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TECHNICAL RISKS AND MITIGATION MEASURES IN COMBUSTION TURBINE PROJECT DEVELOPMENT

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ABSTRACT

Project developers, insurers, financiers and maintenance organizations have an interest in quantifying technical risks and evaluating risk mitigation alternatives for combustion turbine (CT) power plants. By identifying exposure to risk early in the project development process, optimal procurement decisions and mitigation measures can be adopted for improved financial returns. This paper describes a methodology used to quantify all non-fuel O&M costs, including scheduled and unplanned maintenance, and business interruption costs due to unplanned outages. The paper offers examples that demonstrate the impact of technical risk on project profitability. An overview of activities required for addressing technical risk as part of the equipment selection and procurement process is provided, and areas of technical improvements for reducing life cycle costs are described.

INTRODUCTION

The potential impact on project profitability of risks associated with the electricity market, fuel prices, regulatory activities, and various mitigation alternatives are typically quantified during project development. By contrast, technology risk evaluations are often subjective and anecdotal. Even though technology-related risks can be difficult to quantify, these risks should also be assessed to determine their effect on project profitability and rate of return. As project developers continue to select advanced technologies to obtain competitive advantages in heat rate, emissions performance and specific costs, a quantitative risk assessment becomes more critical [1].

To reduce financial exposure to technical risk, long-term maintenance agreements and other forms of O&M contracts are becoming more prevalent in the financial structure of new CT plant project development. Maintenance contracts, extended warranties, parts costs guarantees, machinery breakdown insurance, and business interruption insurance are all approaches to control negative financial consequences to unforeseen technical problems. These risk mitigation methods are becoming more common as developers incorporate the next generation of gas turbines into their development plans as a means to be competitive in the marketplace. Unfortunately, technical risk and mitigation issues are often addressed late in the project development process, resulting in less optimal technology procurement decisions and higher costs for risk mitigation. At this late stage, some alternatives may no longer be available or feasible.

To achieve early recognition of technical risk factors and quantify identified risks, a comprehensive methodology is required. The analysis includes a statistically-based assessment of unplanned maintenance events and costs, scheduled maintenance variability and parts life evaluation, detailed estimation of total non-fuel O&M costs, and pro forma assessment of cash flow impacts. Combined with an overall project financial analysis, the methodology provides a means of quantifying the impact of technical risk on project financial performance, as well as a means of assessing the benefits of fixed price approaches to mitigating the risk.

AREAS OF TECHNICAL RISK

Quantitative risk involves both event cost and probability of occurrence. To obtain a proper perspective, an estimate of the overall maintenance costs associated with operating the plant and a valuation of the other costs associated with electricity production needs to be considered with technical risk costs. Some cost items, such as those associated with operating personnel, consumables and periodic maintenance, can be estimated at a single value (i.e., these are deterministic variables). Some cost categories involving uncertainty, such as unplanned maintenance and scheduled maintenance, vary over a range (i.e., these are stochastic variables). In the approach described in this paper, the latter costs are estimated with probability distributions based on statistical data and a Monte Carlo simulation to determine the range of costs expected.

In this methodology, the following major areas of uncertainty related to technical risk are addressed: scheduled maintenance frequency, unplanned maintenance frequency, costs and outage duration. Other cost components of operations and maintenance are handled deterministically. The uncertainty in frequency and cost directly impacts the maintenance costs for the unit. Unplanned maintenance and forced outages also decrease revenue due to fewer operating hours, and therefore also impact the profitability of the plant in the form of business interruption and reduction from planned revenues.

APPROACH TO QUANTIFYING RISK

Using this approach, the major stochastic variables are defined statistically, based on actual fleet data, theoretical modeling and field experience. Probability distributions are assigned to the failure rate data, with distribution type, mean and standard deviation values determined from fleet statistics. Three categories of failure events are defined in this analysis: minor, major and catastrophic. Events are classified according to their magnitude of cost and time-to-repair duration. Examples of minor events include trips due to loss of flame, software errors, and minor repairs such as fuel gas control valve repair. Examples of major events include shutdown and repair to correct high bearing vibrations, as well as repair of fuel gas line leaks, combustion liners, and fuel gas nozzles. Catastrophic events include significant CT repair, such as repair of turbine wheel micro-cracking, stage 2/3 wheel spacer modifications, and generator ground problems.

Within each event category, a probability distribution for repair cost and repair duration is determined from the statistical data. Figures 1 and 2 show the generalized probability distributions of cost per event and time to repair. Statistical data from a subset of the fleet of F-class gas turbines is used, although the analysis methodology is also applicable to other classes of turbines with operating experience.

An analysis of the statistical data indicates several correlation factors. Failure event frequency for minor and major events decreases with time after initial model introduction. Therefore, a "learning curve" effect is included in the modeling to account for CT model maturity. In addition, minor and major events are sensitive to the duty cycle (or "mission") of the gas turbine (i.e., peaking, cyclic, or base load duty). Therefore, these effects are included as well. Engineering judgement is exercised in extrapolating roughly five years of F-class data forward another ten years, based on previous experience with older classes of machines. For example, Figure 3 shows the mean value for major event frequency (i.e. failure rate) as a function of calendar year for peaking, cyclic, and base load duty.

