SIEMENS
Westinghouse

TP-03143

Unrestricted

MISSILE ANALYSIS METHODOLOGY FOR GE NUCLEAR STEAM TURBINE ROTORS BY THE SWPC

<u>SUBMITTED TO</u>:
THE NUCLEAR REGULATORY COMMISSION AS TOPICAL REPORT TP-03143-NP-A FOR PUBLIC RECORD

GENE BARSNESS AND PETER BIRD
Steam Turbine Service Engineering
S326

ORLANDO, FL

July 31, 2003

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

July 22, 2003

Mr. Stan Dembkowski, Director
Operating Plant Services
Siemens Westinghouse Power Corporation
4400 Alafaya Trail, MC650
Orlando, FL 32826-2399

SUBJECT: SAFETY EVALUATION FOR ACCEPTANCE OF REFERENCING THE SIEMENS WESTINGHOUSE TOPICAL REPORT, "MISSILE ANALYSIS METHODOLOGY FOR GENERAL ELECTRIC (GE) NUCLEAR STEAM TURBINE ROTORS BY THE SIEMENS WESTINGHOUSE POWER CORPORATION (SWPC)" (TAC NO. MB5679)

Dear Mr. Dembkowski:

On May 16, 2002, the Siemens Westinghouse Power Corporation (SWPC) submitted its inspection and missile analysis methodology for General Electric (GE) nuclear low pressure (LP) steam turbine rotors to the staff. This was supplemented by letters dated October 11, 2002, November 19, 2002, and January 17, 2003.

The staff has found that the topical report "Missile Analysis Methodology for GE Nuclear Steam Turbine Rotors by the SWPC," is acceptable for referencing in licensing applications or other regulatory applications to the extent specified and under the limitations delineated in the report and in the associated NRC safety evaluation (SE). The SE defines the basis for acceptance of the report.

Pursuant to 10 CFR 2.790, we have determined that the SE provided as Enclosure 1 contains proprietary information. Proprietary information contained in Enclosure 1 is indicated by marginal lines. We have prepared a non-proprietary version of the SE (Enclosure 2) that we have determined does not contain proprietary information. However, we will delay placing Enclosure 2 in the public document room for a period of 10 working days from the date of this letter to provide you with the opportunity to comment on the proprietary aspects only. If you believe that any information in Enclosure 2 is proprietary, please identify such information line by line and define the basis pursuant to the criteria of 10 CFR 2.790.

Our acceptance applies only to matters approved in the subject report. We do not intend to repeat our review of the acceptable matters described in the report. When the report appears as a reference in license applications, our review will ensure that the material presented applies to the specific plant involved. License amendment requests that deviate from this topical report will be subject to a plant specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that SWPC publish an accepted version of this topical report within 3 months of receipt of this letter. The accepted version shall incorporate this letter and the enclosed safety evaluation between the title page and the abstract. It must be well indexed such that information is readily located. Also, it must contain in appendices historical review information, such as questions and accepted responses, and original report pages that were replaced. The accepted version shall include a "-A" (designated accepted) following the report identification symbol.

If the NRC's criteria or regulations change so that its conclusion in this letter, that the topical report is acceptable, is invalidated, the SWPC and/or the applicants referencing the topical report will be expected to revise and resubmit its respective documentation, or submit justification for the continued applicability of the topical report without revision of the respective documentation.

If you have any questions, please contact Brian Benney at (301) 415-3764.

Sincerely,

Herbert N. Berkow, Director
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 721

Enclosure: 1. Proprietary Safety Evaluation
2. Non-Proprietary Safety Evaluation

cc w/encl 2: See next page

cc w/enclosure 2:
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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

July 21, 2003

Mr. Peter Bird
Field Service Engineering S326
Siemens Westinghouse Power Corporation
4400 Alafaya Trail
Orlando, FL 32826-2399

SUBJECT: SIEMENS WESTINGHOUSE – REQUEST FOR WITHHOLDING INFORMATION FROM PUBLIC DISCLOSURE (TAC NO. MB5679)

Dear Mr. Bird:

By letter dated July 14, 2003, Siemens Westinghouse (SWPC) submitted an affidavit dated July 14, 2003, executed by Alfred A. Pallota, requesting that the following document be withheld from public disclosure pursuant to Title 10 of the *Code of Federal Regulations* (10 CFR) Section 2.790:

> Siemens Westinghouse Topical Report, "Missile Analysis Methodology for General Electric (GE) Nuclear Steam Turbine Rotors by the Siemens Westinghouse Power Corporation (SWPC)"

A nonproprietary copy of the document was not provided for placement in the Nuclear Regulatory Commission's (NRC's) Public Document Room and for addition to the Agencywide Documents Access and Management System Public Electronic Reading Room.

It is our understanding that Siemens will provide a non-proprietary version of the NRC accepted topical report (referenced above) to the Commission by August 30, 2003.

The affidavit stated the reasons that the submitted information should be considered exempt from mandatory public disclosure. The NRC staff agrees that the following reasons apply:

(a) The information reveals details of SWPC research and development plans and programs or their results.

(b) Use of the SWPC information by a competitor would permit the competitor to significantly reduce its expenditures, in time and resources, to design, produce, or market a similar product or service.

(c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for SWPC.

We have reviewed your application and the material in accordance with the requirements of 10 CFR 2.790 and, on the basis of your statements, have determined that the submitted information sought to be withheld contains proprietary commercial information and should be withheld from public disclosure.

Therefore, the document entitled, "Missile Analysis Methodology for General Electric (GE) Nuclear Steam Turbine Rotors by the Siemens Westinghouse Power Corporation (SWPC)" marked as proprietary, will be withheld from public disclosure pursuant to 10 CFR 2.790(b)(5) and Section 103(b) of the Atomic Energy Act of 1954, as amended.

Withholding from public inspection shall not affect the right, if any, of persons properly and directly concerned to inspect the documents. If the need arises, we may send copies of this information to our consultants working in this area. We will, of course, ensure that the consultants have signed the appropriate agreements for handling proprietary information.

If the basis for withholding this information from public inspection should change in the future such that the information could then be made available for public inspection, you should promptly notify the NRC. You also should understand that the NRC may have cause to review this determination in the future, for example, if the scope of a Freedom of Information Act request includes your information. In all review situations, if the NRC makes a determination adverse to the above, you will be notified in advance of any public disclosure.

If you have any questions regarding this matter, I may be reached at (301) 415-3764.

Sincerely,

Brian Benney, Project Manager, Section 2
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 721

cc: See next page

cc:

Mr. Chuck Patrick, Manager
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Mr. Stan Dembkowski, Director
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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

SIEMENS WESTINGHOUSE TOPICAL REPORT

"MISSILE ANALYSIS METHODOLOGY FOR GENERAL ELECTRIC

(GE) NUCLEAR STEAM TURBINE ROTORS BY THE SIEMENS WESTINGHOUSE POWER

CORPORATION (SWPC)"

PROJECT NO. 721

1.0 INTRODUCTION

By letter dated May 16, 2002, the Siemens Westinghouse Power Corporation (Siemens or SWPC) submitted for NRC review and approval its inspection and missile analysis methodology for General Electric (GE) nuclear low pressure (LP) steam turbine rotors. The methodology was summarized in Attachment 6, "Example of General Electric Missile Probability Analysis," of the May 16, 2002, submittal. However, in its letter dated October 11, 2002, responding to the NRC's request for additional information (RAI), SWPC requested that the NRC instead review Attachment 5 of the May 16, 2002, submittal, "Engineering Report ER-9605: Missile Analysis Methodology for Limerick Generating Station, Units 1 & 2 With Siemens Retrofit Turbines, Revision No. 2, June 18, 1987," otherwise known as the Siemens turbine missile methodology (Siemens methodology). In completing all efforts in addressing the staff's RAI, SWPC submitted additional RAI responses on November 19, 2002, and January 17, 2003, respectively. SWPC intends to reference this topical report in future plant-specific applications, demonstrating that the calculated missile generation probability for SWPC's GE nuclear LP rotors would satisfy the NRC's turbine system reliability criteria.

2.0 REGULATORY EVALUATION

General Design Criterion (GDC) 4 requires that structures, systems, and components (SSCs) important to safety be protected against the effects of missiles that might result from equipment failures. The steam turbine is analyzed because if its massive rotors failed at a high rotating speed during normal operating conditions of a nuclear unit, it could generate high energy missiles that could potentially damage safety-related SSCs.

