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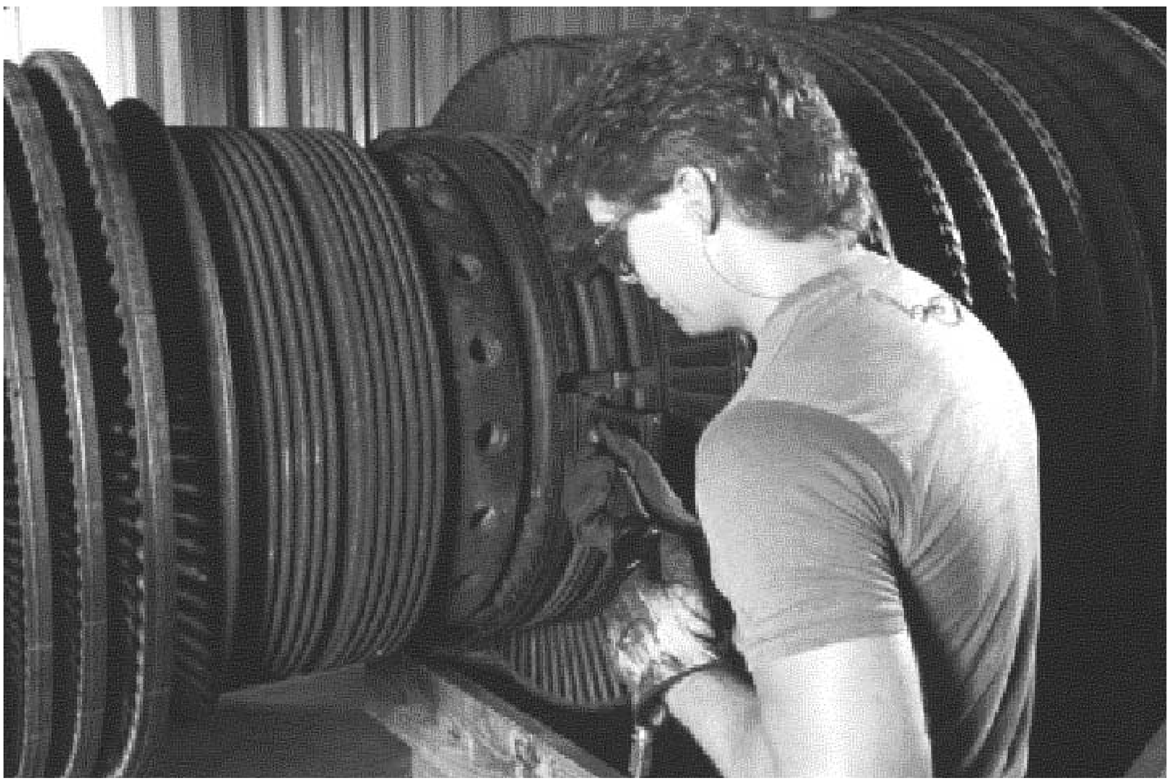
ASSESSMENT OF TURBINE MISSILE PROBABILITY: TECHNICAL AND REGULATORY ISSUES

Phase I

1001267



Assessment of Turbine Missile Probability: Technical and Regulartory Issues

Phase I

1001267

Technical Evaluation, December 2000

EPRI Project Manager

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CONTENTS

1.0 Report Summary

The possibility of nuclear turbine disk rupture and subsequent damage to plant safety-related equipment has resulted in a NRC requirement that this scenario be evaluated in the plant Final Safety Analysis Report (FSAR). Component in-service NDE inspections and operational tests on steam valves are required in order to comply with NRC requirements. Plant operators, tasked with optimizing O&M activities, are seeking a less conservative and more condition-based approach to the activities required as part of the risk evaluation.

1.1 Background

Although the turbine-generator is not considered part of the nuclear plant's safety-related equipment, a possibility exists that high-energy low pressure (LP) turbine missiles (created by turbine disk failure) could penetrate intervening barriers and damage plant safety-related equipment. Disk and rotor failures have occurred in a number of fossil turbine and generators, and one nuclear turbine located outside the U.S. The primary disk failure mechanism is intergranular stress corrosion cracking (IGSCC) which can cause brittle disk rupture if it occurs at the highly stressed bore and keyway regions. A second cause of disk rupture is failure of the turbine overspeed control system, which prevents the turbine rotor from achieving speeds that could cause ductile failure of the disks. NRC regulations specify that probability of missile generation must remain below certain levels. Each nuclear plant's FSAR defines who is responsible for evaluating the failure probability, and the NRC Standard Review Plan defines how the FSAR will be evaluated.

1.2 Objective

Identify any areas of conservatism, in either the present risk assessment process or NRC regulatory risk limits, which could become the basis for modifying current NDE inspection and valve testing requirements on a unit-specific basis. Prepare and propose acceptable alternative practices applicable to both nuclear and fossil units. Initiate the process for NRC and insurer approval of this process in nuclear plants.

1.3 Results

The Phase 1 effort described in the present report provides an overview of the technical and regulatory issues. It provides the planned project approach developed jointly by EPRI, the project utility advisory committee, and industry consultants. Follow-on work will focus on technical details of advanced NDE wheelsonics and risk assessment methodology.

1.4 EPRI Perspective

EPRI's industry role as a managing organization for electric utility collaborative research is important in this effort. With responsibility currently shared by the steam turbine generator OEMs and plant operators, regulatory approval of safety analysis procedures (FSAR) will require their joint involvement and consensus. EPRI foresees benefits from this evaluation to include more flexibility by plant operators in O&M practices required to meet NRC regulations and insurance requirements.

2.0 Introduction

2.1 Objective

Operators of nuclear power plants are seeking ways to maximize production and reduce operating and maintenance costs, within the constraints of safe plant operation. A major plant O&M issue involves adhering to the regulatory requirement to maintain the probability of LP turbine disk rupture at an acceptable level. Plant operators perform in-service disk inspections, and steam valve surveillance testing as part of the required actions for maintaining disk failure probabilities below acceptable levels. These inspections and valve tests increase maintenance costs, and thus affect unit availability and production.

The objectives of this evaluation are to examine: 1) the current methodology for determining LP steam turbine disk failure probabilities, 2) the current risk limits imposed by regulators, and 3) interact with regulatory agencies and insurers on behalf of EPRI member utilities to help develop a more flexible, machine-specific, risk management methodology. The project goal will be to identify any areas of conservatism, in either the present risk assessment process or regulatory risk limits, which could become the basis for modifying current NDE inspection and valve testing requirements on a unit-specific basis.

2.2 Historical Perspective

The possibility of disk failure in built-up LP rotors of large nuclear steam turbines presents a risk to plant safety. The risk is due to the potential for rupture of these shrunk-on disks, and the subsequent damage to reactor safety-related systems by the resulting turbine missiles. The high-energy missiles that would be created by a disk rupture could penetrate intervening barriers and damage reactor safety-related components. This possibility has resulted in the creation of various regulatory requirements, review procedures and supporting analyses used by the Nuclear Regulatory Commission (NRC) to ensure a sufficiently low probability of safety-related system failure due to turbine missiles [1,2,3,4]. These requirements pertain to both the manufacturing as well as the operation of rotor assemblies consisting of shrunk-on disks.

