

Turbine Optimization Programs to Extend Outage Periods and Manage Equipment Breakdown Risk

by

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Abstract

With the highly competitive nature of today's power generation markets, you cannot afford to do major steam turbine generator outages too frequently. Conversely, waiting too long to perform an outage may result in more damage to repair, or worse, having to repair disabling damage. How do you decide the right interval to schedule an outage? One proven approach is to utilize equipment risk to manage and optimize outage intervals. Risk models for steam turbine generator optimization are discussed in detail along with the practical experience and benefits accumulated with utilizing these types of models for risk management of turbine generators.

1. Introduction

Steam turbine generators in fossil plants and combined cycle gas turbine plants are major contributors to revenue. In attempting to balance revenue potential versus costs, the plant asset manager has to recognize the risks and consequences of losing his critical equipment. In today's competitive environment, maintenance budgets are shrinking, plant staffing levels are being reduced, and equipment knowledge at the plant level and with the equipment manufacturers is decreasing due to downsizing and retirements. Compounding these issues are the facts that most power generation equipment is old and continuing to age and that newly designed equipment has no reliability history and their initial operating experience has been less than desired. These issues have resulted in more significant and catastrophic failures that have to be avoided in management of the plant assets.

Examples of these types of failures in various types of equipment are shown in the next several figures. Figure 1 shows the result of a boiler explosion. Figure 2 shows an overheated 100 MVA transformer. Figure 3 shows melted generator windings. Figure 4 shows utility combustion turbine compressor and turbine section major damage. Figure 5 shows the result of a steam turbine overspeed event with the generator field embedded in the stator windings.



Figure 1 – Boiler Explosion



Figure 2 – Overheated Transformer



Figure 3 – Melted Generator Windings

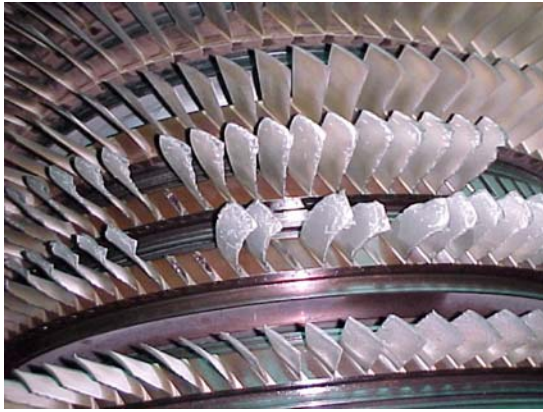


Figure 4 – Major Compressor and Turbine Damage of Utility Combustion Turbines



Figure 5 – Steam Turbine Overspeed Resulting in Generator Rotor Imbedded in Stator

There were several common threads in most of these catastrophic or major failures:

- Major plant equipment was involved
- Repair or replacement times reflected 6 to 30 months
- Plant or supplier personnel contributed to the failures
- Operating or maintenance procedures were not followed
- Design issues with the equipment or supporting systems were involved

As such, effective management of plant equipment has to deal with several key issues. These include the following:

1. Preventing catastrophic failures (explosions, fires, overspeeds, etc.)
2. Preventing unscheduled outages for major repairs (burned or melted windings, damaged turbine flowpath components, design deficiencies, etc.)
3. Minimizing unscheduled outages for minor repairs

4. Scheduling major inspections, repairs, and overhauls with the proper workscopes at the proper intervals
5. Scheduling minor inspections, repairs, and overhauls with the proper workscopes at the proper intervals
6. Utilizing/preparing proper O&M procedures
7. Training operators and maintenance personnel
8. Utilizing/establishing plant monitoring capabilities that are effective in determining and trending equipment condition and health
9. Accomplishing necessary maintenance without delay
10. Replacing or upgrading obsolete, unreliable, high maintenance, aging, and end-of-life plant equipment

How these issues are dealt with is not a simple task, particularly when you deal with critical, high-dollar, long-lead equipment including turbines, generators, boilers, and transformers. Premature failure of any of this equipment has a major economic effect on the plant's profitability. While insurance provides protection for catastrophic and some major damage, the deductibles are paid by the plant. Insurance, however, does not pay for lost customers or lost opportunities. As such, management of this equipment requires balancing projected income with expected O&M and capital expenditures to address the ten issues listed above.

