

# **Probability of Missile Generation from Low Pressure Turbines**

**Non-Proprietary Version**

**June 2013**

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Revision	Page	Description
2	2-1	<p>The report is revised based on the following NRC comments.</p> <ol style="list-style-type: none"> <li data-bbox="656 338 1451 533">(1) The specific LP rotor material designated as 3.5%-Ni-Cr-Mo-V steel ([ ]) shall be placed in this turbine missile analysis report so that the acceptance criteria of as-built rotor are bounded by the mechanical properties used in this turbine missile analysis.</li> <li data-bbox="656 554 1451 684">(2) The fracture toughness <math>K_{IC}</math> shall be calculated using the possible minimum mechanical properties specified in the purchase specification, which means that <math>K_{IC}</math> shall be calculated using the Upper Self Energy (USE) of [ ].</li> <li data-bbox="656 705 1451 835">(3) A 20 percent margin shall be taken into account for the compensation of the uncertainty of the Begley-Logsdon Method at the calculation of <math>K_{IC}</math> which is to be used in the turbine missile analysis.</li> </ol> <p>The followings are the major parts of this revision 2.</p> <p>The second paragraph is modified as follows.</p> <p><u>“In addition to lower local stress throughout the rotor, the integral structure also has the benefit of reduced average tangential stress of the discs and this fact allows us to thus applying lower yield strength material with traditional safety margins remaining as they are unchanged. Many years of experience and testing of the rotor material have demonstrated better ductility, toughness and resistance to stress corrosion cracking at lower yield strength. These benefits can be important factors in reducing the possibility of turbine missile generation. The integral rotor forgings of the 3.5% Ni-Cr-Mo-V alloy steel [ ] are to be applied to the US-APWR LPT rotors and heat-treated to obtain minimum yield strengths of [ ], Charpy V-notch energy at 21-27 deg.C of [ ], maximum FATT of [ ], and minimum upper shelf energy of [ ], depending upon the requirements of the particular application. Many years of experience and testing the of the 3.5% Ni Cr Mo V alloy steel rotor material have demonstrated better ductility, toughness and resistance to stress corrosion cracking at a lower yield strength. These benefits can be important factors to reduce the possibility of turbine missile generation.”</u></p>

Revision	Page	Description
	2.1-1	<p>The second paragraph is modified as follows.</p> <p><u>“The specification for the integral rotors requires testing at the locations shown in Figure 2.1-1 to confirm uniformity of the rotor.– Using these specimens, the tensile test (tensile strength, yield strength, elongation and area reduction) and Charpy test (Charpy V-notch energy, 50% FATT and upper shelf energy) will impact test (absorbed energy, 50% FATT and upper shelf energy) shall be performed to and confirm that if the required <math>K_{IC}</math> of [ ] and the other mechanical properties used in this report specifications are satisfied.”</u></p>
	3.3-2	<p>The fourth paragraph is modified as follows.</p> <p><u>“The fracture toughness <math>K_{IC}</math> of [ ] is applied on this analysis. The fracture toughness <math>K_{IC}</math> of [ ] was obtained through the Begley-Logsdon Method with a safety margin of 20% using the upper shelf energy of [ ] specified in the purchase specification as a minimum allowable value.”</u></p>
	3.3-2	<p>The sixth paragraph is modified as follows.</p> <p><u>“The stress range of <math>\Delta\sigma</math> is taken to be a combined stress range occurring during a start-up and shut-down considering centrifugal and thermal stresses as previously discussed. conservatively determined to be [ ], respectively at rated speed, trip setting speed and design overspeed. These values are the sum of centrifugal stress and the maximum anticipated thermal stress during start-up cycle. The rotor metal temperature distribution at the rated condition is shown in Figure 3.3-1 for reference.”</u></p>

Revision	Page	Description
	3.3-2	<p>The following sentence is inserted after the third paragraph from the last in Section 3.3.</p> <p><u>“The probability of missile generation due to LCF (<math>P_{LCF}</math>) is calculated using the following equation under the assumption that probability of reaching design overspeed per year is conservatively assumed to be 100% although it is expected to be on the order of <math>10^{-5}</math> with proper inspection and maintenance of the turbine valves and the control system.</u></p> <p>(3.7) <math>P_{LCF} = q_{cr} \cdot q_{os}</math>.</p> <p><u>where,</u></p> <p><math>q_{cr}</math> = <u>the probability of flaw propagation up to critical crack size (<math>a_{cr}</math>) due to LCF,</u></p> <p><math>q_{os}</math> = <u>probability of reaching design overspeed [ _____ ] per year</u></p> <p><u>= assumed to be 100% per year”</u></p>

