REACTOR PRESSURE VESSEL THERMAL ANNEALING

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ABSTRACT. The steel plates and/or forgings and welds in the beltline region of a reactor pressure vessel (RPV) are subject to embrittlement from neutron irradiation. This embrittlement causes the fracture toughness of the beltline materials to be less than the fracture toughness of the unirradiated material.

Material properties of RPVs that have been irradiated and embrittled are recoverable through thermal annealing of the vessel. The amount of recovery primarily depends on the level of the irradiation embrittlement, the chemical composition of the steel, and the annealing temperature and time.

Since annealing is an option for extending the service lives of RPVs or establishing less restrictive pressure-temperature (P-T) limits; the industry, the Department of Energy (DOE) and the Nuclear Regulatory Commission (NRC) have assisted in efforts to determine the viability of thermal annealing for embrittlement recovery.

General guidance for in-service annealing is provided in American Society for Testing and Materials (ASTM) Standard E 509-86. In addition, the American Society of Mechanical Engineers (ASME) Code Case N-557 addresses annealing conditions (temperature and duration), temperature monitoring, evaluation of loadings, and non-destructive examination techniques.

The NRC thermal annealing rule (10 CFR 50.66) was approved by the Commission and published in the *Federal Register* on December 19, 1995. The Regulatory Guide on thermal annealing (RG 1.162) was processed in parallel with the rule package and was published on February 15, 1996.

RG 1.162 contains a listing of issues that need to be addressed for thermal annealing of an RPV. The RG also provides alternatives for predicting re-embrittlement trends after the thermal anneal has been completed.

This paper gives an overview of methodology and recent technical references that are associated with thermal annealing. Results from the DOE annealing

prototype demonstration project, as well as NRC activities related to the proposed Palisades anneal are also described.

Keywords: Thermal annealing, NRC annealing rule and regulatory guide, Department of Energy annealing demonstration project, Palisades.

INTRODUCTION

Reactor pressure vessels (RPVs) are fabricated from thick steel plates and/or forgings, and welds that are subject to embrittlement from neutron irradiation in the RPV beltline region. Embrittlement causes a decrease in the fracture toughness of the beltline materials. This decrease in fracture toughness is primarily a function of: 1) the total amount of neutron irradiation (fluence), 2) chemical composition of the steels, and 3) irradiation temperature.

In order to limit the amount of neutron irradiation damage to the RPV beltline materials, many utilities have redesigned their fuel loading patterns to reduce the amount of neutron leakage from the core, or have used neutron poisons or shielding to protect the RPV in regions of high neutron flux. However, these techniques have only a limited effect if incorporated late in the life of the RPV.

The level of embrittlement is particularly sensitive to the chemical composition (specifically, the amounts of copper and nickel) of these steels. The NRC regulations (10 CFR 50.61, and Appendix G to 10 CFR Part 50) and Regulatory Guide (RG) 1.99, Revision 2, provide methodologies to conservatively estimate the increase in the transition temperature (TT) and decrease in the upper shelf energy (USE) of the beltline materials as a result of neutron irradiation.

An increased TT makes the RPV beltline materials more susceptible to rapid crack growth during startup or shutdown and under accident conditions such as pressurized thermal shock (PTS). The PTS rule (10 CFR 50.61) contains screening criteria to conservatively limit the amount of the shift in the TT. The decrease in USE resulting from neutron irradiation can create the potential for ductile crack growth under normal operating and accident conditions. Appendix G to 10 CFR Part 50 contains screening criteria that conservatively limit the allowable decrease in USE.

A licensee can use a staff approved analysis to justify operation beyond the embrittlement screening criteria of 10 CFR 50.61 or Appendix G to 10 CFR Part 50, or choose to thermally anneal the RPV.

Annealing is also an option for extending the service lives of RPVs beyond the current expiration-of-license (EOL) or for establishing less restrictive plant operational pressure-temperature (P-T) limits for startup and shutdown.

