RISK-BASED MANAGEMENT OF ROTATING EQUIPMENT

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Abstract

There is increasing emphasis on improving the effectiveness of all physical assets, particularly major assets such as rotating equipment where the financial and business consequences of failure are significant. A number of approaches to asset (or maintenance) management have been proposed and attempted with varying degrees of success. Maintenance philosophies such as Total Productive Maintenance, Condition-Based Maintenance and Reliability Centered Maintenance are being heavily promoted by users and consultants alike. However, a consistent and comprehensive solution to business needs has not always resulted and implementation of these new techniques has often been only partially successful. This lack of success is often caused by the absence of a comprehensive approach to asset management that considers all aspects of the equipment life cycle. It is now beginning to be recognized that a risk-based approach offers a unique opportunity for providing an integrated perspective on the management of physical assets. Risk-based methods not only offer a powerful method for assisting in decision-making that can span from high level to lower level decisions but also provides specific tools that can be brought to bear on design, operational and maintenance needs. These methods fully support a life cycle view of assets that optimizes their effectiveness in the context of overall business goals and objectives. This paper describes the application of risk-based management and associated techniques to the life cycle of major rotating equipment in pipeline operation. A comprehensive framework consistent with best practices and international standards is established providing the basis for design, construction, operation and maintenance phases of the life cycle. Of key importance is the presentation of a decision-making process based on integrated risk that brings major value to operators of physical assets. Relevant risk-based techniques are described and evaluated for applicability to rotating equipment.

Introduction

Harnessing the concept of risk is not a new idea. It has been proposed by Bernstein (1996) that the ability to master risk by understanding, measuring and evaluating it, separates modern society from the past. Risk is best known in its application to financial risk and to safety, both personal and public. Its value in the management of physical assets is less well known and appreciated although its influence can readily be seen in reliability and maintenance techniques.

The major benefit of a risk-based approach is that it enables the decision-making process. Its ultimate value lies in allowing us to better predict the future based on an understanding of the past. A structured consideration of risk offers the opportunity to control potential risks by reducing their likelihood or to plan for the mitigation of consequences.

Since the context of this paper is the effective use of physical assets, especially rotating equipment, the focus will be on what is often referred to as technological risk, as opposed to investment, corporate, enterprise, political, project or other types of risk. Technological risk considers the hazards related to physical assets as they pertain to safety of personnel and the public, customer impact, lost production, environmental consequences and resultant financial impact. The essential risk assessment and management process is similar for all applications of risk, but the specific techniques are somewhat different.

Risk assessment has been extensively applied to management of pipelines and is presently included as a non-mandatory component of CSA Standard Z-662, Oil and Gas Pipeline Systems, as Appendix B – Guidelines for Risk Assessment of Pipelines. A comprehensive overview of the
status of risk management in Canada and Europe is given by Shires et al (1996) and shows the fundamental transition to risk management as the way in which pipelines are regulated. U.S regulations now require the development of a Risk Management Plan (see Mannan et al., 1996) which promotes a more proactive and effective approach instead of compliance with rigid prescriptive regulations which do not consider specific situations. Miller (1996) has recognized that this should not be viewed as unnecessary overhead but actually makes business sense since risk analysis is a very effective way of making decisions and optimizing expenditures.

The application of risk to machinery and rotating equipment has generally not been included in pipeline regulations because the consequences of failure are usually more limited in terms of their societal or customer impact. This could change in the future. However, the most important reason to embrace a risk management approach for rotating equipment is because it makes major business sense. A comprehensive risk-based approach is of prime importance both to management who are charged with minimizing corporate risk at reasonable cost and to technical staff who are required to assess and evaluate hazards and to control risks.

As clarification, it should be noted that some companies prefer to use the term ‘integrity’ instead of risk. The two terms are essentially complementary since integrity of facilities is obtained when risk is minimized and controlled to acceptable levels. For the sake of consistency with general usage in the industry and by regulatory agencies and standards bodies, risk will be used here.

