APPLICATION OF PROBABILISTIC FRACTURE MECHANICS TO OPTIMIZE INSPECTION FREQUENCY OF POWER PLANT COMPONENTS

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ABSTRACT

The forced outages of power plants have been under much scrutiny due to the large cost of replacement power. The scheduled outages, however, vary from utility to utility and from plant to plant within the same utility, thus affecting the availability. A quantitative approach based on the total cost (inspection cost and failure cost) is discussed in this paper for establishing optimum inspections. The approach is discussed first in general and then its application demonstrated for a specific steam turbine component. The methodology uses statistical and probabilistic techniques, fracture mechanics principles and economic considerations.

KEYWORDS

Probability, Fracture Mechanics, Turbine discs, Power Plant, Cost, Optimium Inspection Interval, Stress Corrosion Cracking.

BACKGROUND

Replacement power costs have escalated so much that the overall availability of power plants has become a major concern of both the equipment manufacturers and utilities. It is estimated by EPRI (1982) that an increase in plant availability of 1% will yield additional revenues of $300M annually to the U.S. electrical utility industry. The term "availability" refers to the percentage of total calendar time in a year during which a turbine-generator is available for operation.

The overall availability of power plants in U.S.A. for 1975-1980 period has been 79.3% for 200-574 MW size and 74.6% for greater than 575 MW. The availability of nuclear plants for the same period is 72.2%. There are several detractors from availability. These include unanticipated equipment failures (forced outages) resulting from component breakdowns, human errors, control system failures, consequential damages, etc., and planned maintenance, inspection and repairs (scheduled outages).

Forced outages usually result in the use of more expensive source(s) of power supply. The utilities estimate replacement power costs of up to $1M per day for units of more than 800 MW capacity. Consequently, the avoidance of forced outages has received considerable attention in the past from the equipment manufacturers and utilities.

The overall outcome has been a significant reduction in forced outages so that most (88%) of the unavailability of turbine generators is now due to scheduled outages. One of the major purposes of scheduled outages is to uncover impending component failures soon enough to permit taking appropriate corrective actions prior to the occurrence of a forced outage. Too frequent inspections and repairs, while minimizing forced outages, can and do affect the overall availability and, hence, cost.

Turbine generators of similar designs can differ greatly in their availability. This variation occurs not only from utility to utility but also from plant to plant within the same utility. This strongly suggests differing philosophies of scheduling maintenance outages. Table 1 compares the turbine generator availability of two very similar plants (A&B) but operated by two different utilities. Despite their similarity in design and minimal forced outages, their availability differs by as much as 6.2%. Plants C, D and E are similar in design and owned by the same utility yet differ in their availability by as much as 8.3%.

TABLE 1 - Turbine Generator Availability for 1976-1982

	AVAILABILITY FOR PLANT				
YEAR	A	B	C	D	E
1976	92.6	100.0	85.0	86.9	100.0
1977	89.0	97.3	73.4	85.2	86.0
1978	91.2	78.1	91.2	84.4	91.8
1979	93.7	99.2	90.1	80.3	84.9
1980	82.2	100.0	68.9	94.2	91.5
1981	81.4	95.6	79.2	84.7	91.8
1982	87.1	89.9	87.7	80.8	87.7
AVERAGE	88.2	94.4	82.2	85.2	90.5

This paper discusses a general concept for determining the optimum inspection frequency and then demonstrates its application for a specific steam turbine component. The concept is based on quantifying the probability of component failure as a function of time since last inspection and costs for inspections and component failures.

CONCEPT OF OPTIMUM INSPECTION FREQUENCY

The ultimate objective of any inspection should be to minimize the TOTAL cost. The total cost (over the life of the unit or per year) refers to the cost associated with the inspection and the expected cost associated with equipment failure. The former decreases with decrease in inspection frequency (increase in time between inspections), while the latter increases with decrease in inspection frequency. The equipment failure cost increases because the probability of component failure increases with longer time between inspections. The total cost, therefore, initially decreases with decrease in inspection frequency reaches a minimum and increases again (Fig. 1). This suggests that there is an optimum inspection interval which results in the lowest total cost.

