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EMPLOYING THE RISK SCIENCES TO IMPROVE THE PERFORMANCE OF COMPLEX ENGINEERED SYSTEMS

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This paper addresses the question of not only how the risk sciences enable quantification of the risks associated with complex engineered systems, but how the same thought process represents a general approach for quantifying and adding rigor to essentially any type of performance measure having to do with design, operations, maintenance, productivity, and investment. Such a rigorous and quantitative capability is critically important for analyzing complex engineered systems having the potential for accidents and releases that can catastrophically impact human health and safety, the environment, or the resources of the operating companies.

The changes that have to be made to use the methods of risk assessment to quantify different performance measures of a total system are generally only the boundary conditions and the success and failure criteria of the relevant structures, systems, components, and processes (SSCP). For example, the failure and success criteria are different depending on whether the performance parameter being quantified is risk, benefits, or costs; or subsets of these such as availability, reliability, maintainability, productivity, or cost-benefit; or even more detailed performance parameters such as specific safety systems, corrosion rate, efficiency, thermal performance, and throughput.

Basically, what is being advocated in this paper is more rigor in the investigations and assessments that support the design, operation, maintenance and accident management of complex engineered systems—the type of rigor that can prevent or better manage their catastrophic failure. Such rigor can not only save lives and lessen the risk of facility and property damage, but can also provide direct benefits in terms of the efficiency and economics of system performance. Quantitative performance assessment should be the way of the future for systems whose catastrophic failures can render harm to workers and the public, have adverse environmental impacts, or be a threat to the financial health of the owners and operators of engineered systems. One of the most important outputs of the analyses is the quantification of the uncertainties involved, as future projects and their likelihood of success is inevitably dependent on how well the uncertainties are understood and represented.

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The distinguishing features of the quantitative approach advocated are (1) it is scenario based, (2) the uncertainties are quantified at the parameter level and propagated through the models making transparent what is known and not known, and (3) probability, the language of uncertainty, is the basic parameter of the model. It is a method developed to better enable quantifying the risk of rare but catastrophic events and the performance of systems for which there is limited experience. The framework for the methodology is the “triplet definition of risk” (Kaplan and Garrick, 1981), which in the context of this paper is presented as a framework for quantifying the performance of essentially any type of system, engineered or natural.

A convenient way to think about using the “triplet” risk perspective for evaluating performance parameters in general is in terms of “what is the risk of not meeting the intended goal of any conventional performance measure, be it cost-benefit, productivity, reliability, availability, maintainability, or regulatory requirements.” The contributing factors of failure to meet different performance goals are exposed and are rank ordered providing a meaningful basis for taking corrective actions and performing systematic and science based risk management. The experience with applying the risk triplet has been enormously successful, resulting in hundreds of millions of dollars in savings in several large engineering projects.

TRIPLET DEFINITION OF RISK

The basic framework of quantitative risk assessment adopted by many to achieve the above described benefits is based on the “set of triplets” definition of risk. This definition represents risk (or other performance measures) in terms of scenarios, consequences, and likelihoods. In particular, risk is defined as

$$R = \{< S_i, L_i, X_i >\}_c$$

where R is the risk of the system, process, event, parameter, or activity of interest. Depending on the application, R may have a different meaning such as unavailability, unreliability, or negative benefit. S_i *i*s the risk scenario associated with the selected R (a description of something that can go wrong), L_i is the likelihood of that scenario happening, and X_i represents the consequences of that scenario if it does happen. The angle brackets < > enclose the risk triplets, the curly brackets { } are mathspeak for “the set of,” and the subscript “c” denotes “complete,” meaning that all scenarios, or at least all of the important ones, must be included in the set. The body of methods used to identify the scenarios (S_i) constitutes an evolving “theory of scenario structuring” (Kaplan, et al., 2001). Quantification of the L_i and the X_i is based on the available evidence. Bayes theorem is the basis for processing the evidence (Kaplan, 1986).

In accordance with this “set of triplets” definition of risk, the actual quantification of risk consists of answering the following three questions:

1. What can go wrong? (S_i)
2. How likely is that to happen? (L_i)
3. What are the consequences if it does happen? (X_i)

The first question is answered by describing a structured, organized, and complete set of possible risk scenarios for the parameter of interest. As above, we represent scenarios by S_i. The second question requires us to calculate the “likelihoods,” L_i, of each of the scenarios, S_i . Each such likelihood, L_i, is expressed either as a “frequency,” a “probability,” or a “probability of frequency” curve to characterize the uncertainty in the scenario. Probability of frequency is the preferred way of expressing likelihood, as it embodies both the notion of frequency, that which is observed, and probability, to characterize the uncertainty in the frequency if based on limited information.

The third question is answered by describing the “damage states” or “endstates,” X_i, resulting from these risk scenarios. Of course, the endstates are going to be different depending on the performance indicator being evaluated. For example, for risk the endstate is generally a catastrophic failure whereas for something like reliability the endstate could be a simple component failure or maintenance malfunction. These damage or failure states are also, in general, uncertain. Therefore these uncertainties must also be quantified as part of the risk assessment process. Indeed, it is part of the philosophy to quantify all the uncertainties in all the parameters in the risk or performance assessment.

Some authors have added questions to the triplet definition of risk such as “What are the uncertainties?” “What corrective actions should be taken?” and “What are the contributors?” The uncertainty question is embedded in the interpretation of “likelihood.” Above we note the preferred interpretation to be “probability of frequency.” The question about corrective actions is interpreted here as a matter of decision analysis and risk management, not risk assessment. The question about contributors is a matter of importance ranking the scenarios and decomposing them into contributors, which is part of the process of implementing the risk triplet framework and protocol.

