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Financially Optimizing the Timing of Major Equipment Maintenance Against the Consequence of Lost Reliability

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Abstract

The timing of major equipment maintenance is being planned with advanced techniques of predictive maintenance or reliability centered maintenance. A limitation of these techniques is that they do not have a direct connection to the financial side of corporations, therefore they stay focused on the on the engineering side of the corporation. As financial constraints are placed on maintenance resources there is increasing need to communicate to the financial side of the corporation the importance of investment in major equipment maintenance in terms and techniques that they know and accept. This presentation will directly address the use of the techniques of decision/financial analysis to extend predictive maintenance and reliability centered maintenance information and to make the case for the maintenance investment to support equipment reliability.

1. THE SITUATION

Across the energy-related infrastructure industries in the U.S., engineers are finding it increasingly difficult to obtain the necessary resources to maintain large equipment. This is especially critical since much of this equipment is quite old and there are few plans for replacement. Predictive maintenance and reliability centered maintenance were developed to focus on equipment requiring maintenance resources. However, engineers have been ill-equipped to convincingly “tell their story” to corporate financial decision makers. This paper suggests a process to aid in this communication and guide corporate resources into maintenance expenditures that maximize corporate value.

1.1. Aging Equipment

The upward pressure on maintenance cost comes from equipment that is in the aging part of its life cycle. Most major equipment used in the energy-related infrastructure industries in the United States is in this part of the life cycle. The U.S. went through massive growth in the post World War II era, causing a large growth in base infrastructure industries, such as refineries, petrochemical plants and electric utilities. This equipment was installed in the 50s, 60s and early 70s. As a result of this, and the way it was designed and operated, this equipment is in the aging part of its life cycle in the 1990s.

An example of this for the electric utility industry is shown in the failure rate; i.e., Forced Outage Rate versus calendar time curve for 50MW to 200MW coal-fired boilers published in 1985.[1] This curve, shown in Figure 1, shows the classic shape of the Weibull life cycle curve.

To the left is the decreasing failure rate of the curve, usually called "infant mortality." It is dominated by failures from initial defects, either in manufacture or design. The center section is a period of constant failure rate, and is the period when minimum prudent maintenance causes the failure rate to remain constant. This period is the sum of infant mortality and the aging part of the life cycle. The right section is the "aging period," and has an exponentially increasing failure rate because of the dominance of aging failure mechanisms. This life cycle curve is classic and can be used to describe the life of not only engineering components, but almost anything in nature that has a birth, life span, and death. What is experienced in equipment is very normal and predictable.

Some industries have been surprised by large increases in maintenance cost, especially in the aging part of equipment life cycles. During the constant failure rate period, it was generally felt that if prudent maintenance were performed, the rate of failures would not increase. This is the period of the life cycle when many managers gained their experience.

The original plan by engineers was to replace equipment at the end of its life cycle, in anticipation of aging. However, competition has prevented the necessary resources from being available. This is because the U.S. no longer dominates world markets. As a consequence, corporations are faced with the need to keep aging equipment running with limited resources.

1.2. Worldwide Competition

The limitation on maintenance resources comes from rising maintenance cost and a lowering of product prices because of competition from low-cost producers worldwide, or excess commodity supplies. This situation may not be true for other parts of the corporation that are feeling the effect of lower prices, but not the severe upward pressure analogous to rising maintenance costs.

Until this point in history, a sound engineering analysis was considered adequate to convince management that maintenance expenditures were necessary. However, corporate resources have tightened, and engineering analysis alone has lost the appeal necessary to obtain maintenance resources. In short, engineering for engineering's sake is losing its strength.

Anytime that resources become limited, more quantitative methods are used to aid in difficult decisions using systematic input processes. Because choices are not as clear, there is a need to extract all possible information from inputs, and to process this information in a very quantitative manner in an attempt to promote more objectivity and ease of review.

1.3. Competing for Maintenance Resources

Engineers are finding themselves competing against other segments of the corporation for investment resources to support maintenance. The refining and petrochemical industries, like other energy-related infrastructure industries, are finding an extreme limitation put on maintenance resources. Engineers are having a difficult time being heard because they do not normally speak in financial terms and do not usually have the necessary tools to compete in this arena.

Competition for corporate resources occurs on the turf of corporate finance, using accepted fully-quantitative methods. Increasingly, the control of financial resources in many corporations is in the hands of financial decision makers. The methods used in this arena to judge one investment versus another have been financial analysis and decision analysis.

The limitation on maintenance resources due to lower prices and competition, and the increased need for maintenance resources because of aging, has placed maintenance decision making in a dilemma. In the past, when there were more resources, there was more margin to be conservative and to include maintenance actions that may not have been entirely necessary. With current and future limited resources, this degree of conservatism can no longer be tolerated. More fully-quantitative techniques are now needed to better discriminate between maintenance actions.

2. CONVENTIONAL METHODS

The conventional methods of maintenance planning, predictive maintenance and reliability centered maintenance, do a good job of focusing maintenance resources when the primary goal is reliability and the failure rate is constant. However in the aging part of the equipment life cycle and when communication to financial decision makers is necessary these methods can fall short.

