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U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

OFFICE OF NUCLEAR REACTOR REGULATION

5.4.2.1 STEAM GENERATOR MATERIALS

REVIEW RESPONSIBILITIES

Primary - Materials Engineering Branch (MTEB)

Secondary - Chemical Engineering Branch (CMEB)

I. AREAS OF REVIEW

General Design Criteria 1, 14, 15, and 31 of Appendix A of 10 CFR Part 50 require that components of the reactor coolant boundary be designed, fabricated, erected and tested so as to have an extremely low probability of abnormal leakage, of rapidly propagating failure and of gross rupture. Also, that such design will have sufficient margin to assure that design conditions are not exceeded during normal operation and anticipated operational occurrences.

A review is made of the following areas reported in the applicant's safety analysis report (SAR). These are all related to the ASME Boiler and Pressure Vessel Code (hereinafter "the Code") Class 1 and Class 2 components of pressurized water reactor (PWR) steam generators, including all components that constitute part of the reactor coolant pressure boundary.

MTEB reviews the following areas as part of its primary review responsibility:

1. Selection and Fabrication of Materials

   The materials selected for the steam generator are reviewed.

   Components of the steam generator are divided into two classes: Class 1, which includes material for those parts exposed to the primary reactor coolant, and Class 2, which includes materials for parts exposed to the secondary coolant water.

   The selection and fabrication of materials for all Class 1 and Class 2 components of pressurized water reactor (PWR) steam generators is reviewed for adequacy and suitability and for compliance with the requirements of the Code.

Examples of materials that are currently being used for Class 1 components include the following:

Tubing	-	ASME SB-163, Ni-Cr-Fe, annealed (Inconel 600)
Tube Sheet	-	ASME SA-502, Cl 2 and 2a, weld-clad with Inconel 600 on the primary coolant side
Channel Head Casting or	-	ASME SA-216, Grade WCC, Class 1, weld-clad with austenitic stainless steel
Channel Head Plate	-	ASME SA-533, Grade A, B, or C
Forged Nozzles	-	ASME SA-508, Class 2, and 2a

Examples of materials that are currently being used for Class 2 components include the following:

Shell Pressure Plates	-	ASME SA-533, Grade A, B, or C, Class 1 and 2
Bolting	-	ASME SA-193, Grade B-7 ASME SA-540, Grade B 23 or B 24
Tube Support Plates or Grids	-	ASME SA-240 ASME SA-479

The fracture toughness properties and requirements for ferritic materials of Class 1 and Class 2 components are reviewed.

2. Steam Generator Design

The design and the fabrication procedures are reviewed to determine that the extent of crevice areas are minimized in the completed steam generators. A "tube denting" phenomenon has occurred in a number of steam generators. Based on operating experience and laboratory testing, it is believed that the denting is associated with the growth of a corrosion product (principally Fe_3O_4) in the crevice. The corrosion is caused by the concentration of steam generator water impurities in the annulus. The growth of corrosion product puts inward pressure on the tube resulting in radial deformation of the tube. As corrosion proceeds and in-plate forces accumulate, there are a number of secondary effects in the steam generator. These include (a) tube support plate hole dilation; (b) tube support plate flow hole distortion, flow slot hour-glassing; (c) tube support plate expansion with cracking between hole ligaments; (d) wrapper distortion; (e) leg displacement of the smallest radius U-bend heat tube, and (f) tube leakage.

The extent of the tube to tube sheet contact and the contact area of the tube/tube support are of particular interest. The reviewer will evaluate the design and material selection used to minimize the support plate corrosion.

The tubes are commonly welded to the tube-sheet cladding and expanded into the tube sheet by rolling or explosive-expanding (explanding). Full depth expansion is the preferred design.