Revision	Page	Description
	3.3-3	<p>The second paragraph from the last of Section 3.3 is modified as follows.</p> <p><u>“The calculated results in regard to the probability of a LP rotor rupture due to LCF are summarized in Table 3.3-2, which includes three case studies. In each case, the maximum rotating speed during start-up/shut-down is assumed to be 100%, 111% and 120% of rated speed respectively. The 111% overspeed is the trip set point of the overspeed trip device and the 120% overspeed is design overspeed which can only occur when the control system fails to function. Table 3.3-2 shows the probability of rupture at [ ] start-up/shut-downs and the number of start-up/shut-downs at which the probability of rupture reaches the NRC’s guideline of <math>P_1 &lt; 1 \times 10^{-5}</math> per year being specified in SRP 3.5.1.3 (Reference 12), Table 3.5.1.3-1. It should be noted that the margin of [ ] in the number of start-up/shut-down used and listed in the Table 3.3-2 is taken into account for compensating the uncertainty in the variation of the propagation speed of cracks in the rotors. In the Case-2 which assumes maximum rotating speed of 111% of rated speed at every start-up/shut-down and is conservative enough compared to the actual operation of the nuclear units, the number of the start-up/shut-down at the probability of rupture of <math>1 \times 10^{-5}</math> per year is [ ]. Even in the assumption of 120% overspeed at every start-up/shut-down (Case-3), it is demonstrated that the above NRC’s guideline is satisfied in the range up to [ ] start-up/shut-downs while 120% overspeed can only occur with the control system failure. The number of start and stops, at which the crack size is increased up to a critical one, is very large.”</u></p>
	3.3-3	<p>The last paragraph of Section 3.3 is modified as follows.</p> <p><u>“It takes [ ] of start and stops for the initial cracks to grow up to the critical size with their maximum potential, which corresponds even under the assumption of weekly start and stops for [ ] with [ ] overspeed condition. It is concluded that a low pressure rotor rupture due to the LCF can-not actually happen occur before under the postulated plant life actual-plant operation has expired.”</u></p>
	3.3-4	<p>Table 3.3-1 “3.5% Ni-Cr-Mo-V Rotor Steel, n and <math>C_0</math> Parameters in the Paris Equation:” and Table 3.3-2 “Probability of Low Pressure Rotor Brittle Rupture due to Low Cycle Fatigue (start-up/shut-down cycle)” are modified as are shown in Page 3.3-4.</p>

Revision	Page	Description
	3.4-1	<p>The second paragraph is modified as follows.</p> <p>“For this analysis, it is <del>only</del> necessary to consider [ _____ ] on the rotor. [ _____ ] of the LP rotor is exposed to superheated steam and experience has demonstrated that SCC does not occur in dry superheated steam. Experience with built-up rotors has also shown that the probability of cracking and the crack growth rates of the discs beyond the [ _____ ] is so low that it is not necessary to consider them in determining the probability of rotor bursting.”</p>
	3.4-1	<p>The third and fourth paragraph is modified as follows.</p> <p>“The probability of missile generation due to SCC is expressed as follows:</p> $(3.87) \quad P_{SCC} = q_i \cdot q_{cr} \cdot q_{os}$ <p>where, <math>q_i</math> is the probability of crack initiation, <math>q_{cr}</math> is the <u>total</u> probability of flaw propagation up to the critical size by SCC for [ _____ ], and <math>q_{os}</math> is the probability that the unit will reach design overspeed.</p> <p>—For the purpose of conservative evaluation, <del>it is assumed that <math>q_i</math> is assumed regarded to be as 100%.</del> <u>It is noted that this assumption is equivalent to ignoring the incubation period before initiation of SCC cracks propagation. although we have Note that MHI has no experience of finding cracks initiating on the integral low pressure rotors in the inspections of about 40 integral low pressure rotors through until-2012. 2007 The first integral low pressure turbine rotor of the same material was put into commercial operation approximately 20 years ago.</u>”</p>
	3.4-5	<p>Due to the revision of <math>K_{IC}</math> from [ _____ ] to [ _____ ], Table 3.4-2 “Probability of Missile Generation (per year) due to Stress Corrosion Cracking” and Figure 3.4-1 “Probability of Missile Generation (per year) due to Stress Corrosion Cracking” shall be revised as shown on attached on Page 3.4-5.</p>

Revision	Page	Description
	4-1	<p>The second sentence from the last of Section 4.0 shall be modified as follows.</p> <p><u>“Analysis of the LCF mechanism demonstrates that the probability of failure by this scenario is extremely low even under conservative assumptions. [_____]. It is concluded that a low pressure rotor rupture can not happen before [_____], and the NRC safety guidelines can be satisfied by the periodic inspection in a proper interval within [_____]. In the case of assuming maximum rotating speed of 111% of rated speed at every start-up/shut-down cycles and being conservative enough compared to the actual operation of the nuclear units, the number of the start-up/shut-downs at which the probability of rupture reaches the NRC’s guideline of <math>P_1 &lt; 1 \times 10^{-5}</math> per year being specified in SRP 3.5.1.3 (Reference 12), Table 3.5.1.3-1 is [_____]. With the assumption of 120% overspeed at every start-up/shut-down, it is demonstrated that the above NRC’s guideline is satisfied in the range up to [_____] start-up/shut-down while 120% overspeed can only occur with the control system failure. It can be concluded that this number of cycles before the low-pressure rotor rupture probability due to LCF exceeds the NRC guide line is greater than the number of start-up/shut-downs expected to experience in the postulated plant life. Therefore, it is not necessary to take the LCF calculation results into consideration for determining the periodic inspection interval, provided that the life of the low-pressure rotors due to LCF is under the control of the plant license holder.”</u></p>
	4-1	<p>The last paragraph is modified as follows.</p> <p><u>“The SCC has the greatest influence on rotor integrity. The probability of failure by the SCC this mechanism is however significantly reduced by the application of integral rotor design. The analysis shows that a running time [_____] may can elapse before the first inspection without exceeding the above NRC safety guidelines even under highly conservative assumptions would occur. Considering the fact that the most probable crack locations are readily accessible during normal turbine inspections and maintenance, it is concluded from the design view-point considerations show that the NRC safety guidelines can be satisfied by the periodic inspection in a proper interval within [_____].”</u></p>



