U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

5.4.1.1 PUMP FLYWHEEL INTEGRITY (PWR)

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 (GDC) 4 of Appendix A to 10 CFR Part 50 requires that structures, systems, and components of nuclear power plants important to safety be protected against the effects of missiles that might result from equipment failures. Because flywheels have large masses and rotate at speeds of 900 revolutions per minute (rpm) or 1200 rpm during normal reactor operation, a loss of flywheel integrity could result in high energy missiles and excessive vibration of the reactor coolant pump assembly. The safety consequences could be significant because of possible damage to the reactor coolant system, the containment, or the engineered safety features. GDC 1 and 10 CFR Part 50.55a(a)(1) require that structures, systems, and components important to safety shall be designed, fabricated, erected and tested to quality standards which shall be identified and evaluated to determine their applicability, adequacy, and sufficiency to assure a quality product in keeping with the required safety function. Reactor coolant pump flywheel failure can result in reduction or loss of forced coolant flow.

Revision 2 - March 2007

The specific areas of review are as follows:

1. Materials Selection and Fabrication. Reactor coolant pump flywheels are of a simple geometric shape, and are made of ductile material. Their quality can be closely controlled and their service conditions are not severe. Therefore, the use of suitable material and fabrication, coupled with adequate design and inservice inspection can provide a sufficiently small probability of a flywheel failure that the consequences of failure need not be protected against.

   Information in the applicant's safety analysis report (SAR) on materials selection and the procedures used to minimize flaws and improve mechanical properties is reviewed to establish that sufficient information is provided for staff to evaluate the adequacy of the flywheel materials.

2. Fracture Toughness. Information related to the fracture toughness properties of the materials, including materials tests, correlations of Charpy specimens to fracture toughness parameters, or the alternate use of a nil-ductility transition reference temperature (RT_{NDT}), are reviewed to establish that the flywheel materials will exhibit adequate fracture toughness at normal operating temperature.

3. Preservice Inspection. Descriptive information is reviewed to verify that the bore of the flywheel is machined to final dimensions if it is flame cut, and that ultrasonic and surface inspections are performed on all finished machined surfaces.

4. Flywheel Design. Flywheel design information, including allowable stresses, fracture analysis, design overspeed considerations, and shaft and bearing design adequacy, is reviewed.

5. Overspeed Test. The applicant's overspeed test procedures are reviewed to establish their adequacy.

6. Inservice Inspection. Descriptions of the preservice and postoperational phases of the inservice inspection program as it relates to the reactor coolant pump flywheel, including types of inspections, areas inspected, frequencies of inspection, and flaw acceptance criteria, are reviewed.

7. 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 structures, systems, and components (SSCs) related to this SRP section in accordance with 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 SRP 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.

8. 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.

9. Operational Program Description and Implementation. For a COL application, the staff reviews the Pre-Service Inspection, Inservice Inspection, and Inservice Testing Programs description and the proposed implementation milestones. The staff also reviews final safety analysis report (FSAR) Table 13.x to ensure that the Pre-Service Inspection, Inservice Inspection, and Inservice Testing Programs and associated milestones are included.

Review Interfaces

Other SRP sections interface with this section as follows:

1. The reviewer responsible for this section will coordinate with the reviewer responsible for performing quality assurance for pump flywheels. Review for quality assurance for pump flywheels is performed under SRP Chapter 17. The specific acceptance criteria and review procedures are contained in SRP Chapter 17.

For COL reviews of operational programs, the review of the applicant's implementation plan is performed under SRP Section 13.4, "Operational Programs."

The specific acceptance criteria and review procedures are contained in the referenced SRP sections.

II. ACCEPTANCE CRITERIA

Requirements

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

1. GDC 1 and 10 CFR Part 50.55a(a)(1), as they relate to pump flywheel design, materials selection, fracture toughness, preservice and inservice inspection programs, and overspeed test procedures to determine their adequacy to assure a quality product commensurate with the importance of the safety function to be performed.

2. GDC 4, as it relates to protecting safety-related structures, systems, and components of nuclear power plants from the effects of missiles that might result from reactor coolant pump failure.