In U.S. fossil-generating plants, several rotor failures occurred in the 1950s [5,6, 7]. Some were generator rotors, which due to their size were the most difficult to forge. Reference 4 tabulates twenty-six failures of rotors/disks between 1951 and 1977 worldwide, of which fifteen produced external missiles. Many of these were traced to manufacturing defects caused by material discontinuities. A combination of improvements in material properties, forging techniques, and the application of non-destructive examination (NDE) applied during the manufacturing phase greatly reduced the future possibility of disk ruptures due to metallurgical defects in the manufacturing phase.

There has been no nuclear turbine disk failures in U.S. generating plants. Outside the U.S., a failure occurred in 1969 at the Hinkley Point Nuclear Station in England. The subsequent investigation indicated that stress corrosion cracking (SCC), originating at the disk keyways, was the primary cause of complete brittle failure of an LP shrunk-on disk [8]. The Hinkley Point failure alerted the industry that service-related disk cracking due to IGSCC was a potential factor relative to nuclear safety-related system damage.

2.3 Role of EPRI in Disk Failure Probability Assessment

EPRI project 047015 has been established to investigate alternative means for satisfying NRC regulatory requirements in the area of turbine disk failure probability. EPRI will manage this project, using both in-house expertise and contracted specialists. The project is considered collaborative in the sense that EPRI utility members will participate in the advisory process. It is recognized that success of this effort is strongly dependent on forming a consensus within the industry, including the plant operators, turbine-generator OEMs, and the regulatory agencies. As an independent and objective organization, EPRI is in the best position to create this consensus and manage the project.

2.4 Scope of Report

The purpose of this report is to clearly define the objectives of the LP disk failure probability project, and outline the proposed technical approach. Following a review process, this report will then serve as a basis for discussions in 2001-2 among the member utilities participating in this project, the OEMs, and ultimately the regulatory agencies. Specific technical assessment procedures will be created as separate documents subsequent to this present report.

The report scope includes: 1) factors affecting safe operation of shrunk-on disks, 2) a discussion of the current regulatory guidelines which affect plant O&M activities, and 3) summary of project plan and technical approach to meeting the project objectives as stated above.

3.0 Components of Safety-Related System Failure

The NRC defines three components of the probability of failure assessment derivation [4]:

1. Probability of missile penetrating turbine casing (P_1)
2. Probability of missile striking safety-related system (P_2)
3. Probability of struck safety system malfunctioning (P_3)

The calculated probability of safety-related system failure (P_4) is the product of the three components above:

$$\mathbf{P_4 = P_1 \times P_2 \times P_3}$$

The work of Spencer Bush [4] describes the derivation of typical values for P_1, P_2 and P_3. From this work, NRC guidelines (Standard Review Procedure Section 2.2.3 and Regulatory Guide 1.115) states that P_4 must be less than or equal to 10^{-7} per year.

The NRC stipulates that P_3 is assumed to be 1.0, and that P_2 is dependent on orientation of the turbine relative to the reactor, safety-related equipment, essential systems, and the auxiliary building. Essentially, favorable orientation means that potential turbine missile trajectories are not aimed at *any* plant system that is needed to safely operate, or shut down, the reactor. This would include reactor cooling pumps, the control room, etc. Figure 1 contains a diagram defining favorable and unfavorable orientation of the turbine-generator. In the favorable orientation, P_2 x P_3 is assigned a probability of 10^{-3}. In the unfavorable orientation, P_2 x P_3 is assigned a probability of 10^{-2}. Therefore, the corresponding missile generation probability (P_1) upper limits are 10^{-4} and 10^{-5} for favorable and unfavorable turbine orientations respectively. P1 is actually composed of a summation of individual failure probabilities for all low-pressure turbine disks. Due to the relatively high energy of the L-0 stage disk, it is a major contributor to the P_1 risk evaluation.

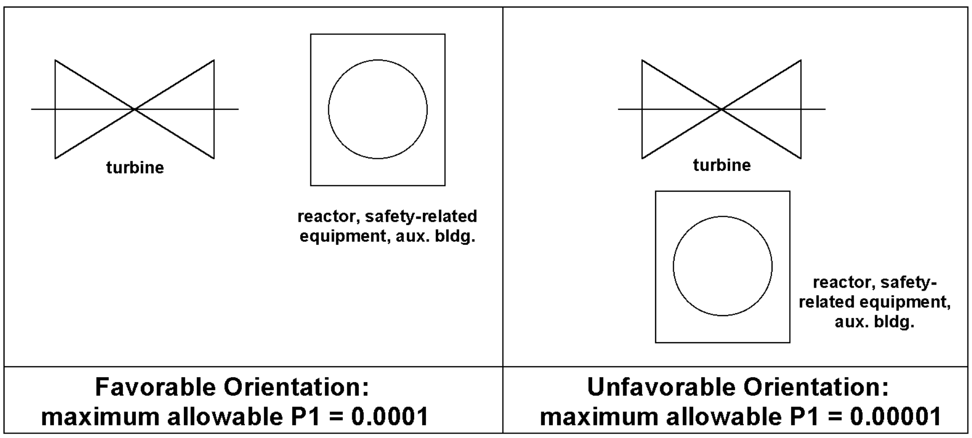

Figure 1 - Turbine Orientation

4.0 Disk Failure Mechanisms and Factors Affecting Failure Probability P_1

This chapter gives an overview of the factors that affect reliable and safe operation of shrunk-on turbine disks. This is not intended to be a detailed explanation on the subject. References 9-12 provide more detailed material. In this chapter, the failure mechanisms are first identified, then three key areas which affect failure are described: 1) disk design and manufacture, 2) turbine operational factors, and 3) maintenance practices that affect the potential for turbine overspeed.

Figure 2 shows the interrelationships between the various factors affecting probability of damage to safety related equipment (P_4) and in particular the probability of disk rupture and penetration through the turbine casing (P_1). An analysis which quantifies the effect of each element shown in the diagram is used to derive the disk failure and missile generation probability (upper limit of 10^{-4} and 10^{-5} for favorable and unfavorable turbine orientation respectively).

