedings: 2000 EPRI Workshop on PWSCC of Alloy 600 in PWRs (PWRMRP-27)", EPRI Report 1000873, 2000 (workshop took place February 14-16, 2000), pages 2-1 through 2-2 and presentation paper A1.

67. "Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan", EPRI report (draft final) 1007830, March 2004, at page 4-4 and Table 4-4.

68. *Ibid*, at page 4-4.

69. "RV Head Nozzle and Weld Safety Assessment", Framatome-ANP report 5012567-01, September 28, 2001, at pages 9-10 of 56.

70. "Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan", EPRI report (draft final) 1007830, March 2004, Tables 4-2, 4-3, 4-4, 4-6, 4-8.

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

72. NRC Information Notice IN 2001-05, "Through-Wall Circumferential Cracking of Reactor Pressure Vessel Head Control Rod Drive Mechanism Penetration Nozzles at Oconee Nuclear station Unit 3", April 30, 2001, at page 1.

73. "Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP

Inspection Plan", EPRI report (draft final) 1007830, March 2004, Tables 4-2, 4-3, 4-4, 4-6.

74. "RV Head Nozzle and Weld Safety Assessment", Framatome-ANP report 5012567-01, September 28, 2001, at pages 10-11 of 56.

75. NRC Information Notice IN 2001-05, "Through-Wall Circumferential Cracking of Reactor Pressure Vessel Head Control Rod Drive Mechanism Penetration Nozzles at Oconee Nuclear station Unit 3", April 30, 2001.

76. "Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan", EPRI report (draft final) 1007830, March 2004, Tables 4-2, 4-3, 4-4, 4-6, 4-8.

77. *Ibid*, pages 4-4, 4-5.

78. "RV Head Nozzle and Weld Safety Assessment", Framatome-ANP report 5012567-01, September 28, 2001, at pages 11-12 of 56.

79. "Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan", EPRI report (draft final) 1007830, March 2004, pages 4-4, 4-5.

80. *Ibid*, Tables 4-2, 4-3, 4-4, 4-6, 4-8.

81. "RV Head Nozzle and Weld Safety Assessment", Framatome-ANP report 5012567-01, September 28, 2001, at pages 8-9 of 56.

82. "Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan", EPRI report (draft final) 1007830, March 2004, 4-2, 4-3, 4-4, 4-6, 4-8.

83. *Ibid*, at page 4-5.

84. NRC Bulletin 2001-01: Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles," August 3, 2001.

85. *Ibid*, page 2, 4 through 6.

86. Ibid, pages 6 through 8, 11

87. “PWR Materials Reliability Program Interim Alloy 600 Assessments for US PWR Plants (MRP-44), Part 2: Reactor Vessel Top Head Penetrations,” ERPI report TP-1001491, Part 2, May 2001.

88. “PWR Materials Reliability Program Response to NRC Bulletin 2001-01 (MRP-48),” ERPI report 1006284, August 2001.

89. *Ibid*, Table 2-1 at page 2-5.

90. FirstEnergy letter to the NRC, Serial Number 2731, September 4, 2001, response to item 1.a of NRC Bulletin 2001-01, Attachment 1 at page 1.

91. Memorandum from J.R. Strosnider, Director, Division of Engineering, NRR, to J.T. Larkins, Executive Director, ACRS, dated December 11, 2001, forwarding “Preliminary Staff Technical Assessment for PWR Vessel Head Penetration Nozzles Associated with NRC Bulletin 2001-01, “Circumferential Cracking of Reactor Pressure Vessel Head Penetration Nozzles”, dated November 2001, at pages 2 through 4.

92. “Material Reliability Program Reactor Vessel Closure Head Penetration Safety Assessment for U.S. PWR Plants (MRP-110): Evaluations Supporting the MRP Inspection Plan”, EPRI report (draft final) 1007830, March 2004, Table 1-1 at pages 1-9, 1-10.

93. *Ibid*, page 4-6.