In the past, evaluation of the likelihood of turbine missiles on the public health and safety followed Regulatory Guide (RG) 1.115, "Protection Against Low-Trajectory Turbine Missiles," and three Standard Review Plan (SRP, NUREG-0800) sections: Sections 3.5.1.3, "Turbine Missiles," 10.2, "Turbine Generator," and 10.2.3, "Turbine Disk Integrity." As specified in Section 3.5.1.3, the probability of unacceptable damage from turbine missiles is expressed as the product of the following factors: (1) the probability of turbine missile generation resulting in the ejection of turbine disk (or internal structure) fragments through the turbine casing, P_1,

(2) the probability of ejected missiles perforating intervening barriers and striking safety-related SSCs, P_2, and (3) the probability of struck SSCs failing to perform their safety functions, P_3. Over the years the NRC staff has shifted its emphasis in the review of turbine missile issues from the strike and damage probability $P_2 x P_3$ to the missile generation probability P_1. The minimum reliability requirement for loading the turbine and bringing the system on line was established in Appendix U of NUREG-1048, Supplement No. 6, "Safety Evaluation Report Related to the Operation of Hope Creek Generating Station," as: $P_1 < 10^{-4}$ for favorably oriented turbines and $P_1 < 10^{-5}$ for unfavorably oriented turbines. The favorable turbine placement and orientation is such that safety-related SSCs are outside the low trajectory turbine missile strike zones defined in RG 1.115. The unfavorable turbine placement and orientation is such that safety-related SSCs are within the low trajectory turbine missile strike zones. Currently, the maintenance and inspection of turbine rotors and valves are based on the P_1 calculation, the operating experience of similar equipment, and inspection results. These are the criteria that future plant-specific applications using the Siemens methodology will be expected to meet.

3.0 <u>TECHNICAL EVALUATION</u>

The NRC approved the replacement of a nuclear plant turbine rotor using the Siemens methodology in a safety evaluation (SE) dated February 3, 1998, "Limerick Generating Station (LGS), Units 1 and 2, Main Turbine Rotor Replacement, Extension of Turbine Rotor Inspection Intervals and Valve Testing Frequencies." The review was focused on the calculated turbine missile probabilities and disk burst probabilities, and the design features of the replacement rotors for the Limerick units to reduce these probabilities. The discussion on the Siemens methodology itself was very limited; therefore, a complete review of the Siemens methodology is warranted.

The Siemens methodology considers two distinct LP rotor disk failures in its P_1 calculation: (1) failure at normal operating speed up to 120 percent of the rated speed, and (2) failure due to run-away overspeed greater than 120 percent of the rated speed. The first failure can be expressed by three probabilities: the probability of the turbine running up to 120 percent of the rated speed, P_{1r}; the probability of disk burst at up to 120 percent of the rated speed, P_{2r}; and the probability of casing penetration given a disk burst at up to 120 percent of the rated speed, P_{3r}. The corresponding probabilities for the second failure due to overspeed are P_{1o}, P_{2o}, and P_{3o}. Note that P_{2r}, P_{2o}, P_{3r}, and P_{3o} are part of the P_1 calculation; they are not related to the P_2 and P_3 calculations mentioned in Section 2.0. In the Siemens methodology, P_{1r}, P_{2o}, and P_{3o} have been conservatively assumed to be 1.0. Hence, the probability of an external missile P_1, which was expressed as: $P_1 = \sum(P_{1r} X P_{2r} X P_{3r} + P_{1o} X P_{2o} X P_{3o})$, has reduced to: $P_1 = \sum(P_{2r} X P_{3r} + P_{1o})$, where P_{2r} can be obtained by multiplying the probability of initiation, P_{2ri}, to the probability of crack growth to the critical depth, P_{2rg}. This general approach is consistent with those that have been approved by the NRC staff, and the focus of the current review is the underlying methodologies of the computer program, PDBURST, for calculating P_{2rg} and the computer program, PDMISSILE, for calculating P_{3r} and the methodology for calculating P_{1o}. Both computer programs adopt the Monte-Carlo simulation technique. Some important elements of the Siemens methodology are discussed below.

3.1 Factors Affecting PDBURST Results: P_{2rg}

As mentioned above, PDBURST is a computer program that calculates the probability P_{2rg} for an assumed crack in a turbine disk to grow to the critical depth. The deterministic part of the

PDBURST computer program is based on linear elastic fracture mechanics (LEFM), with the disk burst failure defined as the critical condition when the calculated crack depth equals the critical crack depth. The Siemens methodology includes a crack branching effect and a Siemens stress corrosion cracking (SCC) crack growth rate in the disk burst failure criterion. The discussion below addresses the staff's concern about the characterization of these two factors and the SWPC's responses to this concern. Also discussed are SWPC's responses regarding some key technical elements, such as the contribution due to other degradation mechanisms, the validity of the indirectly-derived fracture toughness values, and the appropriateness of using the assumed shrink fits in P_{2rg} calculations. The probabilistic part of the Siemens methodology is a typical Monte-Carlo simulation, which considers seven statistical, or random parameters. The staff finds this portion of the methodology to be acceptable.

3.1.1 Crack Branching Effect

SCC in turbine disk keyways and bores have been found to yield multiple, irregular branched cracks. These secondary, branched cracks would share the crack opening displacement at the tip of a main crack, causing a reduction in the stress intensity factor for the main crack. Although this effect has long been identified, as indicated in Attachment 1 to SWPC's May 16, 2002 submittal, Westinghouse report MSTG-1-P, "Criteria for Low Pressure Nuclear Turbine Disk Inspection," dated June 1981, it was not represented as a variable in Westinghouse's turbine missile methodology that was approved by the NRC on February 2, 1987. Instead, it was used to increase the margin for the fracture toughness values for the turbine disks. The Siemens methodology makes the turbine missile calculations more realistic by considering both crack branching factor and fracture toughness to be random variables. The mean value and the standard deviation assumed in the Siemens methodology for the crack branching factor are 0.65 and 0.175, respectively, which are consistent with the analytical results by Lo (Reference 1) and Chatterjee (Reference 2) and the experimental results by Hodge and Mogford (Reference 3). Hence, the NRC staff agrees with SWPC in using these values in its turbine missile methodology. However, since crack branching is likely to stop for a crack exceeding three inches in length, PDBURST should have considered this phenomenon to better describe the entire history of a crack growth. SWPC resolved this issue by revising PDBURST in setting the crack branching factor to zero for cracks growing beyond three inches.

3.1.2 Crack Growth Mechanisms

The Siemens methodology considers growth of postulated cracks in turbine disks due to SCC only. In regard to the NRC staff's concern over other growth mechanisms such as high and low cycle fatigue, SWPC provided qualitative and quantitative evaluations of crack growth due to high and low cycle fatigue. High cycle fatigue is caused by cyclic bending loads on the rotor, and low cycle fatigue is caused by plant startups and shutdowns. Attachment 8 to SWPC's October 11, 2002, RAI response, WSTG-4-P, "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Rotors," reports additional results from quantitative analyses for these two fatigue mechanisms. This report also discussed another mechanism, ductile burst. The NRC staff agrees with SWPC's conclusion on excluding these mechanisms from the proposed turbine missile analysis because the quantitative results in either SWPC's response to the NRC staff's concerns, or those contained in WSTG-4-P, indicate that the effects due to mechanisms other than SCC would be small. For instance, WSTG-4-P indicates that the probability of disk burst from a sample turbine missile analysis considering low cycle fatigue is several orders of magnitude lower than that due to SCC at a comparable turbine speed.

3.1.3 SCC Crack Growth Rate

The Siemens methodology discussed three SCC crack growth rate models: the Westinghouse, the Siemens Power Generation Group (KWU), and the GE model. The NRC staff approved the use of the Westinghouse crack growth rate model in the February 2, 1987 SE and the use of the GE rate model implicitly in the February 3, 1998 SE, with the comment, "GE stress corrosion crack growth rates are assumed by Siemens Power Corporation (SPC or later SWPC) for evaluating the stress corrosion crack growth life. The GE rates are about two to four times higher than the rates predicted by rates based on actual experience of SPC units." Since the Siemens methodology will only be applied to GE turbines, and the February 3, 1998 SE determined that the GE rate bounds those based on actual experience of the SPC units, the NRC staff accepts the use of the GE crack growth rate model on GE turbines. PDBURST allows the user to choose either the Westinghouse or the GE rate. The KWU model, which is least conservative, has not been adopted by PDBURST.

3.1.4 Fracture Toughness Values

Since fracture toughness (K_{lc}) tests are not normally performed for turbine disks, the Westinghouse methodology obtained K_{lc} values from measured Charpy V-notch (CVN) data and yield strength using the Rolfe-Barsom equation. Siemens also used this empirical equation to estimate K_{lc} values for turbine disks in its proposed turbine missile methodology. In response to the NRC staff's concerns regarding the determination of K_{lc} values using the Rolfe-Barsom equation, SWPC further clarified that the Siemens methodology will use the Rolfe-Barsom equation only for disks operating in the upper shelf region, and for disks operating below the upper shelf region, it will use a K_{lc} and (T-FATT) correlation based on GE data, where FATT stands for the test-determined fracture appearance transition temperature. This procedure in determining the K_{lc} values, which will be used as mean values in the subsequent Monte-Carlo simulations, is more rigorous than the previously approved ones, and is therefore acceptable to the NRC staff.