Revision	Page	Description
	4-1	<p>The following sentences shall be added at the end of Section 4.0.</p> <p><u>“These calculation results demonstrate that the low-pressure rotor inspection before [ ] operation is sufficiently conservative to keep the turbine missile generation probability less than the NRC guideline during operation.”</u></p>
	5-1	<p>Reference No.11 is revised as follows.</p> <p>“MUAP-07029(R3)-P, Proprietary and MUAP-07029(R3)-NP, Nonproprietary, “ Probabilistic Evaluation of Turbine Valve Test Frequency,” Revision 3, June 2013.”</p>
	5-2	<p>Added Reference 12:</p> <p><u>12. U.S. Nuclear Regulatory Commission, Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, NUREG-800, Section 3.5.1.3 Rev.3, March 2007.</u></p>

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## **Abstract**

The purpose of this document and analyses is to show the probability of missile generation from integral low pressure rotors.

Four failure mechanisms are evaluated; destructive overspeed bursting, fracture due to high cycle fatigue, low cycle fatigue and stress corrosion. Stress corrosion cracking was identified as the dominant mechanism in determining the probability of missile generation.

The probability of missile generation by these mechanisms does not exceed  $10^{-5}$  per year before [ ] of running time. It is concluded that the NRC safety guidelines can be satisfied through the periodic inspection in a proper interval within [ ].

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## List of Acronyms

The following list defines the acronyms used in this document.

a	Crack Size in Depth
$a_i$	Initial Critical Crack Size in Depth
$a_{cr}$	Critical Crack Size in Depth
F	Flaw Shape Parameter = SQRT (Q/1.21)
FATT	Fracture Appearance Transition Temperature
HCF	High Cycle Fatigue
$K_{IC}$	Fracture Toughness (of the rotor)
LCF	Low Cycle Fatigue
LPT rotor	Low Pressure Turbine Rotor
MT	Magnetic Particle Test (=surface examination)
N	Number of Cycles (ex. Number of Start & Shut-down)
$N_f$	Number of Cycles of Failure
OS	Over Speed
$P_{LCF}$	Probability of Missile Generation due to LCF
$P_{SCC}$	Probability of Missile Generation due to SCC
$q_i$	Probability of Crack Initiation
$q_{cr}$	Probability of Flaw Propagation up to Critical Crack Size due to LCF or SCC
$q_{OS}$	Probability of Reaching Design Overspeed (120% of rated speed) per year
Q	Flaw Shape Parameter
SCC	Stress Corrosion Cracking
SF	Safety Factor (ex. $\Delta\sigma_{fail} / \Delta\sigma_{peak}$ )
T	Temperature
TS	Tensile Strength
YS	Yield Strength
$\gamma$	Crack Depth Growth Rate
$\epsilon$	Uncertainty Term
$\sigma$	Stress
$\sigma_{fail}$	Failure Stress
$\sigma_{ys}$	Yield Strength
$\Delta\sigma$	Stress Range
$\Delta\sigma_{al}$	Allowable Stress Range
$\Delta\sigma_{fail}$	Failure Stress Range
$\Delta\sigma_{peak}$	Peak (Maximum) Stress Range
$\Delta K$	Stress Intensity Range
$\Delta K_{th}$	Threshold Stress Intensity Range

## 1.0 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. The rotor of the high pressure element generally consists of a single forging with blades being attached in a fashion dependent upon the specific manufacturer's preferences. On the other hand, recently, a larger size of nuclear low pressure rotors has been used integrating the individual shaft and discs. Each disc is usually shrunk on and keyed to the shaft.

Advancement in steel making technologies and facilities mitigated the restriction for the size of high quality ingot and the size of forging in the manufacturing process of low pressure rotors. This advancement made possible the application of the high quality integral low pressure rotor to the nuclear turbine. The advantage of applying integral low pressure rotors, which are to be applied to US-APWR, is discussed in the following sections.

The purpose of this document is to assess the integrity and safety of US-APWR integral LP rotor designs in order to establish requirements on the nature and frequency of inservice rotor inspections. This assessment is accomplished by evaluating the possibility of a rotor fracture which could lead to bursting and missile generation from the low pressure turbine.



## 2.0 DESIGN FEATURES

A typical integral rotor is shown in Figure 2-1. A major advantage of this design is the elimination of the disc bores and keyways. Rotors with shrunk-on discs have peak stresses around the locations where the discs are shrunk-on and keyed to the shaft. The elimination of these structures has shifted the location of peak stress from the keyways to the blade fastening regions at the rim of the rotor, whose local stress is much lower than that of the shrunk-on discs. Since cracks are likely to occur in high stressed regions, reduction of the peak stress throughout the rotor significantly contributes to the reduction in rotor burst probability.

