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Regulatory Perspective on Management of Alloy 82/182/600 Susceptibility and Cracking

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Abstract

The Nuclear Regulatory Commission (NRC) has assembled foreign and domestic information concerning Alloy 82/182/600 (and other nickel-based alloys) penetration nozzle cracking and boric acid corrosion. The current regulatory framework in the U.S. includes reliance on inspections beyond the American Society of Mechanical Engineers (ASME) Code requirements that are performed as a result of related NRC bulletins and industry guidance. NRC bulletins and industry guidance, in general, involve one-time inspections. Based on its review of this information, the NRC staff has concluded that additional inspections beyond one-time inspections are warranted for identifying leakage from primary water stress corrosion cracking (PWSCC) and for precluding boric acid corrosion as a result of such through-wall leakage.

Operating experience in the U.S. and in Europe and Japan has demonstrated that nickel-based alloy materials used to make dissimilar metal (DM) weld connections in the reactor coolant pressure boundary (RCPB) of pressurized water reactor (PWR) plants may be susceptible to PWSCC. PWSCC has been identified in welds to hot leg piping, pressurizer surge lines, pressurizer valve nozzles, as well as a drain line weld. Axial and circumferential PWSCC has been identified in these butt welds. This experience does not appear to be widespread; however, because of its safety significance, additional inspections or mitigative actions are needed to manage this issue. Additional inspections are likely to result in an improved understanding of the actual state of this problem in PWR plants. While this issue was not known or considered at the time the NRC granted leak-before-break (LBB) approvals, the issue applies to all DM welds in the RCPB regardless of the LBB status of the piping.

The NRC has several ongoing activities that address inspection of nickel-based alloy components susceptible to PWSCC. A number of inspections have been conducted by licensees as a result of these activities. Likewise, industry is developing inspection and evaluation guidelines to manage degradation, such as PWSCC. This paper will discuss the status of the NRC's regulatory approach to manage degradation in pressurized water reactor coolant systems.

Introduction

This paper is divided into two principal sections. Part I is concerned with Alloy 82/182/600 components in PWR reactor coolant system components other than steam generator tubing and butt welds. The second section is concerned with PWSCC in Alloy 82/182 butt welds and Alloy 600 safe ends. (NRC perspectives on steam generator tube integrity are addressed in a separate paper for this symposium.) While both sections of this paper are concerned with management of PWSCC, there are sufficient difference in operational experience, industry actions, management strategies, and regulatory involvement to treat these two classes of components separately.

The NRC can rely on industry actions in response to a materials degradation issue. The NRC considers reliance on industry actions to be the preferred approach provided the actions are technically comprehensive and timely, and provided information from industry is sufficient for the NRC to conclude that all affected licensees are implementing guidance issued by industry. The NRC relied extensively on actions taken by owners of boiling water reactors (BWR) to address intergranular stress corrosion cracking under the BWR Vessel and Internals project. The U.S. industry group known as the Materials Reliability Program (MRP) undertook an initiative in 2003 to develop a program for proactive management of materials degradation issues. Under this program, the MRP can issue guidelines for inspection and evaluation that essentially become mandatory for all licensees potentially affected by a particular degradation issue.

The NRC has a history of taking actions in response to materials degradation issues. The NRC has a number of regulatory vehicles it can use to address such issues. Actions taken in response to materials degradation issues are usually necessitated by a determination that the ASME Code, Section XI, does not require inspections that address a new degradation mechanisms and that industry response is untimely. NRC regulatory vehicles include bulletins and generic letters that suggest inspections the staff believes are needed to ensure that broadly framed regulations will continue to be met; bulletins and generic letters also gather information from licensees on their plans to conduct additional inspections. Bulletins are effective upon issuance. Generic letters are issued for stakeholder comments prior to being finalized. Another vehicle that is infrequently used is an order. An order may be issued by the Commission and upon issuance becomes a regulatory requirement. An order would be issued in the event that the NRC believes that specific actions are needed promptly to ensure the protection of public health and safety.

Regardless of whether the industry actions on a particular materials issue result from NRC or industry action, an essential aspect of NRC oversight is the inspections performed by NRC inspectors to ensure that the actions taken by licensees are consistent with their commitments.

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PART I

Background

Part I of this paper is concerned with Alloy 82/182/600 components in pressurized water reactor (PWR) reactor coolant systems other than steam generator tubing and butt welds.