The NRC staff also questioned whether the standard deviation for K_{lc} is large enough to account for the scatter and uncertainties associated with limited test data and whether a randomly selected K_{lc} value used in the Monte-Carlo simulations might be unrealistically high. In response to this concern, SWPC decided to use [ ] percent of the mean K_{lc} value as the standard deviation and use a value of [ ] ksi$\sqrt{in}$ for the maximum upper-shelf mean K_{lc} value in its disk burst analysis. The staff considers these values to be acceptable because the same standard deviation for K_{lc} and the maximum upper-shelf mean K_{lc} value has been used successfully in vessel probabilistic fracture mechanics (PFM) analyses for twenty years for similar types of steels.

3.1.5 Shrink Fits

The shrink fit contributes to the applied bore stresses, which in turn affect the critical crack depth and the final missile probability. In its October 11, 2002 response to the staff's RAI regarding bases for choosing an assumed shrink fit for disks having no measured shrink fit data, SWPC clarified that a conservative assumed bore stress of [ ] ksi was based on measured radial shrink fits ranging from [ ] inch to [ ] inch. Further, SWPC performed a sensitivity study of bore stresses (caused by shrink fits) of 40, 50, and 60 ksi on calculated missile probability as a function of operating hours. This study indicated that only when the bore stress is greater than 60 ksi, does the probability of a missile began to increase significantly. The NRC staff accepts the use of [ ] ksi as the assumed bore stress when the measured shrink fit is not available because (1) Figure 6.2 of SWPC's response indicated that the threshold bore stress is higher than 60 ksi, below which the impact on the probability of missile generation is negligible, and (2) [ ] ksi bounds published data in the range of 40 to 60 ksi on GE rotors as indicated by SWPC's response.

3.1.6 Initial Crack Depth

The Siemens methodology assumes an initial crack depth of 0.12 inch for the evaluation of P_{2r} after the initial operating period for disks showing no indications when examined by nondestructive examination. This selection was based on the inspection technique detection tolerance using Siemens equipment. Additional information regarding detectability was provided by SWPC in its January 17, 2003, response to the NRC staff's RAI. This information indicates that one of the requirements which form the bases for the development of Siemens' disk inspection system is to be able to detect small surface cracks with radial depth $\leq$ 0.1 inch and to size the detected cracks reliably. In addition, Siemens' investigations and experiences associated with the corner reflection technique of UT have shown that very small defects with radial depth $\leq$ 0.02 inch are detected. Based on the above, the staff determines that using an initial crack size of 0.12 inch for disks showing no indications in the evaluation of P_{2r} is appropriate.

3.2 Factors Affecting PDMISSILE Results: P_{3r}

PDMISSILE is a computer program that calculates the probability of casing penetration given a disk burst up to 120 percent of the rated speed. The deterministic part of the PDMISSILE computer program is based on an energy balance that equates the external missile energy to the difference between the total missile energy at the moment of disk burst at a given rotor speed and the energy dissipation by blade deformation, blade crushing, blade bending, blade vane break-off, friction between the missile and inner casing, and deformation of the inner casing up to breakage and penetration of the outer casing. Among the 26 random variables for PDMISSILE, only seven are major contributors to the calculated P_{3r} value, according to information in Attachment 7 to SWPC's October 11, 2002, response to the NRC staff's RAI. These seven variables are: friction coefficient, tensile strength, fracture elongation, yield strength, material volume, section modulus for the turbine inner casing material, and the mass moment of inertia for the rotating turbine section. The NRC staff agrees with SWPC's assessment of sensitivity for these 26 variables and discusses the acceptability of the values chosen for these 7 variables below.

3.2.1 Friction Coefficient (Generic)

Among the seven key variables, only the friction coefficient is generic, which will remain the same for future plant-specific applications. The mean and standard deviations of the friction coefficient were originally specified by SWPC arbitrarily. Without the support of test data, the staff considered these values to be unjustified and suggested the use of a more conservative friction coefficient. As a result, SWPC proposed to use 0.25, a value much more conservative than what SWPC used before for various applications, for the friction coefficient that will be used in future plant-specific applications. Considering the very rough surface of a missile, the NRC staff believes that employing this value in the PDMISSILE analysis is appropriate.

3.2.2 Other Parameters (Plant-specific)

SWPC has provided appropriate measures to determine the tensile strength, fracture elongation, yield strength, material volume, and section modulus for the turbine inner casing material and the mass moment of inertia for the rotating turbine section. In future plant-specific applications, the applicants are required to report any deviation from the following approaches in determining the six plant-specific parameters important to the P_{3x} calculations using PDMISSILE.

1. Tensile Strength: This value will be derived from hardness and chemistry using ASTM A371 adjusted for the specific alloy.

2. Fracture Elongation: This value will be derived from hardness and chemistry using the specification for the specific alloy.

3. Yield Strength: This value will be derived from correlation between yield strength and ultimate tensile strength for the specific material.

4. Material Volume: Geometry of the material will be measured for each rotor.

5. Section Modulus: Geometry of the component will be measured for each unit.

6. Mass Moment of Inertia: This value will be derived from measurements of each turbine disc on the actual rotor or from identical (interchangeable) spare rotors.

3.3 Factors Affecting Probability of a Run-Away Overspeed: P_{1o}

The last parameter needed for calculating P_1 is the probability of run-away overspeed events greater than 120 percent of the rated speed, P_{1o}. This event occurs when the overspeed protection system fails. The overspeed protection system consists of speed monitoring devices, trip devices, and fast closure of steam stop and control valves. The Westinghouse methodology for calculating P_{1o} was evaluated and accepted by the NRC as part of the general review of the turbine missile methodology as indicated in the February 2, 1987, SE. The corresponding methodology for GE rotors was approved in July 1986 as indicated in NUREG 1048. In the current submittal, SWPC proposes to use P_1 at time zero as P_{1o} for GE rotors. The P_1 value is provided in each turbine inspection report prepared by GE for plants using GE's service in their turbine missile applications. Using the documented P_1 values at time zero would exclude the contribution due to the time dependent SCC and use only the contribution due to overspeed. The staff determines that this approach is conservative and can be applied to GE rotors.

To address the NRC staff's concern regarding the P_{1o} calculation for Siemens rotors, SWPC provided Attachment 11, to the January 17, 2003, RAI response, "Probability of Turbine Missiles from 1800 RPM Nuclear Steam Turbine-Generators with 46 Inch Last Stage Blades," Engineering Report ER-504 (October 1975), for the NRC staff to review. This report contains detailed information regarding the P_{10} calculation method for Siemens rotors which uses a fault tree event process and historical failure data pertinent to Siemens stop and control valves and trip and control system elements. The use of these failure data to calculate failure rates for various components is also discussed in this report. The staff's review determined that the Siemens P_{10} calculation method described above is similar to that of the approved Westinghouse method, and is therefore acceptable. Further, SWPC's response to the NRC staff's concern contains a comparative study using the Siemens and the Westinghouse P_{10} calculation methods. Although the Siemens and the Westinghouse P_{10} values from this study are for different rotors, the NRC staff still considers the Siemens method to be more conservative because the Siemens P_{10} values are greater than the Westinghouse values by at least an order of magnitude, depending upon valve test intervals. Based on the above, the staff determined that it is appropriate to apply the Siemens method to Siemens rotors in future plant-specific applications.

4.0 CONCLUSION

The NRC staff has completed its review of SWPC's submittals and has determined that the proposed turbine missile methodology is appropriate based on the evaluation discussed above in Section 3.0. The NRC staff approval of the Siemens methodology includes approval of the use of the PDBURST and PDMISSILE computer programs, and the use of specified values for some key input and built-in parameters for these two programs for future plant-specific turbine missile probability analyses for GE and Siemens rotors.

All future plant-specific applicants that intend to apply the Siemens methodology in evaluating their turbine missile probabilities will need to verify that they have used the values for certain selected parameters as discussed in Section 3.0 and summarized below:

Input to PDBURST:
- Standard deviation for K_{Ic}: [ ]
- Initial crack depth: 0.12 inch

Internally defined parameters for PDBURST:
- Maximum mean K_{Ic}: [ ] ksi$\sqrt{in}$
- Maximum crack depth for considering crack branching: 3 inch
- Mean value for the crack branching factor: 0.65
- Standard deviation for the crack branching factor: 0.175
- Bore stresses due to shrink fit with no record: [ ] ksi

Input to PDMISSILE:
- Friction coefficient: 0.25
- Plant-specific parameters: See Section 3.3.2

Use of other values for these parameters in plant-specific applications will have to be justified and provided to the NRC staff for review and approval.

