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REGULATORY GUIDE

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FORMAT AND CONTENT OF REPORT FOR THERMAL ANNEALING OF REACTOR PRESSURE VESSELS

A. INTRODUCTION

The thermal annealing rule, § 50.66, "Requirements for Thermal Annealing of the Reactor Pressure Vessel," of 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facility," provides that:

> For those light water nuclear power reactors where neutron radiation has reduced the fracture toughness of the reactor vessel materials, a thermal annealing may be applied to the reactor vessel to recover the fracture toughness of the material. The use of a thermal annealing treatment is subject to the requirements in this section. A report describing the licensee's plan for conducting the thermal annealing must be submitted in accordance with § 50.4 at least three years prior to the date at which the limiting fracture toughness criteria in § 50.61 or Appendix G to Part 50 would be exceeded.

This regulatory guide describes a format and content acceptable to the NRC staff for the Thermal Annealing Report to be submitted to the NRC for describing the licensee's plan for thermal annealing a reactor vessel. This guide also describes the Thermal Annealing Results Report that is required by 10 CFR 50.66 to be submitted after the thermal annealing. Use of this format by the applicant would help ensure the completeness of the information provided, would assist the NRC staff in locating specific information, and would aid in shortening the time needed for the review process.

This regulatory guide also describes alternative methods that are acceptable to the NRC for determining the recovery of fracture toughness after the thermal annealing and for estimating the degree of post-annealing reembrittlement expected during subsequent plant operations; 10 CFR 50.66 requires these to be reported.

This regulatory guide contains guidance on mandatory information collections that are contained as requirements in 10 CFR Part 50 and that are subject to the Paperwork Reduction Act of 1980 (44 U.S.C. 3501 et seq.). These requirements were approved by the Office of Management and Budget, approval number 3150-0011.

The public reporting burden for this collection of information is estimated to be an average of 6000 hours per respondent, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Information and Records Management Branch (T-6 F 33), U.S.

Nuclear Regulatory Commission, Washington, DC 20555-0001; and to the Desk Officer, Office of Information and Regulatory Affairs, NEOB-10202 (3150-0011), Office of Management and Budget, Washington, DC 20503.

B. DISCUSSION

BACKGROUND

Criterion 31 of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50 requires that:

> The reactor shall be designed with sufficient margin to assure that when stressed under operating, maintenance, testing, and postulated accident conditions, (1) the boundary behave in a nonbrittle manner and (2) the probability of rapidly propagating fracture is minimized.

A major concern in this regard is that the material properties of reactor vessels degrade progressively when exposed to neutron radiation during service, resulting in a loss in fracture toughness and ductility. To maintain adequate toughness and preclude nonductile failure in the vessel, a number of mitigating actions are taken during the operating life of a reactor: periodic changes are made in the pressure-temperature (P-T) limits required to preclude nonductile fracture of the materials during startup and cooldown, limitations are placed on the reduction of Charpy upper-shelf energy to maintain an adequate margin of safety against ductile fracture, and additional restrictions are placed on toughness properties by screening criteria imposed to avoid vessel failure from pressurized thermal shock.

If neutron radiation embrittlement becomes so severe that the required margins cannot be maintained, 10 CFR 50.61 and Appendix G to 10 CFR Part 50 permit the application of a thermal annealing treatment to recover the toughness properties of the vessel materials, which would avoid premature retirement of the reactor pressure vessel. Thermal annealing, the heating of the reactor vessel beltline to a temperature well above the operating temperature of the reactor for an extended period of time sufficient to remove the microstructural changes caused by radiation, is the only known method for restoring toughness properties to materials degraded by neutron radiation. The requirements for conducting thermal annealing and restarting the plant after annealing are set forth in 10 CFR 50.66.

Although thermal annealing has not yet been applied to a U.S. commercial power reactor, it has been successfully applied to other reactors. Two reactor vessels that have been successfully annealed are the Army's SM-1A in 1967 (Ref. 1), and the BR-3 in Mol, Belgium, in 1984 (Ref. 2). Both of these reactors operated at temperatures low enough to permit "wet annealing" at a temperature of 650°F using the reactor coolant pumps as the heat source. In addition, at least 12 Russian-designed VVER-440 PWRs, which operate at conditions similar to U.S. PWRs, have been annealed in Russia and Eastern Europe at temperatures of approximately 850°F, using dry air and radiant heaters as the heat source. Details of the thermal annealing of the Novovoronezh Unit 3 have been reported (Ref. 3) by a U.S. delegation that witnessed the operation.

CURRENT STATE OF KNOWLEDGE ON THERMAL ANNEALING

A significant amount of information has been reported in the literature on thermal annealing and on the effects of thermal annealing variables (e.g., temperature, time, materials chemistry, fluence levels), on the recovery of toughness properties. Server (Ref. 4) summarized the state of knowledge, as of 1985, for in-place thermal annealing of commercial reactor pressure vessels. He reviewed data on annealing recovery and reirradiation effects for high-copper welds and concluded that significant recovery occurs for annealing at 850°F for both the transition temperature shift (ΔRT_{NDT}) and reduction in Charpy upper-shelf energy. He also reviewed engineering studies and concluded that annealing of U.S. reactors at 850°F is feasible using existing commercial heat treating methods, but that plant-specific engineering problems would need to be resolved. Server (Ref. 4) also performed a thermal and structural analysis for a typical PWR vessel annealed at 850°F, which predicted that vessel dimensional stability would be maintained and that post-anneal residual stresses would not be significant. However, Server's results indicated that excessive bending of the attached piping from differential thermal expansion of the vessel could be a problem that required careful temperature control.

Mager and others (Refs. 5 and 6) reported on research to determine the extent of fracture toughness recovery as a function of annealing time and temperature for materials that are sensitive to neutron embrittlement. They concluded that excellent recovery of all properties could be achieved by annealing at 850°F for 168 hours, and that the reembrittlement after annealing would follow the same trend as the pre-annealing embrittlement rate. These reports also describe a thermal annealing procedure developed for field application.

Additional research that includes data on irradiation-anneal-reirradiation property trends for reactor pressure vessel welds has been reported by Hawthorne and Hiser (Ref. 7).

More recently, Eason et al. performed analyses of existing data on annealing of irradiated pressure vessel steels using both mechanistic and statistical considerations. Eason et al. also developed improved correlation models for estimating Charpy upper-shelf energy and transition temperature after radiation and annealing. This work is reported in NUREG/CR-6327 (Ref. 8), and it provides the basis for equations for estimating recovery of fracture toughness following annealing (Section 3.1.3 of this regulatory guide).

General guidance for inservice annealing may be found in ASTM Standard E 509-86 (Ref. 9). ASTM Standard E 509-86 contains general procedures for conducting an in-service thermal anneal of a reactor vessel and for demonstrating the effectiveness and degree of recovery. ASTM Standard E 509-86 also provides direction for a post-anneal vessel radiation surveillance program.

CURRENT REGULATORY REQUIREMENTS FOR FRACTURE TOUGHNESS OF VESSELS

Fracture toughness requirements for light-water-cooled reactor pressure vessels are addressed in several regulations. Appendix G, "Fracture Toughness Requirements," to 10 CFR Part 50 provides the fracture toughness requirements for vessels during normal operation and anticipated accident conditions. Appendix G also permits the use of thermal annealing to restore fracture toughness degraded by neutron radiation when embrittlement degrades mechanical properties to such an extent that adequate margins of safety cannot be demonstrated during operation. Appendix H, "Reactor Vessel Material Surveillance Program Requirements," to 10 CFR Part 50 requires surveillance programs to monitor irradiation embrittlement of reactor vessel beltline materials. The pressurized thermal shock (PTS) rule, 10 CFR 50.61, establishes screening criteria for embrittlement beyond which the plant may not operate without further justification.

The application of these regulations in the late 1980s and early 1990s demonstrated a need for clarification and improved guidance. The NRC review of the reactor pressure vessel integrity of the Yankee Nuclear Power Station highlighted the need for such changes and resulted in a detailed plan described in SECY-91-333 (Ref. 10) and SECY-92-283 (Ref. 11).

To implement this plan, a proposed rule to amend the regulations was issued on October 4, 1994 (59 FR 50513). This rule was issued in final form on December 19, 1995 (60 FR 65456). The rule includes a new § 50.66, "Requirements for Thermal Annealing of the Reactor Pressure Vessel," which sets forth the NRC's requirements for annealing of reactor pressure vessels. Also, changes were made to both Appendix G and the PTS rule to reference the thermal annealing requirements in § 50.66, as an option for reducing embrittlement when the toughness requirements of those rules cannot otherwise be met.

The thermal annealing rule, 10 CFR 50.66, permits the thermal annealing of reactor vessels to restore fracture toughness of the reactor vessel material that was reduced by neutron radiation. Section 50.66(a) requires that, prior to initiation of thermal annealing, a Thermal Annealing Report be submitted to describe the licensee's plan for conducting the thermal anneal. The report must be submitted at least 3 years prior to the date at which the limiting fracture toughness criteria in 10 CFR 50.61 or Appendix G to Part 50 would be exceeded. This 3-year period is specified to provide the NRC staff with sufficient time to review the thermal annealing program. Within 3 years of submittal of a licensee's Thermal Annealing Report and at least 30 days prior to the start of the thermal annealing, 10 CFR 50.66(a) requires the NRC staff to review the Thermal Annealing Report and place the results of its evaluation in its Public Document Room. In order to provide for public participation in the regulatory process, 10 CFR 50.66(f) requires that the NRC hold a public meeting a minimum of 30 days before the licensee starts to thermal anneal the reactor vessel. The licensee may begin thermal annealing after the NRC has placed the results of its evaluation of the Thermal Annealing Report in the Public Document Room and after the public meeting is held.

