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Your ref: Docket No. 52-006
Our ref. DCP/NRC1570

April 10, 2003

SUBJECT: Transmittal of Westinghouse Documents, "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines," WCAP-15783-P, Rev. 1 (Proprietary) and WCAP-15783-NP, Rev. 1 (Non-proprietary) dated April 2003

Attached please find proprietary and non-proprietary versions of Revision 1 of WCAP-15783, "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines." This report has been revised consistent with the revised response to NRC RAI 251.026 that was transmitted to the NRC in Westinghouse letter DCP/NRC1556 dated March 25, 2003.

The Westinghouse Electric Company Copyright Notice, Proprietary Information Notice, Application for Withholding, and Affidavit are also attached to this submittal letter as Enclosure 1. Attachment 1 contains Westinghouse proprietary information consisting of trade secrets, commercial information or financial information which we consider privileged or confidential pursuant to 10 CFR 2.790. Therefore, it is requested that the Westinghouse proprietary information attached hereto be handled on a confidential basis and be withheld from public disclosures. Attachment 2 contains no proprietary information.

This material is for your internal use only and may be used for the purpose for which it is submitted. It should not be otherwise used, disclosed, duplicated, or disseminated, in whole or in part, to any other person or organization outside the Commission, the Office of Nuclear Reactor Regulation, the Office of Nuclear Regulatory Research and the necessary subcontractors that have signed a proprietary non-disclosure agreement with Westinghouse without the express written approval of Westinghouse.

DO63

April 10, 2003

Correspondence with respect to the application for withholding should reference AW-03-1626, and should be addressed to Hank A. Sepp, Manager of Regulatory Compliance & Plant Licensing, Westinghouse Electric Company, P.O. Box 355, Pittsburgh, Pennsylvania, 15230-0355.

Please contact me if you have questions regarding this submittal.

Very truly yours,



M. M. Corletti
Passive Plant Projects & Development
AP600 & AP1000 Projects

/Enclosure

1. Westinghouse Electric Company Copyright Notice, Proprietary Information Notice, Application for Withholding, and Affidavit AW-03-1626

/Attachments

1. WCAP-15783-P, Rev. 1, "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines," dated April 2003, Proprietary Class 2
2. WCAP-15783-NP, Rev. 1, "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines," dated April 2003, Non-Proprietary Class 3

April 10, 2003

Enclosure 1

Westinghouse Electric Company
Copyright Notice, Proprietary Information Notice, Application for Withholding,
and Affidavit AW-03-1626



Westinghouse Electric Company
Nuclear Power Plants
P.O. Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

April 10, 2003

AW-03-1626

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555

ATTENTION: Mr. John Segala

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

SUBJECT: Transmittal of Westinghouse Revised Proprietary Class 2 and Non-Proprietary Class 3 versions of Document: "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines" (WCAP-15783-P & WCAP-15783-NP)

Dear Mr. Segala:

The application for withholding is submitted by Westinghouse Electric Company, LLC ("Westinghouse") pursuant to the provisions of paragraph (b)(1) of Section 2.790 of the Commission's regulations. It contains commercial strategic information proprietary to Westinghouse and customarily held in confidence.

The proprietary material for which withholding is being requested is identified in the proprietary version of the subject documents. In conformance with 10 CFR Section 2.790, Affidavit AW-03-1626 accompanies this application for withholding setting forth the basis on which the identified proprietary information may be withheld from public disclosure.

Accordingly, it is respectfully requested that the subject information which is proprietary to Westinghouse be withheld from public disclosure in accordance with 10 CFR Section 2.790 of the Commission's regulations.

Correspondence with respect to this application for withholding or the accompanying affidavit should reference AW-03-1626 and should be addressed to the undersigned.

Very truly yours,

A handwritten signature in cursive script, appearing to read 'M. M. Corletti'.

M. M. Corletti
Passive Plant Projects & Development
AP600 & AP1000 Projects

/Enclosures

COMMONWEALTH OF PENNSYLVANIA:

SS

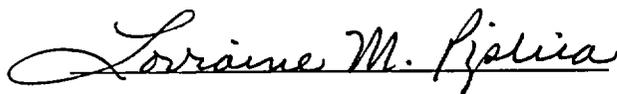
COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared James W. Winters, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company, LLC ("Westinghouse"), and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

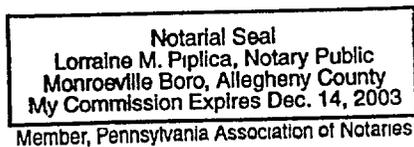


James W. Winters, Manager
Passive Plant Projects & Development
Nuclear Power Plants Business Unit
Westinghouse Electric Company, LLC

Sworn to and subscribed
before me this 10th day
of April, 2003



Notary Public



- (1) I am Manager, Passive Plant Projects & Development, in the Nuclear Power Plants Business Unit, of the Westinghouse Electric Company LLC ("Westinghouse"), and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rulemaking proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Electric Company, LLC.
- (2) I am making this Affidavit in conformance with the provisions of 10 CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.
- (3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Electric Company, LLC in designating information as a trade secret, privileged or as confidential commercial or financial information.
- (4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.
 - (i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.
 - (ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

- (a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.
- (b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.
- (c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.
- (d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.
- (e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.
- (f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

- (a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.
- (b) It is information which is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.
- (c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

- (d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.
 - (e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.
 - (f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.
- (iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10 CFR Section 2.790, it is to be received in confidence by the Commission.
 - (iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

The proprietary information sought to be withheld in this submittal is that which is appropriately marked in Attachment 1 as Proprietary Class 2 in the Westinghouse document DCP/NRC1570 for submittal to the Commission: (1) "Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines".