2.1. Limitations of Reliability Centered Maintenance and Predictive Maintenance

When equipment is in the aging part of its life cycle, described above, the failure rate is exponentially increasing as opposed to being constant. In many forms of reliability centered maintenance the failure rate is assumed constant. This means that the applications of major maintenance my not be soon enough. On the other hand predictive maintenance can miss this exponential increase if measurements are not applied often enough to the critical equipment.

The function of equipment is produce product that results in net revenue. If equipment will be used to produce product for sale every moment that it is available to operate then reliability centered maintenance and a financially based maintenance program will produce the same result. However, in many industries this is not the case. It can either be that the unit that the equipment is in is not needed all the time or that the equipment is spared. This results in a disconnection between reliability and net revenue for the product production. This means that we are using reliability as a surrogate variable for net revenue instead of using net revenue directly in timing the maintenance. For many years engineers were able make engineering based arguments strictly in the engineering part of the organization to gain maintenance resources. Times are quickly changing where maintenance resources have to be obtained from the financial part of the organization. This is occurring because the support role of the maintenance function is not viewed as critical to the direct line of production.[2]

2.2. An Extension of Reliability Centered Maintenance and Predictive Maintenance

In view of this an extension of the philosophies of reliability centered maintenance and predictive maintenance would be useful in carrying their message into the world of corporate finance so that the case of maintenance can be presented on an equal basis with the other cases for corporate financial investments.

3. FULLY-QUANTITATIVE RISK-BASED PREDICTIVE MAINTENANCE/ INSPECTION PLANNING

Decision analysis allows the modeling of the decision problem being addressed. This format also stresses the maximization of production output because it focuses on the minimization of production loss for equipment in its current and future condition.

The primary tool used in decision analysis is the influence diagram, which will be described later. This tool emphasizes the relationships involved in the decision. It also has an important benefit in that it can be used in a spreadsheet form to optimize what maintenance needs to be performed and when, based on equipment conditions. The model clearly demonstrates the reason for the priorities to everyone. The use of decision analysis through the model developed in the influence diagram can demonstrate and guide how maintenance and operation personnel can interact to achieve maximum production output.

3.1. Engineering Linked to Finance

Perhaps one of the most important steps in the fully-quantitative process is the conversion of engineering analysis results to financial consequences. The barrier to understanding the engineering position on an important maintenance project proposal is that the engineer usually speaks in engineering units, such as time to failure or probability of failure. He talks of the probability of occurrence, not consequence of occurrence. “Consequence of occurrence” is a term that business-oriented managers understand. In the business-oriented environment, engineers need to convert engineering units into financial units.

The term that the decision maker is most concerned with is not whether a component will fail, but what this failure will mean to the health of the company. A more accepted term in engineering and other technical communities with which to describe this is risk.[3] In the financial community this same formulation is called the “expected value” of the consequence.[4] Because of this similarity in definitions, we now have a common link between the engineering world and the financial world. This relationship, defined by risk or expected value of a failure, will be a key in the formulation of the decision model for fully-quantitative maintenance decision making.

3.2. Decision Analysis

Decision analysis, supported with financial analysis and optimization techniques, is already being used for large investment decisions when large segments of resources are involved. It can be found as part of a course, or as a whole course, in almost every MBA program in the U.S., and in many foreign countries. This method for decision making was developed almost thirty years ago[5] to account for conditions of uncertainty. It is very well suited for maintenance decision making because of the uncertainty of trying to maintain equipment during the aging part of its life cycle.

Decision analysis fits the situation for maintenance, when limited resources make decisions not as obvious. This requires fully-quantitative methods that can stand the test of challenge and review. The methods that have survived for a long time are those of decision analysis and financial analysis. This is because they are classic and well grounded in the principles of probability theory and of maximizing long-term return to the stockholder. Their appeal has been their ability to fully quantify and process input information through a decision model.

In most major corporations, particularly in utility companies, and in exploration and production organizations, using decision and financial analysis techniques is an accepted way of doing business. These types of companies are already accustomed to looking at financial decisions on a fully-quantitative basis, and accounting for uncertainty in the decision in a fully-quantitative manner, using classical methods. Because senior management views this type of approach as an accepted method, it seems reasonable, therefore, to use the same techniques for maintenance decision making since maintenance is competing for the same resources.

3.3. Basic Predictive Maintenance Decision Model

3.3.1. The Decision Model

In decision analysis, the first decision to be made is the criterion to be optimized. Based on textbooks used most frequently in MBA corporate finance courses, this criterion would be Net Present Value (NPV).[6] This criterion insures that there will be a maximum return for the invested corporate dollar when decisions are being looked at over multiple years. In addition, some of the more recent terms used to emphasize stockholder value of a corporate investment are maximized when NPV is maximized. This makes NPV the most robust of the financial criteria to be used for optimization.

There is a danger, practiced by some engineers, in sometimes using reliability as a criterion for decision making. Reliability is an engineering term, not a financial term. It is not well understood in the battle for corporate resources. Secondly, reliability and NPV analysis can produce the same results when the equipment of concern is in demand a high percentage of the time. However, the difficult maintenance decisions are those for equipment that is not highly utilized. In this case, NPV will guide the decision toward highest value, rather than highest reliability, since highest reliability is not always needed.