5.0 REFERENCES

1. Lo, K.K., "Analysis of Branched Cracks," ASME Journal of Applied Mechanics, Vol. 45, pp. 792-802, 1978.

2. Chatterjee, S.N., "The Stress Field in the Neighborhood of a Branched Crack in an Infinite Elastic Sheet," International Journal of Solids and Structures, Vol. 2, pp. 521-538, 1975.

3. Hodge, J.M. and Mogford, I.L., "UK Experience of Stress Corrosion Cracking in Steam Turbine Disk," Proceedings for Institute of Mechanical Engineers., Vol. 193, pp. 93-109, 1979.

Principle Contributor: S. Cheng

Date: July 22, 2003

Written By: Barsness, Gene and Bird, Peter July 31, 2003

Reviewed By: Banks, Robin L.

Approved By: Auman, James R.

MISSILE ANALYSIS METHODOLOGY FOR GE NUCLEAR STEAM TURBINE ROTORS BY THE SWPC

Abstract

This report describes methods of calculating probability of missile generation (P_1) for General Electric (GE) Nuclear LP rotors by Siemens Westinghouse Power Corporation (SWPC). Siemens and Westinghouse were corporately joined in 1998. Both Siemens and Westinghouse had developed NRC approved methodologies for calculating probability of missile generation previous to this acquisition. While the methods are similar, the Westinghouse method has been applied to Westinghouse manufactured turbines and the Siemens method has been applied to both Siemens and General Electric turbines.

The missile analysis methodology described in this report can be applied to GE nuclear steam turbine rotors using either of the traditional Westinghouse or Siemens methods. Each individual case may have various sources of information available from the utility that would be better served by using one or the other methods.

This report is the unrestricted version of report TR-03142[1] and is made available for public record.

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[1] Specific portions of this report have been deleted, as indicated by [ ], such as text, tabulated data and figures because they are considered to be of a proprietary nature. SWPC submitted an Affidavit to the NRC dated July 14, 2003 on this basis, which was accepted by the NRC. Criteria identified in the deletions include one or more of the following:

a) The information reveals details of SWPC research and development plans and programs or their results.

b) Use of SWPC information by a competitor would permit the competitor to significantly reduce its expenditures, in time and resources, to design, produce, or market a similar product or service.

c) The information includes test data or analytical techniques concerning a process, methodology, or component, the application of which results in a competitive advantage for SWPC.

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1.0 INTRODUCTION

As indicated in our submittal letter (Reference 1), Siemens Westinghouse Power Corporation proposes to inspect and perform missile analysis on General Electric low pressure nuclear rotors currently licensed under the United States Nuclear Regulatory Commission (NRC). Included in the submittal are attachments that had been submitted previously by either Westinghouse Electric Corporation or Siemens Power Corporation as the missile analysis methodology used for determining inspection interval based on disc inspection results of LP rotors.

In 1998, the two companies, previously known as Westinghouse Electric Corporation and Siemens Power Corporation, were combined into one entity known as Siemens Westinghouse Power Corporation (SWPC) for doing business in the Americas. Thus both methodologies are available to perform missile analysis as appropriate to each LP rotor design.

The Westinghouse Method was submitted during the 1981 through 1984 period and approved by the NRC in 1987 (References 3-7). This method uses a fracture mechanics approach and conventional regression techniques.

The Siemens Method was submitted in 1997 and approved by the NRC in 1998 (References 9 and 10). This method follows the same fracture mechanics approach and includes a Monte Carlo statistical analysis.

SWPC is now proposing to perform the same P1 missile analysis on General Electric (GE) nuclear LP rotors with shrunk-on discs. Our submittal was initially based on the method described in Reference 11. This method had been used for missile analysis of a GE LP rotor for a previous application.

Based on subsequent evaluation, we have decided not to pursue the methodology described in Reference 11 but, instead, to return to the traditional Westinghouse and Siemens methodologies previously reviewed and approved by the NRC. The only difference will be that we are applying these methodologies to GE LP rotors for which we are not the Original Equipment Manufacturer (OEM). With regard to disc material properties, normally available to the OEM and utility, we propose to address them in one of two ways:

1) When made available by the utility, we will use actual disc material properties taken from supplier certified test reports.

2) When not made available by the utility, we will take hardness, chemistry and dimensional measurements of the rotors and discs at the site and apply them to get conservative material disc properties.

Once the material properties are established, they will be processed through the missile analysis calculations according to the existing and NRC approved Westinghouse or Siemens methods.

2.0 METHODOLOGY

The probability of unacceptable damage is defined as $P_1 x P_2 x P_3$ where P_1 is the probability of ejecting missiles from the turbine casing, P_2 is the probability of striking a safety related item and P_3 is the probability of causing failure of the safety related device. In Reference 7, page 5, the NRC staff made the following statement:

"Through experience of reviewing various licensing applications, the staff has concluded that $P_2 x P_3$ analyses provide only "ball park" or "order of magnitude" values. Based on simple estimates for a variety of plant layouts, the staff also concludes that the strike and damage probability product ($P_2 x P_3$) can be reasonably taken to fall in a characteristic narrow range which is dependent on the gross features of plant layout with respect to turbine generator orientation; i.e., (a) for favorably oriented turbine generators $P_2 x P_3$ tends to lie in the range of 10^{-4} to 10^{-3} and (b) for unfavorably oriented turbine generators $P_2 x P_3$ tends to lie in the range 10^{-3} to 10^{-2}. In addition, detailed analyses such as those discussed in this evaluation show that, depending on the specific combination of material properties, operating environment, and maintenance practices, P_1 can have values from 10^{-9} to 10^{-1} per turbine year depending on the turbine test and inspection intervals. For these reasons, in the evaluation of $P_4 (= P_1 x P_2 x P_3)$, the probability of unacceptable damage to safety-related systems from potential turbine missiles, the staff is giving credit for the product of the strike and damage probabilities of 10^{-3} for a favorably oriented turbine and 10^{-2} for an unfavorably oriented turbine, and is discouraging the elaborate calculations of these values."

Therefore P_1 is limited to 10^{-5} for unfavorably oriented plants and 10^{-4} for favorably oriented plants.

The determination of P_1 in both of the Siemens and Westinghouse methods is based on similar safety criteria, fracture mechanics and crack growth rate determinations, although the statistical approaches for calculating probabilities are somewhat different. The NRC has reviewed both the Westinghouse (References 3-7) and Siemens methods (References 9 and 10).

Siemens Method

Specific nomenclature of the Siemens method is:

The probability of an external missile is based on two distinct types of failures: 1) failure at normal operating speed up to 120% and 2) failure due to run-away over-speed greater than 120%.

$P_1 = P_r + P_0 = \Sigma(P_{1r} * P_{2r} * P_{3r}) + \Sigma(P_{10} * P_{20} * P_{30})$ for all LP discs

Where:

P_1 = Probability of an external missile.

P_r = Probability of an external missile for speeds up to 120% of rated speed.

P_0 = Probability of an external missile for speeds greater than 120% of rated speed.

Σ = Sum of probabilities for all LP discs.

P_{1r} = Probability of turbine running up to 120% of rated speed. Normally assumed equal to 1.

P_{2r} = Probability of disk burst up to 120% of rated speed due to stress corrosion crack growth to critical crack size.

P_{3r} = Probability of casing penetration given a burst up to 120% of rated speed.

P_{10} = Probability of a run-away over-speed incident due to the failure of the control and protection system.

P_{20} = Probability of a disk burst above 120% of rated speed. Normally assumed equal to 1.

P_{30} = Probability of a casing penetration at run-away overspeed. Normally assumed equal to 1.

The equation then depends only on computing the values of P_{2r}, P_{3r}, and P_{10}. P_{2r} is the product of the probability of crack initiation (P_{2ri}) times the probability of crack growth to the critical crack size (P_{2rg}).

A sample calculation for the Siemens Method is described in Reference 9, Appendix Table A2.

<u>Westinghouse Method</u>

A comparable set of sample calculations for the Westinghouse Method (References 5-7) has been prepared for the existing GE rotor in question and includes a sensitivity study of disc toughness. In the sensitivity study, disc toughness values of 160, 180, 200 and 240 ksi√inch were assumed.