THERMAL ANNEALING PROCESS

For a given annealing time and temperature, the amount of recovery primarily depends on the level of the irradiation embrittlement and the chemical composition of the steel. Server *(Ref. 1)* has shown that an annealing temperature 100°F above the RPV irradiation temperature is not high enough to obtain substantial mechanical property recovery. Therefore, to achieve a measurable amount of recovery in a relatively short time, a practical minimum for the annealing temperature would be on the order of at least 150°F above the RPV irradiation temperature.

For typical western RPVs with a nominal irradiation temperature of 550°F, this would imply a minimum annealing temperature of 700°F. A maximum temperature has not been defined; however, 940°F was agreed upon as the upper limit for ASME Code Case N-557 *(Ref. 2)*. The 940°F limit was set to limit the potential for creep and other forms of metallurgical degradation that can result at elevated temperatures.

Durations of 168 hours have been typical for experimental annealing treatments that have been conducted in the 700°F — 900°F range. For western RPV steels and weldments, these treatments can restore the TTs and USEs to more than 90 percent of their initial values. Due to the relative scarcity of data from annealing treatments in the 700°F — 800°F range, proposed annealing treatments in the U.S. have been focused to occur in the 800°F — 900°F range.

TECHNICAL CODES AND STANDARDS FOR THERMAL ANNEALING

ASTM Standard E 509

General guidance for in-service annealing is provided in American Society for Testing and Materials (ASTM) Standard E 509-86 *(Ref. 3)*. Specifically, ASTM Standard E 509-86 prescribes general procedures for conducting an in-service thermal anneal of an RPV and for demonstrating the effectiveness and degree of recovery. ASTM Standard E 509-86 also provides direction for a post-annealing vessel radiation surveillance program. A revision to the ASTM Standard was recently approved to provide updated guidance in the areas of technical references and supplemental surveillance programs.

ASME Code Case N-557 on Thermal Annealing

At the American Society of Mechanical Engineers (ASME) Section XI meetings in Chicago in August 1995, the Task Group on Thermal Annealing undertook development of a Code Case on thermal annealing of reactor vessels on a high priority basis. The development of the Code Case was requested by the Consumers Power Company (CPCo, the licensee for the Palisades plant) and supported by the NRC. The Task Group appointed a special team to write the Code Case on an expedited basis. The Code Case (designated N-557) was passed by the ASME main committee on December 1, 1995.

Code Case N-557 addresses annealing conditions (temperature and duration), temperature monitoring, evaluation of loadings, and non-destructive examination techniques. Code Case N-557 received final approval by the ASME Board of Nuclear Codes and Standards (BNCS) on March 19, 1996. The supporting technical basis document for Code Case N-557 was published as an Electric Power Research Institute (EPRI) report in November 1996. *(Ref. 2)*.

NRC ANNEALING RULE AND REGULATORY GUIDE

The thermal annealing rule (10 CFR 50.66) was approved by the Commission and published in the *Federal Register* on December 19, 1995. The rule addresses the critical engineering and metallurgical aspects of thermal annealing. The regulatory process outlined in the proposed rule consists of several elements:

- a thermal annealing report (TAR, describing the licensee's plan for conducting the anneal) to be submitted to the NRC prior to annealing
- requirements for determining the percent recovery of RPV fracture toughness due to annealing and requirements for determining re-embrittlement trends occurring during reactor operations after annealing
- confirmation that thermal annealing was performed in accordance with the TAR submitted in advance by the licensee
- public meetings to be held both before and after the anneal to allow the NRC to respond to questions from interested parties or individuals

The regulatory guide on thermal annealing (RG 1.162) was processed in parallel with the rule package and was published on February 15, 1996. NUREG/CR-6327 *(Ref. 4)*, which provides the supporting technical basis for irradiation embrittlement recovery from thermal annealing, was issued in March 1995. The work in this report was completed by Eason et. al., and provides the basis for the computational embrittlement recovery models in RG 1.162.

OVERVIEW OF METALLURGICAL AND ENGINEERING ISSUES

RG 1.162 contains a detailed listing of metallurgical and engineering issues that need to be addressed for thermal annealing of an RPV. Details regarding fracture toughness recovery and re-embrittlement trends are covered in Section 3.0 of RG 1.162. Specifically, RG 1.162 presents three acceptable methods for estimating recovery, 1) use of the vessel surveillance materials, 2) removal of specimens from the RPV beltline, and 3) a generic computational method.