In many organizations, risks are managed separately by departments and there is no mechanism to integrate their disparate and sometimes contradictory efforts. The lack of an integrated strategy and risk management framework can frustrate the attainment of corporate goals (Nottingham, 1997). A common misconception is that risk deals only with loss, instead of also being seen as an opportunity for gain (Birkbeck, 1998). Where no risk is taken, there is also little opportunity for reward. Without the support of a top-down policy with respect to what is acceptable risk, the bottom-up efforts of technical staff, who are often the first to recognize potential risk areas, can not be effectively harnessed.

It is the purpose of this paper to lay out the fundamentals of a risk-based approach and illustrate how they apply to rotating machinery. It will attempt to integrate the needs of management to make optimum decisions with the requirements of technical specialists who usually carry out the detailed risk assessments since neither can be successful without the other.

THE RISK-BASED APPROACH

Overview of Risk

Although the understanding of risk varies somewhat, there is considerable agreement on its definition and fundamental components. A common definition is the one given in IEC Standard 300-3-9:1997 Risk analysis of technological systems, which states that risk is the “combination of the frequency, or probability, of occurrence and the consequences of a specified hazardous event.”

As the following sections will illustrate, there are various ways of identifying potential hazards, estimating the likelihood of their occurrence and determining possible consequences. The factors involved are very dependent on the specific situation and must therefore be carefully understood and defined. The frequency or probability of occurrence can only be determined statistically and thus any risk analysis will not provide absolute or deterministic results. The care and attention we pay to these three steps will greatly influence the quality and usefulness of the results.

Risk Assessment and Management

The basic elements of risk identified above are usually implemented in a risk assessment and evaluation process referred to as risk management. Illustrated in figure 1, the risk management process contains these fundamental components:

- Corporate values
- Initiation and stakeholder identification
- System definition and scope
- Risk analysis
- Risk control
- Risk monitoring and audit programs.

![Figure 1 - Basic risk management process](image-url)
Corporate Values. Corporate values provide the basis for risk management since the values espoused by the company and its management, stated or implicit, are reflected in:

- The consequence categories considered and relative risk importance.
- The value of risk thresholds deemed to be acceptable
- The return on investment values considered to be appropriate
- The level of expenditures available to control or reduce risk
- The amount of residual risk accepted.

These values are also influenced by societal expectations and business climate and competition.

Initiation and Stakeholder Identification. The first formal step in risk management is to consider to which areas or assets it should be applied and who the relevant stakeholders are, that is, any individual, group, or organization able to affect, be affected by, or believe it might be affected by, a decision or activity. In many organizations, this is often initiated by an identified need, such as a designer wanting to do a fault tree analysis because of a perceived concern about the safety of a design or as the result of a major failure. A much more effective top-down approach is to produce regular (ideally every year with a 3-5 year horizon) Risk Management Plans or Integrity Plans which are reviewed on a quarterly basis. It may be necessary to have a hierarchy of Plans for specific facility or equipment types and a Master Plan that integrates them and sets overall priorities. These Plans will be an integral component of business planning. The purpose is to focus limited financial and other resources on areas of greatest risk, to justify extraordinary expenditures and to establish priorities.

System Definition and Scope. The system definition includes identification of the risk sources, in this case facilities or equipment, risk receptors such as employees and the public and other factors such as existing procedures, management systems, regulations and constraints. Specific projects are normally the result of this step, with identified resources to complete the work and specific objectives to facilitate decision-making.

Risk Analysis. This is the core of the risk process and entails identification of hazardous events (sometimes referred to as risk scenarios), the frequency or probability of occurrence and the possible consequences. Generally accepted methods for performing risk analyses include:

- Preliminary Hazard Analysis (PHA)
- Hazard and Operability Studies (HAZOP)
- Event tree analysis
- Fault tree analysis
- Failure modes and effects analysis (FMEA)
- Reliability Centered Maintenance (RCM).

Preliminary Hazard Analysis is used primarily during initial design to identify general hazards and assess their criticality. HAZOP studies are a qualitative method generally carried out during detailed design to evaluate safety and environmental risks based on deviations from design conditions and to propose design changes or operating and maintenance procedures to control risks. Event and fault trees use logic trees to identify an undesired event and all the contributing factors. They are used mainly to perform frequency analysis. FMEA is a functionally-based hazard identification and frequency analysis technique which analyzes the failure modes of equipment and their effects and consequences. It is sometimes used during design to identify potential functional failures and maintainability issues. FMEA also forms a fundamental component of RCM which is now becoming the most common method of determining the optimum maintenance program.