The Thermal Annealing Report is required by 10 CFR 50.66(b) to include (1) a Thermal Annealing Operating Plan, (2) a Requalification Inspection and Test Program, (3) a Fracture Toughness Recovery and Reembrittlement Trend Assurance Program, and (4) the Identification of Unreviewed Safety Questions and Technical Specification Changes.

The rule also provides three methods for determining the percent recovery. When surveillance specimens are available from a credible surveillance program, the percent recovery for the reactor vessel is required to be determined by using a test program that applies the actual annealing conditions to the irradiated surveillance specimens. If surveillance specimens are not available, the applicant may elect to determine the percent recovery by testing materials removed from the reactor vessel beltline region. The third method permits uses of a generic computational method if adequate justification is provided. Use of the procedure described in this regulatory guide in Section 3.1.3, "Computational Methods," is considered appropriate justification for this application.

Upon completion of the thermal annealing and the associated tests and analyses, the applicant must confirm in writing to the Director of the Office of Nuclear Reactor Regulation (NRR) that the thermal anneal was performed in accordance with the Thermal Annealing Operating Plan and the Requalification Inspection and Test Program. Within 15 days of the licensee's written confirmation that the thermal annealing was completed in accordance with the Thermal Annealing

Plan, and prior to restart, the NRC will (1) briefly document whether the thermal annealing was performed in compliance with the licensee's Thermal Annealing Operating Plan and the Requalification Inspection and Test Program, placing the documentation in the NRC Public Document Room, and (2) hold a public meeting to permit the licensee to explain the results of the reactor vessel annealing to the NRC and the public, allow the NRC to discuss its inspection of the reactor vessel annealing, and provide an opportunity for the public to comment to the NRC on the thermal annealing. The licensee may restart its reactor after the meeting has been completed, unless the NRC orders otherwise. Within 45 days of the licensee's written confirmation that the thermal annealing was completed in accordance with the Thermal Annealing Operating Plan and the Requalification Inspection and Test Program, the NRC staff will complete full documentation of the NRC's inspection of the licensee's annealing process and place the documentation in the NRC's Public Document Room.

If the thermal annealing was completed but not performed in accordance with the Thermal Annealing Operating Plan and the Requalification Inspection and Test Program, including the bounding conditions of the temperature and times, according to 10 CFR 50.66(c)(2) the licensee must submit a summary of the lack of compliance and a justification for subsequent operations. The licensee must also identify any changes to the facility that are attributable to the noncompliances that constitute unreviewed safety questions and any changes to the technical specifications that are required for operation as a result of the noncompliances. This identification does not relieve the licensee from complying with applicable requirements of the Commission's regulations and the operating license; and if these requirements cannot be met as a result of the annealing operation, the licensee must obtain the appropriate exemption per 10 CFR 50.12. If unreviewed safety questions or changes to technical specifications are not identified as necessary for resumed operation, the licensee may restart after the NRC staff places a summary of its inspection of the thermal annealing in the NRC Public Document Room and the NRC holds a public meeting on the thermal annealing. On the other hand, if unreviewed safety questions or changes to technical specifications are identified as necessary for resumed operation, the licensee may restart only after the Director of the Office of Nuclear Reactor Regulation authorizes restart, the summary of the NRC staff inspection is placed in the NRC Public Document Room, and a public meeting on the thermal annealing is held.

The thermal annealing rule also sets forth in 10 CFR 50.66(c)(3)(i) the requirements that a licensee must follow if the thermal annealing was terminated prior to completion. In general, the process and requirements for partial annealing are analogous to situations in which the thermal annealing was completed; that is, when the partial annealing was otherwise performed in compliance with the Thermal Annealing Operating Plan and relevant portions of the Requalification Inspection and Test Program, the licensee submits written confirmation of such compliance and may restart following, among other things, holding a public meeting on the annealing. By contrast, if the partial annealing was not performed in accordance with the Thermal Annealing Operating Plan and relevant portions of the Requalification Inspection and Test Program, the licensee is required by 10 CFR 50.66(c)(3)(iii) to submit a summary of lack of compliance, submit a justification for subsequent operations, identify any changes to the facility that are attributable to noncompliances that constitute unreviewed safety questions, and identify changes to the technical specifications that are required for operation as a result of the noncompliances with the Thermal Annealing Operating Plan and relevant portions of the Requalification Inspection and Test Program. If unreviewed safety questions or changes to technical specifications are identified as necessary for resumed operation, the licensee may restart only after the Director of NRR authorizes restart and the public meeting on the thermal annealing is held.

According to 10 CFR 50.66(d), every licensee who either completes a thermal annealing or terminates an annealing but elects to take full or partial credit for the annealing must provide a Thermal Annealing Results Report detailing (1) the time and temperature profiles of the actual thermal anneal, (2) the post-anneal RT_{NDT} and Charpy upper-shelf energy values of the reactor material to be used in subsequent operations, (3) the projected postanneal reembrittlement trends for both RT_{NDT} and Charpy upper-shelf energy, and (4) the projected values of RT_{PTS} and Charpy upper-shelf energy at the end of the proposed period of operation addressed in the application. The report must be submitted within three months of completing the thermal anneal, unless an extension is authorized by the Director of NRR.

C. FORMAT AND CONTENT FOR THE THERMAL ANNEALING REPORT

The format described here is acceptable to the NRC staff for the Thermal Annealing Report that is to be submitted to the Director of NRR for annealing a reactor vessel to restore fracture toughness of the reactor vessel material. This format addresses the contents of the Thermal Annealing Operating Plan, the Requalification Inspection and Test Program, the Fracture Toughness Recovery and Reembrittlement Trend Assurance Program, and the Identification of Unreviewed Safety Questions and Technical Specifications Changes. It also describes acceptance criteria that the staff will use in evaluating the applicant's proposed programs for determining fracture toughness recovery and establishing reembrittlement rates. This regulatory guide applies to thermal annealing procedures that use heaters (electric or gas) for heating the reactor vessel, the "dry" anneal method. Use of the "wet" anneal method, which applies heat generated by the pump to heat the reactor coolant, will be reviewed separately, on a case-by-case basis.

1. THERMAL ANNEALING OPERATING PLAN

The Thermal Annealing Operating Plan should include sufficient information to permit an independent evaluation of all the elements that went into its development. The following sections provide guidance on the format and content acceptable to the NRC staff for the operating plan, the information that should be included in the plan, the minimum level of detail for this information, and the necessary supporting data.

In all cases, the information described in this guide may be referenced if it has been submitted previously in another document, including any updates to previous submittals.

1.1 General Considerations

This first section should present introductory and general information. It should identify the reactor and give the reasons that thermal annealing is being proposed, including any regulatory requirement being challenged by the loss in fracture toughness. The projected percent recovery from annealing and the projected rate of reembrittlement in subsequent reactor operations should be identified, as well as the expected remaining operating life after annealing. The projected annealing response and reirradiation response should be determined using the provisions of this guide in Section 3, "Fracture Toughness Recovery and Reembrittlement Assurance Program." In using these provisions, the projected recovery should be determined using the annealing time and temperature proposed in the application.

The operating history of the reactor prior to annealing should be described in this section, including the power-time-temperature history during power operations to permit evaluation of temperature and fluence conditions for the reactor vessel; these data may be either actual recorded data or data deduced from other plant information that is identified as such. The specific reactor vessel beltline temperatures during the reactor operation should be reported.

This section should describe the results of the ongoing surveillance program, including the number of specimens, initial values for the reference temperature (RT_{NDT}) and Charpy upper-shelf energy, and all data on shifts of RT_{NDT} and decrease of Charpy upper-shelf energy. It should also provide the pre-annealing RT_{NDT} and Charpy upper-shelf energy values, determined by either analysis or testing.

1.2 Description of the Reactor Pressure Vessel

This section of the report should provide a detailed description of the reactor pressure vessel and identify those parts of the vessel to be annealed. It should also include all vessel data used for determining the Thermal Annealing Operating Plan, the proposed inspections and tests, and the programs for recovery and reembrittlement.

Information to be reported on each heat of material in the reactor vessel beltline region should include material compositions, including all elements relevant to irradiation behavior, mechanical properties, fabrication techniques, nondestructive test results, and neutron fluence exposures. The initial RT_{NDT} as specified in Branch Technical Position MTEB-5-2 in NUREG-0800 (Ref. 12) and NB-2300 of the ASME Boiler and Pressure Vessel Code (Ref. 13), along with the initial Charpy upper-shelf energy as defined in ASTM Standard E 185 (Ref. 14), should be reported for each heat of material. Material heats of base metal and weld metal that will be used for measuring percent recovery and for subsequent surveillance purposes, if any, should be identified.

All reactor vessel dimensions should be reported, including diameter, wall thickness, cladding thickness, nozzle dimensions, flange dimensions, and transition section dimensions. The dimensions of the gaps between the vessel and other potentially affected components such as adjacent concrete structures, internal permanent structures, and insulation should also be reported. Attachments to the reactor that could be affected by the annealing operation and the expected effects should be identified and described. Examples of such effects are:

- Changes in properties of the vessel insulation,
- Effects of thermal growth of the reactor on sliding support structures,
- Overheating of instrumentation and attachments.

1.3 Equipment, Components, and Structures Affected by Thermal Annealing

This section of the report should provide a description of all equipment, structures, and components that could be affected by the annealing operation, either thermally or mechanically, and the expected effects to the level necessary to assess the effects of annealing on the equipment, structures, and components. Examples of these effects include degradation of the biological shield because of loss in strength or reduction in neutron and gamma absorption capacity and the effects of vessel growth and distortions on attached piping. All significant thermal and mechanical loadings projected for each item should be identified, as well as actions proposed to avoid damage from these loadings.

