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INSERVICE INSPECTION OF PRESSURIZED WATER REACTOR 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 ensure 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.

Failure[1] of steam generator tubes, which can be caused by cracking, wastage, and fretting, will release radioactive materials to the secondary coolant system. Furthermore, serious weakening of these tubes from similar causes could, in the event of a loss-of-coolant accident (LOCA), result in tube failures that would release the energy of the secondary system into the containment. This guide describes a method acceptable to the NRC staff for implementing these General Design Criteria by reducing the probability and consequences of steam generator tube failures through periodic inservice inspection for early detection of defects and deterioration. This guide applies only to pressurized water reactors (PWRs). The Advisory Committee on Reactor Safeguards has been consulted concerning this guide and has concurred in the regulatory position.

B. DISCUSSION

The heat transfer area of the steam generators in pressurized water reactors can comprise well over 50% of the area of the total primary system pressure-retaining boundary. The thin-walled steam generator tubing is an important part of a major barrier against fission product release to the environment. The steam generator tubing also acts as a barrier against steam release to the containment in the event of a LOCA. To act as an effective barrier, this tubing must be free of cracks, perforations, and general deterioration. The design criteria used to establish the structural integrity of the steam generator tubing should also define the minimum tube wall thickness required to sustain the pressure and thermal loading caused by the worst postulated LOCA in combination with a safe shutdown earthquake.[2]

Inadequate control of the secondary coolant chemistry has been identified as one of the principal sources

[1] Failure is defined as full penetration of the pressure boundary with subsequent leakage.

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

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Comments and suggestions for improvements in these guides are encouraged at all times, and guides will be revised, as appropriate, to accommodate comments and to reflect new information or experience. This guide was revised as a result of substantive comments received from the public and additional staff review.

Comments should be sent to the Secretary of the Commission, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, Attention: Docketing and Service Section.

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of steam generator tube degradation and failure. There is evidence that excessive steam-side corrosion attack occurs in restricted flow areas that permit high local concentration of free caustic, phosphates, and impurities that may enter the steam generator through condenser inleakage. Therefore, secondary water chemistry specifications must reflect the limitation of the materials in the secondary system, and the supporting auxiliary chemical feed system must be designed to maintain desired feedwater quality to each steam generator. Effective monitoring of water chemistry with in-line continuous analytical instrumentation supplemented by plant laboratory sampling analysis of steam, condensate return, and feedwater is necessary at all times during operation to ensure that water quality is not degraded below acceptable limits by such events as condenser inleakage or chemical feed system maloperation.

Mechanical or flow-induced vibration can cause fretting or fatigue damage to steam generator tubes, which could also lead to tube failures.

A program of periodic inservice inspection of steam generators is essential to monitor the integrity of the tubing, particularly if there is evidence of mechanical damage or progressive deterioration caused by inadequate design, manufacturing errors, or chemical imbalance. Inservice inspection of steam generator tubing can also provide useful information regarding the nature and cause of any tube degradation, thereby assisting the operator in taking proper and timely corrective measures.

Inspection and repairs of steam generator tubing in operating plants cause some radiation exposure to personnel. Careful pre-job planning can assist in maintaining radiation exposures as low as is reasonably achievable. Temporary shielding, decontamination, special tooling, jigs and fixtures for remote inspection and repair, and other design and procedural considerations such as are outlined in Regulatory Guide 8.8, "Information Relevant to Maintaining Occupational Radiation Exposure as Low as Practicable (Nuclear Reactors)." should be used to the extent practical.

The recommendations in this guide are applicable to current "typical" once-through and U-bend steam generators that have Ni-Cr-Fe or stainless steel tubing. The steam generator tubing is usually seamless, cold drawn, and annealed and is manufactured and tested in accordance with specifications of the American Society of Mechanical Engineers and the American Society for Testing and Materials.

The initial quality of manufactured tubing is determined by hydrostatic, eddy current, and ultrasonic tests. The tube-to-tube-sheet welds are inspected visually and by dye penetrant, then finally leak tested.

During reactor operation, steam generator tube leaks are detected by monitoring the secondary system for radioactivity and the presence of boron through instrument analysis of steam and blowdown samples. If leaks are present, they can usually be located by eddy current examination of suspect tubing. Eddy current examination is effective because it detects the presence of defect-caused variations in effective electrical conductivity and/or magnetic permeability of the material being tested. Because the eddy current probing technique has excellent sensitivity in nonmagnetic materials, decreases in effective conductivity due to a discontinuity in a tube wall can be measured directly by increases in coil voltage in the probe. Special eddy current probes designed for scanning tubing from the inside have proved very effective in locating defect areas in steam generator tubes and for assessing the overall condition of the tubing in numerous operating PWRs.