To implement the triplet definition of risk, the key activities are the development of the “what can-go-wrong” scenarios, the interpretation and quantification of the likelihoods of the scenarios, and the identification of the endstates of the scenarios which are determined by the failure/success criteria of the particular performance parameter being analyzed. Of course, the assessment involves extensive analysis of the physical processes to resolve the sequence of events making up the scenarios, just as there is extensive analysis in processing the evidence to quantify the likelihoods.

The triplet definition of risk is a basic framework for quantifying risk and system performance. The framework is based on scenarios, likelihoods, and consequences. Figure 1 shows the relationship between the system being assessed, the threats to the system, and the structuring of the scenarios that indicates the vulnerability of the system.

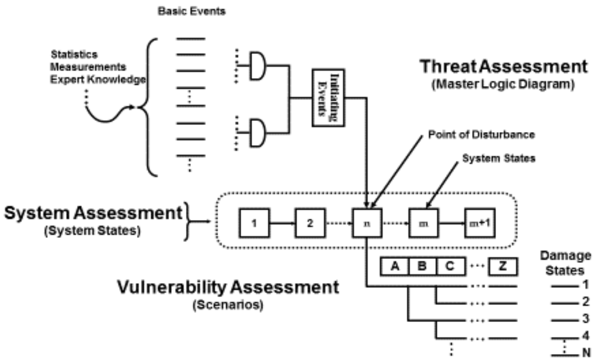


Figure 1. Integrated Risk Assessment

Among the tasks in developing the scenarios are (1) a system assessment, which involves familiarizing and analyzing the system to determine what constitutes the success states for each stage of the system for the particular parameter being assessed; (2) a threat assessment—determination of the appropriate set of initial conditions and initiators that can disrupt or disturb the normal state of the system specialized to the parameter being analyzed; and (3) a vulnerability assessment—that is the performance of a vulnerability assessment of the system by structuring a set of risk scenarios and damage states corresponding to each operating stage or phase. With a structured set of scenarios for each phase or mode, then it is a matter of assembling the individual models at the appropriate pinch points (interfaces) to form an integrated model.

The individual scenarios are quantified based on the supporting evidence. The quantification process involves the use of Boolean expressions to represent the scenarios and Bayes theorem to transform the frequencies of the individual failure events into the frequencies of the scenarios, based on the supporting evidence. The scenarios are assembled for each system operating state. Repeating this process for each stage results in the quantification of the input and output variables needed to assemble the stages into a complete system model. Numerous methods are available for the assembly process (Garrick, et al., 2008).

THE FORM OF THE RESULTS

Costs, benefits, and risks are often used as overarching performance indicators of a system. If all three are determined in monetary terms, then it is possible, at least in principle, to represent performance by a probability curve of the net benefit. There are problems with such an approach. One is trying to establish the monetary value of a human life to account for fatalities and another is the lack of transparency at the net benefit level of the underlying contributors to performance. Still another is that when one is at the point of a decision, other factors than system performance have to be considered. These have to do with preferences and judgment. So, the preferred approach is to choose parameters for evaluation that indeed drive system performance and link them as needed to higher order parameters such as costs, benefits and other metrics necessary for decision making.

For quantitative risk assessments the practice has been to present results in the form of curves, tables, various charts, and figures. The most important output is a discussion and interpretation of the results with a set of recommendations. Figures 2 and 3 are two popular methods for displaying bottom line results with the uncertainties quantified.

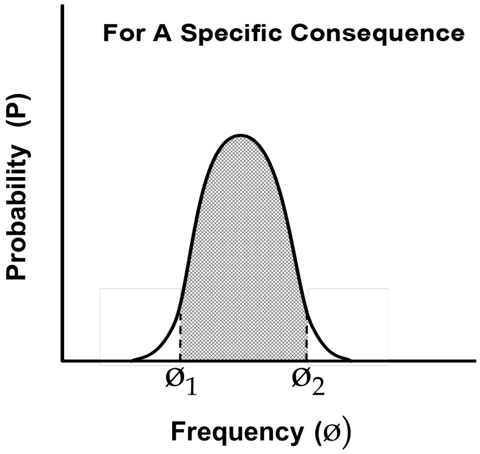


Figure 2. Risk of a Specific Consequence

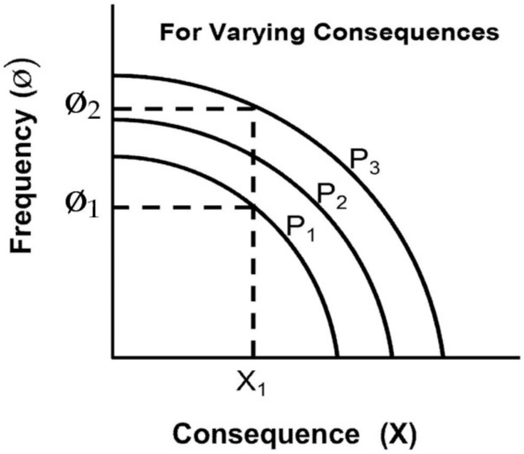


Figure 3. Risk of Varying Consequences

Figure 2 is the form generally used to represent the risk of a specific event, for example, the core damage frequency of a nuclear power plant or the catastrophic explosion of a large diameter gas pipeline. If the area under the curve between $\emptyset_1$ and $\emptyset_2$ of Figure 2 is 90% of the area under the whole curve, this indicates that we are 90% confident that the frequency range is between $\emptyset_1$ and $\emptyset_2$.

To illustrate how to read Figure 3, suppose P_3 has the value 0.95 and we want to know the risk of an event having an X_1 consequence. According to the figure, we are 95% confident that the frequency of an X_1 consequence or greater is $\emptyset_2$. To illustrate how to read Figure 3 in terms of a confidence interval, let P_1 have the value of 0.05, P_3 the value of 0.95, $\emptyset_1$ the value of 1 in 10,000, $\emptyset_2$ the value of 1 in 1,000, and X_1 the value of 10,000 fatalities. Given that P_3 minus P_1 is 0.90 the appropriate language is we are 90% confident that the frequency of a 10,000-fatality consequence or greater varies from 1 every 10,000 years to as much as 1 every 1,000 years.