In addition to lower local stress throughout the rotor, the integral structure also has the benefit of reduced average tangential stress of the discs thus applying lower yield strength material with traditional safety margins remaining unchanged. Many years of experience and testing of the rotor material have demonstrated better ductility, toughness and resistance to stress corrosion cracking at lower yield strength. These benefits can be important factors in reducing the possibility of turbine missile generation. The integral rotor forgings of the 3.5% Ni-Cr-Mo-V alloy steel [ ] are to be applied to the US-APWR LPT rotors and heat-treated to obtain minimum yield strengths of [ ], Charpy V-notch energy at 21-27 deg.C of [ ], maximum FATT of [ ], and minimum upper shelf energy of [ ].

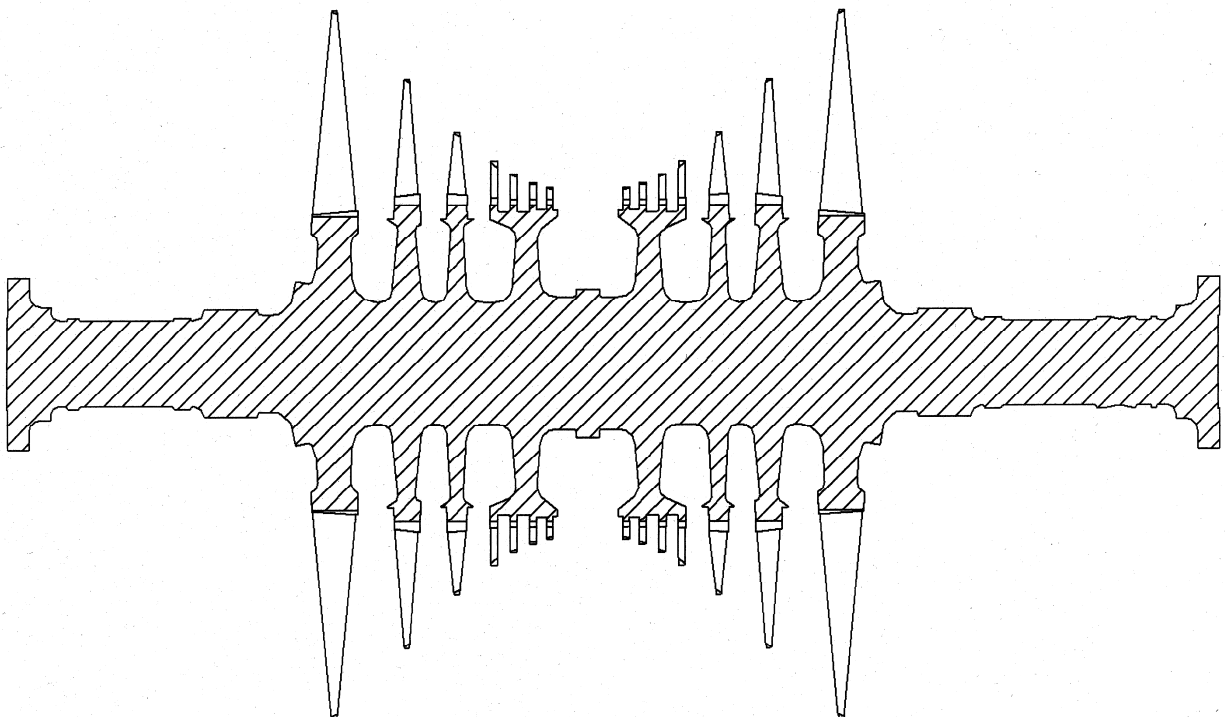
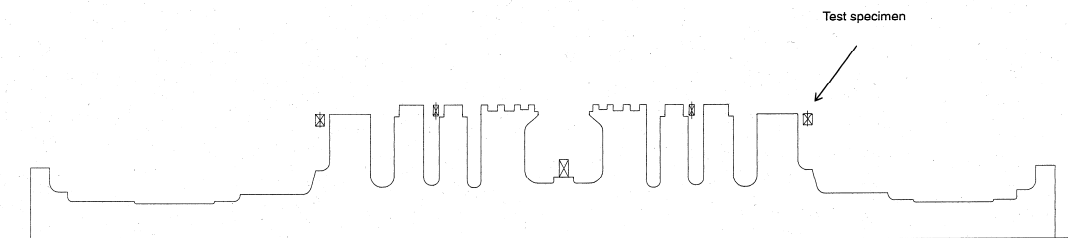


Figure 2-1 Typical Integral Rotor Structure

## 2.1 Material Features

In addition to increased capability in manufacturing large size rotor forgings, improvements in the steelmaking process have resulted in improved toughness, uniformity of properties and reductions in undesirable embrittling elements over previous manufacturing technologies.

The specification for the integral rotors requires testing at the locations shown in Figure 2.1-1 to confirm uniformity of the rotor. Using these specimens, the tensile test (tensile strength, yield strength, elongation and area reduction) and Charpy test (Charpy V-notch energy, 50% FATT and upper shelf energy) will be performed to confirm that the required  $K_{IC}$  of [ ] and the other mechanical properties used in this report are satisfied.



