# RISK-BASED MAINTENANCE OF TURBOMACHINERY

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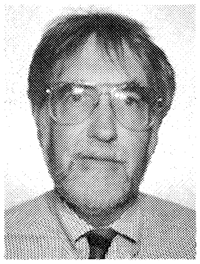

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## ABSTRACT

The authors help maintenance staff compete effectively for scarce corporate resources. Their presentation defines important concepts, including expected cost of failure ("risk"), avoided consequential cost, and value of maintenance/timing decisions. They link these concepts to maintenance expenditure. They describe evolving methods for applying them to turbomachinery, and they illustrate their use in optimizing maintenance strategy for the corporation.

## INTRODUCTION

A number of factors have raised the importance of risk-based methods in operations and maintenance of plant and machinery—aging of equipment and competition head the list. With sufficient age, many pieces of equipment demonstrate an increasing probability of unplanned forced outage, as illustrated in Figure 1. Unplanned forced outage has an associated cost that includes the cost of repair and the loss of profitable revenue, and, sometimes, the cost of providing alternative sources to meet a contract or avoid penalty. Intangible cost may include a perceived lack of reliability by clients. In the past, costly preventive maintenance programs and schedules for equipment replacement, overhaul, or refurbishment have helped minimize the probability of failure. In addition, this was occurring during the constant failure rate of plant equipment (10 to 40 years of age, Figure 1), since most of it was installed during the 1950s and 60s. Without competition (e.g., in a strong seller's market or in a regulated monopoly), all costs of preventive maintenance can be passed on to the end user as justifiable expenditures.

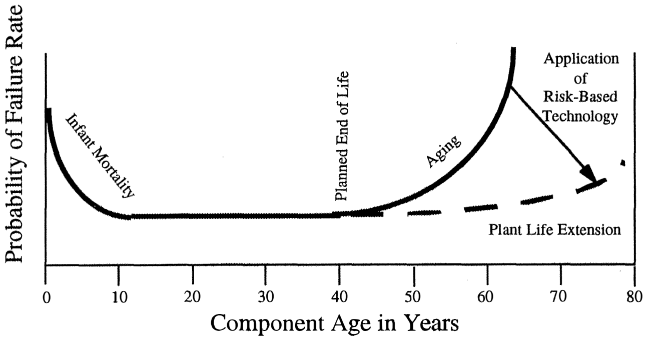

*Figure 1. Plant Component Life Cycle.*

Deregulation and strong competition change the financial part of the equation. The aging of plant equipment changed the engineering part of the equation. Competition limits gross revenue, and profit is what is left after covering all costs of operation! Reducing maintenance (on the surface) contributes to profitability—that is, until the cost of resulting failures starts to exceed the savings in reduced maintenance expenditure. Thus, competition and aging equipment create two competing financial pressures: production price reduction and the increase of consequential cost of forced outage. Postponing maintenance increases risk of forced outage. Performing major maintenance too soon results in misuse of maintenance resources. Addressed herein is the management of these risks in a quantitative fashion.

## RISK-BASED CONCEPTS

### *Traditional Methods for Scheduling Maintenance*

Preventive maintenance, or time-based maintenance, describes a process generally driven by operating hours or elapsed calendar time. It has the overlying philosophy of executing a series of supposedly beneficial activities (change the oil, replace the bearings, replace hot section components, teardown and overhaul) with sufficient frequency to minimize forced outage due to failure. Intervals may be based on OEM recommendations, sometimes supplemented by experience with some level of safety factor. Time-based maintenance has the advantage of providing a straightforward discipline and being relatively simple to administer. It also has a number of disadvantages. It inevitably involves a significant amount of, perhaps unnecessary, activity and expense. A major overhaul on a large steam turbine may cost two million dollars or more. In many cases, parts with significant remaining life may be replaced, and in some cases, infant mortalities may be introduced due to inadvertent damage or use of a flawed replacement part. Reliance on the clock does not assure the avoidance of random failures or of failures on the early tail of the probability distribution.

In recognition of the problems with time-based preventive maintenance, techniques for condition monitoring and condition-based maintenance have evolved with considerable benefit. Measurements such as vibration and temperature provide an indicator of changes in condition of rotating machinery, and also some protection against catastrophic failure when armed to trip at some limit. Borescoping, oil analysis, ultrasonics, and thermography provide additional condition assessment. Clearly, the ideal goal of being able to run a machine up to a point just short of failure, and then bringing it down for repair and restart, is attractive. However, the reality is much less precise because of all the uncertainties involved. Measurements of condition are normally indirect, and taking appropriate corrective action requires sensitive, reliable measurements, coupled with appropriate interpretation and criteria. Appropriately applied, condition-based maintenance can minimize unnecessary work or part replacement on a machine and should minimize infant mortalities. In the case of vibration, for example, available criteria include OEM recommendations and the widely used Blake-Mitchell [1] criteria for bearing housing vibration (Figure 2). Lifson, et al. [2], present more comprehensive vibration limits. Vibration criteria are normally based on experience with a wide range of machinery and problems. They have broad bands of condition ranging from "no fault" to "danger." They represent the point of view of the machinery engineer seeking reasonable protection for the machine in question. They are not developed from the viewpoint of possible damage mechanisms and probability of failure, via one or more of these damage modes, to address uncertainty, which are key elements of machinery aging. More to the point, condition monitoring, as widely practiced, does not provide the basis for a business decision. A business decision would balance the cost and penalties associated with a preemptive shutdown against the cost of failure that is expected to occur in the future because of not performing the preemptive shutdown.

In summary, time-based maintenance decisions are costly and imprecise, and do not take advantage of advances in sensor and monitoring technology, and aging life management techniques. Condition-based maintenance is an excellent step forward, and brings to bear advances in sensor and monitoring technology. However, its criteria remain imprecise, experience-based, and still do not provide the basis for a business decision.

### *Risk*

Introducing, developing, and applying the concept of risk to machinery and plant can link condition-based maintenance to the associated business. As will be shown, risk brings together contributory elements of the business and multiple engineering disciplines. It provides a basis for reducing the engineering decision (shutdown, repair, replace, or refurbish) to a business decision based on money. Risk combines the probability of an undesirable event (failure and forced outage) with the consequences of that undesirable event (loss of product revenue).

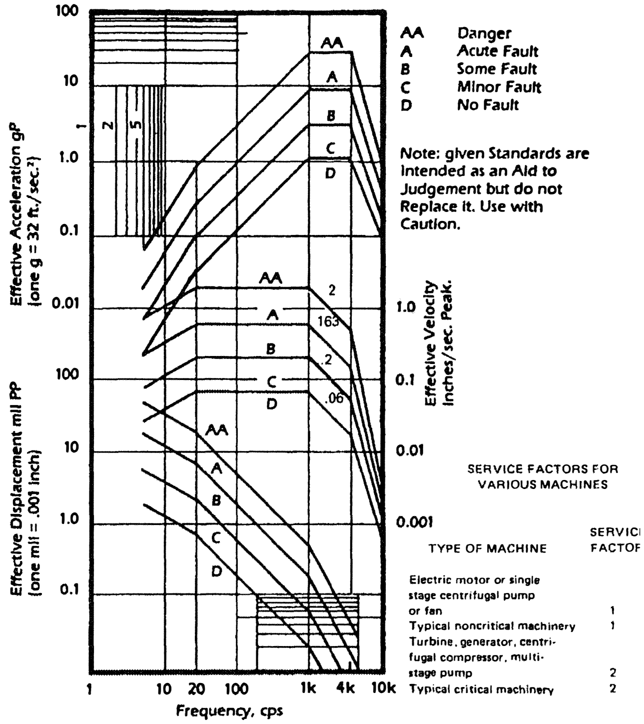

*Figure 2. Bearing Cap Vibration Limits [1].*

The elements of risk are probability of occurrence and consequence of occurrence—multiplied together, these two elements constitute expected failure cost or "risk," as illustrated in Figure 3.