In the case of maintenance, the “Net” of Net Present Value is created by looking at the choice between two maintenance decisions.[7] The first possible decision is doing nothing different. That is, run the equipment as it is, performing normal routine maintenance. This we call the “base case.” Here, we consider the consequence of shutdown or derating as a result of keeping the aging equipment operating. The intent of the maintenance action is to avoid this consequence. We call this the benefit of the maintenance action, since we are taking credit for preventing the consequence of shutdown or derating. The second possible decision is to take a mitigating maintenance action to avoid the potential consequences of failed equipment and shutdown. This we call the “alternative case.” It is the cost of taking maintenance action. Here, we look at the cost of the maintenance action, plus the consequence of a shutdown or derating that might still occur due to the maintenance action not being perfect.

The diagrammatic representation of this is shown in Figure 2 by a decision analysis influence diagram. This diagram is constructed by placing the decision criterion to be optimized on the right. The diagram and its relationships are constructed as we ask the question: "What do we need to know to determine the NPV in this case?" We need to know the benefit and cost side as shown above and below the horizontal line in Figure 2. The expected consequence of failure (risk of failure) without the action is the benefit, and the cost is the cost of the maintenance action plus the expected consequence of failure (risk of failure) with the action. Ultimately, on the far left we have the decision of whether or not to take the action represented in a square. Note that this diagram establishes a relationship between the decision, the specific terms in the maintenance action and its consequences, and the decision criterion of NPV. What is seen in this diagram is the cash flow streams created by the relationships in this decision problem.

The "Present Value" part of Net Present Value considers the effect of taxes and the time value of money. Because maintenance decisions on aging equipment have to do with timing, this is an important consideration in any maintenance decision analysis. In taxed corporations, the tax effects on maintenance expenditures, as well as losses declared from shutdowns or deratings are significant. Engineers usually are not concerned with these, but in the financial arena they need to be accounted for, especially in fully-quantitative analyses. The same is true for time value of money. This accounts for inflation and the expected return to be passed to the shareholder. The discount rate is usually used, so that the expected return for the invested maintenance dollar has to meet or exceed a minimum desired return to the shareholder over time.

This is further represented in the development of the maintenance action decision influence diagram shown in Figure 3.[4] Note the addition of the probability of failure, consequential failure cost, and the conversion of the consequential failure cost node into the expected consequential failure cost (risk of failure) nodes. The "with" and "without" maintenance action cash flow streams create the net value of the decision criterion. The year to perform the maintenance action is added to this figure given that it has been decided to perform the action. The arrows that may seem strange in this figure are the ones pointing from year of performance of the action to the probability of failure without the action, and the one pointing from the probability of failure without the action to the expected consequential failure cost (risk of failure) with action. The reason for these two arrows is to establish the relationship for the expected consequential failure cost (risk of failure) if the maintenance action is delayed. During the delay to the year in which the maintenance action is performed, the expected consequential failure cost (risk of failure) will be the same as if the project action had not been taken. Note that after the year to perform the maintenance action, the probability of failure with action is used to determine the expected consequential failure cost (risk of failure) with the action.

For inspection planning it has been found that the best maintenance cost to use is not the cost of the inspection but the cost of the major repair or replacement that the inspection is being performed to support. This keeps the maintenance decision in perspective. In addition, the inspection cost is usually so low relative to the expected consequential cost or risk of failure without maintenance, that the timing for inspection would usually be right away for all equipment, which is not realistic.

3.3.2. Engineering Inputs

The use of "probability of failure" with time is an all-inclusive expression of the engineering condition of the equipment. For many years worst case analyses were typically performed. A probability of failure was set to an absolute certainty, i.e., the value of one, with full consequences at that same time for purposes of financial analyses. By intent, this approach is very conservative. Worst case scenario inputs in this type of analysis are meant to account for the uncertainty in the inputs. However, engineering input is limited to the worst side of the distribution rather than using the whole distribution. In addition, engineering, by using single numbers for equipment lives, was, by implication, leading decision makers to believe that the equipment condition was more precisely known than it actually was. The use of full distributions to describe inputs is an all-inclusive description of the inputs and their uncertainty, rather than just a restrictive worst case value. The advent of probabilistic fracture mechanics started an awareness that a complete expression of the engineering state of the equipment could best be expressed with a probability of failure versus time curve. It is clear from the financial discussions above that an expression of the engineering condition of the equipment in this form directly integrates into already established classical probabilistic, decision, and financial analysis methods.

On large maintenance decisions, a lack of credibility is created in the mind of the financial decision maker when excessively large financial consequence estimates, and the worst case probability of failure, are used. However, if a prudent, fully-quantitative engineering probabilistic analysis is performed, and the financial consequences of a failure are appropriately estimated, there is more credibility to the risk or expected value of the consequence provided to the decision maker. As a result, it is appropriate in aging large equipment maintenance decisions that the engineer use all possible technologies to assess the condition of the equipment from the standpoint of failure.