WHY PROBABILISTIC

To illustrate how quantifying the uncertainties in performance parameters enables better decision making, consider the following two examples. The first example is for the case where – on the basis of point estimates (no uncertainty considered) – two contributors turn out to be approximately equal in their contribution to risk or performance. Thus, the decision maker is left with the understanding that the risks of both contributors are the same and it doesn’t matter which one is chosen for taking corrective action. Now, suppose we quantify the uncertainties of the two contributors and find that there is a major difference in our state of knowledge about them even though their central tendency parameters (means and medians) are about the same, as illustrated in Figure 4. This situation frequently occurs in practice. With quantitative information about the uncertainties, we would be foolish to rank the two contributors equally, as Contributor 2 is a much greater risk than Contributor 1.

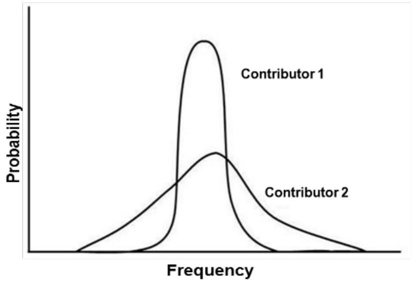


Figure 4. Similar “Point Estimates”

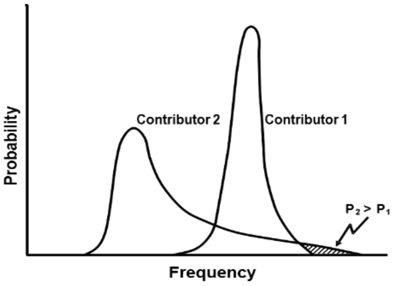


Figure 5. Dissimilar “Point Estimates”

Another important and often encountered case is illustrated in Figure 5. Suppose a point estimate analysis indicates that Contributor 2 is far less of a contributor than Contributor 1. The difference is that we know much more about Contributor 1 than we do about Contributor 2, a situation that often exists when replacing an old piece of equipment or process with a new piece of equipment or process involving a different design. Quantifying our state-of-knowledge results in a probability, perhaps small, that Contributor 2 can in fact be a greater risk than Contributor 1. Obviously, it is very important to know what that probability is when it comes to establishing priorities and making decisions. In the illustration, the issue is not just the tail of the distribution beyond Contributor 1. It’s also the probability of being beyond the central tendency values of Contributor 2, which can sometimes be quite high. The point is quantifying the uncertainties provides much more information for making the right decision.

This kind of transparency in regard to the uncertainties of the contributors can only be achieved through their quantification. Quantifying the contributors is like turning up the microscope on the truth about their importance. It is not the truth, but is closer to it, which is the type of information needed to develop meaningful strategies to mitigate the risk of poor performance. Obviously such resolution of the uncertainties becomes less important with increasing evidence of the system performance.

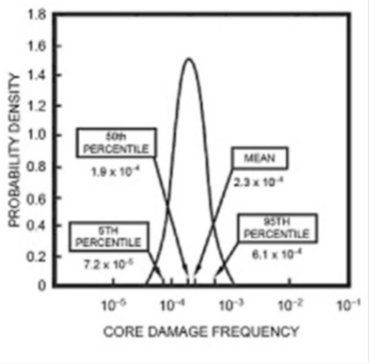
EXAMPLES

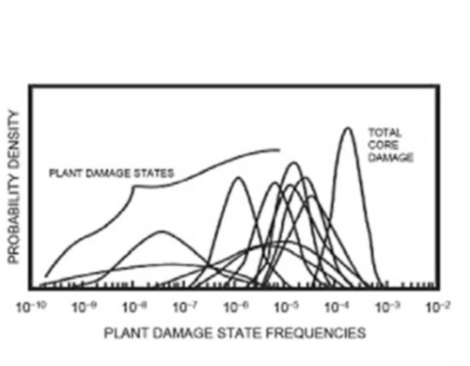
The point has been made that the risk triplet methodology has been developed to quantify the risk of rare events and the analysis of complex or new designs where the information is more limited and the threats are more difficult to understand. Thus, the emphasis is on making uncertainty an integral part of the results by their propagation through the scenarios.

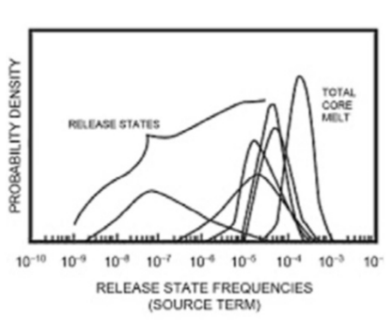
Several real world examples are provided in abbreviated form to illustrate the diversity and depth of the triplet approach. The examples cover risk, cost-benefit, design, procurement, tradeoff studies, maintenance, and reliability.

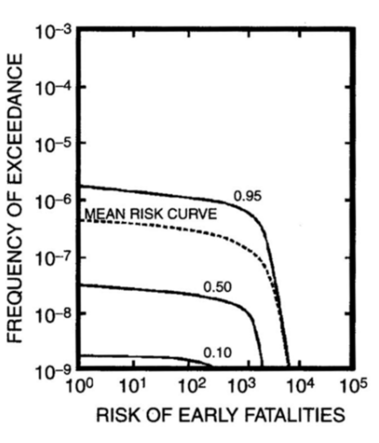
EXAMPLE 1: NUCLEAR PLANT RISK

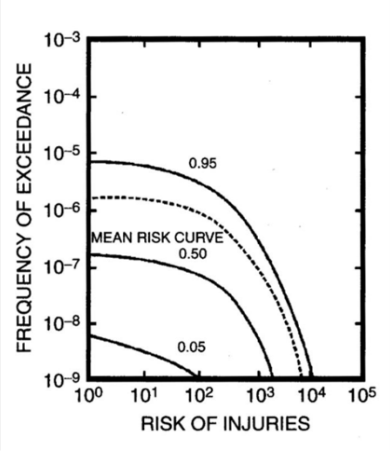
The first example is the bottom line results of a full scope risk assessment of a U.S. nuclear power plant. The plant is not identified, but the results are actual results from a full scope risk assessment utilizing the risk triplet definition and framework.