**Engineering** **Finance**

**Risk = Probability of Failure X Failure Consequences = Expected Failure Cos**

**⇧**

**Downtime Cost**
**Loss in Efficiency**
**Damage Created by Failure**

*Figure 3. Link of Engineering to Finance.*

#### *Probability of Occurrence*

The probability of occurrence represents the traditional maintenance point of view. If a failure or forced shutdown occurs, maintenance staff can, from past experience, expect the blame. As a result, maintenance staffs are motivated to reduce probability of occurrence, or seek to control or minimize the frequency with which failures occur. This responsibility or motivation addresses one element of risk.

#### *Consequence of Occurrence*

Consequence of failure or forced outage represents the perspective of operations staff—they are less concerned with the frequency or probability of failure than with what effect failures have on the operation and their ability to make the plant produce. The consequence in terms of reduced output will normally translate directly into a financial consequence. The consequence will vary from machine-to-machine and often with time of day, season, or other measures of time relative to a business cycle. The consequence is influenced both by current demand for plant output and revenue from plant output. When substantial over capacity exists for current demand, the consequences, even for machines that are critical at other times, may be small. At other times, loss of certain machines may directly translate into a reduction in plant capacity for which there is demand, with direct financial impact to the bottom line.

### *Expected Failure Cost*

The viewpoints of operations and maintenance, in their traditional motivations, represent two parts of the corporate viewpoint. The probability of failure and the consequences of that failure need to be combined to give a corporate point of view. Instead of engineers using a worst case consequential cost for decision making, a better approach is to use a probability weighted cost, or expected cost of forced outage, and incorporate both elements of engineering risk. Thus, expected cost or risk is defined as the product of consequential cost and probability of failure.

Although translating probability and consequence into risk may represent a new concept for engineers, it is a natural way of thinking for those involved with corporate finances. Financial decisions are often based on expected value that is a probability of meeting some objective and the value of meeting that objective. Thus by accepting, embracing, and using this concept, those responsible for machinery now have a convenient tool and vocabulary for communicating the machinery viewpoint to those who control the resources. Thus, an underlying goal of this presentation is to arm those responsible for machinery with a tool with which to compete rationally and effectively for maintenance resources.

### *Time/Value of Money*

In addition to their comfort with the concept of risk or expected cost, those in finance are very concerned, not only with the best target for expenditure of dollars, but with when the dollars are spent. One thousand dollars ($1,000) spent two years from now will "cost less" than $1,000 spent today. It has a lower net present value because of the time value of money. Having that $1,000 in hand for two more years allows it to earn at some expected, indeed necessary, rate of return. Looked at another way, the expenditure of $1,000 two years from now can be accomplished by investing less than $1,000 now, to earn at a rate that will grow the value invested to $1,000 in two years. The rate of growth used in analyzing the effects of time is typically called the discount rate and accounts for the expected, or needed, revenue from competing investments. Thus, using time value of money in this way puts the engineering decision analysis on an equal basis with alternative corporate financial analyses, and, thereby, accounts for the corporate value measure.

### *Risk with Time*

The concept of risk and the importance of time in financial analyses have been introduced previously. Combining risk with time will lead toward a basis for communicating the value of engineering decisions and their timing to those involved with the finance who control the corporate resources.

Three axes (probability, consequence, and time) are presented in Figure 4. Probability will vary with time. In the absence of maintenance action and associated cost of that action, the probability will tend to grow with time on older machinery. The consequence of forced outage for a particular machine or component will, in general, depend on time as a result of expected changes in market share, market volume, price, and changes in spare capacity or changes in mission of a particular machine or plant. Some illustrative curves showing variation of probability with time are included in Figure 4. The variation of probability with time, given no maintenance action anywhere in the time period of interest, is shown in one curve. The variation of probability with time, as a result of maintenance action taken at time zero, is shown in a second curve. The result of maintenance action, scheduled at some point in the time period of concern, is shown in a third curve. Prior to taking this action, the curve coincides with the first (highest) probability curve. At the point of maintenance action, there is a step drop in the level of the curve down, to or close to, the curve for action taken at time zero. Essentially, what this maintenance action has done is to shift the second curve to the right by the nominal "life" of the refurbished machine. In analyzing the timing of the maintenance action, a series of alternative curves is to be compared, based on net present value or another acceptable corporate evaluation criterion that will be discussed in more depth later. The result is shown in Figure 5 of collapsing a three-dimensional graph to a two-dimensional risk *vs* time graph, by calculating risk as the product of consequence and probability for each year. Again, the three curves are shown with the step jump down occurring at whatever time the maintenance action is taken.

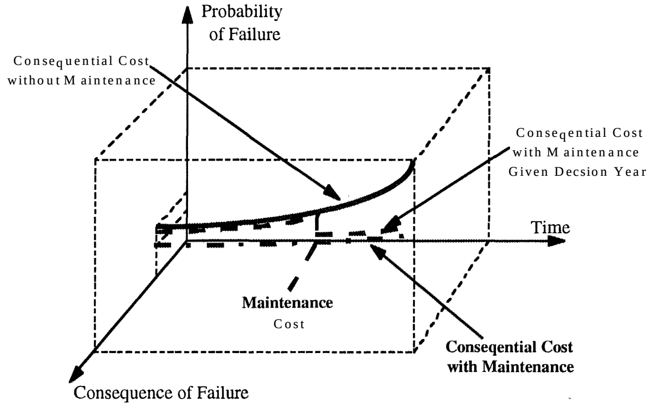

*Figure 4. Probability and Consequence* vs *Time.*

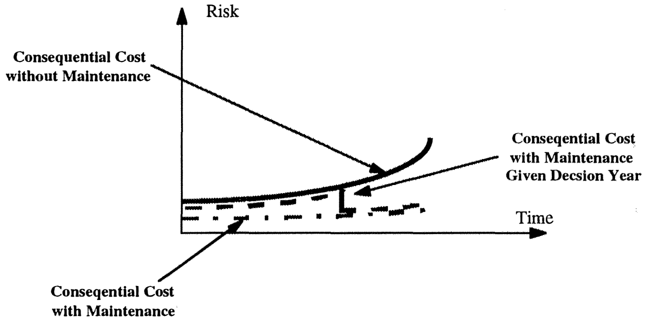

*Figure 5. Risk* vs *Time.*

A decision analysis, using this maintenance optimization, addresses not only whether to take the maintenance action, but when. The curves (Figure 5) introduce decision year as a parameter of a variable adjusted to allow optimization. The result ties maintenance decision making directly to the corporate viewpoint for all investment decisions, and accounts for the entire corporate picture. Thus, as mentioned previously, acceptance and application of the concepts of risk, time value of money, and associated decision analysis provides those seeking maintenance resources with a powerful tool for communicating their needs, and competing on an equal basis with other corporate opportunities for investment. No longer do the maintenance staff's arguments need to be based on the health of the machine, nor on the severity of consequence alone. These concepts, as presented, combine incomplete elements to integrate the competition for scarce resources with the corporate picture.

