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Ralph E. Beedle
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June 26, 1991
IPN-91-025

U.S. Nuclear Regulatory Commission
Mail Station P1-137
Washington, D.C. 20555

Attn: Document Control Desk

Subject: Indian Point 3 Nuclear Power Plant
Docket No. 50-286
Low Pressure Turbine Disc Inspection

References:

1. NYPA Letter J. C. Brons to NRC, "Turbine Disc Inspection," dated January 19, 1989 (IPN 89-006).
2. NRC Letter J. D. Neighbors to J. C. Brons, "Low Pressure Turbine Disc Inspection," dated May 17, 1989.
3. Summary of the Results of Analysis for Turbine Missile Generation Probability for Indian Point 3.

Dear Sir:

In Reference 1, the Authority requested approval to extend the inspection interval for the discs on low pressure turbine rotors LP-1 and LP-3 from the February 1990 Maintenance Outage to the September 1990 Cycle 7/8 Refueling Outage. The Authority had also stated in Reference 1 that it planned to replace all three low pressure turbines (LP-1, LP-2 and LP-3) during the Cycle 7/8 Refueling Outage. If the replacement couldn't be done during that outage, the Authority would have performed a complete inspection of all three LP rotors.

In Reference 2, the NRC approved the Authority's request to extend the inspection interval for LP-1 and LP-3. This approval was granted by the NRC because the turbine missile probability at the start of Cycle 7/8 Refueling Outage satisfied the turbine reliability criteria (Reference 2).

During Cycle 7/8 Refueling Outage, the Authority replaced all three LP turbines with new turbines manufactured by ASEA Brown Boveri (ABB). The Authority has evaluated the vendor data (Reference 3) which is included as Attachment I to this letter. This analysis indicates that for the unfavorably oriented IP-3 turbine with a missile probability of 10^{-5}, the maximum inspection interval is 14 years. The Authority will inspect all three low pressure turbine rotors within this inspection interval. The Authority presently plans to inspect an LP turbine rotor every second refueling outage (approximately every 4 years), with the first rotor inspection scheduled for the

A001

Cycle 9/10 Refueling Outage in 1994. This will result in an approximate 12 year inspection interval for a rotor. However, the actual schedule of rotor inspections may differ from this plan since it is dependent on future plant conditions.

If you have any questions regarding this matter, please contact Mr. P. Kokolakis.

Very truly yours,

Ralph E. Beedle
Executive Vice President
Nuclear Generation

cc: U. S. Nuclear Regulatory Commission
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ATTACHMENT I TO IPN-91-025

Summarized Results of Analysis for Turbine Missile Generation Probability for Indian Point 3

NEW YORK POWER AUTHORITY
INDIAN POINT 3 NUCLEAR POWER PLANT
DOCKET NO. 50-286
DPR-64

ABB's METHOD FOR THE DETERMINATION OF THE TURBINE MISSILE GENERATION PROBABILITY

SUMMARIZED RESULTS OF THE ANALYSIS FOR THE INDIAN POINT UNIT 3

90-08-02/KWDT
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ABSTRACT

The present report summarizes the determination of the turbine missile generation probability of INDIAN POINT unit 3 LP-rotors.

The investigated cases are the influence of stress corrosion cracking (SCC) and the influence of low cycle fatigue (LCF), but the overly dominant mechanism is the stress corrosion cracking.

The requirements of the NRC to derive the inspection intervals for LP-rotors from the probability figure can easily be satisfied by the usual ABB inspection recommendations.

CONTENTS

1. Introduction

The present report summarizes the determination of turbine missile generation probability of LP-rotors of INDIAN POINT unit 3. The investigated cases are the influence of stress corrosion cracking (SCC) during stationary service and the influence of low cycle fatigue (LCF) during starts.

The probability of missile generation of LP-rotors is defined as the probability that an existing crack will grow to the critical crack size. Therefore, both crack growth rate and critical crack size, which are dependent on the loading case (start, nominal speed resp. overspeed), are the main parameters to be considered. Further informations about the different probabilities are given in enclosure 1.

2. Missile Analysis for Stress Corrosion Cracking

Missile analysis for stress corrosion cracking was performed using the methods described in enclosure 1.

2.1 Influence of Nominal Speed (100%)

For nominal speed calculation, it was assumed:

- Crack will grow under nominal speed condition due to stress corrosion cracking up to a critical crack size.

- Critical crack size is fixed by stress intensity K_{IP} at end of plateau range (upper limit of constant crack velocity) and stress at nominal speed.

2.2 Influence of Overspeed (132%)

For overspeed calculation, it was assumed:

- Crack will grow under nominal speed condition, due to stress corrosion cracking up to the critical crack size. (The crack growth rate is the same as for nominal speed).
- Critical crack size is fixed by fracture toughness K_{IC} (brittle fracture criterion) and stress at overspeed.

For the fracture toughness K_{IC}, mean value and standard deviation were calculated from the actual values of the forgings used for the LP-rotors of INDIAN POINT unit 3.

2.3 Inspection Intervals Because of Stress Corrosion Cracking

For the calculation of inspection intervals a new value q for probability of crack initiation was used compared to enclosure 1. Based on the today's ABB experience q=1.0 is lowered to q=0.011. The calculation according to enclosure 1 was performed for 3 double-flow LP-rotors.