The biological shield should be described, including its dimensions, materials, irradiation exposures, any unique features, and all cooling provisions to be used for controlling temperatures. If the biological shield is a tank, any provision for circulating the tank coolant should be described. If the biological shield is a concrete structure, the properties of the concrete should be reported as well as the properties of other concrete structures exposed to higher than normal temperatures. The existing design temperature limitations for the concrete should be described. If the design temperature limitations are to be exceeded during the thermal annealing operation, an acceptable maximum temperature for the concrete should be established as addressed in Paragraph 1.4.

The piping attached to the vessel should be described. This description should include material types, dimensions, and restraints such as supports and snubbers. The design requirements with respect to temperature and bending stress or strain limitations should be identified for the piping. Further, any indications of potential flaws found during inspections of the piping should be described.

Any other equipment or instrumentation that could be affected by the thermal annealing should be described. A description of the overall containment as it relates to core removal and storage, as well as the annealing of the vessel, should be included. Any special requirements should be described in detail. For example, storage of core internals may require a coffer dam approach to isolate the coolant from the heating equipment in the drained vessel, in which case the modifications, the equipment, and the method for ensuring the integrity of the isolation seals should be detailed.

1.4 Thermal and Stress Analyses

This section of the report should provide an evaluation of the effects of mechanical and thermal stresses and temperatures on the vessel, containment, biological shield, attached piping and appurtenances, and adjacent equipment, components, and structures that demonstrates that the annealing operation will not be detrimental to reactor operation. This evaluation should include detailed thermal and structural analyses that establish appropriate time and temperature profiles, including the heatup and cooldown rates of the annealing operation, so that dimensional stability of the system will be maintained. The analyses should demonstrate that localized temperatures, thermal stress gradients, and subsequent residual stresses will not result in unacceptable dimensional changes or distortions in the vessel, attached piping, and appurtenances and that the thermal annealing cycle will not result in unacceptable degradation of the fatigue life of these components.

The parameters to be evaluated in the thermal and stress analyses should include the annealing temperature, hold time at the annealing temperature, heating and cooling rates, the effect of insulation around the vessel including the bottom head, the active heating length of the heating device, the physical constraints on the vessel, structural characteristics of attached piping assemblies, and any other restraints.

The thermal analysis should establish the temperature profiles for the inside and outside surfaces of the vessel wall during heatup, start and end of steady-state conditions, and cooldown conditions. The effects of localized high temperatures should be evaluated for degradation of the concrete adjacent to the vessel, for changes, if any, in thermal and mechanical properties of the reactor insulation and for detrimental effects, if any, on containment and the biological shield. Maximum concrete temperatures should be based on existing design limits or provisions of Section III, Division 2, of the ASME Boiler and Pressure Vessel Code (Ref. 15). If the design temperature limits or the ASME Boiler and Pressure Vessel Code limits for the adjacent concrete structure are projected to be exceeded during the annealing operation, an acceptable maximum temperature for the concrete must be established using appropriate test data. Test data on properties should address irradiated concrete of appropriate type and exposures to time-temperature conditions that bound the expected conditions of the concrete during annealing.

The structural analysis should evaluate, for the complete annealing cycle, residual deformations, residual stresses, elastic-plastic-creep effects (Ref. 16), distortions, bending, piping displacements, effects of thermal gradients (axial, azimuthal, and through-wall), and restraints on the vessel, including nozzles and flange and attached piping. Any potential interference with other equipment, components, or supports should be evaluated. This section should specify the limiting parameters established by these analyses, including maximum temperature, maximum stress, and limiting heatup and cooldown rates.

1.5 Thermal Annealing Operating Conditions

This section of the report should describe the proposed thermal annealing operating conditions, including bounding conditions of temperature and time, and heatup and cooldown schedules. The annealing parameters should be selected to provide sufficient recovery of fracture toughness to satisfy the requirements of 10 CFR 50.60 and 10 CFR 50.61, or any other objective identified in the application, for the proposed post-anneal period of operation. The annealing parameters should be compatible with design stress limits of the reactor and any other component or structure expected to experience significant temperature or stress gradients during the annealing operation. Limitations such as the physical constraints resulting from attached piping, supports, snubbers, and other components and the thermal and mechanical stresses generated in the vessel and piping during the annealing operation should also be considered.

This section should identify the proposed annealing temperature, time at temperature, heatup rate, cooldown rate, and the limitations and permitted variations in these conditions. The limitation on temperature variations should include axial, azimuthal, and through-wall gradients and the permissible temperature profiles in the vessel during heatup, cooldown, and steady-state heating. The bases used to establish these annealing parameters should be described.

The time and temperature parameters identified in the Thermal Annealing Operating Plan should be based on the thermal and stress analyses described in Section 1.4 and should represent the bounding times, temperatures, and heatup and cooldown schedules for the thermal annealing operation that should not be violated during the annealing operation. If these bounding conditions for times and temperatures are violated during the thermal annealing operation, the analysis will no longer be valid and the annealing operation is considered not in accordance with the Thermal Annealing Operating Plan. In that case, the licensee should follow Section 5.2 of this regulatory guide.

1.6 Description of Annealing Method, Instrumentation, and Procedures

This section of the report should describe in detail the method selected for annealing the vessel as well as the proposed instrumentation and procedures to be applied during the annealing operation. The annealing operation should not degrade the reactor or other equipment, components, and structures to such an extent that their ability to perform intended safety functions can no longer be maintained. The annealing operation must be compatible with the original design limits of the reactor system or the incompatibility should be described and justified. In such cases, additional design analysis may be required.

The annealing method should be determined based on constraints from reactor design and accessibility to the reactor vessel to allow insertion of equipment and instrumentation. Selection of the method also should be based on the expected structural effects on the primary system that result from temperature gradients in the pressure vessel.

The reactor vessel and adjacent equipment, components, and structures should have instrumentation that permits on-line measurement of temperatures at locations that are needed to assess the entire temperature profile of the reactor pressure vessel and the adjacent equipment, components, and structures. Instrumentation should also be installed to determine the stress profiles in these items, including the effects of thermal gradients in the axial, azimuthal, and through-thickness directions during all transient and steady-state aspects of the annealing operation. The accuracy and reliability of the measurements should be demonstrated. The stresses and strains caused by temperature gradients may be established by analysis in combination with on-line measurements of temperature or displacements.

The annealing procedure should detail the operational steps to be taken during the annealing operation and should include all quality assurance measures needed to ensure an effective annealing operation. The annealing procedure should identify the controls that will be in place and how these will be applied and maintained throughout the annealing operation. The annealing procedure should describe how the heat treatment equipment will be installed and removed from the vessel; what procedures will be instituted to control radioactive contamination before, during, and after the annealing operation; and how the vessel will be drained and dried prior to annealing. The procedures should detail the precautions to be taken to preclude cooling water leakage into the vessel during the annealing operation; such leakage could result in a steam explosion or a thermal shock to the vessel.

1.7 Proposed Annealing Equipment

This section of the report should provide a description of the equipment to be used for the in-service annealing. It should describe the heating apparatus and the general plant layout to support the annealing operation; the controls and instrumentation, including redundant controls; and equipment for measuring and recording the temperatures and temperature profiles. This section should describe how the equipment will operate, as well as what provisions will be made to protect personnel from radiation exposure and to protect instruments and equipment from temperature effects during the annealing operation.

The heating apparatus should be designed, provided with instrumentation, and controlled so that the entire section of the vessel to be annealed is effectively held at a uniform temperature, within the bounds established by the Thermal Annealing Operating Plan, throughout the annealing period. Redundancy in heating devices, controls, and instrumentation should be discussed in the operating plan. The temperature control system should be able to control temperatures sufficiently to avert adverse effects from thermal gradients during heatup, annealing, and cooldown operations.

1.8 ALARA Considerations

This section of the report should describe the steps to be taken to minimize occupational exposure, in accordance with the "as low as is reasonably achievable" (ALARA) principle and the provisions of 10 CFR 20.1206. Special training of the personnel who will actually perform the annealing operations should be described. Equipment and procedures for monitoring and control of airborne radioactive particles during the operation should be identified. This section should specifically address precautions to be taken to avoid excessive exposure from radiation streaming when the reactor internals are being removed and stored, when the reactor coolant is removed from the reactor, and when the heating equipment is being moved into and out of the reactor vessel. It should also describe steps taken to minimize occupational exposure from radioactive waste processing, radioactive materials decontamination, and radioactive waste shipment.

1.9 Summary of the Thermal Annealing Operating Plan

The Thermal Annealing Report should contain a summary of the Thermal Annealing Operating Plan that includes the highlights of each section, the key parameters of annealing, and the major conclusions of the plan. The projected percent recovery and the projected reembrittlement rate should be identified, as well as the projected end-of-license values of RT_{NDT} and Charpy upper-shelf energy after annealing.

2. REQUALIFICATION INSPECTION AND TEST PROGRAM

The inspection and test program to requalify the annealed reactor vessel should include the detailed monitoring, inspections, and tests proposed to demonstrate that the limitations in the operating plan on temperatures, heat treatment times, temperature profiles, and stresses have not been exceeded. The detailed monitoring, inspections, and tests should also establish the thermal annealing time and temperature to be used in quantifying the fracture toughness recovery. The program should also demonstrate that the annealing operation has not degraded the reactor vessel, attached piping or appurtenances, or the adjacent concrete structures to a degree that could affect the safe operation of the reactor after annealing.

The program should identify the limiting parameters established for the thermal annealing operation conditions, identify the physical measurements and tests to be made to ensure that these conditions are not exceeded, describe the instrumentation to be used for making these measurements and tests, and state the quality assurance provisions to be applied.