The basic equations in the Westinghouse method are:

P_1 = PROB(R) + PROB(O) + PROB(D)

Where,

P_1	= probability of a turbine missile
PROB(R)	= probability of a turbine missile at rated speed
PROB(O)	= probability of a turbine missile at design overspeed up to 120% of rated speed
PROB(D)	= probability of a turbine missile at destructive overspeed greater than 120% of rated speed = [ ] b,c (derived from available GE missile reports at 7/30/7 valve test interval)

PROB(R) = P(R) x P(m | R)

PROB(O) = P(O) x P(m | O)

Where,

P(R)	= probability of reaching rated speed = 1.0
P(m | R)	= conditional probability of a turbine missile due to stress corrosion cracking at rated speed (calculated by computer program)
P(O)	= probability of reaching design overspeed = [ ] b,c
P(m | O)	= conditional probability of a turbine missile due to stress corrosion cracking at design overspeed (calculated by computer program)

SAMPLE WESTINGHOUSE METHOD CALCULATION
FOR 6 YEAR INSPECTION INTERVAL

Assumptions:

- Initial Crack Size = 0 inch
- Valve Test Frequency: 7/30/7 days
- One year = 8760 hours
- Pre-warming is required to ensure disc toughness is in the upper shelf range
- Disc toughness (KIC) = [ ] b, c ksi√inch for all discs on LPA
- LPB and LPC probabilities taken from available GE missile reports

Term	LPA	LPB	LPC	UNIT
P(R)	1.0			
P(m|R)	[ ] b, c			
PROB(R)	[ ] b, c			
P(O)	[ ] b, c			
P(m|O)	[ ] b, c			
PROB(O)	[ ] b, c			
PROB(D)	[ ] b, c	[ ] b, c	[ ] b, c	[ ] b, c
TOTAL	[ ] b, c	[ ] b, c	[ ] b, c	[ ] b, c

P_1 = PROB(R) + PROB(O) + PROB(D) for all rotors = [ ] b, c per 6 yrs
NRC Limit = 1.0E-05

This sample calculation has shown that the P_1 missile probability remains below the NRC limit for all three LP rotors out to an inspection interval of 6 years for an assumed disc toughness of KIC= [ ] b, c ksi√inch. In this sample calculation, disc inspection is planned for LPA, for which complete missile calculations are provided. Total missile probabilities exist for LPB and LPC through available missile reports provided to SWPC.

Sources of conservatism in the Westinghouse and Siemens Methods are summarized in the tabulation.

	Source of Conservatism	Applicable to Current Methodology
1	Residual compressive stresses introduced during manufacture.	No, GE rotors are of older design vintage.
2	Crack initiation probabilities are based on experience base of older designs.	Yes, although GE rotors are part of the older design experience base.
3	GE stress corrosion crack growth rates are assumed for evaluating the stress corrosion crack growth life.	No, for the Westinghouse Method. Yes, for the Siemens Method. See Reference 9, Figure 12 for a comparison of OEM crack growth rates.
4	Probability of achieving speeds up to 120% of rated speed is assumed to be 1.0.	No, in the Westinghouse Method. Yes, in the Siemens Method.
5	Internal disc burst probability under normal operation up to 120% speed is less than NRC probability limit for an external missile up to 100,000 hours of operation.	No, in the Westinghouse Method based on current calculations of GE rotor. No, in the Siemens Method based on current calculations of GE rotor.
6	Crack size exceeding 100 mm rather than actual critical crack size.	Yes, but Westinghouse Method uses 8-inch (200 mm) maximum critical crack size. Yes, Siemens method historically uses 100-mm maximum critical crack size. In the future, we propose to use 200 mm consistent with the Westinghouse Method.
7	For the casing penetration probability, conservative mean values are used for input variables.	No, Westinghouse Method does not use casing penetration probability; the missile is either contained or liberated. Yes, in the Siemens Method.
8	Probabilities of both burst and casing penetration for a runaway event >120% of the rated speed are assumed to be 1.0 for all discs.	Yes for both methods.
9	Use of Siemens overspeed probability (P_{10}).	No, the GE value of destructive overspeed probability will be derived from existing missile reports on the rotors.

Table 2.1 Sources of Conservatism in Methodology

The sensitivity of disc toughness on missile probability due to stress corrosion cracking of the discs at both rated speed and design overspeed is shown on Figure 2.1.

[

] b, c

Figure 2.1 Westinghouse Method – Disc Toughness Sensitivity vs. Missile Probability

The sensitivity of disc toughness on the total P_1 missile probability calculation is shown on Figure 2.2. Disc inspection interval would be set based on remaining below the NRC limit. Comparison is made to the most recent GE results provided in the existing missile reports.

[

]b, c

Figure 2.2 Westinghouse Method – P_1 Calculation Results

3.0 PROBABILITY OF BURST

3.1 Stress Corrosion Crack Growth Rate

3.1.1 Crack Growth Mechanism

For nuclear LP rotors, the primary cause of crack growth is stress corrosion cracking. Fatigue growth was considered in WSTG-4-P, Reference 8, which is a report for fully integral rotors that included analysis of the impacts of high and low cycle fatigue compared to stress corrosion cracking.

High Cycle Fatigue

In this scenario, it is postulated that a failure can occur from a fatigue crack, which propagates in a plane transverse to the rotor axis as a result of cyclic bending loads on the rotor. These loads are developed by gravity forces and by possible misalignment of the bearings. Missile generation by this mechanism is highly unlikely because:

1) Large safety factors used in design minimize the initiation and propagation of a fatigue crack in both shrunk-on disc and integral rotors.

2) A large transverse crack will create eccentricity and the resulting high vibration will cause the unit to be removed from service before failure occurs. This is also true in both shrunk-on and integral rotors.

Low Cycle Fatigue

This mechanism postulates that a crack grows in an axial-radial plane due to startup/shutdown cycles. The example shown is for fully integral rotors with an extremely conservative upper bound of 600 cycles. This is equivalent to 20 cycles per year for 30 years, which is conservative in nuclear power plants. The difference with shrunk-on disc rotors is some change in the range of stress cycles that will slightly modify the probability but will still be very small compared to the stress corrosion cracking mechanism. Entry No. 2.1.471.9 from the Westinghouse Fracture Mechanics Handbook shows the correlation between Fatigue Crack Growth Rate and Δ Stress Intensity Factor.

- Assuming normal stress cycles of 49,000 ksi for operating stress and 37,000 ksi for at rest condition, the range is approximately 200 x 37,000/49,000 = 151 to 200 ksi $in^{.5}$.
- Therefore, delta K_1 is 49.
- The resulting fatigue crack growth rate is 2E-05 inches/cycle.
- This would give a crack growth of 0.012 inches for 600 cycles, which is considered insignificant compared to the impact of stress corrosion cracking.

3.1.2 Determination of Ultimate Tensile Strength and Yield Strength

ASTM A370 describes approximate correlation between hardness and ultimate tensile strength for various metals. It is recommended that specific material relations be adjusted for each steel composition, heat treatment and part. During the inspection outage, the rotor discs are individually measured for chemistry to confirm that the alloys are within the same statistical family, normally NiCrMoV for nuclear LP rotors. Hardness is measured for each disc using portable testers.

Hardness (Ld) versus ultimate tensile strength and yield strength was developed from scrap GE rotors and replacement SWPC discs, using the following sources:

- 6 discs from governor end of a scrap GE rotor for rim properties
- 6 discs from generator end of a scrap GE rotor for both rim and deep-seated properties
- 11 discs from SWPC refurbished GE rotors for rim properties
- 3 discs from SWPC refurbished GE rotors for both rim and deep-seated properties

Correlations developed from this data are:

<u>Ultimate Tensile Strength (UTS)</u>

UTS = [ ] b, c

S=4.92462 R-Sq=75% R-sq(adj)=73.7%

Statistically, this equation gives a reasonable correlation of hardness to UTS.

<u>Yield Strength (YS)</u>

YS = [ ] b, c

S=2.12916 R-Sq=98.7% R-Sq(adj)=98.4%

Statistically, this equation gives a strong correlation between UTS and YS.

The yield strength correlation is based on the average value of SWPC material data for each disc family in the database. When the residuals for all values in the database are plotted against the values predicted by the regression equation for YS, the standard deviation (S) becomes 4.15.

3.2 Critical Crack Size

3.2.1 Crack Branching and Aspect Ratio

Stress corrosion cracking in turbine discs has been found to have multiple, irregularly branched cracks as described in Reference 3. This finding in conjunction with the shape factor causes a reduction in stress intensity.

Westinghouse Probabilistic Method

The Westinghouse method is described in Reference 5. The general equation for critical crack size a_{cr} (inch) is:

$$a_{cr} = \left(\frac{Q}{1.21 * \pi}\right)\left(\frac{K_{IC}}{\sigma}\right)^2$$

To incorporate variability, the quantity G is introduced that includes the affect of both the shape factor and the branching factor, where:

$$a_{cr}^* = \left(\frac{1}{1.21 * \pi}\right)\left(\frac{K_{IC}}{\sigma}\right)^2$$

and

$$a_{cr} = G\left(a_{cr}^*\right)$$

The variation in G is a uniformly distributed random variable on the range of 1 to 2 that reflects only one of the effects of flaw shape and branching for conservatism even though they may both exist.