A secondary review is performed by CMEB and the results are used by MTEB to complete the overall evaluation for the steam generator materials. CMEB will review the following areas the results of its evaluation are transmitted to MTEB for incorporation into the SER:

1. Compatibility of the Steam Generator Components with the Primary and Secondary Coolant

The possibility of stress-corrosion cracking, denting, pitting, and wastage of the tubes as determined by the chemistry of both the primary and secondary coolants, are reviewed. The methods to be used in monitoring and maintaining the chemistry of the secondary coolant within the specified ranges are reviewed. The compatibility of austenitic and ferritic stainless steels, ferritic low alloy steels and carbon steels with the primary and secondary coolants is reviewed.

2. Cleanup of Secondary Side

The provisions for access to, as well as the procedures and methods for, the removal of surface deposits, sludge, and corrosion products from the secondary side of the steam generator are reviewed. These provisions are to supplement the removal of sludge by blowdown.

II. ACCEPTANCE CRITERIA

The acceptance criteria for the areas of review described in subsection I of this SRP section are based on meeting the following relevant requirements of General Design Criteria 1, 14, 15, and 31, and Appendix B to 10 CFR Part 50:

1. GDC 1 - Quality Standards and Records

Structures, systems, and components important to safety shall be designed, fabricated, erected, and tested to quality standards, commensurate with the importance of the safety functions to be performed. Where generally recognized codes and standards are used, they shall be identified and evaluated to determine their applicability, adequacy, and sufficiency, and shall be supplemented in order to provide adequate assurance that these structures, systems, and components, will perform their safety functions and that records shall be maintained.

2. GDC 14 - Reactor Coolant Pressure Boundary

The reactor coolant pressure boundary shall be designed, fabricated, erected, and tested so as to have an extremely low probability of abnormal leakage, of rapidly propagating failure, and of gross rupture.

3. GDC 15 - Reactor Coolant System Design

The reactor coolant system, and associated auxiliary control, and protection systems shall be designed with sufficient margin to assure that design conditions of the reactor coolant boundary are not exceeded during any condition of normal operation, including anticipated operational occurrences.

4. GDC 31 - Fracture Prevention of Reactor Coolant Pressure Boundary

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

5. Appendix B, 10 CFR Part 50 - "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants."

   This regulation states that measures be established to control the cleaning of material and equipment in accordance with work and inspection procedures to prevent damage or deterioration.

Specific criteria necessary to meet the relevant requirements of the Commission regulations identified above are:

A. Primary Review Criteria

   1. Selection and Fabrication of Materials

      a. To meet the requirements of GDC 1, the acceptable materials for steam generator components are those identified and permitted in the ASME Code, Appendix I of Section III, and specified in detail in the Code Parts A, B, and C of Section II. Any materials specified in the design to meet code-case requirements must also meet the requirements given in Regulatory Guide 1.85, "Code Case Acceptability - Materials." Any materials selected for the tube support structure should be justified on the basis of minimizing the denting and corrosion of the tubes.

      b. To meet the requirements of GDC 1, 14, and 31, the fracture toughness of ferritic materials used for Class 1 components in the steam generator must meet the requirements of Appendix G of 10 CFR Part 50, as augmented by Subarticle NB-2300, Section III of the Code and Appendix G, Article G-2000 of the Code.

         The fracture toughness properties of the ferritic materials selected for Class 2 components in the steam generator must meet the requirements of Subarticle NC-2300 of the Code.

      c. To meet the requirements of GDC 1, the welding qualification, weld fabrication processes and inspection during fabrication and assembly of the steam generator must be conducted in conformance with the requirements of Section III and IX of the Code.

      d. To meet the requirements of GDC 1, the corrosion-resistant weld-deposited cladding on the tube sheet and on other primary side components must be fabricated and inspected according to the requirements given in Articles I, II, III, and IV, Part QW of Section IX of the Code.

      e. To meet the requirements of GDC 1, the welds between the tubes and the tube sheet must meet the requirements of Section III and Section IX of the Code.

      f. To meet the requirements of GDC 14, the processing and heat treatment of the steam generator tubing will be evaluated on a case basis. Special heat treatment to improve the corrosion resistance of the tubing should have supporting data.