The comparison between the two different speed conditions (Fig. 1) shows that overspeed yields lower time dependent probabilities. This means, that nominal speed condition is dominant for determination of inspection intervals.

As the INDIAN POINT UNIT 3 plant is obviously unfavourably oriented the 10^{-5} figure has to be taken as a minimum limit (see table 5 of enclosure 1).

From this a maximum inspection interval of 14 years results - see Fig. 1.

3. Missile Analysis for Fatigue Crack Growth

3.1 Influence of Start Condition and Overspeed

For fatigue crack growth calculation, it was assumed:

- Crack will grow during start-up due to fatigue crack growth (cold start condition is used since this is the worst case. Number of starts is 250 which includes cold, warm and hot starts during 40 years of service).
- Critical crack size is fixed by fracture toughness K_{IC} (brittle fracture criterion) and maximum stress at overspeed.

3.2 Inspection Intervals Because of Fatigue Crack Growth

Since number of starts (250) is low, probability of missile generation due to fatigue crack growth is far below the NRC figure 10^{-5}. From this an inspection interval larger than 250 starts or 40 years of service results (see figure 3).

4. Inspection of LP-Rotors

4.1 Determination of Inspection Intervals

The maximum allowable inspection intervals are determined evaluating the results for the turbine missile generation probability P_1 (T) for the individual turbine generator.

According to the NRC requirements given in figure 5 of enclosure 1, the limit for P_1 will be either 10^{-4} for favorably oriented plants of 10^{-5} for unfavorably oriented plants.

In the general inspection and overhaul plans, ABB recommend major rotor inspection intervals of 50'000 equivalent operating hours, see Fig. 2. The results obtained with the probabilistic approach (see section 2 and 3 of this report) reveal much longer inspection intervals. Therefore the risks of stress corrosion cracking and fatigue crack growth are covered by the usual inspection and overhaul programs and no additional measures have to be introduced.

4.2 Recommended LP-Rotor Testing

If a welded LP-rotor is affected by SCC, the cracks will initiate at the outer surface of the rotor body. In the case of LCF cracks, the cracks can initiate in the whole rotor body.

The usual recommended LP-rotor testing of welded ABB rotors during major overhauls assure that any indications of SCC will be detected. The testing includes a thorough visual inspection for erosion and corrosion and a surface crack testing at selected areas. In the case of indications additional ultrasonic examinations will be performed.

Therefore, a complete volumetric ultrasonic inspection for SCC is not necessary in the case of welded LP-rotors.

Since a very low probability of failure due to fatigue crack growth is calculated, 100% volumetric ultrasonic inspection is not necessary.