3. 10 CFR 52.47(b)(1), which requires that a DC application contain the proposed inspections, tests, analyses, and acceptance criteria (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 plant that incorporates the design certification is built and will operate in accordance with the design certification, the provisions of the Atomic Energy Act, and the NRC's regulations;

4. 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.

SRP Acceptance Criteria

Specific SRP acceptance criteria acceptable to meet the relevant requirements of the NRC's regulations identified above are as follows for the review described in 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.

Regulatory Guide (RG) 1.14 provides positions acceptable to the staff in meeting these requirements to ensure the potential for failures of the flywheels of reactor coolant pump motors in light-water-cooled power reactors is minimized. Specific criteria necessary to meet the relevant requirements of GDC 1 and 4 and 10 CFR Part 50.55a(a)(1) are as follows.

1. Materials Selection and Fabrication. The applicant's materials selection and fabrication are acceptable if they comply with the following criteria, which are derived from Subsections C.1.a and C.1.c of RG 1.14.

   The flywheel material is acceptable if it is produced by a process (such as vacuum melting or degassing) that minimizes flaws in the material and improves its fracture toughness properties. If the flywheel is flame cut from a plate or forging, at least 1.3 cm (1/2 inch) of material should be left on the outer and bore radii for machining to final dimensions.

2. Fracture Toughness. The pump flywheel fracture toughness properties are acceptable if they comply with the following criteria, which are derived from Subsection C.1.b and supplemented by Subsection B of RG 1.14 and the ASME Boiler and Pressure Vessel Code (ASME Code), Section III, Appendix G, Protection Against Nonductile Failure.

   The material should be examined and tested to establish its fracture toughness property. The minimum K_{IC} of the material at the normal operating temperature of the flywheel should be 165 MPa $\sqrt{m}$ (150 ksi $\sqrt{in}$). Use of the direct test method to obtain K_{IC} is encouraged.

   Direct Test. The plane-strain fracture toughness, K_{IC}, should be obtained in accordance with ASTM E 399-05 if linear elastic fracture mechanics is used in the fracture mechanics analysis. The J-resistance curve should be obtained in accordance with ASTM E 1820-05a if elastic-plastic fracture mechanics is used. Either test should be conducted at or below the operating temperature of the pump flywheel.

Indirect Tests for Certain Steel. For flywheel materials made of ASME SA-533-B Class 1, ASME SA-508 Class 2, ASME SA-508 Class 3, and ASME SA-516 Grade 65 steel, the fracture toughness values can be found in the ASME Code, Section XI, Appendix A as a function of the difference between operating temperature (T) and the RT_{NDT} of the flywheel material, i.e., $T\text{-}RT_{NDT}$. The RT_{NDT} of the flywheel material should be determined in accordance with NB-2320 and NB-2330 of the ASME Code, Section III based on the nil-ductility transition temperature (T_{NDT}) determined by dropweight tests (DWT) and the impact energy determined by Charpy V-notch (C_v) tests. NB-2320 specifies ASTM E-208-95a as the Standard for DWT tests and ASTM A-370 as the Standard for C_v tests.

If this indirect approach is applied to flywheel materials other than ASME SA-533-B Class 1, ASME SA-508 Class 2, ASME SA-508 Class 3, or ASME SA-516 Grade 65 steel, justification should be given to establish equivalence of fracture toughness between the proposed flywheel material and those mentioned here.

3. Preservice Inspection. The applicant's preservice inspection program, including finish machining and ultrasonic and surface inspections, is acceptable if it complies with the following criteria, which are derived from Subsection C.4.a of RG 1.14.

   A. Each finished flywheel should be subjected to a 100% volumetric examination by ultrasonic methods using procedures and acceptance criteria specified in ASME Code, Section III, NB-2530 for plates, and NB-2540 for forgings.

   B. If the flywheel is flame cut from a plate or forging, at least 1.3 cm (1/2 inch) of material should be left on the outer and bore radii for machining to final dimensions.

   C. Finish machined bores, keyways, splines, and drilled holes should be subjected to magnetic particle or liquid penetrant examination.