In response to a recommendation from a “lessons learned” task force formed after the Davis-Besse event in 2002, the NRC research staff collected and summarized information available worldwide on Alloy 600, Alloy 690 and other nickel-based alloy nozzle susceptibility to stress corrosion cracking for use in evaluating revised inspection requirements (Reference 1). In a related task the NRC collected and summarized information available on boric acid corrosion (BAC) of pressure boundary materials for use in evaluation of revised inspection requirements (Reference 1). This same recommendation from the Davis-Besse Lessons Learned Task Force also stated that the NRC should propose a course of action to address the results of these studies on operating experience with PWSCC and BAC.

Discussion

NRC regulatory staff reviewed this report and other supporting information, including industry inspection activities, ASME Code activities, and industry materials degradation initiatives. Based on this review, NRC staff concluded that the positions established by NRC Order EA-03-009 (the Order) issued in 2003 (and revised in 2004) concerning inspection of the reactor vessel upper head, penetrations, and associated welds continue to be acceptable. The ASME Code is deliberating a Code case to establish a recommended inspection plan for reactor pressure vessel upper heads and associated penetration nozzles, as an alternative and, potentially in the long-term, a replacement for the Order.

Regarding other susceptible components, on August 21, 2003, NRC issued Bulletin 2003-02, "Leakage from Reactor Pressure Vessel Lower Head Penetrations and Reactor Coolant Pressure Boundary Integrity," to address, in part, the issue of the susceptibility to PWSCC of nickel-based alloy penetrations in the lower reactor pressure vessel head. On May 24, 2004, NRC issued Bulletin 2004-01, "Inspection of Alloy 82/182/600 Materials Used in the Fabrication of Pressurizer Penetrations and Steam Space Piping Connections at Pressurized-Water Reactors," to address, in part, the issue of the susceptibility to PWSCC of nickel-based alloy pressurizer penetrations and pressurizer steam space piping connections.

On January 20, 2004, the Materials Reliability Program (MRP) issued a letter that recommended direct visual inspection of the bare metal (or equivalent alternative examinations) be performed at all Alloy 82/182/600 pressure boundary locations normally operated at greater than or equal to 350E F in the primary system within the next two refueling outages at each plant, unless performed during the most recent refueling outage.

These actions provide confidence that appropriate visual inspections are being conducted to identify leakage that may potentially occur as a result of PWSCC in Alloy 82/182/600

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components. Nevertheless, these actions have shortcomings from the point of view of long-term assurance that potential PWSCC in nickel-based alloy components in the primary system will be promptly identified and corrected. These actions do not provide for long-term inspections. While the bulletins discussed above request information on inspection plans, they do not ensure that visual inspections will continue to be performed over the long-term. Also, the possibility that non-visual inspections may ultimately be necessary to manage degradation by PWSCC in some components will need continual reassessment by the industry and the NRC.

In addition to the report on information available worldwide on boric acid corrosion (BAC) of pressure boundary materials discussed above, the NRC issued a report prepared by Argonne National Laboratory (ANL) entitled, "Boric Acid Corrosion of Light Water Reactor Pressure Vessel Materials" (Reference 2). This report presents the results of tests conducted at specific conditions to better understand corrosion associated with various nozzle-to-vessel annulus conditions regarding temperature, pressure, flow rate, and boric acid concentrations. A new finding from these tests is that very high corrosion rates were observed for low-alloy steel at 140 - 170E C (284 - 338E F) in molten salt solutions of boric acid with addition of water. Short-term corrosion rates up to 150 mm/yr (6 in/yr) were measured at 150E C (302E F). These corrosion rates are in the same range that has been observed in saturated boric acid solutions at 97.5E C (207.5E F). The molten boric acid corrosion rate finding may be an explanation for field observations of boric acid corrosion that were not understood, such as the Sequoyah Unit 2 event in 2003. This event was discussed in NRC Information Notice 2003-02, "Recent Experience With Reactor Coolant System Leakage And Boric Acid Corrosion." This is a new finding that enhances our understanding of the conditions under which BAC may occur and, hence, may influence our understanding of actions that are appropriate in response to known leakage from borated systems. Notwithstanding, the new finding does not alter the fact that the overall consequences of boric acid corrosion have been well known and reasonably well documented.

