RISK BASED MANAGEMENT OF POWER PLANT EQUIPMENT

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I MECH E

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Preface

In the past decade, deregulation and privatisation has had a major impact on the electricity industry throughout the world. It has resulted in a more competitive operating environment and has led to an increased focus on ways to reduce production costs. One of the few areas where production costs can be controlled is in the method and frequency of maintenance activities. In the past large utilities frequently employed significant numbers of technical staff to manage the integrity of their plant or relied heavily on OEM recommendations and services. Typically the first step in cost reduction is reducing staffing levels particularly in the technical specialist areas. However, as experienced by many generators, at times this can result in significant deterioration in performance and can even yield lower levels of safety. Acknowledging this, the drive to reduce maintenance related costs without compromising plant safety or performance has seen a move towards using the concept of risk as the basis for maintenance programme development and decision making. To do this, utilities now have to develop a systematic approach for measuring the main plant risks in terms of plant safety, environment and costs that can be expressed in a readily comprehensible form.

As we know Risk is the probability of occurrence of an undesirable event and the magnitude of the consequences of the event. Risk is defined by the following factors: the event, probability of the event occurring, and the undesirable consequences. A formal risk assessment of an existing plant highlights areas where risk mitigation is required or where performance can be enhanced. A risk-cost optimisation process then allows selection of the most cost-effective risk management strategies. However, one problem for an individual plant management or a utility has been the lack of national or international guidelines on the risk based assessment in power plant. ASME and API codes do exist but these were primarily developed for nuclear and petrochemical industry. Their interpretation and use in the fossil power industry can be costly. While some plant and utilities have developed in-house practices the overall goal of the power industry remains the production of overall robust procedures which are economical and easy to use by non-specialist staff. Such procedures will allow more plant to gain benefit from applying formal risk-based approaches to plant management through improved targeting and scheduling of inspections and maintenance activities.

This International Seminar has been organised with this background and objective in mind. Its aim is to exchange views on the current level of industry uptake of risk-based inspection, maintenance and management and to review current methodologies and strive to identify targets and directions for future strategy.

These Proceedings have brought together papers from a large number of experts; from research specialists through materials experts to plant engineers and senior managers. They are all either utilising their in-house procedures to manage their plant or engaged in the development of these. As some of the papers show efforts are also underway to develop national or regional guidelines. Then there are issues of software development – important aspect of any project or procedure these days, as well as insurance, spare parts etc. All these are discussed in the papers presented in these Proceedings.

A key objective is to initiate discussions and dialogue between the specialists and utility participants to ensure that the methodologies being developed are in harmony with user needs. To facilitate this the Seminar includes *panel discussions* which provide an opportunity for the experts and delegates to interact over the more burning issues raised during paper presentations and discuss in detail the more critical issues and any perceived shortcomings of current approaches. After the Conference edited versions of these discussions, together with those papers that could not be included in the Proceedings, will be published in a special issue of a refereed journal.

We must express our gratefulness to the Conference sponsors Innogy and IMechE for their support in the organisation of this event and to the authors, session chairpersons and all the delegates for making this conference a success.

I A Shibli
On behalf of Conference Organising and Technical Committee

1.1
Innogy's Approach to Managing Risks in Power Generation

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Increasing competition in power generation means plant owners have to be ever more rigorous in their approach to optimising plant running regimes and plant condition. Innogy has developed a methodology for optimising the operation and maintenance of its plant with the objective of maximising financial return. This comprises an internal market, that introduces the concepts of risk separation and commoditisation to all aspects of the power generation and fuel and power trading processes, and a suite of risk assessment tools. Together these allow the true cost of generation and option contracts to be determined. This brings objectivity and clarity to the process. Systematic data capture allows future plant investment decisions to be evaluated and the optimum running regime to be applied.

GLOBAL TRENDS: DE-REGULATION AND COMMODITISATION

The world of power generation is changing rapidly. Over the last ten years generation in many countries is ceasing to be in the hands of large monopolistic generators as markets are opened up to competition. New entrants are building new plants and incumbent owners are being made or are finding it economically desirable to sell assets to new entrants. The old model of state run generating companies buying fuel from indigenous state-owned suppliers and selling monopolistically to customers at a regulated price has been superseded by diversity of fuel sources, diversity of generators and choice of supplier for industrial and domestic consumers. With this have come markets in fuel and electricity that were previously associated with the worlds of finance and commodities.

Some countries are resisting these changes. There are various reasons for this. Perhaps it is out of genuine concern that de-regulation will bring about instability in the supply of one of modern economies' most fundamental resources. It could be because of fear of social unrest as jobs are threatened. Or it could be that they wish to preserve their state owned company intact enough for long enough to stand the best chance of dominating the international utility scene in years to come.

The adoption of de-regulation may suffer setbacks but the trend is clear and the implications for generating companies are:

- The imperative is not to keep the lights on but to make the greatest return for shareholders, or in some cases simply to make enough money to survive.
- Power generation becomes commoditized. Plants themselves are a commodity, contracts for fuel and power supply are a commodity, and plant operation and maintenance services are a commodity.
- Plant does not exist to generate but to be capable of generating when power prices dictate and to be turned off and the fuel sold on when they do not. In this sense, all services provided by generators – including keeping the lights on – are regarded as commodities and the generator provides them because it is paid to do so. Services that are 'worth' less than they cost, as indicated by the price, are no longer provided.

The associated processes of deregulation, commoditisation, market opening and increased transparency act to drive the output of power generation plant to the lowest achievable price drives down price. This is good for the customer.

Innogy, like its predecessor National Power, has been at the forefront of these developments since the privatisation of the UK electricity supply industry in 1989. The UK power generation and electricity supply markets have become amongst the most competitive in the world. Over-capacity and the introduction of the New Electricity Trading Arrangements (NETA) in March 2001 have subjected Generating companies in the UK to even greater price pressure. Not only are prices reduced but also there are significant penalties for non-fulfilment of contracts. The generating company that can manage these risks effectively has a distinct advantage.

To minimise penalties for non-fulfilment within the gate closure period, many generators plan to generate more than they need. In this, incidentally, they provide the 'system' with free reserve capacity.

1. THE INTERNAL MARKET

Innogy believes that establishing an internal market is the key to maximising profitability in the competitive, commoditised world. The internal market that Innogy has implemented is one in which each participant, generator, fuel trader, power trader or insurer has the sole objective of making money in power generation and trading. Key features of this market are:

- Risk and accountability are placed where they can best be managed (known as risk separation).
- The language of the internal market mirrors the language of the external trading world. Participants do not need to be expert in each other's parts of the business, only their own.
- Power plants gain 'budgetary certainty' because their costs and revenues of operation are secured in advance.
- The best decisions can be made about investment in plant improvements and major rehabilitations. This is done by formalising and capturing the 'option' value.
- The right plant is called upon by the Traders to run at the right time, or alternatively power required to fulfil contracts is bought in the market, the best decision being made each time. Decisions take account of plant start-up and running costs, the cost of load cycling and the environmental cost of using fleet emissions allowances. Most importantly, the cost of starts in terms of their effect on reliability are captured and taken into account.
- Plant reliability data and how it varies with running regime is captured automatically.
- On the day scheduling is automatically optimised with respect to market prices (as opposed to demand volumes). The Power and Fuel Operations team engages directly with the market on behalf of the power stations taking into account operational factors such as start-up cost and run-up time.
- The annual schedule is automatically optimised by including such factors as environmental restrictions into the option sold to the traders.

2. OPERATION OF THE INTERNAL MARKET

The internal market is illustrated in Figure 1.

In the internal market there are three principal participants, the asset steward, the trader and the owner.

The asset stewards are the experts in power plant operations and maintenance. Their role is to maximise the asset return over the remaining life of the asset. They have responsibility for the station's profit and loss account. It is essential that asset stewards have the best possible understanding of reliability risk for the station under a range of operating scenarios because they have to pay to cover that reliability risk. Overestimating the risk will result in too high a premium being paid. Underestimates will be penalised by higher payments in later years. We will see below what information the asset steward needs to quantify this risk and how this information is obtained.

The trader is responsible for managing market risk. The trader buys the fuel from the external market and sells to the asset steward. Similarly, the trader sells power in the external market and buys from the steward. The trader's income is the bid-offer spread and it is one of the roles of the risk management group (or 'middle office') to ensure this is a fair margin. (The trader also seeks a profit through taking what he believes to be an advantageous position in the market. This need not concern us here, except to note that that separation of risk allows the trader to concentrate his efforts on trading).

The asset owner requires a return on the investment that the asset represents. The asset steward is judged on the return he makes (for the owner) on the market value of the plant and whether this is greater or less than the company's weighted average cost of capital. To determine the market value of the plant, Innogy needs to know both its condition and what the market would pay to acquire plant in that condition. The asset steward is therefore charged a cost of capital based on the market value and also for any degradation in plant condition compared to the agreed condition or credited with any improvement. The asset steward is protected from fluctuations in market value by buying the plant from the asset owner at market value today and selling it 'forward' back to the owner at a particular date in the future. Plant condition is determined using a method described below and needs to be reviewed at the start and finish of the period of stewardship.

3. FORWARD AND OPTION CONTRACTS

A series of forward and option contracts is put in place between the asset steward and the trader.

The core contract is a forward contract to run to a regime that is determined by the application of a fleet running model. The inputs to this model are the plant costs (fuel, plant life usage, starting, changing load and shutting down) and the fuel and power forward price curves, as 'discovered' by the trader in his trading activities. The contract price paid to the station depends on a 'fair valuation' of that contract, which is produced by the fleet running model. A further degree of sophistication is added by evaluating the optimum fleet running position with constraints on the total tonnage of sulphur dioxide that may be emitted.

In addition, option contracts are put in place to allow the trader to call for changes in running regime in the light of market conditions that may prevail when the time comes to generate and the trader's option contract position. The prices paid to the asset steward for these option contracts is again determined by 'fair valuation' from the fleet running model and remunerates the stations fixed costs associated with providing the option. Revenue for turning fuel into electricity pays the variable costs.

The fleet internal market model can also allow for the station being required to burn a range of different coals, each of which results in different costs in terms of plant efficiency and plant life usage.

One of the core competencies needed to operate this model is a precise understanding of the impact different running regimes have on plant running cost, degradation and reliability. The last factor has typically been underestimated in the past.

The contracts between the asset steward and the trader are expressed in the standard trading language of 'buy or sell, weight, rate and date'. Thus the trader can make objective decisions without having to be an expert in the internal workings of the power station and can choose correctly whether to call an option with his own generation fleet or to trade externally. The asset steward does not need to follow the markets directly in order to decide his optimum running regime. The trader regularly evaluates the worth of the option contracts and hence can give the station regular signals about changes to the anticipated running.

4. 'BRIMSHAW'

The nature of traded markets is such that contracts once placed cannot be cancelled: if the asset steward cannot generate the power he has to buy it from someone else. All plant is subject to unreliability and failures will occur from time to time. Indeed, the need to keep the plant in the optimum condition rather than uneconomically to chase perfection will mean that a certain rate of failures will be anticipated and is acceptable. Because contracts with the trader cannot be cancelled, plant breakdown means the asset steward will be exposed to the need to put in place a new contract to meet the needs of his contract to run, often at short notice. The asset steward is required to avoid taking market risk so an internal insurance product is created to give cover whenever required. Innogy calls its internal insurance product 'Brimshaw'. The premium paid to Brimshaw by the asset steward is determined by a risk assessment carried out on the plant and historical plant reliability data.

Brimshaw provides:

- Optimal hedging (because Brimshaw places a base load forward contract to match the expectation of loss)
- A valuation of reliability (through the premiums paid)
- A performance measure (comparing the claims made with the expected level of claims).

Brimshaw obtains cover from the trader. The trader may place contracts with peaking oil-fired plant in Innogy's portfolio. Longer-term failures are insured through Innogy's in house insurance company 'Electra' which reinsures through the external insurance market.

We can see therefore that the market allows contracts to be placed for all the key parameters: power generation, fuel, flexibility, reliability, environmental emissions etc. Power and fuel have long been treated as commodities, distinguishable only on price. Innogy's approach has commoditised flexibility, reliability and emissions, allowing each to be managed optimally by experts and properly valued.