The key unplanned maintenance dependent variables--outage hours and maintenance costs--are statistical distributions determined from the failure rate (i.e., events per time period), outage hours, and cost distributions. Unplanned outage hours and unplanned maintenance costs are determined from the three types of event statistics (i.e., minor, major and catastrophic) for the selected duty cycle by summing as follows (for 8760 hours per year):

- Unplanned Outage Hours = $\sum$ ((Failure Rate)$_{Type}$ x Service Factor x 8760 x (Outage Hours per Event)$_{Type}$)

- Unplanned Maintenance Cost = $\sum$ ((Failure Rate)$_{Type}$ x Service Factor x 8760 x (Cost per Event)$_{Type}$)

The key stochastic variables for scheduled maintenance are expected life for repair and replacement of major parts. Overall life and its variability are determined from a statistical analysis (mean value and standard deviation) of the intervals between scheduled hot gas path inspections). The recommended frequency of scheduled maintenance is based on vendor-specific algorithms for relating operating hours and number of starts (i.e. factored hours and starts, or equivalent operating hours, as applicable).

Component repair and replacement costs and relative life estimates are based on a combination of vendor guidelines, analytical estimates, and industry experience [2]. Figure 4 indicates the general approach used to derive risk judgements and RAM-D data inputs.

Early experience with the advanced F-class machines indicates significant reductions in serviceable life of some hot gas path parts--on the order of 50 percent or more for some components. This includes higher scrap rates during refurbishment cycles. Many owners have identified these replacement parts costs to be the dominant maintenance issue. Durability and repair yield data are relatively scarce, and gathering such data is further complicated by a continuing evolution of design modifications. Fleet leaders experience--tempered by engineering judgement--has been used to estimate hot section component service lives.

Fleet statistics are determined from the Operational Reliability Analysis Program (ORAP). ORAP is an automated system for monitoring and reporting the Reliability, Availability, Maintainability and Durability (RAM-D) of over 1500 gas and steam turbine driven units, covering various applications, duty cycles and plant arrangements for both simple and combined cycles.

O&M COST FRAMEWORK

The plant operation and maintenance costs are consolidated in a software tool, the CT Project Risk Analyzer [3]. The software, built as a Microsoft Excel-based workbook with multiple spreadsheets, is the analysis framework for determining O&M costs and quantifying technical risk mitigation alternatives and benefits. The workbook uses an add-in software product for performing the statistically-based Monte Carlo simulations on the stochastic variables and determining the cost and probability distributions.

The CT Project Risk Analyzer provides a means to estimate all non-fuel operating costs (i.e., labor, materials and consumables), scheduled maintenance (including parts replacement and repair costs), and unplanned maintenance. In addition, risk mitigation costs for maintenance contracts, extended warranties, machinery breakdown, and business interruption insurance can be included. The spreadsheet provides cash flow projections for O&M components, a present worth and annualized cost analysis, as well as a cost-benefit comparison of mitigation options. Thus, the framework software consolidates both statistical and conventional costs into a unified cost structure.

The CT Project Risk Analyzer also provides a framework for studies of O&M cost sensitivity to various parameters. For instance, the typical sensitivity of maintenance costs to service factor can be determined. To do this, a model of the number of starts as a function of service factor was developed using the results of a production cost modeling study in the western U.S. (see Figure 5). Although specific site locations and local supply and demand characteristics can affect the number of starts per year, the curve represents an average finding for the area.

Figure 6 shows typical maintenance cost estimates, as a function of service factor and number of starts. The relatively high annualized maintenance cost at low service factors is due to the significant number of starts per year assumed for peaking duty and cycling duty plants. For plants with many starts but low service factor, the maintenance costs can be similar, whether operating at 15 percent or 50 percent service factor. This is due to the high number of starts characteristic of peaking duty plants.

PROJECT COSTS INCLUDING O & M

Project cash flow and financial performance is readily determined with the use of an overall performance and costing model such as State-of-the-Art Power Plant (SOAPP-CT) software. When combined with inputs from the CT Project Risk Analyzer, impacts on financial performance due to changes in O&M costs can be estimated.

The following examples assume assessment of a combined-cycle power plant operating at 70 percent service factor (moderate baseload duty), configured with two F-class gas turbines, two heat recovery steam generators (HRSG's), and a single steam turbine. Financial assumptions include a natural gas price of $3.50/MMBtu, electricity sales at $40/MWh (average price), a base case internal rate of return (IRR) of 18 percent, and a 20-year economic life. A similar approach can be used for specific gas turbine models operating at any other duty conditions.

Figure 7 shows the relative distribution of costs from an overall project cash flow perspective. Fuel costs have the largest impact on project profitability; maintaining operating efficiency and minimizing fuel cost is clearly an important factor. O&M costs are also a significant portion of cash outflow; the annualized O&M costs for the CT-based plant represent about 6-8 percent of the revenue cash flow for a combined-cycle plant operating at moderate base load duty. Allocating the O&M costs into major components shows that about one-half of the O&M budget for advanced F-class CT-based plants is dedicated to scheduled maintenance parts repair and replacement—a typical result (see Figure 8).

PLANT PROFITABILITY SENSITIVITY AND RISK

Technology risk primarily affects scheduled maintenance and unplanned maintenance. Variability in these areas can significantly affect plant net revenue and plant profitability. The CT Project Risk Analyzer results, combined with an overall plant financial analysis, enable sensitivity studies on variables of interest. For example, the variability in plant profitability can be determined as a function of the variability in maintenance frequency.

Figure 9 shows the variability in plant profitability, as measured by either net present value at a 12 percent discount rate (NPV_{12}) or IRR after taxes. The arithmetic mean at 18 percent IRR occurs at about 56 percent probability. For this example, the difference in NPV_{12} from the 80^{th} percentile to the 20^{th} percentile is about $14 million, due only to variability in maintenance frequency. The IRR varies from 16.7 percent to 19.4 percent for the same percentile range in probability (due to the use of annualized maintenance estimates and consistent escalation with inflation for all parameters, the shape of the IRR and NPV curves overlap, which does not necessarily occur in general). For a project with an initial capital cost of roughly

$250 million, a $14 million variation in NPV due only to variability in maintenance frequency is significant, representing 5.6 percent of the initial cost..