Frequencies can be estimated singly or jointly from historical data, analytical or simulation techniques, or using expert judgment. They will normally be of a statistical nature although simple qualitative categories (e.g. unlikely, likely, very likely) can be used. In all cases, the degree of uncertainty needs to be established since this will influence the final confidence in making decisions. Since frequency analysis can entail considerable effort, it is crucial to tailor it to the required results.

Consequence analysis is used to estimate the likely impact of an event and can likewise be determined quantitatively or qualitatively. Determination of consequences should consider existing practices and procedures and other factors which will influence or mitigate the consequences.

The final risk is the combination of the frequency (or probability) and consequences and is often expressed on a graph with each value on a separate axis, for example, frequency vs. number of people suffering a specified level of harm or frequency vs. the cost of damage.

A more general approach is to construct a consequence matrix which integrates all relevant categories of consequences and serves to calculate a non-dimensional value of risk which can be used in the evaluation step to determine acceptability of risks. This approach has been used successfully by several companies to integrate the diverse needs of safety, environmental requirements, business criteria such as customer impact and financial considerations (Birkbeek, 1999). Each company has to construct their own consequence matrix with categories that apply to their business and that reflect their corporate values and risk tolerance.

The final risk score for a scenario is computed by estimating the frequency and consequence for each category, multiplying them together and summing the categories. There will be a basic frequency for the event but the frequency for each category may be less. It is also possible to include a statistical distribution for the consequences although the consequence probability for each category needs to add up to 1.0. For safety-related categories, one also has to multiply the risk score by the probability of exposure of personnel. A consequence matrix that might be applicable to rotating equipment is shown in Figure 2 and an example risk evaluation based on the matrix is presented later.
Consequence categories

<table>
<thead>
<tr>
<th>Health and safety</th>
<th>Environment</th>
<th>Production</th>
<th>Financial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of life (10)</td>
<td>Widespread pollution</td>
<td>Financial impact less than $10 million</td>
<td></td>
</tr>
<tr>
<td>Loss of life (1)</td>
<td>Major outages more than 1 week</td>
<td>Financial impact less than $1 million</td>
<td></td>
</tr>
<tr>
<td>Major injury</td>
<td>Major outages up to 1 week</td>
<td>Financial impact less than $100k</td>
<td></td>
</tr>
<tr>
<td>Minor injury</td>
<td>Minor outages less than 1 day</td>
<td>Financial impact less than $10k</td>
<td></td>
</tr>
<tr>
<td>First aid</td>
<td>Small spills or releases</td>
<td>Financial impact less than $1k</td>
<td></td>
</tr>
</tbody>
</table>

Please note that the categories and severity points are for illustrative purposes only.

Risk = (Frequency A * Σ (Probability * Consequences for A)) + (Frequency B * Σ (Probability * Consequences for B)) + ...

Figure 2 – Example of an integrated consequence matrix

**Risk Evaluation.** Evaluating risks and making decisions about their acceptability is the most crucial component of risk management. In any risk evaluation, there are three regions:

- **Unacceptable** – risk cannot be justified on any grounds
- **As low as reasonably achievable** – Tolerable only if risk reduction is impractical or if its costs are disproportionate to the benefits gained
- **Acceptable** – negligible risk.

This leads usually to one of three decision scenarios as shown in figure 3:

- **Risk reduction:** risk is initially not acceptable and options need to be considered to reduce risk
- **Cost reduction/opportunity:** risk is already acceptable but options are explored to see if costs can be reduced or revenue increased without increasing risk to unacceptable levels
- **Sustainability:** risk is acceptable but will increase to unacceptable levels if a capital asset or system is not renewed or replaced (e.g. maintenance, software or hardware replacement).

Whenever a current scenario entails a risk that is either unacceptable or higher than desired, possible options have to be established. Each option is then evaluated for its risk and the cost required to achieve it. A final decision can then be made on the best available option.

**Risk Control.** Many risk control techniques are already accepted practice. They usually fall into one of these categories:

- avoid exposure altogether
- reduce the frequency (training, ongoing monitoring and maintenance programs, better materials)
- reduce the consequences (emergency response plans, diking around storage tanks, protective safety equipment)
- separate the exposures (land use controls, barriers between hazards and people)
- duplicate assets (redundancy of equipment, backups, duplicate suppliers)
- transfer the risk (insurance, other agreements).