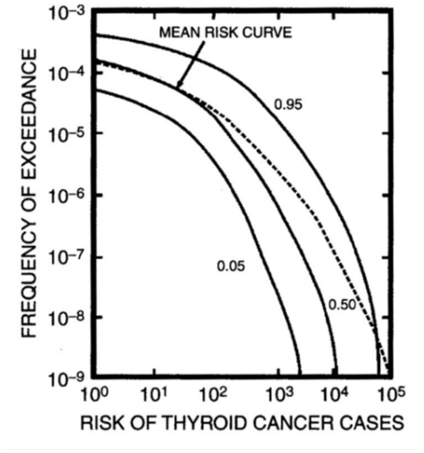












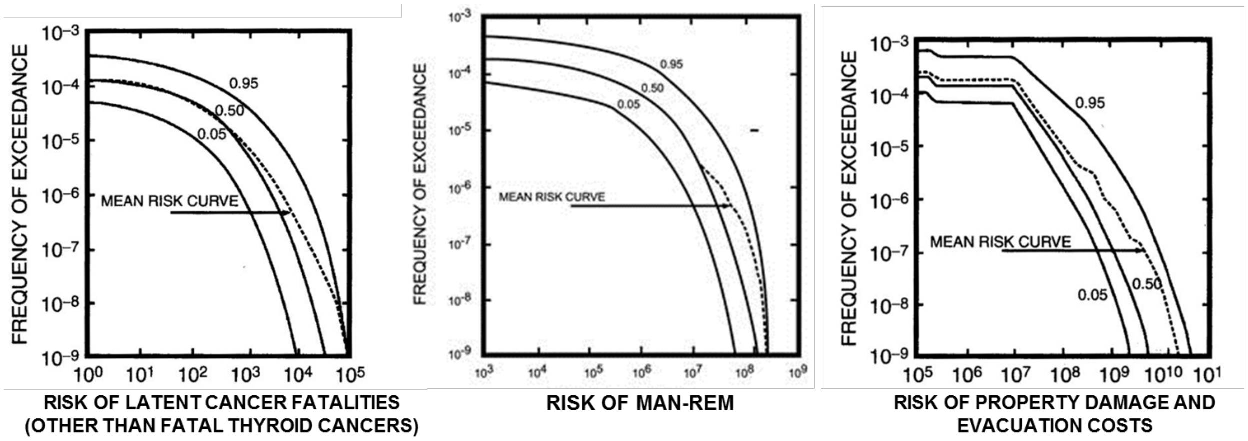


Figure 6. Nuclear Power Plant Risk Assessment Results

Figure 6 is an example of using several parameters to reasonably represent the risk of a complex system. In this analysis, performed by U.S. industry under the leadership of the lead author of this paper, there were nine different risk measures, including core damage frequency, plant damage, injuries, fatalities, and property damage. Core damage frequency and a large early radionuclide release are generally used as measures of nuclear plant risk as that is more or less all that is required by federal regulations in the U.S.[3] In the above full-scope example, the mean core damage frequency calculated was about once in some 4,300 years. The core damage risk curve also tells us that the core damage frequency is uncertain by a factor of 8.5 between the 5th and 95th percentile. The risk assessment made it possible to importance rank the contributors to each of the nine risk measures to facilitate corrective actions and science based risk management.

EXAMPLE 2: CONTRIBUTORS TO RISK

Figure 7 is a result from an actual risk assessment of a different nuclear power plant than Example 1 and graphically illustrates the contribution and sensitivity of selected external events to the core damage frequency of a specific plant. It also shows the contribution of the internal events as a group, which in the full set of results were decomposed into specific contributors in rank order. The form of the results includes not only the identification, quantification, and importance ranking of the contributors to risk, but also a visual indication of the sensitivity of the core damage frequency to different contributors. A critically important result for this plant is that while seismic has a great amount of uncertainty, it contributes little to the core damage frequency and thus requires no further analysis. Had the goal been to quantify seismic risk by itself, of course much more time and money would have been expended to reduce the uncertainty. Thus, the important question is not what the seismic risk is, but rather how the seismic risk impacts the risk of the plant. The curve answers that without the added burden of a much greater investment to reduce the seismic risk.

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[3] We believe that selected offsite consequences of the type noted in Figure 6 should also be included in the results to provide greater visibility of the low risk of severe nuclear accidents.

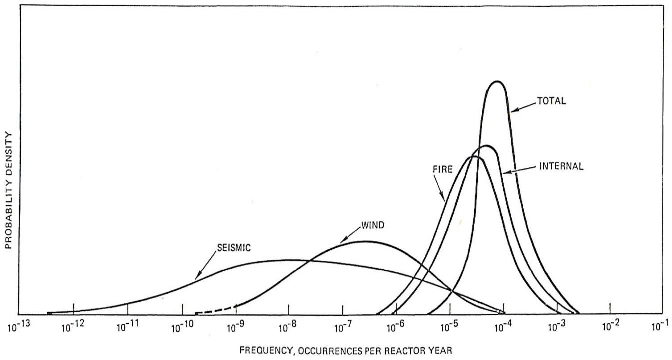


Figure 7. Contributors to Risk

EXAMPLE 3: TURBINE GENERATOR PERFORMANCE

This project involved applying the triplet framework to analyzing the net-benefit of four proposed changes intended to improve a power plant's availability by improving the performance of the turbine generator. The basis of the analysis was cost-benefit, which involved converting outage hours saved into benefit dollars. Figure 8 presents in concise form the bottom line of the analysis, which tells the story for net benefits and uncertainties.