5. BUSINESS RISK ASSESSMENT PROCESS (BRAP)

Because an understanding of the risks involved in power generation is a key part of the job of the asset steward, Innogy has developed a suite of risk assessment tools to complement the internal market. This is known as the Business Risk Assessment Process or BRAP. This process is a comprehensive evaluation of the risks involved in power plant operation: engineering risk, plant condition, operational risk, and environmental risk. It allows a balanced view of the plant in the context of the market in which it operates. It is built on actual detail provided by plant engineers, operators and commercial staff evaluated in the light of benchmarks developed from Innogy's experience.

The Business Risk Assessment Process comprises:

- A systematic survey of the risks associated with operation of the plant, including reliability, and prioritisation of areas for action to meet anticipated running regimes.

- Determination of the plant condition, residual life and value, and how these relate to maintenance spend and running regime.

- An environmental risk assessment, to consider environment-related issues with potential to affect the business of the power station, identify principal issues, and identify possible management strategies to reduce risk and opportunities for increasing net revenue.

- A review of plant performance, operation and flexibility issues, in the context of market-driven operating scenarios.

- A market assessment, to characterise the critical market factors for the power station, and to determine to likely operating pattern of the units over the medium term.

The BRAP process is a highly collaborative, market-related assessment of the business risks that a power plant needs to be able to manage if it is to respond optimally to changing market conditions.

Its component parts are illustrated in Figure 2.

We will now consider each of these in turn.

6.1 Engineering Risk Assessment Process (ERAP™)

Innogy has developed a methodology for assessing the level of engineering and operational risk at a power station based on "scoring" the plant against a standard set of some 600 plant failure scenarios. This is to identify the level of engineering and operational risk at a power plant, compare these with benchmarks for comparable plant, and to recommend appropriate risk reduction strategies. This method has been used at most of Innogy's UK power stations and on other owners' stations around the world where Innogy has an operations and maintenance involvement. Innogy also undertakes this process as a consultancy service.

The process requires site visits by a team of typically 10-15 specialist engineers from Innogy who conduct interviews with local staff. The plant is divided into areas and the risk affecting each area is evaluated against high, medium and low probability of occurrence and high medium and low impact. The impacts on personnel safety, plant availability and repair cost are considered separately. Innogy maintains a handbook of Reference Sheets for every 'Area of Concern'. These provide a definition of each concern, and a standardised method of scoring. As well as giving a measure of the scale of the risk, the process also rates the risk in terms of the controls being applied by the station to minimise it and the adequacy of human and financial resources being applied to the problem.

The end result of the ERAP assessment is a risk scoring for each area of the plant and comparisons with Innogy's data on UK and international norms. From this, recommendations can be made as to where resources should best be applied to reduce risk, if such reduction is deemed appropriate to the plant's market position.

An understanding of the plant risk, together with historical plant data, is used to quantify the premiums that should be paid by the asset steward to Brimshaw. If the asset steward underestimates the plant's risk of failure this will become apparent to Brimshaw and he will ultimately face higher premiums.

6.2 Plant Life Usage System (PLUS)

This is a plant life usage study which determines the plant condition using a standard measure, predicts plant degradation and its effect on reliability under current and future operating requirements, enables maintenance spending to be compared against benchmarks, and gives guidance for future maintenance spending requirements.

The PLUS assessment methodology will give a measure of plant life or value usage consequent upon the operating regime and maintenance expenditure. It looks at the degradation that arises from normal operation and maintenance. The output is an evaluation of residual life or asset value, which are closely related, and the rate at which that life or asset value is being used up.

The process does not look at risks from "unplanned incidents", nor does it deal with plant damage arising from operations or maintenance errors that may happen in the future. It does however, in assessing the current state of the plant, account for such events that have occurred in the past. It does not deal with Engineering threats and in this respect is complementary to the ERAP process.

The output of PLUS is used as an input to the fleet running model to ensure that the degradation in plant condition as a result of starting, running, changing load and shutting down is properly taken into account. Periodic PLUS assessments also give an objective measure of the value reduction or improvement in the plant and verification of the charge or credit for this to the asset steward.

6.3 Environmental Risk Assessment Process (EnvRAP™)

The objectives of EnvRAP are:

To consider systematically the range of environmentally related issues with the potential to affect the business of the power station both currently and in the future.
To classify those issues based on the significance and nature of the potential impact and indicative frequency or timescale of occurrence.
for the principal issues identified, to suggest possible management strategies
to identify possible opportunities for increasing income and/or reducing cost

In the context of EnvRAP, environmental risk is taken to include both risks to the environment arising from normal plant operations and risks to plant operation arising from the environment.

The focus of the EnvRAP is 'normal' operation, in contrast to the companion engineering risk assessment ERAP in which technical or operator faults are the focus. The basis of the assessment is taken to be 'in the anticipated operating regime of the power station'. This takes into account the expected range of possible modes of operation as determined by, for example, seasonal factors, variation in fuel sourcing, expected load profiles etc.

6.4 Operational Risk Assessment Process (OpRAP)

Crucial to the reliable operation of the plant to meet market needs is the ability of the people and operational systems. In the Operational Risk Assessment Process, Innogy considers the operational, people and logistical factors that might impact on plant flexibility. OpRAP will consider:

Staff competence, training and succession.
Whether the plant is operated consistently by the range of shift teams and operators. This can have a major impact on the risk associated with new or unfamiliar operational techniques that might be required if plant flexibility is to be increased.
How well costs are determined and recorded: for example heat accounting and cost of efficiency losses.
How well the organisation can adapt to the sourcing and delivery of unfamiliar fuels.
Management of safety. Poor safety management has cost and reliability as well as human consequences.

6.5 Fleet Running Model/ Market Assessment

The Fleet Running Model and a Company Option Model are used to value options and to determine individual plant and fleet running regimes. This model optimises the running schedule of the plant using price signals, while recognising constraints such as environmental limits. The model outputs predicted plant life usage correlating with the Plant Life Usage System and also gross conversion revenue from fuel to power. Whilst the model uses market signals to determine the running schedules it also needs to take account of any overall environmental restrictions such as might be applied by regulations. If environmental emissions are taxed, the tax forms a market signal. If not, an internal 'tax' is applied to ensure that emissions restrictions are not breached and optimum use is made of allowable emissions quotas.

Analysis of the market indicates the expected running regime of the plant over a period of time and provides a value for the various 'options' that the asset steward can give the trader.

The final BRAP assessment is a drawing-together of the component parts described above. A degree of iteration between stages is required. The ranking of the various risks that have been identified and the economic benefit of mitigation will depend on the anticipated running scenario. So, for example, the risk of plant damage through two-shifting may be less significant if the market assessment indicates that the plant is likely to operate on base load for the foreseeable future. Also, if the plant is projected to have a very short life before environmental constraints force closure, the plant damage cost associated with starts will be much lower than if the plant has to be maintained at a high condition for an indefinite period.

6. FURTHER IMPLICATIONS OF INNOGY'S APPROACH

- The approach is sophisticated and is not easy to establish initially. Innogy has however found that the benefits of improved decision-making far outweigh the cost of adopting this model of operation.

- The necessary data to determine the cost of starts in terms of plant degradation and reliability is not easy to obtain. The approach does however make the best and most efficient use of available data and acts as a spur to continuously gather and improve knowledge. The facility for orderly collection of failure data that the internal market offers means that knowledge will be captured in the most efficient way and that decision making will improve inexorably.

- The overall system may be complex but the 'risk separation' concept allows individuals to become expert in their part of the value chain. All participants communicate in the same simple language (buy/sell, weight, rate, date). Only a handful of people needs to have detailed knowledge of the big picture.

- Determination of plant life usage depends on the ultimate life required of the plant. For example, if the plant is required to run only until the statutory certificate expires and no further, the cost of the next overhaul does not need to be taken into account. This is not a problem for plant that is expected to run at a similar duty for many years. Plant that is nearing the end of it life can be dealt with by the trader supplying option prices for continued operation beyond a planned closure date.

- The Plant Life Utilisation approach remains under development, as is the EOH approach in the CCGT industry. The internal market concept encourages us to develop our knowledge in the following areas:

identifying interactions between "hours-type" damage such as creep, high cycle fatigue, and flow assisted corrosion, and "starts-type" damage such as low cycle fatigue and corrosion damage that is sensitive to stress and thermal cycling,
modeling the relationships between PLU formulae in the various plant areas, and the overall PLU for the plant,
understanding the sensitivity to the simplifying assumptions such as a single warmth of start, component redundancy and interaction, and non-destructive testing intervals and sensitivity.

7. CONCLUSION

Innogy has developed a methodology for optimising the operation and maintenance of its plant with the objective of maximising financial return. The individual parts of this process, the internal market and the suite of BRAP risk assessment tools are valuable in themselves but the real strength comes from the integration of risk management and economic decision making. This brings objectivity and clarity to the process and systematic data capture allows future plant investment decisions to be evaluated and the optimum running regime to be applied. The internal market model allows each participant to concentrate on his area of expertise and provides the incentives for each to maximise his contribution to profit. Innogy has been able to do this because it has been able to correlate plant condition with plant reliability, to be able to quantify the condition of the plant and to understand the effect on that condition of the range of operations the plant may be subject to.

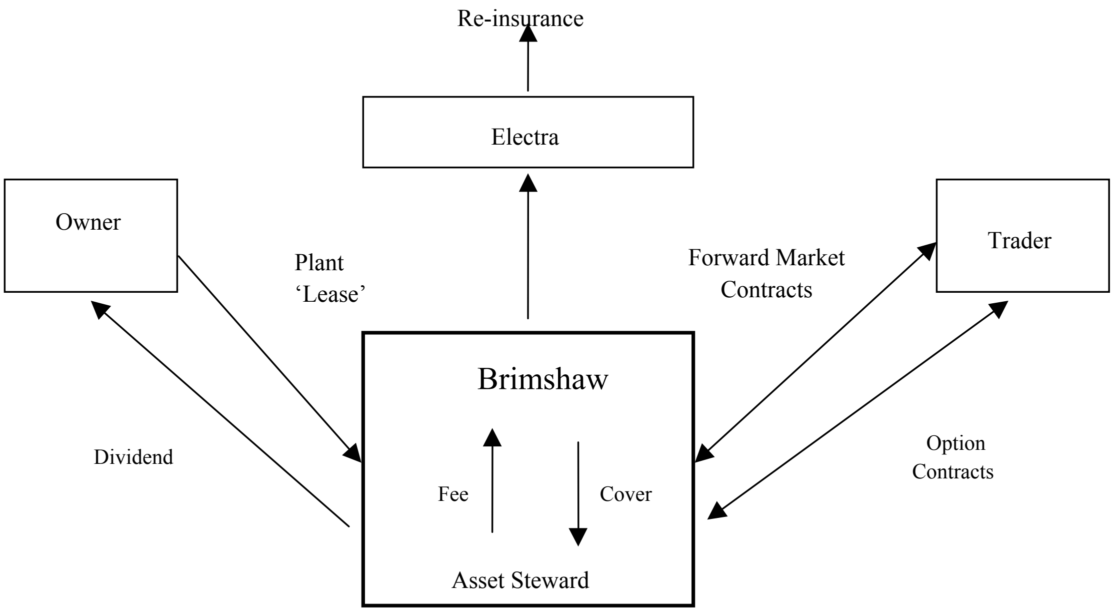

Figure 1: ***The internal market.***

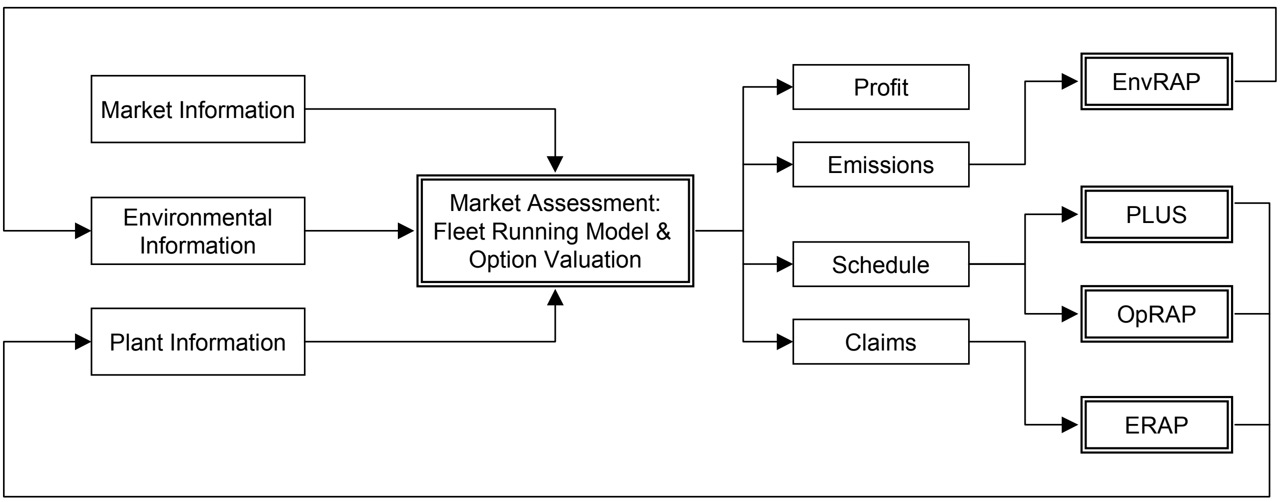

Figure 2 : BRAP Overview

1.3
Maintenance Planning and Cost Reduction by RBM Techniques in Fossil-Fired Power Boilers

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Abstract

In order to provide the strategy for optimizing inspection and maintenance, an RBM technique was applied to an industrial power boiler. In the present study, risk ranking of all the components were performed and optimization of maintenance cost was considered under the RBM assessment results. As a result, it is found that RBM could improve the reliability of the plant and optimize the maintenance cost.