Siemens Probabilistic Method

The Siemens method is described in Reference 9. The stress intensity factor is given by:

$$a_{cr} = \left[\left(\frac{Q}{1.21 * \pi}\right)\left(\frac{K_{IC}}{k/K * \sigma}\right)^2\right] - \left(\frac{d}{2}\right)$$

The factor Q is assumed to be uniformly distributed between 0.77 to 2.2, which represents cracks with aspect ratios (depth/length) between 0.0 to 0.5. The (k/K) factor is assumed to be normally distributed with a mean of 0.65 and a standard deviation of 0.175.

Originally the limit of 100-mm (roughly 4 inches) was based on limitations of the a_{cr} equation. Subsequently, after discussion with the staff, the (k/K) factor will be removed from the equation after the crack reaches a 3.0-inch depth, where crack branching is very unlikely. This adjustment is consistent with the approach used in the Westinghouse method.

a_{cr} = Critical crack size
a_{cr}^* = Lower critical crack size
G = Flaw geometry factor
Q = Crack aspect ratio factor
K_{1c} = Fracture toughness
k/K = Crack branching factor
σ = Bore tangential stress
d/2 = Keyway radius, where applicable

3.2.2 Crack Growth Models

There are three models for predicting crack growth rate. The Westinghouse model was proposed in Reference 3 in 1981 and has been adjusted over the years as more data has been developed. The variability of the rate is discussed in Reference 5. The Westinghouse model was compared to GE rates for a sample unit and found to be consistent. The standard deviation for crack growth rate for the Westinghouse method is 0.651 and for the Siemens method 0.587, as stated in Reference 12. The other models are not published but include a GE model and a Siemens model. A comparison of the crack growth models is presented in Figure 12 of Reference 9.

3.2.3 Shrink Fit and Bore Stress Calculation

SWPC is replacing discs on multiple GE rotors as part of a refurbishment program. Shrink fit was measured after the existing discs were de-stacked from the rotor. The results of the measurements are shown in Table 3.1 for discs #3-7. Discs #1 and 2 because they operate dry and have not experienced cracking, are not replaced; hence there are no measurements.

		Bore Stress (ksi)	
Disc	Nominal Radial Shrink Fit (inch)	Preliminary Calculations	Final FEA Calculations
1	Not available	[ ] b, c	[ ] b, c
2	Not available	[ ] b, c	[ ] b, c
3	[ ] b, c	[ ] b, c	[ ] b, c
4	[ ] b, c	[ ] b, c	[ ] b, c
5	[ ] b, c	[ ] b, c	[ ] b, c
6	[ ] b, c	[ ] b, c	[ ] b, c
7	[ ] b, c	[ ] b, c	[ ] b, c

Table 3.1 Measured Shrink Fits and Resulting Bore Stresses

In preliminary calculations a sensitivity study of shrink fit on calculated bore stress was performed considering shrink fits of [ ] b, c with the measured disc dimensions from on-site inspection of the rotors. In Table 3.1, calculated bore stresses in the range of [ ] b, c ksi are inline with published bore stresses of 40 to 55 ksi on GE rotors as documented by EPRI (Reference 16). For discs #1, 2, 6 and 7, bore stresses of [ ] b, c ksi were initially assumed in the preliminary calculations submitted to the NRC.

The effect of bore stress on critical crack size is given by equation 2 of Reference 3, page 6. Higher bore stress results in smaller critical crack size. The smaller the resulting critical crack size, all other things being equal, the higher is the probability of a missile over time.

To assess the impact of bore stress on missile probability as a function of operating hours, another sensitivity was performed for disc #3, the most critical disc, at rated speed. The results are shown in Figure 3.1 at bore stresses of 40, 50, and 60 ksi. The results show that in the range of 40 to 60 ksi, missile probability is not very sensitive to bore stress. For bore stress greater than 60 ksi, the probability of a missile began to increase significantly.

Another investigation was made to assess at what speed the disc shrink fit was lost with the rotor. In Westinghouse rotors, the discs are designed to maintain [ ] [b, c]% shrink fit at 120% design overspeed. In our investigation of the GE rotors, we found that shrink fit was maintained to about [ ] [b, c]% of rated speed for discs #1-4, about [ ] [b, c]% for disc #5 and about [ ] [b, c]% for discs #6 and 7 at the back end.

[

] [b, c]

Figure 3.1 Bore Stress vs. Missile Probability Sensitivity

For the particular GE rotor of interest,
[ ] [a]

Final bore stress calculations, which were more recently completed with known shrink fit dimensions, are also summarized in Table 3.1. Final bore stresses reasonably match the initial calculations except for disc 7. The bore stress at disc 7 does not impact missile probabilities because this disc operates at such low temperature at the back end. Its contribution is insignificant.

3.2.4 Fracture Toughness Values

K_{1c} tests are not normally performed on each disc; therefore the value is determined with empirical correlations for Ni-Cr-Mo-V steels using Barsom Rolfe in the upper shelf region and Begley Logsdon below the upper shelf region as described in References 17 and 18 with conservatism added. Relations for this steel have been described in GE's plot of K_{1c} vs. Excess Temperature (T-FATT) where FATT is the 50% Fracture Appearance Transition Temperature based on these correlations and GE data (Figure 3.2 and Reference 17). After discussion with the NRC staff, the standard deviation for K_{1c} will be set to [ ] [b, c] % of the mean value of K_{1c} and the maximum upper shelf K_{1c} will be set at [ ] [b, c] ksi $in^{.5}$ to provide sufficient margin for scatter and uncertainties.

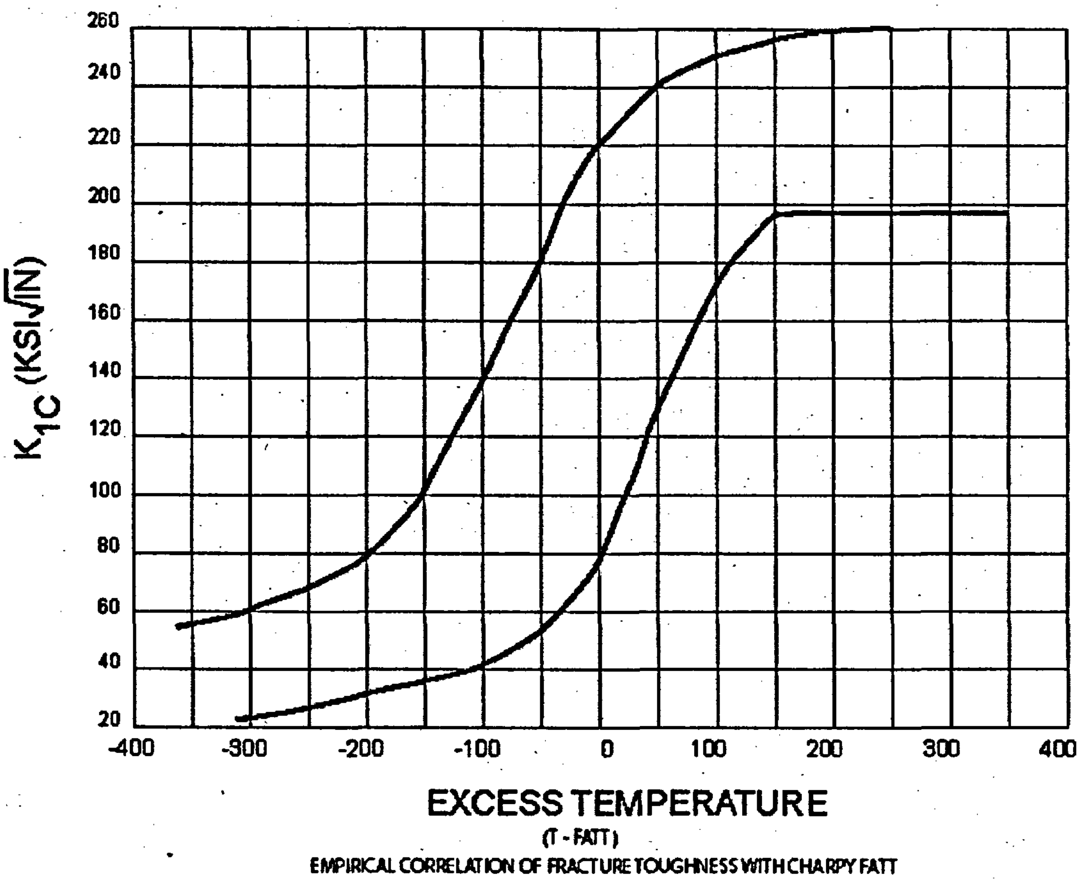

Figure 3.2 Toughness (K_{1c}) versus Excess Temperature

Method when material properties are not available:

The material properties required for P_1 analysis include the following:

- K_{1c}. The size of specimen for K_{1c} requires that it usually be developed through a correlation with an indirect measurement such as Charpy V-notch energy (CVN) or FATT. There are two general correlation procedures, V-notch energy vs. K_{1c} and excess temperature (T-FATT) vs. K_{1c}. Both correlations use the coupons from the actual forgings.