2. Steam Generator Design

To meet the requirements of GDC 14, 15, and 31, the steam generators must be designed to avoid extensive crevice areas where the tubes pass through the tube sheet, and where the tubes pass through tubing supports, as indicated in Branch Technical Position MTEB 5-3, "Monitoring of Secondary Side Water Chemistry in PWR Steam Generators."

At the tube/tube sheet interface, the tubes should be rolled or expanded for the full depth of the tube sheet to avoid the presence of a crevice. The tube support structure should be designed to promote high velocity flow along the tubes. This will minimize the buildup of corrosion product and sludge in the crevices of the tube/tube support structure.

B. Secondary Review Criteria

1. Compatibility of the Steam Generator Tubing with the Primary and Secondary Coolant

The requirements of GDC 14, 15, and 31 are met if the acceptance criteria for primary coolant chemistry given in Standard Review Plan Section 5.2.3, "RCPB Materials," are used and if the secondary coolant purity are monitored as described in Branch Technical Position MTEB 5-3.

2. Cleanup of Secondary Side

To meet the requirements of GDC 14 and 15, the steam generators must be designed to provide adequate access to the internals so that tools may be inserted to inspect and clean up deposits, on the tube sheet and on the tube/tube support. Procedures, such as lancing to remove deposits, should be described.

3. To meet the requirements of GDC 1 and Appendix B to 10 CFR Part 50, onsite cleaning and cleanliness control should be in accordance with the position given in Regulatory Guide 1.37, "Quality Assurance Requirements for Cleaning of Fluid Systems and Associated Components of Water-Cooled Nuclear Power Plants," and in ANSI N45.2.1-1973, "Cleaning of Fluid Systems and Associated Components During Construction Phase of Nuclear Power Plants."

III. REVIEW PROCEDURES

The reviewer will select and emphasize material from the procedures described below, as may be appropriate for a particular case.

For each area of review, the following review procedure is used by the:

A. Primary Reviewer

1. Selection and Fabrication of Materials

The reviewer examines the materials and fabrication procedures as given in the SAR for Class 1 and Class 2 components of the steam generators, to determine the degree of conformance with the acceptance criteria stated in subsection II.1 of this SRP section, and verifies that information relative to toughness tests is in conformance with the acceptance criteria stated in subsection II.A.1.b, above. The reviewer verifies that the tubes are properly welded and expanded into the tube sheet, and that proper care is taken to maintain cleanliness during fabrication, assembly, and installation of the unit.

2. Steam Generator Design

The reviewer examines the design of the steam generators to verify that tight crevice areas where tubes pass through the tube supports and tube plate(s) are minimized, as discussed in subsection II.2 of this SRP section.

B. Secondary Reviewer

1. Compatibility of the Steam Generator Tubing with the Primary and Secondary Coolant

The reviewer examines the controls to be placed on the composition of the primary and secondary coolants to determine that they meet the acceptance criteria cited in subsection II.B.1 of this SRP section.

2. Cleanup of Secondary Side

The reviewer examines the design provisions that allow implementation of the procedures and methods to be used for removal of surface deposits, sludge, and corrosion products from the tube sheet and the tube/tube support areas.

IV. EVALUATION FINDINGS

The reviewer verifies that sufficient information is provided in accordance with the requirements of this SRP section and that his evaluation supports conclusions of the following type, which are to be included as applicable in the staff's safety evaluation report:

The staff concludes that the steam generator materials specified are acceptable and meet the requirments of GDC 1, 14, 15, and 31, and Appendix B to 10 CFR Part 50. This conclusion is based on the following:

1. The applicant has met the requirements of GDC 1 with respect to codes and standards by assuring that the materials selected for use in Class 1 and Class 2 components will be fabricated and inspected in conformance with codes, standards, and specifications acceptable to the staff. Welding qualification, fabrication, and inspection during manufacture and assembly of the steam generator will be done in conformance with the requirements of Sections III and IX of the ASME Code.