ABB

PROBABILITY P AS A FUNCTION OF TIME

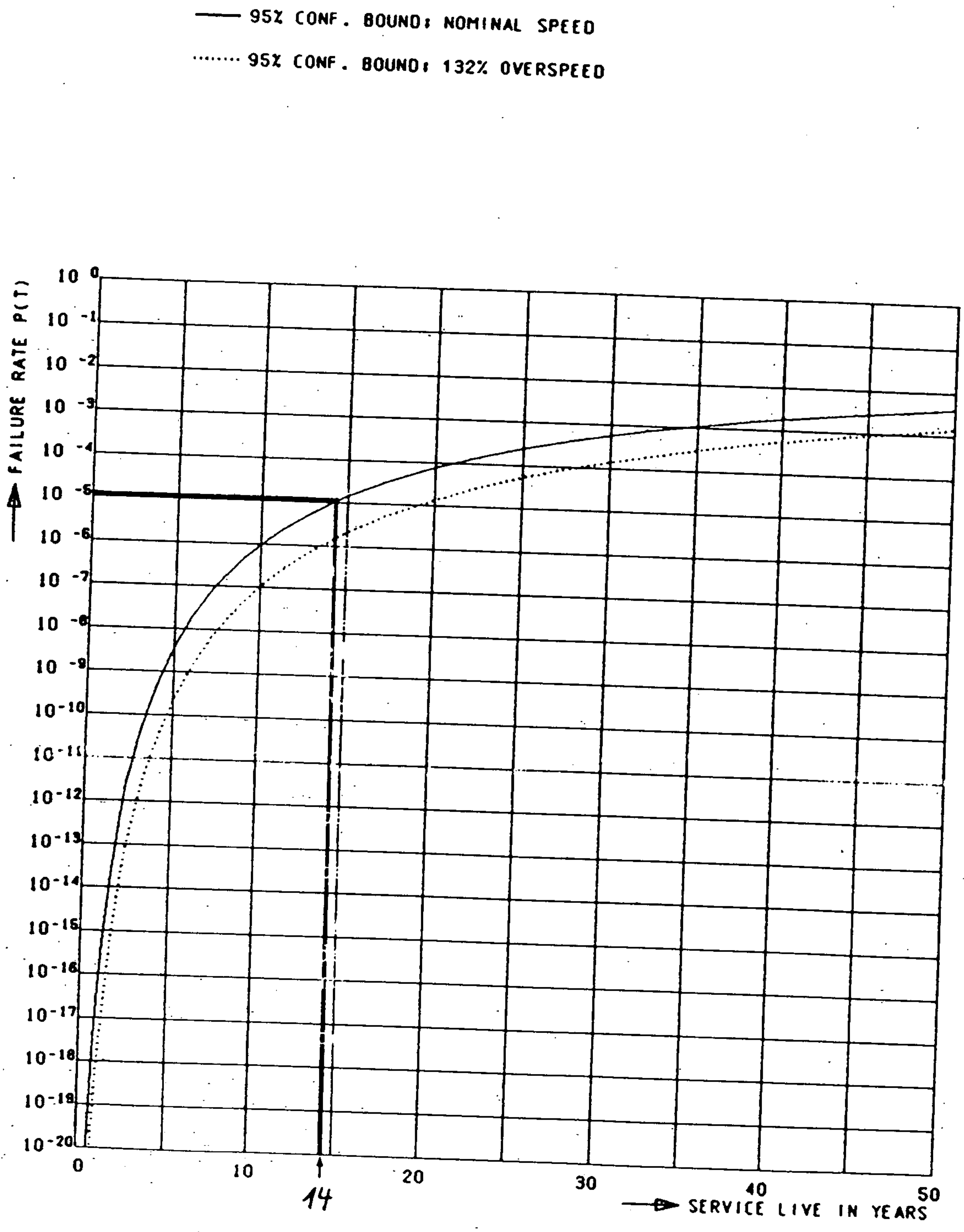
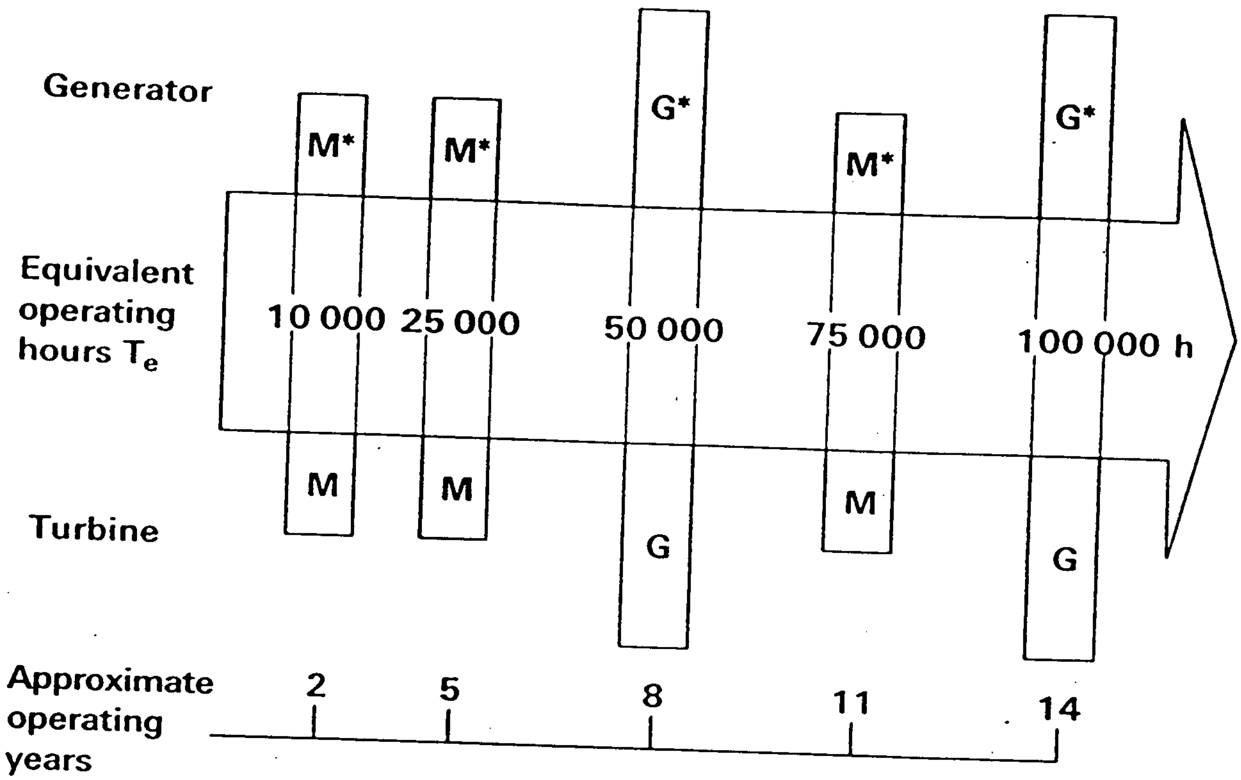


Fig. 1

ABB	LP-RETROFIT INDIAN POINT 3 ASSESSMENT OF THE PROBABILITY OF STEAM TURBINE RUPTURE FROM STRESS CORROSION CRACKING	DATE: 90-03-05 SIG.:



G = Major overhaul
M = Minor overhaul
* With diagnosis

$T_e = T_{eff} + n_s \cdot T_s$

T_e = Equivalent operating hours

T_{eff} = Actual operating hours

T_s = Operating hours charged for one start

n_s = Number of starts

Fig. 2 Recommendations for Inspection Intervals of Large Turbine-Generators

ABB

PROBABILITY P AS A FUNCTION OF LOAD CYCLES

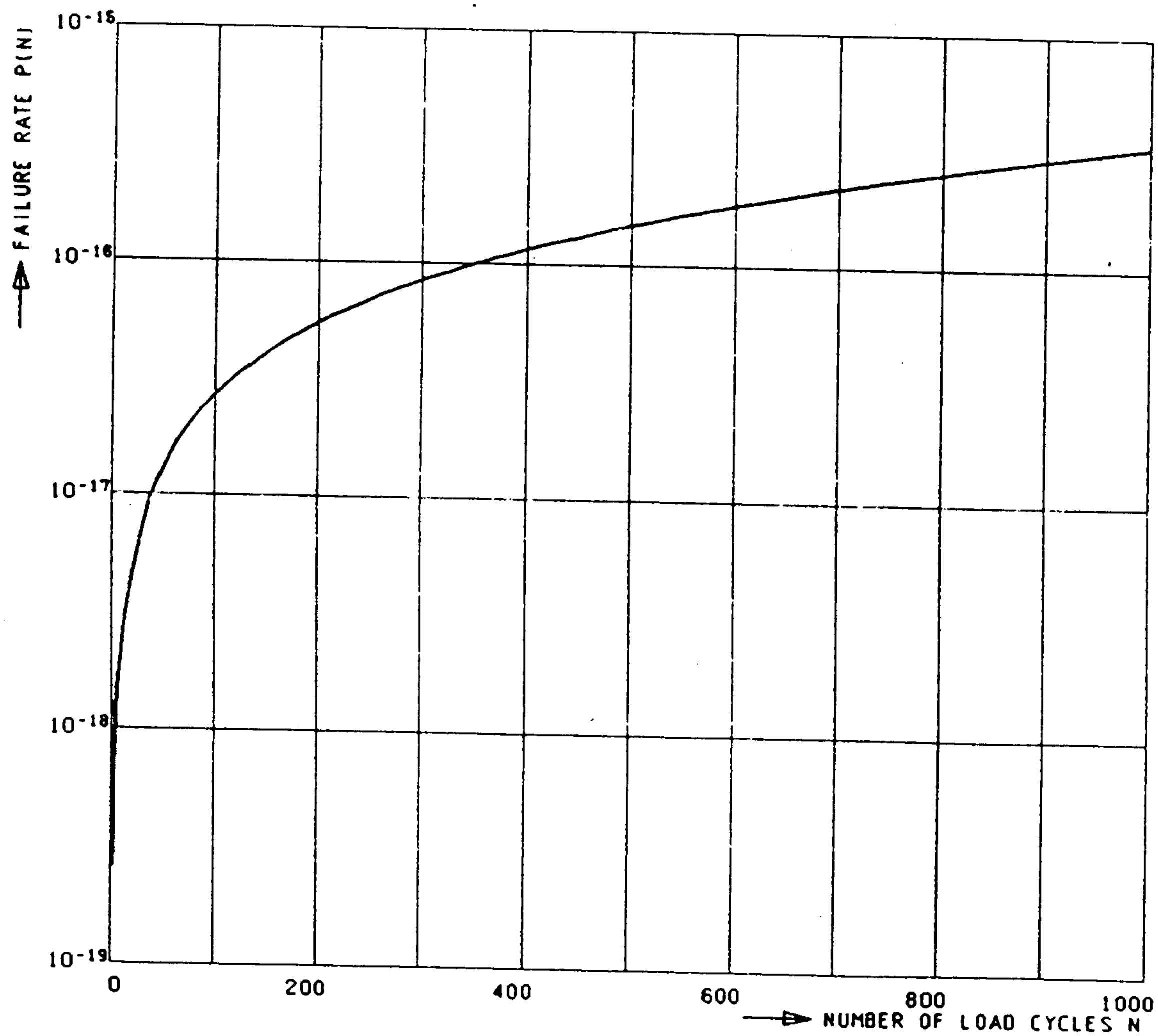


Fig. 3

ABB	LP-RETROFIT INDIAN POINT 3 ASSESSMENT OF THE PROBABILITY OF STEAM TURBINE RUPTURE FROM LOW CYCLE FATIGUE	DATE: 90-03-20 SIG.:

Title: Results of Missile Analysis for Different Types of Large Low Pressure Rotors for Nuclear Application

Autors: A. Czeratzki
H. Lüdi
BBC Brown, Boveri & Company, Ltd.
Baden, Switzerland

ABSTRACT

The NRC request a turbine missile analysis which accounts for the recent experience with stress corrosion cracking in large nuclear low pressure rotors of the shrunk-on disk type.

The paper presents results of the determination of the probabilities of turbine missile generation for the shrunk-on disk type and the welded rotor. The analysis is based on the proposal of the NRC to review the procedure for the determination of inspection intervals of low pressure turbines.

LARGE LOW PRESSURE ROTORS for nuclear application of the shrunk-on disk type suffer from stress corrosion cracking (SCC) at the keyway and bore area Refs. [1], [6].

The majority of the stress corrosion cracks have been observed by inspection before the cracks grew to critical size and thus, catastrophic failure was avoided in nearly all cases. Altogether, only three catastrophic failures of low pressure turbine disks have been reported for nuclear power plants and some disks have also burst due to stress corrosion cracking in fossil fired power stations.