The RG also provides methods for predicting post-annealing re-embrittlement trends. The potential for elevated temperature degradation (e.g., creep, temper embrittlement) of western RPV steels is addressed in a technical basis document prepared for ASME Code Case N-557. Based on the information that is available at this time, elevated temperature degradation of material properties for Western-style reactors is not considered to be an overriding concern for thermal annealing treatments in the range of 700°F – 900°F. The potential for creep, in particular, can be minimized by following the guidelines of ASME Code Case N-557. Specifically, the Code Case specifies an annealing time of approximately one week (168 hours), so creep should not be an issue in the specified temperature range *(Ref. 2)*.

Examples of engineering issues that need to be addressed for thermal annealing include, 1) development of appropriate thermal and structural models for predicting limiting stress conditions and providing guidance for the placement and quantity of instrumentation, 2) control of thermal gradients during heatup and cooldown to minimize stresses and deformations in the vessel and attached piping, 3) adequate instrumentation (for temperature, strains and displacements) for monitoring the response of the RPV and piping to the anneal, 4) adequate onsite fire protection and proper adherence to National fire codes and standards (particularly with regard to gas-fired heating methods), 5) protection of personnel from radiation hazards, including those associated with air-lifting internals within the containment and placement of instrumentation inside the bio-shield cavity, and 6) protection of other equipment, components, and structures affected by the annealing (e.g., minimizing bio-shield wall temperatures).

DEPARTMENT OF ENERGY ANNEALING DEMONSTRATION PROJECT

In February 1994, the Department of Energy's (DOE's) Sandia National Laboratories, and EPRI sponsored an RPV thermal annealing workshop to assemble international experts and discuss the viability of annealing in the U.S. Utility representatives attending the workshop clearly stated that there would be little chance of a thermal anneal in the U.S. until it was demonstrated that major components (e.g., the RPV, reactor coolant system (RCS), and concrete biological shield wall--bio-shield) would not be damaged during the annealing process.

Subsequent to the thermal annealing workshop, the DOE initiated an annealing prototype demonstration project (ADP) to evaluate the viability of thermal annealing as an embrittlement management option. In May 1995, the DOE awarded two contracts to evaluate the feasibility of annealing U.S. licensed plants. These contracts were with two separate consortia to be carried out at two canceled plant sites, Marble Hill, Indiana and Midland, Michigan. The Marble Hill contract was awarded to the ASME Center for Research and Technology Development (CRTD), and the Midland contract was awarded to MPR Associates (MPR).

The Marble Hill RPV is a Combustion Engineering fabricated 4-loop nozzle supported design, and the Midland RPV is a Babcock and Wilcox fabricated 2-loop skirt supported design. Both Marble Hill and Midland are uncompleted commercial nuclear power plants, and were therefore unirradiated.

The NRC staff was represented at meetings of both the Marble Hill and Midland Steering Committees and Design Reviews. The NRC Office of Research (RES) has the lead in representing the NRC's interests in the ADPs. RES has prepared a memorandum of understanding (MOU) regarding NRC participation in the ADPs. This MOU was signed by NRC and DOE on August 4, 1995.

The first annealing demonstration was performed at the Marble Hill site and employed an indirect, gas-fired heating method. The Marble Hill annealing demonstration was completed in July 1996. The RPV was held at 850°F for 168 hours. The heater had five independently controlled zones. Three of the zones were across the annealing zone, and the top and bottom zones controlled the thermal gradient. Representatives from RES and the NRC's Office of Nuclear Reactor Regulation (NRR) were observers on-site during the Marble Hill anneal. NRC had confirmatory instrumentation installed on the RPV.

There were some unanticipated occurrences, but overall the project was successful in that the anneal was controlled within prescribed limits. In general, the predicted and measured results agreed. In addition, the appropriate RPV dimensions were held within required criteria, and there was no damage to the RPV, RCS piping, bio-shield or other important components. *(Ref. 5).* The Marble Hill annealing demonstration helped to address some of the engineering issues and concerns that were outlined by industry, and showed that annealing is a viable option for RPV embrittlement management.