2. Equipment Management Approaches Observed Today

In visiting plants for risk assessments and due diligence evaluations, several different equipment management approaches have been observed. In principle, the practices range from reactionary or ineffective practices to vision-based or highly effective practices. These are indicated in the chart in Figure 6.

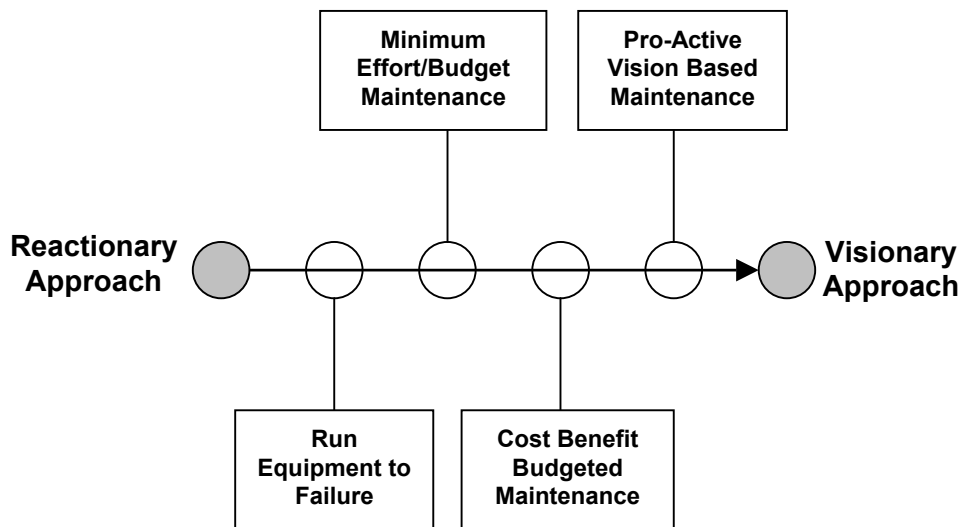


Figure 6 – Range of Observed Equipment Management Practices

Of the various approaches observed, the vision-based approach has been the most effective. First, major emphasis is placed on continually assessing the condition and health of major equipment. Second, maintenance, inspection, and overhaul efforts are pro-active to avoid unscheduled outages for either major or minor problems. And lastly, investing in both short term and long term improvements is strongly encouraged to improve efficiency/output, reduce O&M costs, eliminate obsolete designs, and replace end-of-life equipment. Even in this approach there are budget and staffing constraints, but the plant has established a vision for the future where their efforts are directed toward short and long term improvements and improving competitiveness and profitability, while maintaining availability and reliability at high levels.

Obviously, there may be different approaches or combinations of approaches for different equipment types, ages, sizes, and duty cycle but there are some key ingredients to being successful in managing equipment. These include:

- Knowing how your major equipment will fail and what the current failure drivers for your equipment are, based on past experience
- Knowing what the expected lives of your major equipment are and overhauling, upgrading, or replacing them before failure.
- Knowing when there is a change in the health and condition of your major equipment
- Knowing that your plant maintenance efforts are concentrating on the areas and equipment of highest risk
- Knowing that you have adequate equipment O&M procedures and practices and that they are being followed
- Knowing that you have trained your personnel to safely and reliably start, operate, and shutdown the plant or equipment under normal and casualty conditions
- Knowing that your personnel will make the correct decision when faced with abnormal circumstances because they know the “why” as well as “what” needs to be done
- Knowing that you have contingency plans and spares in place to minimize the recovery time should an unplanned repair or inspection become necessary.