There are a number of ongoing activities to address the area of inspection of carbon steel and low-alloy steel components susceptible to boric acid corrosion and to address BAC potentially resulting from leakage through stress corrosion cracks in nickel-based alloy components. As a result of the staff's review of the responses to NRC Bulletin 2002-01, "Reactor Pressure Vessel Head Degradation and Reactor Coolant Pressure Boundary Integrity," the staff issued Regulatory Issue Summary (RIS) 2003-13, "NRC Review of the Responses to Bulletin 2002-01." The staff noted in this RIS that the inspections performed for BAC under the recommendations of Generic Letter 88-05, "Boric Acid Corrosion of Carbon Steel Reactor Pressure Boundary Components in PWR Plants," as well as the inspections performed during ASME Code system pressure testing do not require the removal of insulation and, thus, are generally not capable of detecting leakage resulting from PWSCC. Thus, BAC could take place over an extended period of time before it is identified.

By letter dated August 19, 2002, the NRC requested ASME Section XI to create a task group to re-evaluate the inspection and corrective action requirements for all systems that are

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potentially subject to stress corrosion cracking and boric acid corrosion. In response to this letter, ASME Section XI chartered the Task Group (TG) on Boric Acid Corrosion. The task group noted that the most recent editions and addenda of Section XI of the ASME Code as well as earlier editions and addenda do not require the visual inspection of bare metal surfaces of pressure retaining components when examining these components for evidence of leakage. The degradation being experienced in the industry today includes wastage caused by boric acid attack of susceptible materials such as carbon and low-alloy steel vessels from pressure boundary leakage resulting from PWSCC of the Alloy 82/182/600 materials. Nuclear plant operators have relied on their commitments to Generic Letter 88-05, "Boric Acid Corrosion of Carbon Steel Reactor Pressure Boundary Components in PWR Plants," to detect and manage borated water leakage throughout plant borated systems. In order to ensure detection of boric acid corrosion in pressure retaining components prior to failure, the task group concluded that more rigorous inspections than those currently provided by the ASME Code must be performed in the areas most susceptible to PWSCC. The task group developed proposed ASME Code Case N-722, "Additional Inspections for PWR Pressure Retaining Welds in Class 1 Pressure Boundary Components Fabricated with Alloy 82/182/600 Materials, Section XI, Division 1," to enhance the current Code requirements for detection of leakage and corrosion in the components considered to be susceptible to PWSCC. The bare metal visual examinations of Proposed ASME Code Case N-722 would be specified for all pressure retaining components fabricated from Alloy 82/182/600 materials regardless of the component operating temperature. This Code case has been approved by the ASME Main Committee. Based on the scope, methods, and frequency of inspection, the staff considers that the inspection provisions in this Code case are suitable for identifying leakage from PWSCC and for precluding BAC as a result of such through-wall leakage. When it receives final approval by ASME, the Code case does not become a requirement but, nevertheless, constitutes a recommended set of inspections for PWSCC/BAC issued by an industry consensus body.

Proposed Course of Action

As noted above, with the exception of reactor vessel upper heads, the NRC staff concluded that nickel-based alloy components susceptible to PWSCC warrant additional inspection. The Discussion section above identifies shortcomings with inspection-related activities that are currently underway. The principal shortcoming is that no long-term recommendations or requirements are in place for inspection of components susceptible to PWSCC. The issue of inspections for BAC is closely related to the issue of inspections for PWSCC. The concern for BAC identified by both the NRC and industry is that there are no long-term recommendations or requirements in place for visual inspection of components susceptible to PWSCC; without suitable inspections for PWSCC, BAC could take place over an extended period of time before it is identified. The ANL test results under molten boric acid conditions reveal a new situation in which very high corrosion rates can occur under conditions previously believed to be of no concern and underscore the need for a robust inspection program.

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The staff believes that because of the susceptibility to PWSCC of the RCPB components covered in Part I of this paper, it is technically appropriate that these components be subjected to an on-going program of inspections. PWR owners may be able to rely primarily on visual inspections, at this time. If leakage is detected, it is important to characterize the flaw by volumetric or surface exams and determine the need for sample expansion. However, future circumstances, such as the occurrence of circumferential cracking in certain types of components, may dictate the need for volumetric instead of visual examination. The NRC is currently deliberating the appropriate regulatory vehicle to address this issue. Additional details on the regulatory vehicle to be used and recommended inspection methods and frequencies are expected to be available from the NRC website during the summer 2005 and may be available for discussion during the NuPEER Symposium in June 2005.

PART II

Background

Part II of this paper is concerned with Alloy 82/182 butt welds and Alloy 600 safe ends in the reactor coolant system (RCS) of PWR plants.

