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BASES FOR PLUGGING DEGRADED PWR STEAM GENERATOR TUBES

A. INTRODUCTION

General Design Criteria 14, "Reactor Coolant Pressure Boundary," and 31, "Fracture Prevention of Reactor Coolant Pressure Boundary," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Licensing of Production and Utilization Facilities," require that the reactor coolant pressure boundary have an extremely low probability of abnormal leakage, of rapidly propagating failure, and of gross rupture. General Design Criterion 15, "Reactor Coolant System Design," requires that the reactor coolant system and associated auxiliary, control, and protection systems be designed with sufficient margin to assure that the design conditions of the reactor coolant pressure boundary are not exceeded during any condition of normal operation, including anticipated operational occurrences. Furthermore, General Design Criterion 32, "Inspection of Reactor Coolant Pressure Boundary," requires that components that are part of the reactor coolant pressure boundary be designed to permit periodic inspection and testing of critical areas to assess their structural and leaktight integrity.

Rupture[1] of the steam generator tubes, which constitute a portion of the reactor coolant pressure boundary, could permit flow of reactor coolant into the secondary coolant system or vice versa. In addition, the weakening of these tubes due to service-induced tube degradation processes could, in the event of a postulated loss-of-coolant accident (LOCA), result in rupture of tubes and release of fluid energy from the secondary system into the containment or the reactor vessel. The rupture of a number of single tube wall barriers between primary and secondary fluid has safety consequences only if the resulting fluid flow exceeds an acceptable amount and rate.

1 "Rupture" is defined as any perforation of the tube pressure boundary accompanied by a flow of fluid either from the primary to the secondary side of the tubes or vice versa, depending on the differential pressure condition prevailing during normal plant operation or developed in the event of postulated pipe break accidents within either the primary reactor coolant pressure boundary or the steam system pressure boundary.

This guide describes a method acceptable to the NRC staff for establishing the limiting safe conditions of tube degradation of steam generator tubing, beyond which defective tubes as established by inservice inspection should be removed from service by welding plugs at each end of the tube. This guide applies only to pressurized water reactors (PWRs).

B. DISCUSSION

The heat transfer area of the steam generators associated with pressurized water reactors can comprise well over 50% of the total primary system pressure-retaining boundary. The steam generator tubing therefore represents an integral part of a major barrier against fission product release to the environment. The steam generator tubing also represents a barrier against steam release to the containment in the event of a postulated LOCA. The design criteria used to establish the structural integrity of the steam generator tubing should include analyses that define the minimum tube wall thickness that can sustain, with adequate margins and under normal plant operating conditions, the pressure and thermal load resulting from postulated accident conditions, including a safe shutdown earthquake (SSE)[2] in combination with a LOCA break, a steam line break, or a feedwater line break.

Regulatory Guide 1.83, "Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes," defines defective tubes (i.e., tubes with wall thickness less than the minimum acceptable thickness) as being unacceptable for continued service and recommends that these and leaking tubes be plugged. Partially degraded tubes with a wall thickness greater than the minimum acceptable tube wall thickness are acceptable for continued service, provided the minimum required tube wall thickness includes an operational allowance for tube degradation that may occur before the next scheduled tube inspection.

Calculations and analytical procedures and the operational history of the steam generator are used to arrive at the minimum acceptable tube wall thickness and thus are the basis for defining the plugging criteria. For degraded steam generator tubes, plugging criteria have been developed by licensees on a case-by-case basis, using analyses and tests to establish the maximum tube degradation that can be tolerated. This maximum is such that the degree of loading required to burst or collapse a tube wall is consistent with the safety factor in Section III of the American Society of Mechanical Engineers' Boiler and Pressure Vessel Code.[3]

Tests have demonstrated[4] that degraded steam generator tubes have a safety margin against burst or collapse, because new steam generator tubes

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2 As defined in Appendix A, "Seismic and Geologic Siting Criteria for Nuclear Power Plants," to 10 CFR Part 100, "Reactor Site Criteria."

3 Copies may be obtained from the American Society of Mechanical Engineers, 345 East 47th Street, New York, N.Y. 10017.

4 "The Effect of Wall Degradation on the Burst and Collapse Pressure of Inconel 600 Steam Generator Tubes," presentation by Combustion Engineering on October 25, 1973, at Bethesda, Md.

are manufactured with a wall thickness much greater than the minimum thickness indicated by the design rules of Section III of the ASME Code. Heavier wall thicknesses than required by design rules are used in procurement documents for steam generator tubes primarily to accommodate fabrication procedures and installation and handling requirements. For certain cases, analytical results indicate that steam generator tubes that are locally thinned or cracked will remain intact under loads postulated from a LOCA in combination with an SSE.[5]

However, to establish an operational limit for a steam generator whose tubes have been subject to degradation, three factors should be considered: (1) the minimum tube wall thickness needed in order for tubes with defects to sustain the imposed loadings under normal operating conditions and postulated accident conditions, (2) an operational allowance for degradation between inspections, and (3) the crack size permitted to meet the leakage limit allowed per steam generator by the technical specifications of the license.