3. Equipment Risk-Based Models

To deal with these key areas for steam turbine generators, Hartford Steam Boiler (HSB) developed risk-based models and analysis tools to specifically quantify the risk levels of steam turbines and generators. From the risk analysis results, the right maintenance, inspections, monitoring, and major outage inspection intervals can be defined. Why risk models? These models are concerned with the probability of failure, the financial consequences of equipment failure, and the technical factors that may increase or decrease the probabilities or consequences of failure. As such, risk models inherently identify which equipment is the most important to apply limited company resources. Risk models combine technical and reliability factors to arrive at the best possible decision.

For steam turbines and generators, HSB has developed two risk-based analysis programs. The first program is called TOOP (Turbine Outage Optimization Program). This program, which completed initial development in 1996, is utilized for multiple case steam turbines and for

generators. Repair costs are utilized for risk calculation consequences. The second program is called STRAP (Steam Turbine Risk Assessment Program). This program, which completed development in 1998, is utilized for single case steam turbines where the turbine is an integral part of the manufacturing process (integrated paper and steel mills; chemical, oil and gas plants). In these applications, the equipment cost is small as compared to the process so lost production days for the process are utilized for turbine consequences.

Models Technical Approach

The risk models were developed with industry representatives in accordance with American Society of Mechanical Engineers (ASME) Risk-Based Inspection Guidelines for Fossil Plants (1994) and the associated methodologies. The development approach followed the five primary ASME risk-based inspection guidelines including:

1. System definition
2. Qualitative risk assessment
3. System assessment ranking
4. Inspection program development
5. Economic optimization

The first part of the process requires defining the overall system and pertinent lower-level subsystems. After system boundaries and appropriate subsystems have been defined, applicable failure modes and probabilities of failure are established. Lastly, the failure mode consequences (repair/replacement costs, lost production time, or as otherwise defined) for each subsystem component must be defined. As a practical matter, there usually is not extensive data available, particularly for low probability and high consequence events, necessitating reliance on expert opinion and appropriate analyses. When such data is not available, a team of industry experts can be assembled to estimate the failure probabilities and consequences based on their experience.

Once the subsystems, failure modes, failure rates, and consequences have been defined, the risk values are calculated by subsystem component, subsystem, and the total system. From these results, risk levels are ranked to identify the highest risk subsystem components and subsystems. The system total risk is used to benchmark or risk rank with comparable systems. From the risk rankings, it is relatively easy to prioritize and justify maintenance decisions and develop inspection plans to more effectively use company resources.

TOOP Risk Model

A typical power generation steam turbine, as shown in Figure 7, consists of a high-pressure (HP) steam turbine, intermediate-pressure (IP) turbine, low-pressure (LP) turbine, and electrical generator (GEN). For TOOP these major system components are broken down into subcomponents (Figure 8 shows a typical turbine rotor) and their corresponding failure modes [fatigue, creep, stress corrosion cracking (SCC), erosion, foreign object damage (FOD), overload, electrical breakdown, etc.], probabilities of failure, and consequences. These

components only include internal turbine and generator subcomponents that require major disassembly for inspection and repair.