**Figure 2.1-1 Typical Integral Rotor Material Test Locations**

### **3.0 PROBABILITY OF MISSILE GENERATION**

Four potential failure mechanisms are considered for the assessment of the missile generation probability of an integral low pressure rotor;

1. Ductile burst,
2. Fracture due to high cycle fatigue(HCF),
3. Fracture due to low cycle fatigue(LCF),
4. Fracture due to stress corrosion cracking(SCC).

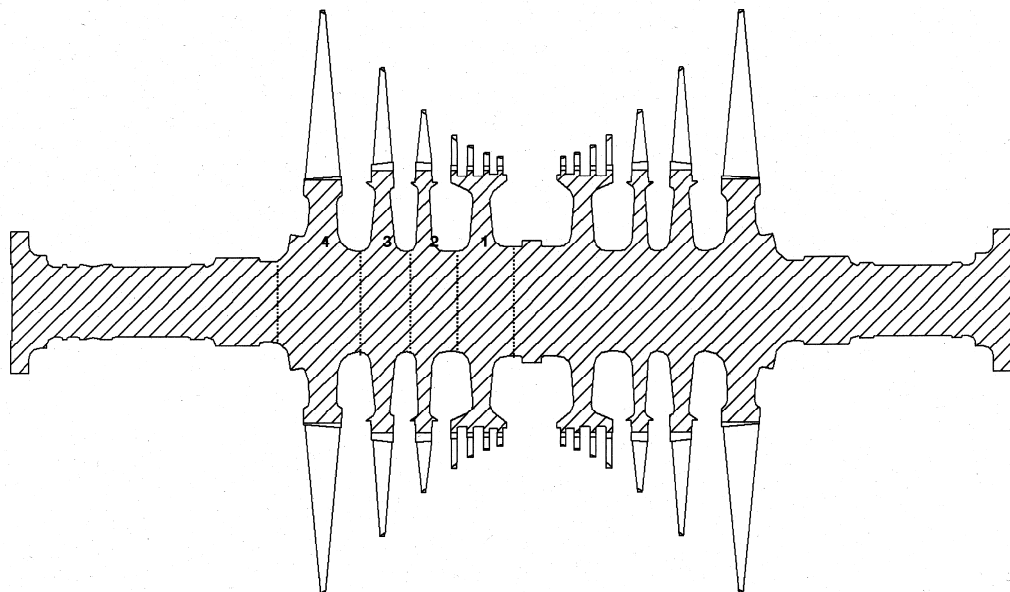
For the purposes of conservative analyses, a rotor burst is considered sufficient to create a missile although it is recognized that the turbine casing could provide resistance against the generation of external missiles. The methodology and results for each of the failure mechanisms are analyzed and discussed in the following sections.

### 3.1 Ductile Burst

Tests have been performed by a number of investigators in which model turbine discs have been spun to the point of failure. The results demonstrate that ductile failure can be predicted by assuming the average tangential stress equals the tensile strength of the disc at burst. It becomes possible to calculate the speed at which failure would occur by knowing the stress required for failure. The integral rotor body is divided into individual discs as shown in Table 3.1-1 for this analysis. It is conservatively assumed that failure occurs when the average tangential stress in any individual disc is equal to the [ ] of the disc rather than the tensile strength.

The results of this analysis are summarized in Table 3.1-1. We can conclude from this analysis that ductile bursting of the rotor will not occur until the speed of the rotor is increased to equal or be greater than [ ], although this analysis is conservatively evaluated by using [ ]. Since this is well beyond the design overspeed, the rotor cannot fail by this mechanism unless the control and overspeed protection system fails to function. The probability of this event is therefore determined by the reliability of the control and protection system, and periodic rotor inspections have no effect on the probability of failure by this mechanism.

**Table 3.1-1 Safety Factors for Ductile Bursting**



### 3.2 Fracture Due To High Cycle Fatigue (HCF)

In this scenario it is postulated that a failure can occur from a fatigue crack that 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 are used in the design to minimize the initiation and propagation of a fatigue crack.
2. A large transverse crack will create eccentricity and the resulting high vibrations will cause the unit to be removed from service before fracture occurs.

The following analyses are performed to assure that rotor burst by this scenario will not occur during service operation;

1. Initiation of HCF cracks,
2. Propagation of cracks by HCF.

Initiating a HCF cracks are evaluated by comparing the magnitude of the bending stress with the failure stress  $\sigma_{fail}$ , obtained from a Goodman Diagram and reduced to account for size effects. Table 3.2-1 shows the calculated safety factor against HCF at each surface position of each low pressure rotor. It is seen that [ ] is the location where the minimum safety factor of [ ] is observed, while the safety factor on the same position is big enough to prevent the initiation of cracks due to HCF. These rotors therefore have sufficient strength against the HCF fracture from the viewpoint of crack initiation.