## PRIORITIZATION

### *Decision Analysis*

The concepts of decision analysis to handle uncertainty, consequences, risk, and their variation with time are not new to the disciplines of engineering economics or operations research. Their effective application to the prioritization of maintenance and the optimization of maintenance resources, however, is quite recent, and its application to rotating machinery is still in an evolutionary state. Many business problems have been addressed with the techniques of operations research, linear programming, and more advanced optimization techniques. The recognition that maintenance decisions, timing, and prioritization can be effectively managed, by the optimization of competing cost and benefit streams, is recent. As often happens, the very discipline of organizing the problem for decision analysis has its own stand-alone benefits, both in focusing the thinking, and in providing tools for communication across all levels of the business and its operation. Applying the concepts of risk and time will help optimize value to the corporation of maintenance decisions and their timing. Mauney [3] shows how multiple decisions and their timing can be addressed in a single optimization.

A primary decision analysis tool in problem organization is the influence diagram. The influence diagram indicates a flow of information from a decision or other inputs on the left of the diagram to a single output node at the right of the diagram, namely, "net present value." The choice of net present value represents the most robust measure of value to the corporation and retains its effectiveness in optimization as a function of time and across multiple projects. Quantities such as benefit/cost ratio, payback period, or internal rate of return help to measure single project "yes/no" decisions quite effectively. However, in addressing timing and multiple competing projects with multiyear constraints, net present value is a more accurate, effective, and robust measure.

The influence diagram consists of connected nodes. Construction is best accomplished by moving from right to left, starting with the node to be optimized. The net present value equals the difference in value between the benefit and the cost. Thus, three nodes are feeding the net present value, as illustrated in the very simple influence diagram of Figure 6. Namely, the expected failure *cost without* maintenance, the expected failure *cost with* maintenance, and the *cost of* maintenance. The outcome of these three is the net present value. These three in turn are fed by the decision on whether to perform maintenance or not, and by the year of that decision. Essentially, this diagram presents the reduction in expected cost of failure achieved by the maintenance action, offset by the cost of the maintenance action. Since the failure probability changes with time, the year of the maintenance action influences the failure cost. The year of maintenance action also influences the cost of maintenance because of time value of money and inflation. Clearly, Figure 6 is a simplified influence diagram of the problem. Behind it lie details of other nodes that influence these nodes. However, even the simplification of the influence diagram supports its primary benefits:

- As a framework for organizing the problem
- As a problem definition tool
- As a communication tool
- As a basis for identifying data needed to support the decision

At the same time, the influence diagram is not a fully quantitative logic diagram. Detail needs to be added. The process of calculating net present value as a function of decision year, and the process of optimizing net present value as a function of decision year are presently implemented in a spreadsheet. This spreadsheet has been developed at an institute in Texas. Examine the individual nodes and flow streams of the simple influence diagram shown in Figure 6.

### Net Present Value

The creation of net present value involves two steps:

- Calculation of the year-by-year net increment or decrement in expected value for that year. This is the net of: the increment in expected cost of failure, *without maintenance* action for all years in the analysis; the increment in expected cost of failure, *without maintenance* action until the year of maintenance action; and *with maintenance* action starting at the year the maintenance action is performed; and the cost of maintenance if it occurs in that year.
- Having established the increment in value (positive or negative) for each year of the period of analysis (typically 20 years), the process of inflating and discounting the increment for each year back to the initial year of analysis to create their net present value.

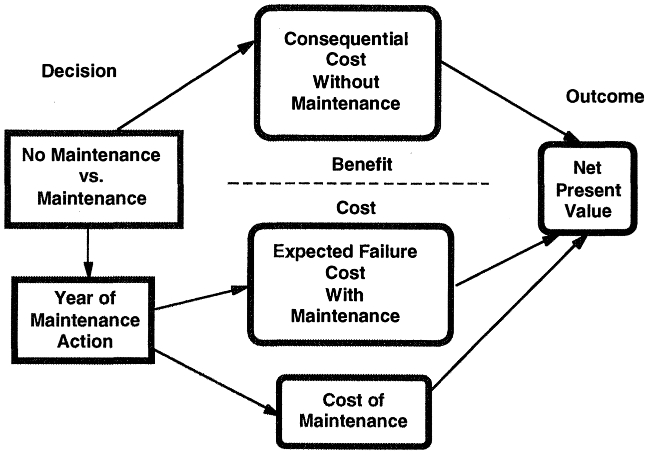

*Figure 6. Simplified Decision Analysis Influence Diagram for Maintenance Action.*

### Cash Flow Without Maintenance Action

The cash flow *without maintenance* action is the risk or expected cost of failure and forced outage, previously discussed at length, and obtained by multiplying probability of failure by consequential cost (cost of repair plus cost of forced outage). To define the increment for an individual year, the increment in cumulative probability in that year (the probability of failure change just in that specific year) is multiplied by consequential cost of failure in that year. Clearly, establishing this cash flow stream requires data on probability of failure and its variation with time in the future, and an estimate of the consequence in that year if failure occurs. Sources of such data will be discussed subsequently.

### Maintenance Cost—Cash Flow Stream

The maintenance cost is the focus of the decision. Postponing it has a beneficial effect as far as time value of money is concerned. It is a relatively well known quantity, based on either experience, or recent quotations for equipment replacement, added to the cost of unavailability of the component in question during the maintenance action. In the case of large equipment and expensive overhauls with many subcomponents, the cost estimate may be influenced in part by the possible damage that might be discovered only after the decision to shut down and perform maintenance action has been taken, and may also be influenced by the extent of the overhaul that has been decided upon (bearings, turbine). For example, there may have been a plan not to rebuild bearings. If, after the rotor is pulled from the bearings, cracked bearings are found, then an extra cost of $5000 to respin the bearings, and up to an extra week down is now involved. Thus, cost is basically a known quantity with some incremental uncertainty, and, in some cases, a subdecision involving the extent of the planned or undertaken overhaul.

### Cash Flow with Maintenance Action

Cash flow requires again a calculation of expected cost of failure and forced outage, if maintenance action is taken. The consequential cost curve will probably be the same as for no maintenance action, but the probability of failure should be greatly reduced—normally not to zero, but to some much lower level—usually shifted well back on what might be the same or similar probability curve to the no maintenance action curve when the machinery was newer.