2.1 Monitoring the Annealing Process

This section should identify the measurements, with their locations, that will be used to monitor the annealing process and to make certain that the proposed annealing conditions evaluated in the operating plan (see Section 1.5 of this guide) are not exceeded. Temperature measurements should be made at sufficient locations to establish temperature profiles for both the inside and outside surfaces of the reactor vessel. These measurements should be made for the entire length of the vessel along axial directions where it is physically possible, at a minimum of two different azimuthal locations (which should include the top and bottom positions of the heating zone), at locations within the heating zone where there may be cold spots (e.g., at joints between the heaters), at locations on each nozzle, and on any other component that is expected to be significantly affected by the annealing treatment. Measurements should be made with sufficient frequency to identify any temperature excursions that could lead to violating the established temperature limits. When appropriate, the measurement devices should be in physical contact with the component when the temperature is being measured. The measurement records should be retained for possible review and inspection by the NRC, in accordance with the requirements of 10 CFR 50.71(c), until the facility license is terminated. The temperature measurements should be monitored and compared to pre-established tolerance bounds during heatup, steady-state operation, and cooldown to ensure that temperature and stress limits have not been exceeded.

Stress limitations should be monitored by a procedure established by the licensee that uses strain gauges or alternative methods, for example, deflection measurements or temperature measurements. Experimental evidence of the validity of alternative methods should be provided. Measurements should be made to establish stress levels at the vessel locations of highest stress, on the vessel nozzles, on the flange, and on high-stress piping locations.

This section should describe the measurement type, the number of measurements to be made for each component, measurement sensitivity, measurement frequency, and recording method.

2.2 Inspection Program

This section should describe the inspection program proposed to affirm that the annealing operation has not damaged the reactor vessel or related equipment, components, or structures. The inspection program, as a minimum, should include a pre- and post-anneal visual examination of critical regions of the vessel, piping, and any other equipment, component, or structure that might be affected by the annealing operation. The inspection program should also describe a nondestructive examination program for the reactor vessel beltline region that will ensure that the vessel will continue to perform its safety function after the annealing operation. The description of the inspection program should include acceptance criteria, type and number of examinations, qualification requirements, and reporting requirements.

2.3 Testing Program

This section should describe the testing program that will be performed to demonstrate the effectiveness of the annealing operation and to assure that the reactor vessel, attached piping and appurtenances, and adjacent concrete will continue to perform their intended safety function following the annealing operation. This program is expected to be unique to each plant and should be established by the applicant. The testing program may, for example, test the effects on the vessel of annealing, the integrity of the concrete, the operability of instrumentation, and the post-anneal functioning of affected components, equipment, and structures.

3. FRACTURE TOUGHNESS RECOVERY AND REEMBRITTLEMENT ASSURANCE PROGRAM

The fracture toughness recovery and reembrittlement assurance program should describe the methods to be used for quantifying the percent recovery, the reembrittlement trend and for establishing the post-anneal RT_{NDT} and Charpy upper-shelf energy values. These tasks are important for evaluation of the safety margins of the reactor pressure vessel in subsequent operating periods. The methods outlined below provide experimental and computational means for quantifying both the recovery of fracture toughness following the thermal anneal and the reembrittlement rate with subsequent plant operation.

3.1 Fracture Toughness Recovery Program

This section of the assurance program should describe the method planned to determine the percent recovery, including any computations or tests. The methods discussed below provide experimental and computational means for determining the percent recovery of ΔRT_{NDT}, R_t, and the percent recovery of Charpy upper-shelf energy, R_{USE}.

As provided in the thermal annealing rule (10 CFR 50.66), one of three methods may be used to evaluate the recovery in fracture toughness following the thermal annealing. One method requires the use of surveillance specimens from "credible" surveillance programs (as defined in the PTS rule, 10 CFR 50.61) to develop material-specific data, if such specimens are available. The most accurate, but difficult, second method uses material removed from the reactor pressure vessel beltline to develop plant-specific data. The third method uses generic computations to estimate the recovery. These three methods are described below. Values of percent recovery (R_{USE} and R_t) may not exceed 100 percent.

3.1.1 Vessel Surveillance Program Method

If the plant's surveillance program has resulted in "credible" data (as defined in the PTS rule, 10 CFR 50.61), and broken specimens from that program have been retained (as recommended in NRC Information Notice No. 90-52, "Retention of Broken Charpy Specimens," Reference 17), the thermal annealing rule (10 CFR 50.66) requires that broken specimens from surveillance specimens and any remaining untested surveillance specimens be used to evaluate annealing recovery on a material-specific basis. The broken specimens should be reconstituted (see Section 3.1.4 of this guide) to form new, full-size specimens with the insert material being the only material from the original surveillance specimen. These reconstituted specimens, and any untested specimens from the original specimen complement, should be annealed at time and temperature conditions that are equal to or are bounded by the actual vessel annealing conditions.

This method may be applied to broken specimens from a single capsule or multiple capsules from the surveillance program. Specimens from at least two capsules should be used, with the fluences of the two capsules spanning the peak fluence of the reactor pressure vessel beltline; this ensures that an interpolation of the annealing recovery is possible. If broken specimens from only a single capsule are used, the specific surveillance capsule chosen should be the one for which the fluence most closely matches the peak fluence of the reactor pressure vessel beltline.

As an alternative, materials test reactor (MTR) irradiations of the vessel-specific limiting material may be used as a method for determining percent recovery on a material-specific basis (see Section 3.3 of this guide).

Methods for testing the specimens and using the resultant data are discussed in Sections 3.1.5 and 3.1.6 of this guide.

The assurance program should describe the plans for using the surveillance results, including a description of the procedure for generating post-anneal properties (e.g., reconstituted specimens or whole previously untested specimens) and the method for using the surveillance measurements of percent recovery to evaluate the percent recovery for the vessel material.

3.1.2 Irradiated Vessel Material Method

An alternative method for determining the percent recovery uses the results of a verification test program employing materials removed from the beltline region of the reactor vessel. For this method, the samples removed from the vessel are used to evaluate the as-irradiated or pre-anneal condition of the material and the post-anneal condition of the material. The post-anneal condition is evaluated from specimens that have been annealed at the time and temperature conditions equal to or bounded by the reactor vessel annealing conditions.

The number of samples to be removed from the vessel depends on many factors, including the size of the samples, the reason for the annealing (determining both RT_{NDT} and Charpy upper-shelf energy requires more tests than determining only one of these quantities), the testing plans (specimen size and type), and the acceptability of removing the samples from the vessel. The samples removed from the vessel beltline can be used to fabricate full-size Charpy specimens, inserts for reconstitution into full-size Charpy specimens, or sub-size Charpy specimens (see subsections 3.1.4.3 and 3.1.6.4). Other test methods for irradiated vessel material may be used if appropriate justification is provided.

This method is plant-specific and, as described below, several criteria must be satisfied to demonstrate the acceptability of this method for a specific application or plant.

The assurance program should provide a complete description of the plans for using samples removed from the vessel beltline, including the method for removing the samples; the number, size, and location of the samples; analyses to demonstrate acceptability of the sample removal; the experimental plans for using the samples (size and number of specimens, test plans and procedures, etc.); and the method for determining the percent of recovery of the vessel material from the results of the tests from the samples.

3.1.2.1 Acceptability of Removing Material from the Vessel. The acceptability of the method used for removing samples from the vessel beltline is based on local and global considerations, both of which should be addressed in the assurance program. The global considerations concern the impact on overall vessel integrity of the depression, hole, or surface discontinuity remaining after removal of the sample, and they are addressed through analysis. The local considerations concern thermal and mechanical effects and surface quality effects on the surrounding material remaining after removal of the samples.

The sample removal process should be described in the assurance program, including a description of the measures to ensure the identification and documentation of the orientation of the sample relative to the vessel.

The removal of samples from the vessel beltline will result in a depression or other surface discontinuity in the vessel wall. As required in the thermal annealing rule (10 CFR 50.66), it must be demonstrated that the resulting depressions satisfy the stress limits of the applicable portions of the ASME Code Section III, regardless of the applicable section of the Code for the vessel design. The analyses used to demonstrate compliance with the applicable stress limits of Section III of the ASME Code must include consideration of the effects of fatigue and corrosion on the exposed base metal following removal of the samples, and the analyses should consider any thermal and mechanical effects on the surface and near-surface material remaining after removal of the sample.

The assurance program should describe the method proposed to characterize the depression remaining after sample removal to ensure that the condition of the remaining material is bounded by the assumptions in the analysis and is acceptable. Any proposed repairs, including weld repair, should be described in the Thermal Annealing Operating Plan.

3.1.2.2 Testing of Material Removed from the Vessel Beltline. One impediment to the quantitative use of data from testing of material removed from the vessel beltline in determining the percent recovery of ΔRT_{NDT} and Charpy upper-shelf energy is that this material represents surface or near-surface properties of the material. In contrast, ASTM Standard E 185 (Ref. 14) requires the use of material from the 1/4T location of plate and forging products, and more than 0.5 in. from the surface of weld metals, to determine ΔRT_{NDT} and Charpy upper-shelf energy.

To permit a quantitative use of material removed from the vessel beltline to determine the percent recovery of ΔRT_{NDT} and Charpy upper-shelf energy, samples removed from the vessel beltline should be used to evaluate both the pre-anneal and the post-anneal properties of the near-surface material. Specimens used to evaluate the post-anneal properties should be annealed at time and temperature conditions that equal or are bounded by the actual vessel annealing conditions. The resulting percent recovery of transition temperature at the 30 ft-lb level may be used to determine the percent recovery for ΔRT_{NDT}, R_I. The resulting percent recovery of the Charpy upper-shelf energy may be used to determine the Charpy upper-shelf energy, R_{USE}.

Samples removed from the vessel beltline material can be used to develop test specimens in several manners. The samples can be used to fabricate fullsize Charpy specimens, inserts for reconstitution into full-size Charpy specimens, sub-size Charpy specimens or other test specimens of the approved plan. Preparation and use of these various specimen types is described in Section 3.14.