In nuclear power stations, everything is done to prevent catastrophic failures of steam turbine rotors as a consequence of stress corrosion cracking. Because of more demanding safety requirements, stress corrosion cracking of turbines is closely watched and regulated by government regulatory commissions.

The U.S. Nuclear Regulatory Commission (NRC), for example, request a turbine missile generation analysis which accounts for the stress corrosion phenomena. In this missile analysis, the probability of unacceptable damage resulting from turbine missiles has to be demonstrated. The calculated probability figures determine the necessary inspection intervals of the low pressure turbine rotors.

It is the aim of this paper to compare the probability figures and hence the inspection intervals for the two commonly employed types of low pressure rotors in half speed nuclear turbines, namely the shrunk-on disk type rotor and the welded rotor.

TODAYS LP ROTOR DESIGNS FOR HALF SPEED TURBINES

There are two types of low pressure rotors in service in todays half speed turbines of nuclear power plants:

(1) the built-up rotor with shrunk-on disks

(2) the welded rotor

Schematic representation of both designs is shown in Fig. 1, Ref. [2].

The shrunk on disk-type rotor consists of a center shaft on which the bladed disks are shrunk on. To avoid a loosening of the disks during operation and overspeed a certain amount of shrinkfit has to be introduced leading to additional circumferential stresses in the bore area where the centrifugal stresses are highest, as shown in Fig. 2, upper half. To prevent rotating of the disk on the center-shaft, axial or radial keys are used to connect disks and shaft. The accompanying keyways in the disks generate stress concentrations with peak stresses reaching the yield strength of the material, Ref. [3].

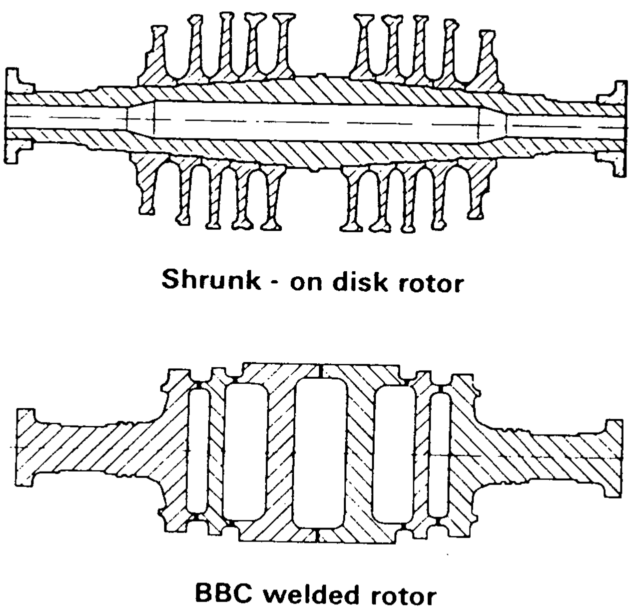


Fig. 1 - LP rotor designs

The welded rotor consists of separate small forgings welded together to form an integral rotor. The welds are positioned at the circumference where the centrifugal stresses are smallest, compare Fig. 2, lower half.

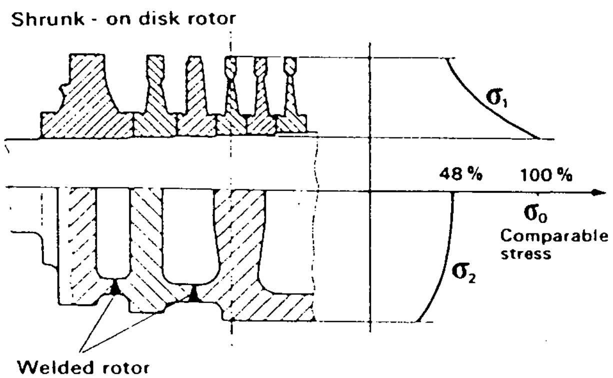


Fig. 2 - Comparison of stresses in LP rotors

In both designs, the steam enters in the middle and expands to both ends. The expanding steam becomes wet at some intermediate stage (Wilson Line). It is in this region of first wetness that stress corrosion cracking of disks has most often been found, but there are a number of other sites for stress corrosion crack initiation as shown in Fig. 3.

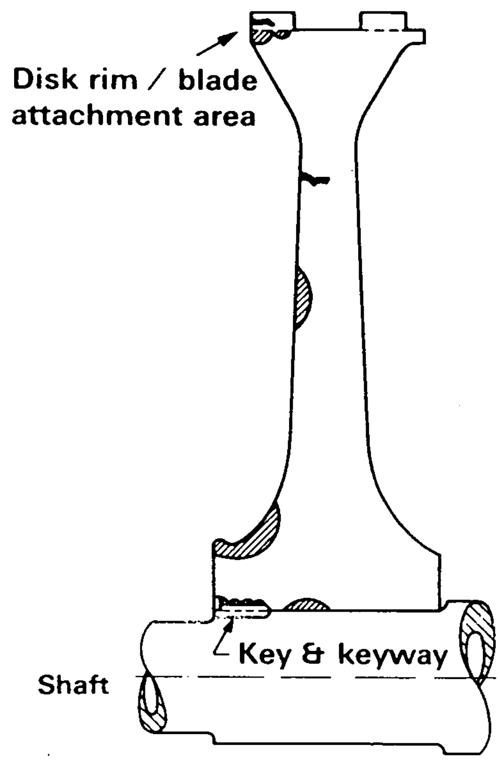


Fig. 3 - Stress corrosion cracks in shrunk-on disks

In connection with possible disk explosion, the keyway cracking appears to be most severe and probable for the shrunk-on disk type rotor.