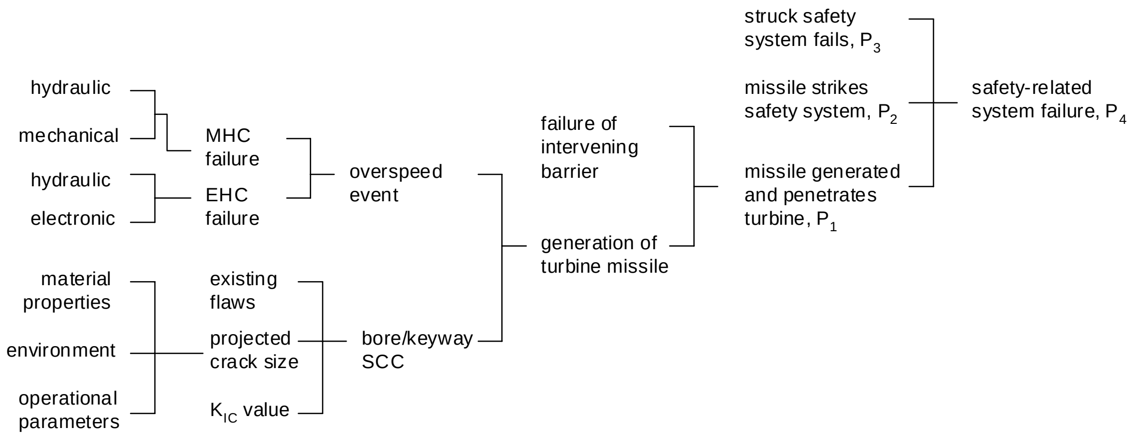

Figure 2 - Factors Affecting Failure of Safety-Related system

4.1 Failure Mechanisms

Turbine missiles that have sufficient energy to penetrate the turbine casing require disk failure (blade attachment cracking cannot create a missile of sufficient size). The emphasis of this project, therefore, is strictly on bore/keyway cracking.

Shrunk-on disks can experience either *ductile* or *brittle* failure. Ductile failure could occur in an unflawed disk if the rotor speed (and corresponding centrifugal stress) were allowed to exceed the design upper limit. Although it is the disk which ultimately fails in this case, it is actually caused by a failure of the turbine overspeed protection system.

Brittle failures occur as a result of cracks initiating in the bore region, and propagating in the radial direction. The most common type of cracking observed in disks is intergranular stress corrosion cracking (IGSCC). This intergranular cracking occurs under steady (not cyclic) stress conditions, and the crack growth rate is a function of material properties and environmental factors [13]. Figure 3 describes the nature of IGSCC crack growth as a plot of crack growth rate (da/dt) versus stress intensity (K_I). When the stress intensity exceeds the threshold level, K_{th}, crack growth is essentially constant and independent of K_I. Growth rate increases as K_I approaches critical stress intensity, K_{Ic}. Finally, when K_I reaches K_{Ic}, rapid crack growth occurs. The ensuing disk rupture will be a combination of brittle, then ultimately ductile, failure.

Because of the lower operating temperature of the L-0 stage disk, crack growth rates are so low that IGSCC, as a failure mechanism, is very unlikely. The L-1 through L-5 disks typically exhibit higher crack growth rates, and are also nearer to the aggressive environment of the steam phase transition zone (Wilson Line). Therefore, the risk of keyway cracking is greater for the relatively lower-energy upstream disks. Missiles from these disks, however, have a correspondingly lower probability of penetrating the turbine casing. Since P_1 is the sum of the probabilities for each individual disk, these factors are all included in the risk analysis.

4.2 Turbine Design and Manufacture

The built-up rotor design evolved due to the early inability to produce a quality forging of sufficient size for fully-integral nuclear rotors. Disks were shrunk (or “stacked”) on a stepped shaft. The shrink-fit is necessary to maintain contact at the disk-shaft interface at turbine operational speeds since the disk bore diameter increases due to centrifugal loading. In case of turbine overspeed events (in which the interference shrink-fit may be lost) a keyway(s) is machined into the disk and shaft as shown in Figure 4, to ensure that the disk is locked to the rotor. Loss of shrink-fit typically occurs at about 25 percent turbine overspeed, which would require multiple control system failures.

As discussed in the Chapter 1, experience with fossil disk failures of large steam turbines in the 1950s resulted in an improvement in the quality of disk elements, and the benefit of these efforts were applied to the nuclear industry in the initial turbine designs. Improved forging techniques and full NDE inspections have greatly reduced the number, and particularly the size of initial defects in the disks of newer machines. The use of 3.5 NiCrMoV steel also provided improved material toughness relative to previous rotor materials.

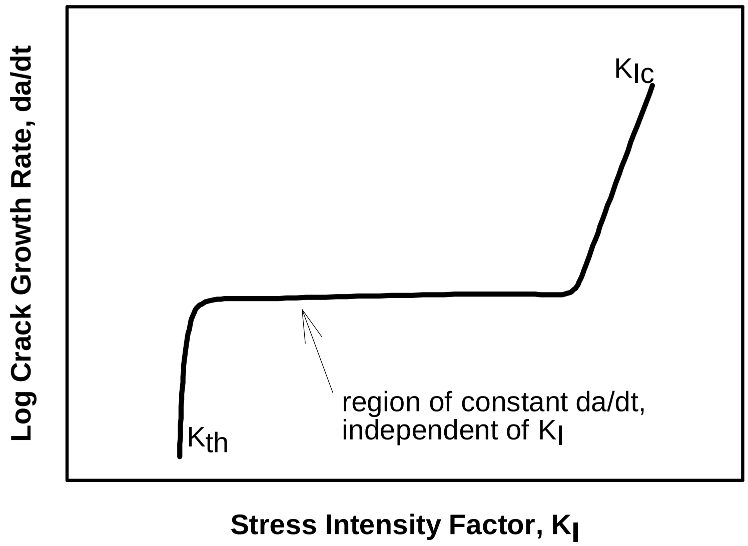

Figure 3 - Typical IGSCC Crack Growth Rate Curve

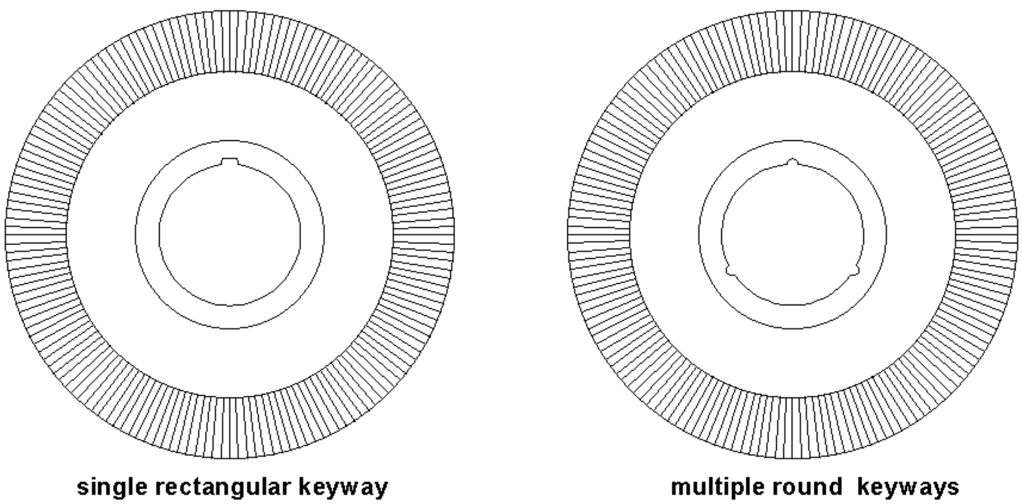

Figure 4 - Turbine Disks with Keyways

The mechanical design of built-up rotors produces inherently high-stress areas of the disk. In particular, the bore and keyway experience high tensile stresses due to centrifugal loading and thermal effects. The bore is nominally the most highly stressed area, subjected to both centrifugal and thermal loading. The disk keyway presents a stress concentration feature, which further increases the maximum local tensile stress [14].

