U.S. NUCLEAR REGULATORY COMMISSION

OFFICE OF NUCLEAR REACTOR REGULATION

SAFETY EVALUATION OF "BWRVIP VESSEL AND INTERNALS PROJECT, EVALUATION OF STRESS CORROSION CRACK GROWTH IN LOW ALLOY STEEL VESSEL MATERIALS IN THE BWR ENVIRONMENT (BWRVIP-60)," EPRI REPORT TR-108709.

1.0 INTRODUCTION

1.1 Background

By letter dated March 30, 1999, the Boiling Water Reactor Vessel and Internals Project (BWRVIP) submitted the Electric Power Research Institute (EPRI) propriety Report TR-108709, "BWR Vessel and Internals Project, Evaluation of Stress Corrosion Cracking in Low Alloy Steel Vessel Materials in the BWR Environment (BWRVIP-60)," March 1999.

Intergranular stress corrosion cracking (IGSCC) is a significant issue for the austenitic materials used in boiling water reactor (BWR) internals. There have been a limited number of incidents where cracking has initiated in weldments attached to nozzle butter or where vessel cladding cracks have come into contact with the underlying vessel materials. These occurrences have prompted the BWRVIP to address integrity issues arising from the service related degradation phenomena.

The BWRVIP-60 report provides a formal methodology for the determination of stress corrosion cracking (SCC) in low alloy steel (LAS) reactor pressure vessels (RPV) and nozzles in a BWR environment. In particular, an evaluation is presented to assess the long-term potential susceptibility of the austenitic stainless steel cladding and the LAS base metal to SCC during normal water chemistry (NWC) or hydrogen water chemistry (HWC) plant operation. It also furnishes operational (membrane and bending stresses) and residual stresses along with the associated fracture mechanics stress intensity factor (K) distributions at key vessel locations to estimate the SCC growth behavior within LAS components. The allowable circumferential and axial flaw sizes were also calculated based on the guidelines provided in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section XI, "Rules For Inservice Inspection of Nuclear Power Plant Components," Article IWB-3600, "Analytical Evaluation of Flaws." Other BWR-related issues that were considered in this report were: vessel attachment types and configurations, a summary of RPV global operating experience with an emphasis on SCC, a review of the laboratory test data pertaining to SCC in LASs, and a discussion of the various crack growth theories.

1.2. Purpose

The NRC staff reviewed the BWRVIP-60 report to determine whether its guidance will provide an acceptable assessment methodology of stress corrosion crack growth in BWR LAS pressure vessels and nozzles. The review considered the past service experience with SCC in LASs, the validity of the fracture mechanics crack propagation models used, the residual stresses and through-wall stress intensity factor distributions produced in the welds and cladding, and whether the allowable flaw size analysis meets Code established criteria.

Enclosure

1.3. Organization of this Report

Because the BWRVIP report is proprietary, this SE was written not to repeat information contained in the report. The staff does not discuss in any detail the provisions of the guidelines nor the parts of the guidelines it finds acceptable. A brief summary of the contents of the BWRVIP-60 report is given in Section 2 of this SE, with the evaluation presented in Section 3. The conclusions are summarized in Section 4. The presentation of the evaluation is structured according to the organization of the BWRVIP-60 report.

2.0 SUMMARY OF BWRVIP-60 REPORT

The BWRVIP-60 report addresses the following topics:

- RPV Configurations, Vessel Attachment Types and Locations - Accompanied by a series of illustrations, the BWR pressure vessel structural configurations are described in considerable detail along with brief descriptions of each component's function and materials/welding characteristics. The various vessel attachments are classified, according to weld type and its RPV location.

- Operating Experience with BWR Pressure Vessels Related to SCC - The status of global operating experience with BWR RPVs is reviewed with regard to environmentally assisted cracking (EAC) in general and SCC in particular. A summary of all cases of damage is provided for domestic and foreign plants according to their cladding/base material, type, mechanism, and root cause of degradation, and the remedial measures that were taken. SCC susceptibility in the austenitic stainless steel cladding and the LAS base metal was evaluated.

- Laboratory Studies of SCC In LAS Within a BWR Environment - The current state of understanding SCC in LASs is examined based on data from laboratory test specimens. Experimental studies have shown that low alloy pressure vessel steels may be prone to SCC at high stress intensities, depending on the environment, load transient and material conditions. Investigations performed by General Electric (GE) and EPRI, as well as confirmatory reactor site testing is presented in order to research crack growth in LAS specimens exposed to actual plant water chemistry. The numerous variables which can affect cracking behavior such as MnS inclusion morphology, dissolved oxygen content, solution conductivity and flow rates are discussed in context of its relevance to crack growth modeling and crack propagation vs. stress intensity disposition curves.