The actual cash flow curve for *with maintenance action* is the same as for the *without maintenance action* cash flow curve until the maintenance action year, and then drops down to the calculated *with maintenance action* cash flow curve after the maintenance action year.

*The Decision of Maintenance or No Maintenance*

This essentially influences which path in the influence diagram is followed, and it provides a step between expected cost without maintenance and expected cost with maintenance. It provides a point to label the two alternative cash flow paths of the decision.

*The Decision of Timing If Maintenance Action is Performed*

This decision influences the year at which the jump between the two curves occurs for expected cost. Delaying this action has a beneficial effect on the maintenance cost and, therefore, the net present value by delaying the year when the expenditure is incurred because of time value of money. It generally has a deleterious effect on the net present value of expected cost by keeping this connected with the higher probability of failure without maintenance action.

*Constraints*

Reaching a global optimum, given infinite resources, is sometimes possible. However, should the optimum decision year for several expensive components occur in the same year, it will likely exceed the available maintenance budget. In this case, moving the decision year for some components back or forward in time can satisfy the maintenance budget constraint, reach a value that is nearly optimum globally, and that maximizes value subject to budget constraint. Recognizing and imposing this constraint on the optimization process is important in considering multiple projects.

A second factor that can impose a constraint is safety. If a particular mode of failure has safety implications, such as a rotor burst for a large steam turbine, then a probability of failure limit must be set by the corporation such that, in some cases, this limit is hit as a result of delaying maintenance action in order to optimize net present value, and must then take over as setting the constrained optimum.

Thus, in summary, a maintenance budget limit and a safety limit must be considered in most maintenance optimization studies, and may constrain the optimization process such that a global optimum cannot be reached before one or both limits are encountered. Optimizing net present value within these constraints is the goal.

## GATHERING INFORMATION ON CRITICAL COMPONENTS

The value calculation requires data on probability of failure. Accounting for time requires probability of failure as a function of time if the maintenance action is not performed, and as a function of time following maintenance action. They also require data on consequential cost of failure. Methods of generating probability of failure data include:

- Analysis and inference from historical data
- Knowledgeable opinion
- Inspection and simulation of flaw growth
- Life prediction based on operating conditions
- Operational monitoring and failure mode analysis

These are discussed below:

*Analysis and Inference from Historical Data*

The first of these—analysis and inference from historical data—requires, first of all, the existence of a relevant database. Some insurance companies involved with industrial plant and machinery maintain such records. In these databases, the effect of type equipment coverage and deductibles needs to be considered. Individual companies may maintain failure records on their plant equipment. Cooperative action of a large group of electric utilities developed and maintains a database for power plant equipment.

The operational reliability analysis program (ORAP) database contains reliability data for combustion turbines [4]. ORAP relies on data provided regularly by operating companies for their particular units. In return, these operating companies get regular feedback on the entire fleet operated by those companies supplying data.

When working with reliability databases, a second requirement is a method of inference and analysis. Given the existence within database records of operating hours before failure, two-parameter Weibull analysis fits historical failure data with a relationship of the form:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{1}$$

Processing of the data by two-parameter Weibull analysis finds values for the alpha and beta parameters in the above equation that best represent that data in a least square sense. One parameter tends to control the shape of the equation; the other parameter tends to control the scale of the fitted equation. In the aforementioned power plant maintenance database, failures are categorized by specific cause codes (or components). It is possible, and most appropriate, to find the probability of failure as a function of time for each cause code. The database also contains consequence information as forced outage time and lost MW-hours per outage, from which a consequential cost can be inferred. Presented in Figure 7 is a typical risk plot of frequency *vs* consequence for different components obtained by analysis of these databases for boiler tube components. The two cause codes with highest consequence in this figure (1060 and 1080) represent first reheater and economizer, respectively.

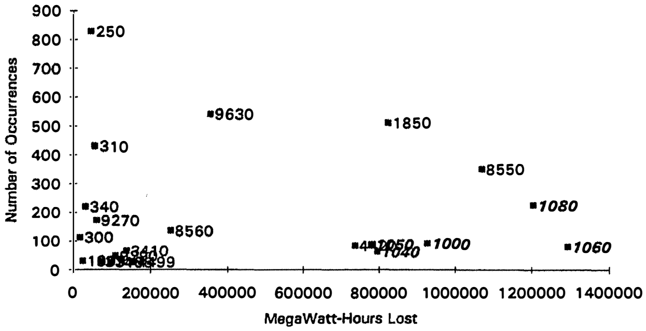

*Figure 7. Typical Risk Plot Showing Frequency and Consequence by Cause Code [3].*

*Knowledgeable Opinion*

Knowledgeable opinion, appropriately extracted and managed, has been a remarkably effective approach for estimating the reliability upon which maintenance optimization decisions are to be made. The individual who has responsibility for a piece of equipment (i.e., the person who possesses historical knowledge of the equipment's characteristics, of evolving problems, of the extent and level of past maintenance, and of time since the equipment's last major overhaul), acts both as a transducer and integrator. The intuition of this individual, appropriately "mined," can compete with extrapolation of historical data and inferential analysis for establishing future probability of failure curves. Systematic interview techniques have established themselves for extracting probability of failure information. The *ASME Risk-Based Inspection Handbook*, to be published in 1997, documents one such approach in which the individual being interviewed (who must have established knowledge of operation of the machine in question) is first asked to estimate the shortest and longest periods that the machine could possibly run without a significant forced outage. For each of these extremes, he is asked to tell a story or create a scenario that would rationalize each extreme. The longest interval is then divided into five equal subintervals. The interviewee is then asked to take a stack of 50 washers and divide them into five stacks, one for each subinterval, such that the relative height of the washers represents the probability that forced outage will occur in each interval. The only constraints are that all washers must be used, and that all washers cannot be placed in a single stack. The screen from a computerized version of this interview technique that can be used for self interview by knowledgeable individuals for a particular piece of equipment is presented in Figure 8. This software is being incorporated into a software package to assist overhaul interval optimization for large steam turbine generators.

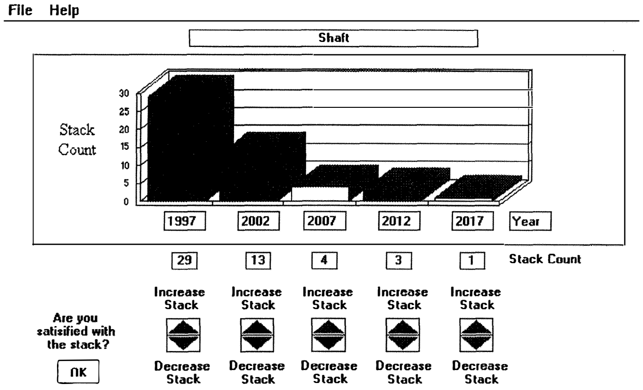

*Figure 8. Sample Screen for Self Interview Software.*

The package also contains the capability for "Bayesian" combination of probability of failure information from two sources, i.e., from Weibull fit to historical reliability data, and from an interview. The result is a single probability curve that makes appropriate combination of the two inputs. A qualitative illustration of this Bayesian update process is presented in Figure 9.

