U.S. NUCLEAR REGULATORY COMMISSION

DESIGN-SPECIFIC REVIEW STANDARD FOR mPOWER™ iPWR DESIGN

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), "Environmental and Missile Dynamic Effects Design Bases," of Appendix A to 10 CFR Part 50 requires that structures, systems, and components (SSCs) 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 which could affect safety related SSCs and risk-significant SSCs . 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 rotors 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 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 turbine rotor is a non-safety-related component which could affect safety-related SSCs and risk-significant SSCs. The purpose of this section of the Design-Specific Review Standard (DSRS) 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 which could affect safety-related SSCs and risk-significant SSCs.

All safety-related and risk-significant systems, structures, and components (SSCs) are subject to missile protection. An SSC may be classified as:

1. Safety-related and risk-significant equipment

2. Safety-related and nonrisk-significant equipment

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3. Nonsafety-related and risk-significant Regulatory Treatment of Nonsafety Systems (RTNSS) equipment

4. Nonsafety-related nonrisk-significant equipment.

The mPowerTM application will include the classification of SSCs, a list of risk significant SSCs, and a list of RTNSS equipment. Based on this information, the staff will review according to DSRS Section 3.2, SRP Sections 17.4 and 19.3 to confirm the determination of safety-related and risk-significant SSCs.

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 evaluate 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. Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC). For design certification (DC) and combined license (COL) reviews, the staff reviews the applicant's proposed ITAAC associated with the SSCs related to this DSRS section in accordance with Standard Review Plan (SRP) Section 14.3, "Inspections, Tests, Analyses, and Acceptance Criteria." The staff recognizes that the review of ITAAC cannot be completed until after the rest of this portion of the application has been reviewed against acceptance criteria contained in this DSRS section. Furthermore, the staff reviews the ITAAC to ensure that all SSCs in this area of review are identified and addressed as appropriate in accordance with SRP Section 14.3.

7. COL Action Items and Certification Requirements and Restrictions. For a DC application, the review will also address COL action items and requirements and restrictions (e.g., interface requirements and site parameters).

   For a COL application referencing a DC, a COL applicant must address COL action items (referred to as COL license information in certain DCs) included in the referenced DC. Additionally, a COL applicant must address requirements and restrictions (e.g., interface requirements and site parameters) included in the referenced DC.

Review Interfaces

Other SRP and DSRS sections interface with this DSRS section as follows:

1. Review of turbine missile probability analysis and protection against turbine missiles is performed under DSRS Section 3.5.1.3 using the guidance in Regulatory Guide (RG) 1.115, "Protection Against Turbine Missiles," Revision 2.

2. Review of the Probabilistic Risk Assessment is performed under SRP Section 19 for potential risk significance of SSCs.

II. ACCEPTANCE CRITERIA

Requirements

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

1. GDC 4 of Appendix A to Title 10 of *Code of Federal Regulations* (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(b)(1), which requires that a DC application contain the proposed ITAAC that are necessary and sufficient to provide reasonable assurance that, if the inspections, tests, and analyses are performed and the acceptance criteria met, a facility that incorporates the design certification has been constructed and will be operated in conformity with the design certification, the provisions of the Atomic Energy Act (AEA), and the U.S. Nuclear Regulatory Commission's (NRC's) regulations.

3. 10 CFR 52.80(a), which requires that a COL application contain the proposed inspections, tests, and analyses, including those applicable to emergency planning, that the licensee shall perform, and the acceptance criteria that are necessary and sufficient to provide reasonable assurance that, if the inspections, tests, and analyses are performed and the acceptance criteria met, the facility has been constructed and will operate in conformity with the combined license, the provisions of the Atomic Energy Act, and the NRC's regulations.

DSRS Acceptance Criteria

Specific DSRS acceptance criteria acceptable to meet the relevant requirements of the NRC's regulations identified above are as follows for review described in this DSRS section. The DSRS is not a substitute for the NRC's regulations, and compliance with it is not required. Identifying the differences between this DSRS section and the design features, analytical techniques, and procedural measures proposed for the facility, and discussing how the proposed alternative provides an acceptable method of complying with the regulations that underlie the DSRS acceptance criteria, is sufficient to meet the intent of 10 CFR 52.47(a)(9), "Contents of applications; technical information."

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 (0°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. 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. 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.

6. 10 CFR 52.47(b)(1), which requires that a DC application contain the proposed ITAAC that are necessary and sufficient to provide reasonable assurance that, if the inspections, tests, and analyses are performed and the acceptance criteria met, a facility that incorporates the design certification has been constructed and will be operated in conformity with the design certification, the provisions of the Atomic Energy Act, and the NRC's regulations;

Technical Rationale

The technical rationale for application of these acceptance criteria to the areas of review addressed by this DSRS 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 DSRS 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. REVIEW PROCEDURES

These review procedures are based on the identified DSRS acceptance criteria. For deviations from these acceptance criteria, the staff should review the applicant's evaluation of how the proposed alternatives provide an acceptable method of complying with the relevant NRC requirements identified in Subsection II.

Following these review procedures, the acceptability of the turbine rotor design may be determined based on review of the corresponding information in the technical submittal and identification of programmatic requirements such as ITAAC that provide reasonable assurance the turbine rotor material properties, design, fabrication, installation, pre-service and in-service inspection and testing requirements, will satify the acceptance criteria in Subsection II.