Perhaps the most significant design factor affecting the operational life of shrunk-on disks is the potential for introduction of corrosive species into the disk-shaft interface. Salts and acids, which invariably precipitate out of solution at the steam phase transition zone [Wilson zone] of the low pressure turbine, migrate as an aqueous solution into the highly-stressed bore and keyway regions. A corrodent concentration mechanism in the crevices of the disk-shaft areas then aggravates the problem. The flashing of steam (containing corrosive species) off relatively hot surfaces (i.e. metal above the local saturation temperature) results in a relatively large concentration of these corrosive species in the highly stressed keyway and blade attachment areas [13].

4.3 Turbine Operational Factors Affecting Disk Cracking

Shrunk-on disk design increases the risk of turbine rotor failure for the reasons described above. Operational factors such as cycle chemistry control and operating profile enhance the effect of these design factors on reliable disk life.

Wet Steam Chemistry

Wet steam at high temperatures can produce IGCSS under the right circumstances, even high purity steam. The nuclear cycle produces higher temperature wet steam than the fossil cycle, since the onset of phase change occurs at a higher pressure in a nuclear LP turbine. This higher metal temperature accelerates crack growth, and likewise any dissolved oxygen accelerates both initiation and growth of IGSCC cracks.

NaOH (caustic) is a contributor to IGSCC. The caustics precipitate out of the turbine steam near the phase transition zone, and the levels are determined in part by the feedwater chemistry. IGSCC often appears initiates at corrosion pits, which often form during turbine lay-up in moist environments. Test data indicates that corrodent concentration reduces the threshold stress intensity, and increases the IGSCC growth rate.

Most IGSCC related damage has been observed on disks operating in relatively high temperature wet steam, found in the immediate region of the LP turbine phase transition zone of the nuclear cycle. Although the presence of corrodents such as NaOH accelerate crack, it is not a requirement that it be present for cracking to initiate.

4.4 Overspeed Protection

Steam turbine rotors are designed to safely operate at nominal levels of overspeed (disk bore stress increases with rotor speed squared). However, even an uncracked disk would eventually experience ductile failure at rotor speeds above the design upper limit (typically above 180 percent of rated speed). Primary and back-up control systems are employed, which are intended to prevent overspeed by isolating the turbine from the steam supply at rotor speeds beyond 112 percent of rated speed. If these systems malfunction, it is possible for the rotor speed to approach rupture speed. NUREG 1275 Vol. 10 describes an event at the Salem Nuclear Plant in which the turbine overspeed protection system failed. Other relevant incidences related to fossil and nuclear turbine overspeed is tabulated in Reference 4. From 1956 to 1960, ten incidences occurred in fossil plants, five of which produced turbine missiles. From 1970 to 1975, nine incidences of valves failing to fully close were reported in U.S. nuclear plants, although none produced an overspeed condition.

Valve surveillance testing and mechanical overspeed trip testing must be periodically performed to ensure that the control systems function properly, and valves fully close to isolate the steam supply. Requirements for valve surveillance testing can impact plant operations by requiring either load reduction, or off-line testing at relatively frequent intervals. In a base-loaded nuclear plant, there are few opportunities to perform these valve tests without reducing unit availability or unit load. Although valve testing decreases the likelihood of an overspeed protection system failure it also results in a loss of MW production, as well as increasing the number of speed cycles and thermal cycles.

5.0 Overview of Current Regulatory Guidelines

The current regulatory constraints designed to limit the probability of disk failure can be summarized as follows:

1. General Design Criteria 4, “Environmental and Missile Design Bases” of Appendix A, “General Design Criteria for Nuclear Power Plants” to 10 CFR Part 50, “Licensing of Production and Utilization Facilities” states that safety related systems be protected against effects of missiles resulting from equipment failures. This essentially states that the disk integrity issue must be included in the Final Safety Analysis Report (FSAR).
2. NRC Regulatory Guide 1.115, “Protection Against Low-Trajectory Turbine Missiles”, provides an overview of the acceptable methods for

protecting safety related equipment by appropriate orientation of the turbine generator. This document defines the acceptable probability limits, for both favorable and unfavorable orientations. The P_4 value of 10^{-7} and the P_1 values of 10^{-4} and 10^{-5} are defined in Regulation Guide 1.115.

3. In the licensing process, the applicant submits an FSAR, which contains an analysis of the disk failure probabilities and associated maintenance plan. The guidelines for NRC evaluation of the SAR are contained in NUREG-0800 (formerly NUREG-75/087), section 10.2.3 of the NRC Standard Review Plan. NUREG-0800 requires the FSAR to address material properties and toughness testing, disk strength and overspeed limits, pre-service and in-service NDE inspection. There is significant flexibility in how the FSAR addresses the issue of disk integrity. Some licensees simply state that they will comply with OEM recommendations, in which case the OEM will define disk failure probabilities and corresponding inspection intervals. Other licensees will use their own analysis, which means that any modification to the inspection interval requires an amendment to the FSAR.
4. The NRC produces a Safety Evaluation Report (SER), which essentially confirms the approval of the FSAR, and re-states the key constraints such as disk inspection intervals and valve surveillance test frequencies. Currently, the NRC imposes a maximum inspection interval of six years for shrunk-on disks, and ten years for fully-integral (FI) rotors. (Fully-integral rotors are machined from a single forging, and thus contain no shrunk-on disks).

The NRC requires that FSARs be amended whenever a change in equipment or maintenance procedures will *“result in more than a minimal increase in the likelihood of occurrence of a malfunction of a structure, system or component (SSC) important to safety previously evaluated in the FSAR as updated”*

5.1 Operational Impact of Guidelines

In general, the NRC guidelines on disk integrity affect nuclear plant operations in three ways by defining:

1. The frequency with which individual LP turbine disks require NDE inspection of the keyway area.
2. The frequency of testing for the main stop, control, and intercept valves.
3. The frequency of testing of the mechanical overspeed trip system.

Each of the above items affect, or have the potential to affect, megawatts production. Costly LP turbine disassembly is required to inspect disk keyways. This LP turbine work is typically performed within the refueling outage, and thus remains off critical path. If the FSAR and/or OEM recommendation allow a maximum six-year inspection on all disks, the plant will run four 18-month refueling cycles between LP inspections. For a typical nuclear plant in which there are four turbine sections (one HP turbine section, and three LP sections), a single section is disassembled and overhauled during each refueling outage, which maximizes the chance that turbine maintenance work will remain off critical path. Problems arise if the reactor permits longer refueling intervals (20 or 24 months). In these cases, an extension of the six-year maximum inspection interval would be strategically important, to avoid the need to overhaul more than one turbine section during a refueling outage (and risk turbine maintenance becoming critical path work).

On-line valve surveillance testing requires a reduction in megawatts as each of the four control valves is sequentially closed. Stop valves and control valves are tested as part of this process. The intercept valve requires the unit to be off line, or at significantly reduced load, for testing and therefore has a large effect on megawatts production.