This information is being transmitted by Westinghouse's letter and Application for Withholding Proprietary Information from Public Disclosure, being transmitted by Westinghouse Electric Company (W letter AW-03-1626) and to the Document Control Desk, Attention: John Segala, DIPM/NRLPO, MS O-4D9A.

This information is part of that which will enable Westinghouse to:

- (a) Provide documentation supporting determination of APP-GW-GL-700, "AP1000 Design Certification Document," analysis on a plant specific basis
- (b) Provide the applicable engineering evaluation which establishes the Tier 2 requirements as identified in APP-GW-GL-700.

Further this information has substantial commercial value as follows:

- (a) Westinghouse plans to sell the use of similar information to its customers for purposes of meeting NRC requirements for Licensing Documentation.
- (b) Westinghouse can sell support and defense of AP1000 Design Certification.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar methodologies and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended for performing and analyzing tests.

Further the deponent sayeth not.

Copyright Notice

The documents transmitted herewith each bear a Westinghouse copyright notice. The NRC is permitted to make the number of copies of the information contained in these reports which are necessary for its internal use in connection with generic and plant-specific reviews and approvals as well as the issuance, denial, amendment, transfer, renewal, modification, suspension, revocation, or violation of a license, permit, order, or regulation subject to the requirements of 10 CFR 2.790 regarding restrictions on public disclosure to the extent such information has been identified as proprietary by Westinghouse, copyright protection notwithstanding. With respect to the non-proprietary versions of these reports, the NRC is permitted to make the number of copies beyond these necessary for its internal use which are necessary in order to have one copy available for public viewing in the appropriate docket files in the public document room in Washington, DC and in local public document rooms as may be required by NRC regulations if the number of copies submitted is insufficient for this purpose. Copies made by the NRC must include the copyright notice in all instances and the proprietary notice if the original was identified as proprietary.

Proprietary Information Notice

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

Docket No. 52-006

DCP/NRC1570

April 10, 2003

Attachment 1

**WCAP-15783-P, Rev. 1, "Analysis of the Probability of the Generation of Missiles
from Fully Integral Nuclear Low Pressure Turbines"**

Westinghouse Non-Proprietary Class 3

WCAP-15783-NP
Revision 1

April 2003

Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines



WCAP-15783-NP
Revision 1

Analysis of the Probability of the Generation of Missiles from Fully Integral Nuclear Low Pressure Turbines

Mitsubishi Heavy Industries, Ltd.

April 2003

Reviewer: 
D. F. Hutchings
Passive Plant Projects and Development

Approved: 
J. W. Winters, Manager
Passive Plant Projects and Development

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1 ABSTRACT

The purpose of this report is to analyze the probability of the generation of missiles from fully integral nuclear low pressure rotors.

The potential for rotor bursting is analyzed for AP1000 low pressure turbine rotors. Four failure mechanisms are evaluated: destructive overspeed, high cycle fatigue, low cycle fatigue, and stress corrosion.

Stress corrosion is found to be the dominant mechanism for determining the potential for missile generation. Analyses show that the probability of a rotor burst by this mechanism does not exceed 10^{-5} even after []^{b,c} years of running time. Therefore, it is concluded that periodic in-service inspections are not required for fully integral nuclear low pressure rotors to meet NRC safety guidelines.

2 INTRODUCTION

A typical steam turbine for modern nuclear power stations consists of a double-flow high pressure element and two or three double-flow low pressure elements in tandem, as shown in Figure 2-1. The rotor of the high pressure element generally consists of a single monoblock forging with blades attached in a fashion dependent upon the specific manufacturer's preference. Until recently, the large size of nuclear low pressure rotors has necessitated that they be constructed by building together a number of individual disc forgings. One typical construction method utilizes individual discs that are shrunk on and keyed to a central shaft.

Advances in the steel making industry have extended the capability to produce large ingots and forgings, and have removed the size restrictions on low pressure rotor designs. Turbine designers recognize the advantages of this new technology, and fully integral nuclear LP rotors are now designed and manufactured. Fully integral rotors are applied to LP rotors for AP1000.

The purpose of this report is to assess the integrity and safety of the AP1000 fully integral LP rotor designs to establish requirements on the nature and frequency of in-service rotor inspections. This assessment is accomplished by evaluating the possibility of a rotor fracture, which leads to bursting and the generation of missiles. Where possible, the probability of a rotor burst is determined directly.