**Risk Monitoring and Audit Programs.** Since risk analysis is not a one-time event (or should not be), it is important to monitor risk performance and establish audit programs to ensure compliance with risk controls.

The purpose of monitoring is:

- to detect and adapt to changing circumstances
- to ensure that the risk control and financing options are achieving the expected results
- to ensure proper implementation of control, financing and communication strategies (auditing)
- to verify the correctness of assumptions used in the various analyses.

If a consequence matrix has been developed, it can be used to score the consequences of actual incidents and thus enable the trending of actual risk. The risk score can be broken out by asset types and consequence categories for more detailed tracking. It is probably best to do this by quarter with a yearly rolling average.

**Life Cycle Management and Risk**

It is necessary to consider risk in conjunction with a life cycle approach to facilities so that longer term consequences are considered and a proper optimization is achieved. Risk analysis techniques play different roles depending on the life cycle phase. The application of the risk management process to rotating equipment described in the next section is structured by life cycle phase to clarify where risk techniques can be used.

**APPLICATION OF RISK TO ROTATING EQUIPMENT**

**Risk Applied to Rotating Equipment**

The use of risk-based techniques is now well established for static or structural equipment such as pressure vessels and pipelines to provide a justification for inspections and a basis
predicting future degradation. Although the frequency of failure is generally very low, the consequences of production outage, repair costs and safety have driven the application of probabilistic assessment for this type of equipment.

Rotating equipment, on the other hand, fails much more frequently but usually with consequences that are much reduced compared to major structures. It hardly seems worthwhile to expend the effort required to utilize probabilistic risk-based assessment techniques to assist with design or maintenance decisions. A number of factors are now changing this attitude to the use of more sophisticated analysis techniques for all types of major equipment including assets such as rotating equipment.

The first driver is the increasing criticality of major rotating equipment. Unplanned outages now have a greater effect on power plants, pipelines, oil and gas facilities and chemical plants. This is due to a combination of higher availability requirements and limited redundancy in design largely because of cost constraints.

The second factor is that the age of equipment is increasing well beyond initial life expectations. This entails increasing risk which needs to be understood, quantified and mitigated. Risk evaluation is needed to manage equipment in the later portion of its life cycle and finally to justify retirement and disposal.

On the positive side, assessment techniques and analysis support tools are now much more widely and economically available. Although some education of management, design, operating and maintenance staff will be needed to implement them, this is much more feasible today then it would have been in the past.

The remaining sections will illustrate how the risk-based approach described in the previous section can be applied to rotating equipment of all types. To clarify where it applies, the discussion is focused around the major life cycle phases (IEC 300-3-3:1996). The specific risk-based methods referred to below are described more fully in IEC 300-3-9:1997 as well as various national standards. A specific example related to gas turbines is provided at the end.

**Concept and Definition**

It is at the earliest stages that the potential risk associated with rotating equipment needs to be considered. The initial decision to choose a type of rotating equipment, for example, a gas turbine instead of an electric motor or steam turbine has risk implications, both positive and negative. A major component of the ultimate life cycle cost is also determined by these decisions. A high level risk analysis is appropriate in many cases. This can not only support the initial design choices but also point out the need to deal with issues such as noise or safety concerns. A sound understanding of the risk associated with the overall concept can aid in evaluating potential options and lead to better cost estimates.

The appropriate method for doing this high level analysis is referred to as a Preliminary Hazard Analysis or a Screening Level Analysis. General hazards to people, equipment, production and the environment are identified and their frequency and consequences determined. The integrated consequence matrix shown in figure 2 is an excellent way to understand design impacts and to estimate and compare alternatives. The technique is very similar to the example shown later except that the hazard scenarios will be at a higher level and the uncertainty of the risk analysis will be greater although still appropriate for the purpose.

