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,

/RA/

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

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

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Enclosures: 1. Proprietary Safety Evaluation
2. Non-proprietary Safety Evaluation

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*Concurrence provided by memo from Richard Barrett to Brian Sheron dated March 26, 2003

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cc w/enclosure 2:

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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 TECHNICAL EVALUATION

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_{Ic}) tests are not normally performed for turbine disks, the Westinghouse methodology obtained K_{Ic} 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_{Ic} values for turbine disks in its proposed turbine missile methodology. In response to the NRC staff's concerns regarding the determination of K_{Ic} 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_{Ic} 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_{Ic} 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_{Ic} is large enough to account for the scatter and uncertainties associated with limited test data and whether a randomly selected K_{Ic} 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_{Ic} value as the standard deviation and use a value of **[ ]** ksi$\sqrt{}$in for the maximum upper-shelf mean K_{Ic} value in its disk burst analysis. The staff considers these values to be acceptable because the same standard deviation for K_{Ic} and the maximum upper-shelf mean K_{Ic} 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_{3r} 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_{1o} 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_{1o} 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_{1o} calculation methods. Although the Siemens and the Westinghouse P_{1o} values from this study are for different rotors, the NRC staff still considers the Siemens method to be more conservative because the Siemens P_{1o} 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