- Current Crack Propagation Rate/Stress Intensity Disposition Relationships - Different crack growth theories are discussed relating crack propagation to oxidation at the crack tip and the stress/strain conditions at the crack tip. These theories have been supported by a correlation between the average oxidation current density on a straining surface and the crack propagation rate for a number of systems. The film rupture/slip-oxidation model, predicated on the experimentally validated elements of earlier proposals, is quantitatively and qualitatively addressed. Based on the existing crack growth data from laboratory analysis of pre-cracked specimens, overall experience of cracking of LASs in BWRs, and a mechanistic understanding of fracture mechanics, the possible disposition lines are assessed as a function of the crack tip strain rate and the concentration of MnS in solution.

- Stress Determination and Fracture Mechanics Considerations - This section describes the residual stress distributions for vessel cladding and the vessel attachment welds. Experimental and analytical weld and clad residual stresses are presented for these locations. Stresses associated with the BWR attachment welds are classified into fabrication and operational stresses. Also explained are the fracture mechanics models used to determine the K distributions for the through-wall stress profiles for the clad and the attachment weld residual stress profiles. Furthermore, K distributions were derived for operational stresses which consist of membrane and bending stresses. The allowable axial and circumferential flaw sizes were calculated using Code and accepted procedures.

- Examples of Fracture Mechanics Methodology for RPV and Attachments - Two examples illustrate the use of this report's methodology to evaluate crack propagation through SCC in LAS RPV material. The examples are presented for the top head flange and the shroud support plate. In both cases, through clad cracks are assumed as the initial condition and a crack growth evaluation is performed on the vessel wall. The analyses were conducted for both axial and circumferential flaws.

3.0 STAFF EVALUATION

LAS alloys, which are used in the fabrication of RPVs and associated nozzles, generally have a combination of high strength and excellent fracture toughness properties that make them suitable for design of the vessels at operating conditions. For BWR vessels designed using Section III of the 1965 Edition of the ASME Code, ASTM A-302 Grade B material was used for the fabrication of the vessel. For vessels designed using subsequent editions of the ASME Code, SA-533 Grade B Class 1 LAS plate material was used. The associated forging material used in nozzles is typically SA-508, Class 2. These materials are usually clad with austenitic stainless steel weld metal, typically Type 308 stainless steel, to provide improved general corrosion or pitting resistance during a low temperature shutdown as well as to allow for welding of attachments without the requirement for post weld heat treatment.

Examination of the materials used in the various vessel attachment welds indicate that some of them are fabricated from Alloy 182 weld metal, which has been shown to be susceptible to IGSCC. Recent findings at two BWR plants also demonstrated that under some circumstances, cracking can occur in the stainless steel cladding, especially in areas where manual welding is performed. Any initiated crack could propagate by SCC to the LAS RPV. The crack growth of stainless steel and the Alloy 182 weld material was addressed previously in the BWRVIP-14 and BWRVIP-59 reports, respectively. The staff has issued an initial SE for the BWRVIP-14 report dated June 8, 1998, and is reviewing the BWRVIP-59 report.

While there have been a limited number of incidents where cracking has initiated in weldments attached to a nozzle butter, or where vessel cladding cracks have come into contact with the underlying vessel materials, there have been no reported incidents of significant propagation of the cracks in LAS due to SCC.

Experimental studies performed under the auspices of EPRI and GE has shown that RPVs manufactured of LASs may be susceptible to SCC at high stress intensities, depending on the environment, load transient and material conditions. Laboratory testing as well as confirmatory reactor site testing results were presented in this report, which has determined that, based on available field experience and applicable laboratory test results, in the context of its relevance to crack growth modeling and disposition curves, there is a large number of variables that can affect cracking behavior, many of which were not always adequately controlled during the testing.

The various crack growth theories that relate crack propagation to oxidation at the crack tip and the stress/strain conditions at the crack tip are discussed in the BWRVIP-60 report. These theories have been supported by a correlation between the average oxidation current density on a straining surface and the crack propagation rate for a number of systems. Experimentally validated elements of these proposals have been incorporated into the discussed slip-dissolution model which relates the crack propagation to the oxidation that occurs when the protective film at the crack tip is ruptured. Continued crack advance will then depend primarily on a further oxide rupture process due to the action of a strain rate at the crack tip.