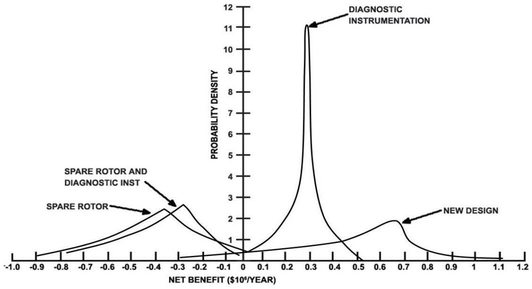


Figure 8. Net Benefits of Corrective Actions

In this example the net benefits for "spare rotor" and "spare rotor and diagnostic instrumentation" are mostly negative, and therefore are not cost-effective options. "Diagnostic instrumentation" gives a strong certainty for limited positive net benefit. "New design" thus involves risk. "Diagnostic instrumentation" is, therefore, the best selection for a conservative decision-maker; "new design" for one who is willing to gamble a little for a larger benefit. The new design case reflects the dilemma noted in Figure 5, namely that there is some probability that the net benefit would be less. In such cases the wisest decision is often to ask for more information in an attempt to reduce the uncertainty. For example, additional information and analysis might eliminate the tail in the negative direction for the new design option.

Figure 8 presents the results in terms of net benefits. Figure 9 presents the results in a form that exposes directly both benefits and costs including, therefore, benefit to cost ratios. Both clearly show the uncertainties.

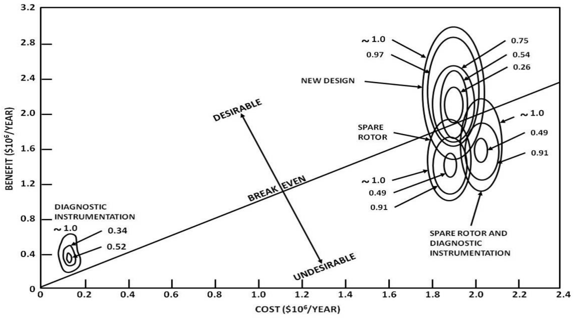


Figure 9. Costs and Benefits of Corrective Actions

EXAMPLE 4: DESIGN

In one two-unit nuclear plant the decision was made to use the risk triplet as a fundamental design tool. The table below illustrates the results of the process. On the left are the most important systems and operator actions contributing to the risk of this particular plant. The numbers in the columns are the mean values of the percent reduction in core damage frequency if the frequency of the contributing event or action is reduced to zero. The result of each iteration of the risk assessment was a basis for taking corrective actions to reduce the contribution of individual systems or operator actions.

The end result of the process is a much more cost-effective and better balanced system of safeguards and a lower core damage frequency than most likely would have been the case had a risk assessment not been a part of the design process. The reason for the increase in contribution of some systems with each iteration is that as dominant contributors are removed through design actions, the importance of the other contributors increases, as the core damage frequency decreases, unless they too were impacted by design changes. It is analogous to removing big rocks from a pool of water. As the big ones are removed or partially removed, the pool level drops (the core damage frequency level drops) and other rocks (contributors) become more important while new rocks become exposed.

Table 1. Risk as a Design Basis

System(s) or Operator Action	Percent Reduction in Core Damage Frequency if the Individual System (or Operator Action) Failure Frequency Could Be Reduced to Zero			
	First Iteration	Second Iteration	Third Iteration	Fourth Iteration
1. Electric Power	11	65	43	52
2. Auxiliary Feedwater	9	11	11	31
3. Two Trains of Electric Power Recovered				21
4. Low Pressure Injection / Decay Heat Removal	4	3	8	19
5. Failure to Reclose PORV / PSVs		5	20	17
6. ESFAS / ECCAS			14	15
7. High Pressure Injection Systems	3	9	15	14
8. Operator Recovery of Electric Power During Station Blackout		50	14	14
9. Sump Recirculation Water Source				11
10. Component Cooling Water			3	8
11. Throttle HPI Flow (Operator Action)			1	4
12. Failure of Main Steam Safety Valve to Reclose			1	4
13. Service Water	32	<1	10	4
14. Safeguards Chilled Water	20	8	13	1
15. BWST Suction Valve				1
16. Containment Isolation			1	
Relative Core Melt Frequency	1.00	0.30	0.10	0.06

EXAMPLE 5: FEEDWATER HEATER SYSTEM DESIGN

This example has to do with selecting a feedwater heater system design for a base load coal-fired 650 MWe power plant. The options presented for analysis were (1) one string of 90-10 CuNi feedwater heaters, (2) no feedwater heaters, (3) two strings of 90-10 CuNi (one string as an in-line spare), and (4) one string of feedwater heaters with tubes made of 304 stainless steel (SS) rather than 90-10 CuNi, but designed to provide the same feedwater heating. The outcomes of each design option are the effects on plant heat rate, plant availability, capital cost, and operating costs. The desire is to select the option that minimizes the net cost. The net cost is the sum of annualized capital cost, annual operations and maintenance cost, equivalent dollar cost of changes in plant heat rate, and the equivalent dollar cost of loss in plant availability due to feedwater heaters. Based on the available evidence, probability distributions were developed for each of the cost items and the failure rates.

The results of the analysis are presented in Figure 10.