Lastly, the mechanical overspeed trip system (MHC) can be partially tested on line, by temporarily isolating the hydraulic system, and inducing the centrifugal speed sensor to trip at synchronous speed. This tests only the trip mechanism; not the hydraulic valve control system and corresponding valve closure. Full testing of the mechanical overspeed prevention system requires that the turbine be intentionally operated (off-line) at increased speed. In this way, the entire system consisting of the speed sensor, hydraulic/electronic controls, and valve closure is tested. This is typically performed as part of system startup, prior to grid synchronization. If the unit runs reliably for extended periods of time, then the requirement to fully test the mechanical overspeed protection system does significantly affect unit availability, since the unit must be brought off-line.

In summary, operators seek to decrease the frequency of valve testing for a number of reasons:

1. Effect on megawatts production
2. Need to change reactor conditions; including possible shutdown
3. Increased chance of operator error during test, causing unit trip

6.0 Approach to Achieving Industry Objectives

Operators of nuclear power plants are seeking ways to maximize production and reduce operating and maintenance costs, within the constraints of safe operation. Identifying and removing any conservatism in the requirements for turbine valve surveillance testing and/or turbine disk inspections can contribute to this objective. The goal of this EPRI project is to identify, prioritize, and seek regulatory and insurance provider approval for changes to O&M procedures which would result in members having increased flexibility for managing disk integrity issues. Although the primary motive is decreasing O&M costs and maximizing production, this may be best achieved in different ways at each plant due to individual differences in turbine condition, refueling outage cycles, and maintenance practices. For example, some plants may benefit from *increased* valve surveillance testing, if the benefit were reduced disk inspection intervals. Other plants may already have long disk inspection intervals, and desire reduced valve surveillance testing (which reduce operating costs).

6.1 Project Direction

Potential directions that this project could take that would advantagously affect plant O&M costs include:

(a) Increase in the maximum allowable P_4 from the 10^{-7} value currently imposed by the NRC

(b) Re-evaluate the P_2 and P_3 probabilities to identify any conservatism. Any reduced values for these ‘standard’ probabilities will correspondingly increase the allowable maximum value for P_1 (disk failure probability).

(c) Refine the methodology for calculating P_1 (disk failure probability). Reduce possible conservatism by parameterizing the process to allow plant operators to take greater advantage of increased knowledge of:

- (i) current physical condition of the disk (applying advanced NDE techniques to disk bore and keyway area)
- (ii) operating environment of the disk, including steam chemistry and speed/thermal cycling
- (iii) crack propagation rate and failure probability given the current and projected physical environment, duty cycles, etc.
- (iv) effect of variations in the intervals and scope of surveillance tests of stop, control, and intercept valves; i.e. adjust failure probability to reflect more rigorous or frequent maintenance of easily accessible valves

Regarding step (2) above, operators may not wish to return units to service with P_1 probability values higher than the current maximum limit of 10^{-4}. Even in the absence of a regulatory requirement, the risk of damage and high consequential cost may be a practical constraint to increasing P_1. Re-evaluating P_2 and P_3 for unfavorably oriented turbines may be justifiable.

Part of the refinement in step (3) above would include possible enhancements to the basic probabilistic analysis process. Increasing the parameters used in the Monte-Carlo simulation, and increasing the number of Monte-Carlo iterations are examples of improvements to this basic process. A second aspect of step (3) refinement involves reducing the uncertainty in the values of each parameter used in the probabilistic risk assessment (refer to diagram in Figure 2). Material toughness, sizing of existing cracks, stress intensity vs. crack size, and calculated critical crack size are examples of key parameters affecting disk failure probability due to keyway IGSCC. Likewise, overspeed protection system failure rates (industry-wide) could be used to evaluate any reduction in failure rate that is justified by historical plant operating data, or by improved maintenance/inspection of the system and it components [15].

Any, or all, of the tasks defined in 1) through 3) above could be undertaken. Prioritization of the factors affecting disk IGSCC is necessary to identify those uncertainties that most affect the final P_1 probability. The best approach would be that which provides the maximum relief (i.e. increased intervals for disk inspection and/or valve testing) at minimum R&D cost, <u>and</u> the best chances of gaining regulatory approval.

6.2 Summary of Proposed General Strategy

EPRI will address all potential issues affecting disk integrity, as identified above, in a multi-phase approach:

1. **Phase 1** will evaluate feasibility of changing the NRC-imposed values for P_2 and P_3, both from a cost and regulatory approval perspective. At the same time, the feasibility of increasing the current P_4 probability limit of 10^{-7} will be assessed.
2. **Phase 2** will strictly address P_1, and include issues involved in both keyway IGSCC and overspeed protection. The result of Phase 2 will be a recommendation for new industry-wide procedure for probabilistic risk analysis of disk failure.
3. **Phase 3** will consolidate results of Phase 1 and 2 and approach the NRC for approval of both Phase 1 and Phase 2 recommendations.

The Phase 1 and 2 work will be undertaken in parrallel.

7.0 Approach to Achieving Industry Objectives

This chapter will provide a general discussion of the technical issues involved in improving and standardizing the process for evaluating P_1. Addressing these issues is one of the project goals for 2001-2.

7.1 Steam Valve Surveillance Testing

Reference 15 describes revised valve surveillance test options proposed in 1993 for operators of General Electric nuclear T-G sets. These new options were based on work initiated in 1991 by the BWR Owner's Group (BWROG). The standard intervals, since 1984, had been weekly/monthly/weekly for the main stop, main control, and intermediate stop/intercept valves respectively. Reference 15 defines three 'schedules' for valve surveillance testing that may be offered to each owner following in-service inspection of shrunk-on disks (see Table 1). These various test intervals are factored by General Electric into the P_1 probability calculation. As would be expected, the increased valve test intervals correspondingly increase the P_1 probability. However, the new P_1 values may still not produce probabilities that exceed the upper limits of 10^{-4} and 10^{-5} as defined in Table 1. This is because the disk condition may be such that risk of brittle failure due to IGSCC may be relatively low.

Table 1 – Alternative Steam Valve Testing Intervals for GE Turbines (from GET-8039.1)

Schedule no.	**Test Interval** (main stop/main control/intermediate)
1	weekly/monthly/weekly *or:* monthly/weekly/weekly
2	monthly/quarterly/monthly *or:* quarterly/monthly/monthly
3	quarterly/quarterly/quarterly

The type of process defined above reduces conservatism by giving credit for the reduced risk of one mode of failure while relaxing the constraints on the other. It recognizes that the NRC requirement states only that the <u>total</u> probability must not exceed a certain value, and that the relative <u>portions</u> of this risk due to brittle IGSCC failure and malfunctioning of the overspeed protection system is not mandated. The NRC appears increasingly open to this approach. This same process of re-evaluating surveillance test intervals, used by General Electric, should be extended to include other turbine-generator OEM's.

The revised failure probabilities for turbine overspeed protection systems developed by GE on behalf of BWROG were based on an extensive industry survey of operating experience with GE turbines up to 1991, in which data from 62 turbines was solicited. Use of historical data to justify revised failure probabilities is considered the most accurate and most likely to receive regulatory approval. Since 1991, there has been an additional nine years of industry operating experience, so it is believed that both General Electric, as well as other OEM's, would benefit from re-assessing industry operating history on steam valve failures. Factoring in this experience gained may reduce any conservatism inherent to the original risk assessment methodology.