1. Programmatic Requirements and Guidance - In accordance with the guidance in NUREG-0800 "Introduction," Part 2 as applied to this DSRS Section, the staff will review the programs proposed by the applicant to satisfy the following programmatic requirements . If any of the proposed programs satisfies the acceptance criteria described in Subsection II, it can be used to augment or replace some of the review procedures. It should be noted that the wording of "to augment or replace" applies to nonsafety-related risk-significant SSCs, but "to replace" applies to nonsafety-related nonrisk-significant SSCs according to the "graded approach" discussion in NUREG-0800 "Introduction," Part 2. Commission regulations and policy mandate programs applicable to SSCs. Examples of those programs and associated guidance follows:

   - Maintenance Rule SRP Section 17.6 (DSRS Section 13.4, Table 13.4, Item 17, Regulatory Guides 1.160, "Monitoring the Effectiveness of Maintenance at

Nuclear Power Plants." and RG 1.182; "Assessing and Managing Risk Before Maintenance Activities at Nuclear Power Plants".

- Quality Assurance Program SRP Sections 17.3 and 17.5 (DSRS Section 13.4, Table 13.4, Item 16).

- Technical Specifications (DSRS Section 16.0 and SRP Section 16.1) – including brackets value for DC and COL. Brackets are used to identify information or characteristics that are plant specific or are based on preliminary design information.

- Reliability Assurance Program (SRP Section 17.4).

- Initial Plant Test Program (RG 1.68, "Initial Test Programs for Water-Cooled Nuclear Power Plants," DSRS Section 14.2, and DSRS Section 13.4, Table 13.4, Item 19).

- ITAAC (DSRS Chapter 14).

2. In accordance with 10 CFR 52.47(a)(8),(21), and (22), and 10 CFR 52.79(a)(17) and (20), for new reactor license applications submitted under Part 52, the applicant is required to (1) address the proposed technical resolution of unresolved safety issues and medium- and high-priority generic safety issues which are identified in the version of NUREG-0933 current on the date up to 6 months before the docket date of the application and which are technically relevant to the design; (2) demonstrate how the operating experience insights have been incorporated into the plant design; and, (3) provide information necessary to demonstrate compliance with any technically relevant portions of the Three Mile Island requirements set forth in 10 CFR 50.34(f), except paragraphs (f)(1)(xii), (f)(2)(ix), and (f)(3)(v). These cross-cutting review areas should be addressed by the reviewer for each technical subsection and relevant conclusions documented in the corresponding safety evaluation report (SER) section.

3. <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 DSRS 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 DSRS 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 DSRS section. The applicant is permitted to use any of the three alternative test methods identified in Subsection II.2 of this DSRS 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 DSRS 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 DSRS 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 DSRS section.

For review of a DC application, the reviewer should follow the above procedures to verify that the design, including requirements and restrictions (e.g., interface requirements and site parameters), set forth in the final safety analysis report (FSAR) meets the acceptance criteria. DCs have referred to the FSAR as the design control document (DCD). The reviewer should also consider the appropriateness of identified COL action items. The reviewer may identify additional COL action items; however, to ensure these COL action items are addressed during a COL application, they should be added to the DC FSAR .

For review of a COL application, the scope of the review is dependent on whether the COL applicant references a DC, an early site permit or other NRC approvals (e.g., manufacturing license, site suitability report or topical report).

For review of both DC and COL applications, SRP Section 14.3 should be followed for the review of ITAAC. The review of ITAAC cannot be completed until after the completion of this section.

IV. EVALUATION FINDINGS

The reviewer verifies that the applicant has provided sufficient information and that the staff's technical review and analysis, as augmented by the application of programmatic requirements in accordance with the staff's technical review approach in the DSRS Introduction, 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 the staff's evaluation of requirements and restrictions (e.g., interface requirements and site parameters) and COL action items relevant to this DSRS section.

In addition, to the extent that the review is not discussed in other SER sections, the findings will summarize the staff's evaluation of the ITAAC, including design acceptance criteria, as applicable.

V. IMPLEMENTATION

The staff will use this DSRS section in performing safety evaluations of mPower™-specific DC, or COL, applications submitted by applicants pursuant to 10 CFR Part 52. The staff will use the method described herein to evaluate conformance with Commission regulations.

Because of the numerous design differences between the mPower™ and large light-water nuclear reactor power plants, and in accordance with the direction given by the Commission in SRM- COMGBJ-10-0004/COMGEA-10-0001, "Use of Risk Insights to Enhance the Safety Focus of Small Modular Reactor Reviews," dated August 31, 2010 (ML102510405), to develop risk-informed licensing review plans for each of the small modular reactor (SMR) reviews including the associated pre-application activities, the staff has developed the content of this DSRS section as an alternative method for mPower™ -specific DC, or COL submitted pursuant to 10 CFR Part 52 to comply with 10 CFR 52.47(a)(9), "Contents of applications; technical information."

This regulation states, in part, that the application must contain "an evaluation of the standard plant design against the Standard Review Plan (SRP) revision in effect 6 months before the docket date of the application." The content of this DSRS section has been accepted as an alternative method for complying with 10 CFR 52.47(a)(9) as long as the mPower™ DCD FSAR does not deviate significantly from the design assumptions made by the NRC staff while preparing this DSRS section. The application must identify and describe all differences between the standard plant design and this DSRS section, and discuss how the proposed alternative provides an acceptable method of complying with the regulations that underlie the DSRS acceptance criteria. If the design assumptions in the DC application deviate significantly from the DSRS, the staff will use the SRP as specified in 10 CFR 52.47(a)(9). Alternatively, the staff may supplement the DSRS section by adding appropriate criteria in order to address new design assumptions. The same approach may be used to meet the requirements of 10 CFR 52.79(a)(41) for COL applications.

VI. REFERENCES

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

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

4. ASTM E-208, "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.

5. ASTM A-370, "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.

6. 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.

7. 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.