2. The requirements of GDC 14 and 15 have been met to assure that the reactor coolant boundary and associated auxiliary systems have been designed, fabricated, erected, and tested so as to have an extremely low probability of abnormal leakage, of rapid failure and of gross rupture, during normal operation and anticipated operational occurrences.

The primary side of the steam generator is designed and fabricated to comply with ASME Class 1 criteria as required by the staff. (The secondary side pressure boundary parts of the steam generator will be designed, manufactured, and tested to ASME Class 1 criteria although the staff required classification is ASME Class 2.)*

The crevice between the tube sheet and the inserted tube will be minimal because the tube will be expanded to the full depth of insertion of the tube in the tube sheet. The tube expansion and subsequent positive contact pressure between the tube and the tube sheet will preclude a buildup of impurities from forming in the crevice region and reduce the probability of crevice boiling.

(The tube support plates will be manufactured from ferritic stainless steel material, which has been shown in laboratory tests to be corrosion resistant to the operating environment.)* (The tube support plates will be designed and manufactured with broached holes rather than drilled holes. The broached hole design promotes high velocity flow along the tube, sweeping impurities away from the support plates locations.) (The tube support structure will be manufactured to the egg crate design. The egg crate design eliminates the narrow annular gap at the tube supports, because the support may contact the tube at only four lines on the tube circumference, and provides almost complete washing of the tube surface with steam generator water.)*

3. The requirements of GDC 31 have been met with respect to the fracture toughness of the ferritic materials since the pressure boundary materials of ASME Class 1 components of the steam generator will comply with the fracture toughness requirements and tests of Subarticle NB-2300 of Section III of the Code. The materials of the ASME Class 2 components of the steam generator will comply with the fracture toughness requirements of Subarticle NC-2300 of Section III of the Code.

4. The requirements of Appendix B of 10 CFR Part 50 have been met since the onsite cleaning and cleanliness controls during fabrication (will)* conform to the recommendations of Regulatory Guide 1.37, "Quality Assurance Requirements for Cleaning of Fluid Systems and Associated Components of Water-Cooled Nuclear Power Plants." The controls placed on the secondary coolant chemistry are in agreement with staff technical positions.

   Reasonable assurance of the satisfactory performance of steam generator tubing and other generator materials is provided by (a) the design provisions and the manufacturing requirements of the ASME Code, (b) rigorous secondary water monitoring and control, and (c) the limiting of condenser in-leakage. The controls described above combined with conformance with applicable codes, standards, staff positions, and regulatory guides constitute an acceptable basis for meeting in part the requirements of General Design Criteria 1, 14, 15, and 31, and Appendix B, 10 CFR Part 50.

V. IMPLEMENTATION

The following is intended to provide guidance to applicants and licensees regarding the NRC staff's plans for using this SRP section.

*Include material within parentheses as applicable.

Except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the method described herein will be used by the staff in its evaluation of conformance with Commission regulations.

Implementation schedules for conformance to parts of the method discussed herein are contained in the referenced regulatory guides.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, General Design Criteria 1, "Quality Standards and Records," 14, "Reactor Coolant Pressure Boundary," 15, "Reactor Coolant System Design," and 31, "Fracture Prevention of the Reactor Coolant Pressure Boundary."

2. ASME Boiler and Pressure Vessel Code, Parts A, B, and C of Section II, Section III, and Section IX, American Society of Mechanical Engineers.

3. ANSI N45.2.1-1973, "Cleaning of Fluid Systems and Associated Components During Construction Phase of Nuclear Power Plants," American National Standards Institute.

4. Regulatory Guide 1.37, "Quality Assurance Requirements of Cleaning of Fluid Systems and Associated Components of Water-Cooled Nuclear Power Plants."

5. Regulatory Guide 1.85, "Code Case Applicability-Material."

6. Standard Review Plan Section 5.2.3, "RCPB Materials."

7. Branch Technical Position MTEB 5-3, "Monitoring of Secondary Side Water Chemistry in PWR Steam Generators," attached to this SRP section.