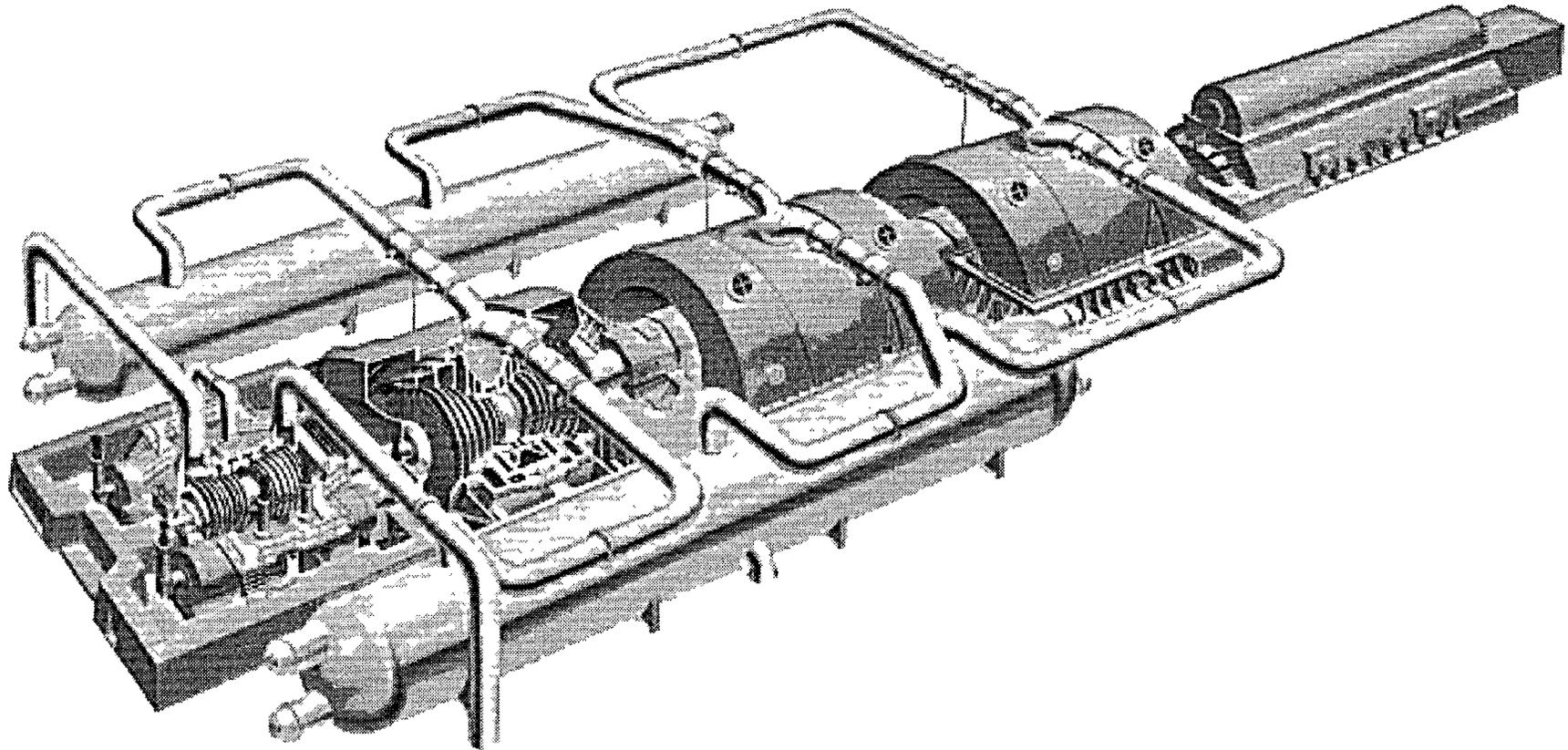


Figure 2-1 Typical Turbine Installation

3 DESIGN FEATURES

A typical fully integral rotor construction is shown in Figure 3-1. A major advantage of this design compared with built-up rotors is the elimination of the disc bores and keyways. Rotors with shrunk-on discs have peak stresses at locations where the discs are keyed to the shaft. The elimination of these regions has transferred the location of peak stress from the keyways to the lower stressed blade fastening regions. To further reduce peak stresses, the blade grooves in fully integral rotors are machined with []^{b,c}. These grooves have reduced the rotor peak stresses significantly. Since the regions of peak stress are the locations where cracks are likely to initiate, this large reduction in peak stresses leads to significant reductions in the probability of a rotor burst.

An additional, equally important, benefit derived from the peak stress reductions achieved in fully integral rotors is that lower stress levels permit the use of lower strength materials while maintaining traditional factors of safety. The fully integral rotor designs utilize forgings heat treated to minimum yield strengths of []^{b,c}, depending upon the requirements of the particular application. Many years of experience and testing of the 3.5% Ni-Cr-Mo-V alloy steel rotor material have demonstrated that the ductility, toughness, and resistance to stress corrosion cracking increase as the yield strength is decreased. These benefits give additional reductions of the probability of rotor fracture.

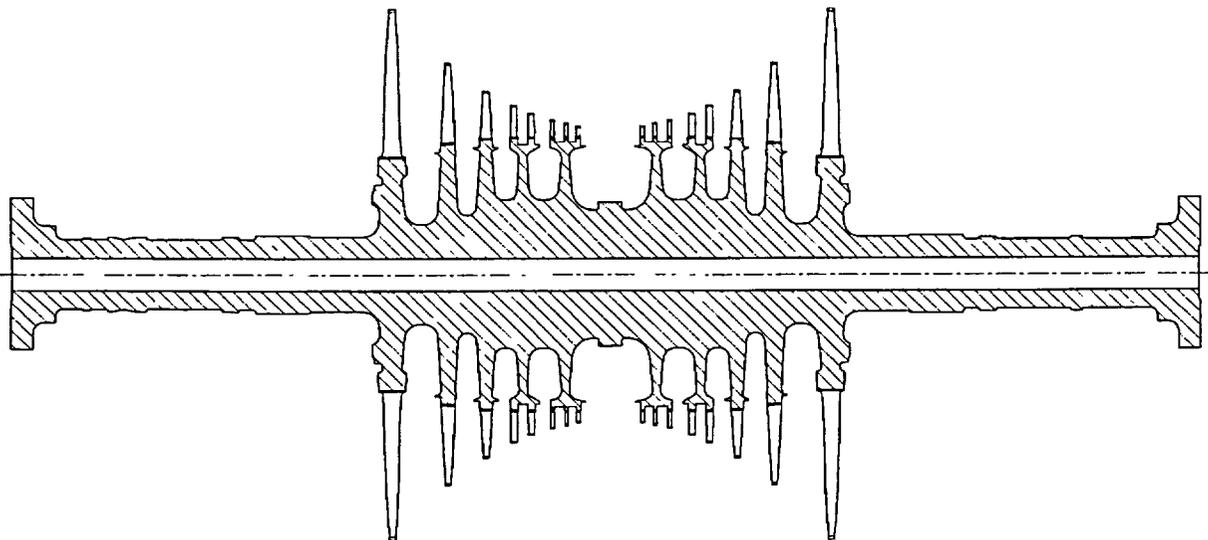


Figure 3-1 Typical Fully Integral Rotor Construction

3.1 MATERIAL FEATURES

In addition to the increased capability to manufacture very large rotor forgings, improvements in steel making practices have resulted in products with improved toughness, uniformity of properties and reductions in undesirable embrittling elements. Specifications written for fully integral rotors incorporate these enhancements.