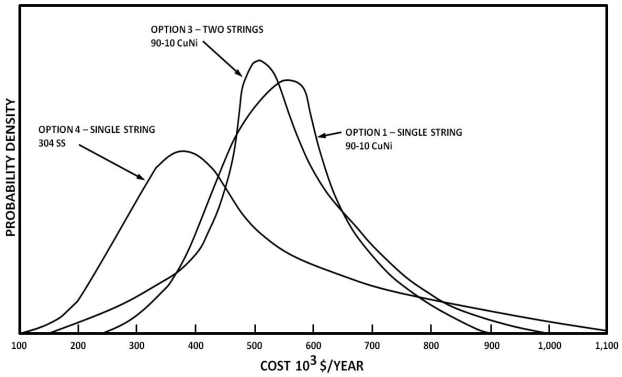


Figure 10. Feedwater Heater Options 1, 3, and 4

Accounting for the risks involved illustrates the importance of developing the “whole story” when comparing costs. Quantifying the uncertainties tells a different story than is told performing only a deterministic or point estimate analysis. The most interesting difference between the deterministic and probabilistic calculations is the comparison of single strings of 90-10 CuNi and 304 SS feedwater heaters. On an average or mean cost basis, the 304 SS tubes are favored. However, note that the curve for 304 SS tubes in Figure 10 has a long, high cost tail. This means that although the mean and most probable costs for 304 SS are lower than 90-10 CuNi, the probability of very high costs is greater with 304 SS. The ranking here is not at all clear but is very sensitive to the individual risk aversion of the decision-maker. A risk-averse person will sacrifice lower average cost to avoid the small chance of very high cost and choose 90-10 CuNi. An alternative is to try to reduce the high tail for 304 SS before making a decision. The major contributor to the high tail for 304 SS is the small chance of much higher failure rates with 304 SS than with 90-10 CuNi. This is primarily due to the chance of severe oxygen pitting corrosion if stagnant aerated water is permitted to stand in a secured heater. With careful attention to procedures or possibly design features to prevent such an occurrence, the problem and the high tail can be avoided. Given such changes, we can update the failure rate histograms using Bayesian techniques and recalculate Option 4.

The probabilistic approach may not always make the decisions easier, but at least it will not be hiding the truth, which point estimates so often do. You can see the full implication of each option. Use of deterministic methods in the face of uncertainty is misleading at best and can lead to very unfortunate consequences.

EXAMPLE 6: MAINTENANCE

Of the activities involved with engineered facilities, none benefits more from having a rigorous risk-based performance assessment than maintenance. Such rigor provides a roadmap for numerous maintenance activities. These activities include the prioritizing of the maintenance of structures, systems, components, and processes (SSCP) in order to meet performance goals. The quantitative performance assessment greatly turns up the microscopic on the linkage between SSCPs and performance. But the advantages and uses go beyond optimizing the maintenance program. Other activities that are greatly facilitated are exposing on-line maintenance opportunities, quantifying the impact of plant or system modifications, spare parts inventorying, upgrading technical specifications, identification of the highest payoff of equipment monitoring requirements, and the development of an effective inspection program.

One of the better programs of using risk-informed methods to evaluate maintenance activities was initiated by the U.S. Nuclear Regulatory Commission popularly referred to as the “maintenance rule.” This rule (10 CFR 50.65) requires that “the licensee shall assess and manage the increase in risk that may result from the proposed maintenance activities. The scope of the assessment may be limited to structures, systems, and components that a risk-informed evaluation process has shown to be significant to public health and safety.”

This has been a very successful program that has greatly benefited the performance of nuclear plants and the protection of the health and safety of the public. However, it has only scratched the surface of its potential. While all U.S. nuclear plants have some form of a risk assessment, they vary in scope and in general are not full scope risk assessments. While changes are in the wind in the direction of requiring greater scopes than is the general practice, the limited scopes put a cap on the benefits that could otherwise be received. This is a concrete example of where the owners and operators could step up and provide the added benefits by taking the lead in making their risk and performance assessments more complete.

EXAMPLE 7: CAPITAL SPARES

A category of spare parts where the probabilistic aspects of risk can very favorably impact spares inventory and plant performance costs is “capital spares.” Capital spare parts are spare parts that are generally very reliable, but if they do fail because of the often long time it takes to replace them they have the potential to cause long and costly shutdowns of important equipment. The uncertain nature of these and other key decision elements makes the probabilistic consideration of capital spares a natural application of the "triplet" framework.

Table 2 lists candidate components to be included in capital spares at a specific power plant (ABS Consulting and the South Texas Project, 2000). Priority for investing capital was given to those components that would limit lost production and have a reasonable likelihood of being used.

Table 2. Recommended List of Capital Spares

Priority	Description	Est. Cost	Lead Time of Spare
1	**Turbine 1R blade**	**$200,000**	**6 months**
2	**Condensate (CD) motor**	**$36,000**	**surplus value - ready upon request**
3	**CW 96" valve (additional)**	**$100,000**	**18 weeks**
4	**Moisture separator drip tank (MSDT) pump**	**$16,000**	**18 weeks - possible O&M cost**
5	**Circulating water (CW) motor**	**$180,000**	**surplus value - vendor has not validated availability**
6	**Open loop auxiliary cooling water (OC) pump**	**$135,000**	**20 weeks**
7	**Essential chiller (300T) compressor**	**$113,500**	**24 weeks - non safety related - 3rd party dedication**
8	**Circulating water (CW) pump (internals less casing)**	**$400,000**	**1 year**
9	**Condensate (CD) pump**	**$235,000**	**1 year**
10	**Feedwater regulator valve**	**$225,000**	**1 year**
11	**Feedwater regulator actuator**	**$75,000**	**1 year**
12	**Auxiliary feedwater pump motor**	**$350,000**	**1 year**
	Total	***$2,065,500***	

To support a decision on which spares should actually be purchased, it was necessary to (1) assess the risk of different failure scenarios of the system for which the spare part was being considered; this of course was to determine the likelihood that the capital spare would be needed, (2) determine the impact on production should the identified capital spare be needed, and (3) take into account the uncertainties in the actual costs and lead times associated with installation of the spare. Other cost considerations that can be taken into account are options for leasing or selling the spare.