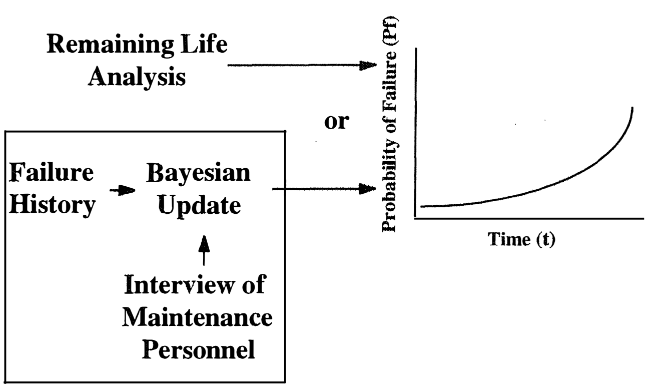

*Figure 9. Diagram Describing the Flow of Input Data into a Bayesian Analysis to Produce Component Probability of Failure or the Direct Use of Remaining Life Analysis.*

*Inspection and Simulation of Flaw Growth*

The combination of inspection for flaws and prediction of crack growth using fracture mechanics has been used for several years to predict failure probability in large steam turbine rotors. The primary concern is that the rotor might develop a crack large enough that it would burst and fly apart with catastrophic damage, and possible safety implications. A number of such rotor bursts have occurred in the past, some with very serious consequences. Boresonic inspection identifies internal cracks and their magnitude. Fracture mechanics will predict how the identified cracks will grow in the future, thereby identifying their severity and the likely life of the turbine rotor. By prediction of crack growth with time, a probability of failure *vs* time can be generated by this combination of inspection and prediction of crack growth. A computer program [5] is widely used for this purpose. Presented in Figure 10 is a representative probability of failure curve obtained by the analysis [5].

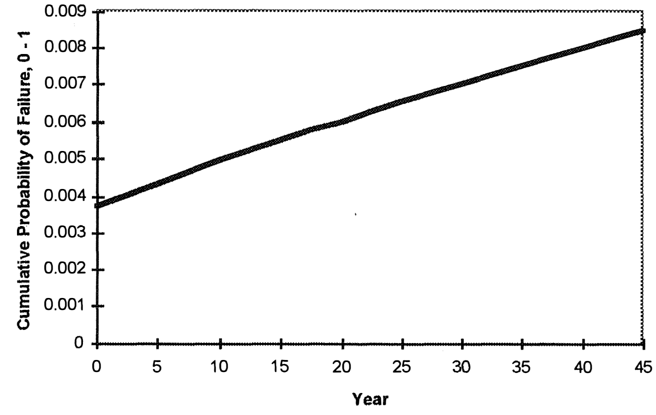

*Figure 10. Typical Probability of Failure Curve [5].*

A similar inspection and prediction process can be applied to the casings of high pressure steam turbines and compressors. Applied to casings, this process predicts the probability of failure by loss of pressure containment.

The rate of crack growth for rotors or casings is influenced by the present crack size, the prevailing stress field at the crack, and the material temperature and material properties. Thus, measurements, calculations, and estimates of these quantities are a necessary part of the crack growth prediction.

If an inspection identifies no internal flaws, the result is not a zero probability of failure. In this case, the capabilities of the inspection process in terms of probability of detection *vs* crack size should be incorporated into the analysis.

*Life Prediction Based on Operating Conditions*

For gas turbine hot section components, other failure mechanisms must be considered in predicting probability of failure. These include coating degradation, thermomechanical fatigue, creep fatigue, and hot corrosion. The technology to inspect for condition relative to these failure mechanisms is less precise than for the growth of cracks in a known stress field by fracture mechanics analysis. Use of algorithms to predict life relative to these failure mechanisms, based on turbine operating conditions, has seen some success. The package developed for the Frame 7B and Frame 7E combustion turbines, documented by Bernstein [6], can predict mean life and has been correlated against several experience points. The natural next step in the implementation of such algorithms is being performed, which will incorporate a probabilistic analysis and predict probability of failure as a function of time. Since many operating conditions needed for life prediction are contained on the data highway of modern technology control systems for power generating combustion turbines, a natural evolution would be to take such algorithm driven life management systems on line, or at periodic intervals, and integrate them with economically based overhaul optimization output, based on maximizing net present value.

*Operational Monitoring and Failure Analysis—Vibration*

Vibration measurement is very widely deployed on modern turbomachines. The eddy current shaft displacement transducer has enabled static and dynamic measurement of shaft motion relative to the bearing, and is very commonly specified and installed on compressors, turbines, pumps, motors, and generators. This technology has penetrated some industry's applications more slowly than others. Many power generating gas turbines still have only accelerometer or vibration velocity measurements on the housings of their fluid film bearings, with no shaft displacement measurements. For many years, shaft riders were the preferred vibration measurement on U.S. manufactured large steam turbines, and some large steam turbine manufacturers still prefer only to install housing vibration measurement. At the insistence from users, most new installations of turbines in the U.S. now include shaft displacement measurements. With ability to provide information, both on shaft position and on shaft dynamic motion, the operator of the equipment has a wider basis for evaluating the current severity of vibration, and for prognosis on probability and time to failure. These measurements expand the potential for enhancing existing vibration criteria to incorporate risk-based thinking, and, thereby, to balance probability of failure against the cost of shutdown for diagnosis and/or repair.

Smalley, et al. [7], in 1996, presented some initial concepts regarding the role of vibration, and the value and approach for risk-based thinking about vibration driven shutdown decisions.

As Smalley, et al. [7], point out, existing vibration criteria suffer from several limitations. In particular, they present rather broad bands of severity based on experience and observation of a variety of machinery. They do not address specific damage mechanisms, and they offer no direct means to incorporate them into an economic analysis with expected cost of failure as a cost stream. By contrast, a risk-based vibration assessment could include the following characteristics:

- Analysis is more model or unit specific
- Analysis considers possible damage mechanisms
- Analysis generates probability of failure and expected cost

Performing machine specific analysis and establishing the basis for shutdown decisions in response to high vibration has its own cost. Thus, undertaking such analysis should be justifiable, based on the value of the product from the machine in question. As methodology develops and experience is gained, risk-based methods for vibration may evolve for providing machine specific limit parameters without detailed and intensive analysis on an individual machine basis.

### *Damage Mechanisms Associated with Vibration and Misalignment*

Consideration of vibration/misalignment damage mechanisms starts to address the questions:

- What specific damage will the observed vibration cause?
- If that vibration is growing and continues to grow, what damage could it cause in the future?
- What underlying damage mechanism could an existing or growing vibration be a symptom of? How severe will that damage be now or in the future?

Several damage mechanisms that can *result from* high vibration are presented in Table 1. These are the mechanisms by which vibration of sufficient magnitude will cause damage or failure. A turbomachine operates with clearance between stationary and rotating parts at bearings, seals, labyrinths, and at tips of impeller wheels and blades. If, at any instant, extremity of position creates an interference between a rotating member and the stationary clearance, then a rub will occur. Even without the physical contact, pressure modulation, due to vibration at a bearing, may be sufficient to cause fatigue of the babbitt or other bearing material. A rotor forced to run in misaligned bearings will experience one per rev stress variation, which for sufficient magnitude, and coupled with a sufficiently high local stress concentration factor, will initiate and grow a crack.