To confirm uniformity, the specifications for fully integral nuclear rotors require testing at the locations shown in Figure 3-2. Using these specimens, tensile test, impact test, and K_{IC} measurements are performed and are used to confirm conformity to specification requirements.

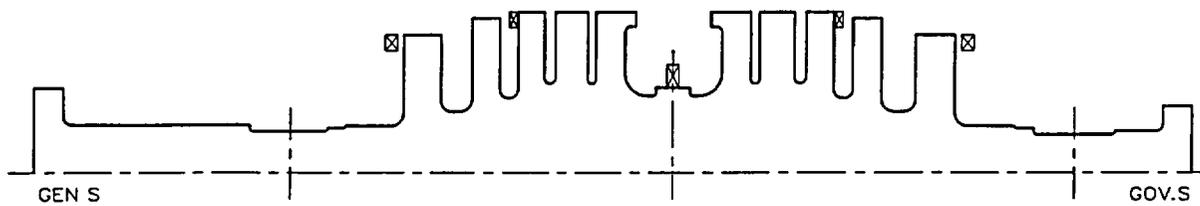


Figure 3-2 Typical Fully Integral Rotor Test Locations

4 PROBABILITY OF MISSILE GENERATION

To assess the probability of missile generation resulting from the bursting of a fully integral nuclear low pressure rotor, four potential failure mechanisms are considered:

1. Ductile burst from destructive overspeed.
2. Fracture resulting from high-cycle fatigue cracking.
3. Fracture resulting from low-cycle fatigue cracking.
4. Fracture resulting from stress corrosion cracking.

For purposes of this report, a rotor burst is considered sufficient to create a missile although it is recognized that the turbine casing offers resistance to the creation of external missiles. The methodology and results for each of the failure mechanisms analyzed are discussed in the following sections.

4.1 DUCTILE BURST FROM DESTRUCTIVE OVERSPEED

Tests have been performed by a number of investigators in which model turbine discs have been spun to failure. The results demonstrate that ductile failure can be predicted by assuming that at burst; the average tangential stress is equal to the tensile strength of the disc. By knowing the stress required for failure it is possible to calculate the speed at which failure would occur. This has been accomplished using a finite difference analysis method, [

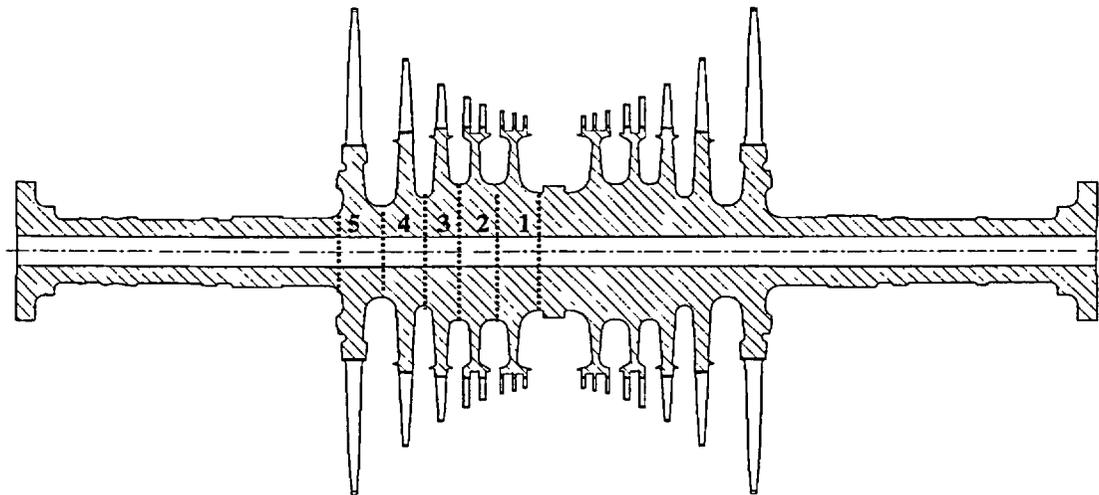
] ^{b,c}, which calculates the average tangential stress at any given speed. For this analysis, the integral rotor body is treated as individual discs as shown in Table 4-1. To be conservative, it is assumed that failure occurs when the average tangential stress in any individual disc equals the [] ^{b,c} of that disc, rather than the tensile strength.

The results of this analysis are summarized in Table 4-1. From this analysis, we conclude that ductile bursting of the rotor will not occur until the speed of the rotor is increased to greater than [] ^{b,c} % of rated speed, even when evaluated conservatively using [] ^{b,c}. Since this is well beyond the design overspeed, the rotor cannot fail by this mechanism unless the [] ^{b,c} fails to function. Therefore, the probability of this event is determined by the [] ^{b,c}, and periodic rotor inspections have no effect on the probability of failure by this mechanism.