The chemical environment of the secondary side of the steam generator has been identified as one of the prime sources of steam generator tube degradation, and plants experiencing chemical imbalance have exhibited corrosion-induced defects that manifest themselves as wastage, intergranular penetration, and cracking. Mechanical and flow-induced vibrations have been known to cause fretting and fatigue damage that also leads to degradation of steam generator tubes. The latter effects have been less severe than corrosion effects.

Remote and rapid probing of steam generator tubes using eddy-current techniques has proven to be a successful means for establishing the depth of imperfections in degraded steam generator tubes. Tubes with imperfections located through eddy-current probing that exceed the minimum acceptable tube wall thickness and the operational limit can be taken out of service by blocking both ends of the tube in the tube sheet with welded plugs. Two methods are presently available for plugging: (1) manual and automatic welding and (2) explosive welding.

C. REGULATORY POSITION

As noted in Regulatory Guide 1.83, applicants or licensees may submit plugging criteria to NRC for approval. In any event, this information will be needed when degraded steam generator tubes are detected through eddy-current inspections (conducted according to Regulatory Guide 1.83) in order to indicate to NRC the bases for determining the number of tubes to be plugged.

To define minimum acceptable wall thickness and unacceptable defects, both analytic and experimental justification is necessary.

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5 Westinghouse Report WCAP-7832, "Evaluation of Steam Generator Tube, Tube Sheet and Divider Plate Under Combined LOCA Plus SSE Conditions."

1. Unacceptable Defects

Unacceptable defects fall into the following three broad categories:

a. Thru-wall cracks that do not have adequate margins of safety during either normal operation or postulated accident conditions and that could lead to tube rupture. Eddy-current inspection and radiation monitoring of the reactor coolant fluid leaking into the feedwater through a steam generator tube crack should be used to detect thru-wall cracks. The limit of reactor coolant in-leakage to the secondary coolant system stated in the plant's technical specifications should be of such magnitude that the corresponding single crack size through which this leakage is shown to occur under normal operating conditions meets Regulatory Positions C.2.(a)(3), (4), and (5).

b. Part thru-wall cracks and wastage, occurring together or separately such that the remaining wall thickness is less than the minimum acceptable wall thickness.

c. Thru-wall and part thru-wall cracks, wastage, and combinations of these that exceed the operational limit.

2. Minimum Acceptable Wall Thickness

a. Information should be developed to provide a basis for ensuring that tube integrity will be maintained during postulated design basis accidents such as a LOCA or a steam line break in combination with an SSE. Such information should be developed by performing analyses that demonstrate that the following goals are met:

(1) Tubes with detected part thru-wall cracks should not be stressed during the full range of normal reactor operation beyond the elastic range of the tube material.

(2) Tubes with part thru-wall cracks, wastage, or combinations of these should have a factor of safety against failure by bursting under normal operating conditions of not less than 3 at any tube location.

(3) If thru-wall cracks with a specified leakage limit occur either on a tube wall with normal thickness or in regions previously thinned by wastage, they should not propagate and result in tube rupture under postulated accident conditions.

(4) The margin of safety against tube rupture under normal operating conditions should be not less than 3 at any tube location where defects have been detected.

(5) Any increase in the primary-to-secondary leakage rate should be gradual to provide time for corrective action to be taken.

(6) The margin of safety against tube failure under postulated accidents, such as a LOCA, steam line break, or feedwater line break concurrent with the SSE, should be consistent with the margin of safety determined by the stress limits specified in NB-3225 of Section III of the ASME Boiler and Pressure Vessel Code.

b. An additional thickness degradation allowance should be added to the minimum acceptable tube wall thickness to establish the operational tube thickness acceptable for continued service. An imperfection that reduces the remaining tube wall thickness to less than the sum of the minimum acceptable tube wall thickness plus the operational degradation allowance is designated as an unacceptable defect. A tube containing this imperfection has exceeded the tube wall thickness limit for continued service and should be plugged before operation of the steam generator is resumed.

3. <u>Analytical and Loading Criteria Applicable to Tubes with Either Part Thru-Wall or Thru-Wall Cracks and Wastage</u>

a. Conservative analytical models should be used to establish the minimum acceptable tube wall thickness generally applicable to those areas of tube length where tube degradation is most likely to occur in service due to cracking, wastage, intergranular attack, and the mechanisms of fatigue, vibration, and flow-induced loadings. The wall thickness should be such that sufficient tube wall will remain to meet the design limits specified by Section III of the ASME Boiler and Pressure Vessel Code for Class 1 components, as well as the following criteria and loading conditions:

(1) Loadings associated with normal plant conditions, including startup, operation in power range, hot standby, and cooldown, as well as all anticipated transients (e.g., loss of electrical load, loss of offsite power) that are included in the design specifications for the plant, should not produce a primary membrane stress in excess of the yield stress of the tube material at operating temperature.