Operating experience, both domestic and foreign, has demonstrated that Alloy 82/182 materials used to make DM weld connections in the RCPB of PWR plants are susceptible to PWSCC.

A through-wall circumferential flaw was found in 1993 in a pressurizer nozzle-to-valve DM weld at Palisades. The flaw was found because of a leak in the heat affected zone of the Inconel safe end weld. The circumference of the crack was about 3.5 inches long in the 4-inch diameter pipe. Metallurgical analysis of the sample removed characterized the cracking as due to PWSCC.

In 2000, evidence of a large accumulation of boric acid deposits observed during a refueling outage at V. C. Summer led to the discovery of cracking in the "A" hot leg pipe-to-reactor pressure vessel (RPV) nozzle DM weld. The weld was found to have a through-wall axial flaw and other small part through-wall axial flaws and a circumferential flaw. Based on destructive examination of the piping and weld material that was removed, the flaws were determined to be due to PWSCC. The axial crack growth of the flaw was bounded by the low-alloy steel or stainless steel at either end of the weld. The depth of the circumferential flaw was limited by low-alloy steel it ran into. Small axial and circumferential cracks were identified in the "B" hot leg pipe to reactor pressure vessel (RPV) nozzle DM welds; a small circumferential crack was identified in the "C" hot leg pipe-to-RPV nozzle DM weld; and a small circumferential crack was found in both the "A" and "C" cold leg pipe to RPV nozzle DM welds.

Through ultrasonic examination in 2000, a hot leg pipe-to-reactor pressure vessel nozzle weld at Ringhals 3 in Sweden was found to have four axial part through-wall

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flaws. Boat samples were removed and the cracking was determined to be due to PWSCC.

Through ultrasonic examination in 2003, the surge line to hot leg nozzle weld at TMI-1 was found to have an axial part through-wall indication in a DM weld. The indication was attributed to PWSCC.

Evidence of boron deposits on the surface of a pressurizer relief valve nozzle at Tsuruga 2 in Japan led to the discovery in 2003 of five axially-oriented flaws in the DM weld material used in the fabrication of the nozzle-to-safe end welds. Subsequent non-destructive examination (NDE) performed on a safety valve nozzle of similar diameter resulted in the discovery of two additional axial flaws in its nozzle-to-safe end DM weld. Fractographic analysis of the flaw surfaces confirmed PWSCC as the mechanism for flaw initiation and growth.

In 2003 a shallow axial indication was found by ultrasonic examination in the pressurizer-to-surge line weld at Tihange 2 in Belgium. This indication was attributed to PWSCC.

In 2005 two part through-wall axial indications, approximately 180 degrees apart, were identified by ultrasonic examination in a 2 inch hot leg nozzle-to-drain line dissimilar metal weld at Calvert Cliffs 2. The indications were attributed to PWSCC.

In 2005 an axial part through-wall indication was identified by ultrasonic examination in a pressurizer nozzle-to-safe end dissimilar metal weld for the pressurizer safety valve at D. C. Cook 1. The indication was attributed to PWSCC.

Two of the eight events noted above involve circumferential cracking. Axial cracking is likely to be limited in length to the width of the weld between the ferritic and stainless steel components being joined. Circumferential cracking is a more serious safety concern because, if undetected by NDE, it could lead to complete severance of the piping.

The occurrence of PWSCC in nickel-alloy weld materials used in the fabrication of reactor coolant system piping is not surprising. PWSCC has occurred widely in partial penetration welds in pressurizers and reactor vessel upper heads and the temperatures in these locations are similar to the temperatures in pressurizer surge line welds and in RCS hot leg piping which have experienced PWSCC. Further incidents of PWSCC may be expected to occur in these materials and an effective degradation management program beyond current ASME Code, Section XI inservice inspection requirements (ISI) is warranted to ensure that the regulations, including the regulatory requirements associated with leak-before-break, continue to be satisfied.

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Discussion

RCS piping components, including the DM welds, are an integral part of the RCPB, and their integrity is important to the safe operation of the plant. Inspection programs of DM welds include requirements for volumetric and surface examinations and are based on the requirements of the ASME Code.

As noted above, several incidents of PWSCC have been identified through the discovery of boric acid deposits from through-wall leaks or by ultrasonic examination. The acceptability of relying on ultrasonic examination as a degradation management program for DM welds is predicated on the frequency of the examinations and the ability of the examinations to detect PWSCC before it grows to a size that could challenge the integrity of the piping.