Table 4-1 Fully Integrals Rotor Safety Factors Considering Ductile Bursting

Disc	Temp (°C)	Bore Yield Strength At Temp (MPa)	Avg. Tang. Stress at Rated Speed (MPa)	Safety Factor	$\frac{\text{Burst Speed}}{\text{Rated Speed}}$
				$\frac{\text{Bore Y.S.}}{\text{Avg. Tang Stress}}$	$\sqrt{\frac{\text{Bore Y.S.}}{\text{Avg. Tang Stress}}}$
1					
2					
3					
4					
5					

b,c



4.2 FRACTURE RESULTING FROM HIGH CYCLE FATIGUE CRACKING

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 since:

1. Large safety factors used in the design minimize the initiation and propagation of a fatigue crack.
2. A large transverse crack will create an eccentricity and the resulting high vibrations will cause the unit to be removed from service before fracture occurs.

However, to assure that rotor burst by this scenario will not occur during service operation, the following were evaluated:

1. Strength over stress ratios,
2. The likelihood of formation of a high-cycle fatigue crack, and
3. The propagation of a pre-existing crack by high-cycle fatigue.

Strength to stress ratios and the likelihood of initiating a high cycle fatigue crack are evaluated by comparing the magnitude of the bending stress with the failure stress, σ_{fail} , obtained from a Goodman Diagram and reduced to account for size effects. The safety factors obtained for three representative, sample rotors are presented in Table 4-2. From this table, it is seen that the minimum safety factor at location []^{b,c} is more than 3.0 in all three rotors. Therefore, from the viewpoint of crack initiation, these rotors have sufficient strength against high-cycle fatigue fracture.

The propagation of a postulated pre-existing crack is evaluated as follows:

The rotors have the threshold stress intensity range, ΔK_{th} , for fatigue crack propagation that is obtained from the relation:

$$\Delta K_{th} = F \cdot \Delta\sigma \sqrt{\pi \cdot a} \quad (4.1)$$

where $\Delta\sigma$ is the alternating bending stress, and a is the existing crack size. The flaw shape parameter, F , is obtained from the equation below:

$$F = \sqrt{Q/1.21} \quad (4.2)$$

where Q , which is determined by assuming semi-elliptical crack at the material surface, and where a depth to length ratio of about []^{b,c} is applicable $Q = []$ ^{b,c}.

It is conservatively assumed that the threshold stress intensity range, ΔK_{th} , is 2.5 MPa*m^{1/2} (general alloy steel) and the minimum allowable crack size, a_{min} , is []^{b,c} mm (the assumed maximum undetectable crack size) leads to estimation of the minimum allowable vibration stress, $\Delta\sigma_{al}$, as:

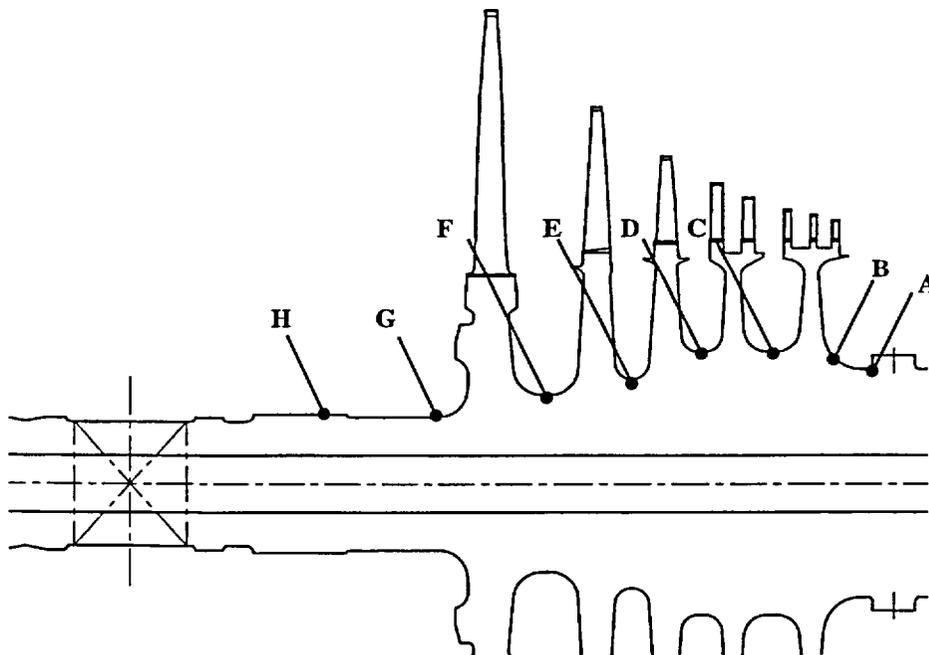
$$\Delta\sigma_{al} = \Delta K_{th} \cdot \sqrt{\frac{1.21}{Q \cdot \pi \cdot a_{min}}} = []^{b,c} \quad (4.3)$$

When compared to the peak stress on Table 4-2, it can be seen that all of the peak stresses, $\Delta\sigma_{peak}$, are well below $\Delta\sigma_{al} = []^{b,c}$. This shows that the rotors have a safety margin on the propagation of a postulated pre-existing crack.

From the above analyses, it is seen that the rotors have large safety factors against high-cycle fatigue. Therefore, concerned with the AP1000 low pressure rotors, periodic in-service inspections for transverse fatigue fractures are not required.