For the welded rotor, the discussion of a failure due to stress corrosion cracking is purely hypothetical because there are no indications of stress corrosion cracks found up to date. However, for the comparison of both rotor types presented here, it is assumed that stress corrosion cracking occurs in the area of the Wilson Line at the outer surface of the welded rotor.

enclosure 1

NRC REQUIREMENTS ON TURBINE MISSILES

Failures of large steam turbines have the potential to eject large high energy missiles which can damage other main components like the reactor. The probability P_4 of unacceptable damage resulting from turbine missiles is generally expressed as the product of

(1) the probability of turbine failure resulting in the ejection of turbine disk fragments through the turbine casing, P_1.

(2) the probability of ejected missiles striking main components, P_2.

(3) the probability of struck main components to fail, P_3.

$$P_4 = P_1 \times P_2 \times P_3 \leq 10^{-7} \text{ per year}$$

Because of the uncertainties involved in calculating P_2 and P_3, the NRC have defined the product $P_2 \times P_3$ depending on the arrangement of the power plant, see Fig. 4:

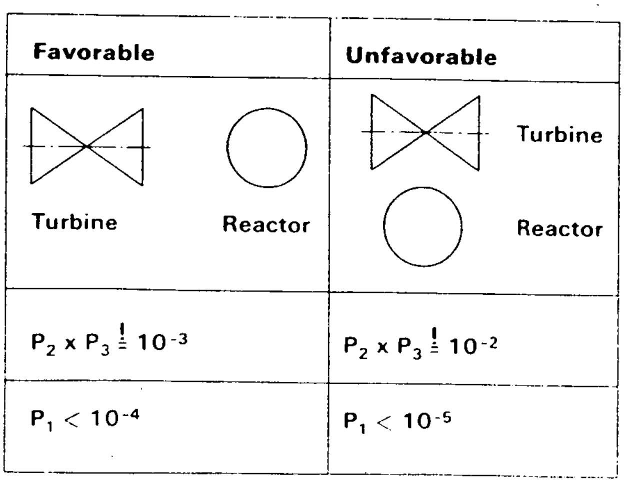


Fig. 4 - Arrangement of power plants

(1) For favorably oriented turbine generators:

$$P_2 \times P_3 = 10^{-3}$$

(2) For unfavorably oriented turbine generators:

$$P_2 \times P_3 = 10^{-2}$$

The NRC safety objective with regard to turbine missiles can be summarized in terms of two sets of criteria as shown in Fig. 5. For a given arrangement the procedure is reduced to the determination of the turbine missile generation probability P_1 as a function of time.

Case	Probability P_1 — Turbine - Generator Set: Favorably oriented	Probability P_1 — Turbine - Generator Set: Unfavorably oriented	Required licensee action
A	$< 10^{-4}$	$< 10^{-5}$	Loading turbine
B	$10^{-4} < P_1 < 10^{-3}$	$10^{-5} < P_1 < 10^{-4}$	Turbine may be kept in service until next scheduled outage
C	$10^{-3} < P_1 < 10^{-2}$	$10^{-4} < P_1 < 10^{-3}$	Turbine is to be isolated from steam supply within 60 days
D	$10^{-2} < P_1$	$10^{-3} < P_1$	Turbine is to be isolated from steam supply within 6 days

Fig. 5 - New NRC-proposal; Reliability criteria

TURBINE MISSILE GENERATION PROBABILITY

The turbine missile generation probability P_1 consists of two factors (1) the probability of disk failure producing an internal turbine missile P_1' and (2) the probability that this internal missile penetrates the turbine casing P_1'':

$$P_1 = P_1' \times P_1''$$

MATHEMATICAL MODEL FOR P_1' - The probability of producing a disk fragment can be determined by means of fracture mechanics using crack growth rates and critical crack sizes.