3.1.3 Computational Method

The computational method uses generic equations (Equations 1 and 2) to determine the percent recovery of Charpy upper-shelf energy (USE) and ΔRT_{NDT} respectively. Alternative computational methods may be used if appropriate justification is provided. When determining the projected percent recovery for the annealing plan, the proposed lower-bound annealing time and temperature are used in Equations 1 and 2. However, when computing the post-anneal percent recovery, the actual annealing time and the lower bound of the range of actual annealing temperatures determined from the instrumentation (see Section 2.1 of this guide) should be used.

$$R_{USE} = \{[1-0.586 \exp(-t_a/15.9)] \times [0.570\Delta USE_i + (0.120T_a-104)\ Cu+0.0389T_a-17.6]\} \times \{100/\Delta USE_i\} \quad \text{(Equation 1)}$$

where

R_{USE} = percent recovery of USE from annealing,
ΔUSE_i = (mean USE unirradiated - mean USE after irradiation),
t_a = time at annealing temperature in hours,
T_a = annealing temperature in °F,
Cu = copper content of material in weight-percent.

$$R_t = [0.5 + 0.5 \tanh\{(a_1T_a - a_2)/95.7\}] \cdot 100 \quad \text{(Equation 2)}$$

where

R_t = percent recovery of transition temperature from annealing,
a_1 = $1 + 0.0151 \ln(t_a) - 0.424Cu^{(3.28 - 0.00306Ta)}$
a_2 = $0.584(T_i + 637)$, for $T_a \geq 800°F$
or a_2 = $0.584T_i - 15.5\ln(\Phi) + 833$ for $T_a \leq 750°F$

where

Φ = flux rate, n/(cm2-s),
T_i = temperature of irradiation.
Cu = copper content of material in weight percent with maximum value of 0.3%.

The current R_t equation is not accurate between annealing temperatures of 750 and 800°F. Until a complete equation is developed an extension of the effect of the flux term (a_2) is assumed to a temperature of 775°F. Between 775 and 800°F, a linear interpolation between Equation 2 evaluated at 775°F with the flux term and Equation 2 evaluated at 800° without the flux term should be made.

Since plant operational characteristics do not result in a unique value of irradiation temperature throughout a plant's lifetime, the method used for evaluating T_i should be described in the assurance program.

Equations 1 and 2 are documented in Reference 8 and represent mean values of the percent recovery of RT_{NDT} and USE.

3.1.4 Specimen Handling and Preparation Procedures

3.1.4.1 Specimen Handling Procedures. For reconstituting surveillance specimens or removing samples from the vessel beltline, the assurance program should describe the methods to be used for marking and handling the test materials to ensure that the orientation of the material relative to the vessel is unambiguous and traceable.

3.1.4.2 Specimen Orientation. The assurance program should address the orientation of the specimens to be tested. For testing materials from a "credible" surveillance program for the evaluation of percent recovery of ΔRT_{NDT}, it is preferable to test the post-anneal specimens in the same orientation as the original surveillance tests. In contrast, for evaluation of Charpy upper-shelf energy, it may be preferable to use specimens oriented in the transverse direction, the T–L orientation, according to ASTM Standard E 399 (Ref. 18).

3.1.4.3 Reconstitution of Charpy Specimens. Reconstitution of Charpy specimens is used to provide new full-size Charpy specimens from the broken pieces of previously tested specimens and to conserve material. Several methods are available for welding end-tabs onto the test material section, with the goal of each method to provide a structurally sound and testable specimen (i.e., the specimen does not fracture at the reconstitution welds) without overheating (possibly inducing annealing) the test section.

The assurance program should describe the procedures to be used for the reconstitution process. The procedures and criteria of ASTM Standard E 1253–88 (Ref. 19), "Standard Guide for Reconstitution of Irradiated Charpy Specimens," are sufficient to demonstrate an adequate reconstitution method. Other proposed methods should have appropriate justification.

3.1.5 Specimen Testing

3.1.5.1 Test Procedures. The assurance program should describe the procedures used for testing the Charpy specimens, either full-size or sub-size. For testing full-size Charpy specimens, either reconstituted specimens or specimens fabricated from samples removed from the vessel beltline, testing should be performed using equipment and testing procedures similar to those used to develop surveillance data, as outlined in ASTM Standards E 185–82 (Ref. 14) and E 23–88 (Ref. 20).

Testing of sub-size Charpy specimens should follow the general procedures and methods in ASTM Standard E 23–88 (Ref. 20) for testing of full-size Charpy specimens. For testing sub-size Charpy specimens, a description of the general test procedures and the testing equipment should be provided in the assurance program. In addition, a method for applying the results from the tests of the sub-size specimens should be described.

3.1.5.2 Test Plan. The assurance program should describe the test plan, including the number of specimens to be tested and the method for selecting test temperatures. This description should include the steps taken to ensure that a reasonable measure of recovery is achieved by the testing; the description should also include the proposed method for handling uncertainty in the test results.

Testing to evaluate percent recovery of ΔRT_{NDT} should result in an unambiguous evaluation of the temperature at which the average Charpy energy versus temperature curve achieves an energy level of 30 ft-lb. It is preferable that the testing cover a broad range of results based on the shear percentage (from near 0 percent to greater than 95 percent) to permit a more complete assessment of the Charpy data trends for the material and to preclude false trends from data clustering around the 30 ft-lb level.

Testing to evaluate Charpy upper-shelf energy recovery should provide an unambiguous definition of the Charpy upper-shelf energy for the material. All tests used in evaluating the Charpy upper-shelf energy should result in 100 percent shear.

3.1.6 Quantification of Post-Anneal Initial Properties

Quantification of the post-anneal initial properties, RT_{NDT} and Charpy upper-shelf energy, is dependent on the method used to determine the percent recovery by annealing.

3.1.6.1 Vessel Surveillance Program Method. The assurance program should describe the surveillance results to be used in evaluating percent recovery, along with the proposed method to relate the observed percent recovery from the surveillance results to the percent recovery of the vessel material.

One method for relating the observed recovery to the vessel recovery is to compare the measured recovery from the test (or tests) of surveillance specimens to the percent recovery from Equations 1 and 2 for the surveillance capsule. The average ratio (or the ratio from a single capsule) between the measured recovery from the surveillance capsules and that evaluated from Equations 1 and 2 for the surveillance capsule provides a material-specific adjustment for the generic equation. In this method, the vessel percent recovery would be calculated by multiplying the percent recovery determined from Equations 1 and 2 for the vessel by the average ratio adjustment. Values of R_t and R_{USE} determined from surveillance data may not exceed 100.

Once suitable values of R_t and R_{USE} have been determined from the surveillance data, the post-anneal reference temperature (RT_{NDT}) and Charpy upper-shelf energy are evaluated using Equations 3 and 4:

$$RT_{NDT(A)} = RT_{NDT(U)} + \Delta RT_{NDT} \times (100 - R_t) / 100 \qquad \text{(Equation 3)}$$

$$CvUSE_{(A)} = CvUSE_{(U)} \, [1 - D \times (100 - R_{USE})/10000] \qquad \text{(Equation 4)}$$

where

$RT_{NDT(A)}$ = reference temperature, RT_{NDT}, of the material in the post-anneal condition in °F,

$RT_{NDT(U)}$ = reference temperature, RT_{NDT}, of the material in the preservice or unirradiated condition in °F,

ΔRT_{NDT} = mean value of the transition temperature shift, or change in RT_{NDT}, from irradiation (before annealing) in °F,

R_t = percent recovery of ΔRT_{NDT} from annealing,

$CvUSE_{(A)}$ = Charpy upper-shelf energy of the material in the post-anneal condition in ft-lb,

$CvUSE_{(U)}$ = Charpy upper-shelf energy of the material in the preservice or unirradiated condition in ft-lb,

D = percent decrease in Charpy upper-shelf energy from irradiation (before annealing), and

R_{USE} = percent recovery of Charpy upper-shelf energy from annealing.

The values of $RT_{NDT(A)}$ and $CvUSE_{(A)}$, calculated using Equations 3 and 4, respectively, should be used as the values of reference temperature (RT_{NDT}) and Charpy upper-shelf energy, respectively, at the initiation of continued plant operation.

3.1.6.2 Irradiated Vessel Material Method. Since the Charpy data evaluated by this method represent the surface or near-surface properties of the plate, weld, or forging, the measured values cannot be used directly to represent the plate or forging 1/4T or weld bulk properties as called for by Regulatory Guide 1.99, Revision 2 (Ref. 21). However, evaluations of the pre-anneal and the post-anneal properties of the sample removed from the vessel beltline will provide sufficient data to evaluate the expected recovery at the plate or forging 1/4T level or the weld bulk properties.

The assurance program should describe the procedures used to evaluate percent recovery for the vessel materials from the measurements resulting from this method.