**Design and Development**

The design phase offers the opportunity to apply a number of risk-based techniques. Hazard and Operability Studies, Fault Trees and Failure Modes and Effects Analysis are all used to enable detailed evaluation of risk. However, these techniques should only be used to evaluate specific risk areas. These can best be identified by first performing a more detailed version of the Preliminary Hazard Analysis done during the concept and definition phase. This PHA can now be more specific to the equipment and system design. A simplified and shortened version of the risk scenarios that might result for a gas turbine application is shown in figure 4. The frequency and consequence analysis applied to these scenarios will again be similar to the example given later. Scenarios that yield risk values that are higher than desirable are candidates for HAZOP, FMEA or Fault Tree Analysis.

In particular, where designs or equipment are new or operating conditions are different, further analysis is warranted and should be mandatory. One area of significant exposure in rotating equipment is the design of control systems which is being altered continuously. The most critical area is that of protective systems such as ESD, engine overspeed and fire and gas detection. The increasing use of software and new computer hardware introduces new elements of risk. The need to meet more stringent environmental requirements adds major design complexity to combustion hardware and control systems and thus introduces more risk.

The use of standard designs and change management processes to control risk associated with changes to design or equipment selection is crucial to managing risk in the design process. However, economic and competitive pressures often overshadow best judgment (remember the Space Shuttle
disaster) and these studies are often not carried out. An inadequate design results and operations and maintenance staff are then left to deal with the consequences.

The design phase is also the ideal time to consider maintainability aspects. Once a FMEA has been done, it is quite easy to follow this up with a Reliability Centered Maintenance analysis so that maintenance requirements can be identified. If the design and the application of the equipment has been proven and a sound maintenance program exists, then there is little need to do this. Where these are lacking, it makes long term sense to do this work up front instead of being surprised later.

Manufacturing

The focus during the manufacturing phase with respect to risk is on ensuring a quality product is produced, that is, one that meets the functional, performance, safety, environmental and economic requirements of the customer. Statistical techniques are widely utilized to ensure these are met in manufacturing processes to reduce the risk (that is, the frequency) of manufacturing errors and defects. Otherwise, formal risk-based techniques are normally not used, except possibly on the manufacturing machinery.

The major factor that can be controlled by a purchaser relative to rotating equipment is the acceptance test. Because the behavior of rotating equipment (e.g. vibration, power output, operating pressures and temperatures) will vary, it is important to fully specify acceptable conditions and quality and then carefully monitor the acceptance test. This also applies to major overhauls.

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>DESCRIPTION</th>
<th>SYSTEMS/EQUIPMENT</th>
<th>OPERATING</th>
<th>STANDBY</th>
<th>MAINTENANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire/explosion</td>
<td>Oil fire due to piping, attachment or connection failure in the lube oil system</td>
<td>Lube oil system piping</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fire from flammable liquids used during maintenance</td>
<td>Building containing gas turbine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jet gas fire due to failure of piping or attachments in the fuel gas system</td>
<td>Fuel gas system piping on engine skid</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposure of employees to hazardous materials</td>
<td>Risk due to exposure of employees to lube oils during maintenance</td>
<td>Engine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Risk due to exposure of employees to blade wash chemicals during a blade wash</td>
<td>Blade washing equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Risk due to burns to employees from hot surfaces on the engine</td>
<td>Engine</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Risk due to an uncontrolled failure of the engine</td>
<td>Engine</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>Risk to employees due to exposure to noise during routine checks and monitoring</td>
<td>Engine</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Risk to the public due to exposure to low level noise</td>
<td>Engine</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical</td>
<td>Risk to employees of electrical shock due to contact with electrical equipment during maintenance</td>
<td>Electric cables and equipment</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Damage to environment</td>
<td>Risk due to discharge of CO2/N0x from engine exhaust</td>
<td>Engine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Risk due to emission of oil vapors from vent lines</td>
<td>Oil system</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment integrity</td>
<td>Risk due to failure of the engine</td>
<td>Engine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Risk due to failure of engine auxiliary systems</td>
<td>Oil and fuel gas systems</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 – A sample list of scenarios for a gas turbine

Installation and commissioning is very similar to manufacturing when it comes to risk. Errors made and lack of attention to details introduce risk that is usually unanticipated. Methodical procedures and careful testing are critical to controlling this type of risk. The on-site acceptance test is the final opportunity to minimize future risk during the operation and maintenance phase.

Operation and Maintenance

The operation and maintenance phase offers many opportunities for risk management.