According to present knowledge, Refs. [1], [5], on stress corrosion

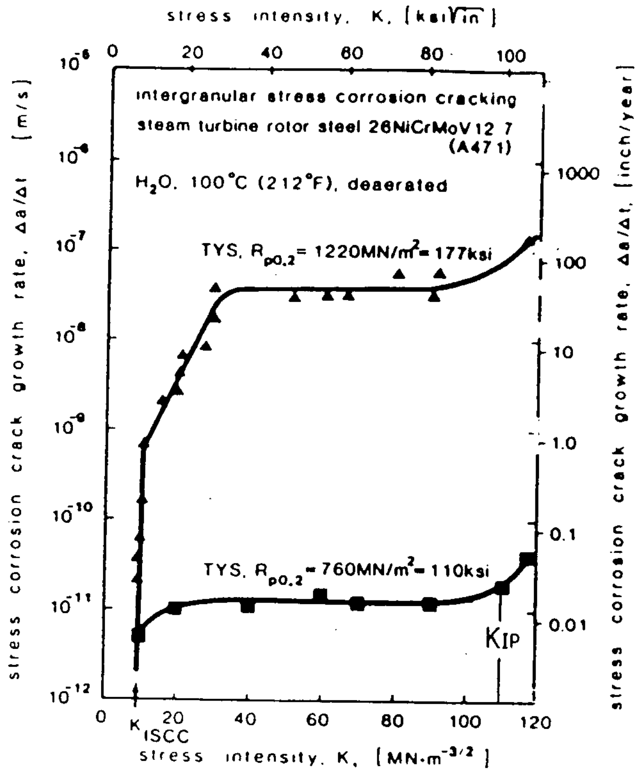


Fig. 6 - Effect of stress intensity and yield strength on the growth rates of stress corrosion cracks

(1) Crack initiation or incubation phase. It is commonly accepted that a threshold value K_{ISCC} exists. If the stress intensity K_I is below this threshold value crack growth is not possible.

(2) Constant crack growth rate. If the stress intensity clearly exceeds the threshold value the crack growth rate remains constant on a plateau value for quite a large range of stress intensities K_I.

(3) Accelerated crack growth rate. Available data, Ref. [5], indicate that the constant plateau region extends to at least K_{IP} = 110 MPa$\sqrt{m}$.

A mathematical model for the probabilistic approach to this problem was presented by Clark, Seth and Shaffer in Ref. [4]. We would like to follow their proposal closely and give only a brief survey of the procedure and the modifications we have introduced.

The probability P_1' consists of two factors, the probability of crack initiation q and the probability that this crack will grow to the critical size before time t, p (t):

$$P_1' = q \times p\ (t)$$

The value of q is determined by inspection results of low pressure rotor disks using a binominal distribution with 50% confidence bound.

The function p(t) is calculated using the main input variables as random distributed as shown in Fig.7.

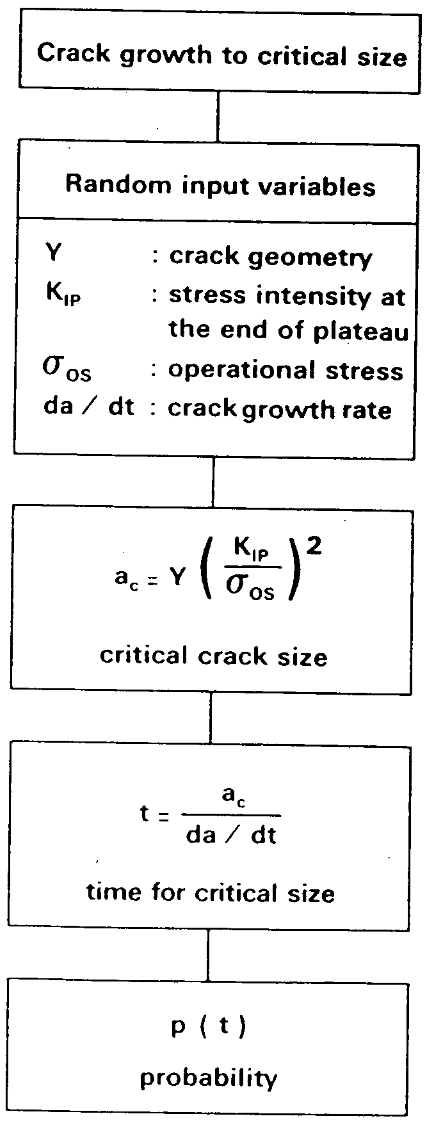


Fig. 7 - Mathematical model for crack growth, p(t).

The most important feature of the method is the use of the constant plateau crack growth rate. Differing from the proposal given in Ref. [4] we use the stress intensity K_{IP} at the end of the plateau region and the net stress at nominal speed instead of the fracture toughness K_{IC} at room temperature. Fig. 6 indicates that the crack growth rate will be increased rapidly when the stress intensity exceeds clearly the K_{IP} value. Because the fracture toughness K_{IC} is in the range of K_{IC} = 200 MPa$\sqrt{m}$ the use of K_{IC} leads to results, which are much to optimistic by a factor of 3,3.

METHOD FOR DETERMINATION OF P_1" - The procedures for estimating P_1" are not as sophisticated as the procedures for calculating P_1'. The usual method is to compare the kinetic energy of a potential disk fragment with the energy necessary to penetrate the turbine casing. The result of such an estimation will be either

$$P_1" = 0 \text{ or } P_1" = 1.$$

CASE STUDY: SHRUNK-ON DISK VERSUS WELDED ROTOR

In this case study it is assumed that in both turbine generators one disk is affected by stress corrosion cracking and that the corresponding disk fragment will perforate the casing.

This means:

(1) probability of crack initiation, q = 1.0

(2) probability of perforating the casing, P_1" = 1.0.

These assumptions allow a direct comparison between both designs concerning critical crack sizes and crack growth rates.

The input data are listed in Table 1. Adopting the procedure summarized in the previous section the probabilities have been computed. The results of the two designs are plotted for different years of operation in Fig. 8.

The reasons for the superior results of the welded rotor are:

(1) The lower net stress, leading to a critical crack size which is eight times greater than that one of the shrunk-on disk type.