The sensitivity of profitability to hot gas path (HGP) parts costs was also examined. For a project initially at 18 percent IRR, a 35 percent reduction in replacement costs for HGP components increased IRR to 19 percent, equivalent to a $5 million dollar improvement in NPV_{12} for the nominally $250 million plant (see Figure 10). Note that over the 20-year life of the project, the total HGP components cost about $30 million; a 35 percent HGP parts cost reduction of $10.5 million is equivalent to about $5 million in NPV_{12} (after taxes).

TECHNICAL RISK MITIGATION ALTERNATIVES

Maintenance contracts, often called "Long Term Service Agreements" or "Long Term Programs, are a rapidly growing business for the original equipment manufacturers (OEM) and third-party service suppliers. Although the contracts are individually tailored to each situation, contracts typically cover the supply of parts, material, labor and expertise required to perform the major inspections and maintenance on the unit or component. A wide variety of contracts are available, ranging from simply a pre-negotiated parts agreement to a broad scope O&M agreement in which all O&M costs, including unplanned maintenance, are covered on a fixed price basis. In these contracts, a bonus is generally negotiated for performance exceeding requirements, while liquidated damages apply when requirements are not met.

Insurance provides another means of controlling technology risk costs. Machinery breakdown insurance covers the cost to repair accidental damage or failure, subject to significant deductible amounts. Business interruption insurance can be used to cover loss of income and extra expenses when operations are curtailed or suspended due to equipment failure.

Extended warranties may also be available from the OEM to provide more financial recourse for the buyer, if the equipment fails to meet contract performance requirements or minimum parts life requirements. Of course, extended warranties, maintenance contracts, and insurance policies cost money. These risk mitigation measures also provide benefits—the financial value of which is difficult to quantify because technical risk is involved. However, the risks should be quantified to the extent necessary to identify the impact on profitability of risk mitigation, or at least identify the extent to which higher-than-expected costs are reduced. The CT Project Risk Analyzer provides the framework for such economic comparisons.

LIFE CYCLE COST REDUCTION

In addition to financial approaches, a number of technical approaches are improving CT availability/reliability, mitigating risk, and reducing overall maintenance life cycle cost. These developments, when viewed collectively, ensure that advanced machines will progress along an improving, although perhaps not entirely steady, design maturity path over the next decade. A unified approach to risk assessment also enables refinement of the information and tools for O&M assessment and identification of areas in which the most improvement can be made (see Figure 11).

Enhanced on-line monitoring techniques can improve life-cycle costs. On-line monitoring provides levels of machine status information suitable for supporting the trading floor, the plant operators, and the asset manager. Sensor information can be processed and remotely accessed via the company Intranet or over secured Internet sites. Monitored machine performance, including wear and tear incurred over a start/run/shutdown mission, determine the profitability of a trading position. Plant operators and asset managers/engineers use diagnostic software capable of discerning early trends in deterioration as machine fleet histories are accumulated in mega-process history databases. Neural networks and artificial intelligence techniques, such as fuzzy logic, will efficiently screen data for abnormal conditions, determine likely causes, and recommend counter measures. New sensors for detecting compressor instabilities, burner dynamics, blade hot spots, and material degradation are required to supplement normal control instrumentation.

New inspection techniques provide an early indication of problems that decrease parts life and can enable more timely remedial action. Inspection of the combustion section and hot gas path are prescribed maintenance activities typically performed visually or assisted by borescope. Techniques are nearing readiness for evaluating the degree of metallic coating degradation based on changes in electromagnetic properties, such as impedance. Other techniques suitable for field use will be required to assess thermal barrier coating thickness and bond integrity. Such inspections probes may be introduced through borescope ports or the engine exhaust using flexible lances. Other concepts under investigation include addition of certain easily detectable trace elements that track thickness or diffusion mechanisms and signal loss of oxidation protection.

Improved repair techniques can extend the life of high value parts. Repair is integral to achieving hot section durability goals of 48,000 to 72,000 hours. Sacrificial oxidation protection coatings are assumed to be stripped/recoated once or twice during the component life. If the coating is breached, oxidation damage to the underlying thin-walled casting may render the component unrepairable. Early indications show that as much as one-half of first-stage blades may be scrapped in these cases. Inspection and improved coatings under development will address this issue. Repair of wall loss and cracking in new directionally solidified (DS) alloys and single crystal (SC) alloy materials using precision laser welding techniques seek to restore full structural integrity. Such techniques could extend weld repair beyond blade tip buildups to more highly stressed areas, including trailing edge cracks near the platform or airfoil mid-span [4].

Improved components using advanced materials, coating systems, and novel air/steam cooling circuits have been accompanied by upgrades in firing temperature. The material innovations in the form of wear extender packages and use of DS alloys and thermal barrier (TB) coatings are now being introduced to improve the durability of conventional machines. As component field experience is accumulated and aero-thermal stress analysis focuses on life limiting critical areas, subtle changes in airfoil shapes and cooling passages are being introduced in refined designs. Techniques to improve the yield rate of SC castings and reparability are of high priority with manufacturers and their suppliers in reducing the highest cost components.

All the above approaches to reducing technical risk need to be carefully considered before committing to a risk mitigation strategy, especially those strategies that extend beyond the first major maintenance inspection.

CONCLUSIONS

Technical risk should be quantified and assessed early in the project development and procurement process. A frame-work for quantifying technical risks in CT-based power plants provides economic results based on quantitative assessment of the costs associated with the risks. The methodology presented is supported by data on the fleet of gas turbines in service and analysis results from the ongoing EPRI program to reduce CT life cycle costs. Technical risks can significantly impact the project financial performance and economic return to the equity owner, but can be mitigated through both financial and technical approaches. Reducing maintenance costs over time can make a valuable improvement to project financial performance.