The area of probabilistic fracture mechanics best describes these techniques. These techniques establish a damage propagation mechanism mathematical model with a failure criterion. This model is then integrated over the range of input distributions with a "Monte Carlo" program or fast probability integration techniques. This integration produces a probability of failure versus time curve.[4,8,9]

There are less rigorous methods that are fully quantitative for obtaining probability of failure versus time. These methods are good for obtaining preliminary engineering inputs for the maintenance decision analysis. This allows a first level look at the possible allocation of maintenance resources. The first of these methods is the trending of failure history data on a plant component of concern, or on similar components at other plants. A method used for this is standard linear regression analysis using the Weibull distribution function. The reason to use this function is that it was derived to express the reliability of equipment with time. It has been used extensively for this purpose. A second method is a structured interview for future failure projection with plant personnel most familiar with the equipment. This method is called a probabilistic assessment interview, or expert elicitation. It was developed by cognitive psychologists in the decision analysis community over the last fifteen years, and has been extensively used with senior corporate executives on large corporate decision analyses.[4,8,9]

The Bayesian update analysis is a classical method of combining failure history projections with plant personnel structured interviews. The Bayesian method, developed over two hundred years ago,[10] focuses on the combination of current probabilistic information of an event with newly found information for the same event, resulting in updated information. It is objective and can be used to combine failure history projection data and plant personnel interview projections, using a weighted averaging technique based on the normalized product of the two projections for each year. Using a technique of this type provides a balanced projection of the future failure probability because of the use of both data sources. In addition, using these preliminary techniques allows the decision to be assessed inexpensively as a first iteration to determine the need for a higher cost, fully-quantitative engineering analysis.

3.3.3. Financial Inputs

The financial assumptions used in this type of analysis are usually well established in the financial or economic planning organization of a corporation. For the engineer, it becomes a matter of seeking them out. These financial assumptions need to be included in a fully-quantitative analysis because they have significant effects on the timing of the maintenance project.

One set of financial assumptions affects the time value of money. First is the projected inflation rate, to account for the eroding value of the dollar with time. Second is the corporate discount rate used to insure that any investment is expected to have a return that is at least equal to the planned return for the stock and bond holders.

The other financial assumptions that are seldom thought of are the composite income tax rate and the property tax rate. Of these two, the composite income tax rate is the most significant and has a large effect on the value of a maintenance decision. The effect is that financial loss consequence can be viewed as a business loss, and a significant portion can be written off. The impact of the maintenance cost itself can be greatly reduced for the same reason if the maintenance cost is classified in an expense category. If the maintenance cost is capitalized, it still can be written off but at a much lower rate, over time, through the tax effect of depreciation.

3.4. Optimizing the Decision Model for the Maintenance/Inspection Plan

The objective in decision making is to optimize the decision criterion. In this maintenance decision situation we are trying to determine a maintenance action year to maximize NPV, while not exceeding either of the constraints of maintenance budget limit or downtime limit. The goal is to optimize NPV by maintenance action timing.[4,8,9]

Operations research methods can perform this function on the decision model described. In fact, the decision model has been constructed in a spreadsheet model, and an operations research type optimizer has been written as a spreadsheet macro.[4,8,9]

4. THE APPLICATION IN A REFINERY SYSTEM

An example refinery application of this process is for an unspared, 4700 horsepower reciprocating hydrogen recycle compressor, which operates in a 30,000 barrel/day hydrocracker unit with a net unit margin for summer operation at \$2.89/barrel.[11] The situation that is modeled is when the compressor fails, the hydrocracker unit is shut down for six days, and the reformer is derated by 16,000 barrels of naphtha feed at \$1.00/barrel net unit margin. Damage is assumed to be confined to the compressor. The maintenance decision is whether or not to overhaul the compressor, which is estimated to be \$20,000. The with and without maintenance probability of failure vs. time curves are shown in Figure 4. The NPV vs. time curve for this situation is shown in Figure 5 with the highest positive NPV of \$4,035 falling in year 1999, indicating the optimum year to take maintenance action.

5. THE APPLICATION IN A FOSSIL POWER SYSTEM

The following is an example of how this maintenance optimization process was applied across a power system.[4,8] It demonstrates that application of this process across a power system, as opposed to the independent selection of these dates based on engineering by individual power plants, can result in multi-million-dollar savings. The first step in an optimization analysis is to select those components in the power plant that present the greatest economic risk to the power system. The metallurgically assessable components that contributed the greatest risk were identified using the power system data in a risk plot shown in Figure 6. The top five system-wide components selected are from the 1000 series, which are to the right and upper portion of the figure.

In this example, the probability of failure versus time curves for this optimization were obtained by combining component failure history with simplified metallurgical engineering remaining life analysis results using a Bayesian updating analysis process. This process was further used to combine the previous curve with the results of formal probabilistic interviews of plant personnel for each component. This approach insured that all points of view from the engineering perspective were used as inputs to the optimization model.

The maintenance optimization process was applied to eleven individual plant components shown in Figure 7 along with the year of component replacement based on conventional engineering analysis. Note that this figure includes component replacement cost and the annual consequential cost of failure for the component, called Annual Component Individual Forced Outage Cost. These engineering replacement dates and consequential costs resulted in an NPV of \$50,000 using the maintenance optimization model calculation scheme described above. After the optimization is run, a new list of component replacement dates is shown in Figure 8 based on the combination of engineering and financial considerations within budget constraints. The NPV for these optimized dates is \$1,214,000, or an increase of \$1,164,000 in NPV savings by considering maintenance optimization in an engineering and finance framework. By examining each of the date changes and the associated cash flows in the open spreadsheet format, a clear interpretation can be made as to the driver that caused the date changes.