Table 4-2 High Cycle Fatigue Peak Alternating Stresses and Safety Factors								
Location	A	B	C	D	E	F	G	H
$\Delta\sigma_{fail}$, MPa								
LP-1								
LP-2								
LP-3								
$\Delta\sigma_{peak}$, MPa								
LP-1								
LP-2								
LP-3								
Safety Factors								
LP-1								
LP-2								
LP-3								

b,c
 b,c
 b,c



4.3 FRACTURE RESULTING FROM LOW-CYCLE FATIGUE – STARTUP/ SHUTDOWN CYCLES

An analysis was carried out to determine the probability of turbine missile generation due to a startup/shutdown cycle fatigue crack growth. In this postulated scenario, the failure mechanism is a brittle fracture, where a crack initiates in an axial-radial plane at the bore of a fully integral rotor and grows to a critical size as result of speed cycling during the operating life of the turbine.

The probability that such a failure will occur depends on the magnitudes of and interrelationships among the following six factors:

1. The size of cracks in the bore at the beginning of turbine operation
2. The shape of these cracks
3. The size of the critical crack (dependent on the stresses experienced at running speed or design overspeed and toughness of the rotor)
4. The magnitude of the range of stress cycles experienced during the operation of machine
- 5&6. The two parameters, C_0 and n , in the Paris fatigue crack growth rate equation:

$$\frac{da}{dN} = C_0 (\Delta K)^n \quad (4.4)$$

where da/dN is the crack growth rate (per cycle), ΔK the stress intensity range, and n and C_0 are parameters of the fatigue crack growth rate equation which are determined experimentally.

These factors are related to the number of cycles for failure, N_f , by the equation:

$$N_f = \frac{2}{(n-2) \cdot C_0 \cdot M^{n/2} \cdot \Delta\sigma^n} \left(a_i^{-(n-2)/2} - a_{cr}^{-(n-2)/2} \right) \quad (4.5)$$

where

- N_f = The number of cycles to reach critical crack size
- M = $1.21 \cdot \pi/Q$, Q being the flaw shape parameter
- a_i = Initial largest crack depth
- a_{cr} = Critical crack depth
- $\Delta\sigma$ = Range of stress cycles in operation.

To estimate the probability of a failure by this scenario, []^{b,c} factors, described in the previous paragraphs, are considered []

[]^{b,c}. The probability distributions of the []^{b,c} variables []^{b,c} are then taken as follows:

- Q : []^{b,c} over []^{b,c}
- a_i : []^{b,c} over []^{b,c} (mm), the maximum undetectable crack size
- a_{cr} : []^{b,c} over, a_{cr} where a_{cr} = []^{b,c} mm for running speed.
- Δσ : []^{b,c} over []^{b,c} MPa for Running speed and Designed Over speed.
- C₀ : []^{b,c} with a mean of []^{b,c}
- n : []^{b,c} with a mean of []^{b,c}

The flaw shape parameter, Q, is determined by assuming that a semi-elliptical crack, with a depth-to-length ratio of about []^{b,c}, is formed at the bore surface. Such a flaw crack shape parameter would be no more than []^{b,c}, independent of the stress. Therefore, Q is set to []^{b,c}, conservatively.

The critical crack size, a_{cr}, is obtained from the relation:

$$a_{cr} = \frac{Q}{1.21 \cdot \pi} \left(\frac{K_{IC}}{\sigma} \right)^2 \tag{4.6}$$

where K_{IC} is the fracture toughness of the rotor and σ is the stress at operating speed and design overspeed. It is assumed that the stress, σ, is []^{b,c} over []^{b,c} MPa, []^{b,c} MPa, respectively, at running speed and design overspeed of 120%. These values are the sum of rotation stresses plus the maximum anticipated thermal stress during a start-up cycle. Therefore, it is regarded as most conservative value.

The fracture toughness, K_{IC}, is taken to be []^{b,c}, where []^{b,c}

The value of a_{cr} resulting from the use of []^{b,c} for Q, K_{IC}, and, σ may be too conservative. However, as a safety approximation, []^{b,c} was used for a_{cr} with its value determined by the value of Q, K_{IC} and σ.

The size of the initial crack depth, a_i , is taken to be over []^{b,c} mm since the inspection procedures used for fully integral rotor forgings will reliably detect flaws as small as []^{b,c} mm deep, which is considered with the depth-to-length ratio of about []^{b,c}.

The range of $\Delta\sigma$ is taken from the expected range of stress occurring during a start-up to running speed cycle, considering rotation and thermal stresses as previously discussed.

The probability distributions of the random variables are obtained as follows:

The distribution of C_0 and n were obtained from fatigue crack growth rate data for 3 1/2% Ni-Cr-Mo-V rotor steel, which are presented in Table 4-3, and by taking the logarithm of both sides of equation (4.4). This results in the following:

$$\log \frac{da}{dN} = \log C_0 + n \cdot \log(\Delta K) \tag{4.7}$$

Equation (4.7) expresses a linear relationship between $\log da/dN$ and $\log (\Delta K)$. Such a linear relation is completely characterized by two parameters, the slope and the intercept. For instance, equation (4.4) for fatigue crack growth rate can be expressed in terms of the slope n and the intercept at the $\Delta K = 1.0$ axis, $\log C_0$. The value of slope n is unique, but the value of intercept depends on the choice of the axis of intercept.

Furthermore, the value of intercept can be greatly influenced by the value of slope n , especially if the axis of intercept is far away from the range of data.

Table 4-3 3 1/2% Ni-Cr-Mo-V Rotor Steel n and C_0 Parameters in the Paris Equation: $\frac{da}{dN} = C_0 (\Delta K)^n$

No.	Data Source	n	C_0 , mm/cycle
1	TEST ROTOR	[]	[]
2	TAKAHAMA 3T LP-2	[]	[]
3	TAKAHAMA 4T LP-1	[]	[]
4	TAKAHAMA 4T LP-2	[]	[]
5	2ART4V	[]	[]

b,c

The probability of failure due to startup/shutdown cycle fatigue crack growth also depends on the number of cycles the turbine will experience during its operating life, as well as the six factors described previously. The actual number of cycles is unknown, but, based on the best available information, an upper bound of []^{b,c} cycles over the life of machine was assumed. However, to assess the sensitivity of the analysis to this assumption, calculations were also made for []^{b,c} cycles.