ACKNOWLEDGMENTS

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REFERENCES

[1] *Technology Risk Assessment in Combustion Turbine Based Power Plants*, EPRIGEN, Palo Alto, CA: 1999, TR-113988

[2] *Combustion Turbine Design Evolution and Risk: Pedigree Matrices for ABB, General Electric, Siemens Westinghouse and Siemens Power Advanced Machines*, EPRIGEN, Palo Alto, CA: 1999 TR-114081

[3] *CT Project Risk Analyzer Workbook Software Version 1.0: User's Manual and Tutorial*, EPRI, Palo Alto, CA: 2000, 1000338

[4] *Overview of Hot Section Component Repair Methods*, Gandy, D. W., Frederick, G.., Viswanathan, R., and Stover, J. T., ASM Utilities and Energy Sector Conference on Gas Turbine Materials Technologies, October 9-12, 2000, St. Louis, Missouri

Figure 1 – Unplanned Maintenance Event Costs

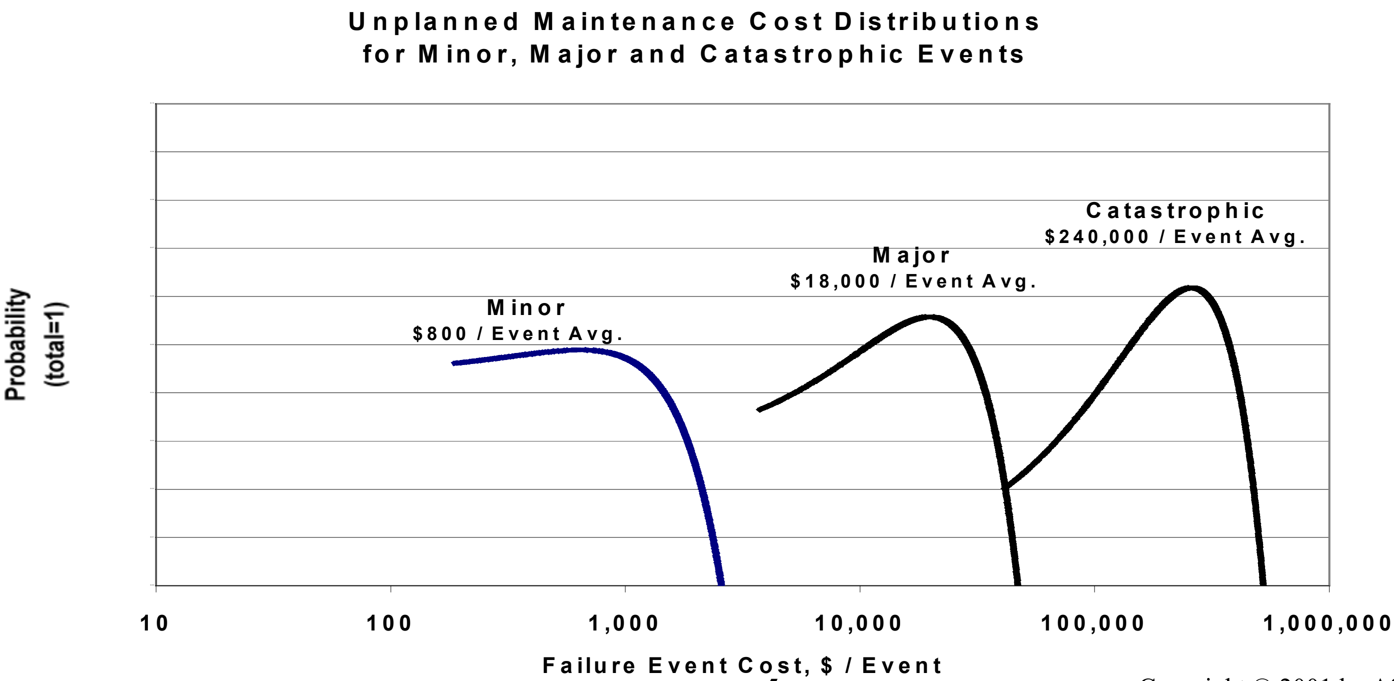

Figure 2- Time-to-Repair of Unplanned Maintenance Events

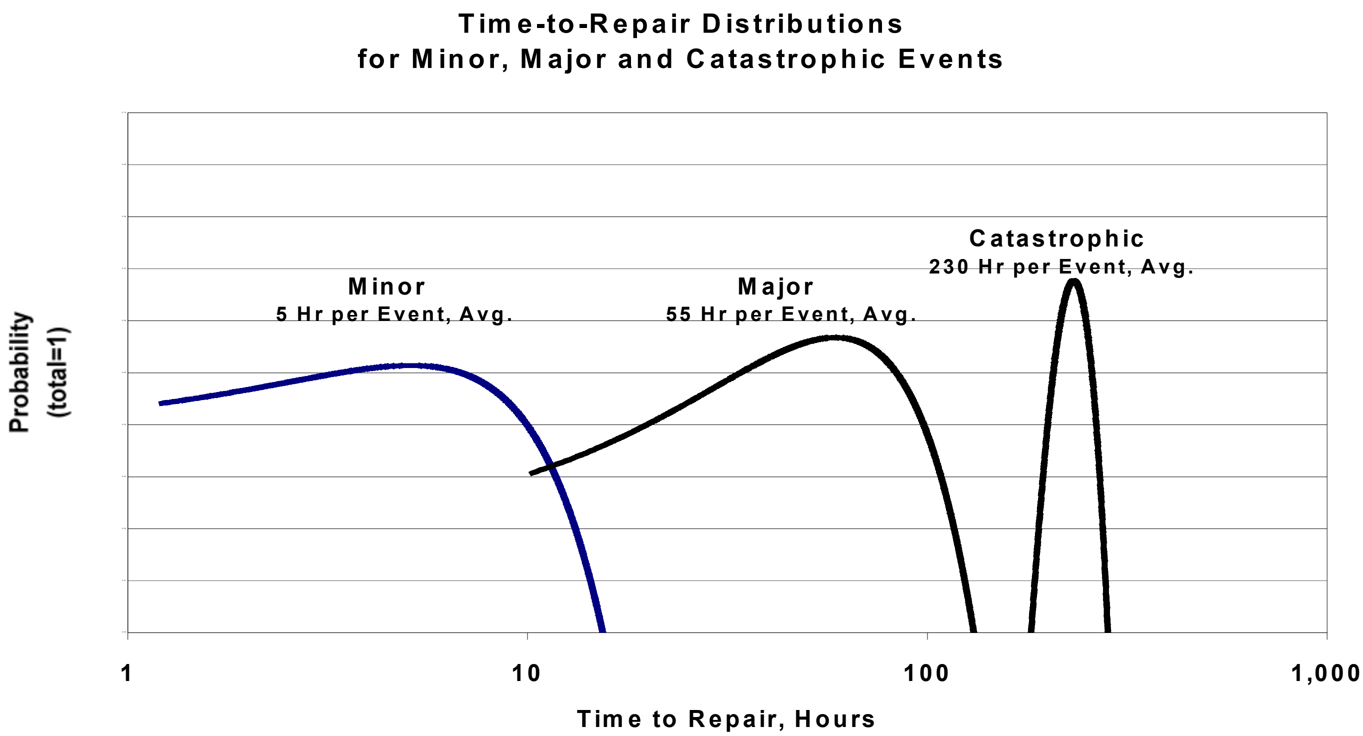

Figure 3- Failure Rate as a Function of Duty Cycle and Year after Model Introduction