7.2 Advanced Disk Boresonics Techniques

Advanced ultrasonic inspection techniques are being applied to a variety of plant components that were previously inspected with conventional NDE technology. Implementation of advanced techniques for other turbine inspection applications have resulted in improved performance in terms of flaw sizing and flaw characterization. Disk keyway/bore inspection may also benefit from implementation of similar ultrasonic technology. Of the many factors that affect the determination of failure probability for individual disks, ultrasonic defect detection and sizing information is a key component. For the past 20 years, ultrasonic inspections of the disk bore and keyway area have been performed to detect IGSCC.

Current state-of-the-art techniques for inspection of the disk bore/keyway area use a series of individual, conventional, single angle, ultrasonic probes (Figure 5). The use of non-focused, fixed angle probes, in a long metal path application, limits flaw sizing performance and maximum inspection coverage of the area of interest [16]. Consequently the limitations of these techniques require assumption of a minimum default flaw size for every unsized target detected. This default condition impacts disk remaining life predictions resulting in a shorter time interval between in-service inspections.

The task of the NDE investigation, performed as part of this project, will be to evaluate the application of two advanced ultrasonic inspection techniques to wheelsonic testing: a) linear phased array probe technology, and b) time-of-flight diffraction.

Linear Phased Array

A linear array probe is a series of individual, small ultrasonic transducers arranged in a row. Each transducer element has its own electrical connections and is acoustically isolated from the other elements. Each element has its own pulser/receiver circuit and produces its own radio frequency, time/amplitude response, called an “A-scan”. The individual A-scans are summed and the resulting A-scan is saved. The angle, mode and focus of the ultrasonic beam are controlled by varying the timing pulse and reception for each element before the individual element responses are summed. The array probe successively generates longitudinal-mode or shear-mode sound beams, or both, from (typically) 30 to 80 degrees, in one-degree increments. This capability may allow increased coverage of the bore/disk interface area. Beam focusing is also possible and may provide improved defect sizing capability (Figure 6).

Use of the linear array probe is predicted to provide better signal-to-noise ratio and a more concise beam profile resulting in improved detection, sizing, and characterization of service-induced flaws as compared to current inspection practices [17].

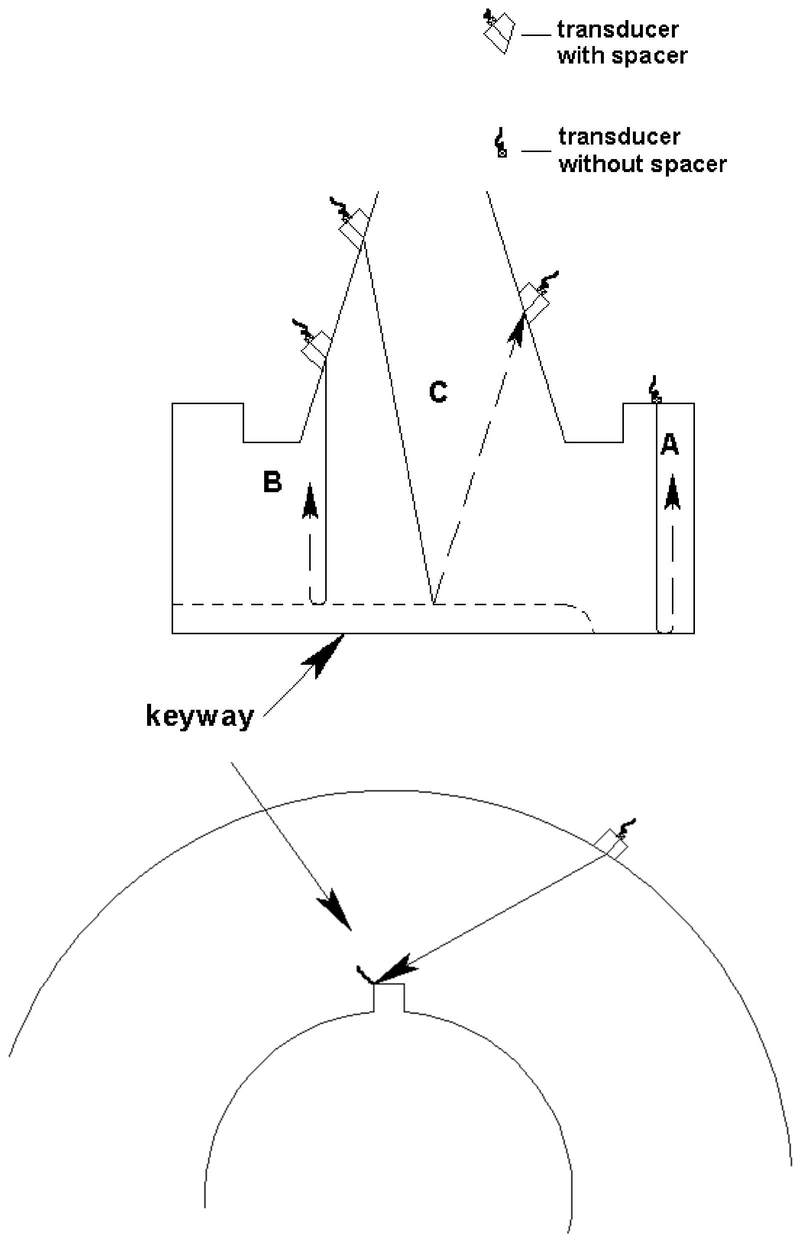

Figure 5- Typical Ultrasonic Transducer Placement for Disk/Bore Inspection

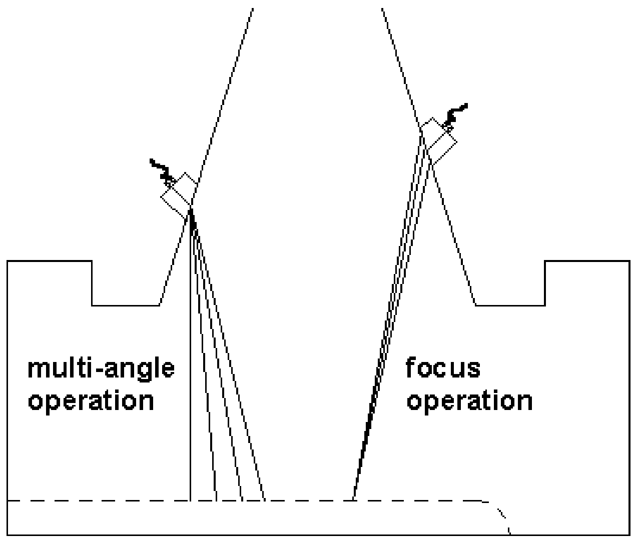

Figure 6 - Applications of Linear Phased Array Technology to Turbine Disks

Time-of Flight Diffraction

The second technique, time-of-flight-diffraction (TOFD), is a variation of the pitch-catch technique using a transmitting transducer and a receiving transducer (Figure 7). Transmitted ultrasonic energy is diffracted from the tip of a crack as well as transmitted along the scanning surface and reflected from the backwall. One advantage of TOFD over the conventional pulse-echo is its insensitivity to flaw orientation. TOFD may also offer an advantage in depth and length sizing of cracks [18].