(2) The margin between the maximum internal pressure to be contained by the tubes during normal plant conditions and the pressure that would be required to burst the tubes should remain consistent with the margin incorporated in the design rules of Section III of the ASME Code.

(3) Loadings associated with a LOCA or a steam line break, either inside or outside the containment and concurrent with the SSE, should be accommodated with the margin determined by the stress limits specified in NB-3225 of Section III of the ASME Code and by the ultimate tube burst strength determined experimentally at the operating temperature.

b. (1) The stress calculations of the thinned tubes should consider all the stresses and tube deformations imposed on the tube bundle during the most adverse loadings of the postulated accident conditions. The dynamic loads should be obtained from the modal analysis of the steam generator and its support structure. All major hydrodynamic and flow-induced forces should be considered in this analysis.

(2) The fatigue effects of cyclic loading forces should be considered in determining the minimum tube wall thickness. The transients considered in the original design of the steam generator tubes should be included in the fatigue analysis of degraded tubes corresponding to the minimum tube wall thickness established. The magnitude and frequency of the temperature and pressure transients should be based on the estimated number of cycles anticipated during normal operation for the maximum service interval expected between tube inspection periods. Notch effects resulting from tube thinning should be taken into account in the fatigue evaluation.

c. The combination of loading conditions for the postulated accident conditions should include, but not be limited to, the following sources:

(1) Impulse loads due to rarefaction waves during blowdown,

(2) Loads due to fluid friction from mass fluid accelerations,

(3) Loads due to the centrifugal force on U-bend and other bend regions caused by high velocity fluid motion,

(4) Loads due to the dynamic structural response of the steam generator components and supports,

(5) Seismic loads,

(6) Transient pressure load differentials.

d. For tubes with thru-wall cracks on either walls of normal thickness or regions previously thinned by wastage, the following goals should be met:

(1) The maximum permissible length of the largest single crack should be such that the internal pressure required to cause crack propagation and tube rupture is at least three times greater than the normal operating pressure. The length and geometry of the largest permissible crack size should be determined analytically either by tests or by refined finite element or fracture mechanics techniques. The material stress-strain characteristics at temperature, fracture toughness, stress intensity factors, and material flow properties should be considered in making this determination.

(2) Adequate margin should be provided between the loadings associated with a large steam line break or a LOCA concurrent with an SSE and the loading required to initiate propagation of the largest permissible longitudinal crack resulting in tube rupture. The loadings associated with the postulated accident conditions should include the transient hydraulic and dynamic loads listed in C.3.(c).

(3) The primary-to-secondary leakage rate limit under normal operating pressure is set forth in the plant technical specifications and should be less than the leakage rate determined theoretically or experimentally from the largest single permissible longitudinal crack. This would ensure orderly plant shutdown and allow sufficient time for remedial action if the crack size increases beyond the permissible limits during service.

e. When applicants or licensees present plugging criteria to NRC, a summary of the analysis should be provided. This should include at least the following:

(1) Stress allowables used in the analyses, including justification for those which differ from the limits listed in C.3.(a).

(2) The geometrical configuration of the tube bundle and the support structure and the mathematical model used in the dynamic computer analysis.

(3) The assumptions made in the elastic and elastic/plastic analyses.

(4) The nature and development of the loads outlined in C.3.(c), including pressure-time histories of the loadings.

(5) The postulated LOCA or steam line breaks, including break opening time and duration of the pulses.

(6) The structural and thermal-hydraulic computer codes used in the dynamic analysis.

(7) The critical areas of the tube bundle and the primary membrane and bending stresses due to the most adverse load components.

(8) The analytical or experimental determination of the largest permissible crack length based on the most adverse loadings as described in C.3.(d)(1) and (2).

(9) Experimental or theoretical justification for the primary-to-secondary leakage rate data used in meeting Regulatory Position C.3.(d)(3).

(10) Experimental verification of the design bases and safety margins, if available, and fatigue effects.

f. The basis used in setting the operational degradation allowance, as added to the minimum tube wall thickness established for continued operation of steam generators, should be provided. It should include:

(1) The maximum number of tubes allowed to have a wall thickness less than the minimum acceptable thickness,

(2) The method and data used to predict continuing degradation,

(3) Consideration of measurement error and any other significant eddy-current testing parameters.

D. IMPLEMENTATION

The purpose of this section is to provide information to applicants and licensees regarding the NRC staff's plans for using this regulatory guide.

Except in those cases in which the applicant or licensee proposes an acceptable alternative method, the staff will use the methods described herein in evaluating an applicant's or licensee's capability for and performance in complying with specified portions of the Commission's regulations after April 1, 1977.

If an applicant or licensee wishes to use the method described in this regulatory guide on or before April 1, 1977, the pertinent portions of the application or the licensee's performance will be evaluated on the basis of this guide.

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