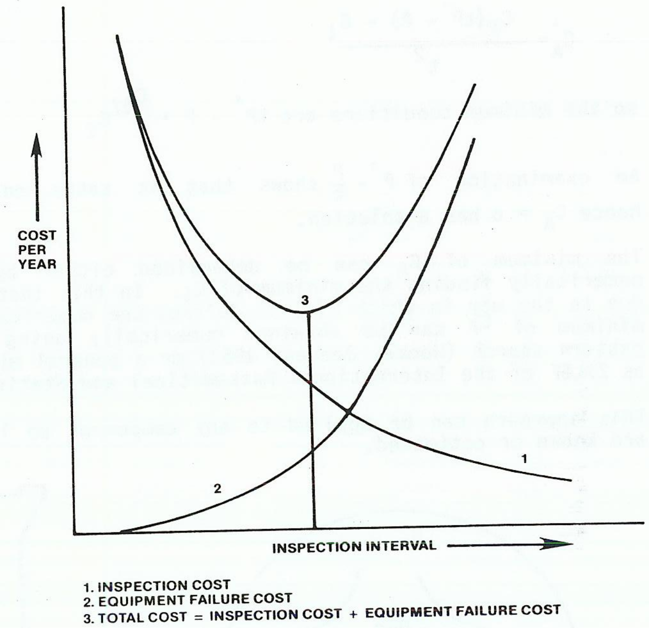


FIG. 1 Optimum inspection frequency concept

OPTIMUM INSPECTION FREQUENCY DETERMINATION

If a probability function, $P(t)$, could be obtained that would relate the probability of component failure to the time since the last inspection, then a cost minimization, recognizing both preventive (inspection) and repair (failure) costs could be conducted as follows: let C_1 be the cost of conducting an inspection and let C_2 be the cost as a result of component failure. Then the total expected cost for a period of t can be expressed as

$$C = C_2P(t) + C_1 \tag{1}$$

$C_2P(t)$ is the expected cost associated with the probability of component failure at time t since the last inspection. C_1 gives the cost of a single inspection only, since additional inspections during the period would change the time scale for the failure probability. To make this quantity more readily comparable among various power plants, we use an annualized cost,

$$C/t = \frac{C_2 P(t) + C_1}{t} = C_A \quad (2)$$

The optimal inspection interval can be defined as that value of t which minimizes C_A.

One first can note that such a minimum exists. C_A is a differentiable function for t>o. Thus a minimum would exist only for $C_A' = o$

$$C_A' = \frac{C_2(tP' - P) - C_1}{t^2} \quad (3)$$

so the minimum conditions are $tP' - P = {}^{C_1}/_{C_2}$ (4)

An examination of $P' - \frac{P}{t}$ shows that it takes on all positive values, hence $C_A' = o$ has a solution.

The minimum of C_A can be determined either by solving $C_A' = o$ or by numerically finding the minimum of C_A. In this instance it turns out that, due to the way in which P(t) is defined the numerical route is better. The minimum of C_A can be obtained numerically using either the method of pattern search (Hooke, Jeeves, 1961) or a general minimization program such as ZXLSF of the International Mathematical and Statistical Library (1982).

This approach can be applied to any component so long as P(t), C_1 and C_2 are known or estimated.