The probability of the rotor burst by low-cycle fatigue can be expressed as:

$$P_r \left(a_{cr} \leq a(N) \equiv \int_0^N \frac{da}{dN} dN \right) \tag{4.8}$$

where $N = [\quad]^{b,c}$, and the value of a_{cr} is fixed on $[\quad]^{b,c}$ mm, as previously discussed. The propagation size of crack loaded N times cyclic stress is obtained from the following:

$$a(N) = \left[a_i \left(\frac{2-n}{2} \right) - (n-2) \cdot C_0 \cdot \phi \right]^{\left(\frac{2}{2-n} \right)} \tag{4.9}$$

$$\phi = \left(\frac{1.21 \cdot \pi}{Q} \right)^{\frac{n}{2}} \cdot \Delta\sigma^2 \cdot N \tag{4.10}$$

Results are obtained by finding the maximum combination probability of C_0 and n when $a_{cr} \leq a(N)$.

The values of C_0 and n are normally distributed with a mean of $[\quad]^{b,c}$ and with a mean of $[\quad]^{b,c}$. Other parameters are determined conservatively as fixed numbers, and the final results are reported in Table 4-4.

The probability values reported are the largest values among the probability values obtained using various importance densities for C_0 and n , and they are the conditional probabilities meeting the condition that the specified turbine speed condition exists.

Table 4-4 shows that the probabilities of the generation of missiles by this mechanism are extremely low. Therefore, rotor burst by this scenario will not occur.

Table 4-4 Rotor Brittle Rupture Probability Due to Startup/Shutdown Cycle Fatigue Crack Growth		
Probability of Rupture		
Speed Condition	Number of Cycles	
	[] ^{b,c}
Running Speed	[] ^{b,c}
Design Overspeed of 120%	[] ^{b,c}

4.4 FAILURE DUE TO STRESS CORROSION CRACKING

An analysis was performed to determine the probability of a fully integral rotor bursting due to stress corrosion cracking. A crack is assumed to initiate at the rim where the stresses are highest, and propagate radically inward until it reaches the critical crack size for bursting. The probability of rotor fracture due to this failure mechanism is a function of the probability of crack initiation, the rate at which a crack could grow due to stress corrosion, and the critical crack depth that will lead to a burst at either the running speed or the design overspeed. Each of these factors is discussed below.

For this analysis, it is only necessary to consider the []^{b,c} integral discs on the rotor. During operation []^{b,c}, is surrounded with superheated steam. Experience has demonstrated that stress corrosion cracking does not occur in dry steam. Experience with built-up rotors has also shown that the probability of cracking and the crack growth rates of the discs beyond the []^{b,c} are so low that it is not necessary to consider them in determining the probability of bursting.

The probability of missile generation due to stress corrosion crack is obtained from the following equation:

$$P_{SCC} = q_i \cdot q_{cr} \cdot q_{OS} \quad (4.11)$$

where,

q_i is the probability of crack initiation

q_{cr} is the probability of flaw propagation until critical crack size on stress corrosion crack mode

q_{OS} is the probability that the unit will reach design over speed

For conservative evaluation of this probability, it is assumed that q_i , which is the probability of crack initiation, is 100%, even though we have not experienced finding cracks on fully integral nuclear low pressure rotors at inspection, through 2001. Also, q_{OS} is assumed to be 100%, even though it is actually on the order of 10^{-5} , with proper maintenance of the turbine valve and control system. Therefore, the probability of missile generation due to stress corrosion crack is obtained conservatively by this analysis.

Furthermore, we have not experienced stress corrosion cracking on fully integral nuclear low pressure rotors, which are designed with relatively low yield stress materials, $\sigma_{ys} \approx []^{b,c}$ MPa, compared to center shaft built-up rotors, which have keyways. However, this probability analysis due to stress corrosion cracking is based on experimental high yield stress materials data, because it has the same composition, 3 1/2% Ni-Cr-Mo-V rotor steel.

4.4.1 Probability of Crack Initiation

The probability of crack initiation in disc i , q_i , is obtained from inspection records of nuclear turbines with built-up rotors, and is calculated for each disc number within each turbine style. This gives conservative estimates since the built-up rotors have stresses and yield strengths, which are significantly higher than those of fully integral rotors.

Suppose that N number i discs in a particular turbine style have been inspected and a total of K have been found with one or more cracks. We take:

$$[\quad]^{b,c} \quad (4.12)$$

for any number i disc in that particular turbine style.

We have not experienced to finding any cracks during the inspection of 31 existing rotors. However, for conservative estimation, the probability of crack initiation is assumed to be 100%.

4.4.2 Crack Growth Rates

The crack growth rate model used is as follows:

$$[\quad]^{b,c} \quad (4.13)$$

where,

$$[\quad]^{b,c}$$

The actual values used for the parameters on the crack growth rate model are the same as those used for keyway stress corrosion crack growth rate in built-up rotors. These values are:

$$[\quad]^{b,c}$$

$$[\quad]^{b,c}$$

$$[\quad]^{b,c}$$

For []^{b,c} a normal distribution with a mean value of []^{b,c} is used. The distribution of []^{b,c} is obtained from fatigue crack growth rate data for 3 1/2% Ni-Cr-Mo-V rotor steel presented in Table 4-5. These rotors steel have different material strength properties than the AP1000 rotor, but have same composition. So they can be regarded as having the same deviation of term uncertainty on the crack growth rate, []^{b,c}. The methods used to obtain the values of these parameters were described in Reference 7.