*Table 1. Damage Mechanisms.*

| |
|---|
| • Seal Rub |
| • Bearing Fatigue |
| • Bearing Overload |
| • Operator Discomfort |
| • Shaft Fatigue |
| • Blade Tip Rub |
| • Damage to Supports |

Thus, a machine specific evaluation of vibration severity, based on potential damage, would involve inferring the probability of contact between rotating and stationary members, the probability of pressure modulation exceeding fatigue limits for the bearing material, and the probability of stress reversals in the shaft and high stress concentrations exceeding the fatigue limit for the stress material. Smalley, et al. [7], describe illustrative methodology for evaluating probability of damage or failure via the mechanisms of seal rubs, bearing fatigue, and shaft fatigue, which are summarized below.

### *Inferential Analysis from Vibration Measurement*

These illustrative methods start with measurements of shaft position in the bearing, and measurement of vibration about that position. For bearing fatigue probability, values are calculated for extremes (minimum and maximum) of unit load, i.e., force per unit area. This range of overall applied pressure loading on the bearing is compared with a curve generated experimentally by Gyde [8], showing probability of fatigue failure as a function of modulation and applied bearing pressure (Figure 11).

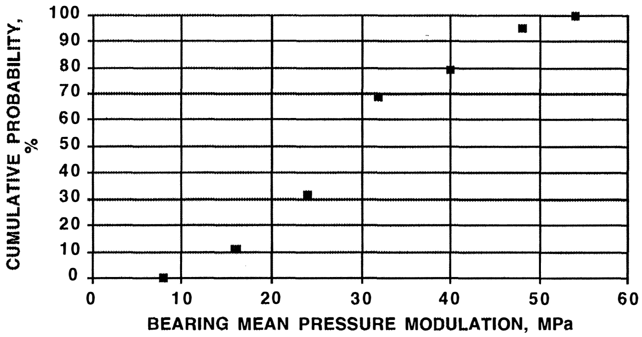

*Figure 11. Cumulative Probability of Failure* vs *Mean Pressure Modulation, Average Fatigue Strength = 29.25 Mpa ± 37 Percent (Extracted from [8]).*

For probability of seal rub, the distribution and amplitude of unbalance that would have caused the observed vibrations at the two bearings are calculated using a rotor response model. The same model is then used to calculate amplitude of the vibration at the seals in response to this unbalance. This calculation is embedded in a probabilistic analysis that accounts for uncertainty in measurement, seal clearance, and other model parameters to give probability of seal rub.

Considering misalignment induced stress reversal, two or more rigidly coupled rotors, each with a pair of bearings with the potential for bearing-to-bearing misalignment, the mean static force at each bearing can be inferred from the shaft position in that bearing. The bearing forces yield a bending moment distribution from which a nominal stress distribution can be calculated, given a corresponding distribution of rotor diameter. Coupled with a distribution of stress concentration factor, maximum stress reversal can be calculated and compared with a material endurance limit. Various parameters involved in this shaft and stress endurance calculation are subject to uncertainty, and embedding it in a probabilistic analysis yields probability of failure.

The probability of bearing fatigue for three different levels of misalignment is presented in Figure 12 [7]. The probability of seal rub is presented in Figure 13 [7]. An influence diagram for evaluating net present value of a shutdown decision based on vibration and misalignment is presented in Figure 14. Net present value of action to correct a seal rub varies with unit size and is shown in Figure 15.

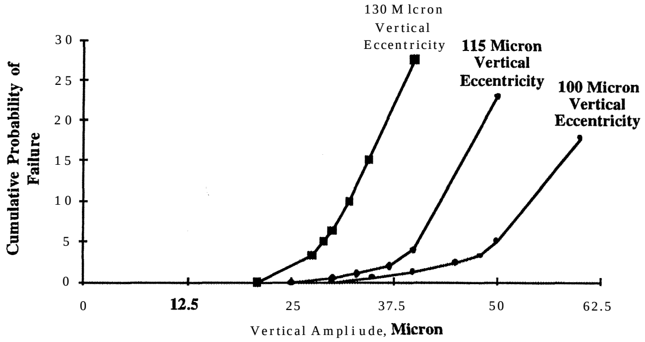

*Figure 12. The Influence of Vibration Amplitude on Probability of Bearing Failure for Three Different Levels of Misalignment [7].*

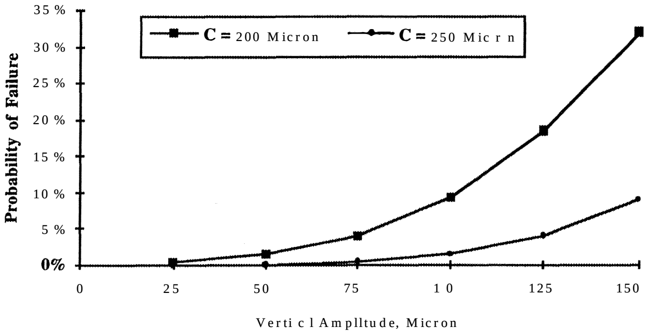

*Figure 13. Probability of Seal Rub as a Function of Measured Vibration Amplitude at the Bearing [7].*

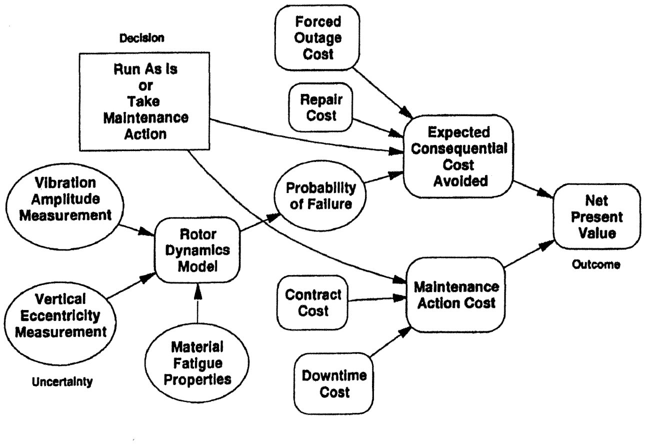

*Figure 14. The Decision Analysis Influence Diagram for Risk-Based Vibration [7].*

The consequence of a seal rub has some dependence on the nature of the installed seals. For many steam turbines, seals or packing are flexibly mounted. In the event of a rub, they move radially with the rotor surface, maintaining contact with the rotor under the influence of a soft spring and differential pressure. There is wear, but not the severe impact that would be expected with a hard rub. Thus, for steam turbines, the consequence of a seal rub may be only a deterioration in performance rather than a catastrophic failure. In evaluating the consequence of the seal rub in Figure 15, an estimate of the performance impact (half a percent increase in heat rate) was used. There is potential for more sophisticated time-based heat rate increase models linking expected loss of performance as a function of time, through the probabilistic seal rub model to bearing shaft position and vibration measurements. As with other risk-based analyses, which are machine specific, the sophistication and effort invested in the modelling process need to reflect the economic significance of the decision involved; else a less comprehensive consequence analysis is needed.