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

The rotors have the threshold stress intensity range  $\Delta K_{th}$ , for fatigue crack propagation and that is obtained from this relation:

$$(3.1) \quad \Delta K_{th} = F \cdot \Delta \sigma \sqrt{\pi \cdot a}$$

where  $\Delta \sigma$  is the alternating bending stress and  $a$  is the existing crack size in depth. And the flaw shape parameter  $F$  is obtained as below:

$$(3.2) \quad F = \sqrt{Q/1.21},$$

where  $Q$ , the flaw shape parameter is also determined by assuming a semi-elliptical crack at the material surface. The number of  $Q$  is [ ] when assuming the depth to length ratio of [ ].

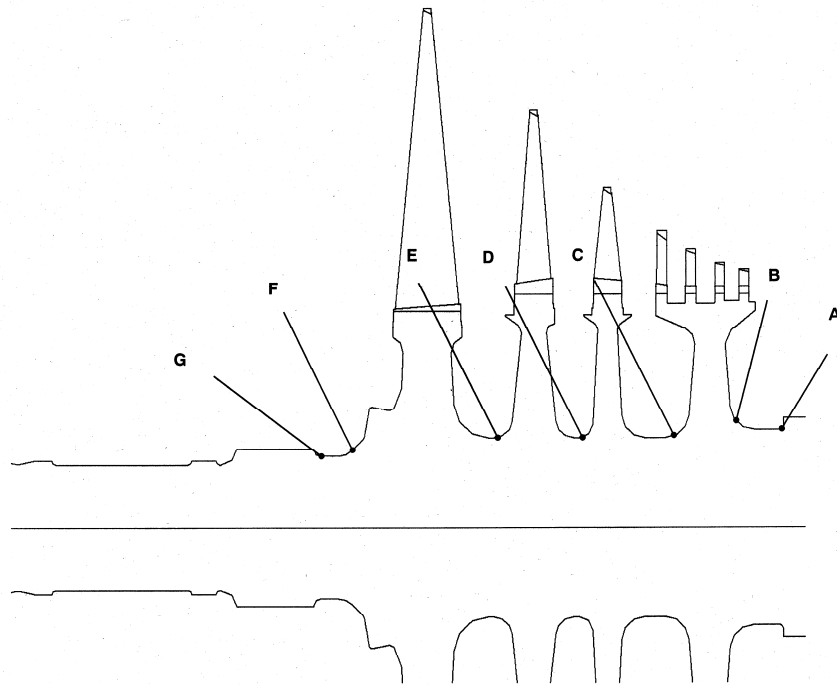
For the purpose of conservative analysis and obtaining allowable vibration stress  $\Delta \sigma_{al}$ , the threshold stress intensity range  $\Delta K_{th}$  is assumed to be [ ]. An initial crack size,  $a_i$  of [ ].

$$(3.3) \quad \Delta \sigma_{al} = \Delta K_{th} \cdot \sqrt{\frac{1.21}{Q \cdot \pi \cdot a_i}} = [ \quad ]$$

By comparing the peak stress with the allowable vibratory stress, in Table 3.2-1, all of the peak stresses  $\Delta \sigma_{peak}$  are well below the minimum allowable vibratory stress  $\Delta \sigma_{al}$ . It is therefore obvious that the rotors have a sufficient safety margin in regard to the propagation of a postulated pre-existing crack.

It is concluded that low pressure rotors have sufficient safety factors against HCF and the periodic inservice inspections for transverse fatigue fractures are not a design basis requirement.

**Table 3.2-1 HCF Peak Alternating Stresses and Safety Factors due to Gravity Bending and Possible Misalignment of the Bearings**





### 3.3 Fracture Due To Low Cycle Fatigue (LCF)- Start-up/Shut-down Cycles

An analysis was carried out to determine the probability of turbine missile generation due to start-up/shut-down cycle fatigue crack growth. In this postulated scenario, the failure mechanism is a brittle fracture, where a crack initiates at the center of the rotor and grows to a critical size as a result of speed cycling during the operating life of the turbine.

Such probability of failure depends on the magnitudes and interrelationships of the following six factors:

1. The size of cracks at the beginning of turbine operation
2. The shape of these cracks
3. The size of the critical crack, which is dependent on the exposed stresses at the design overspeed ([ ] ) and toughness of the rotor( $K_{IC}$ )
4. The magnitude of the stress range cycles experienced during the operation of machines
- 5&6. The two parameters,  $C_0$  and  $n$ , in the Paris fatigue crack growth rate equation:

$$(3.4) \quad \frac{da}{dN} = C_0 (\Delta K)^n$$

where  $da/dN$  is the crack growth rate per cycle,  $\Delta K$  is the stress intensity range, and  $n$  and  $C_0$  are parameters to determine the fatigue crack growth rate which are determined experimentally.

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

$$(3.5) \quad N_f = \frac{2}{(n-2) \cdot C_0 \cdot M^{n/2} \cdot \Delta \sigma^n} \left( a_i^{-(n-2)/2} - a_{cr}^{-(n-2)/2} \right)$$

where

$N_f$  = The number of cycles to reach critical crack size

$M$  =  $\pi/Q$

$Q$  = Flaw shape parameter

$a_i$  = Initial largest crack depth

$a_{cr}$  = Critical crack depth

$\Delta \sigma$  = Range of stress cycles in operation.