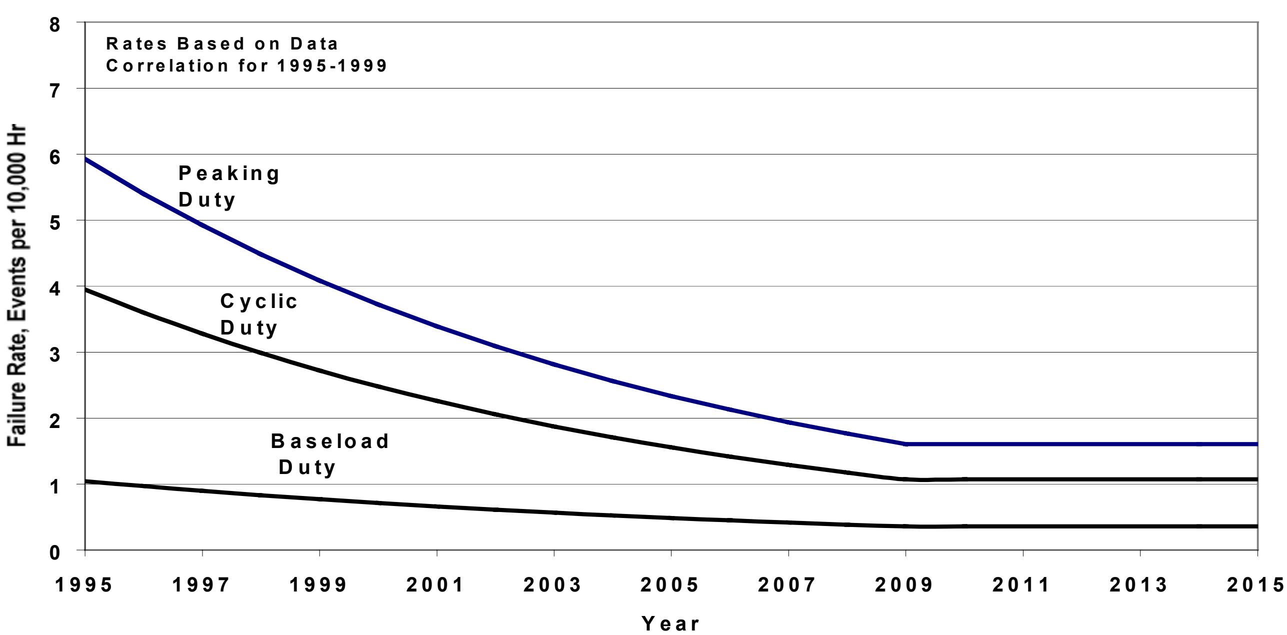

Figure 4- EPRI Risk Assessment Program

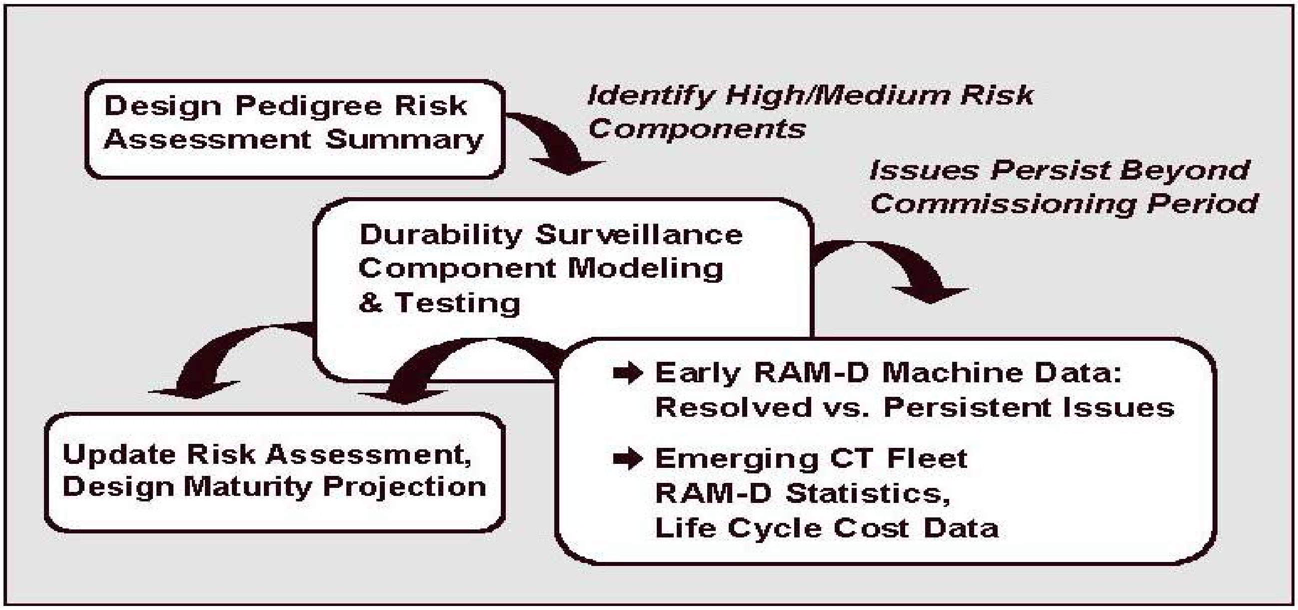

Figure 5- Modeled Number of Starts per Year

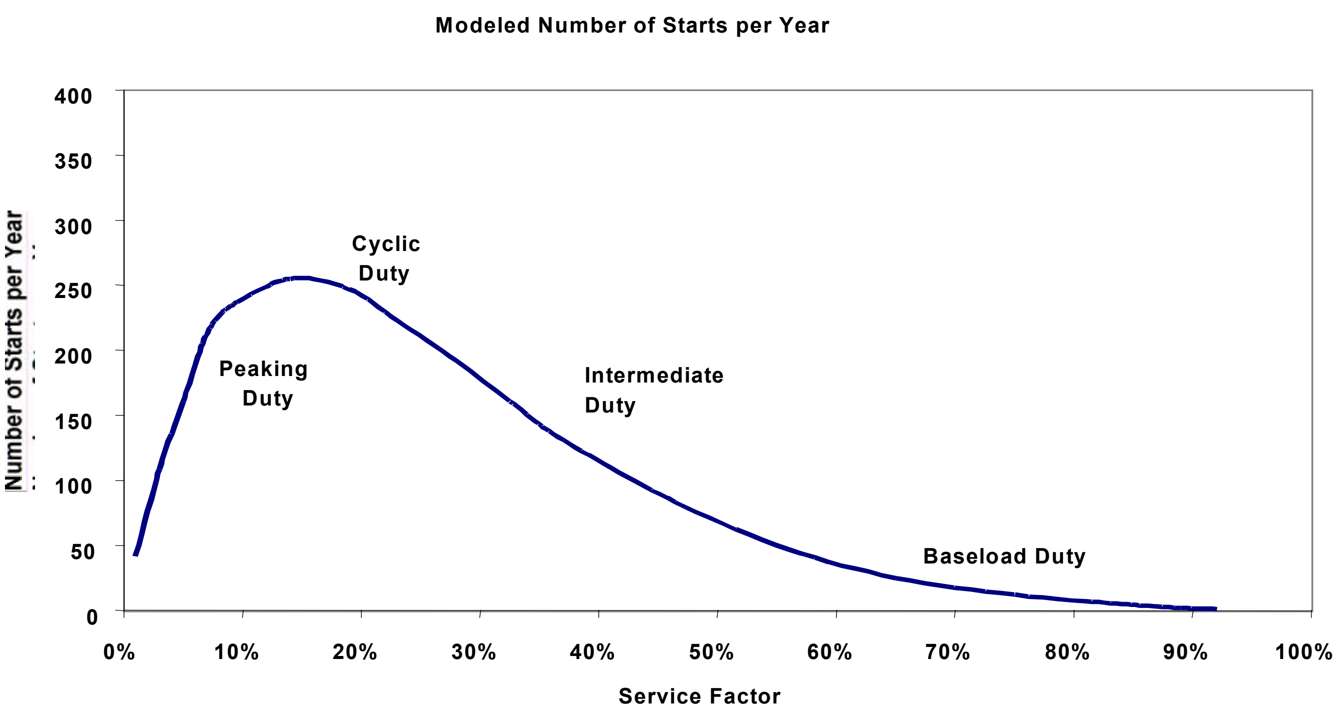