Consideration was given to the numbers of each type of equipment installed at the station, the current availability of installed and warehoused spares, and the normal operating configuration and run time/cycle “exposure” to failure modes for the target equipment.

Two criteria were used to form the risk-based recommendations. First, the analysis had to show that there was a significant likelihood (> 40%) of catastrophic failure of the target equipment over the remaining life of the station. If this criterion was met, then the analysis had to show a 75% or greater probability of positive net benefit over the remaining life of the plant in order for the analysis team to recommend the procurement of a spare.

Based on this analysis, Items 4, 7, 10, 11, and 12 listed in Table 2 were recommended for procurement. These are the moister separator drip tank pump, the feed regulator valve and actuator, the auxiliary feedwater pump motor, and the essential chiller (300T) compressor.

PERFORMANCE-BASED ASSET MANAGEMENT

The examples presented above indicate the broad applicability and utility of the triplet framework to measure risk and performance. There is emerging evidence that risk-based concepts can play an even greater role in the management of assets, particularly with respect to incorporating financial performance into the risk-based performance assessment process. The concept is a fundamental framework for the integration of technical and business metrics for measuring overall performance (risk, productivity, financial, quality, etc.) of either a single facility or an enterprise consisting of multiple operations and lines of business. The principles of the triplet framework can simultaneously focus on a diverse set of metrics representing an integrated performance measure of an enterprise. We refer to this broader application as performance-based or risk-based asset management.

Consider a hypothetical utility that supplies both electricity and natural gas to customers. Its portfolio consists of nuclear, natural gas, wind and hydroelectric generation stations as well as the direct transmission and distribution of natural gas to customers. Other technologies could be added such as solar and geothermal. A profitability model, or any high level enterprise performance model, will necessarily have to address key aspects of each technology and service. In addition, operation of the electric grid as well as the natural gas network requires analysis and integration. The development and implementation of effective energy storage technologies may be necessary for grid stability and efficient coordinated operation of the electric generation sources.

Consider first the electricity generating stations. The units may differ according to how they are connected to the electric grid. The profitability model will have to include such performance measures as risks, operations, costs, and maintenance. Modeling diverse facilities and technologies is well established. The capability exists to add specific features imposed by the utility design, such as the impact on performance of the location of the generation station relative to the customers. The operation of non-base load plants needs to be integrated into the coordinated assessment.

The risk scenarios associated with such complex and diverse activities must take into consideration not only the individual units, but how they are linked to each other, the site and the operation of the electric grid. And it’s not just a matter of the individual units, their interaction with each other and the site, but also other activities that support the overall electric power infrastructure such as transportation, business continuity, and the availability of resources like labor and materials.

Policy is a major factor in assessing risk and performance. Policies may vary on how to view capital and operating expenditures, depending on the decision being made. As noted earlier, even if the options for a decision have the same impact on a given metric of interest as measured by comparable mean values, quantification of the uncertainties may expose major differences in their risks. Policy may require preferences be given to intermittent power sources, such as wind or solar, over traditional base load power sources. This policy could result in operation of base load power sources in an inefficient manner, or even the premature shutdown of specific generation sources, thereby reducing current asset value. Policy requirements represent a critically important boundary condition for quantifying performance.

A probabilistic asset management framework supports the decision making process of many activities associated with an enterprise. An example is comparing an investment in a specific spare part to an enhanced maintenance program for a power generation station. Information from the risk module acts as an overriding constraint in the comparison of alternatives. Specific aspects of any such constraints are established by the utility as well as the regulator. Typically, the various options under consideration have different impacts on the metrics of interest to the decision makers. One option may result in increased availability of the plant via a capital expenditure while another option may improve plant efficiency via changes in operating procedures. By making the quantification of uncertainty a central element of the process and by explicitly exposing the contributors to the change in each metric, the ability to compare the potential impact of various options is greatly enhanced.

The point is risk contributors must be systematically identified including external events, severe weather and seismic phenomena; policy; infrastructure performance; common design characteristics; system and plant interactions on the same site, and regulation. The modeling of severe weather and seismic events is well established. The performance characteristics (risk, availability, costs, etc.) can be modeled in a straightforward and consistent manner. Such modeling has been demonstrated for the diverse technologies.

The natural gas portion of the hypothetical utility is to be modeled in a manner analogous to the electric generation and delivery functions. Gas supply, how it’s obtained, stored, transported and distributed are all factors that must be considered. The search for factors that could influence multiple portions of the gas system – as well as elements of the electric and gas system – is vitally important in the characterization of performance. Specific metrics for the gas system and combined electric/gas systems should be defined.

It is obvious that a quantitative asset management system involves a great number of factors to consider and it is a challenge to be accountable to all of them in a manner that aids the decision making process, whether it be operations, maintenance, or design; or financial versus technical performance. In practice, a screening process is required to eliminate scenarios known to not be a contributing factor to the bottom line results. Modern day computers have made it possible to model almost any level of complexity, so computational complexity is not the major issue. The major issue is making sure all the important contributing factors to the particular performance measure being computed are included in the scenario set constituting the model.

A key issue is being able to assemble the scenarios into a form that embraces all the contributing factors in a manner that is easily interpreted for making decisions on system performance and how it can be improved. Again, there is experience in doing just that and part of that experience is represented by the risk curve presented earlier and repeated here for convenience.