- Ultimate and yield strength: These values are traditionally measured from prolongs as part of the forgings, which are tested in normal tensile testing.

- Available on-site non-destructive testing, which includes chemistry and hardness measurements.

The behavior of low alloy steel (NiCrMoV) for GE rotor wheels is reported in the literature (Reference 17) as a correlation between Excess Temperature and K_{1c}, as shown in Figure 3.2. This relationship was developed by Westinghouse and added to by data from measurements by Westinghouse and other turbine OEMs. Non-destructive chemistry measurements will confirm that the material is NiCrMoV (A471 disc steel) and that it is included in the GE scatter for their type of disc. As discussed previously, a number of GE discs from previously operated GE rotors were sectioned and coupons were tested for critical properties including CVN, FATT, yield and ultimate strength.

Determination of disc by disc relation to the FATT/K_{1c} relationship can be developed from the missile probability and burst probability reports previously issued to the customer by GE using the "Probability of Missile Generation in General Electric Nuclear Turbines" method that was approved by the NRC in 1986. These reports include Table II, Table III, and IV, which are:

Table II – Summary of Missile Probabilities

Table III – Summary of Burst Probabilities

Table IV – Summary of Probability Information for Total Rotor

These reports present probabilities disc by disc for the following variables:

- With and without prewarming. After experiencing disc (or wheel) cracking years ago, GE recommended prewarming of the LP rotors to improve material toughness during startup operation. Prewarming assures metal temperatures of at least 100F.
- Three schedules of valve testing are listed: weekly/monthly/weekly (7/30/7), monthly/quarterly/monthly (30/90/30), and quarterly/quarterly/quarterly (90/90/90).
- Each case has both the missile probability that includes containment probability and the burst probability that does not include containment.

Each disc is checked in the probability of burst tables for both conditions with and without prewarming. Discs will fall into one of two cases: 1) those that fall into the upper shelf region and 2) those that fall below the upper shelf region.

Case 1: Upper Shelf Region

When there is no significant change in probability after prewarming, it can be ascertained that the disc excess temperature falls in the upper shelf region. If a disc is found to fall into this region, an upper shelf toughness value will be used as derived from a statistical distribution.

Case 2: Below Upper Shelf Region

When there is a significant change in probability after pre-warming, it can be ascertained that the disc excess temperature falls below the upper shelf region. For discs that are below the upper shelf region, they fall into the range of the Figure 3.2 curve between the excess temperature of 150 °F and the lower bound temperature of 100 °F, which is the material specification minimum. If any discs are found to fall into this range, their position will be determined by selecting the disc with the greatest change in probability and assuming conservatively that it is at the lower bound value of K_{1c}. The positions of the other discs that fall into this range are then calculated based on [

] [b, c]. A statistical distribution will be applied as in Case 1.

Method if the preheating probabilities are not available:

The distribution will be determined by the probability change across the range of discs correcting for crack growth rate at the operating temperature and bore stress.

Method if no probability reports are available:

In this case a distribution about the lower bound will be used.

3.2.5 Initial Crack Depth

There are two aspects to be considered in UT testing for disc crack indications or flaws. The first aspect is flaw detection and the second aspect is flaw size measurement. As part of the inspection process, the tangential aim procedure is used to detect indications and the radial aim procedure is used to measure the size of indications.

In the Westinghouse UT inspection method (Reference 3), the requirement is that the inspection procedure must detect an indication and size the indication within an uncertainty of 0.06 inch. Operating experience over the last 20 years has upheld this limit. When performing missile analysis, the size of the reported flaw is increased by 0.06 inch to account for this uncertainty.

In the Siemens UT inspection method (Reference 21), the requirement is that the inspection procedure will detect a crack with radial depth as small as 0.5 mm (0.02 inch) and size a crack with radial depth greater than 2.5 mm (0.10 inch). The accuracy of sizing is 3 mm, which means that the true size of a crack could be a maximum 3 mm larger than the size found by UT inspection. When performing missile analysis, an initial crack size of 3 mm (0.12 inch) is assumed in the PDBURST Program input for all discs with no known defects after the initial operating cycle.

4.0 PROBABILITY OF MISSILE GENERATION

The GE probability reports contain tables of both burst probabilities and missile probabilities. Burst probability is the probability that a disc will rupture due to stress corrosion cracking when operated in a wet steam environment under operating temperature and stress conditions. Missile probability is the probability that the disc will rupture and that the resulting fragments will not be contained by the turbine casings surrounding them and thus become liberated. The difference between these values is an adjustment to the probabilities due to casing penetration.

One approach is to use this adjustment to the burst probabilities that gives the impact of being contained. This will be site specific and will derived from the GE missile reports for each individual plant and rotor.

An alternative approach is the use of the PDMISSILE program. This program calculates missile energy at speed and the energy absorbed by blades and deformation of inner and outer casings with friction of these various components. The program requires 26 random variables with 7 major contributors including material properties, dimensions and friction factor.

4.1 Plant Specific Values

Values for tensile strength, fracture elongation, yield strength, and blade or casing materials for various components will be sampled for each individual component by physical measurements of dimensions and hardness for use in PDMISSILE.

1. Ultimate Tensile Strength (UTS): This value will be derived from hardness and chemistry measurements using ASTM A371 to adjust for the specific alloy.
2. Fracture Elongation: This value will be determined from the material specification derived from chemistry measurement of the specific alloy.
3. Yield Strength: This value will be derived from UTS for the specific alloy.
4. Material Volumes: Geometry of the rotor, discs and stationary components will be measured.
5. Section Modulus: This value will be derived from geometry of the rotor, discs and stationary components that will be measured.
6. Mass Moment of Inertia: This value will be derived from measurements of each turbine disc or from identical spare rotors.

4.2 Generic Values

The only generic value in PDMISSILE is friction factor, which is difficult to determine because of rough surfaces. The value to use is somewhat arbitrary and, for conservatism, will be chosen as 0.25.

5.0 PROBABILITY OF DESTRUCTIVE OVERSPEED (P_{10})

The P_1 missile analysis will be performed on GE rotors at customer plants with GE control and protection systems. The GE method was submitted to the NRC in 1984 and approved in 1986. The results of the GE missile analysis reports are provided to the customer in each inspection report and non-proprietary portions are available from the customer. SWPC proposes to use the values from the GE report that are derived from disc burst values at time zero as the P_{10} probabilities. Values at time zero have no stress corrosion cracking impact, so the only remaining part is the P_{10} value for probability of a runaway overspeed incident due to failure of the control and protection system. No changes to any component or control system will be made; therefore, we intend to use this value for each plant specific application.

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

19. Greenberg, H.D, Wessel, E. T., and Pryle, W. H., "Fracture Toughness of Turbine-Generator Rotor Forgings", Westinghouse Research Laboratories, Pittsburgh PA, 15235, USA, 1970.

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21. Jestrich, H. J., Schreiner, T., Hamel, H. J., "Ultrasonic In-Service Inspection of Shrunk-on LP Turbine Discs", Siemens KWU, presented at the Steam Turbine/Generator Workshop (NDE and Life Assessment), Charlotte, NC, July 16-19, 1991.

APPENDIX A

SWPC SUBMITTAL LETTER

MAY 16, 2002

May 16, 2002

United States Regulatory Commission
Document Control Station P1-37
Washington, D. C. 20555-001

Subject: **Missile Analysis Methodology for General Electric (GE) Nuclear Steam Turbine Rotors by Siemens Westinghouse Power Corporation (SWPC).**

Dear Sirs,

Siemens Westinghouse Power Corporation proposes to inspect and perform missile analysis on General Electric low pressure nuclear rotors currently licensed under the United States Nuclear Regulatory Commission. Siemens Westinghouse Power Corporation (SWPC) experience combines the activities of formerly Westinghouse Electric Corporation and Siemens Power Corporation in the inspection for and analysis of rotor missile probabilities. SWPC currently has over 100 nuclear rotors in operation by licensee/users in the U.S.

We request that the NRC provide us with their position on this proposal with required actions if required for SWPC of the licensee/user to adopt this methodology.

SWPC has significant history in the submission and subsequent approval by the NRC of documents relating to the inspection and approval of missile probability analysis and inspection interval calculations since 1981. A list of these documents is shown in figure 1. The reports and approval documents are attachments 1 to 5a. A sample probability analysis report for General Electric rotors is shown in attachment 6. SWPC plans to follow the methodology summarized in this attachment when performing the missile analysis.

Data for the analysis could be retrieved from licensee/user files. If not available, information may be determined by physical measurements and non-destructive chemical measurements and hardness readings. These values can be correlated through relations derived from the database of rotor discs of similar chemistry in SWPC files including SWPC and General Electric records.

If possible, we request an estimate of time and expense for providing a review of our proposal. Your reply to our submittal by June 15, 2002 would be kindly appreciated. Our internal target to begin implementation of this plan is November 2002. Your help in achieving this date would be most helpful.