The first application of maintenance optimization, as described in this example, was for a medium size electric utility with a fossil power system of 19 boilers which was considering 140 critical tube components. This optimization resulted in excess of $50 million in NPV savings versus using conventional engineering planning approaches.[4]

6. CONCLUSION

Maintenance optimization provides a balance between the concerns for equipment condition and the financial concerns of investment in maintenance. As such it provides a natural and valuable extension to the philosophies of reliability centered maintenance and predictive maintenance.

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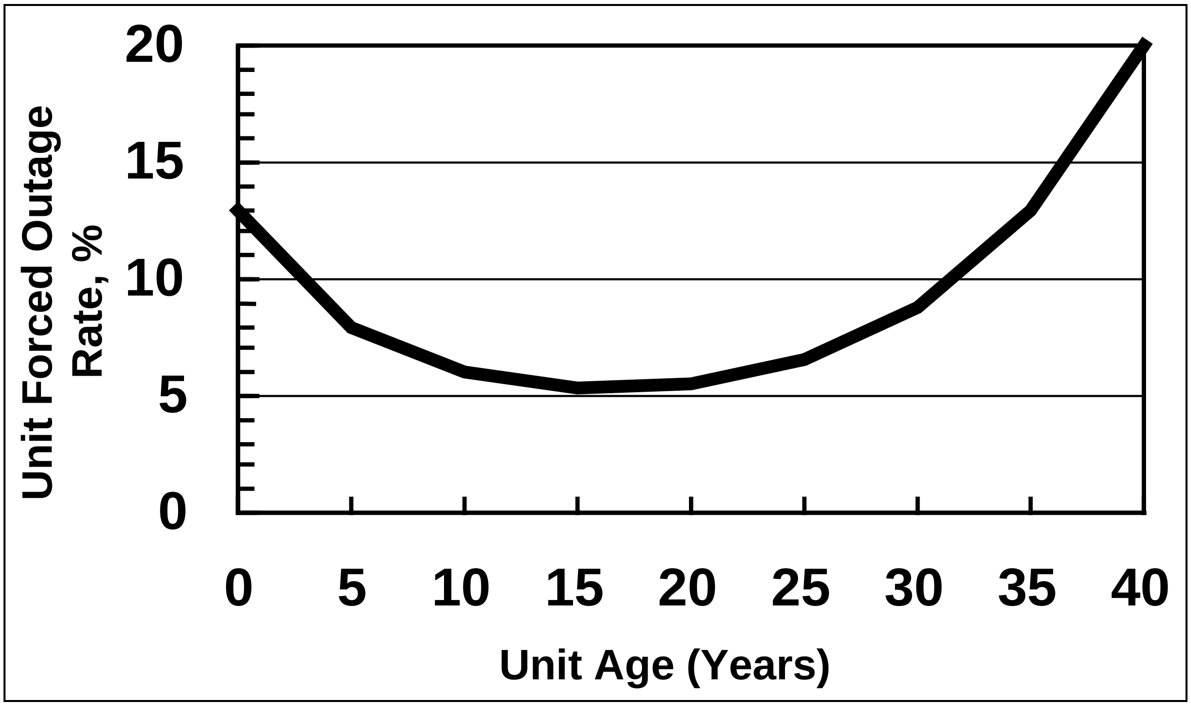

Figure 1. NERC-GADS Data for Forced Outage Rate for Coal-Fired Units From 50 to 200 MW