1. INTRODUCTION

Aged degradation would occur in components that constitute a plant as a result of long-term operation. Efficient management of equipments and reduction of maintenance cost are required. In Japan, the accountability attitude to plant maintenance is reaching the standard in Europe and the United States. That is, companies are faced with the necessity of introduction of risk management to assess and determine the acceptability of the risk of a plant on their own responsibility. In such a situation, in order to realize risk management at an optimal cost, it is required to develop the maintenance program to make the risk of each component of the whole plant less than or equal to a certain level.

Risk-based maintenance (RBM) or risk-based inspection (RBI) describes causes and results including future uncertain factors [1] as probability, and provides the priority of inspection and/or maintenance according to the level of risk. RBM/RBI is a tool to optimize the maintenance program of a plant, and has been drawing attention as an objective technique in recent years [2]. RBI and RBM are used in inspection planning and maintenance planning, respectively. Risk is defined as the product of the likelihood of damage in plant components by the consequence due to failure of the components or systems.

Authors collaborated with AEA Technology (UK) in applying RBM technique to a domestic fossil-fired power plant for the first time in Japan [3]. Based experiences including engineering, manufacturing, remaining life prediction technique and etc., we have been performing RBM assessment aiming to high reliability. In this paper, an application and the effect of introduction of RBM technique are shown in consideration of the relation between maintenance cost and risk of a fossil-fired power boiler.

2. RBM ASSESSMENT PROCEDURE

Overview of RBM assessment procedure is shown in the following. Details are discussed in Reference [3][4].

2.1. Preparation of data requirements

First, for all the locations that degradation and damage may occur with accumulation of operating time, a plant is subdivided into hierarchical structure, or systems, components, and locations. After classification, damage mechanism (e.g. fatigue, creep etc.) is defined for each location.

At the same time, design condition, operating history, inspection/maintenance history, future operating condition, and financial data are gathered and put into database.

2.2 Risk assessment

(a) Assessment of likelihood of failure

The likelihood of failure is assessed within a defined period (usually, up to the next periodic inspection). Specifically, the level of the likelihood is determined according to a judgment module for the parameters including current damage condition, effectiveness of inspection, and variation of operating condition etc. Assessment result is rated for each parameter with weighting, and then likelihood of failure is ranked according to a total point.

(b) Assessment of consequence of failure

The consequence of failure is assessed in the worst scenario, on safety and financial efficiency respectively, by evaluating its influence from many viewpoints including personal hazard, repair cost, and the secondary loss resulting from failure, etc.

(c) Primary qualitative risk ranking

The assessment result on each location defined above is plotted at an appropriate category out of “Acceptable”, “Acceptable with controls”, “Undesirable”, or “Unacceptable” in the risk matrix as shown in Figure 1. Following the risk category, actions requirement defined in Table 1 are determined. This is the result of risk assessment for the current condition (e.g. inspection standard etc.).

(d) Revised risk assessment

Revised risk assessment is effective to assess the effectiveness of risk reduction or cost reduction. In the former, risk reduction is assessed in the case that addition of inspection, performance of maintenance, and action to lower the consequence are implemented for locations assessed as “Undesired” or “Unacceptable”. In the latter, the effect of mitigation or omission of inspection or maintenance can be assessed for locations assessed as “Acceptable”.

Furthermore, the propriety of extension of inspection interval can be judged by assessing the risk in case of that interval is extended.

3. EFFECT OF INTRODUCTION OF RBM

3.1. Risk reduction by in-service inspection

The inspection could reduce the risk for not only a fossil-fired power boiler but also any equipment. Figure 2 shows the concept of risk reduction by inspection. Although the life consumption increases with accumulation of operating time, the increase has uncertainty with the scattering. Remaining life is defined as the difference between the upper bound value of the consumed life curve and 100% of the life. When inspection is performed, the uncertainty disappears because the life consumption rate can be determined at the point. After inspection, the life consumption rate is represented as a curve with a range (i.e. uncertainty) again, but the range becomes narrow in comparison with that before inspection. On the other hand, if inspection is not performed, the life consumption rate is provided by the upper bound value of the initial curve with a wide range, so the remaining life is evaluated shorter than that in case of performing inspection. Consequently, risk is reduced by inspecting. In RBM, based on the idea as mentioned above, the effect of inspection contributes the likelihood of failure, or risk assessment closely.

3.2. Risk assessment results of an industrial boiler

A risk assessment of an industrial boiler is taken as an example of the effect of application of RBM. The assessment was performed in pressure parts of a natural circulation type of boiler, which had been operated for more than 30 years. Operating history of the boiler is shown in Table 2. Results of the risk ranking are shown in Table 3 and Fig. 3. Because this boiler is utilized as a main boiler, financial consequence is so large that financial risk was ranked higher than safety risk at all assessed locations. In primary qualitative risk ranking, financial consequences of assessed locations were almost ranked larger than “Major”, and furthermore locations more than 40% were ranked as “Critical” or “Catastrophic”. Locations ranked as “Unacceptable” or “Undesirable” were about 6% of components, and others were ranked as “Acceptable with controls” or “Acceptable”.

Details of major locations assessed as “Unacceptable” or “Undesirable” in primary qualitative risk ranking are shown as follows.

(A) *Furnace wall tube - outside surface*
This location had been subject to thinning of wall tube resulting from corrosion due to the shutdown for seven years. Thickness measurement was performed before the restart. Tubes with thickness less than that as the specified required thickness, T_{sr}, in Japanese code were replaced. But tubes with thickness near to T_{sr} still existed. Because time had passed from the last inspection when the assessment was performed, risk of this location was ranked as “High”. Thickness measurement and remaining life assessment were recommended to reduce the risk.

(B) *Final superheater outlet header - shell*
At this location, remaining life assessment on creep was performed at 10 years ago and significant damage has not been confirmed after that. However, risk of this location was assessed as “High”, because the life consumption had reached 50% of the life and the consequence of failure was ranked at “High”.

As above two cases, in case that inspection has not been performed for a long time, risk is assessed as “High” due to high uncertainty as mentioned in paragraph 3.1 even at the location of which degradation or damage makes slow progress. In many cases, if integrity of the location is confirmed at the next inspection, risk is mitigated and the inspection could be omitted after that.

(C*) Furnace front wall burner wall box – corner weld*
At this location, fatigue at the tube outside surface weld and corrosion fatigue at the tube inside surface by thermal stress were considered. In addition, because the location had been under cyclic loading due to the cyclic operation that had not been considered in original design for the past dozen years or so, risk was ranked as “High”. Mitigation of stress concentration at the wall box corner by improving the configuration was recommended to reduce the risk.

(D*) Tie lugs on economizer - tube weld*
At this location, fatigue due to cyclic operation was considered. Actions to reduce the risk were recommended as follows;

(1) Renewal of the whole package to a rudder system without tube welding, or
(2) Repair of tube welds with high risk and continuous use of the other low-risk locations in the economizer

The action (2) shows that it is possible to distinguish high-risk locations and low-risk locations and to make a careful maintenance plan by the RBM assessment.

Also, (C) and (D) were ranked as high-risk due to failure cases and experiences in other boilers with same conditions and their own cyclic operation. It is advantage of boiler-makers to have failure cases and experiences in many similar boilers in risk assessment.

The inspections of the 20 locations were possible to be omitted. For example, the frequency of thickness measurement of the steam drum shell plate can be mitigated. Thickness measurement for thinning at the location had been performed every two years or so. But, because no thinning and sufficient remaining life were confirmed, the risk would not become higher if the frequency of the inspection is mitigated.

Actual maintenance planning is determined in discussion by the user and us based on results as mentioned above. RBM is so objective that it is easy to obtain consensus to necessity of actions proposed in the assessment. In addition, technical tradition would be achieved at the same time because the information on maintenance is supplied systematically at the RBM assessment.

3.3 Procedure of maintenance planning
The procedure of maintenance planning based on the RBM assessment is discussed. In the conventional technique, maintenance program is planned based on mainly the past operation and maintenance history. In RBM, major locations are sorted by assessing all locations considering cases and design information of the other similar boilers. Ordinarily, high-risk-ranked locations are inspected in the first periodic inspection after RBM assessment. If damage or defects are found in the inspection, the location could be repaired during the inspection. Locations that cannot be repaired during the inspection or take a long time until the inspection result appears should be dealt with in the next inspection. Thus, it takes a time to improve reliability of the boiler.

At the same time, validity of the conventional maintenance planning can be assessed by comparing with that by the RBM technique. For the industrial boiler shown in paragraph 3.2, the conventional maintenance planning almost corresponds to that of RBM assessment result.

3.4 Optimization of maintenance cost

The maintenance cost could be assumed as the sum of planned maintenance cost and cost loss due to likelihood of failure. As shown in Fig. 4, if planned maintenance is insufficiently performed, the likelihood of failure of a boiler is high. If planned maintenance is sufficiently performed, the likelihood of failure is very low. By introduction of RBM technique, waste in maintenance could be avoided by abbreviation of inspection etc., and high-risk locations are concentrated on. Therefore, likelihood of failure is reduced with a maintenance cost as the same as before, and reliability of the boiler can be improved.

If planned maintenance is insufficiently performed, because likelihood of failure is high, cost loss due to failure is high. If RBM is introduced, likelihood of failure is mitigated by efficient maintenance in concentration on high-risk locations and cost loss is reduced. Consequently, the total maintenance cost is reduced and cost efficiency is optimized.

In the short term, if planned maintenance is insufficiently performed, planned maintenance cost in the first periodic inspection after RBM assessment will increase because of the addition of inspection item for high-risk locations. If integrity is confirmed in the inspection, risk is mitigated and inspection after the next periodic inspection is needless or systematic inspection interval is developed. In the long term, inspection cost could be reduced by development of efficient inspection item and interval. At the same time, likelihood of failure is mitigated, and maintenance cost efficiency increases. Consequently, improvement of reliability and optimization of cost could be expected.

If planned maintenance is sufficiently performed, likelihood of failure decreases, but the whole maintenance cost would increase. If RBM is introduced, the total maintenance cost could be reduced, because waste in maintenance is avoided.

4. CONCLUSIONS

RBM techniques were applied to an industrial boiler. And the effect of introduction of RBM was considered. It is concluded as follows.

(1) The assessment can be performed to all components by subdividing a plant into hierarchical structure.
(2) The priority in maintenance is clarified by distinguish High-risk-ranked locations and low-risk-ranked locations.
(3) Efficient inspection item and cycle can be decided in the RBM assessment.
(4) The technique on maintenance is inherited and the maintenance performance can be improved.
(5) It is possible to obtain the consensus to the maintenance strategy.