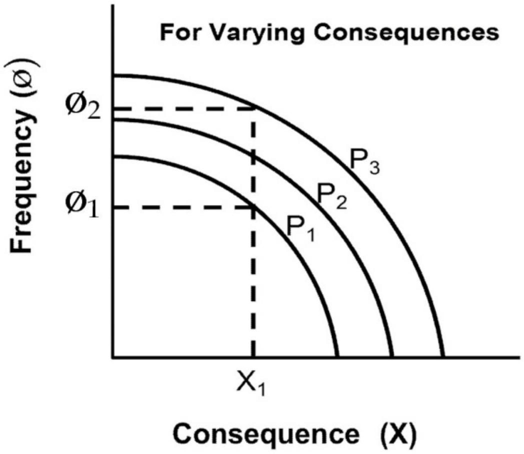
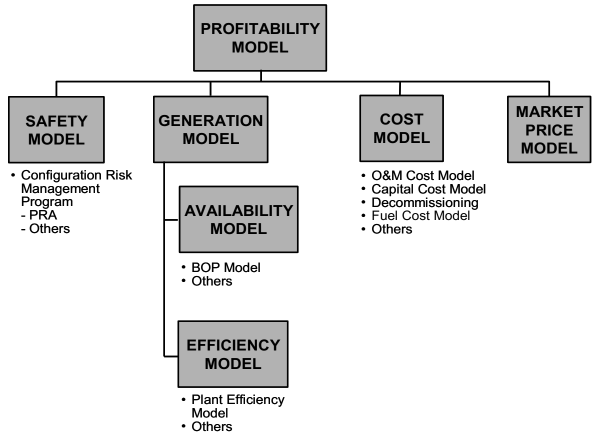


Figure 3. Risk of Varying Consequences

Figure 3 is a form that has been demonstrated to be a very effective bottom line representation of probabilistic performance measures for complex systems. For example, it would be possible to create one such curve for profit and one for loss, as well as one for safety risk and one for benefits if so desired. The various risk curves can be correlated over their respective operating times. The strengths of this type of presentation are (1) it is risk-based, that is, the uncertainties are embedded in the results, (2) a vertical cut for any consequence provides the risk with uncertainty of that particular consequence, and (3) the results are easily decomposed into specific contributors to risk of individual structures, systems, components, and processes.

It is not known whether any enterprise has taken a quantitative risk-based approach to the level just described. It is known that some are moving in this direction as we noted earlier as “emerging evidence of risk based asset management.” An example in the United States is with respect to the South Texas Project Nuclear Operating Company (Liming, et al., 2005). The South Texas nuclear facility supplies electric power to an electric grid owned by a different entity; thus representing a real case of supplying electric power without total responsibility of the power system. Decisions for this facility essentially stop at the connection point to the grid. While the extension of the framework beyond a single generation station to an entire electric utility enterprise requires the development of additional linked and potentially more complex models to address a broader set of metrics, the fundamental concept of using the framework for risk-based asset management remains the same.

Fig. 11 presents a general overview of an asset management model developed for the South Texas Project Nuclear Operating Company.



Source: ABS Consulting

Figure 11. Performance Based Asset Model Overview

The model is essentially a probabilistic cash flow or “value stream” model for a target facility or fleet of facilities. It is designed using the "triplet" thought process to provide a consistent method and tool for continuously predicting facility risk-informed performance and monitoring associated actual performance. The model is visualized as a fundamental decision support tool for facility resource management.

In this application, the metrics of interest included the plant availability, risk, efficiency and generation costs. These metrics are modeled probabilistically through linked modules. While the impact on each metric is of interest to the decision makers, a high level comparison of alternatives is made via revenue and profitability models. The revenue model was developed considering the market price of electricity along with the plant availability, power production and efficiency. The linking of the individual models is necessary as various external influencing factors – such as extreme weather events, regulatory changes or changes in the regional economy – can impact multiple metrics and therefore must be represented in each module of the overall model. The revenue and cost metrics are combined in a profitability model.

While South Texas is an important beginning, the possibilities and expectations go much farther. It is clear that a more sophisticated economic model is required. The vision is a completely integrated asset management system that integrates the appropriate performance indicators from different cost centers, while allowing individual operations to utilize the performance measures best suited to their line of business.

CONCLUDING REMARK

This paper basically calls for greater accountability of the designers, constructors, owners, and operators of engineered systems; especially engineered systems having the potential for severe accidents that can harm people and the environment. And it isn't just a matter of the risk to people and the environment of engineered facilities. It is also a matter of the financial and reputation risk of companies that own, operate, and maintain the facilities. The paper also calls for more comprehensive assessments of performance through the integration of technical and financial measures.

Disturbing trends affecting risks to society are the increased dependence of the owners and operators on government for protection of the public and the companies' resources, new technologies not well understood in terms of their risks, and an increasing number of engineered facilities involving greater amounts of hazardous and toxic materials.

The engineered facilities are key to making new technologies available to society, so the answer is not to stop building them. On the contrary, more are needed particularly in the resource and energy fields. The most disturbing trend is the increasing dependence on government rules and regulations for managing the safety and financial risk of engineered facilities that are heavily regulated by the government. Disturbing because general rules and regulations generated by those not engaged in the details and inner workings of the facilities simply cannot cover all the combinations and permutations of things that can go wrong at a specific facility. Yet, there is evidence that even those in the know that design, build, and operate the facilities are so burdened with compliance management that the real risks, both safety and financial, are not getting the facility-specific rigorous investigation necessary to give them the edge on preventing, managing, and recovering from severe accidents should they occur. *Compliance is the law, but it is not the answer.* There needs to be more evidence that the owners and operators do indeed have the depth of knowledge necessary to have the answers.

The take-away-message of this paper is the need for more rigor and independent analysis of the things that can go wrong on a facility-specific basis than is required by law. The take-away message is also that the metrics of performance must include both financial and plant performance components. It is believed that the risk sciences provide the tools to do the rigorous analysis required to have full confidence that those closest to the action have the facility-specific knowledge necessary to protect the public, the environment, and the companies' resources. The issue is their willingness to use the tools available to them and go beyond that required to be in compliance with government rules and regulations.

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