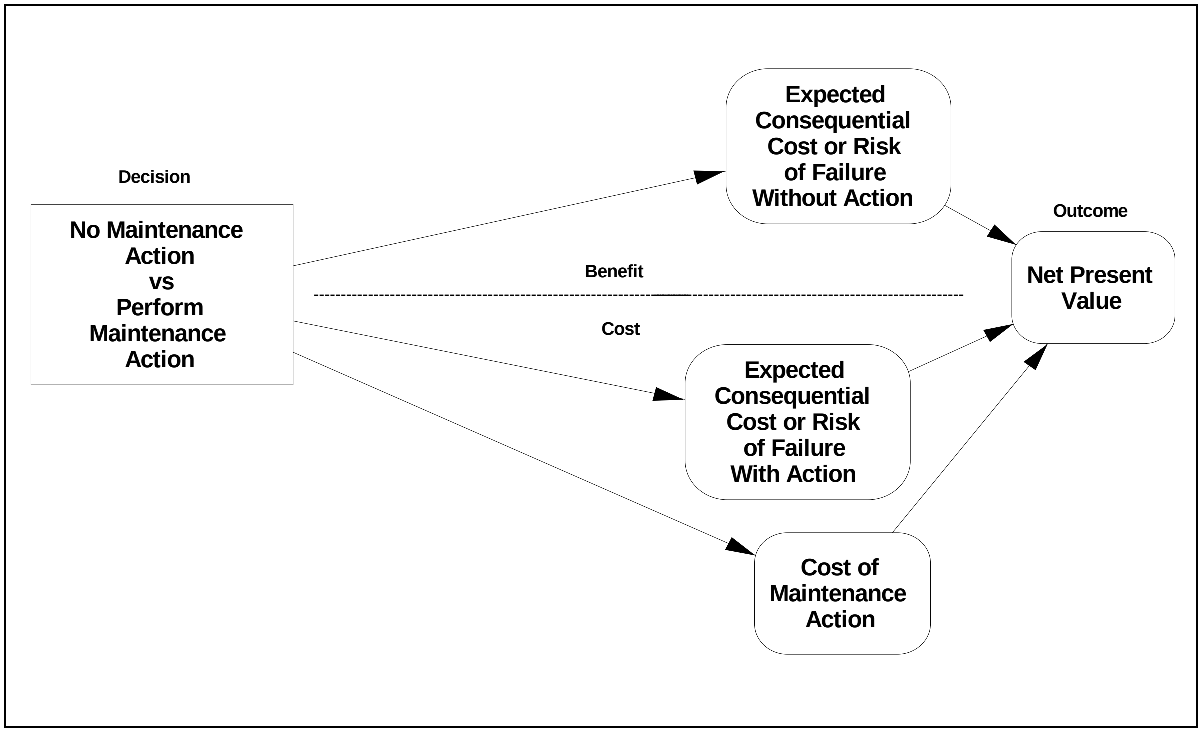

Figure 2. Influence Diagram Emphasizing the Links Between Net Present Value and the Maintenance Action Decision

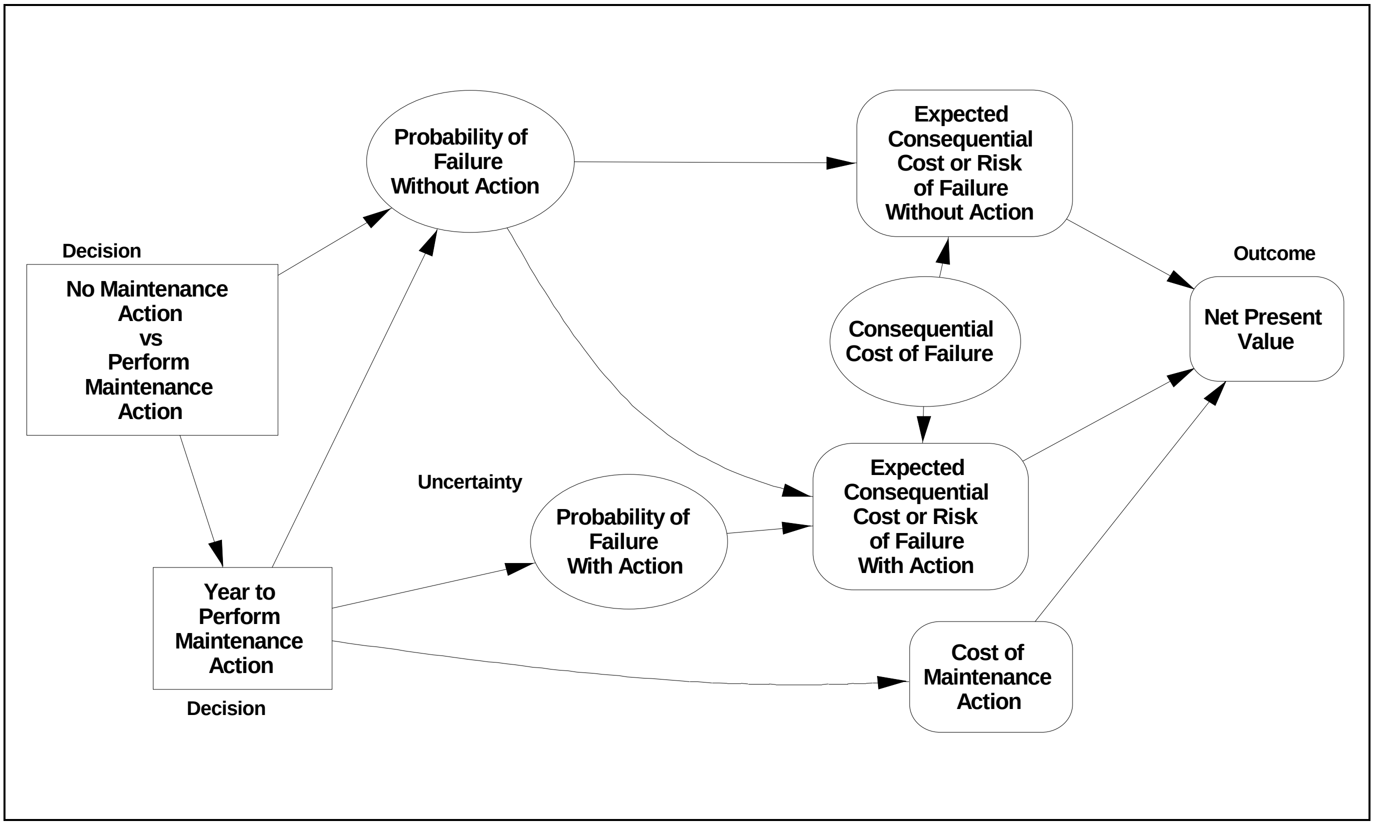

Figure 3. Influence Diagram Emphasizing the Replacement of Consequential Cost with Expected Consequential Cost or Risk

