U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

10.2.3 TURBINE ROTOR INTEGRITY

REVIEW RESPONSIBILITIES

Primary - Organization responsible for the review of materials engineering issues related to flaw evaluation and welding.

Secondary - None

I. AREAS OF REVIEW

General Design Criterion 4 (GDC 4), "Environmental and Missile Dynamic Effects Design Bases," of Appendix A to 10 CFR Part 50 requires that structures, systems, and components important to safety shall be appropriately protected against environmental and dynamic effects, including the effects of missiles, that may result from equipment failure. Because turbine rotors have large masses and rotate at relatively high speeds during normal reactor operation, failure of a rotor may cause excessive vibration of the turbine rotor assembly and result in the generation of high energy missiles. Measures taken by the applicant to ensure turbine rotor integrity and reduce the probability of turbine rotor failure must satisfy the relevant requirements of GDC 4.

The low-pressure turbine rotor assembly may consist of a rotor shaft with shrunk-on disks or a one-piece rotor using either an integral forging or welded design. Low-pressure rotor are subject to relatively high stresses caused by thermal gradients, the interference fit, and centrifugal forces. The low-pressure turbine operates at lower temperatures than the

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high-pressure turbine. Thus, it is particularly important that low-pressure rotor be made of a tough material. The use of suitable design, materials, fabrication techniques, coating processes, and nondestructive examinations during the fabrication process, and inservice inspection can greatly reduce the probability of a turbine rotor failure.

The purpose of this section of the Standard Review Plan (SRP) is to review and evaluate the information submitted by the applicant to ensure turbine rotor integrity and a low probability of turbine rotor failure with the generation of missiles.

The specific areas of review are as follows:

1. Materials Selection

   The materials properties, including descriptions of the procedures used to minimize flaws and improve fracture toughness, are reviewed to establish that sufficient information is provided to evaluation the adequacy of the low-pressure rotor materials. Included in this information are:

   a. A discussion of the ductile-brittle transition temperatures (fracture appearance transition temperature of nil-ductility transition temperature) of the materials and the tests and standards used to determine them.

   b. The Charpy V-notch test program used to establish minimum upper-shelf energies of the rotor materials.

   c. The fracture toughness test program used to establish minimum upper-shelf toughness of the rotor materials.

2. Fracture Toughness

   The fracture toughness of the materials and the materials tests or correlations of Charpy and tensile data to toughness properties are reviewed to establish that the turbine rotor materials exhibit adequate fracture toughness at normal operating temperature and during startup.

3. Pre-service Inspection

   The pre-service inspection program information is reviewed to verify:

   a. the rotor forgings are first machined with minimum excess stock prior to heat treatment;
   b. visual and surface inspections are performed on all finished machined surfaces;
   c. a 100% volumetric (ultrasonic) examination is performed;
   d. before welding and/or brazing, all surfaces prepared for welding will be surface examined;
   e. after welding and/or brazing, all surfaces exposed to steam will be surface examined, giving particular attention to stress risers and welds;
   f. welds will be ultrasonically examined in the radial and radial-tangential sound beam directions.

4. Turbine Rotor Design

The low-pressure turbine rotor design information, including allowable stresses, temperature distributions, and design overspeed considerations, is reviewed.

5. Inservice Inspection

Descriptions of the baseline and inservice phases of the inservice inspection program, including types of inspections, areas to be inspected, frequencies of inspection, and acceptance criteria, are reviewed.

6. Inspection, Test, Analysis, and Acceptance Criteria (ITAAC). For design certification and combined license (COL) reviews, the applicant's proposed information on the ITAAC associated with the systems, structures, and components (SSCs) related to this SRP section is reviewed in accordance with SRP Section 14.3, "Inspections, Tests, Analyses, and Acceptance Criteria - Design Certification." The staff recognizes that the review of ITAAC is performed after review of the rest of this portion of the application against acceptance criteria contained in this SRP section. Furthermore, the ITAAC are reviewed to assure that all SSCs in this area of review are identified and addressed as appropriate in accordance with SRP Section 14.3.

Review Interfaces

There are no direct interfaces between this SRP section and the evaluations performed under any other SRP sections.

II. ACCEPTANCE CRITERIA

Requirements

Acceptance criteria are based on meeting the relevant requirements of the following Commission regulations:

1. General Design Criterion 4 of Appendix A to 10 CFR Part 50, as it relates to structures, systems, and components important to safety being appropriately protected against the environmental and dynamic effects, including the effects of missiles, that may result from equipment failure.