From the effects as mentioned above, improvement of reliability on the boiler and optimization of the maintenance cost could be expected. At the same time, introduction of the life-cycle maintenance (LCM) concept [5] may be required with the RBM assessment.

ACKNOWLEDGEMENTS

The authors are grateful to Mr. Bob Browne and Dr. David Worswick of AEA Technology for providing consultation while the study was being conducted.

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Table 1 *Risk categories and required actions*

Risk category	Required actions
1. Acceptable	No inspection or other actions required unless to satisfy national legislative or insurance requirements.
2. Acceptable with controls	Inspection strategy or other controls
3. Undesirable	Reduce, by next outage, to category 1 or 2 by: • Improved operating practices or controls • On-line plant monitoring • Engineering measures to mitigate consequences • Inspection
4. Unacceptable	Reduce immediately to category 1 or 2 as above

Table 2 *Operating history of the boiler assessed in this study*

Total operating hours	About 180,000 hours
Total number of starts	About 65 times
Commencement of commercial operation	Late ‘60s

Table 3 *Result of financial risk ranking*

Risk categories	Primary risk ranking		Revised risk ranking	
	The number of locations	Percentage (%)	The number of locations	Percentage (%)
Acceptable	241	57.1	241	57.1
Acceptable with controls	155	36.9	170	42.9
Undesirable	15	3.6	0	0
Unacceptable	10	2.4	0	0

Table 4 *Descriptions of major high-risk locations*

Location	Damage mechanism	Actions
(A) Outside surface of furnace wall tube	Thinning	Thickness measurement and remaining life assessment
(B) Final superheater outlet header shell	Creep	Remaining life assessment
(C) Furnace front wall burner wall box corner weld	Corrosion fatigue	Remaining life assessment and improvement of structure based on the assessment result
(D) Tie lugs on economizer tube weld	Fatigue	Fine inspection for a typical panel and improvement of structure based on the inspection result

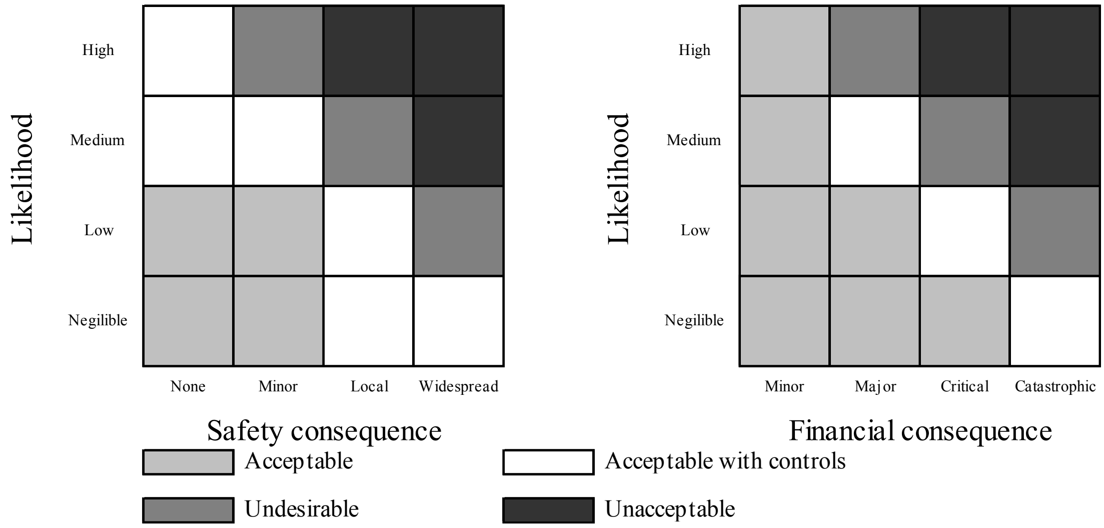

***Figure 1** Risk matrices.*

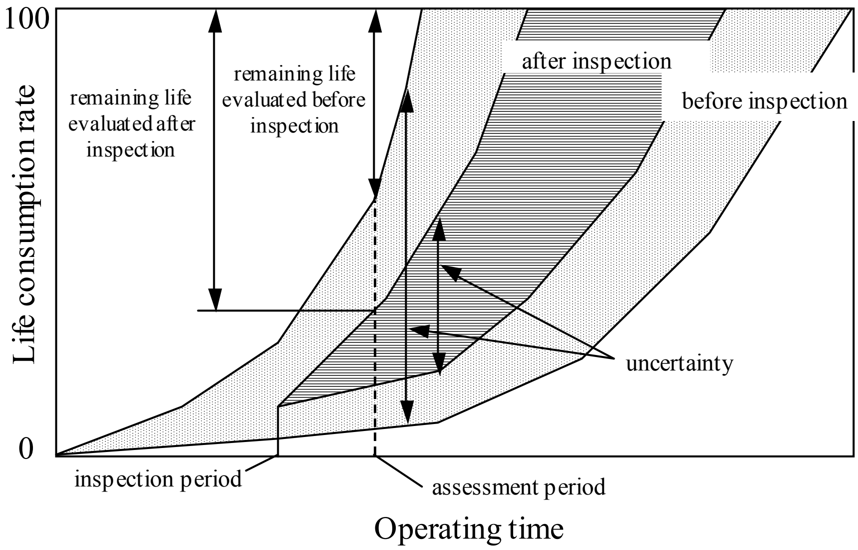

***Figure 2** Concept of risk mitigation by in-service inspection.*

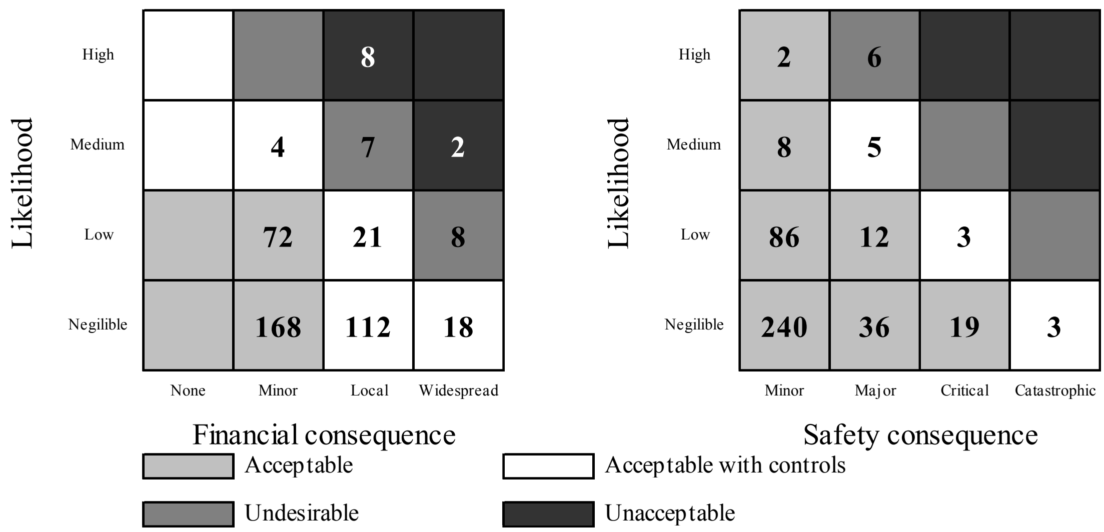

Figure 3 *Assessment results in this study.*

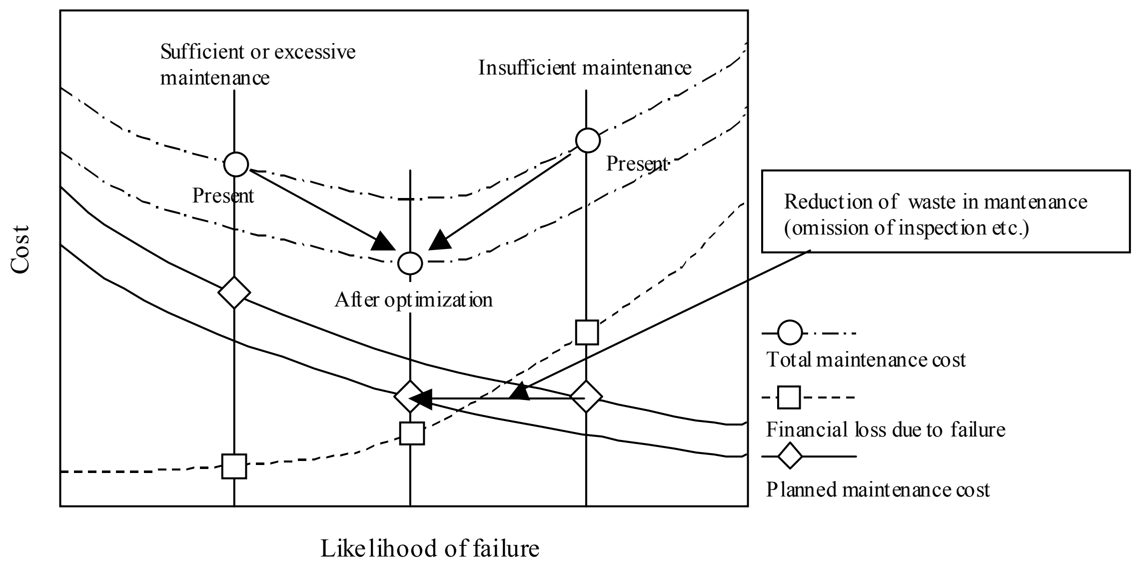

Figure 4 *Concept on optimization of maintenance cost.*

1.4
ProMax- Approach in Power Plant Risk Management

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Abstract
This paper describes the ProMax approach developed by Fortum Energy Solutions. The approach is used to enhance risk management in power plant operation and maintenance. The ProMax approach covers both investment projects and the production phase of power plants. ProMax solutions are provided by experienced maintenance and reliability engineers using sophisticated software tools to support the service.

During an investment project, decrease in the contractual risks by using case-specific estimations produced by ProMax simulation is emphasised. Special attention is devoted to effects of the various maintenance and spare policies and critical systems for production output. During the production phase, the maintenance programmes of critical systems can be balanced through combined use of ProMax simulation and economic ranking of risk items.

ProMax APPROACH

ProMax is the essential tool in Fortum Energy Solutions’ O&M service concept when maximizing the life cycle profit of power plant investments. In investment projects ProMax is applied to create a stable foundation for cost-effective long-term maintenance and to enhance the risk management of an O&M contract.

ProMax is based on reliability simulation and Reliability Centered Maintenance (RCM). RCM effectively supports the training of O&M staff by producing the best available understanding on factors governing the maintenance of plant's critical components and systems. ProMax approach is also used to link Fortum's and EPC's experiences and knowledge to build an initial content of the Optimized Maintenance Programme. The basic content of the Optimized Maintenance Programme is illustrated in Figure 1.