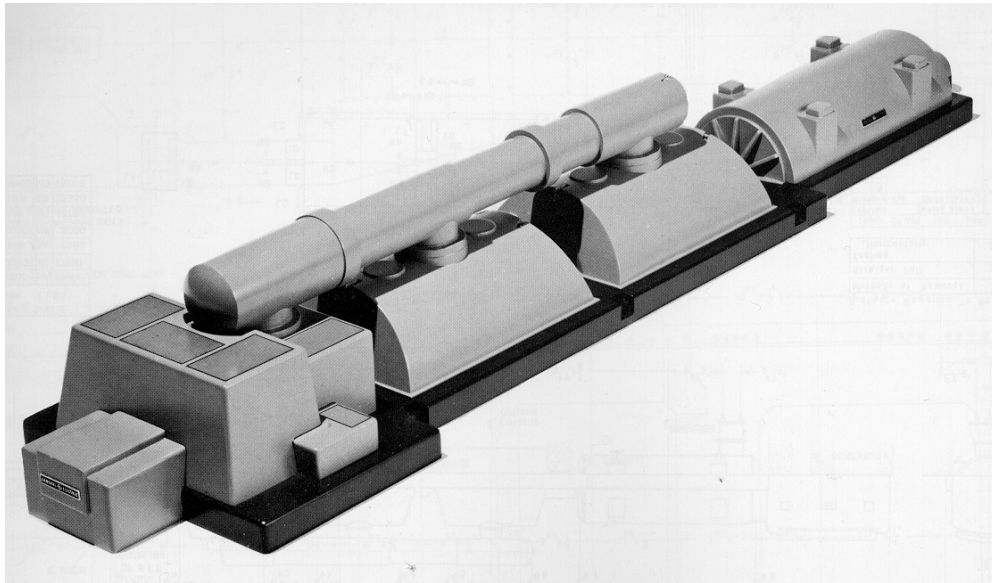


Figure 7 – Typical Power Generation Steam Turbine Generator

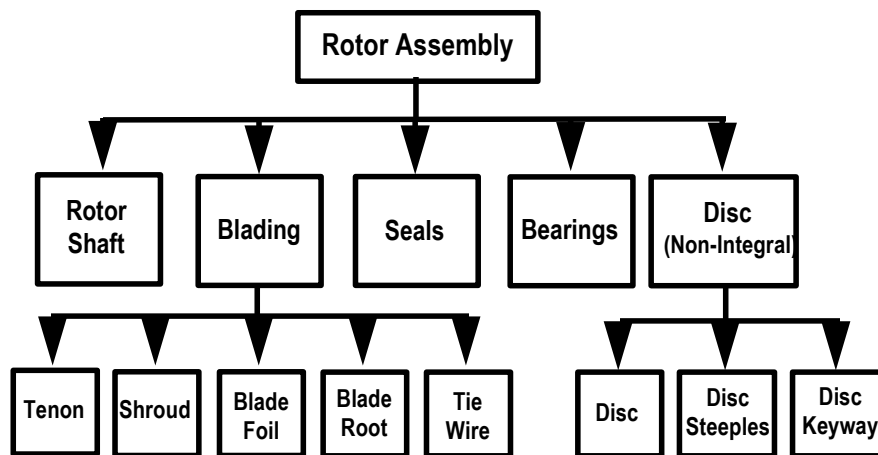


Figure 8 – Subcomponent Breakdown for Turbine Rotor

Failure rates and consequence data were obtained from HSB’s insurance claims database, from the team of experts, and from available industry data. To differentiate between turbines and generators in different service, the team designed a questionnaire which requires the owner or operator to identify equipment design features, monitoring capabilities, past operating and failure history, and current operating experience, inspection and maintenance practices. From these responses, the baseline subcomponent failure probabilities in the model are modified (raised or lowered) based on the specifics of the unit being analyzed.

Commercial database software was utilized to perform the risk calculations, risk rank and sort the results by subcomponent and failure mode. The results for a typical HP turbine risk ranking

by component and failure mechanism are indicated in Figures 9 and 10. The largest risk item (impulse wheel and foreign object damage) is indicated first in both figures and then the risk of the next largest item (disc steeples and fatigue), and so on.

This risk ranking shows that the first 7 items represent over 90% of the total HP turbine risk. The most effective place to apply company resources is on maintenance practices, inspections, and improvements that can reduce the risk (failure mechanism probability or consequence or both) of these 7 subcomponents and their failure mechanism combinations. These high risk areas become the basis for developing risk reduction recommendations as well as conducting “what if” analyses of the recommendations to quantify the cost benefits.