2. 10 CFR 52.47(a)(1)(vi), as it relates to ITAAC (for design certification) sufficient to assure that the SSCs in this area of review will operate in accordance with the certification.

3. 10 CFR 52.97(b)(1), as it relates to ITAAC (for combined licenses) sufficient to assure that the SSCs in this area of review have been constructed and will be operated in conformity with the license and the Commission's regulations.

SRP Acceptance Criteria

Specific SRP acceptance criteria acceptable to meet the relevant requirements of the NRC's regulations identified above are as follows for each review described in Subsection I of this SRP section. The SRP is not a substitute for the NRC's regulations, and compliance with it is not required. However, an applicant is required to identify differences between the design features, analytical techniques, and procedural measures proposed for its facility and the SRP acceptance criteria and evaluate how the proposed alternatives to the SRP acceptance criteria provide acceptable methods of compliance with the NRC regulations.

1. Materials Selection

The turbine forged or welded rotor should be made from a material and by a process that tends to minimize flaw occurrence and maximize fracture toughness properties, such as a NiCrMoV alloy processed by vacuum melting or vacuum degassing. The material should be examined and tested to meet the following criteria:

a. Chemical analysis should be performed for each forging. Elements that have a deleterious effect on toughness, such as sulfur and phosphorus, should be controlled to low levels.

b. The 50% fracture appearance transition temperature (FATT) as obtained from Charpy tests performed in accordance with specification ASTM A-370 should be no higher than -18°C (O°F) for low-pressure turbine rotors. The nil-ductility transition (NDT) temperature obtained in accordance with specification ASTM E-208 may be used in lieu of FATT. NDT temperatures should be no higher than -35°C (-30°F).

c. The Charpy V-notch (C_v) energy at the minimum operating temperature of each low-pressure rotor in the tangential direction should be at least 8.3 kg-m (60 ft-lbs). A minimum of three C_v specimens should be tested in accordance with specification ASTM A-370.

2. Fracture Toughness

The low-pressure turbine disk forged or welded rotor fracture toughness properties are acceptable if the following criteria are met.

The ratio of the fracture toughness (K_{Ic}) of the rotor material to the maximum tangential stress at speeds from normal to design overspeed should be at least 10 $\sqrt{mm}$ (2 $\sqrt{in}$), at minimum operating temperature. Bore stress calculations should include components due to centrifugal loads, interference fit, and thermal gradients. Sufficient warmup time should be specified in the turbine operating instructions to ensure that toughness will be adequate to prevent brittle fracture during startup. Fracture toughness properties can be obtained by any of the following methods:

a. Testing of the actual material of the turbine rotor to establish the K_{Ic} value at normal operating temperature.

b. Testing of the actual material of the turbine rotor with an instrumented Charpy machine and a fatigue precracked specimen to establish the K_{Ic} (dynamic) value at normal operating temperature. If this method is used, K_{Ic} (dynamic) shall be used in lieu of K_{Ic} (static) in meeting the toughness criteria above.

c. Estimating of K_{Ic} values at various temperatures from conventional Charpy and tensile data on the rotor material using methods are presented in J. A. Begley and W. A. Logsdon, Scientific Paper 71-1E7-AMSLRF-P1 (Ref 5). This method of obtaining K_{Ic} should be used only on materials which exhibit a well-defined Charpy energy and fracture appearance transition curve and are strain-rate insensitive. The staff should review the test data and the calculated toughness curve submitted by the applicant.

d. Estimating "lower bound" values of K_{Ic} at various temperatures using the equivalent energy concept developed by F. J. Witt and T. R. Mager, ORNL-TM-3894 (Ref. 6). The staff should review the load-displacement data from the compact tension specimens and the calculated toughness data submitted by the applicant.

3. Pre-service Inspection

The applicant's pre-service inspection program is acceptable if it meets the following criteria:

a. Forged or welded rotors should be rough machined prior to heat treatment.

b. Each finished forged or welded rotor should be subjected to 100% volumetric (ultrasonic), surface, and visual examinations using procedures and acceptance criteria equivalent to those specified for Class 1 components in the ASME Boiler and Pressure Vessel Code, Sections III and V. Before welding and/or brazing, all surfaces prepared for welding and/or brazing should be surface examined. After welding and/or brazing, all surfaces exposed to steam should be surface examined, giving particular attention to stress risers and welds. Welds should be ultrasonically examined in the radial and radial-tangential sound beam directions.

c. Finish machined bores, keyways, and drilled holes should be subjected to magnetic particle or liquid penetrant examination. No flaw indications in keyway or hole regions are allowed.

d. Each turbine rotor assembly should be spin tested at 5% above the maximum speed anticipated during a turbine trip following loss of full load.