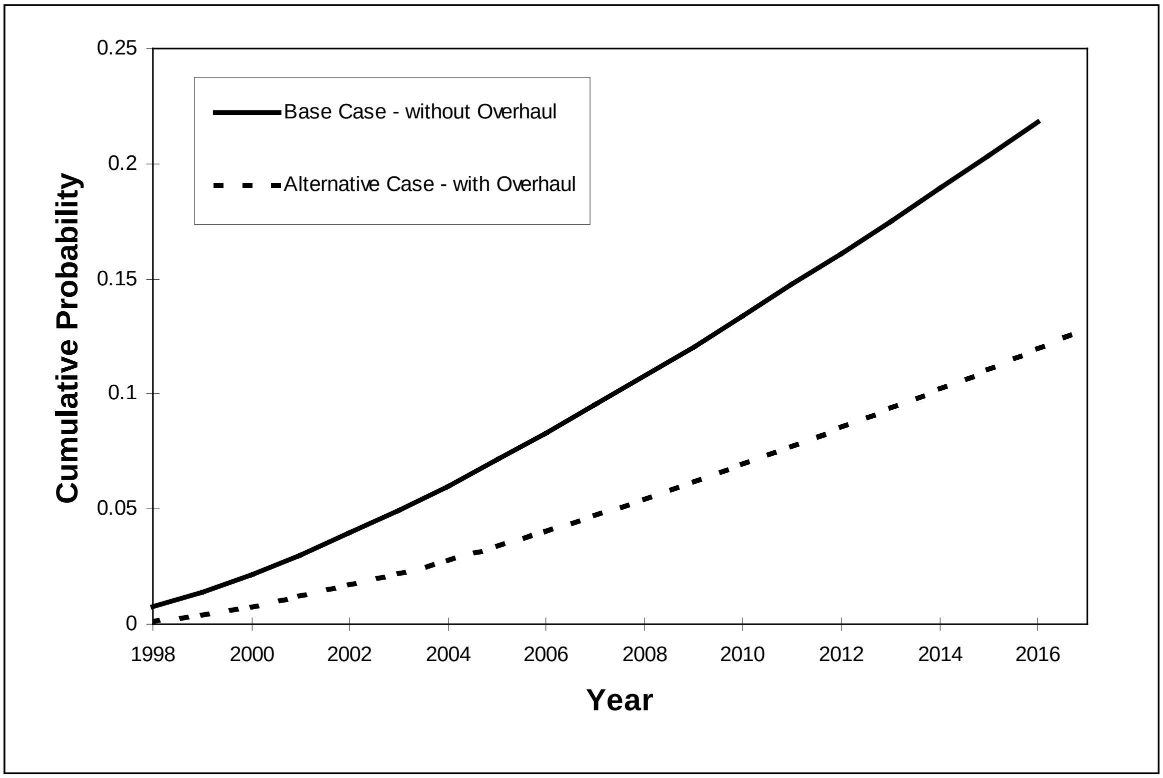

Figure 4. The With and Without Maintenance Probability of Failure Versus Time Curves for the Reciprocating Hydrogen Compressor Example