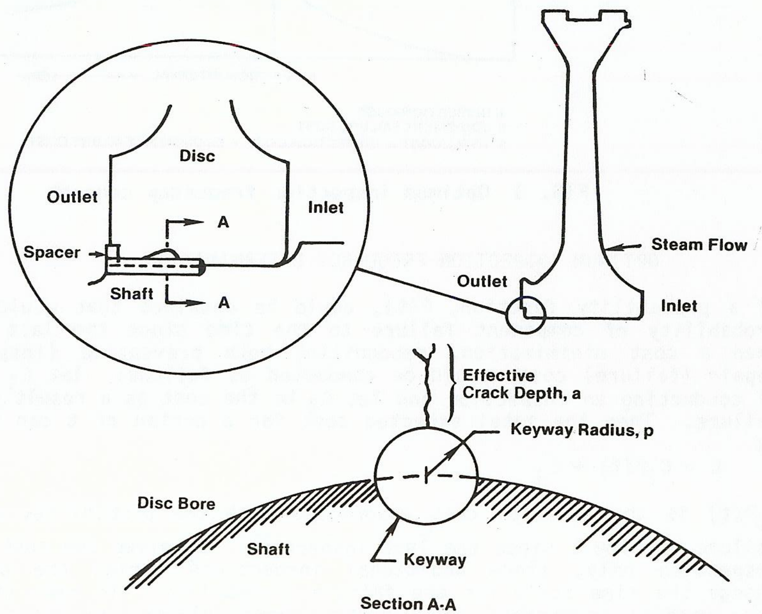


FIG. 2 Disc keyway configuration

DETERMINATION OF OPTIMUM INSPECTION FREQUENCY FOR SHRUNK-ON DISCS

The use of shrunk-on discs for low pressure rotors has been quite common to overcome the difficulty of producing large, high quality forgings. In this design, several individual discs are shrunk-on to a shaft and keyed in place to prevent the spinning of discs independent of the shaft.

In 1969, at the Hinkley Point Nuclear Station in England, discs from a rotor constructed in this manner burst (Hodge and Mogford, 1979) due to stress corrosion cracks emanating from the crown of the keyway. Since then, stress corrosion cracking of bores and keyways in low pressure shrunk-on discs has been experienced widely in both nuclear and non-reheat fossil turbines (Clark, 1981; Curren, 1982; Hodge & Mogford, 1979; Kalderon, 1972; Schleithoff, 1979; Termuehlem, 1980). A typical shrunk-on disc design and location of cracks are shown in Fig. 2.

In an earlier paper (Clark, Seth, Shaffer, 1981), the methodology developed for estimating the probability of disc rupture P(t) was discussed. The methodology was based on the application of probabilistic fracture mechanics. The principal input for determining the probability of disc rupture are: (i) Probability of Crack Initiation, (ii) Crack Growth Rate, and (iii) Critical Crack Size.

Each of the above was modelled probabilistically and is briefly summarized below.

(i) Probability of Crack Initiation

The probability of crack initiation of a disc is treated as a binomial variate and estimated directly from service data showing the number of cracked disc found and the number of discs inspected for each disc position. When the number of cracked discs is zero, instead of using zero, the probability of initiation is computed as $q = 1 - (0.5)^{1/N}$ (5)

where, q = Probability of initiating crack
N = No. of discs inspected.

(ii) Crack Growth Rate

A statistical model was developed for crack growth rate using the field inspection data on crack depth, operating time, disc material yield strength and operating temperature. The mean crack growth rate is given by:

$$\ell nR = -4.968 - \frac{7302}{T} + 0.0278\sigma_{ys} \quad (6)$$

where R = Crack growth rate, T = Temperature ^oR, (^oF + 460), σ_{ys} = Yield Strength of disc at room temperature, ksi.

Thus the Statistical model yields the distribution of crack growth rate if temperature and disc yield strength are known.