In the estimation of the probability of rupture by this scenario, both  $C_0$  and  $n$  factors

described above are considered to be random variables, and other parameters are conservatively determined. The number of cycles to failure  $N_f$  is then dependent on the profile of the above variables. The profiles of the random variables and other parameters are taken as follows:

The flaw shape parameter  $Q$  is determined by assuming that a semi elliptical crack with a depth to length ratio of [ ] is formed at the center of the rotor. Such a flaw crack shape parameter would be [ ], which is independent on the stress.  $Q$  can be set to be [ ] as a conservative number. The critical crack size  $a_{cr}$  is obtained from the relation:

$$(3.6) \quad a_{cr} = \frac{Q}{\pi} \left( \frac{K_{IC}}{\sigma} \right)^2$$

where  $K_{IC}$  is the fracture toughness of the rotor and  $\sigma$  is the stress at the design overspeed [ ].

The fracture toughness  $K_{IC}$  of [ ] is applied on this analysis. The fracture toughness  $K_{IC}$  of [ ] was obtained through the Begley-Logsdon Method with a safety margin of 20% using the upper shelf energy of [ ] specified in the purchase specification as a minimum allowable value.

The size of the initial crack depth  $a_i$  is set to be [ ] under the assumption of [ ] flaw shape, since the inspection procedures used for integral rotor forgings can reliably detect flaws [ ].

The stress range of  $\Delta\sigma$  is conservatively determined to be [ ], respectively at rated speed, trip setting speed and design overspeed. These values are the sum of centrifugal stress and the maximum anticipated thermal stress during start-up cycle. The rotor metal temperature distribution at the rated condition is shown in Figure 3.3-1 for reference.

Profiles of random variables are obtained as follows:

The distribution of  $C_0$  and  $n$  were obtained from fatigue crack growth rate data for 3.5% Ni-Cr-Mo-V rotor steel presented in Table 3.3-1.

The values of  $n$  and  $C_0$  are assumed to have a normally distributed profile with a mean value of [ ] and standard deviation of [ ] and with a mean value of [ ] and standard deviation of [ ] respectively.

The probability of missile generation due to LCF ( $P_{LCF}$ ) is calculated using the following equation under the assumption that probability of reaching design overspeed per year is conservatively assumed to be 100% although it is expected to be on the order of  $10^{-5}$  with proper inspection and maintenance of the turbine valves and the control system.

$$(3.7) \quad P_{LCF} = q_{cr} \cdot q_{os}$$

where,

$q_{cr}$  = the probability of flaw propagation up to critical crack size ( $a_{cr}$ ) due to LCF,

$q_{os}$  = probability of reaching design overspeed [ ] per year

= assumed to be 100% per year

The calculated probability of a LP rotor rupture due to LCF is summarized in Table 3.3-2, which includes three case studies. In each case, the maximum rotating speed during start-up/shut-down is assumed to be 100%, 111% and 120% of rated speed respectively. The 111% overspeed is the trip set point of the overspeed trip device and the 120% overspeed is design overspeed which can only occur when the control system fails to function. Table 3.3-2 shows the probability of rupture at [ ] start-up/shut-downs and the number of start-up/shut-downs at which the probability of rupture reaches the NRC's guideline of  $P_1 < 1 \times 10^{-5}$  per year being specified in SRP 3.5.1.3 (Reference 12), Table 3.5.1.3-1. It should be noted that the margin of [ ] in the number of start-up/shut-down used and listed in the Table 3.3-2 is taken into account for compensating the uncertainty in the variation of the propagation speed of cracks in the rotors. In the Case-2 which assumes maximum rotating speed of 111% of rated speed at every start-up/shut-down and is conservative enough compared to the actual operation of the nuclear units, the number of the start-up/shut-down at the probability of rupture of  $1 \times 10^{-5}$  per year is [ ]. Even in the assumption of 120% overspeed at every start-up/shut-down (Case-3), it is demonstrated that the above NRC's guideline is satisfied in the range up to [ ] start-up/shut-downs while 120% overspeed can only occur with the control system failure.

It is concluded that a low pressure rotor rupture due to the LCF cannot occur before the postulated plant life has expired.

**Table 3.3-1 3.5% Ni-Cr-Mo-V Rotor Steel, n and C<sub>0</sub> Parameters in the Paris Equation:**

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

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**Table 3.3-2 Probability of Low Pressure Rotor Brittle Rupture due to Low Cycle Fatigue (start-up/shut-down cycle)**

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**Figure 3.3-1    Temperature Distributions in the LP Rotor (At Rated Condition)**

### 3.4 Failure Due To Stress Corrosion Cracking (SCC)

An analysis was performed to determine the probability of integral rotor bursting due to SCC. A crack is assumed to initiate at the bottoms of the grooves where the stresses are the highest, and propagate in the radial direction until it reaches the critical crack size before 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 the design overspeed. Each of these factors is discussed below.

For this analysis, it is necessary to consider [ ] on the rotor. Experience with built-up rotors has shown that the probability of cracking and the crack growth rates of the discs beyond the [ ] is so low that it is not necessary to consider them in determining the probability of rotor bursting.