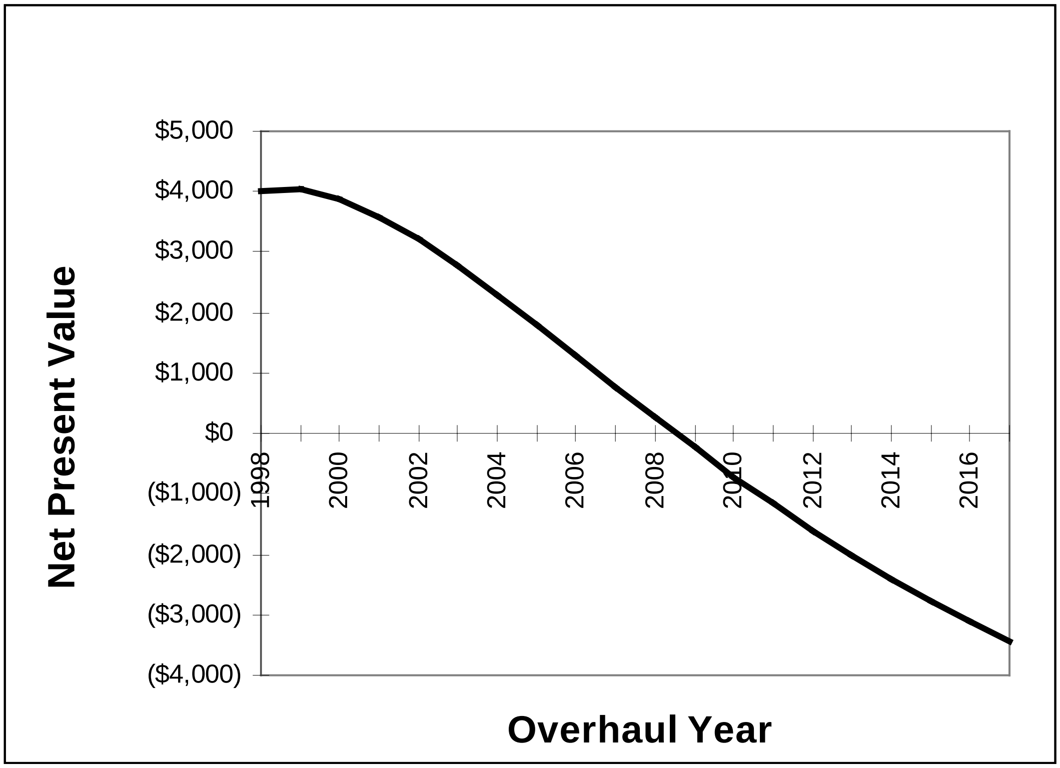

Figure 5. Net Present Value Versus Overhaul Year for Reciprocating Hydrogen Recycle Compressor Overhaul

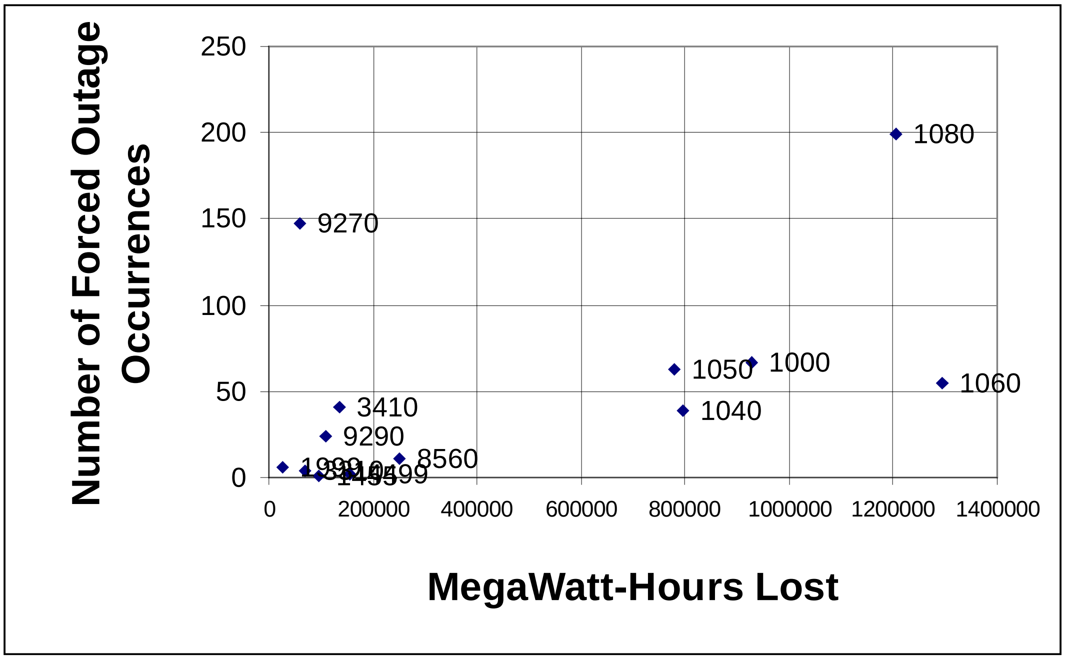

Figure 6. Example of Risk Plot for Consequence of Forced Outage Megawatt-Hours Lost Versus Number of Forced Outage Occurrences by Component Over 9 Years

Plant & Unit	Component	Year of Component Replacement	Yearly Change in Probability of Failure	Annual Component Forced Outage Cost
A1	Sec. Superheater	2003	0.51%	$1,081,942
B3	Sec. Superheater	1996	0.19%	$141,294
C3	Sec. Superheater	1995	0.16%	$57,346
C4	Waterwall	1994	0.03%	$19,000
E2	Sec. Reheater	1999	0.27%	$144,651
F3	Sec. Reheater	1999	0.09%	$181,586
C1	Sec. Superheater	1996	0.18%	$46,686
B3	Waterwall	1992	0.04%	$26,319
F2	Sec. Superheater	2001	0.69%	$103,115
C3	Economizer	1995	0.16%	$12,406
F3	Pri. Superheater	2000	0.26%	$80,477

Figure 7. An Example Listing of The Components Showing Engineering Replacement Dates with a Net Present Value of $50,000

Plant & Unit	Component	Year of Component Replacement	Yearly Change in Probability of Failure	Annual Component Forced Outage Cost
A1	Sec. Superheater	2000	0.38%	$616,377
B3	Sec. Superheater	1996	0.19%	$141,294
C3	Sec. Superheater	1996	0.17%	$105,198
C4	Waterwall	1997	0.05%	$87,252
E2	Sec. Reheater	1995	0.17%	$32,949
F3	Sec. Reheater	1998	0.09%	$127,696
C1	Sec. Superheater	1998	0.19%	$144,979
B3	Waterwall	1994	0.06%	$25,149
F2	Sec. Superheater	1996	0.56%	$30,596
C3	Economizer	1998	0.23%	$85,871
F3	Pri. Superheater	1999	0.26%	$73,016

Figure 8. An Example Listing of the Components Showing the Optimized Replacement Dates with a Net Present Value of $1,214,000