The calculations were carried out for the following discs: []^{b,c}, using the maximum numerical average temperatures at the inlet faces of each disc.

Table 4-5 3 1/2% Ni-Cr-Mo-V Rotor Steel Deviation Crack Growth Rate from Calculation			
Data Source	Growth Rate from Calculation *10 ⁻⁴ mm/h	Growth Rate from Experiment *10 ⁻⁴ mm/h	Logarithm Deviation
1	2.5	1.7	0.386
2	4.5	3.4	0.280
3	2.5	1.8	0.329
4	2.4	1.8	0.288
5	2.6	1.8	0.368
6	1.5	1.7	-0.125
7	1.4	1.7	-0.194
8	1.3	2.2	-0.526
9	1.7	2.2	-0.258
10	1.5	2.2	-0.383
11	1.4	2.2	-0.452
12	2.8	2.9	-0.035

4.4.3 Critical Crack Size

The critical crack depths were obtained for []^{b,c} of fully integral rotors, with []^{b,c} yield strength, by using the relationship between fracture toughness and stress intensity. Stress intensity factors were determined at running speed and 120% overspeed. In each case, the influence of thermal stress was included. The thermal stress used was that determined to be the most severe during a transient condition. At running speed, the stress intensity for all crack depths less than the total depth of the disc was well below the fracture toughness. Therefore, it is conservatively assumed that the total depth of the disc is the critical crack depth on running speed. A limit load analysis confirms that ductile fracture of the rotor would not occur under these conditions.

The depth of the disc is taken as the distance between the rim of the disc and the point where it blends into the main body of the rotor.

In determining critical crack size at overspeed, we use the relationship between fracture toughness and stress intensity. The relationship is obtained as follows:

$$K_{IC_SCC} \geq K_I = \Phi \cdot \sigma \sqrt{\pi \cdot a} \tag{4.14}$$

If the above equation can be satisfied, rotor burst will occur by stress corrosion crack growth. Thus, for conservatism, a larger stress, $\sigma' \equiv n \cdot \sigma$, stress at overspeed is utilized as is a smaller critical crack size, a' . Rotor burst is as follows:

$$a' = \frac{K_I^2}{\Phi^2 \cdot \pi} \cdot \frac{1}{\sigma'^2} \equiv \frac{1}{n^2} \cdot a \quad (4.15)$$

The critical size at 120% over speed is:

$$a_{cr_os} = \frac{1}{1.4^2} \cdot a_{cr} \quad (4.16)$$

4.4.4 Numerical Results

With the distributions of crack growth rates and critical crack sizes described in the previous sections, analyses were made to determine the probability that a crack would grow to the critical size within any time interval, t . To get the probability of a rotor bursting, this probability is modified by the number of discs being considered, the probability of crack initiation, and for the design overspeed conditions, the probability that the unit will reach design overspeed.

Since, the probability that the unit will reach design over speed has been unknown, its probability is assumed to be 100% to evaluate the probability of missile generation conservatively.

The final probability values are given in terms of discrete inspection intervals in Tables 4.6 and are shown graphically in Figure 4.1. The results show that the inspection interval needed to satisfy the requirement that the probability of missile generation be less than 10^{-5} per year is []^{b,c} years or more, even with the conservative assumptions incorporated by this analysis.

Table 4-6 Probability of Rotor Rupture Due to Stress Corrosion [] ^{b,c}		
Probability of Rotor Rupture at		
Inspection Interval (yrs)	Running Speed	120% Design Overspeed
12.0	[]	[] ^{b,c}
16.0		
20.0		
24.0		
28.0		
32.0		
36.0		
40.0		



Figure 4-1 Probability of Rotor Rupture Due to Stress Corrosion

5 DISCUSSION AND CONCLUSIONS

Except for the destructive overspeed mechanism, this report demonstrates that the fully integral AP1000 low pressure rotor design is unlikely to generate a missile by any of the mechanisms considered. The probability of reaching destructive overspeed is primarily dependent upon the []^{b,c}. Reference 11 addresses that issue.

The low pressure rotors are not likely to burst as a result of a high-cycle fatigue mechanism since the maximum alternating stress is less than the endurance stress obtained from the Goodman diagram, and their safety factors are greater than 3.0. Additional assurances against bursting by this mechanism are derived from the following:

1. In fully integral rotors, the locations of maximum stress are readily accessible for inspection during normal maintenance.
2. Bursting by this mechanism is unlikely, since the existence of a large transverse crack is detectable by high vibrations due to rotor unbalance.

It is reasonable to eliminate high cycle fatigue as the controlling mechanism for determining in-service inspection intervals.

Analysis of the low cycle fatigue mechanism demonstrates that the probability of failure by this scenario is extremely low, of the order of []^{b,c}, even when utilizing highly conservative assumptions. This is well below NRC accepted guidelines, and periodic in-service inspections for low cycle fatigue cracks will not contribute significantly to improvement in safety. Therefore, low cycle fatigue is also eliminated as the controlling mechanism for determining inspection intervals.

As with previous designs, the potential for stress corrosion cracking has the greatest influence on rotor integrity. However, in fully integral designs, such as that used in the AP1000 low pressure rotors, the probability of failure by this mechanism has been reduced. The analysis shows that []^{b,c} years or more of running time, also utilizing highly conservative assumptions, may elapse before inspection, without exceeding the NRC safety criteria. Considering typical use factors for nuclear turbines, and considering that the crack locations are readily observable during normal turbine maintenance, it is concluded that periodic safety related inspections are not required within expected life of the turbine.

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