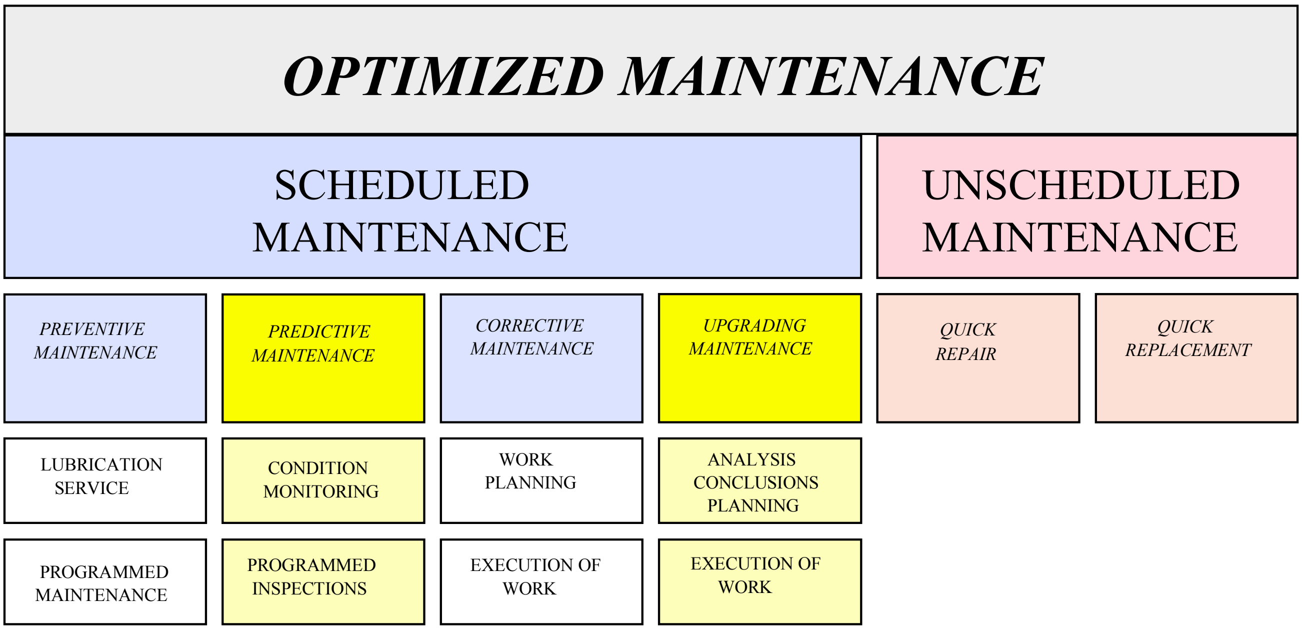

Figure 1 *Content of optimized maintenance programme.*

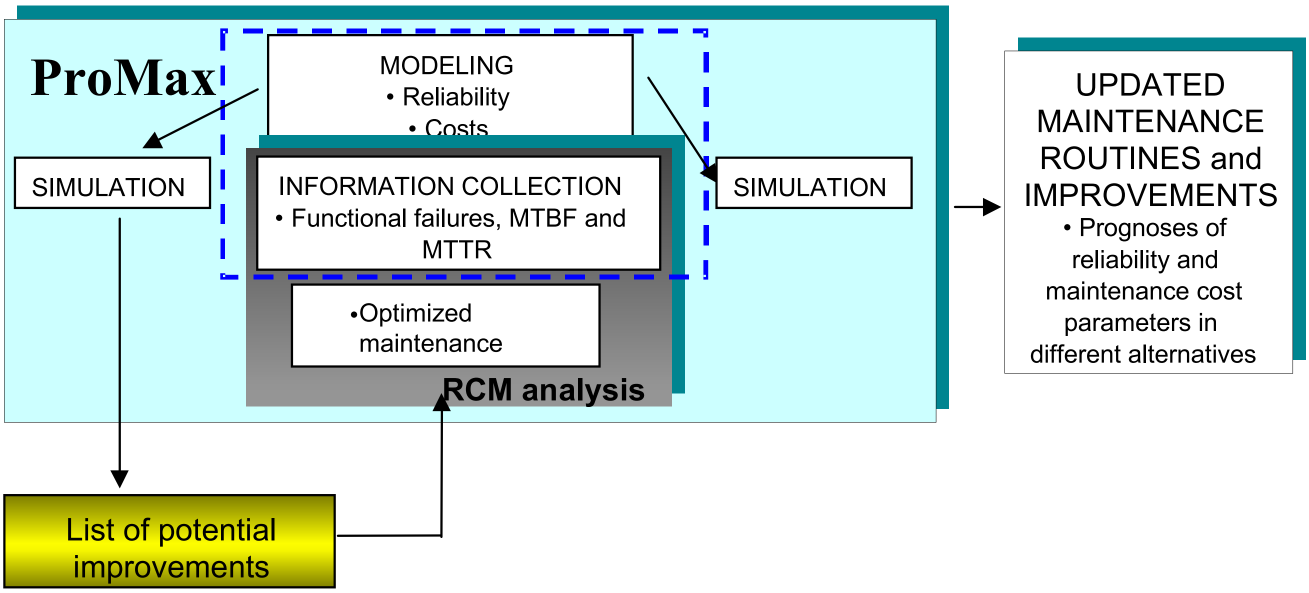

Figure 2 *RCM-Based ProMax approach in maintenance development.*

In the production phase, the main target of the ProMax approach procedure is to identify potential improvements and their economic justifications with combined analyses of accumulated experiences. Potential improvements considered with the procedure include both the content of the Optimized Maintenance Programme and the designed upgradings of the plant's technical concept.
To ensure the desired positive impact of the ProMax –approach on the plant's productivity, the concept is based on combined analyses of plant's long-term reliability and maintenance costs. The basic ideas of the ProMax approach are illustrated in Figure 2.

Reliability modelling and simulation is the essential feature of the ProMax approach. It is used for the creation of customer-specific production, energy and time-based availability and probability distribution, a list of the most critical equipment and their non-availability effects. Several other results such as production volumes, interim storage level variations and other "production statistics" are produced as a result of simulation runs. The effects of the improvements in the Optimized Maintenance can be easily calculated by re-runs of the simulation.

The ProMax simulation tool Miriam-ProMax is based on a new-generation simulation system. The simulation models can be easily made by applying a graphical and user-friendly Reliability Block Figures approach. The main sophisticated features are utilised by facilities modelling different flows of network, storages, and an advanced flow algorithm. The use of many advanced features makes it possible to build models that reflect real-world operation better than before.

APPLYING ProMax

Information used in the ProMax Approach

The majority of the information used in the ProMax approach is based on Fortum's own long-term O&M experiences from different power plants. The maintenance templates drawn up by Fortum's O&M specialists for power plant equipment are often utilized. In case Fortum's experiences are not relevant, the data can be supplemented with EPC's and OEM's data. However, the experience has shown that at times this may be difficult, if the suppliers have not been contractually obliged to provide this data.

Long-term maintenance costs are generated from the annual man-hours and cost and spares cost of preventive and corrective maintenance, which gives a cost model.

Reliability modelling needs several parameters concerning planned O&M practices. Input data include capacities, failure and repair data for each process stage component, information on supplies of utilities and resources, maintenance schedules and system operating rules. The most essential points are related to failure data such as MTBF (Mean Time Between Failure) and MTTR (Mean Time To Repair).

Analysis software used in the ProMax approach

Special Fortum in-house calculation software REPA is used for producing failure data. REPA software enables taking into account the failure data collectively of both the entire equipment population and of each individual piece of equipment, which makes it possible to consider prognoses in the model, including the different modes of operation of the plants and other individual features of the equipment.

The Reliability Simulation tool MIRIAM-ProMax can be used for studies covering a wide range of complexity levels, from high-level facility evaluations to advanced studies including intricate maintenance and operational considerations. The level of detail used for a particular run will depend on data availability and the case's requirements.

MIRIAM-Promax is designed to be as flexible as possible, to allow the user to perform a variety of process analyses. The system to be modelled is defined as a simplified network of elements. The stochastic behaviour of the system over time is represented using the Monte Carlo simulation.

The flow algorithm is one of the features that differentiate MIRIAM-ProMax from other reliability analysis programs. The main advantage of the flow algorithm is the program's ability to handle multiple flows and record production availability for several boundary points. MIRIAM-ProMax is able to perform availability analyses, if the production level changes throughout the lifetime of a process, or if the redundancy in the network is rather intricate.

A simulation run generates a sequence of events, corresponding to system state changes, and performance statistics are gathered as the run proceeds. Output results include system production statistics, production availability and deliverability, planned maintenance, resource and spare parts usage etc. The results are available both as numerical results and playback of the model. The playback shows how the element status changes throughout the simulation.

The third ProMax tool, Experience Based Reliability Centered Maintenance tool, is a combination of a maintenance-based economic risk analysis and the useful features of a Reliability Centered Maintenance process. The possibility of economic calculation is also implemented to support the balancing of the maintenance programme.

ProMax in an investment project

During an investment project, the ProMax simulation is used to produce estimations of plant productiveness. Estimations may contain figures like availability, shutdown distributions for plant life cycle. RCM-based ProMax approach in investment projects is illustrated in Figure 3.

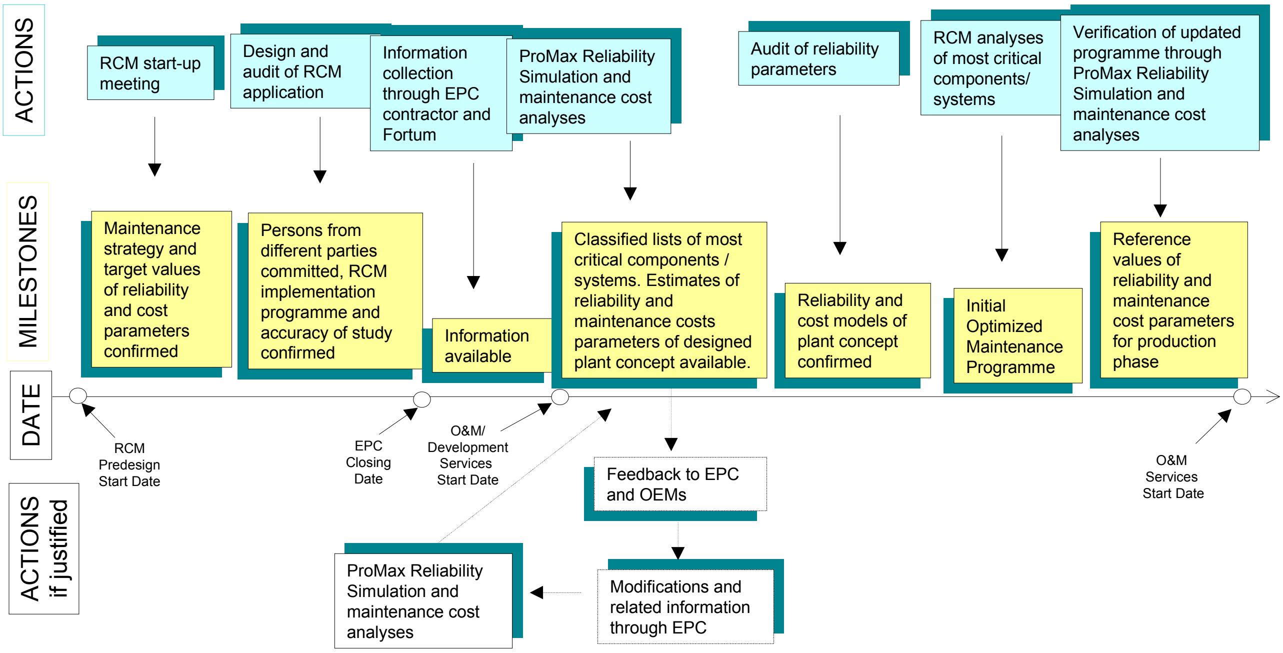

Figure 3 *RCM-based ProMax in investment projects.*

Also ProMax simulation is used, for example, to identify the most critical components and systems to be submitted to more detailed RCM analyses. This ensures that the focus of the initial Optimized Maintenance Programme is on those components and systems that have a major impact on the plant's economy and risk management. The outcome of the procedure is not limited to the initial Optimized Maintenance Programme; it also gives reference values of reliability and cost parameters to be traced during a production phase.

ProMax in production phase

In the production phase, the use of cumulative experiences through daily operation from various plants is ensured through periodical Maintenance Audits performed by qualified and experienced maintenance and reliability engineers. Considering the achieved experiences, reliability and maintenance cost models together with the related parameters are updated and new values are compared with the reference ones. A detailed RCM analysis is carried out whenever the comparison suggests a significant deviation having occurred. RCM-based ProMax approach in the production phase is illustrated in Figure 4.