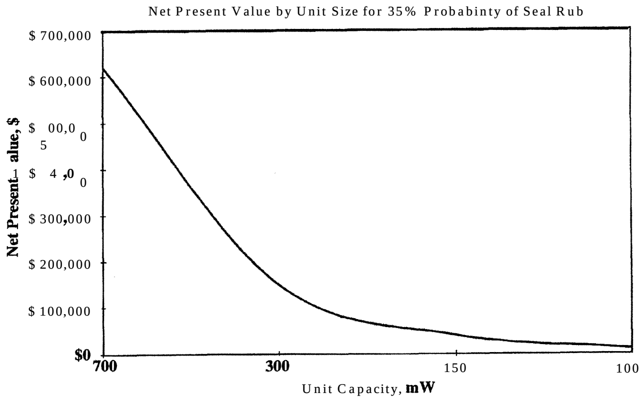

*Figure 15. The Influence of Unit Capacity on the Value of Rapid Action to Correct Seal Rub [7].*

Software and methodology to perform consequence analyses for heat rate and vibration damage remain to be fully developed. Meanwhile, there remains a need for workable methods that can produce probability of failure information somewhat consistent with existing vibration criteria charts. A representative curve showing how probability multiplier would tend to vary with housing vibration is presented in Figure 16. The user of this chart would estimate a value for the reference probability, Pref, based on experience with the machine in question. Then, the value obtained from the curve for M at the observed vibration level, multiplied by the reference probability, gives an estimated probability of failure:

$$\text{Pest}(f) = \text{Pref} \times M(v) \qquad (2)$$

Where:

Pest(f) = The estimated probability of failure contributed by measured vibration

M(v) = The multiplier from the curve at the observed housing vibration velocity, v in/sec

Pref = An estimated value for reference probability level for the class of machine in question

As an example, if experience with a particular type of machine indicates the reference value for probability of failure is 50 percent, then for an observed vibration of 0.4 in/sec, the estimated probability of failure is 0.5 × 0.1, which gives 0.05 or five percent. An increase in vibration to 0.7 in/sec would raise the estimated probability to 24 percent.

Clearly, such an approach is an interim substitute for machine specific failure mode analysis, but may help fill the void when a decision must be made with no probability of failure estimate. While vibration is an important indicator of condition, the contribution of misalignment should not be ignored. Muszynska [9] illustrates how misalignment can mask vibration, but can itself cause a shaft to crack.

### *Influence of Time*

It will be noted that several of the vibration related damage mechanisms discussed have the nature of high cycle fatigue, and

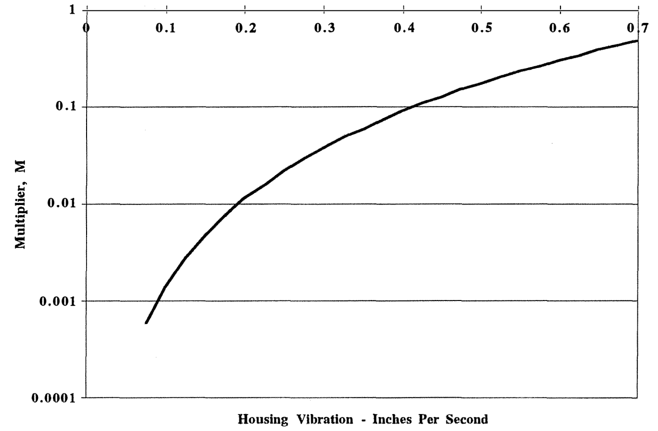

*Figure 16. Representative Probability Multiplier* vs *Vibration Housing Vibration in Inches Per Second.*

lend themselves to decisions without a time element. This implies that either the vibration is sufficient economically to justify a shutdown for repair, or it is not. This is consistent with present vibration criteria that essentially present guidance on severity of vibration without any overt association of time. High cycle fatigue is typically viewed as progressing to failure in $10^6$ to $10^7$ cycle (between one and 10 days with a 60 Hz rate of cycle accumulation). In terms of traditional endurance limits, when severity levels exceed a threshold, the rate of progression to failure is rapid for high cycle fatigue, so if high cycle fatigue is an expected failure mechanism, the corrective action needs to be taken soon. However, the following can add a time element to vibration related damage:

- High damage accumulation rates that only occur at certain points in the operating cycle—in particular, startup and shutdown
- Steadily increasing unbalance due to circumferentially uneven erosion or blade fouling
- The development of a growing crack in a rotor

If vibrations only exceed a level at which damage will accumulate while negotiating critical speeds during startup and shutdown, the time at which the rotor's acceleration leaves it with this high vibration may be only a matter of seconds or minutes. Relevant damage accumulation modes include bearing fatigue, misalignment-induced shaft fatigue, heat rate increase during a seal rub, or high torsional stresses during startup of a synchronous motor or adjustable frequency drive.

Vibration growth due to unbalance may follow a pattern with historical precedent caused by some inherent mechanism such as erosion or deposits, such that past operation provides records of vibration *vs* time. Then, a reasonable basis for developing a probability of failure *vs* time curve exists with the vibration reaching a threshold at some predictable point in the future. If, on the other hand, knowledge of the future is limited to recent observed growth in vibration, then the future rate of increase can be estimated by extrapolating the recent past into the future. With synchronous vibration, this extrapolation would ideally be performed vectorially, accounting for both amplitude and phase changes as reflected in a vector on the vibration polar plot. Given vibration *vs* time in the future, based on its past variation, repeated application of damage models at regular points in the future, based on this projected vibration, will yield probability of failure *vs* time.

The possible existence of a shaft crack that influences the vibration is a case that must be managed with care, since avoiding a catastrophic failure is important. Fracture mechanics analysis can enable a prediction of future crack growth given a known or estimated current crack severity. Rogers, et al. [10], illustrate the use of fracture mechanics to guide action on a cracked steam turbine rotor caused by thermal cycling during a boiler deslag operation. Measured vibration as a function of thermal cycles, and a comparison of crack growth from fracture mechanics, and the predicted vibration that results, is shown in Figures 17 and 18 [10].