If the samples removed from the vessel beltline are from the peak flux location for the material, one procedure to evaluate the post-anneal properties from the measured percent recovery uses the following equations:

$$RT_{NDT(A)} = RT_{NDT(U)} + \Delta RT_{NDT} \times [1 - (TT_{SI} - TT_{SA}) (R_S / \Delta T_S)] \qquad \text{(Equation 5)}$$

$$CvUSE_{(A)} = CvUSE_{(U)} (1 - D / 100) (Cv_{SA} / Cv_{SI}) \qquad \text{(Equation 6)}$$

where

- $RT_{NDT(A)}$ = reference temperature, RT_{NDT}, of the material in the post-anneal condition in °F,
- $RT_{NDT(U)}$ = reference temperature, RT_{NDT}, of the material in the preservice or unirradiated condition in °F,
- ΔRT_{NDT} = mean value of the transition temperature shift, or change in RT_{NDT}, caused by irradiation (before annealing) in °F,
- TT_{SI} = from the measured surface data, the transition temperature at the 30 ft-lb energy level for the pre-anneal condition in °F,
- TT_{SA} = from the measured surface data, the transition temperature at the 30 ft-lb energy level for the post-anneal condition in °F,
- R_S = the ratio of R_t from Equation 2 for the 1/4T location to R_t from Equation 2 for the surface of the plate, forging or weld,
- ΔT_S = the mean value of the transition temperature shift (in °F) at the surface of the plate, forging or weld, determined using the surface fluence and the same calculational method used to evaluate ΔRT_{NDT} for the 1/4T location,
- $CvUSE_{(A)}$ = Charpy upper-shelf energy of the material in the post-anneal condition, for the 1/4T location of plate and forging, or the weld bulk properties in ft-lb,
- $CvUSE_{(U)}$ = Charpy upper-shelf energy of the material in the preservice or unirradiated condition, for the 1/4T location of plate and forging, or the weld bulk properties in ft-lb,
- D = percent decrease in Charpy upper-shelf energy from irradiation embrittlement, for the 1/4T location of plate and forging, or the weld bulk properties,
- Cv_{SI} = from the measured surface data, the Charpy upper-shelf energy for the pre-anneal condition in ft-lb,
- Cv_{SA} = from the measured surface data, the Charpy upper-shelf energy for the post-anneal condition in ft-lb.

The values of $RT_{NDT(A)}$ and $CvUSE_{(A)}$ calculated using Equations 5 and 6 should be used as the values of reference temperature (RT_{NDT}) and Charpy uppershelf energy, respectively, at the initiation of continued plant operation.

If the samples removed from the vessel beltline do not come from the vessel peak flux location, the vessel embrittlement and the annealing recovery will not be as great as that for the vessel peak flux location, and Equations 5 and 6 should underestimate the percent recovery of the vessel. In such cases, the assurance program should describe the procedures used to evaluate percent recovery for the vessel materials from the measurements resulting from this method.

3.1.6.3 Computational Method. For the computational method, the postanneal initial RT_{NDT} and Charpy upper-shelf energy values for each beltline material should be evaluated using Equations 3 and 4, using the values of R_t and R_{USE} from Equations 2 and 1.

The values of $RT_{NDT(A)}$ and $CvUSE_{(A)}$, calculated using Equations 3 and 4, respectively, should be used as the values of reference temperature (RT_{NDT}) and Charpy upper-shelf energy, respectively, at plant restart.

3.1.6.4 Sub-size Charpy Specimens. Sub-size Charpy specimens can provide very useful information concerning the toughness of the material and the recovery of irradiation embrittlement by annealing. Data from sub-size Charpy specimens is not uniquely correlated to data from full-size Charpy specimens in an absolute sense, but quantities such as irradiation embrittlement shift and annealing recovery can be evaluated from sub-size specimen data. Although some work has been under way in the United States in this area using several sub-size Charpy specimen designs, there is no consensus in the U.S. technical community or the nuclear industry as to a preferred specimen design or an appropriate correlation method.

The assurance program should describe the overall test plan for the use of sub-size Charpy specimens, including test specimen design and test procedures. In addition, the assurance program should describe the method proposed for quantitative use of the sub-size Charpy specimen data in evaluating percent recovery, including any experimental demonstration validating the method.

3.2 Reembrittlement Trend Assurance Program

As specified in the thermal annealing rule (10 CFR 50.66(b)(3)(ii)(B)), the reembrittlement trend of both RT_{NDT} and Charpy upper-shelf energy is to be estimated to establish the projected embrittlement at the end of the proposed period of plant operation, and is to be monitored during post-anneal reactor operations to confirm these estimates, using a surveillance program that conforms to the intent of Appendix H of 10 CFR Part 50. An appropriate method for estimating the reembrittlement trend is using a "lateral shift" method. For the "lateral shift" method, the reembrittlement trend is the same as the embrittlement trend used for the pre-anneal operating period, regardless of whether the embrittlement was determined using the procedures of the PTS Rule (10 CFR 50.61(c)) for embrittlement of RT_{NDT}, or the procedures of Revision 2 of Regulatory Guide 1.99 (Ref. 21) for embrittlement of Charpy upper-shelf energy, or whether embrittlement was determined from "credible" surveillance data.

The assurance program should describe the program to estimate reembrittlement trends prior to the development of "credible" data from the reembrittlement surveillance program and should describe the surveillance program to be used for post-anneal plant operation.

3.2.1 Lateral Shift Method

3.2.1.1 Description of the Lateral Shift Method. As illustrated in Figure 1 for both RT_{NDT} and Charpy upper-shelf energy, the lateral shift method results in a shift of the initial irradiation embrittlement curve along the fluence axis, using the post-anneal properties (ΔRT_{NDT} and Charpy upper-shelf energy) as the basis point. This method has been found to be conservative in bounding subsequent embrittlement.

3.2.1.2 Reembrittlement of RT_{NDT}. The reembrittlement of RT_{NDT} is established using the same embrittlement trend as the pre-anneal operating period, with a lateral shift.

For the pre-anneal operating period, RT_{NDT} is given by:

$$RT_{NDT} = RT_{NDT(U)} + \Delta RT_{NDT} + M \qquad \text{(Equation 7)}$$

where

RT_{NDT} = reference temperature, RT_{NDT}, of the material in the irradiated condition in °F,

$RT_{NDT(U)}$ = reference temperature, RT_{NDT}, of the material in the preservice or unirradiated condition in °F,

ΔRT_{NDT} = mean value of the transition temperature shift, or change in RT_{NDT}, from irradiation in °F, and

M = margin term in °F to account for uncertainties in the values of $RT_{NDT(U)}$, nickel and copper content, fluence and the calculational procedures, as determined from Equation 8.

$$M = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2} \qquad \text{(Equation 8)}$$

where

σ_I = standard deviation of $RT_{NDT(U)}$ in °F,

σ_Δ = standard deviation of ΔRT_{NDT} in °F.

From Revision 2 of Regulatory Guide 1.99 (Ref. 21), σ_Δ is 17°F for base metals and σ_Δ is 28°F for weld metals.

Further, ΔRT_{NDT} is given by:

$$\Delta RT_{NDT} = (CF)\ (f)^{(0.28 - 0.10 \log f)} \qquad \text{(Equation 9)}$$

where

CF = chemistry factor (in °F) based on the nickel and copper content of the material, or based upon results from the surveillance program if the program is "credible" according to the criteria in the PTS rule (10 CFR 50.61), and

f = the best-estimate neutron fluence (in units of 10^{19} n/cm², E > 1 MeV), at the clad-base metal interface on the inside surface of the vessel.

For reembrittlement, the lateral shift is accomplished by determining the "transition recovery fluence," f_t, by solving for the fluence value that satisfies Equation 10:

$$RT_{NDT(A)} - RT_{NDT(U)} = (CF)(f_t)^{(0.28 - 0.10 \log f_t)} \qquad \text{(Equation 10)}$$

where $RT_{NDT(A)}$ is the reference temperature, RT_{NDT}, of the material in the post-anneal condition.

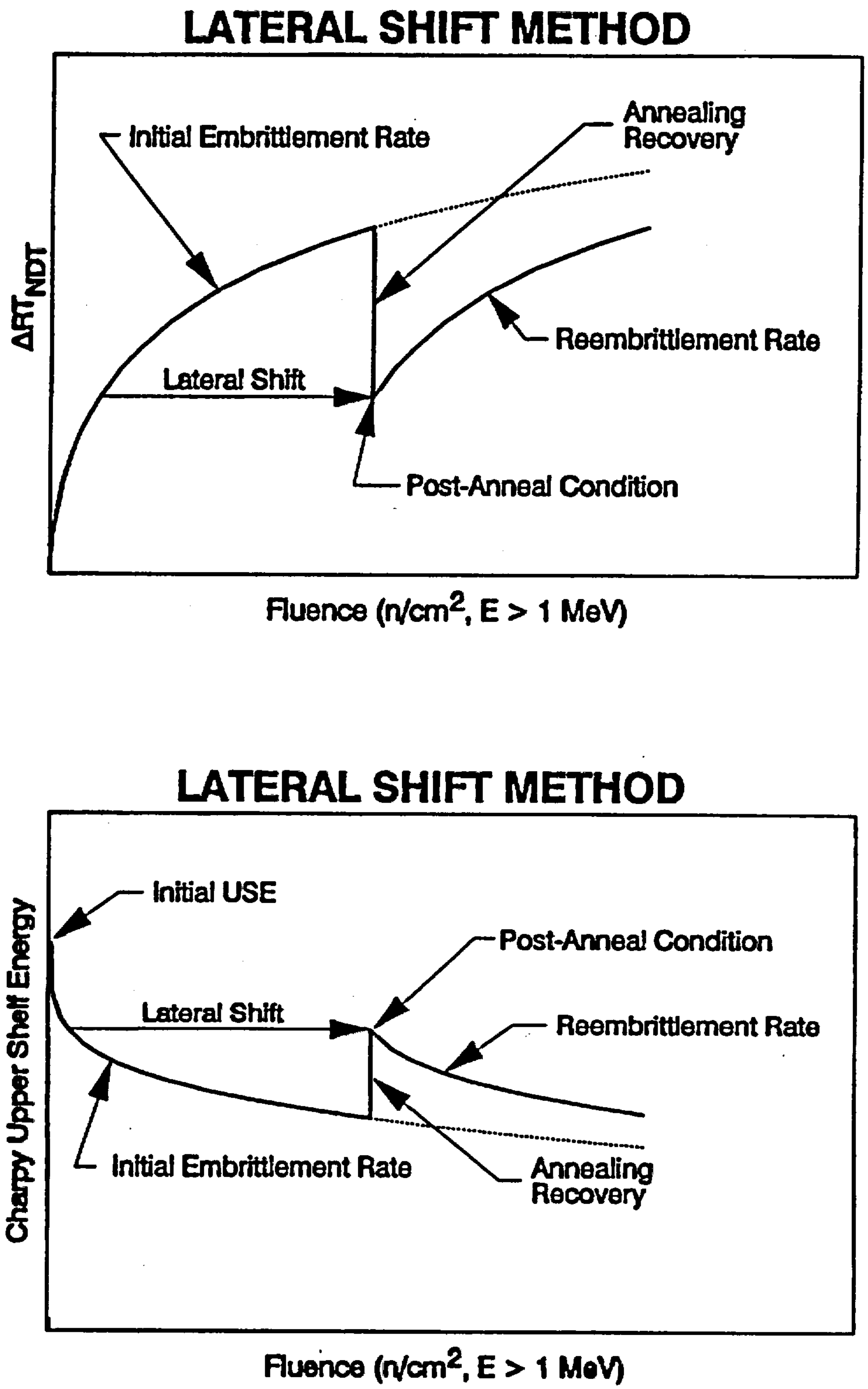
LATERAL SHIFT METHOD
Initial Embrittlement Rate
Annealing Recovery
ΔRT_NDT
Reembrittlement Rate
Lateral Shift
Post-Anneal Condition
Fluence (n/cm², E > 1 MeV)
LATERAL SHIFT METHOD
Initial USE
Post-Anneal Condition
Lateral Shift
Reembrittlement Rate
Charpy Upper Shelf Energy
Initial Embrittlement Rate
Annealing Recovery
Fluence (n/cm², E > 1 MeV)