8. Appendix B, 10 CFR Part 50, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants."

BRANCH TECHNICAL POSITION MTEB 5-3

MONITORING OF SECONDARY SIDE WATER CHEMISTRY IN PWR STEAM GENERATORS

I. BACKGROUND

Effective long-term reliable operation of PWR steam generators requires that operational procedures, design, and selection of materials be such that there is no leakage across the steam generator tubes and that the barrier between the primary and secondary fluids maintains its integrity under operating, maintenance or testing conditions as stated in General Design Criteria 14, 15, and 31 of Appendix A of 10 CFR Part 50.

These objectives are generally met by providing water treatments to remove impurities from the secondary side water, operation procedures to remove accumulated sludges and insoluble impurities from generators, design of equipment to prevent impurities from entering the system with makeup water and design factors to prevent the impurities from concentrating and forming sludges or deposits, especially in crevices.

Less than thoroughly effective water treatment, operational procedures, and design factors have led to the degradation of steam generator tubing, as documented by an extensive history of stress corrosion cracking, wastage, and denting of steam generator tubing in operating PWRs, has developed. Therefore we recommend the following criteria.

II. Branch Technical Position

1. Crevices between the tubing and the tube sheets or tubing supports should be minimized to prevent concentration of impurities or solids in these areas. To achieve this goal the tubes at the tube/tube sheet interface should be expanded for the full depth of the tube sheet.

   To minimize the deposition of corrosion products and sludge between the tubes and the supporting structure, the tube/tube support interface should be designed to promote high velocity water flow at the interface. This would improve the "washing" of this area.

2. Regulatory Guide 1.37 endorses ANSI N45.2.1 and states in part, "The surface (of components) shall appear metal clear. Scattered areas of rust are permissible provided the aggregate area of rust does not exceed two square inches in any one square foot area." Experimental work has shown that a porous packing of oxide in the tube support annulus is one of the conditions resulting in the concentration of contaminants which leads to runaway corrosion of the tube support plate. Nuclear plant operators should start up the steam generators with "metal clean" surfaces. A method of confirmation such as photographing the inside of the steam generator should be undertaken after hot functional testing to confirm the "metal clean" condition.

3. a. In the FSAR, the applicant should describe implementation of a secondary water chemistry and monitoring program (in accordance with reference nuclear steam system supplier's recommended procedure) to inhibit steam generator corrosion and tube degradation. This program should cover the following operational modes: (1) power operation (normal), (2) startup, (3) hot standby, (4) hot shutdown, and (5) cold shutdown/cold wet layup.

Each of the above modes should be defined with regards to percent rated thermal power and approximate temperature range, °F.

b. The secondary water chemistry monitoring and control program should include the following:

(1) Identification of a sampling schedule for critical parameters during each mode of operation and of acceptance control criteria for these parameters. The program should include as a minimum the control of pH, cation conductivity, free sodium, and dissolved oxygen. However, other parameters such as specific conductivity, chlorine, fluorine, suspended solids, silica, total iron, copper, ammonia, and residual hydrazine merit consideration. In plants having more than one steam generator, additives to each steam generator should be controlled separately.

c. The Nuclear Regulatory Commission will review the secondary water chemistry control and monitoring program of each individual plant. The applicant should incorporate the technical recommendations of the steam generator supplier. Any significant deviation from the supplier's recommendations should be noted and justified technically.

Records should be made of the monitored item values, and in accordance with 10 CFR Part 50, §50.71(a) they shall be made available for audit and inspection when deemed necessary.

Each licensee as part of his annual operating report should include an evaluation of the secondary side water chemistry program with an evaluation of the trends and a summary of the total time during the reporting period the various chemistry parameters were out-of-specification.

d. For plants utilizing volatile chemistry:

(1) The composition, quantities, and addition rates of additives should be recorded. Routine changes in these items should be reported under biannual FSAR update as required by 10 CFR Part 50, §50.71. However, nonconservative changes, i.e., relaxation in sample frequency, or changes in impurity limits shall be submitted to NRC for approval before the change is implemented.