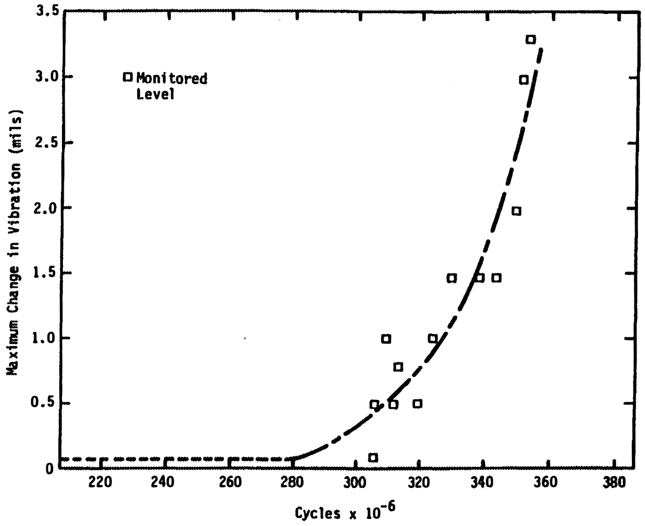

*Figure 17. Maximum Changes in LP Turbine Bearing Cap Vibration During Deslag as a Function of Total Number of Cycles at Thermal Transient Stress State [10].*

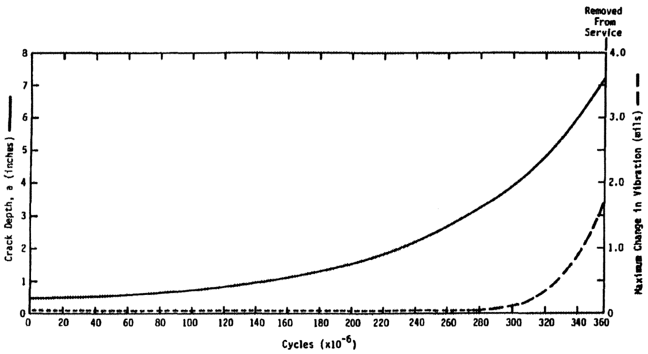

*Figure 18. Correlation of Maximum Change in LP Turbine Bearing Cap Vibration During Deslag with Predicted Rotor Crack Growth [10].*

### *Summary of Information Gathering Technology*

Clearly, predicting probability of failure and how it is influenced by maintenance action presents one of the most significant challenges in implementation of risk-based maintenance methods. However, application of the working methods described previously will enable a start on the application of the process, and show the value of further refinement to these information gathering methods. Presenting projected life in a probabilistic format allows the engineer to express, not only his expectation of the projected life, but a measure of his uncertainty associated with the projected life.

The following examples show how risk-based methodology may be applied to high vibration and turbine overhaul timing.

## EXAMPLES

### *Critical Air Blower in a Refinery*

The problem here is that the vibration measurement on a critical air blower in a refinery is 0.6 IPS. Based on experience on other air blowers in the company, it is the opinion of all the maintenance engineers on this type of equipment that the probability of failure for this blower is now 30 percent. For this particular refinery and the fact that the air blower is critical to the operation of the refinery, the cost of the failure of the blower is estimated to be five days of lost production. It will take one day to balance the blower. Balancing the blower is expected to reduce the probability of failure to a negligible amount. At the refinery, the per day cost of a complete shutdown is $200,000.

Is it advisable to balance the blower now using expected net value as a criterion, without tax effects? The authors are not showing the effect of time value of money in this example, so that the calculations can be easily followed.

Assumptions:

- The personnel performing the balancing will be on site whether the balancing is performed or not.
- The unit is run continuously at full load all year.

NV = Expected failure cost without balancing − Cost of balancing − Expected failure cost with balancing

NV = (0.30 × five days × $200,000) − (one day × $200,000) − (zero days × $200,000) = $100,000

Because the NV is positive and sizable, then balancing the blower now is advisable.

*Gas Turbine Overhaul Timing*

This example is the delay of a gas turbine overhaul beyond the OEM recommendation. The question, based on financial reasoning is, when is it estimated that the overhaul needs to take place without creating negative value for the company.

The overhaul is estimated to cost $400,000. If there were a failure in the hot section, the cost is expected to be $1,000,000 for repairs and 300 hours of lost revenue, due to the shutdown at $2,000 per hour, weighted by a utilization factor of 80 percent. The probability of failure of the hot section is represented by the cumulative probability of failure *vs* time curve in Figure 19. The net present value *vs* overhaul year curve is shown in Figure 20, with a peak in 1998 of $29,863. 1998 is the time to perform the overhaul that produces the optimum value. The curve is fairly flat for another year, indicating that the overhaul could be delayed until 1999 with the NPV going negative after 2000. This curve indicates the sensitivity of the value of the decision to timing. It particularly highlights when the delay is too long to add value to the corporation.

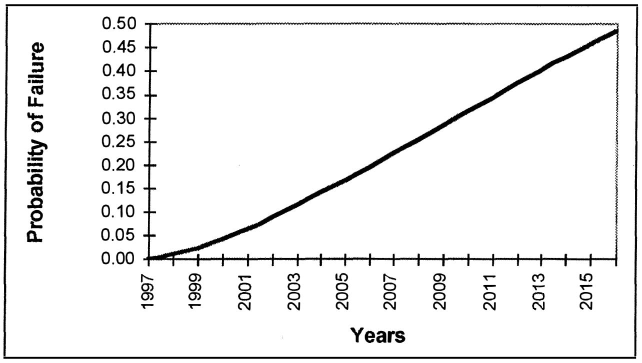

*Figure 19. Probability of Failure* vs *Time Plot for a Gas Turbine Due to Overhaul Delay.*

Assumptions:

- 20 year analysis period
- Discount rate of 10 percent
- Inflation rate of five percent
- Composite tax rate of 40 percent

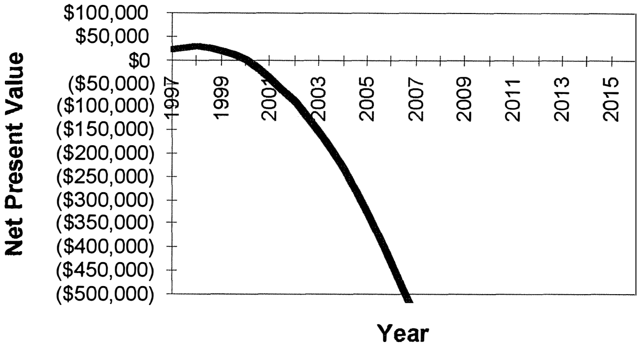

*Figure 20. Net Present Value* vs *Time Curve for Gas Turbine Overhaul Delay Decision.*

## SUMMARY AND CONCLUSIONS

Time-based and condition-based maintenance have been useful for many years in planning maintenance activities. However, as the predominance of major production equipment is now in the aging part of its life cycle, with no plans to replace it, a new situation is arising because of increased need for maintenance resources. Simultaneously, there has been a reduction in product pricing, due to either deregulation in some industries or worldwide competition in others. To maintain profits, companies have reduced maintenance budgets, because the effect of this is not usually seen immediately. This results in a second force on stretching maintenance resources. For engineers to achieve parity with other parts of the corporation in competing for resources, using the same tools and language as the financial areas of their companies is important for them. This is a result of the fact that financial decision makers, increasingly, lack an engineering background. The tools are those of decision analysis and financial analysis. For maintenance planning, these tools require the support of engineering through the projected probability of failure *vs* time for each component under consideration. The various approaches to obtaining probability of failure *vs* time may seem taxing to the engineer at first, but, after some consideration, the engineer can express his total opinion about the future performance of the component by not only giving the expected life, but also the measure of uncertainty associated with that estimate. Risk-based approaches to maintenance planning provide the most thorough corporate view of the benefit of maintenance expenditures, and, when incorporated with optimization algorithms through spreadsheet decision models for multiple component timing decisions, can save the corporation tens of millions of dollars and follow a financially sound process.

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