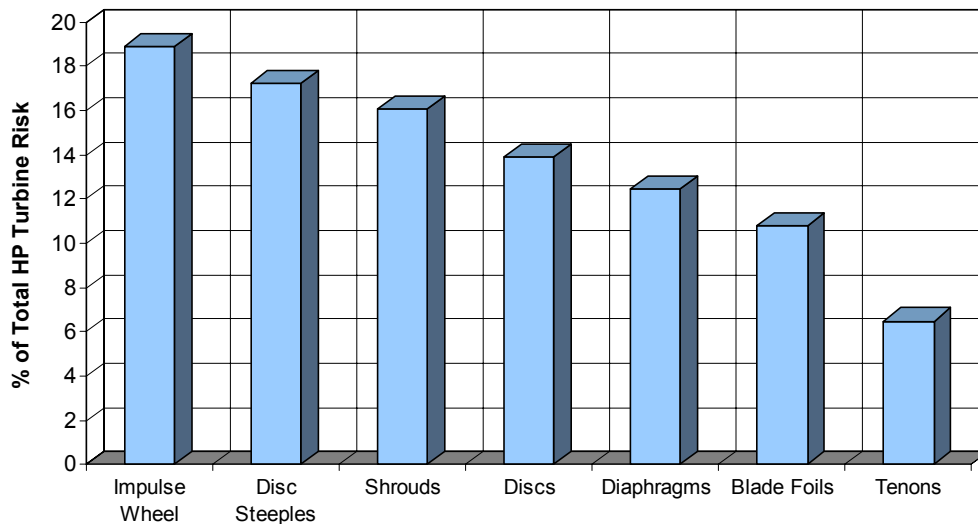


Figure 9 – Typical HP Turbine Risk Ranking by Component

Highest Risk HP Turbine Components	% of Total HP Turbine Risk	% Risk By Component Failure Mechanism							
		Creep	Erosion	Fatigue (Thermal)	Fatigue (Vibratory)	Foreign Object Damage	Material Defect	Overload	Rubbing/Distortion
Impulse wheel	18.88%	0.10%	10.42%			87.54%	0.88%		0.88%
Disc steeples	17.22%	3.28%			81.40%		3.74%	11.58%	
Shrouds	16.08%		4.09%		5.97%	22.92%	0.18%	0.33%	66.37%
Discs	13.91%	15.53%			77.95%		6.05%	0.44%	
Diaphragms	12.48%		7.10%			77.24%			15.45%
Blade foils	10.77%	0.11%	10.94%		4.70%	83.14%	0.65%		0.34%
Tenons	6.49%	0.73%	5.26%		7.67%		0.85%	0.11%	85.25%

Figure 10 – Typical Risk Ranking Summary of HP Turbine Components

The total cumulative risk of the HP turbine in Figure 9 can be benchmarked with other HP turbines analyzed by TOOP. This is shown in the risk distribution/ranking plot in Figure 11. HP turbines with low calculated risks are candidates for inspection outage intervals of 9-12 years while the higher risk LP turbines are candidates for intervals in the 4-5 years time period. This plot also allows comparing units on a common basis within a company for prioritizing resources to the higher risk units.

The TOOP model has provided excellent results and has served well as an independent assessor of steam turbine generator risks. Over 85 turbines and 94 generator units have been analyzed, representing 8 steam turbine and 9 generator manufacturers, sizes from 14 to 820 MW, operating hours from 12,800 to 328,000, and manufacture dates and metallurgies from 1946 to 1996. As shown in Figure 10, a relatively normal distribution of turbine risk was achieved with the risk model regardless of the turbine manufacturer, size, operating hours, and age. Similar results have been achieved for IP turbines, LP turbines, and generators.