Radiography is a supplemental method for inservice inspection of steam generator tubing. Although radiography does not provide the speed and flexibility of eddy current methods, it can supplement eddy current testing for defect characterization on a limited basis.

Leaking tubes, defective tubes, and tubes that exceed the plugging limit should be taken out of service by plugging both ends of the tube at the tube sheet with welded plugs. Various methods are used for plugging and welding. Plugs may be installed mechanically or explosively, and welding may be performed manually, automatically, or explosively.

Experience has indicated that each steam generator design has critical areas (e.g., crevices, low-flow areas, and regions that allow steam blanketing) where attack and degradation of the steam generator tubes may occur even if secondary water chemistry is properly maintained. Mechanical damage to steam generator tubes may also occur in areas subject to flow-induced vibrations. Typically, the number of tubes in these critical areas is less than 20% of the total.

The usual shop examination of tubing can be considered to serve as an adequate baseline examination. An onsite preservice inspection of the steam generator tubing should be performed in the absence of a documented shop or field examination. For plants now operating, the initial inspection should sample tubes on a random basis unless experience with similar designs and chemistry indicate critical areas. Subsequent inspections should concentrate on any critical areas identified so that most defective tubes will be found. This selection method can be expected to result in the ratio of tube defects found to total tubes inspected being considerably higher than the ratio of defective tubes to total tubes in the steam generator. *

*Lines indicate substantive changes from previous issue.

C. REGULATORY POSITION

A program for inservice inspection of steam generator tubing should be established and should include the following:

1. Access for Inspection

a. Steam generators of pressurized water reactors should be designed to facilitate inspection of all tubes.

b. Sufficient access should be provided to perform these inspections and to plug tubes as required.

c. Pre-job planning should be undertaken to make provisions for inspections that ensure that personnel radiation exposure is maintained as low as is reasonably achievable.

2. Inspection Equipment and Procedures

a. Inservice inspection should include nondestructive examination by eddy current testing or equivalent techniques. The equipment should be capable of locating and identifying stress corrosion cracks and tube wall thinning by chemical wastage, mechanical damage, or other causes.

b. The inspection equipment should be sensitive enough to detect imperfections 20% or more through the tube wall.

c. A suitable eddy current inspection system could consist of (1) an internal sensing probe, (2) a two-channel eddy current tester, (3) a viewing oscilloscope, (4) a conventional two-channel strip chart recorder, and (5) a magnetic tape data recorder.

d. Examination results and reports should be stored and maintained for the operating life of the facility.

e. Standards consisting of similar as-manufactured steam generator tubing with known imperfections should be used to establish sensitivity and to calibrate the equipment. Where practical, these standards should include reference flaws that simulate the length, depth, and shape of actual imperfections that are characteristic of past experience.

f. The equipment should be capable of examining the entire length of the tubes.[3]

g. The equipment used for eddy current testing should be designed so that operators may be shielded or the equipment may be operated remotely to limit operator exposure to radiation.

h. Personnel engaged in data taking and interpreting the results of the eddy current inspection should be tested and qualified in accordance with American Society for Nondestructive Testing Standard SNT-TC-1A and supplements.[4]

i. The examinations should be performed according to written procedures.

3. Baseline Inspection

a. All tubes in the steam generators should be inspected by eddy current or alternative techniques prior to service to establish a baseline condition of the tubing.

b. For operating plants without an initial baseline inspection, the first inservice inspection performed according to regulatory positions C.4 and C.5 will define the baseline condition for subsequent inspections.

c. Operating plants instituting a major change in their secondary water chemistry (e.g., phosphate to volatile treatment) should conduct a baseline inspection before resumption of power operation.

4. Sample Selection and Testing

Selection and testing of steam generator tubes should be made on the following basis:

a. The preservice inspection should include all the tubes in the steam generators.

b. Tubes for the inspection of operating plants should be selected on a random basis except where experience in similar plants with similar secondary water chemistry indicates critical areas to be inspected.

c. At least 3% of the total number of tubes in each steam generator to be inspected should be tested during each inspection (see regulatory positions C.3 and C.6).

d. All of the steam generators in a given plant should be inspected at the first inservice inspection. Subsequent inspections may be limited to one steam generator on a rotating schedule encompassing 3% of the total tubes of the steam generators in the plant if the

[3] For U-bend designs, entry for the hot-leg side with examination from the point of entry completely around the U-bend to the top support of the cold leg is considered sufficient to constitute a tube inspection.