Figure 1

For reembrittlement, the reference temperature (RT_{NDT}) is evaluated by

$$RT_{NDT} = RT_{NDT(U)} + \Delta RT_{NDT} + M \quad \textbf{(Equation 11)}$$

where

ΔRT_{NDT} = the mean value of the shift in reference temperature caused by irradiation (as given below by Equation 12) in °F, and

M = margin term in °F to account for uncertainties in the values of $RT_{NDT(U)}$, nickel and copper content, fluence, and the calculational procedures, as given by Equation 13.

$$\Delta RT_{NDT} = (CF)\ (f + f_t)[0.28 - 0.10 \log (f + f_t)] \quad \textbf{(Equation 12)}$$

where

CF = the same chemistry factor (in °F) used for the pre-anneal operating period, based on the nickel and copper content of the material or the results of the "credible" surveillance program,

f = the increment of best-estimate neutron fluence (in units of 10^{19} n/cm^2, E > 1 MeV), at the clad-base metal interface on the inside surface of the vessel, *accumulated during plant operation subsequent to the annealing operation*, and

f_t = the "transition recovery fluence," evaluated from Equation 10.

$$M = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2} \quad \textbf{(Equation 13)}$$

where

σ_I = standard deviation of $RT_{NDT(U)}$ in °F,

σ_Δ = standard deviation of ΔRT_{NDT} in °F,

3.2.1.3 Reembrittlement of the Charpy Upper-Shelf Energy. The reembrittlement of the Charpy upper-shelf energy is evaluated using the same embrittlement trend as the pre-anneal operating period, with a lateral shift. For the pre-anneal operating period, Revision 2 of Regulatory Guide 1.99 (Ref. 21) gives upper-shelf energy decrease in a graphical form only. Merkle (Ref. 22) developed equations that accurately model the various Charpy uppershelf energy decrease curves. Using the equations in Reference 21:

$$CvUSE = CvUSE_{(U)} \times [1 - D/100] \quad \textbf{(Equation 14)}$$

for base metals:
$D = (100\ Cu + 9)\ (f)^{0.2368}$

for weld metals:
$D = (100\ Cu + 14)\ (f)^{0.2368}$

the upper bound:
$D = 42.39\ (f)^{0.1502}$

where

CvUSE = Charpy upper-shelf energy of the material in the irradiated condition (before annealing) in ft-lb,

$CvUSE_{(U)}$ = Charpy upper-shelf energy of the material in the preservice or unirradiated condition in ft-lb,

D = percent decrease in Charpy upper-shelf energy from irradiation (before annealing),

Cu = copper content (weight-percent) for the subject material, and

f = the best-estimate total neutron fluence (in units of 10^{19} n/cm^2, E > 1 MeV), at the clad-base metal interface on the inside surface of the vessel.

The value of D is the lesser of that from the appropriate equation for the material type and that from the upper bound equation. For "credible" surveillance data, guidance is given in Revision 2 of Regulatory Guide 1.99 (Ref. 21) for determining percent decrease in Charpy upper-shelf energy based on the surveillance results.

For reembrittlement, the lateral shift is accomplished by determining the "shelf recovery fluence," f_s, from:

for base metals:

$$f_s = \left[\frac{1 - (CvUSE_{(A)}/CvUSE_{(U)})}{100\ Cu + 9}\right]^{4.223}$$

for weld metals:

$$f_s = \left[\frac{1 - (CvUSE_{(A)}/CvUSE_{(U)})}{100\ Cu + 14}\right]^{4.223}$$

the upper bound:

$$f_s = \left[\frac{1 - (CvUSE_{(A)}/CvUSE_{(U)})}{42.39} \right]^{6.658}$$

(Equation 15)

For both weld metal and base metal, the correct value of f_s is the larger of the values from the appropriate equation for the material type and the upper bound equation.

Reembrittlement of Charpy upper-shelf energy is evaluated from:

$$CvUSE = CvUSE_{(U)} \times [1 - D/100]$$

(Equation 16)

for base metals:
$D = (100\ Cu + 9)\ (f + f_s)^{0.2368}$

for weld metals:
$D = (100\ Cu + 14)\ (f + f_s)^{0.2368}$

the upper bound:
$D = 42.39\ (f + f_s)^{0.1502}$

where

$CvUSE_{(U)}$ = Charpy upper-shelf energy of the material in the preservice or unirradiated condition in ft-lb,

Cu = the copper content (weight-percent) for the subject material,

f = the *increment* of best-estimate total neutron fluence (in units of 10^{19} n/cm^2, E > 1 MeV), at the clad-base metal interface on the inside surface of the vessel, accumulated during subsequent plant operation after the annealing operation, and

f_s = the "shelf recovery fluence," evaluated from Equation 15.

For "credible" surveillance data, the values of "9" and "14" in Equations 15 and 16 are replaced by values that are based on the surveillance results.

3.2.2 Surveillance Method

For the surveillance method, the reembrittlement trend is determined from the surveillance results of a program that conforms to the intent of Appendix H of 10 CFR Part 50, once the surveillance program and results from the program have met the credibility requirements in the PTS rule (10 CFR 50.61).

3.3 Use of Materials Test Reactor (MTR) Irradiations

If archival pieces of the limiting vessel material are available, materials test reactor (MTR) irradiations may be used to evaluate the recovery and reembrittlement trends. Plans for using archival material should be described in the assurance program, including the traceability of the material to the vessel, the proposed experimental matrix, and the method proposed for using the results of the MTR irradiations.

4. IDENTIFICATION OF UNREVIEWED SAFETY QUESTIONS AND TECHNICAL SPECIFICATION CHANGES

Any changes to the facility that are described in the updated final safety analysis report as unreviewed safety questions and any changes to the technical specifications that are necessary to either conduct the thermal annealing or operate the nuclear power reactor following the annealing should be identified in this section. The section should demonstrate that the Commission's requirements are complied with and that there is reasonable assurance of adequate protection to the public health and safety following the changes.

5. COMPLETION OR TERMINATION OF THERMAL ANNEAL

5.1 Annealing Completed, in Compliance

If the thermal annealing was completed in accordance with the Thermal Annealing Operating Plan and the Requalification Inspection and Test Program, the licensee must so confirm in writing to the Director, Office of Nuclear Reactor Regulation (NRR). Within 15 days of the licensee's written confirmation that the thermal annealing was completed in accordance with the Thermal Annealing Plan, and prior to restart, the NRC will (1) briefly document whether the thermal annealing was performed in compliance with the licensee's Thermal Annealing Operating Plan and the Requalification Inspection and Test Program, with the documentation to be placed in the NRC Public Document Room, and (2) hold a public meeting on the annealing. The purposes for the public meeting are to (1) permit the licensee to explain the results of the reactor vessel annealing to the NRC and the public, (2) allow the NRC to discuss its inspection of the reactor vessel annealing, and (3) provide an opportunity for the public to comment to the NRC on the thermal annealing. The licensee may restart its reactor after the meeting has been completed, unless the NRC orders otherwise. Within 45 days of the licensee's written confirmation that the thermal annealing was completed in accordance with the Thermal Annealing Operating Plan and the Requalification Inspection and Test Program, the NRC staff will complete full documentation of the NRC's inspection of the licensee's annealing process and place the documentation in the NRC Public Document Room.

5.2 Annealing Completed, Not in Compliance

If the thermal annealing was completed but not performed in accordance with the Thermal Annealing Operating Plan and the Requalification Inspection and Test Program, including the bounding conditions of the temperature and times, the licensee must submit a summary of lack of compliance and a justification for subsequent operations. The licensee must also identify any changes to the facility that are attributable to the noncompliances that constitute unreviewed safety questions and any changes to the technical specifications that are required for operation as a result of the noncompliances. This identification does not relieve the licensee from complying with applicable requirements of the Commission's regulations and the operating license; and if these requirements cannot be met as a result of the annealing operation, the licensee must obtain the appropriate exemption per 10 CFR 50.12. If unreviewed safety questions or changes to technical specifications are not identified as necessary for resumed operation, the licensee may restart after the NRC staff places a summary of its inspection of the thermal annealing in the NRC Public Document Room and the NRC holds a public meeting on the thermal annealing. On the other hand, if unreviewed safety questions or changes to technical specifications are identified as necessary for resumed operation, the licensee may restart only after the Director of NRR authorizes restart, the summary of the NRC staff inspection is placed in the NRC Public Document Room, and a public meeting is held on the thermal annealing.