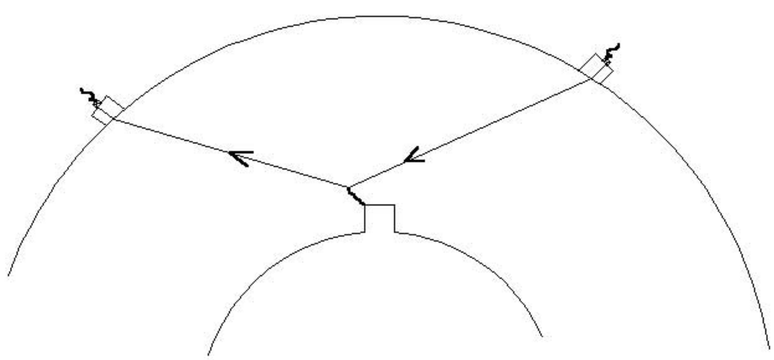

Figure 7 - Time-of-Flight Diffraction Application

Inspection Mockups

Two GE style mockups will be used for evaluation of the proposed advanced ultrasonic techniques. The first is a removed-from-service disk with keyway cracking (Figure 8). The second is a GE style disk manufactured for a previous EPRI project RP2857 [19]. This disk contains five keyways, four of which have EDM notches or cracks of known size (Figure 9).

NDE Project Milestones

Tasks to be accomplished and reported for the NDE portion of this project include;

- Evaluation of linear phased array probe technology flaw detection and sizing on two GE style mockups with disk bore/keyway flaws.
- Evaluation of time-of-flight diffraction techniques for flaw detection and sizing on two GE style mockups with disk bore/keyway flaws.
- Evaluate new wheelsonic methodology on Westinghouse design disk

7.3 Missile Generation and Probabilistic Fracture Mechanics

Fracture mechanics (FM) analysis plays a key role in assessing the probability of missile generation due to failure of shrunk-on disks over the time interval between in-service inspections. Two aspects of missile generation are recognized: 1)-disk fracture at keyway/bore, and 2)-disk fragment penetrating the turbine casing. Fracture mechanics addresses the first aspect by evaluating the growth of IGSCC cracks from their existing size to the critical size, at which rapid unstable growth occurs (i.e. brittle failure).

Disk Fracture

Deterministic FM analysis, using worst-case values for the key parameters, is conservative and often leads to a recommendation to remove or replace the damaged disk. For this reason, a probabilistic fracture mechanics (PFM) analysis is recommended, in which values for the following key parameters are varied according to specific distributions:

1. Stress in vicinity of bore/keyway
2. Initial crack size
3. Rotor speed
4. Fracture toughness vs. FATT

5. FATT
6. Operating temperature of bore/keyway area
7. Crack growth rate vs. temperature and yield strength

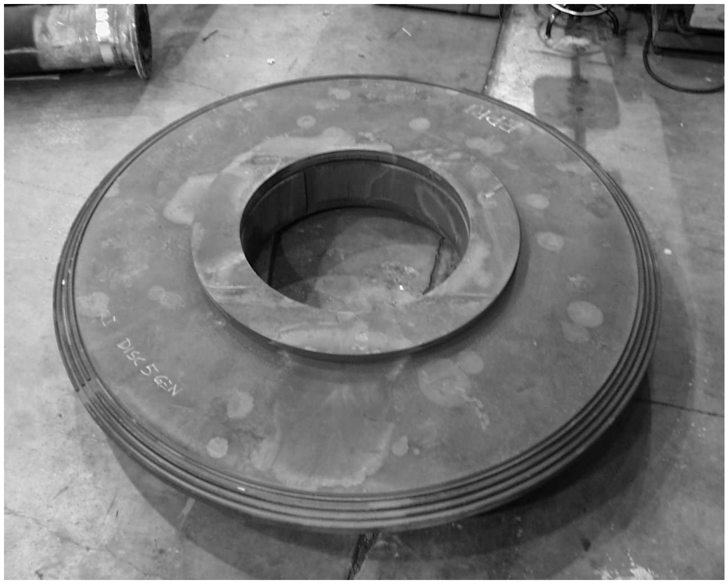

Figure 8 - Retired Disk with Cracking

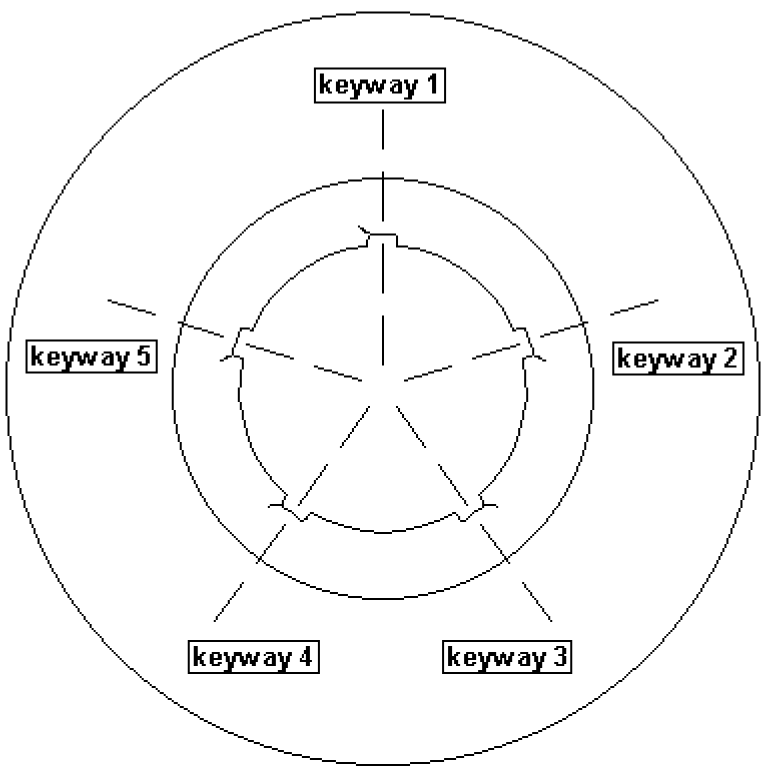

Figure 9 - Test Mock-Up of Disk with Cracking

A probabilistic approach reduces conservatism by allowing for the fact that all worst-case conditions and parameter values are unlikely to occur simultaneously. In two recent disk PFM analyses, a detailed Monte-Carlo simulation was performed to assess the remaining life of disks [20,21]. A large number of iterations (1-10 million) were performed to ensure that the resulting failure probabilities were statistically relevant. Several analyses using the Monte-Carlo method was performed, each using various random number generators and seed values to check repeatability and consistency of results. In one case, the calculated disk failure probabilities were lower than the OEM calculations [20]. The NRC reportedly accepted these revised failure probabilities.