(iii) Critical Crack Size

The basic fracture mechanics approach that relates crack tip stresses (expressed as the stress intensity factor, K_I) to the pertinent loading variables for the case of a semi-elliptical surface crack in an infinite plate subject to tension loading was used and is given by:

$$K_I = 1.12\, \sigma \left(\frac{\pi a}{Q}\right)^{1/2} \quad (7)$$

where K_I = applied stress intensity, ksi $\sqrt{in}$; a = crack depth, ins.;
σ = applied nominal stress, ksi
Q = flaw shape parameter, Equation (7) can be rewritten as

$$a_{cr} = \frac{Q}{1.21\pi} \left(\frac{K_{IC}}{\sigma}\right)^2 \quad (8)$$

where a_{cr} = critical crack size, ins
k_{IC} = fracture toughness of disc, ksi $\sqrt{in}$

The variability of several factors that affect critical crack size is incorporated in the model to develop an overall distribution of the critical crack size. The factors considered included stress, toughness, flaw shape and crack branching.

The probability that a given disc will rupture before time t is given by

$$d\,(t) = q.\ p\,(t) \quad (9)$$

where d (t) = probability of disc rupture, p (t) = probability that a crack once initiated will grow to rupture before time t.

Let X (t) be a random variable representing the depth of a crack in a given disc by time t and Y be a random variable representing the critical crack depth. Also let R be a random variable representing crack growth rate then,

$$p\,(t) = \text{Probability}\ (X\,(t) > Y) \quad (10)$$

or

$$p\,(t) = \text{Probability}\ (R.\ t > Y) \quad (11)$$

This probability can be expressed as an integral that can be evaluated by conventional numerical methods.

A more difficult problem may arise in getting realistic estimates of the required costs. In order to test and illustrate the methodology being proposed here, estimates for C_1 and C_2 were generated somewhat crudely. For C_1 the following assumptions were made: (i) inspections can be made during scheduled outage so that inspection does not impair availability, (ii) inspection cost = $40 K, (iii) opening and closing cost = $340 K.

Thus, we take C_1 = $380 K = $0.38M

For C_2 we assume: (i) outage time for repairs - 12 months, (ii) repair cost = $10M, (iii) $C_2 = 365\ (\alpha \bullet CF_\alpha \bullet P_\alpha + \beta \bullet CF_\beta \bullet P_\beta)$ (12)

where CF_x is capacity factor, P_x is cost of power per day, α is fraction of time at peak load, β is fraction of time at normal load and $x = \alpha$ or β

substituting for these parameters, we obtain C_2 = $164.03M.

It should be clear that any specific analysis will require a detailed investigation to obtain P(t), C_1, and C_2.

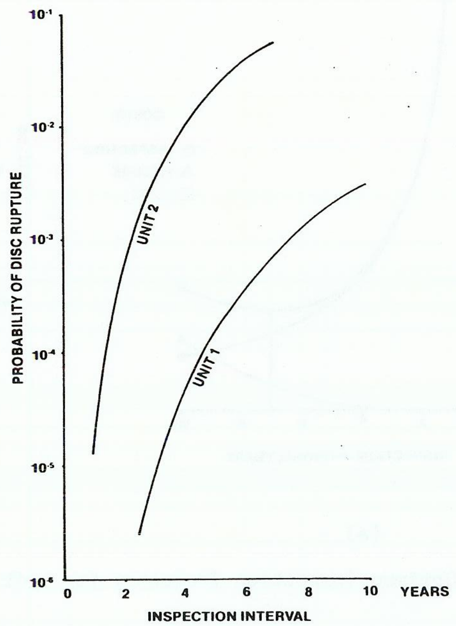
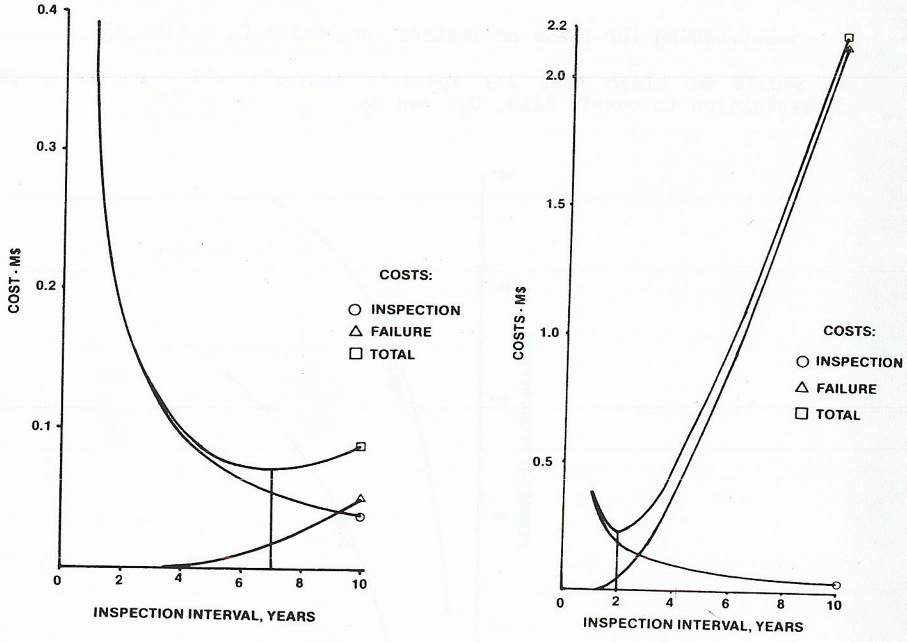