   D. The inspection results should be appropriately documented to establish initial flywheel conditions, accessibility, and practicality of the program to be used as baseline information for future inservice inspections.

4. Flywheel Design. The applicant's flywheel design is acceptable if it complies with the following criteria, which are derived from Subsection C.2 of RG 1.14.

   The flywheel should be designed to withstand normal conditions, anticipated transients, the design basis loss of coolant accident, and the safe shutdown earthquake without loss of structural integrity.

The design of the pump flywheel should also meet the following criteria:

   A. The combined stresses at the normal operating speed due to centrifugal forces and the interference fit of the wheel on the shaft, should not exceed 1/3 of the minimum specified yield strength or 1/3 of the measured yield strength in the weak direction of the material if appropriate tensile tests have been performed on the actual material of the flywheel.

B. The design overspeed of a flywheel should be at least ten percent above the highest anticipated overspeed. The anticipated overspeed should include consideration of the maximum rotational speed of the flywheel if a break occurs in the reactor coolant piping in either the suction or discharge side of the pump. An acceptable basis for the assumed design overspeed, addressing pipe breaks consistent with the design basis for reactor coolant piping, should be submitted to the staff for review.

C. The combined stresses at the design overspeed, due to centrifugal forces and the interference fit, should not exceed 2/3 of the minimum specified yield strength, or 2/3 of the measured yield strength in the weak direction if appropriate tensile tests have been performed on the actual material of the flywheel.

D. The shaft and the bearings supporting the flywheel should be able to withstand any combination of loads from normal operation, anticipated transients, the design basis loss-of-coolant accident, and the safe shutdown earthquake.

E. A fracture mechanics analysis should be conducted for the life time of the flywheel, including extended operation, to predict the critical speed for fracture of the flywheel. The ratio of K_{IC} to the maximum tangential stress at speeds from normal to design overspeed should be at least $2\sqrt{in}$ (consistent with SRP 10.2.3, "Turbine Disk Integrity"), or alternatively, the ratio of K_{IC} to the applied K should be 3.16 for normal and upset conditions and 1.41 for emergency and faulted conditions (consistent with the ASME Code approach). This fracture mechanics analysis should consider crack growth due to identified degradation mechanisms for the largest flaw which could be missed by inspection (use the NRC accepted value of 0.25 inch for Westinghouse Owners Group [WOG] and ABB Combustion Engineering Owners Group [CEOG] flywheels if a smaller value can not be justified). The analysis should be submitted as a topical report to the NRC staff for evaluation.

5. Overspeed Test. The applicant's commitment to perform an overspeed test is acceptable if each flywheel assembly is tested at the design overspeed of the flywheel. This criterion is taken from Subsection C.3 of RG 1.14.

6. Inservice Inspection (ISI). The applicant's ISI program is acceptable if it complies with the following criteria, which are derived from Subsection C.4.b of RG 1.14, operating experience, and staff's evaluation of WOG's and CEOG's fracture mechanics analyses on reactor coolant pump flywheels of operating plants.

A. A volumetric examination by ultrasonic methods of the areas of higher stress concentration at the bore and keyway extending to half of the flywheel radius, or a surface examination by liquid penetrant or magnetic particle methods of all exposed surfaces, at approximately 10 operating year intervals, during the refueling or maintenance shutdown coinciding with the inservice inspection schedule as required by the ASME Code, Section XI. Removal of the flywheel is not required.

B. Examination procedures and acceptance criteria should be in conformance with the requirements specified in Subsection II.3.A of this SRP section.

7. Operational Programs. For COL reviews, the description of the operational program and proposed implementation milestones for the Pre-Service Inspection, Inservice Inspection, and Inservice Testing Programs are reviewed in accordance with 10 CFR Part 50, Appendix A, 10 CFR 50.55a(a)(1) and 10 CFR 50.55a(f). The implementation milestone are completion prior to initial plant start-up, prior to commercial service and after generator on-line on nuclear heat.