The BWRVIP-60 report discusses three possible crack propagation rates versus stress intensity disposition relationships that might be proposed for LASs in high temperature water, and makes the interim recommendation that, under BWR conditions, the GE "low sulfur" line be the upper bound disposition line. This relationship is:

$$V_K = 3.3 \times 10^{-14} K^4 \text{ mm/s, for K in MPa}\sqrt{\text{m}} \; (6.8 \times 10^{-12} K^4 \text{ in/h, for K in ksi}\sqrt{\text{in}})$$

The report further states that, under plane strain and constant load conditions in high purity BWR operating environments, crack growth cannot be sustained. However, although the mechanistic reasons for this are understood, there is a limited database for statistically claiming "no crack growth." Therefore, the report makes an interim recommendation for these conditions, based on engineering judgement:

$$V_K < 2 \times 10^{-8} \text{ mm/s, for } K < 55 \text{ MPa}\sqrt{\text{m}} \; (2.8 \times 10^{-6} \text{ in/h, for } K < 50 \text{ ksi}\sqrt{\text{in}})$$

Experimental and analytical weld and clad residual stress distributions are presented for the vessel cladding and the vessel attachment welds locations. Stresses associated with BWR attachment welds are classified into fabrication and operational stresses. Fabrication stresses consist of weld residual stresses resulting from welding the vessel plates, while clad stresses are due to the application of the clad and subsequent post weld heat treatment, and the stresses resulting from the attachment weld. Operational stresses are those associated with the normal operation of the plant and consist of stresses analyzed in the ASME Code stress reports.

Also presented are the allowable flaw sizes and the fracture mechanics' models used to determine the through-wall stress intensity factor (K) distributions for the through-wall stress profiles for the clad and the attachment weld residual stress profiles. These K distributions were also derived for operational stresses which consist of membrane and bending stresses. The determination of the allowable flaw sizes is based on the methodology provided in ASME Section XI, IWB-3600.

The BWRVIP-60 report presents examples for the top head flange and for the shroud support plate illustrating the use of this methodology to evaluate crack propagation through SCC in the LAS RPV material. In both cases, through clad cracks are assumed as the initial condition and a crack growth evaluation, considering both circumferential and axial flaws, are performed into the vessel wall. For the circumferential flaws, the results indicate that it takes approximately 16 years for the top head flange case and 41 years for the shroud plate case for an initial 360° flaw to reach the ASME Section XI allowable size. The time to reach the allowable flaw sizes increases to 28 and 66 years for the top head flange and the shroud plate respectively, when an initial 90° circumferential flaw is assumed. For the axial flaws, the operating periods to reach the allowable flaw size are eight and 33 years for the top head flange with aspect ratios of 0.1 and 0.5 respectively. The results for the shroud plate are 13 and 38 years.

The BWRVIP proposes that the methodology presented in this report including the crack growth disposition curves be used as a basis for evaluation of stress corrosion crack growth in LAS RPVs.

The NRC staff finds that the results of the SCC growth assessment presented in the BWRVIP-60 report for LAS vessel materials in a BWR environment to be acceptable.

4.0 CONCLUSION

The NRC staff has reviewed the BWRVIP-60 report and finds that the guidance of the BWRVIP-60 report is acceptable for the assessment of SCC growth in BWR low alloy steel pressure vessels and nozzles. The results of the licensee's methodology are acceptable because established fracture mechanic models, integrating existing crack growth rate data and a mechanistic understanding of SCC, were used to determine the through-wall K distributions for the cladding, attachment and vessel welds. In addition, ASME Section XI Code criteria were followed in the calculation of the allowable flaw sizes. Therefore, the staff has concluded that the procedures in the BWRVIP-60 report will provide an acceptable approach in appraising crack growth of the LAS RPV components addressed.

5.0 REFERENCES

1. Carl Terry, BWRVIP, to USNRC, "BWR Vessel and Internals Project, Evaluation of Stress Corrosion Cracking in Low Alloy Steel Vessel Materials in the BWR Environment (BWRVIP-60)," EPRI Report TR-108709, March 1999, dated March 30, 1999.

2. Section XI of the ASME Boiler and Pressure Vessel Code, "Rules for Inservice Inspection of Nuclear Power Plant Components," dated July 1, 1989..

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Please contact C. E. (Gene) Carpenter, Jr., of my staff at (301) 415-2169 if you have any further questions regarding this subject.

Sincerely

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