The probability of missile generation due to SCC is expressed as follows:

$$(3.8) \quad P_{SCC} = q_i \cdot q_{cr} \cdot q_{os}$$

where,  $q_i$  is the probability of crack initiation,  $q_{cr}$  is the total probability of flaw propagation up to the critical size by SCC for [ ], and  $q_{os}$  is the probability that the unit will reach design overspeed.

For the purpose of conservative evaluation,  $q_i$  is assumed to be 100%. It is noted that this assumption is equivalent to ignoring the incubation period before initiation of SCC cracks propagation. Note that MHI has no experience of cracks initiating on the integral low pressure rotors in the inspections of about 40 integral low pressure rotors through 2012. The first integral low pressure turbine rotor of the same material was put into commercial operation approximately 20 years ago.

$q_{os}$  is also assumed to be 100%, nevertheless it is expected to be on the order of  $10^{-5}$  under proper inspection and maintenance for turbine valves and the control system.

Because of the full integral rotor design without shrunk-on rotors and keyways and because of the relatively low yield strength of about [ ], MHI has no experience of emanating SCC on full integral low pressure rotors. Nevertheless, the probability analysis for rotor failure due to SCC is conservatively based on experimental and field data of high yield stress materials.

#### 3.4.1 Crack Growth Rates

The crack growth rate model used in this analysis is expressed as follows:

$$(3.9) \quad \left[ \right]$$

where  $\gamma$  is the crack depth growth rate (millimeters per service hour),  $T$  the absolute temperature in degrees (K),  $\sigma_{ys}$  the yield strength (MPa), and  $\varepsilon$  the uncertainty term.



**Table 3.4-1     3.5% Ni-Cr-Mo-V Rotor Steel Crack Growth Rate Deviation from Calculation**

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### 3.4.2 Critical Crack Size

The critical crack depths were obtained for [ ] of integral rotors by using the relationship between fracture toughness and stress intensity, as is used in LCF evaluation in Section 3.3. Critical crack depths were determined at running speed and design overspeed considering stress concentration at the bottom of the grooves.

### 3.4.3 Numerical Results

Based on the distribution and variance of crack growth rates and critical crack sizes described in the previous sections, analyses were made to determine the probability in a manner that a crack would grow to the critical size within any time interval,  $t$ . This probability of rotor bursting is modified by the number of discs being considered.

The final probability profiles are given in terms of discrete inspection intervals in Table 3.4-2 and are shown in Figure 3.4-1. The results show that the necessary inspection interval to satisfy the requirement of missile generation probability less than  $10^{-5}$  per year is [ ] even under the conservative assumptions used in this analysis.

**Table 3.4-2 Probability of Missile Generation (per year) due to Stress Corrosion Cracking**



**Figure 3.4-1 Probability of Missile Generation (per year) due to Stress Corrosion Cracking**

#### 4.0 DISCUSSION AND CONCLUSIONS

Except for the destructive overspeed mechanism, previous discussions demonstrate that the integral low pressure rotor design is unlikely to generate a turbine missile by any of the mechanisms considered in this document and satisfy the requirement in regard to missile generation. The probability of reaching destructive overspeed is primarily dependent upon the reliability of the control system. Detailed discussion on this matter is addressed in Reference 11.

The low pressure rotors are unlikely to burst as a result of HCF since the maximum alternating stress on the rotor is less than its endurance, and the safety factors are more than 3.0. Additional assurances against bursting by this mechanism are derived from;

1. The locations of maximum stress in integral rotors are readily accessible for inspection during normal maintenance,
2. The existence of a large transverse crack is detectable by high vibrations due to rotor unbalance.

It is reasonable to exclude HCF as a controlling mechanism to determine inservice inspection intervals.

Analysis of the LCF mechanism demonstrates that the probability of failure by this scenario is extremely low under conservative assumptions. In the case of assuming maximum rotating speed of 111% of rated speed at every start-up/shut-down cycles and being conservative enough compared to the actual operation of the nuclear units, the number of the start-up/shut-downs at which the probability of rupture reaches the NRC's guideline of  $P_1 < 1 \times 10^{-5}$  per year being specified in SRP 3.5.1.3 (Reference 12), Table 3.5.1.3-1 is [ ]. With the assumption of 120% overspeed at every start-up/shut-down, it is demonstrated that the above NRC's guideline is satisfied in the range up to [ ] start-up/shut-down while 120% overspeed can only occur with the control system failure. It can be concluded that this number of cycles before the low-pressure rotor rupture probability due to LCF exceeds the NRC guide line is greater than the number of start-up/shut-downs expected to experience in the postulated plant life. Therefore, it is not necessary to take the LCF calculation results into consideration for determining the periodic inspection interval, provided that the life of the low-pressure rotors due to LCF is under the control of the plant license holder.

The probability of failure by the SCC mechanism is significantly reduced by the application of integral rotor design. The analysis shows that a running time [ ] can elapse before the first inspection without exceeding the above NRC safety guidelines even under highly conservative assumptions would occur. Considering that the most probable crack locations are accessible during normal turbine inspections and maintenance, it is concluded from the design considerations show that the NRC safety guidelines can be satisfied by the periodic inspection in a proper interval within [ ].

These calculation results demonstrate that the low-pressure rotor inspection before [ ] operation is sufficiently conservative to keep the turbine missile generation probability less than the NRC guideline during operation.

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