Figure 6- Annual Maintenance Cost

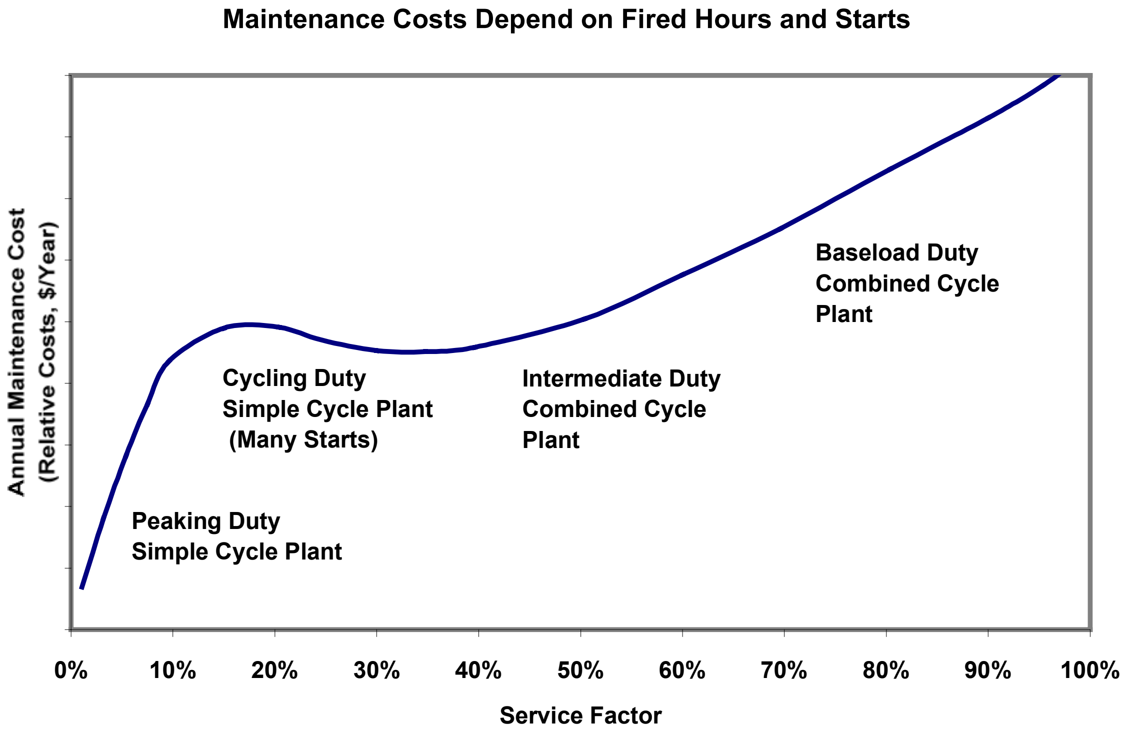

Figure 7- Relative Distribution of Project Cash Flow

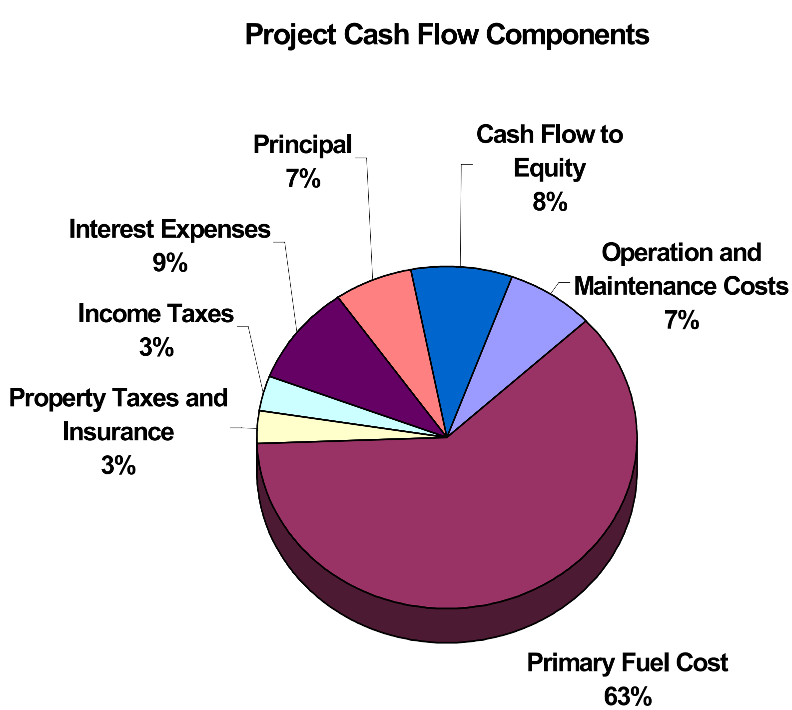