4. Turbine Rotor Design

The turbine assembly should be designed to withstand normal conditions, anticipated transients, and accidents resulting in a turbine trip without loss of structural integrity. The design of the turbine assembly should meet the following criteria:

a. The design overspeed of the turbine should be 5% above the highest anticipated speed resulting from a loss of load. The staff should review the basis for the assumed design overspeed.

b. The combined stresses of low-pressure turbine rotor at design overspeed due to centrifugal forces, interference fit, and thermal gradients should not exceed 0.75 of the minimum specified yield strength of the material, or 0.75 of the measured yield strength in the weak direction of the materials if appropriate tensile tests have been performed on the actual rotor material.

c. The turbine shaft bearings should be able to withstand any combination of the normal operating loads, anticipated transients, and accidents resulting in a turbine trip.

d. The natural critical frequencies of the turbine shaft assemblies existing between zero speed and 20% overspeed should be controlled in the design and operation stages so as to cause no distress to the unit during operation.

e. The turbine rotor design should facilitate inservice inspection of all high stress regions, including bores and keyways, without the need for removing the disks from the shaft.

5. Inservice Inspection

The applicant's inservice inspection program is acceptable if it meets the following criteria:

The inservice inspection program for the steam turbine assembly should provide assurance that rotor flaws that might lead to brittle failure of a rotor at speeds up to design speed will be detected. The inservice inspection and maintenance program for the turbine assembly should comply with the manufacturers recommendations.

Inservice inspection and maintenance activities may be performed during plant shutdown coinciding with the inservice inspection schedule as required by ASME Boiler and Pressure Vessel Code, Section XI, and should include complete inspection of all significant turbine components, such as couplings, coupling bolts, turbine shafts, low-pressure turbine blades, low-pressure rotors, and high-pressure rotors. This inspection should consist of visual, surface, and volumetric examinations, as required by the code.

Technical Rationale

The technical rationale for application of these requirements to reviewing this SRP section is discussed in the following paragraphs:

1. Compliance with GDC 4 requires in part that structures, systems, and components important to safety be designed to accommodate the effects of, and be compatible with, environmental conditions associated with normal operations, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. These structures, systems, and components shall be appropriately protected against dynamic effects, including missiles caused by equipment failures.

   GDC 4 applies to this SRP section because the turbine is a potential source of high-energy missiles that could compromise the function of safety related plant components. Protection from these missiles is provided by placing specific requirements on turbines relative to materials, fabrication, inspections during fabrication, and inservice inspections, thus ensuring that failure of a turbine will be highly unlikely.

   Meeting the requirements of GDC 4 provides assurance that the turbine will not be a source of missiles that could damage systems, structures, and components. Compliance with GDC4 therefore decreases the potential for release of fission products to the environment which could lead to offsite doses in excess of the reference values cited in 10 CFR Part 100.

III. <u>REVIEW PROCEDURES</u>

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 specified in subsection I of this SRP section, the review procedure is identified below. These review procedures are based on the identified SRP acceptance criteria. For deviations from these specific acceptance criteria, the staff should review the applicant's evaluation of how the proposed alternatives to the SRP criteria provide an acceptable method of complying with the relevant NRC requirements identified in subsection II.

1. <u>Materials Selection</u>

   The materials properties and the procedures used to minimize flaws and improve fracture toughness, as described by the applicant, should be reviewed and compared with the requirements of subsection II.1 of this SRP section. If a new material that is not used in prior licensed cases is utilized, the applicant's materials selection should be reviewed and evaluated to establish its acceptability. Such an evaluation should be based on the acceptance criteria of subsection II of this SRP section.

2. <u>Fracture Toughness</u>

   The fracture toughness properties of the low-pressure turbine disk or forged or welded rotor material, including specimen test data, where applicable, should be reviewed and compared with the requirements of subsection II.2 of this SRP section. The applicant is permitted to use any of the three alternative test methods identified in Subsection II.2 of this SRP section to derive the fracture toughness of the rotor materials.