Technical Rationale

The technical rationale for application of these acceptance criteria to the areas of review addressed by this SRP section is discussed in the following paragraphs:

1. GDC 1 and 10 CFR 50.55a require that systems and components be designed, fabricated, erected, constructed, tested, and inspected to quality standards commensurate with the importance of the safety function to be performed. 10 CFR 50.55a also incorporates by reference the applicable editions and addenda of the ASME Code. Reactor coolant pump flywheel failure can result in reduction or loss of forced coolant flow, and the effects of resulting missiles could possibly damage the reactor coolant system, the containment, or engineered safety features which provide functions of considerable importance to safety. Application of 10 CFR 50.55a and GDC 1 provides assurance that established standard practices of proven or demonstrated effectiveness are used to assure that failure of the flywheel will not occur, thereby precluding the effects of such a failure commensurate with its importance to safety.

2. GDC 4 requires structures, systems, and components important to safety be protected against the effects of missiles that might result from equipment failures. RG 1.14 describes methods to minimizing the potential for failures of the reactor coolant pump flywheels. During operation at normal speed, a flywheel has sufficient kinetic energy to potentially produce high-energy missiles and excessive vibration of the reactor coolant pump assembly if the flywheel should fail. Overspeed of the pump rotor assembly during a transient increases both the potential for failure and the kinetic energy of the flywheel. The safety consequences of flywheel failure could be significant because of possible damage to the reactor coolant system, the containment, or the engineered safety features. Application of this criterion ensures that there will be an extremely low probability of missiles from the flywheels resulting in consequences to the reactor coolant system pressure boundary, containment, and engineered safety features.

III. REVIEW PROCEDURES

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

These review procedures are based on the identified SRP 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.

The judgment on areas to be given attention and emphasis in the review is based on the review of the material presented to determine whether it is similar to that recently reviewed on other plants and whether items of special safety significance are involved.

Upon request from the primary reviewer, the review interface organizations will provide input for the areas of review stated in Subsection I of this SRP section. The primary reviewer obtains and uses such input as required to ensure that this review procedure is complete.

The review procedure involves the following:

1. Materials Selection. The materials selection, including the procedures to minimize flaws and improve mechanical properties as described by the applicant, are reviewed and compared with the requirements of Subsection II.1 of this SRP section. If it is a new material not used in prior licensing cases, the materials selection is reviewed and evaluated to establish its acceptability. Based on past evaluations, the following materials are suitable for pump flywheels provided that they meet all the criteria listed in Subsections II.1 and II.2 of this SRP section: ASME SA-533-B Class 1, ASME SA-508 Class 2, ASME SA-508 Class 3, and ASME SA-516 Grade 65. The specification for each of these materials is provided in the ASME Code, Section II.

2. Fracture Toughness. The fracture toughness properties of the flywheel materials, including test data where applicable, are reviewed and compared with the requirements of Subsection II.2 of this SRP section. Two methods for deriving the fracture toughness of the flywheel materials are acceptable: 1) the direct method using fracture mechanics testing as described in Subsection II.2 of this SRP section, and 2) the indirect method using the RT_{NDT} of the flywheel as described in Subsection II.2 of this SRP section for flywheel materials made of ASME SA-533-B Class 1, ASME SA-508 Class 2, ASME SA-508 Class 3, or ASME SA-516 Grade 65 steel. The actual fracture toughness property or the nil-ductility reference temperature of the flywheel materials and the stated normal operating temperature of the flywheel should be consistent with those specified in the licensee's SAR.

3. Preservice Inspection. The preservice inspection program, including finish machining and ultrasonic and surface inspections as described by the applicant, is reviewed and compared with the requirements of Subsection II.3 of this SRP section. The extent to which the proposed ultrasonic inspections and the acceptance criteria in the SAR agree with ASME Code, Section III, NB-2530 for plate materials or NB-2540 for forgings, should be evaluated.

4. Flywheel Design. The stress analysis procedures in support of the flywheel design should be reviewed for allowable stresses and applied stresses for the following loading conditions.