[4] SNT-TC-1A and Supplements, "Recommended Practice for Nondestructive Testing Personnel Qualification and Certification." Copies may be obtained from the American Society for Nondestructive Testing, 914 Chicago Avenue, Evanston, Illinois 60202.

results of the first inspection indicate that all steam generators are performing in a like manner. (Note: Under some circumstances, the operating conditions in one or more specific steam generators may be found to be more severe than those in the other generators. Under such circumstances, the sample sequence should be modified to inspect the steam generator with the most severe conditions.)

e. Every inspection subsequent to the preservice inspection should include all nonplugged tubes that previously had detectable wall penetrations (>20%) and should also include tubes in those areas where experience has indicated potential problems.

5. **Supplementary Sampling Requirements**

a. If the eddy current inspection pursuant to regulatory position C.4.d indicates any tubes with previously undetected imperfections of 20% or greater depth, additional steam generators, if any, should be inspected. If previously degraded tubes exhibit significant (>10%) further wall penetration, additional steam generators should be inspected.

b. If the eddy current inspection pursuant to regulatory position C.4.c indicates that more than 10%[5] of the inspected tubes have detectable wall penetration (>20%) or that one or more of the inspected tubes have an indication in excess of the plugging limit (see regulatory position C.7.a), an additional 3% of the tubes should be inspected, concentrating on tubes in those areas of the tube sheet array where tubes with imperfections were found. In addition, the rest of the steam generators should be inspected according to regulatory position C.4.c.

c. If this additional inspection indicates that more than 10% of these additionally inspected tubes have detectable wall penetration (>20%) or one or more of these additionally inspected tubes has an indication in excess of the plugging limit, additional tubes (no less than 6% of the total tubes in the steam generator) in the area of the tube sheet array where tubes with imperfections were found should be inspected.

6. **Inspection Intervals**

a. The first inservice inspection of steam generators should be performed after 6 effective full power months but before 24 calendar months.

b. Subsequent inservice inspections should be not less than 12 nor more than 24 calendar months after the previous inspection.

c. Inspections may be made coincident with refueling outages or any shutdown for plant repair and maintenance in accordance with the American Society of Mechanical Engineers Boiler and Pressure Vessel Code, Section XI.[6]

d. If two consecutive inspections, not including the preservice inspection, result in less than 10% of the tubes with detectable wall penetration (>20%) and no significant (>10%) further penetration of tubes with previous indications, the inspection frequency should be extended to 40-month intervals. If it can be demonstrated through two consecutive inspections that previously observed degradation has not continued and no additional degradation has occurred, a 40-month inspection interval may be initiated.

e. Unscheduled inspections should be conducted in the event of primary-to-secondary leaks exceeding technical specifications, a seismic occurrence greater than an operating basis earthquake,[2] a loss-of-coolant accident requiring actuation of engineered safeguards, or a major steam line or feedwater line break.

7. **Acceptance Limits**

a. As used in this regulatory guide:

(1) *Imperfection* means an exception to the dimensions, finish, or contour required by drawing or specification.

(2) *Defect* means an imperfection of such severity that the tube is unacceptable for continued service.

(3) *Plugging limit* means the imperfection depth at or beyond which plugging of the tube must be performed. (Note that the plugging limit is *not* a depth of penetration within the defect range but rather an imperfection depth with conservative allowances. These allowances include such considerations as general corrosion and measurement error.)

(4) *Plugging criteria* means those calculational and analytical procedures used to arrive at the plugging limit. These currently may be submitted by a licensee for approval by NRC.

b. If, in the inspection performed under regulatory position C.4, less than 10% of the tubes inspected have detectable wall pentration (>20%) and no tube has imperfections that exceed the plugging limit defect, plant operation may resume.

[5] In all inspections, previously degraded tubes that exhibit significant (>10%) further wall penetration must be included in the 10%.

[6] Copies may be obtained from the American Society of Mechanical Engineers, United Engineering Center, 345 East 47th Street, New York, New York 10017.

c. If, in the inspections performed under regulatory position C.5, less than 10% of the total tubes inspected have detectable wall penetration (>20%) and no more than three tubes exceed the plugging limit, plant operation may resume after required corrective measures have been taken.

d. If, in the inspections performed under regulatory position C.5, more than 10% of the total tubes inspected have detectable wall penetration (>20%) or more than three of the tubes inspected exceed the plugging limit, the situation should be immediately reported to the Commission in accordance with the facility license for resolution and approval of the proposed remedial action. Additional sampling and more frequent inspections may be required.

8. Corrective Measures

All leaking tubes, defective tubes, and tubes with imperfections exceeding the plugging limit should be plugged.

D. IMPLEMENTATION

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

This guide reflects current regulatory practice. Therefore, except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the methods described herein will be used by the NRC staff in evaluating an applicant's program for inspection of steam generator tubes.

Technical specifications for ensuring inspection as recommended in regulatory position C should be incorporated in operating licenses.