At the beginning of FY 1997, all remaining Marble Hill work (i.e., drafting of the report) and Midland work was stopped due to funding restrictions. EPRI agreed to fund the final industry report on the Marble Hill anneal. The report is expected to be completed by the end of fiscal year (FY) 1997. Prior to the stoppage, progress had been made on the second demonstration that was to occur at the Midland site. The Midland demonstration would have employed an electric resistance heating approach.

NRC ACTIVITIES RELATED TO THE PROPOSED PALISADES THERMAL ANNEAL

In the fall of 1994, the Consumers Power Company (CPCo), the licensee for the Palisades plant, developed chemical composition and mechanical property data for welds removed from their retired steam generators *(Refs. 6 and 7).* This new information changed the best estimate chemistry of the limiting RPV beltline weld. This information also indicated an increased variability in chemical composition of the weld when compared to that assumed for the development of the PTS rule. In combination, this information indicated that the plant would exceed the PTS screening criteria prior to EOL.

The staff issued a safety evaluation report (SER) regarding the variability of the Palisades RPV weld properties on April 12, 1995 *(Ref. 8).* The staff agreed with the licensee's best-estimate analysis of the chemical composition of the RPV welds and concluded that continued operation through late 1999 was acceptable. 10 CFR 50.61 requires submittal of a plant-specific analysis justifying operation beyond the screening criteria at least 3 years before exceeding the criteria. In the SER, the staff recognized that submission of information regarding thermal annealing of the Palisades RPV would obviate the need for the plant-specific analysis.

In October 1995, CPCo initiated submittal of a report describing the planned thermal annealing of the Palisades RPV *(Ref. 9).* CPCo's plan called for the annealing to be performed using an indirect, gas-fired heating method, which would heat the reactor vessel beltline region to the 850°F — 900°F temperature range for approximately 168 hours. The licensee projected that this annealing treatment should result in recovery of 80 to 90 percent of the fracture toughness lost as a result of radiation embrittlement.

During the summer outage (May—August, 1995) at Palisades, the licensee obtained baseline information on the condition of the vessel insulation and the temperatures of the RPV supports and the cavity between the vessel and the bio-shield wall.

The final sections of the preliminary thermal annealing report (TAR) were submitted to the NRC on April 29, 1996 *(Ref. 10).* These sections completed CPCo's submittal of the preliminary TAR for the Palisades RPV. At that time, the report was being reviewed by the NRC staff. CPCo was planning to rely heavily on the results of the Marble Hill demonstration anneal (described previously) for completion and verification of the Palisades submittal. The licensee projected that the anneal of the Palisades RPV would commence in May 1998.

However, by letter dated April 4, 1996, CPCo submitted to the NRC a revised neutron fluence analysis for the Palisades RPV *(Ref. 11)*. The analysis projected a 25% reduction in neutron fluence at EOL for the RPV. The reduction consisted of 8% due to physical changes in the plant, 12% due to bias resulting from comparison of calculated to measured fluence values, and 5% due to spectral adjustments. This analysis would have enabled operation of the plant well beyond 1999 without annealing if the entire 25% reduction was approved.

By letter dated December 20, 1996, the staff approved the 8% reduction in fluence that was based on physical changes in the plant. This 8% reduction allows plant operation until the year 2003. Expiration-of-license for the Palisades plant is in 2007. If the construction permit time is claimed, the license will expire in 2011.

CONCLUSIONS

It is difficult to predict what the status will be regarding thermal annealing of commercial RPVs in the United States. The commitment to anneal an RPV involves significant engineering and regulatory analyses and the assignment of substantial resources. However, the approach can recover a large percentage of the fracture toughness lost to neutron irradiation, thereby decreasing constraints on plant operation. This approach could enable plant operation to EOL for RPVs potentially challenged by the PTS screening criteria, and could extend operation beyond EOL for others *(Ref. 11)*.

The successful demonstration of the engineering feasibility of annealing technology and the lessons learned from the DOE Marble Hill ADP will greatly facilitate future considerations for thermal annealing in the United States.

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