   A. Load combinations at normal operating speed,

   B. Load combinations at design overspeed (definition of and basis for selection of design overspeed should also be reviewed),

   C. Shaft and bearing load combinations.

Further, the fracture mechanics analysis procedures in support of the flywheel design considering existence of undetected flaws should be reviewed. This analysis should consider crack growth for the life time of the flywheel, including extended period of operation.

The information given in the SAR should be compared and evaluated against the acceptance criteria in Subsection II.4 of this SRP section.

5. Overspeed Test . The applicant should confirm that an overspeed test will be run in compliance with Subsection II.5 of this SRP section.

6. Inservice Inspection. The inservice inspection program described by the applicant in the plant operational program, including areas to be inspected, methods of inspection, frequency of inspection, and acceptance criteria, is reviewed and compared with the requirements of Subsection II.6 of this SRP section.

7. Operational Programs. The reviewer verifies that the Pre-Service Inspection, Inservice Inspection, and Inservice Testing Programs are fully described and that implementation milestones have been identified. The reviewer verifies that the program and implementation milestones are included in FSAR Table 13.x.

   Implementation of this program will be inspected in accordance with NRC Inspection Manual Chapter IMC-2504, “Construction Inspection Program - Non-ITAAC Inspections.”

8. 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 (ESP) or other NRC approvals (e.g., manufacturing license, site suitability report or topical report).

9. 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 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.

1. The applicant has sufficiently demonstrated that its selection of materials, fracture toughness test data, design procedures, preservice overspeed spin testing program, and inservice inspection program for the reactor coolant pump flywheels meet the requirements for GDC 1 and 10 CFR Part 50, 50.55a(a)(1) with respect to providing adequate assurance of a quality product commensurate with the importance of the safety function.

2. The applicant has met the requirements of GDC 4 by complying with the guidance of RG 1.14. It selected suitable materials with adequate fracture toughness, used conservative design procedures, and established a preservice testing and inservice inspection programs for reactor coolant pump flywheels. The staff has reasonable assurance that the structural integrity of the flywheels will be maintained in the event of design overspeed transients or postulated accidents.

The applicant described the Pre-Service Inspection, Inservice Inspection, and Inservice Testing Programs and its implementation in conformance with 10 CFR Part 50, Appendix A, 10 CFR 50.55a(a)(1) and 10 CFR 50.55a(f).

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 SRP 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 SRP section in performing safety evaluations of DC applications and license applications submitted by applicants pursuant to 10 CFR Part 50 or 10 CFR Part 52. Except when the applicant proposes an acceptable alternative method for complying with specified 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 submitted six months or more after the date of issuance of this SRP section, unless superseded by a later revision.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, "General Design Criteria for Nuclear Power Plants," (General Design Criterion 1, "Quality Standards and Records," General Design Criterion 4, "Environmental and Dynamic Effects Design Bases)."

2. 10 CFR Part 50, §50.55a, "Codes and Standards," paragraph (a)(1).

3. Regulatory Guide 1.14, "Reactor Coolant Pump Flywheel Integrity." (originally Safety Guide 14).

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

5. ASTM E-399-05 (2005), "Standard Test Method for Linear-Elastic Plan-Strain Fracture Toughness K_{IC} of Metallic Materials," Annual Book of ASTM Standards, American Society for Testing and Materials.

6. ASTM E-1820-05a (2005), "Standard Test Method for Measurement of Fracture Toughness," Annual Book of ASTM Standards, American Society for Testing and Materials.

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

8. ASTM A-370-05 (2005), "Standard Test Methods and Definitions for Mechanical Testing of Steel Products, "Annual Book of ASTM Standards, American Society for Testing and Materials.

9. NRC Safety Evaluation, “Acceptance for Referencing of Topical Report WCAP-14535, ‘Topical Report on Reactor Coolant Pump Flywheel Inspection Elimination,’” September 12, 1996.

10. NRC Safety Evaluation, “Acceptance for Referencing of Topical Report SIR-94-080, ‘Relaxation of Reactor Coolant Pump Flywheel Inspection Requirements,’” May 21, 1997.

11. NRC Inspection Manual Chapter IMC-2504, “Construction Inspection Program - Non-ITAAC Inspections,” issued April 25, 2006.