Material toughness and crack growth rate were found to be the dominant factors influencing the failure probability. This suggests that future investigations into these factors, with a goal of reducing uncertainty, has the greatest potential benefit to the overall failure probability assessment effort.

The analysis in Reference 20 took advantage of information on crack growth rate inferred from NDE results that were obtained from two consecutive in-service inspections. This information was used to limit the range of crack growth rates, da/dt, calculated by the equation below obtained from Westinghouse [9] and accepted by the NRC with C1 = –4.968 [22].

$$\ln\left(\frac{da}{dt}\right) = C_1 - \left(\frac{7302}{T}\right) + 0.0278 * \sigma_y$$

The variable T refers to the operating temperature of the disk (°R), and σ_y is the disk yield strength (ksi). The units for crack growth are inches/hour. The use of observed crack growth from sequential NDE inspection results represents a viable way to continually reduce uncertainty in crack growth rate distributions used in probabilistic analyses. This could be applied in the future on an industry basis to further refine the above growth equation.

Fragment Penetration

P_1 includes the probability of a disk fragment penetrating the turbine casing following disk fracture. Size of the fragment, the casing/diaphragm arrangement, and assumed fragment orientation are some of the factors that play a role in the probability of casing penetration by the disk fragment.

Impulse turbines feature more massive diaphragm rings than reaction turbines (Figure 10). These impulse diaphragms reduce the likelihood of disk fragment penetration by "trapping" the fragment inside the turbine. The exception is the L-0 disk, which does not have a diaphragm on each side of the disk, and is therefore at greater risk of becoming a missile in the event of fracture.

In summary, PFM represents the best approach to defining the probability of disk failure over specified time intervals. The overall approach to this EPRI project in 2001-2 should include development of a standardized technical procedure for PFM of disk keyway/bore cracking. Nuclear plant operators, in collaboration with EPRI, could seek regulatory approval for a revised standard procedure.

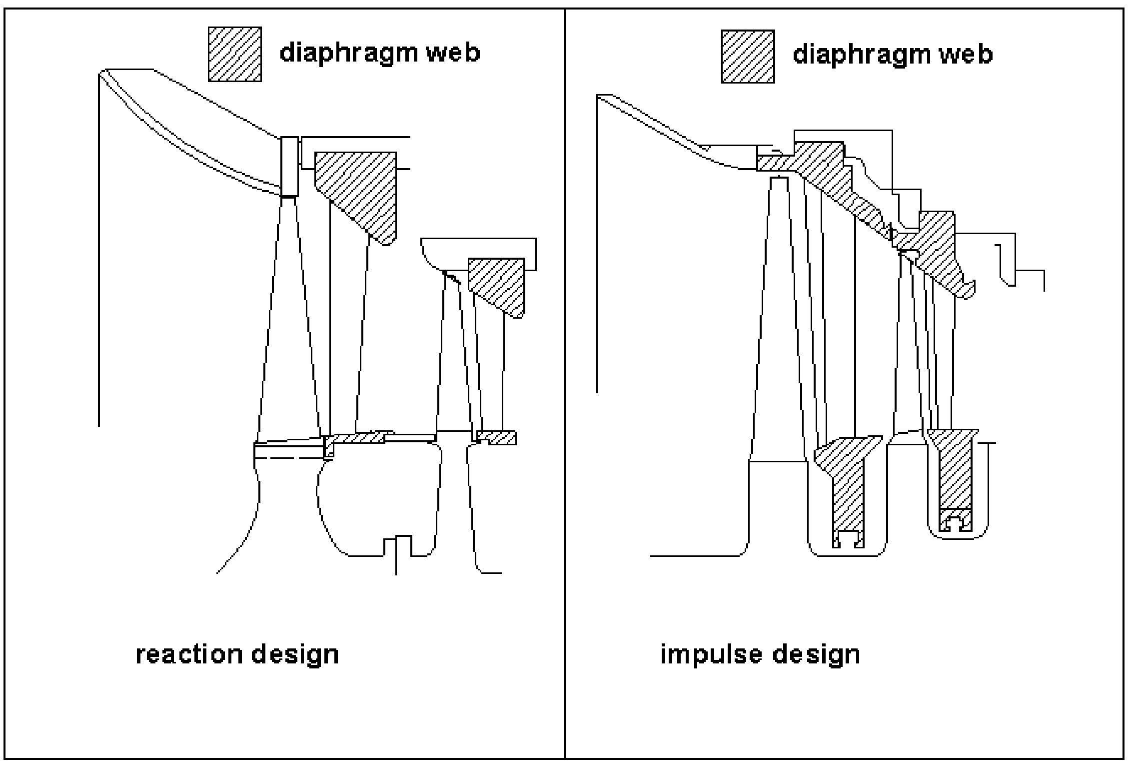

Figure 10 - Diaphragm Designs for Reaction and Impulse Turbines

8.0 Conclusions and Recommendations

Two major factors influence the probability of turbine missile generation by disk rupture; stress corrosion cracking of bore/keyway, and failures of the turbine overspeed protection system. NRC regulations require that the probability of disk rupture be maintained below a specified level to reduce risk of damage to the reactor safety related equipment. Operators are required to perform in-service disk inspections to verify that disk cracking is below critical levels and periodic steam valve tests to ensure overspeed protection systems will perform properly. These inspections and tests increase O&M costs, and thus there is interest by plant operators to reduce conservatism in the assumptions and analyses used to establish these test/inspection intervals.

Probability values for missile impact, and subsequent failure of reactor safety-related equipment (P_2 and P_3 respectively) are essentially fixed by the NRC. Reducing any conservatism in these probabilities requires approval by the NRC, and would likely require extensive analysis of impact effects, with little experimental data to support the calculations. Likewise, the total probability of safety-related equipment failure (P_4) is limited to a maximum of 10^{-7} by the NRC. Obtaining regulatory relief on P_4 would require proving that the original basis for this number was arbitrary, and therefore P_4 limits should be increased to be consistent with the generally increased risk of safety-related system failures caused by aging of other plant equipment.

The best approach for relief on the O&M issues, such as in-service inspection and steam valve testing, is the following:

1. Develop, and obtain regulatory approval, of a new, standard procedure to disk keyway/bore fracture mechanics analysis used to estimate time to failure.
2. Survey the industry experience with steam valve and overspeed protection system failure. Use the data to both reduce overall failure rates of these systems, and/or prove that increased valve test intervals have minimal effect on P_4.

It is recommended that EPRI initiate the following workscope:

1. Organize meeting to consolidate utility position on project priorities.
2. Meet with OEMs to explain project objectives, and assess current methodology for P_1 evaluation.
3. Meet with NEI and NRC to outline objectives and assess their concurrence with project objectives and scope.
4. Meet with NEIL to assess impact of potential new risk assessment technique on insurance issues.

5. Revise process for probabilistic assessment of disk failure.
6. Investigate feasibility of advanced NDE techniques to reduce uncertainty on crack sizes obtained from in-service inspections.
7. Finalize process definition for final approval by NRC
8. Evaluate findings for potential application to fossil shrunk-on disks.

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