At the beginning of this phase, the prime risks are associated with deficiencies in design, manufacturing, installation and commissioning. If a risk-based approach was used during these earlier phases, the likelihood will no doubt be reduced and the ones that do occur will be easier to deal with.

Managing rotating equipment with a risk-based focus can assist first of all with overall planning, both corporate and at the equipment level. Similar to the approach taken for pipeline facilities, leading edge organizations are now beginning to develop Risk (or Integrity) Plans for all types of facilities (structures, machinery, process equipment and rotating equipment). There is actually a hierarchy of Plans with an overall corporate Plan supported by Plans by facility type (structures, machinery, process equipment and rotating equipment). There is actually a hierarchy of Plans with an overall corporate Plan supported by Plans by facility type and/or by major equipment type or vendor. The equipment Plans outline the specific improvements being made and the higher level Plans manage the corporate-wide efforts within the priorities and available resources.

The foundation for planning should be a relevant version of the Preliminary Hazard Analysis developed during the design phase and updated for current conditions. It should be reviewed on a yearly basis to account for recent experience and changes in the risk environment. Whenever projects and improvements are proposed, the aspect of risk can be incorporated and made the basis for decisions as earlier described in the section on risk evaluation and illustrated in figure 3. Specific risk-based techniques such as FMEA and fault trees can also be used to provide detailed evaluation of risk where necessary.

The past number of years has shown a solid trend to the use of risk-based techniques to support maintenance management (Jones, 1995). The prime technique being adopted widely is
Reliability Centered Maintenance (Van Hardeveld, 1995 and 1996). RCM utilizes a FMEA to determine required functions, failure modes, frequencies and failure effects. A logic tree based on failure consequences and an understanding of possible maintenance tasks (condition-directed, time-directed or failure finding) and default actions (redesign, changes in operating or maintenance procedures) enables the optimum decision to be made based on risk balanced by economic criteria. It has been applied with general success to all types of rotating equipment.

In addition to RCM which usually estimates frequencies of failure in a rough quantitative fashion without much statistical analysis, there are more rigorous statistical techniques such as Weibull analysis and Monte Carlo methods to quantify risk. These basic techniques were applied to aircraft gas turbines by Crosby and Reinman, 1987 to assist with major component replacement decisions by balancing risk and cost. Barringer (1999), Jardine (1999) and others are showing that these more sophisticated analysis techniques are now becoming feasible largely because of easier-to-use and inexpensive software tools.

Using an ASME research effort on Risk Based Inspection (CRTD 20(1), 1991 and CRTD 20(3), 1994), Christ et al, 1997 have applied a risk-based approach to determine steam plant maintenance procedures (condition-directed, time-directed or failure finding) and default actions (redesign, changes in operating or maintenance procedures) enables the optimum decision to be made based on risk balanced by economic criteria. It has been applied with general success to all types of rotating equipment.

A sound risk-based approach becomes even more important as equipment ages and surpasses its expected life. This entails decisions about replacement of minor rotating and structural components and ultimately when to retire the equipment itself.

**Disposal**

In contrast with facilities such as nuclear power plants, there are few risks associated with the actual disposal of rotating equipment.

**An Example**

The following is a brief example aimed at showing how a risk-based approach can be used to make a decision. The numbers used are purely representative and are intended only to illustrate the process.

The scenario is from the list previously shown in figure 4, the "risk due to an uncontained failure of the engine". It is being evaluated during design to understand the consequences of this risk and to allow consideration of design changes such as the installation an enclosure. Operating and maintenance implications can then also be identified.

The results of the risk analysis are shown in figure 5 with consequences being based on the matrix in figure 2. Each category is considered separately and the results are then summed to produce the final risk.

The basic frequency of the event is estimated as 0.005, or every 200 years. This number would be based on a larger population of similar gas turbines in similar industrial applications. A better estimate of frequency could be obtained by constructing a fault tree containing the factors that would contribute to an uncontained engine failure (compressor blade failure due to ingestion, turbine blade failure due to combustion section damage or creep, etc.).