FIG. 3 Probability of disc rupture as a function of inspection interval

Two example problems were run to illustrate the results of such an analysis. The values for C_1 and C_2 obtained above were used and two P(t) functions were obtained (Fig. 3) for turbine units, called 1 and 2, within the range of our experience. Figure 4 gives C_A as a function of t. It can be clearly seen that with respect to the criterion of minimizing the total cost for prevention and repair of a turbine disc failure one should inspect Unit 1 every seven years while Unit 2 should be inspected about every two years. These data show that a decrease in the probability of disc rupture by about two orders of magnitude increases the inspection interval by a factor of 3.5. The lower probability of disc rupture for unit one results primarialy from the lower stresses and lower yield strength of its discs.

In order to check for sensitivity of C_A to the estimate of C_2, the analysis was repeated for C_2 doubled and halved. In neither case did the optimal inspection interval change by more than 10%. This suggests that very accurate estimate of costs of component failures (C_2) is not essential for establishing the optimum inspection frequency.



(a) (b)

FIG. 4 Optimum inspection frequency for unit 1 (a) and unit 2 (b)

DISCUSSION

The significant variation in the availability of turbine generators of similar design is believed to be due at least partly to differences in the way scheduled outages are planned. To minimize costly forced outages, the tendency at times is to perform inspections too frequently. While frequent inspections can lower the probability of forced outages, if they are too frequent, the overall availability could be adversely affected. To some degree, this is borne out by the fact that units of comparable designs have shown as much as 6-8% difference in turbine generator availability.

The concept of establishing the optimum inspection interval is rather simple and straightforward. It basically says that so long as one is aiming at optimizing (minimizing) total cost, too frequent an inspection is as undesirable as too infrequent an inspection.

The application of the methodology to shrunk-on discs involved a very complex failure mechanism and, therefore, required rather extensive analysis to determine the probability of disc rupture. For application of the optimum inspection interval determination, if very accurate numbers are not available it may still be better to use approximate values for P(t) and C_1, C_2 rather than to base the inspection frequencies arbitrarily.

The important point, however, is that with reasonable estimates on the probability of component failures (even if these are based on experience and judgment) and reasonable estimates of costs, one can make a better determination of inspection frequency than would otherwise be possible.

SUMMARY

A significant noted variation in turbine generator availability of similar designs is believed to be at least partly due to differing scheduled outage planning. An approach to establishing the optimum inspection interval that results in the lowest total cost is discussed and its application to the low pressure steam turbine disc has been demonstrated. It is believed that the use of the lowest total cost concept to scheduling inspections can have a significant beneficial effect on turbine generator availability. It is further believed that the same approach can be used in a wide variety of other components.

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