(2) The lower yield strength of the employed material leads to a calculated crack growth rate which is only one half of that for the shrunk-on disk rotor material.

Table 1 - Input Data to Case Study

		Symbol	Unit	Welded Rotor	Shrunk-on Disk Rotor
1	Probability of crack initiation	q	-	1	1
2	Material temperature	T	°C	125	125
3	Yield strength at RT	R_e	MPa	685	850
4	Operational net stress	σ_{OS}	MPa	140	400
5	Relative standard deviation	$\frac{S\sigma_{OS}}{\sigma_{OS}}$	-	±5%	±5%
6	Stress intensity	K_{IP}	MPa$\sqrt{m}$	110	110
7	Standard deviation of K_{IP}	SK_{IP}	MPa$\sqrt{m}$	0	0
8	Geometry factor	Y	-	0.395	0.395
9	Standard deviation of Y	SY	-	±0.076	±0.076
10	Critical crack size	a_c	mm	244.	30.
11	Standard deviation of a_c	Sa_c	mm	±53.	±6.5
12	Crack growth rate *)	da/dt	mm/year	0.92	1.80
13	Standard deviation of $\ln \frac{da}{dt}$	$S \ln \frac{da}{dt}$	-	±0.587	±0.587

*) $\frac{da}{dt} = \exp\left(0.4370 - \frac{7302}{1.8\,T+492} + 0.00403 \cdot R_e\right) \cdot 10^3$ see Refs. [4], [6], converted to Units of the SI-System.

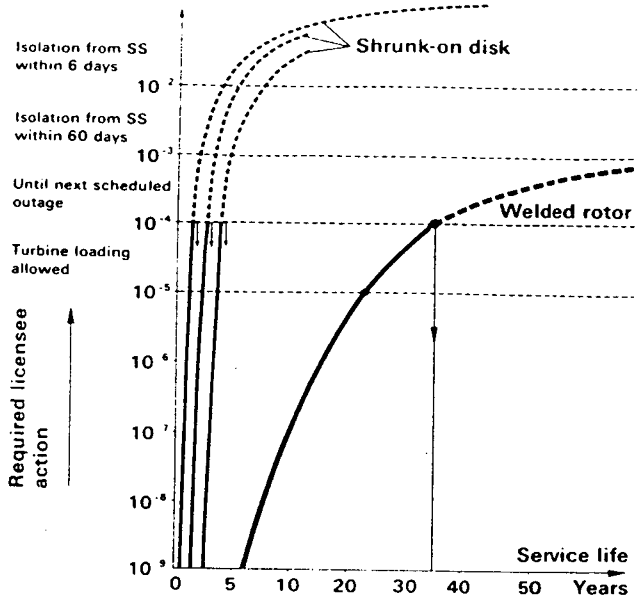


Fig. 8 - Disk failure rate from case study and required inspeciton intervals

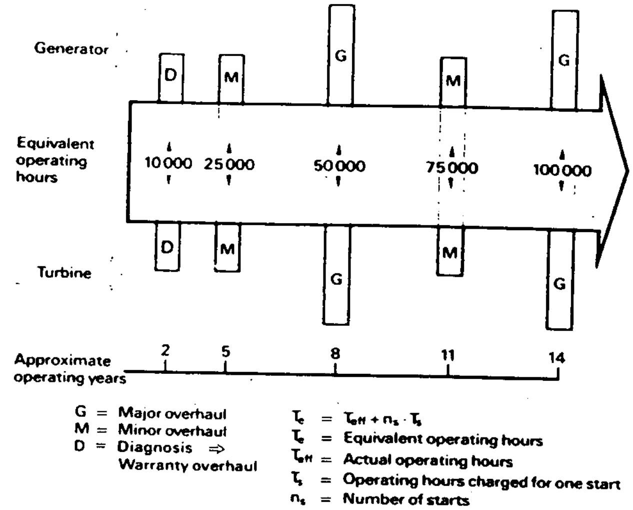


Fig. 9 - Overhauls of turbine and generator

RESULTING INSPECTION INTERVALS, CONCLUSIONS

The probabilities of rotor fragment generation for the welded rotor are orders of magnitudes lower than those for the shrunk-on disk rotor.

Applying the NRC requirements listed in Fig. 5 the following inspection intervals have to be introduced:

	Favorably	Unfavorably
	Oriented	
Welded Rotor	35 years	22 years
Shrunk-on Disk	∿2,5	∿1,5

It must be noted that these results are obtained with simplifying assumptions. The probability of crack initiation and the probability of perforating the casing may, in an actual case lower the probability of missile generation for both designs. On the other hand the number of disks or rotors in the actual power plant will increase the probability of missile generation. In any case, however, the analysis for the welded rotor will reveal much lower probabilities and therefore longer inspection intervals.

BBC have performed missile analysis on all of their LP rotor types in nuclear power plants. The results show that the usual inspection recommendation given in Fig. 9 are in all cases much more stringent than the NRC requirements.

ACKNOWLEDGEMENT

Authors wish to thank J.E. Bertilsson, G. Hårkegard and D. Schlegel, BBC Brown Boveri & Company Ltd. Baden/Switzerland, for valuable discussion and contribution.

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