The potential health and safety risk of an injury or fatality, assuming no engine enclosure is installed, is identified by interviewing operating and safety staff. The direct exposure of operating staff is estimated to be about 15 minutes per day during routine checks and monitoring. This reduces the frequency of a health or safety consequence by a factor of about 100 to 0.00005. A major fatality is expected to occur only 25% of the time, a major injury about 50% of the time and a minor injury the remaining 25%. This yields a total health and safety risk of 1.5E-5. This value is consistent with experience for process plants where a frequency of 10^{-5} is considered to be acceptable for critical events (Stickles and Melhem, 1998).

In this case, environmental consequences are very low and thus not significant.

Depending on the use the gas turbine, production losses may or may not be important. Here it is assumed that this is a critical unit where at least a partial production loss of a week will be incurred, based a spare engine being readily available. The financial consequences are estimated to range between $700,000 and $1,200,000, including both the cost of the failure and production impact.

The total integrated risk comes to 5.3E-3 which is predominantly financial. The frequency appears to be extremely low until one realizes that for a fleet of 100 engines, this can be expected to happen every two years.

One can see from the above that the risk from this scenario

<table>
<thead>
<tr>
<th>Hazardous Event</th>
<th>Health and safety</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Frequency (per year)</td>
<td>Health &amp; Safety</td>
<td></td>
</tr>
<tr>
<td>Frequency (per year)</td>
<td>Health &amp; Safety</td>
<td></td>
</tr>
<tr>
<td>Distribution &amp; Risk</td>
<td>Health &amp; Safety</td>
<td>Total Risk</td>
</tr>
<tr>
<td>Frequency (per year)</td>
<td>Health &amp; Safety</td>
<td>Total Risk</td>
</tr>
<tr>
<td>Distribution &amp; Risk</td>
<td>Health &amp; Safety</td>
<td>Total Risk</td>
</tr>
<tr>
<td>Risk due to an uncontained failure of the engine</td>
<td>0.005</td>
<td>0.00005</td>
</tr>
<tr>
<td>25%</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>50%</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>0%</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>1.5E-05</td>
<td>0.005</td>
<td>100%</td>
</tr>
<tr>
<td>0.0001</td>
<td>5.0E-07</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production</th>
<th>Financial Impact</th>
<th>Total Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Distribution &amp; Risk</td>
<td>Total Risk</td>
</tr>
<tr>
<td>(per year)</td>
<td>Health &amp; Safety</td>
<td></td>
</tr>
<tr>
<td>0.005</td>
<td>100%</td>
<td>5.0E-04</td>
</tr>
<tr>
<td>50%</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>0.7</td>
<td>4.8E-03</td>
<td></td>
</tr>
<tr>
<td>5.3E-03</td>
<td>1.1E+00</td>
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</tbody>
</table>

**Figure 5 - An example risk scenario**
is dependent on a number of factors, most of which can be influenced in one way or another. If the health and safety exposure, both in time and the number of staff, is higher than the 15 minutes per day assumed above, it may well be necessary to consider a containment shield or an enclosure to reduce the consequences, although this will not affect the frequency. Another approach would be to restrict staff from the area around the engine.

The likelihood of an uncontained failure and the amount of damage incurred, and thus the repair costs, will depend on factors such as the type of gas turbine, the maintenance program, the age of the equipment and internal components and the quality of maintenance. The length of the outage is largely dependent on the availability of skilled resources and a replacement engine or components. Outage and production losses can be mitigated by equipment redundancy although this is an expensive option. However, production impact may justify it.

Final decisions that are made based on this risk analysis will ultimately be the result of the level of risk aversion of the organization and constraints such as cost, equipment availability and consistency with equipment already installed.

CONCLUSIONS

This paper has focused primarily on using a risk-based approach to see the big picture and having a complete and consistent strategy for rotating equipment. References have been made to generally accepted techniques for performing risk-based analysis.

The value for management in understanding and managing risk is that it reduces uncertainty (and surprises) and enables justification and prioritization of work with limited resources. It provides a mechanism for engineering and technical staff to address and resolve equipment issues. The risk management framework bridges the gap between these two groups and allows for a common basis for decision making.

For a risk-based approach to be successful, management support is essential. If this does not exist, engineering and technical staff can still utilize and apply the techniques to the equipment under their control and attempt to influence management for a broader application.

The greatest danger for an organization is that risk is not considered and consequences result that could have been mitigated by previous analysis and treatment.

REFERENCES