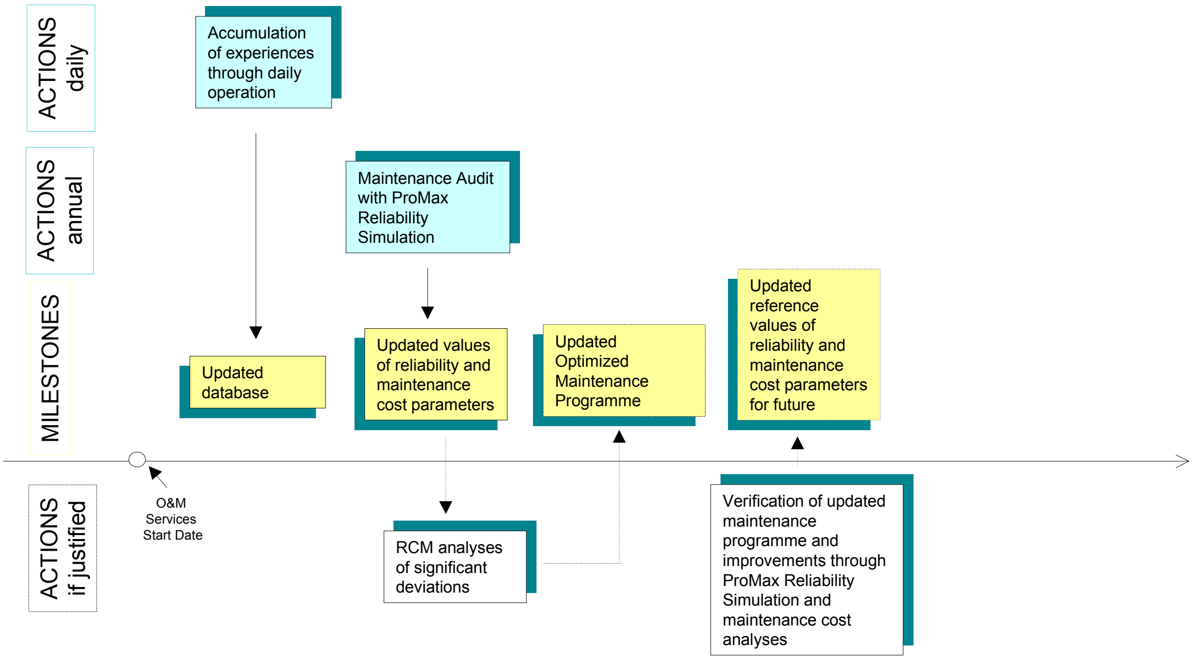

Figure 4 *RCM-based ProMax in the production phase.*

The results of the Maintenance Audits are used to control preventive maintenance and condition monitoring programmes as well as to identify targets for upgrading maintenance. Generally the same approach can be used to indicate the effect of any designed modification or improvement on the maintenance cost and reliability parameters of the plant.

CASE PLANT

The following selected case applying ProMax approach was used in the early phase of a Power Plant investment project. The target of the case was to estimate the availability distributions and non-planned shutdowns in order to enhance risk management concerning the O&M Tender phase.

The availability model was made for the MIRIAM-ProMax reliability modelling and simulation program. In order to model the plant for availability estimation, the plant was broken down into components and systems. The main principle was that the systems having an effect on the capacity of the plant have been taken into account. The planned production process, operation principles and maintenance practices were implemented in the model and simulation parameters. During the detailed design phase, the model can easily be updated according to detailed design solutions given by the ProMax approach.

O&M cost calculations were combined with the Tender process.

The failure data used in the case was a combination of data from Fortum’s own sources, and from the literature also the plant-specific failure data from comparable plants was used in the process of reliability simulation.

The main result of this specific ProMax simulation case, the annual availability distribution, is presented in Figure 5.

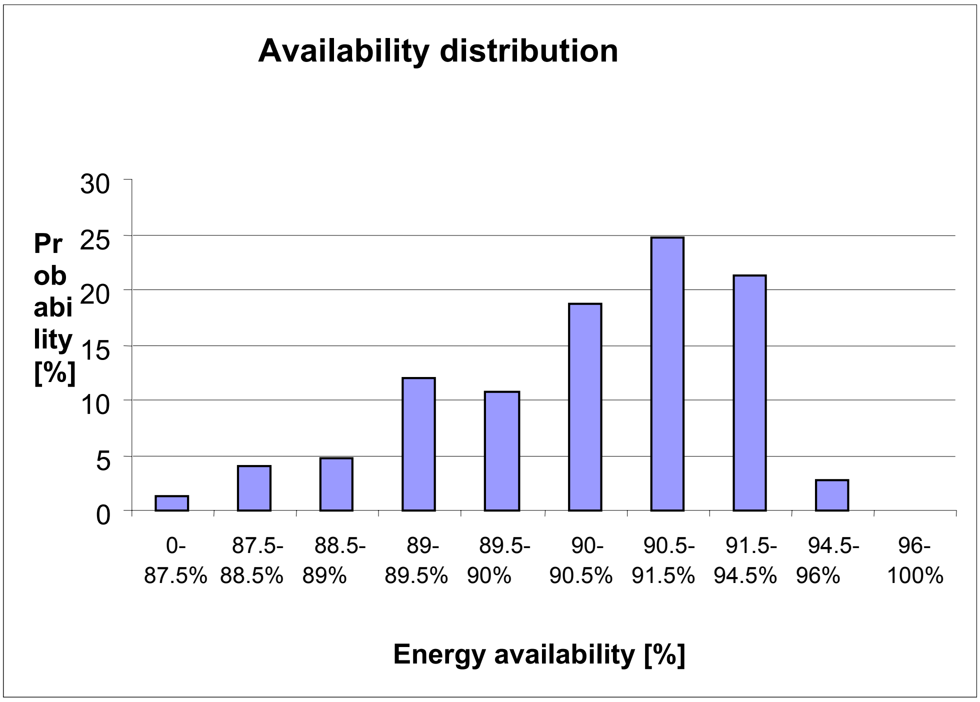

Figure 5 *An example of availability distribution for steam production.*

An annual shutdown distribution based on MIRIAM-ProMax simulation is presented on the next page in Figure 6. It should be noted that partial steam production and delivery was regarded as shutdown. However, MIRIAM-ProMax is capable to calculate shutdowns distributions for user defined levels such as 55%, 60% of the full production.

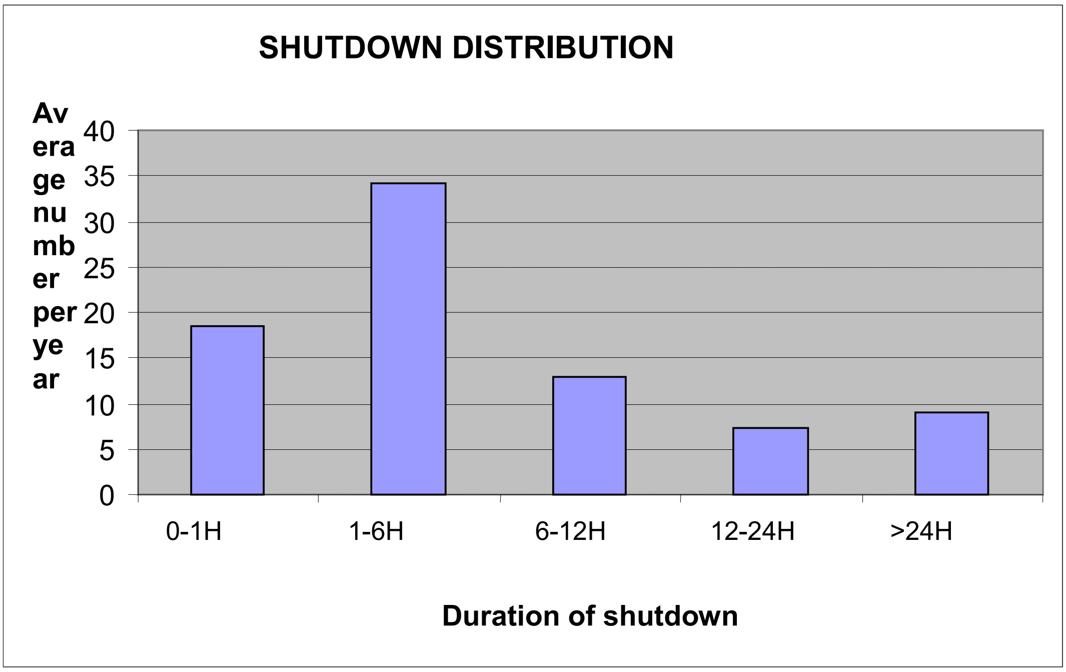

Figure 6 Annual shutdown distribution, production less than demand**.**

The simulation results revealed, e.g., the major availability risks and their sizes at the designed plant under review, the critical areas in terms of availability, the differences caused by the differing modes of operation, and the individual features of the equipment, as regards reliability.

The results were used to enhance risk management in the process of defining the availability-based bonus-penalties. Several design changes and their effects were studied by simulating re-runs.

SUMMARY

This paper introduced the ProMax approach and one case of applying the ProMax. The ProMax approach is developed by Fortum Energy Solutions to improve O&M procedures and risk management in the field of the Power Plant O&M offered by Fortum Energy Solutions. ProMax solutions are provided by experienced maintenance and reliability engineers using sophisticated software tools to support the service.

An O&M operator will benefit by decreasing the contractual risks when maximazing the life cycle profit by using the ProMax tools. In the investment phase, results from the ProMax tools are combined with economic studies supporting the O&M contract. A huge variety of needed estimations can easily be simulated and calculated. In many cases, the results are availability distributions, durations of disturbances or partial loads, amount of needed compensation. Special attention is devoted to the effects of the various maintenance and spare policies and critical systems for production output. In the second phase, the initial Optimized Maintenance Programme will be developed and reference values of reliability and cost parameters are traced during the production phase.

Later in the production phase, the maintenance programs for critical systems will be analyzed in maintenance audits. An audit identifies the need for updating the optimized maintenance programs. MIRIAM-ProMax simulation results will be backed up with the experience of the plant personnel. Additional simulation results will be run in order to support plant manager's analytical decision making for the future.

1.5
Risk Evaluation and Prioritization (REAP)

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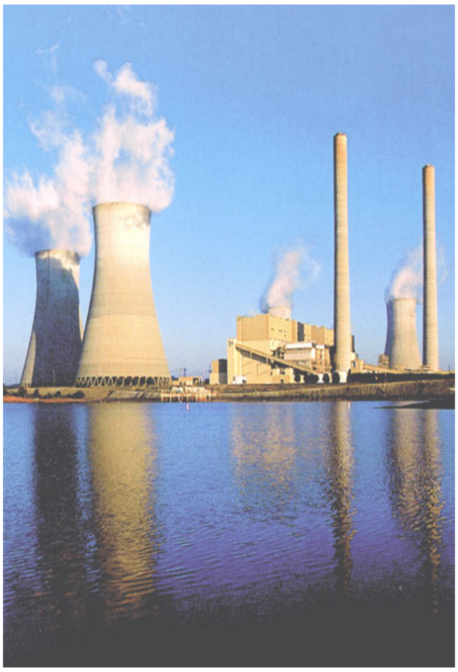


Abstract
The REAP Task Model has been adapted for application on Nuclear outage tasks and fossil Boiler outage tasks. The REAP model is intended to create a means to make business decisions on outage activities associated with the nuclear or boiler outage. Information on the condition of equipment considered in the nuclear outage and in the boiler outage together with information on the equipment task's financial and consequential impact. The model has been successfully applied to streamlining outage work scopes to achieve maximum value with the limited funds associated with today's outage budgets.

INTRODUCTION
Risk Based Management of power producing assets is evolving quickly as the markets move towards a more competitive operation. Risk has always been part of the operational decision making within a power plant. In the past it has been performed on an intuitive basis where leaders would weigh in their minds the conditions of their equipment against the marketplace demand and take risk either in the marketplace or with their equipment. Today with the more sophisticated data gathering tools, risk can be calculated and better weighed against the marketplace. Leaders can even prescribe the amount of risk they are willing to take against changing demands in the marketplace.

Risk can be considered in various applications. There is risk to personnel safety associated with operating deteriorating components in a plant. There is risk to organization effectiveness associated with managing power plant assets without specific programs in place. There is also risk in operating equipment whose condition may likely lead to unexpected failure and subsequent unplanned power derates in the market.

This paper deals with the third risk - of operating equipment whose conditions may lead to failure. Risk is defined as probability of an event times its consequence. Both probability and consequence are dependent on time. The probability of a component failure can worsen over time as components get older or are detected to have developing faults. The consequences can change over time as an unplanned derate can have different values as market pricing varies.

This paper presents risk based decision making for a collection of maintenance tasks, such as those associated with outages. The elements forming risk are the consequences of not performing the task and the probability of the consequence occurring. The elements forming prioritization of tasks are the calculation of risk and the associated cost of performing the task. The ultimate goal is to cover the most risk with the minimum of budget costs. Hence the title of the paper, "Risk Evaluation and Prioritization (REAP)".