3. Pre-service Inspection

The pre-service inspection program, including finish machining, ultrasonic inspection, surface inspection, visual inspection, and spin testing, should be reviewed and compared with the requirements of subsection II.3 of this SRP section. The extent to which the ultrasonic inspections and the acceptance criteria in the SAR agree with ASME Boiler and Pressure Vessel Code, Section III, NB-2530 for plate materials or NB-2540 for forgings, should be reviewed.

4. Turbine Rotor Design

The design and stress analysis procedures used for the low-pressure turbine disks or forged or welded rotors that should be reviewed include the following information.

a. Load combinations and allowable stresses at normal operating speed,

b. Design overspeed and basis for selection of design overspeed, and

c. Load combinations and allowable stresses at design overspeed.

The SAR data should be evaluated and compared with subsection II.4 of this SRP section.

5. Inservice Inspection

The inservice inspection and maintenance program described by the applicant, including areas to be inspected, methods of inspection, frequency of inspection, and acceptance criteria, should be reviewed and compared with the criteria of subsection II.5 of this SRP section.

6. ITAAC

For reviews of design certification and COL applications under 10 CFR Part 52, the reviewer should follow the above procedures to verify that the design set forth in the safety analysis report, and if applicable, site interface requirements meet the acceptance criteria. For design certification applications, the reviewer should identify necessary COL action items. With respect to COL applications, the scope of the review is dependent on whether the COL applicant references a design certification, an ESP or other NRC-approved material, applications, and/or reports.

After this review, SRP Section 14.3 should be followed for the review of Tier I information for the design, including the postulated site parameters, interface criteria, and ITAAC.

IV. EVALUATION FINDINGS

The reviewer verifies that the applicant has provided sufficient information and that the review and calculations (if applicable) support conclusions of the following type to be included in the staff's safety evaluation report. The reviewer also states the bases for those conclusions.

> "The applicant has met the requirements of GDC 4 of Appendix A to 10 CFR Part 50 with respect to the use of materials with acceptable fracture toughness and elevated temperature properties, adequate design, and the requirements for preservice and inservice inspections. The applicant has described a program for ensuring the integrity of low-pressure turbine rotors by the use of suitable materials of adequate fracture toughness, conservative design practices, and preservice and inservice inspections. These provisions provide reasonable assurance that the probability of failure with missile generation is low during normal operation, including transients up to design overspeed.

For DC and COL reviews, the findings will also summarize (to the extent that the review is not discussed in other SER sections) the staff's evaluation of the ITAAC, including design acceptance criteria, as applicable, and interface requirements and combined license action items relevant to this SRP section.

V. IMPLEMENTATION

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

The staff will use this SRP section in performing safety evaluations of design certifications and license applications submitted by applicants pursuant to 10 CFR 50 or 52. Except when the applicant proposes an acceptable alternative method for complying with specific portions of the Commission's regulations, the staff will use the method described herein to evaluate conformance with Commission regulations.

The provisions of this SRP section apply to reviews of applications docketed six months or more after the date of issuance of this SRP section, unless superceded by a later revision.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, General Design Criterion 4, "Environmental and Missile Dynamic Effects41 Design Bases."

2. ASME Boiler and Pressure Vessel Code, Sections III, V, and XI, American Society of Mechanical Engineers.

3. ASTM E-208-95a (Re-approved 2000), "Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," Annual Book of ASTM Standards, Part 31, American Society for Testing Materials.

4. ASTM A-370-05, "Standard Test Methods and Definitions for Mechanical Testing of Steel Products," Annual Book of ASTM Standards, Parts 1, 2, 3, 4, or 31, American Society for Testing Materials.

5. J. A. Begley and W. A. Logsdon, "Correlation of Fracture Toughness and Charpy Properties for Rotor Steels," Scientific Paper 71-1E7-MSLRF-P1, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania, July 26, 1971.

6. F. J. Witt and T. R. Mager, "A Procedure For Determining Bounding Values On Fracture Toughness K_{Ic} At Any Temperature," ORNL-TM-3894,, Oak Ridge National Laboratory, October 1972.

SRP Section 10.2.3

Description of Changes

This SRP section affirms the technical accuracy and adequacy of the guidance previously provided in (Draft) Revision 2, dated April 1996 of this SRP. See ADAMS accession number ML052070578.

In addition this SRP section was administratively updated in accordance with NRR Office Instruction, LIC-200, Revision 1, "Standard Review Plan (SRP) Process." The revision also adds standard paragraphs to extend application of the updated SRP section to prospective submittals by applicants pursuant to 10 CFR Part 52.

The technical changes are incorporated in Revision 2, dated 200X.