Figure 8- Major Cost Components of CT Operations and Maintenance

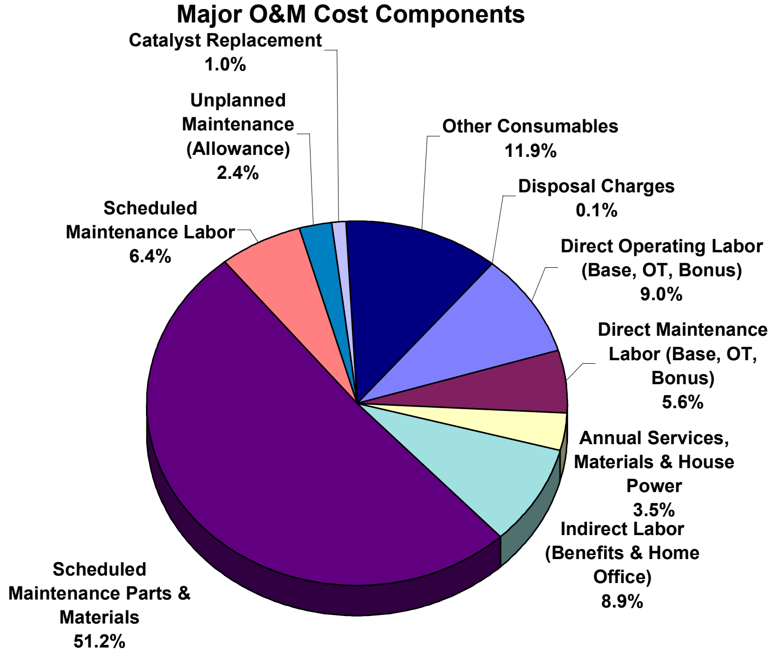

Figure 9- Plant Profitability Sensitive to Variability in Maintenance Frequency

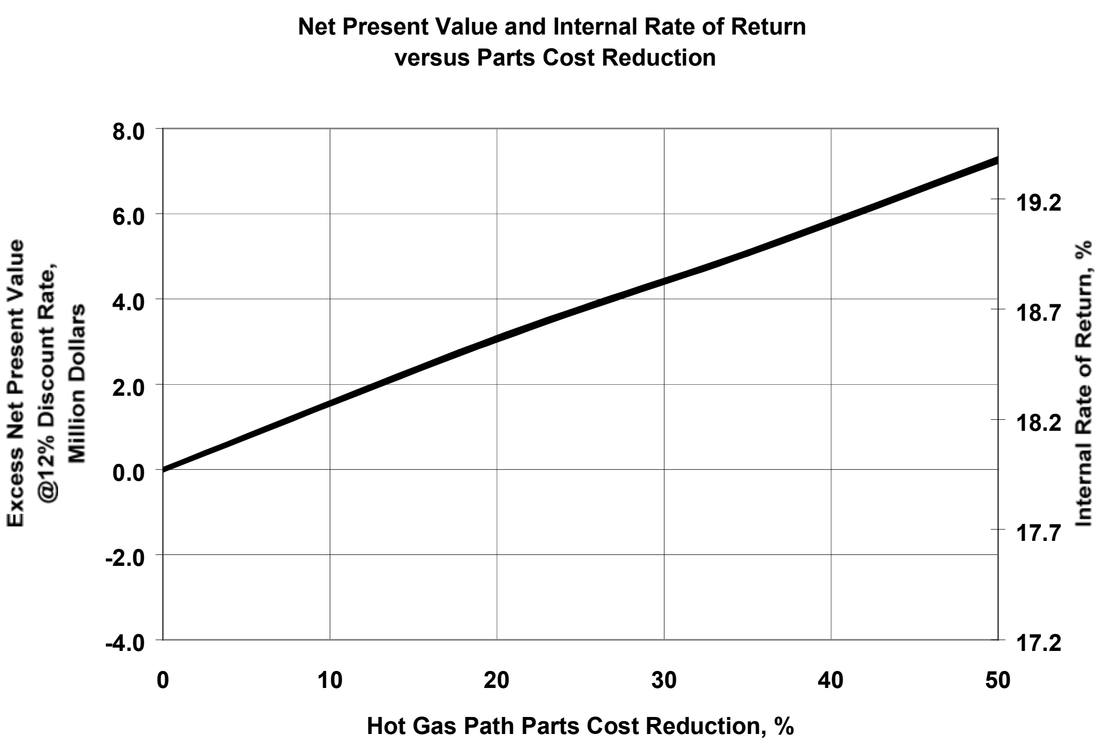