(2) The electrical conductivity and the pH of the bulk steam generator water and feedwater should be measured continuously. Assurance should be provided that the sample taken at the blowdown is typical of the bulk steam generator water and that there is a minimum bypass between the feedwater inlet and the blowdown sampling point.

(3) For once-through steam generators, the pH and electrical conductivity at the coolant inlet should be measured continuously.

(4) Free hydroxide concentration and impurities (particularly chloride, ammonia and silica) in the steam generator water should be measured at least three times per week.

e. For plants utilizing phosphate treatment:

(1) The composition, quantity, and addition rate of each additive should be recorded initially and thereafter whenever a change is made.

(2) The Na/PO_4 molar ratio of the secondary coolant should be recorded initially and whenever a change is made. Na/PO_4 ratio must be rigidly controlled. (Na/PO_4 ratio is to be held $\geq 2.3 \leq 2.6$.

(3) The electrical conductivity and pH of the bulk steam generator water and feedwater should be measured continuously. Assurance should be provided that the sample taken at the blowdown is typical of the bulk steam generator water and that there is a minimum bypass between the feedwater inlet and the blowdown sampling point.

(4) The concentration of suspended/dissolved solids and impurities (particularly free caustic, chloride, and silica) in the steam generator water should be measured daily.

(5) The concentration of dissolved solids (particularly sodium and phosphate) in the blowdown liquid should be measured once each week.

(6) The rate of blowdown should be recorded initially and whenever a change in rate is made.

(7) The hideout and reverse hideout of phosphate should be recorded. The phosphate concentration in each steam generator (or in one steam generator if this is shown to be representative of all) and in the blowdown liquid should be measured before and after each planned power level change of 10% or greater, and should be measured after each unplanned power level change of 20% or greater.

f. For All PWR Plants

(1) Condenser cooling water in-leakage to the condensate has been identified as the major source of impurity ingress in the PWR secondary feedwater. The combination of impurity ingress with corrosion of copper containing alloys and corrosion product transport (Fe_3O_4, NiO_2, etc.) in the secondary water system produces sludge that is difficult to remove and is reactive to steam generator materials.

In reporting the program the following guidelines should be observed:

(a) Monitor the condensate water quality at the condensate pump discharge as a minimum. Supplement as necessary by samples from the condenser hot well and condenser discharge.

(b) Measure the cation conductivity and oxygen.

(c) Maintain condensate impurity level at 0.1 ppm ± 0.05 ppm, oxygen at $\leq$ 5 ppb.

(d) A cation conductivity increase of 0.05 to 0.10 μmho/cm justifies on-line investigation of possible contamination.

(e) An increase of 0.10 to 0.20 μmho/cm is considered an indication of condenser leakage.

(f) When a condenser leak is confirmed, the leak should be repaired or plugged within 96 hours, or before the total integrated conductivity increase reaches 20 μmho/cm hrs. The staff will consider other impurity-time limit proposals for limiting the quantity of impurities entering the steam generator.

(2) Identify the procedures used to measure the value of each of the critical parameters. Provide the procedure title, the applicant/licensee's procedure number, and the basis (i.e., ASTM No.).

(3) Identify sampling points. The program should consider sampling the steam generator blowdown, the hot well discharge, the feedwater, and demineralizer effluent as a minimum of sampling points.

(4) State the procedure for recording and management of data.

(5) State the procedures defining corrective action for various out-of-specification parameters. The procedures should define the allowable time for correction of out-of-specification chemistry.

(6) Identify (a) the authority responsible for the interpretation of the data, and (b) the sequence and timing of administrative events required to initiate corrective action.

(7) Identify major components of the secondary water system and materials in contact with secondary water coolant.