Sincerely,

Peter Bird

Peter Bird
Field Service
(407) 736-4686

Siemens Westinghouse Power Systems (SWPC) Experience in Missile Analysis and NRC Reviews and Approvals
by
Westinghouse Steam Turbine Generator Division
and
Siemens Power Corporation
Now Organized as a part of Siemens Westinghouse Power Corporation

Attachment 1: Memorandum MSTG-1-P: CRITERIA FOR LOW PRESSURE NUCLEAR TURBINE DISC INSPECTION. Submitted to: NUCLEAR REGULATORY COMMISSION, June 1981.
Attachment 1a: Approval of Westinghouse Method of determining inspection intervals for nuclear LP rotors August 26, 1981.

Attachment 2: Topical Report WSTG-1-P:PROCEDURE FOR ESTIMATING THE PROBABILITY OF STEAM TURBINE DISC RUPTURE FROM STRESS CORROSION CRACKING. SUBMITTED TO: NUCLEAR REGULATORY COMMISSION, May, 1981.

Attachment 3:Topical Report WSTG-2-P-A: MISSILE ENERGY METHODS FOR NUCLEAR STEAM TURBINES. Submitted to: NUCLEAR REGULATORY COMMISSION, May 1981.

Attachment 4:Topical Report WSTG-3-P-A: ANALYSIS OF THE PROBABILITY OF A NUCLEAR TURBINE REACHING DESTRUCTIVE OVERSPEED. Submitted to: NUCLEAR REGULATORY COMMISSION, July 1984

Attachments 2, 3 and 4 include Nuclear Regulatory Approval letter dated February 2,1987.

Attachment 5:Engineering Report ER-9605: MISSILE PROBABILITY ANALYSIS METHODOLOGY FOR LIMERICK GENERATING STATION, UNITS 1&2 WITH SIEMENS RETROFIT TURBINES, REVISION NO. 2, June 18, 1987.

Attachment 5a: Approval letter from Nuclear Regulatory Commission including turbine rotor inspection intervals and valve testing frequencies (TAC NOS. M99341 AND M99342), February 3,1998

Attachment 6: Example of General Electric Missile Probability Analysis, June 7. 1999

<u>APPENDIX B</u>

NRC ACCEPTANCE OF SUBMITTAL LETTER

JULY 22, 2002

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

July 22, 2002

Mr. Peter Bird
Siemens Westinghouse Power Corporation
4400 Alafaya Trail
Orlando, FL 32826-2399

SUBJECT: ACCEPTANCE OF MISSILE ANALYSIS METHODOLOGY FOR GENERAL ELECTRIC (GE) NUCLEAR STEAM TURBINE ROTORS BY SIEMENS WESTINGHOUSE POWER CORPORATION (SWPC) FOR REVIEW (TAC NO. MB5326)

Dear Mr. Bird:

The NRC staff has performed an acceptance review of the missile analysis methodology for GE nuclear steam turbine rotors by SWPC . The NRC staff has found that the material presented is complete enough to begin a review. The staff expects to complete its review by November 11, 2002 and estimates that the review will require approximately 240 staff hours. To enable us to complete the review on this schedule, close and frequent communications between our technical staffs will be required.

Sincerely,

Brian Benney, Project Manager, Section 2
Project Directorate IV
Division of Licensing Project Management
Office of Nuclear Reactor Regulation

Project No. 721

cc: See next page

cc:
Mr. Chuck Patrick, Manager
Steam Turbine Marketing
Siemens Westinghouse Power Corporation
4400 Alafaya Trail, MC653
Orlando, FL 32826-2399

Mr. Stan Dembkowski, Director
Operating Plant Services
Siemens Westinghouse Power Corporation
4400 Alafaya Trail, MC650
Orlando, FL 32826-2399

APPENDIX C

RAI RESPONSES LETTER SUBMITTED OCTOBER 11, 2002

[COPY NOT PROVIDED] [a, b and c]

APPENDIX D

RAI RESPONSES LETTER SUBMITTED NOVEMBER 19, 2002

[COPY NOT PROVIDED] [a, b and c]

APPENDIX E

RAI RESPONSES LETTER SUBMITTED JANUARY 17, 2003

[COPY NOT PROVIDED] [a, b and c]

APPENDIX F

NRC ACCEPTANCE OF SWPC MISSILE ANALYSIS METHODOLOGY ON GE ROTORS, ADAMS ACCESSION NUMBER ML030940400, 2003-04-03

From: Brian Benney
To: Bird Peter
Date: 4/4/03 9:01AM
Subject: RE: NRC Acceptance of SWPC Missile Analysis Methodology on GE Rotors

Peter,

That is correct. I am placing the previous e-mail, and this e-mail into ADAMS (the NRC's publicly available document control system). Once I get a control number, I will e-mail that information to you for your records.

>>> Bird Peter <peter.bird@siemens.com> 04/03/03 04:42PM >>>
Brian,

I would like to document our discussion today and the conclusion reached, since it may be several months before our Topical Report is submitted. This is what I understand we agreed to today:

The NRC has agreed with the summary presented in the e-mail below. No additions or changes were made. The Safety Evaluation (SE) report sent with the cover letter will stand as written. The NRC has asked, when we submit our Topical Report to document this whole process, that we present both the Westinghouse Method and the Siemens Method as agreed to.

Since the SE will not be revised, could you please send me back a brief confirmation of this agreement.

Thanks,
Pete Bird
Siemens Westinghouse

> -----Original Message-----
> From: Bird Peter
> Sent: Thursday, April 03, 2003 9:04 AM
> To: 'BJB@nrc.gov'
> Cc: Barsness Gene; McCracken James; Auman Jim
> Subject: NRC Acceptance of SWPC Missile Analysis Methodology on GE
> Rotors
>
>
> Brian,
>
> Could you please clarify application of the recent NRC acceptance of the
> SWPC missile analysis methodology on GE rotors provided in References 1
> and 2.
>
> In the Preface to Reference 3, SWPC stated "we have decided not to pursue
> the methodology described in Attachment 6 but, instead, to return to the
> traditional methodologies previously reviewed and approved by the NRC".
> These two methodologies are:
>
> 1. The Westinghouse Method, which was submitted during the 1981 through
> 1984 period and approved by the NRC in 1987 (Attachments 1-4).
>
> 2. The Siemens Method, which was submitted in 1997 and approved on a plant

> specific basis by the NRC in 1998 (Attachments 5 and 5a).
>
>
> Our understanding is that the Westinghouse Method for missile analysis is
> accepted by the NRC for use on GE rotors as limited by the criteria given
> in Reference 2, Sections 3.1.4 (Fracture Toughness Values) and 3.1.5
> (Shrink Fits).
>
> Our understanding is that the Siemens Method for missile analysis is
> accepted by the NRC for use on GE rotors as limited by the criteria given
> in Reference 2, Sections 3.0 and 4.0.
>
> It is SWPC's intention to be able to apply either the Westinghouse Method
> or the Siemens Method when performing P1 calculations on GE rotors. Would
> you please confirm that our understanding is correct or advise otherwise?
> Should Reference 2 be revised to make this understanding clearer? Please
> advise.
>
> Thanks,
> Pete Bird
>
>
> References:
> 1) Letter from Herbert N. Berkow (NRC) to Stan Dembkowski (SWPC) dated
> April 2, 2003 (TAC No. MB5679)
> 2) Safety Evaluation by the Office of Nuclear Reactor Regulation, Siemens
> Westinghouse Topical Report "Missile Analysis Methodology for General
> Electric (GE) Nuclear Steam Turbine Rotors by the Siemens Westinghouse
> Power Corporation (SWPC), Project No. 721
> 3) SWPC letter to NRC dated October 11, 2002 in response to RAI Questions
>

CC: Brian Benney

SIEMENS WESTINGHOUSE POWER CORPORATION
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..TI-MISSILE ANALYSIS METHODOLOGY FOR GE NUCLEAR STEAM TURBINE ROTORS BY THE SWPC.
..DA-030731.
..PA- 51 p. 21 refs. 4 Illus.
..DT-REPORT.
..KW-MISSILE. GENERAL ELECTRIC. NUCLEAR. LP ROTORS. NRC.
..AB- This report describes methods of calculating probability of missile generation (P_1) for General Electric (GE) Nuclear LP rotors by Siemens Westinghouse Power Corporation (SWPC). Both Siemens and Westinghouse had developed NRC approved methodologies for calculating probability of missile generation previous to this acquisition. While the methods are similar, the Westinghouse method has been applied to Westinghouse manufactured turbines and the Siemens method has been applied to both Siemens and General Electric turbines. The missile analysis methodology described in this report can be applied to GE nuclear steam turbine rotors using either of the traditional Westinghouse or Siemens methods.

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