5.3 Termination Prior to Completion of Anneal

If the thermal annealing was terminated prior to completion, the licensee should immediately notify the NRC of the premature termination of the thermal anneal.

5.3.1 Licensee Elects Not To Take Credit for any Recovery

If the partial annealing was otherwise performed in accordance with the Thermal Annealing Operating Plan and relevant portions of the Requalification Inspection and Test Program, and the licensee does not elect to take credit for any recovery, the licensee need not submit the Thermal Annealing Results Report described in Section 6 of this regulatory guide but instead must confirm in writing to the Director, NRR, that the partial annealing was otherwise performed in accordance with the Thermal Annealing Operating Plan and relevant portions of the Requalification Inspection and Test Program. The licensee may restart its reactor after the NRC places a summary of its inspection of the thermal annealing in the Public Document Room and the NRC holds a public meeting on the thermal annealing.

5.3.2 Licensee Elects To Take Credit for any Recovery

If the partial annealing was otherwise performed in accordance with the Thermal Annealing Operating Plan and relevant portions of the Requalification Inspection and Test Program and the licensee elects to take full or partial credit for the partial annealing, the licensee must confirm in writing to the Director, NRR, that the partial annealing was otherwise performed in compliance with the Thermal Annealing Operating Plan and relevant portions of the Requlification Inspection and Test Program. The licensee may restart its reactor after the NRC places a summary of its inspection of the thermal annealing in the NRC Public Document Room and the NRC holds a public meeting on the thermal annealing.

5.3.3 Termination, Not in Compliance

If the partial annealing was not performed in accordance with the Thermal Annealing Operating Plan and relevant portions of the Requalification Inspection and Test Program, the licensee is to submit a summary of lack of compliance with the Thermal Annealing Operating Plan and the Requalification Inspection and Test Program and a justification for subsequent operation, to the Director of NRR. Any changes to the facility as described in the updated final safety analysis report that are attributable to the noncompliances and constitute unreviewed safety questions, and any changes to the technical specifications that are required as a result of the noncompliances, must also be identified.

If no unreviewed safety questions or changes to technical specifications are identified, the licensee may restart its reactor after the NRC places a summary of its inspection of the thermal annealing in the Public Document Room, and the NRC holds a public meeting on the thermal annealing.

If any unreviewed safety questions or changes to technical specifications are identified, the licensee may restart its reactor only after approval is obtained from the Director, Office of Nuclear Reactor Regulation, the summary of the NRC staff inspection is placed in the public document room, and a public meeting on the thermal annealing is held.

6. THERMAL ANNEALING RESULTS REPORT

Every licensee who either completes a thermal annealing or terminates an annealing but elects to take full or partial credit for the annealing must provide a report that includes the results of the annealing operation and verifies compliance with the approved plan. This report is to be submitted within three months of completing the thermal anneal, unless an extension is authorized by the Director, Office of Nuclear Reactor Regulation. This report should provide the following information:

(1) The time and temperature profiles of the actual thermal annealing,

(2) The post-anneal RT_{NDT} and Charpy upper-shelf energy values of the reactor vessel materials for use in subsequent reactor operation,

(3) The projected post-anneal reembrittlement trends for both RT_{NDT} and Charpy upper-shelf energy, and

(4) The projected values of RT_{PTS} and Charpy upper-shelf energy at the end of the proposed period of operation addressed in the application.

6.1 Description of the Overall Process

A detailed summary of the annealing operation, including an actual time-temperature history, should be provided. The summary should identify the location and method of attachment for the specific instrumentation, including all temperature measurement devices applied to the vessel and other structures and components. A history of the times and temperatures for each temperature measurement device should be included, showing the actual temperatures for the beginning of annealing, the heat-up period, the steady-state conditions, and the cool-down period. Sufficient detail should be included to permit determination of the heat-up and cool-down rates and the variations in temperature measurements during the entire cycle. A summary of key measurements should be provided that shows that the proposed annealing conditions, specifically the time and temperature parameters and stress allowables established in the application, were not exceeded. Additionally, a summary of the worker exposures incurred during the annealing process should be included.

6.2 Evaluation of Requalification Inspections and Tests

The results and evaluations of any inspections and tests used to requalify the annealed reactor vessel, the attached piping or appurtenances, and the adjacent concrete structures should be reported. The Thermal Annealing Results Report should include the results of all inspections and tests to demonstrate that the annealing operation has not caused degradation of the reactor vessel, the insulation, the attached piping or appurtenances, containment, and the adjacent concrete to a degree that could affect the safe operation of the reactor. The report should describe the evaluation and disposition of any indications detected during the post-anneal inspections.

6.3 Determination of Percent Recovery

The method for determining the percent recovery of RT_{NDT} and Charpy upper-shelf energy should be described. The actual time-temperature parameters of the vessel annealing operation should be used and reported. If the percent recovery is determined from testing credible surveillance specimens or from testing materials removed from the beltline region of the reactor vessel, and the testing was subsequent to the annealing operation or was not reported in the Thermal Annealing Operating Plan, the results of these tests should be reported. In this case, the report should include the initial unirradiated properties, the as-irradiated properties just prior to annealing, and the properties of the test specimens in the irradiated and annealed conditions. The report should provide supporting evidence for the licensee's report that the annealing conditions for the test specimens were equal to or bounded by the annealing conditions of the reactor vessel. If the percent recovery is determined by calculation, the evaluation of percent recovery should use the actual vessel lower-bound annealing time and temperature. In all cases, the report should include the post-anneal RT_{NDT} and Charpy upper-shelf energy values.

6.4 Determination of Reembrittlement Trend

The program for determining the reembrittlement trend based on both the reference temperature and the Charpy upper-shelf energy should be described, including the results of any analyses or tests that establish these reembrittlement trends. The program should specifically identify the post-anneal "starting" values of reference temperature and Charpy upper-shelf energy, as well as the projected embrittlement path of these values with increasing neutron fluence, including the basis for this projection. To the degree that this information is the same as the information in the Thermal Annealing Operation Plan, the plan may be referenced.

6.5 Changes to Surveillance Program

Changes to the surveillance program previously described in the Thermal Annealing Report (10 CFR 50.66(b)(3)(ii)(B)) that are the result of the annealing operation should be described in detail. If no changes are necessary, the Thermal Annealing Results Report should so state.

6.6 Allowable Operating Period

Based on the degree of recovery and the projected reembrittlement trend, an analysis should be provided to demonstrate the period of operation for which the requirements of 10 CFR 50.60 and 10 CFR 50.61 will be satisfied.

7. PUBLIC INFORMATION AND PARTICIPATION

7.1 Thermal Annealing Report

Upon receipt of a Thermal Annealing Report, and a minimum of 30 days before the licensee starts thermal annealing, the NRC will:

(1) Notify and solicit comments from local and State governments in the vicinity of the site where the thermal annealing will take place and any Indian Nation or other indigenous people that have treaty or statutory rights that could be affected by the thermal annealing,

(2) Publish a notice of a public meeting in the *Federal Register* and in a forum, such as local newspapers, which is readily accessible to individuals in the vicinity of the site, to solicit comments from the public, and

(3) Hold a public meeting on the licensee's Thermal Annealing Report.

7.2 Completion or Termination of Thermal Annealing

Within 15 days after the NRC's receipt of the licensee's written submittal on the completion or termination of thermal annealing as described in Section 5 of this regulatory guide, the NRC staff will place in the NRC Public Document Room a summary of its inspection of the licensee's thermal annealing, and the Commission will hold a public meeting on the annealing. The purposes of this public meeting are (1) for the licensee to explain to the NRC and the public the results of the reactor pressure vessel annealing, (2) for the NRC to discuss its inspection of the reactor vessel annealing, and (3) for the NRC to receive public comments on the annealing.

7.3 NRC Inspection Report

Within 45 days of NRC's receipt of a licensee's submittals described in Section 5 of this regulatory guide, the NRC staff will fully document its inspection of the licensee's annealing process and place this documentation in the NRC Public Document Room.

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12. NRC, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," NUREG-0800, June 1987.[1]

13. American Society of Mechanical Engineers, "Rules for Construction of Nuclear Power Plants," Section III, Division 1, Subsection NB, of ASME Boiler and Pressure Vessel Code, New York, 1993.

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[1]Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555-0001; telephone (202)634-3273; fax (202)634-3343. Copies may be purchased at current rates from the U.S. Government Printing Office, P.O. Box 37082, Washington, DC 20402-9328 (telephone (202) 512-1800) or from the National Technical Information Service by writing NTIS at 5285 Port Royal Road, Springfield, VA 22161.

[2]Copies may be purchased from EPRI's Research Reports Center, P.O. Box 50490, Palo Alto, CA 94303 (telephone (415)965-4081).

[3]Copies are available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555-0001; telephone (202)634-3273; fax (202)634-3343.

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[4]Single copies of regulatory guides may be obtained free of charge by writing the Office of Administration, Attn: Distribution and Services Section, USNRC, Washington, DC 20555-0001, or by fax at (301)415-2260. Copies are also available for inspection or copying for a fee from the NRC Public Document Room at 2120 L Street NW., Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555-0001; telephone (202)634-3273; fax (202)634-3343.

REGULATORY ANALYSIS

A separate regulatory analysis was not prepared for this regulatory guide. The regulatory analysis prepared for 10 CFR 50.66, "Requirements for Thermal Annealing of the Reactor Pressure Vessel," provides the regulatory basis for this guide and examines the costs and benefits of the rule as implemented by the guide. A copy of the regulatory analysis is available for inspection and copying for a fee at the NRC Public Document Room, 2120 L Street NW, Washington, DC; the PDR's mailing address is Mail Stop LL-6, Washington, DC 20555-0001; phone (202)634-3273; fax (202)634-3343.

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