Ultrasonic inspection of dissimilar metal welds poses significant challenges to the detection and sizing of PWSCC. For example, when examining from the outside surface the crowns on some welds have a contour that can result in probe lift off and, consequently, distorted signals. Weld surface roughness and misalignment during the original fabrication between nozzles and safe ends or between other piping products on either side of a weld can similarly interfere with probe scanning when examining from the inside surface. Beam scatter in stainless steel components may pose a challenge to ultrasonic inspection. Physical interferences on either or both sides of a weld may limit accessibility needed to perform an inspection.

Recognizing these challenges, the MRP issued a letter on April 2, 2004, recommending that licensees take steps not required by the ASME Code by removing insulation from these DM welds to perform visual examinations and, while performing these examinations, obtain plant-specific information on weld joint configurations and available access to prepare for future volumetric examinations. This letter recommended that with this information in hand, licensees review the Performance Demonstration Initiative (PDI) library of mockups to determine if the configurations are qualified for inspection. If not, the letter recommended construction of site-specific mockups to qualify NDE procedures as required by ASME Section XI, Appendix VIII, provided meaningful ultrasonic examinations can be performed on the as found configurations.

Based on operating experience to date, the NRC staff believes that PWSCC in these RCS DM welds is not an immediate safety issue but is a serious problem that warrants prompt attention to ensure that regulatory requirements continue to be met.

The NRC staff considers the current ASME Code, Section XI, ISI requirements for some RCS DM butt welds to be inadequate with respect to frequency. In addition, licensees may have received relief from the NRC to obtain less than full coverage or to reduce the scope of examination based on risk-informed ISI. Reduced coverage examination or scope of examination can be justified when the operating experience indicates that the materials are not experiencing inservice degradation, but may not be appropriate if examinations are being performed to manage a potentially active degradation mechanism in susceptible materials.

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The NRC is developing a generic letter that will include a management program of inspections and mitigative actions that it believes would be acceptable for ensuring that the integrity of DM butt welds in the RCPB is maintained. This program is expected to be available from the NRC website during the summer 2005 after the generic letter is issued for stakeholder comments and may be available for discussion during the NuPEER Symposium in June 2005.

The management program is expected to take into account that RCS locations such as the hot leg and the pressurizer surge line and pressurizer steam space connections will need to be inspected more frequently than other locations such as the cold leg. Inspections are expected to meet performance demonstration requirements of the ASME Code, Section XI, Appendix VIII. It is recognized that certain mitigative actions may have the potential for reducing the frequency of examination to a frequency approaching the original Code requirements. These actions may include full structural weld overlays or application of a stress improvement process. Mitigative actions may also be needed by licensees to address inspection issues such as inadequate weld inspection coverage. Such mitigative actions may include application of weld overlays. The program that is being developed for its proposed generic letter may make use of PWSCC categories such as shown below and provide specific recommendations for inspections of welds in each category.

PWSCC Category	Description of Weldments	PWSCC Category	Description of Weldments
A	Alloy 52/152 material in contact with primary coolant	E	Alloy 82/182 in cold leg locations not mitigated by SI
B	Alloy 82/182 material reinforced by full structural weld overlay (FSWO)	F	Alloy 82/182 weldment is cracked and reinforced by FSWO
C	Alloy 82/182 mitigated by stress improvement (SI)	G	Alloy 82/182 weldment is cracked and mitigated by SI
D	Alloy 82/182 in pressurizer and hot leg locations not mitigated by SI	H	Alloy 82/182 or Alloy 52/152 configuration requiring construction of a site-specific performance demonstration mockup, mitigative actions, and/or examination alternative to Appendix VIII

Conclusions

The NRC staff and, separately, the U.S. industry group known as the MRP have undertaken a number of efforts related to assessing PWSCC in various locations in the RCPB. This paper cites actions taken to date but these actions for the most part call for one-time inspections. PWSCC has the potential to lead to serious reactor coolant system leaks or failures of the

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reactor coolant system and to cause boric acid corrosion of critical components. Accordingly, the NRC staff believes that implementation of a long-term program to manage or mitigate PWSCC is warranted. The NRC staff has been encouraging the U.S. industry to take the lead in this effort but is beginning to take regulatory action to ensure that such programs are implemented in a more timely way.

References

1. NRC NUREG-1823, U.S. Plant Experience with Cracking in Alloy 600 Components and Boric Acid Corrosion
2. Forthcoming NRC NUREG/CR, Boric Acid Corrosion of Light Water Reactor Pressure Vessel Materials

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