The Task REAP Model has been adapted for application on Nuclear Plant outage tasks and Fossil Plant Boiler outage tasks. The REAP model is intended to create a means to make business decisions on outage activities associated with the Nuclear Plant and Fossil Plant Boiler from information on the condition of equipment the task would be performed on and information on the task's financial impact. The model has been successfully applied to streamlining outage work scopes to achieve maximum value with the limited funds associated with today's outage budgets.

The REAP model results in the assignment of risk value to the individual tasks in the outage. This risk value is the amount of risk eliminated by performing the task. This risk value is then plotted against the cost of performing the task. From this plot an optimized decision can be made that identifies those combinations of tasks that result in the most value derived for the plant at a given cost.

REAP METHODOLOGY

The REAP methodology consists of three activities. The first is a high level filtering of all possible outage task activities to assure all code and regulatory required work is included, all work conceivably performed during non-outage operation are eliminated, and all work tasks address identified occurring failure modes. Figure 1 presents the block diagram of the filtering process used in REAP. The REAP model assumes that the outage task activities are PM or CBM tasks. For the purpose of this paper both PM and CBM tasks will be called PM tasks. Once the PM tasks absolutely required and those absolutely not required have been identified, the focus of REAP falls on the balance of proposed PM tasks. The second set of activities is to place value on the PM and place cost on the performance of the PM task. The third activity is to present the data and make the optimum business decision.

TASK RISK EVALUATION AND PRIORITIZATION (REAP) MODEL METHODOLOGY FLOW CHART

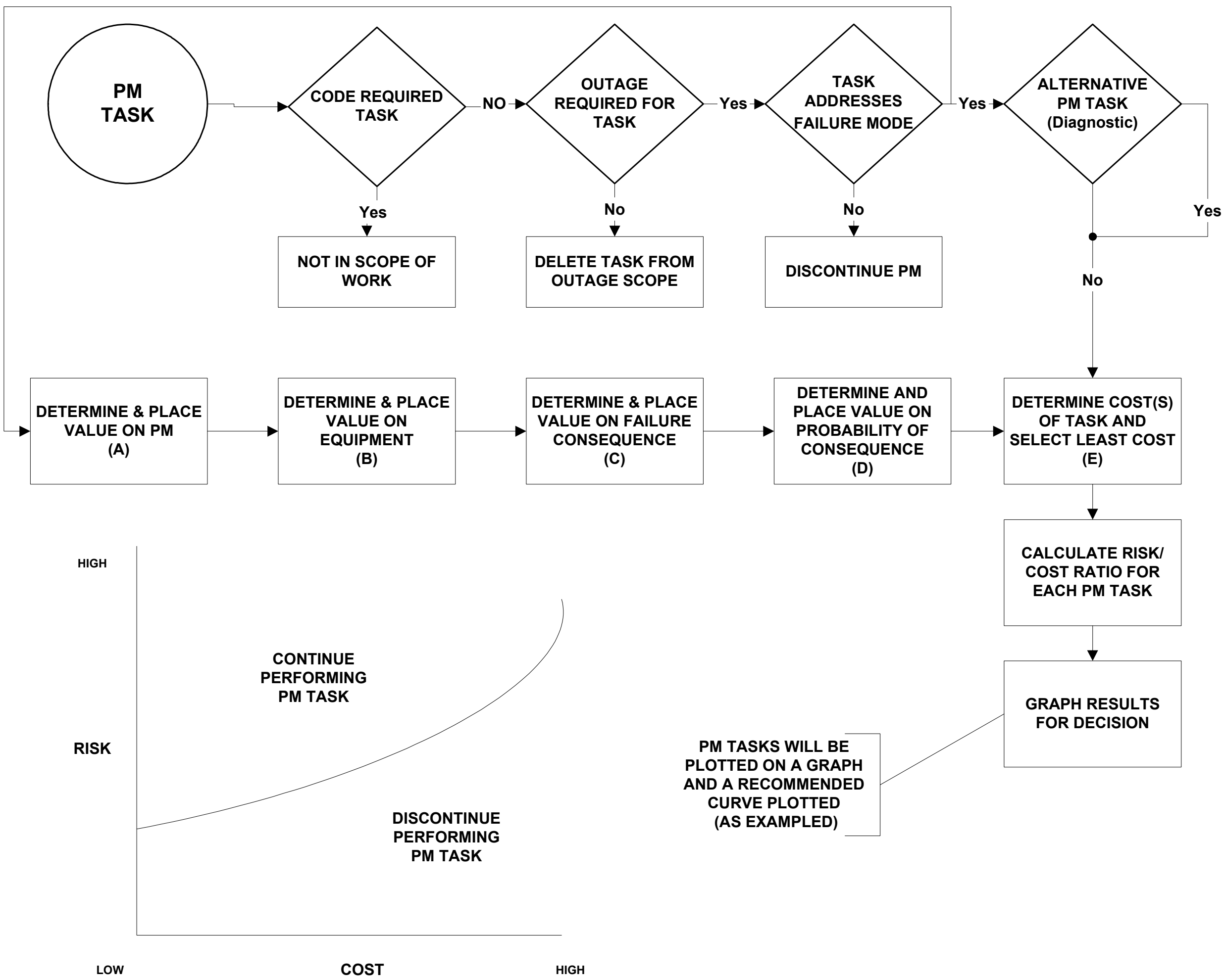


Figure 1

The methodology discussion contained here is constrained to the second and third activities.

METHODOLOGY: ACTIVITY 2, PART ONE: DETERMINATION OF VALUE ON RISK COVERAGE OF THE PM TASK

Placing value on the PM task requires establishing value within four value/risk elements. The dominant element is the actual value of performing the specific PM. This value is expressed as "K" in equation 1. There are three elements that moderate that value of "K". The first moderator is the factor on cost of the equipment on which the PM task is performed. The second moderator is the factor on the value of the component provides to the system to which it belongs. The third moderator is the factor associated with the consequences of failure in not performing the PM. This third factor is where the condition of the components is taken into consideration. These determined factors establish the value on risk for the PM task and is given by the equation:

Eqn 1 $Value = K*(PMV+VEP*VCF)$

Where: Value/Risk = value on risk received by performing the PM task
K = value of the PM task
PMV = value of the specific equipment (component) on which the PM task is performed
VEP = value of the equipment in the system to which the component belongs
VCF = value of the consequences of failure

The factors associated with equation 1 are derived from a series of sub-elements. The factor "K", the value of the PM Task, is determined by the following equation:

Eqn 2 $K=(A+B+C+D+E+F+G)+1$

Where
A: Is absolute accuracy required?
B: Does PM task yield remaining useful life information?
C: Does PM task yield trendable data?
D: Does PM task physically improve the equipment?
E: Does PM provide as found, as left data?
F: Does PM task track a root cause validated failure mechanism?
G: Is there inherent risk to the equipment in performing the PM task?

The answers to the questions are part of a rating system when correlated together establish a relative factor for the value of the PM task.

The first moderating factor is "PMV", the relative cost of the equipment. The equation for "PMV" is given by:

Eqn 3 $PMV = D\ (A+B+C)$

Where
A: What is the cost of materials to replace or repair the component?
B: What is the availability of the component from the supplier?
C: What is the labor requirement to replace or repair the component?
D: Can the equipment be repaired?

These questions provide the rating system to assign a relative cost to the equipment being protected. The equation has the form of a dominant factor, the three elements of cost, moderated by whether the equipment can be repaired or replaced.

The second moderating factor is "VEP", the value of the equipment in the system to which the component belongs. This factor is to take into account the relative operating dependency the system has on the equipment. The equation for "VEP" is given by"

Eqn 4 $VEP = A+B+C+D$

Where A: Is the equipment being protected critical to generation?
B: Will failure cause collateral damage to other equipment?
C: Will failure cause a reportable regulatory event?
D: Does failure have a personnel safety implication?

These questions provide the rating system to assign a relative value to the operation being put into risk if the PM task is not performed. The equation summates all extenuating financial implications of the equipment's potential failure.

The third moderating factor is "VCF", the value of the consequence of failure. This factor is to take into account the condition of the component, its maintenance history, and other Condition Based Maintenance or Predictive Maintenance factors to arrive at a relative evaluation of the probability of failure and the extent of potential damages of that failure. The equation for "VCF" is given by"

Eqn 5 *VCF = 0 (A%) + 1 (B%) + 10 (C%) + 100 (D%) + 1000 (E%)*

Where

A: What is the probability of satisfactory equipment performance to the next scheduled outage (maint. history review)?
B: What is the probability that equipment performance will be degraded?
C: What is the probability that minor incident (repair and revenue costs) will occur to equipment?
D: What is the probability that moderate incident (repair and revenue costs) will occur to equipment?
E: What is the probability that catastrophic incident (repair and revenue costs) will occur to equipment?

These questions provide the rating system to assign a relative value on the probability of various dimensions of failure. It is important that the sum of percentages from all five questions total 100%. This factor will dramatically increase from one outage to the next outage if the PM is not performed. Obviously the probability of failure would increase upon the decision not to perform a PM from the previous outage. The equation summates all extenuating probable failure implications.

METHODOLOGY: **ACTIVITY 2, PART TWO: DETERMINATION OF RELATIVE COST OF PERFORMING PM TASK**

The REAP model requires the calculation of the relative value of the PM task as it relates to the task's value to the equipment and the equipment's value to the operating systems. This is described from the equations above. The REAP model also requires the calculation of the relative cost of performing the PM task.

The equation for the Cost of performing the PM task, "CPM" is given by:

Eqn 6 CPM = C*(F*A)*B

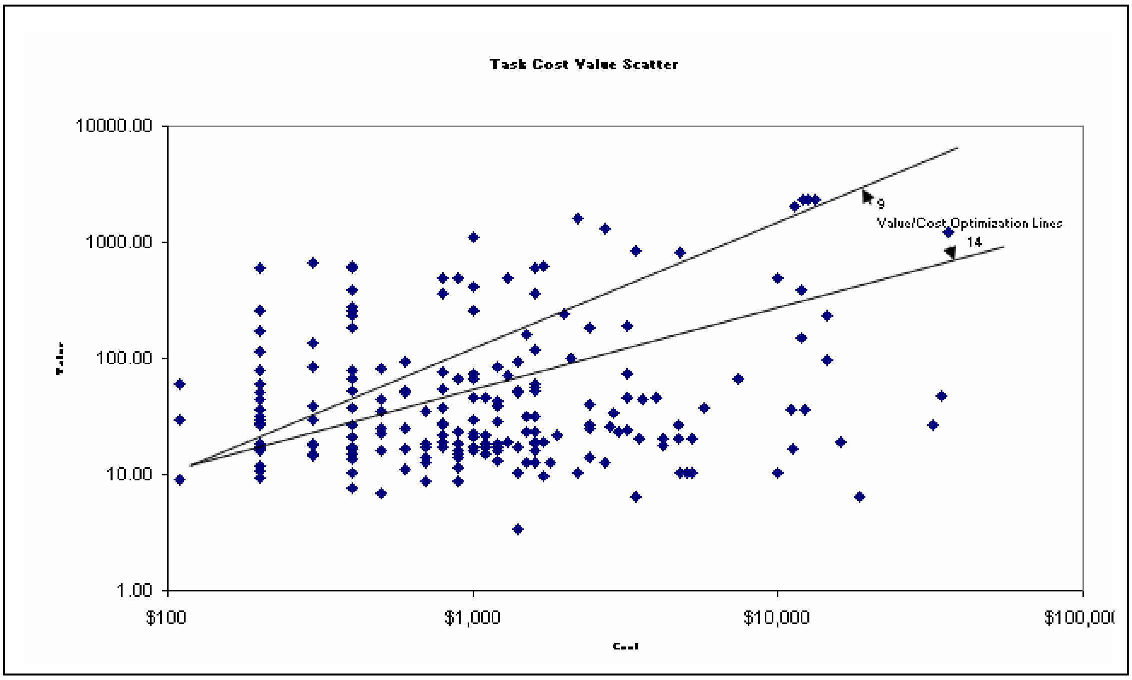
Where: CPM = Cost of performing the PM task
C = What is the labor rate expressed in dollars?
F = What is the labor hours adjustment factor between estimate and ctual(if any)?
A = What estimated labor hours are required?
B = What support (Material, Scaffolding etc.) is required?