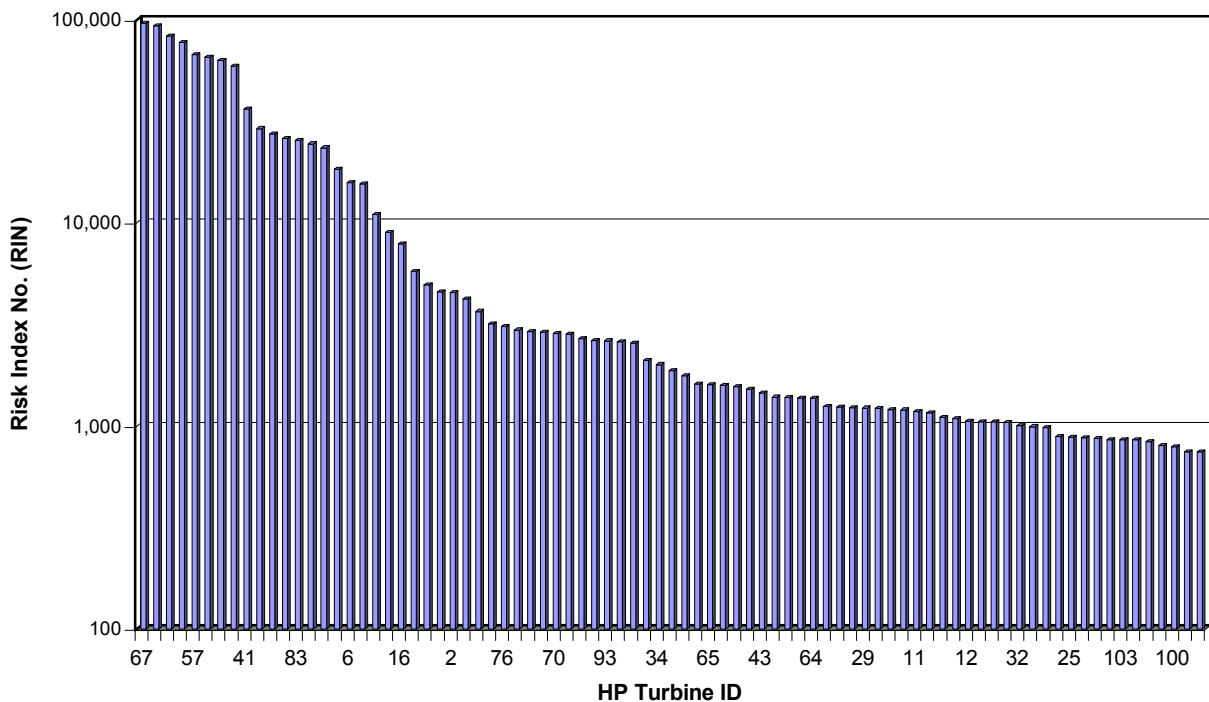


Figure 11 – HP Turbine Risk Distribution

STRAP Risk Model

The STRAP model was constructed following the same principles and processes of the TOOP risk model. The STRAP system is indicated in Figure 12. This model includes the turbine valves, bearings, instrumentation, and the coupling besides the internal turbine components shown in Figure 8.