Figure 10- Plant Profitability Sensitive to Reduction in Hot Gas Path Parts Cost

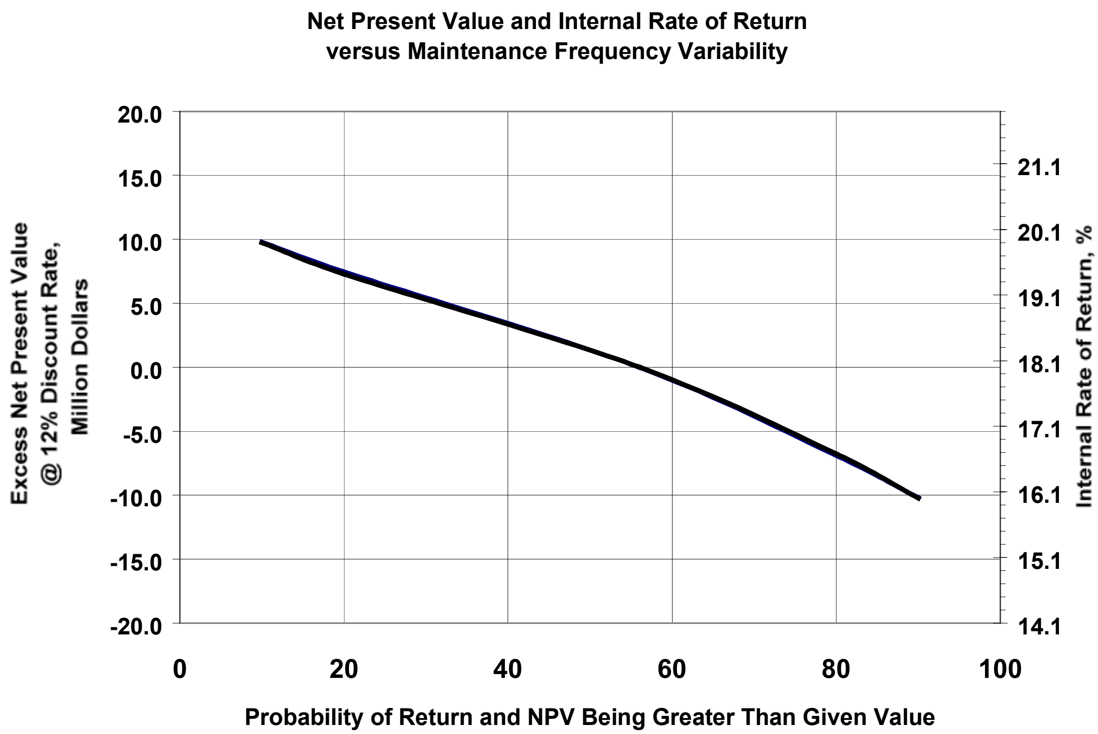

Figure 11- Technical Areas of Improvement for Life Cycle Costs