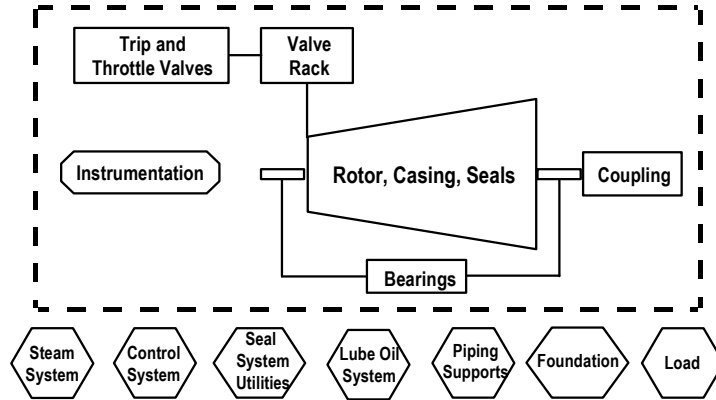
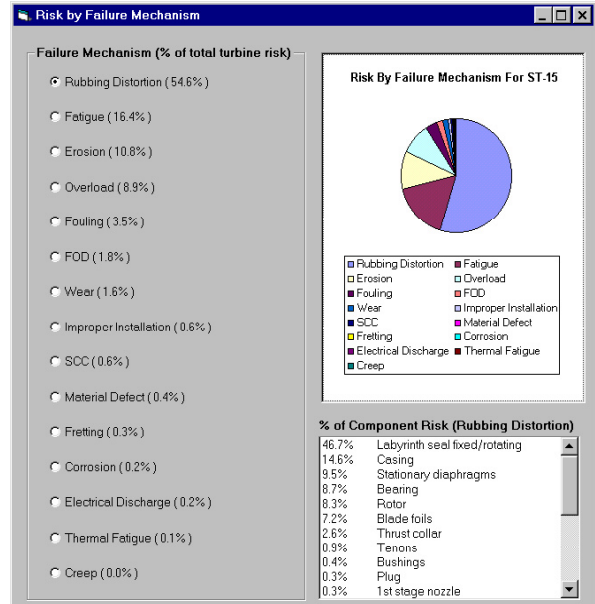
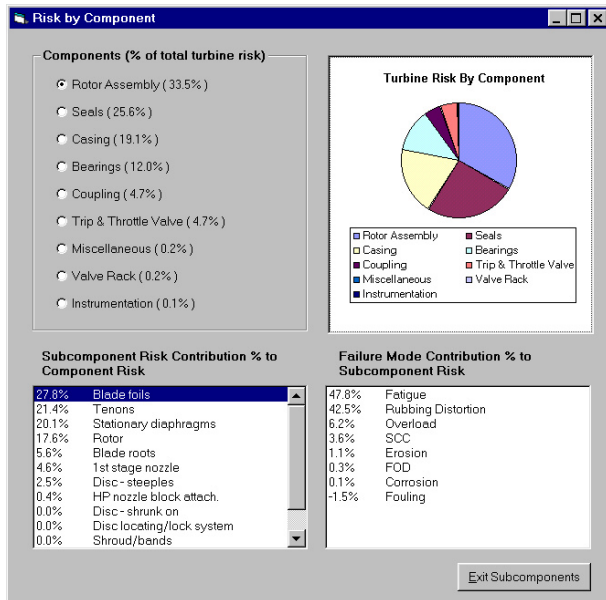


Figure 12 – STRAP System Definition

In a similar fashion to TOOP, turbine risk is calculated by subcomponent/failure mechanism. Examples are indicated in Figures 13 and 14 with cumulative risk ranking shown in Figure 15.



Figures 13 and 14 – Typical STRAP Risk and Failure Mechanism Ranking

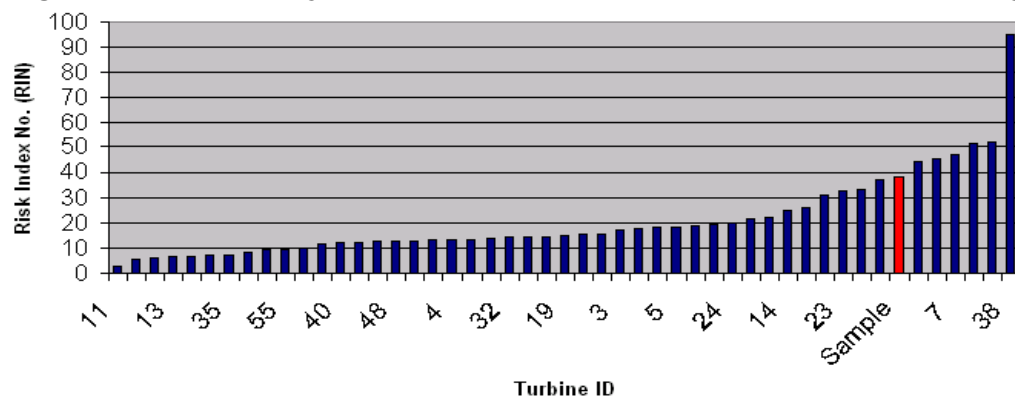


Figure 15– STRAP Risk Distribution

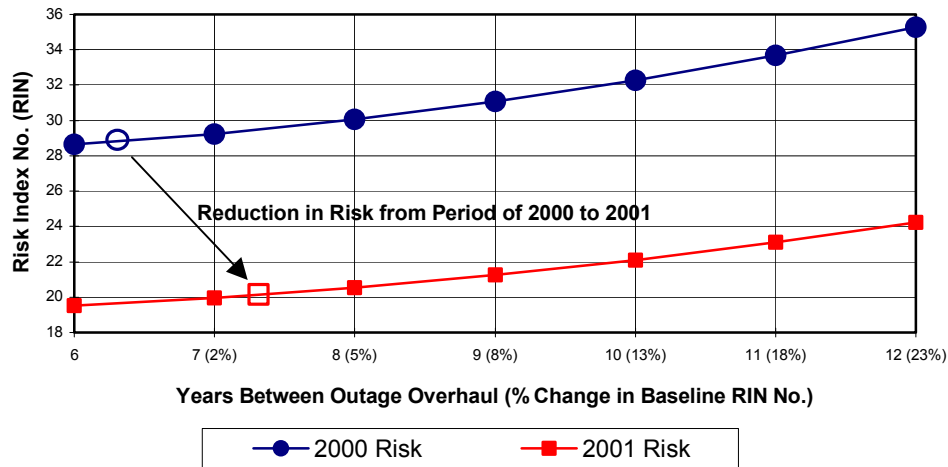


Figure 16 – Change in Turbine Risk with Time and with Yearly Updates

The STRAP model is unique in that not only is the risk for each turbine calculated, but it also calculates the change in risk with time from a baseline period of 6 years. That is exemplified in Figure 16 where the baseline risk levels were determined in CY 2000 and updated in CY 2001 after incorporation of risk-reduction recommendations from the program.

The STRAP model has provided excellent results and has served well as an independent assessor of steam turbine risks. Over 91 turbines have been analyzed, representing 9 steam turbine manufacturers, sizes from 450 to 144,000 SHP, operating time from new to 54 years, and manufacture dates and metallurgies from 1946 to new. As shown in Figure 15, a relatively normal distribution of turbine risk was achieved with the risk model regardless of the turbine manufacturer, size, operating years, and age.

4. Summary and Benefits of Risk-Based Analysis Tools

In summary, the risk-based methodologies as implemented by HSB and its development team of industry experts, have provided a unique, calibrated, unbiased view of steam turbine generators. In particular:

- Risk-based methodology directly combines technical and reliability factors with financial consequences for the limiting components and failure mechanisms in the turbine and generator to arrive at the best possible equipment decision
- Models leveraged HSB and industry team experience to establish what attributes are important and necessary for a unit to achieve a longer time between major outages
- Converted those attributes into risk modifying factors to view turbine and generator risks on a holistic basis - design and construction, operation, maintenance, and monitoring
- Calibrated those factors with analysis of units of all kinds
- Grounded the model and the associated risk levels with units that have run longer intervals

- Achieved objective/consistent risk levels and risk distributions regardless of OEM, operating hours, size, or year of manufacture based on the 176 turbines and 94 generators analyzed to date by HSB risk-based program to date

From the TOOP and STRAP analyses completed to date, the programs have provided owners of steam turbine generators the following benefits:

- Generally has eliminated 1-3 major outages over the remaining life of the turbine and generator
- Usually provides an immediate improvement in outage extension time for many turbine generator major components and allows for sectionalized outages
- Identifies high risk areas to allow focusing and prioritizing company resources to reduce risk/extend outages and justify maintenance actions, spares, and upgrades
- Objectively quantifies the level and location of the risks within the steam turbine and generator
- Identifies how those risks can be reduced to extend outages
- Utilizes the risk results to tailor major outage workscopes to concentrate on the areas of highest risk
- Allows unbiased comparisons or benchmarks of risk levels between steam turbine generators at the same site, with other company units, and with industry units
- Provides risk-based recommendations for maintenance and plant improvements so that company resources can be applied to equipment with the most need

The risk-based analysis advantage can be stated simply as:

- Identifying the Right Equipment to Apply Resources
- Doing the Right Maintenance
- Doing the Right Maintenance at the Right Interval
- Making the Right Plant Improvements or Upgrades
- Buying the Right Spares
- Making the Right Comparisons - Objective, Consistent, and Quantifiable Benchmarking
- Procuring the Right Assets - Due Diligence