These questions provide the cost either relative or absolute depending on available data.

Nuclear Plant Outage Analysis Process

The REAP model was applied to 315 discretionary tasks (as determined from Figure 1 methodology) associated with a Nuclear Plant planned outage. The intent was to streamline the outage to be within the limits provided by the outage budget – a reduction of 10% of the outage estimates for the work anticipated. Each outage task was evaluated for its value to the plant and its cost of performance. Then each PM task was plotted value versus cost as shown in Figure 2.

Figure 2 *Value versus cost.*



The following are a list of sample tasks considered in the nuclear plant analysis:

Pilot Relief Valve Removal Testing and Installation
H.P. Stop Valve Inspection - B Main Feed Pump.
L.P. Stop Valve Inspection - B Main Feed Pump
Containment Service Air Compressor Periodic Maintenance.
Hydrogen Seal Inspection.
Alternate Charging Flow Paths.
Portable Fire Extinguisher Inspection/Maintenance.
18 Month Transformer Yard Deluge System Operational Test.
Fire Hose Station Periodic Valve Cycle Test.
Feed Pump Turbine A Overspeed Trip Mechanism Annual Test.
Feed Pump Turbine B Overspeed Trip Mechanism Annual Test.
ASDV 18 Month Manual Valve Stroke
RCP Oil Collection Tank Refueling Surveillance
Weekly SCCW Flush of the SCCW Heat Exchangers.
Emergency Bearing Oil Pump Test.
Vibration Trending

Recognizing that building an outage entails selecting the highest value (most risk covered), lower cost items first, Figure 3 presents the method used to prioritize each task. Figure 3 presents the results of building the outage task scope from the high value, low cost tasks to the low value, high cost items. The graph integrates all tasks such that each point on the curve builds from the previous points. The shape of the value – cost curve shows that value builds quickly with limited outage funding until a point is reached where achieving further increases in outage value requires substantially more funding. It is clear that by setting priorities to the tasks of the outage that a majority of the value contained in all the tasks can be funded by a small portion of the outage costs.

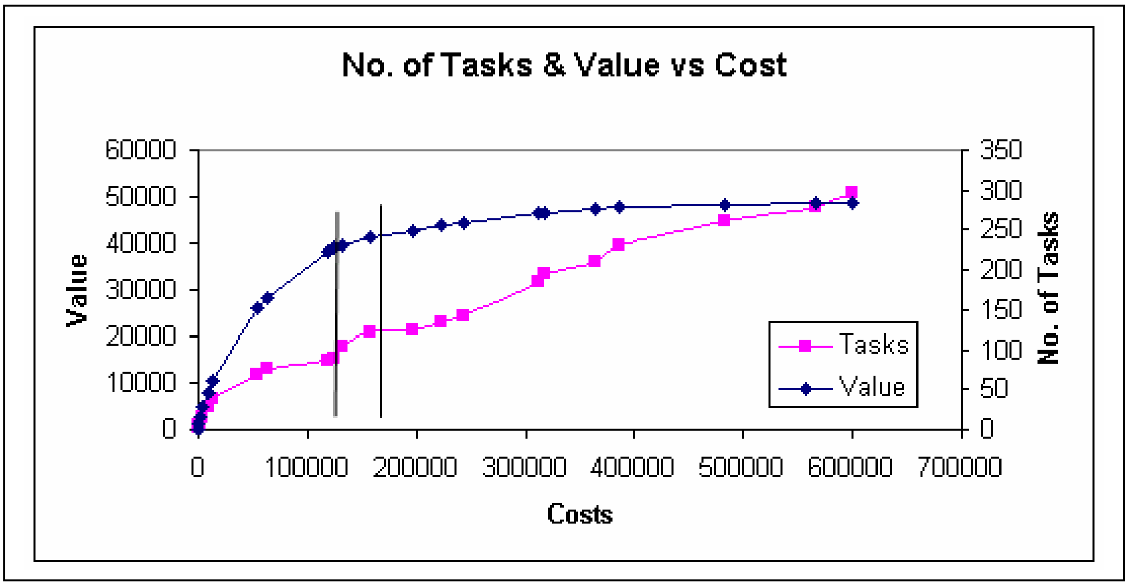
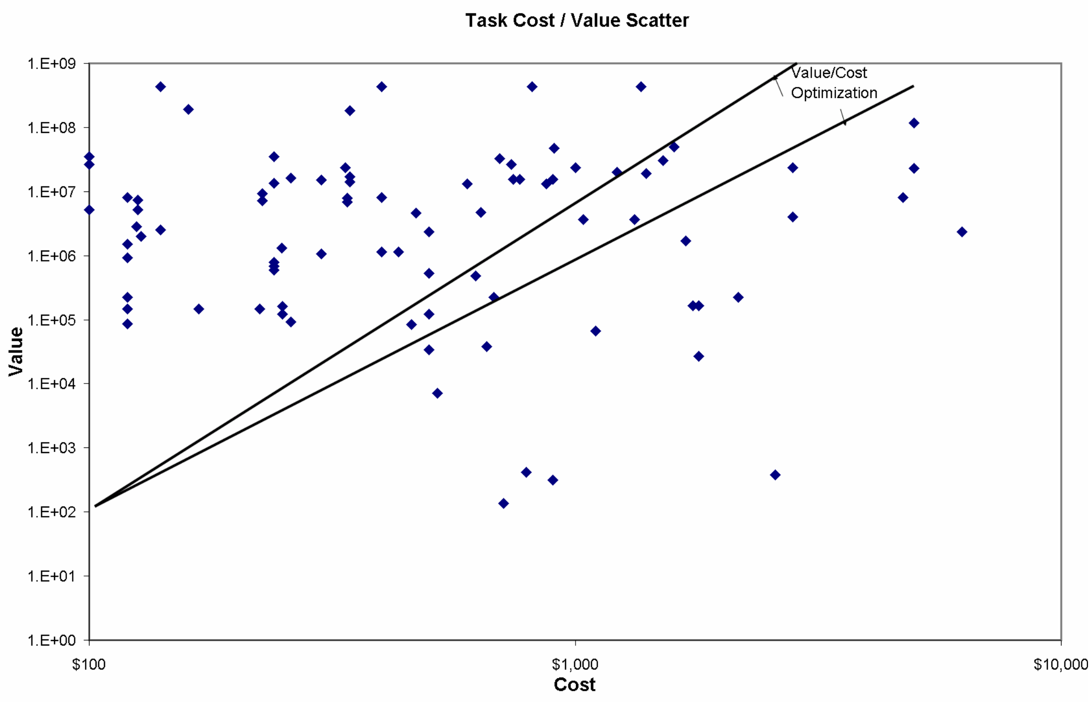


Figure 3 Value versus Cost for Numbers of Outage Tasks

Figure 3 resulted in the recommendation that only 87 of the outage's discretionary 315 (27%) tasks be performed (228 tasks not performed). The reason for this was that those 87 tasks captured task value of 38,430 out of the total value of all tasks of 48,856 (78%). Meaning that 78% of the value of the outage is captured by 27% of the tasks. This is very reasonable in light of Paredo's rule 80:20. In terms of cost of performing those tasks, the results were even more in line with Paredo's rule. Of the tasks included in the analysis from the outage plan, a total cost of $599,520 would have included everything being accomplished. The 87 tasks only cost $119,420 to accomplish or 20% of the cost for all considered tasks – a realized savings of $480,100

FOSSIL PLANT BOILER OUTAGE ANALYSIS PROCESS

The following presents the results of the REAP analysis performed at AEP's Big Sandy for an upcoming boiler outage. The domain of the analysis was the scheduled outage tasks for the boiler maintenance outage. A total of 119 maintenance outage tasks were reviewed. The resultant scatter diagram is presented in Figure 4.



The following is a sample of the typical tasks considered in the exercise:

AIR HEATER SEALS
4KV ROOM WALL
INSPECT GAS OUTLET DUCTS
CIRC WATER PUMP DISCHARGE EXP. JOINTS
DEAERATOR INSPECTION
OVERLAY SIDEWALLS
NDE ON FACTORY WELDS 1ST RH PIPING
PA & FD FANS - CLEAN & INSPECT
BOILER DIVISION VALVE-OPEN, INSPECT & REPAIR
COAL CHUTE RENEW WEAR PLATES
REPLACE COAL CHUTES
REPAIR PENTHOUSE CASING LEAKS
REPLACE 80 TUBES REAR ASH HOPPER SLOPE
REPAIR APERATURE MEMBRANE
801 ASH GATE
BURNER REGISTERS - INSPECT & REPAIR
GENERATOR INSPECTION
MAIN TURBINE OIL COOLERS
INSPECT #1 BEARING ON TURBINE

From this scatter diagram (Figure 5), an optimization algorithm is applied that results in the following graph.

b

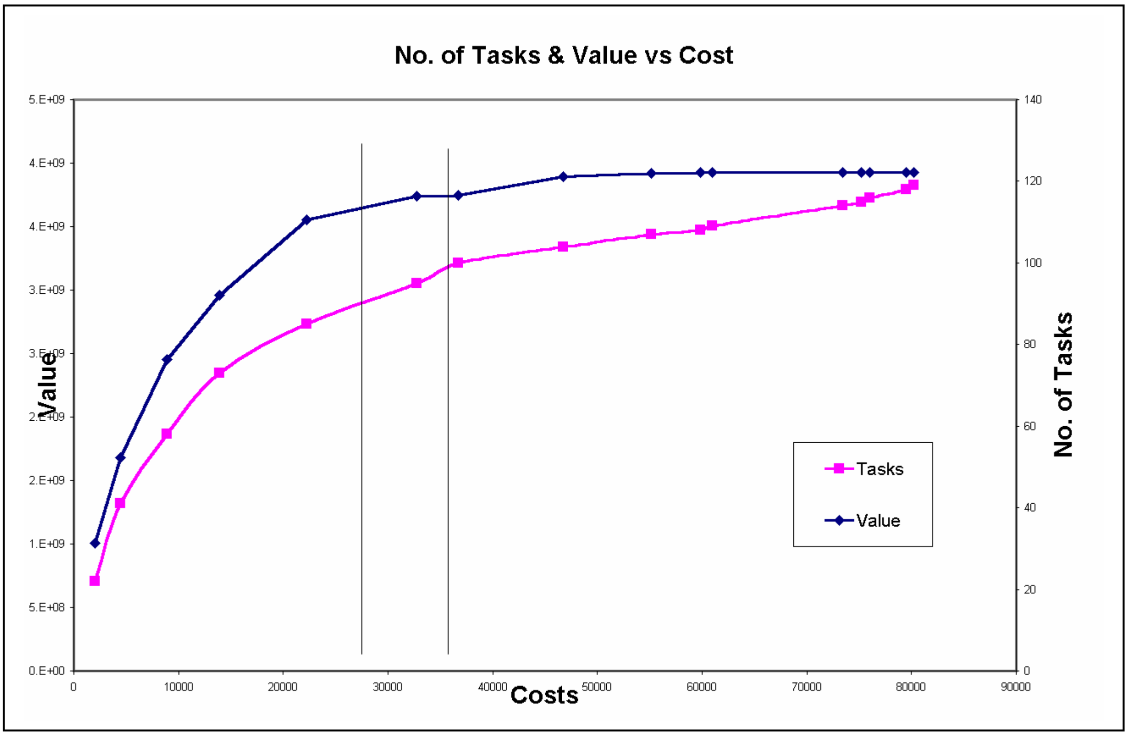


Figure 5 *Accumulated value versus cost versus no. of tasks.*

Figure 2 shows that at the 32,700 relative cost level (mostly labor hours), 3.74 value is captured with 95 of the 119 outage tasks. In other words – with 40% of the outage task hours, 95% of the outage task value can be captured with 80% of the tasks being performed.

SUMMARY

The REAP model provides a method to engage condition based information into an asset managing process moving from time based activity to risk informed tasks associated with business based decision making. The method is intended to focus on discretionary outage tasks, however the method can be applied to a wider audience of outage tasks dependent on how risk adverse the organization is in making business decisions. The REAP model also provides for documentation in business decision making when deciding which outage tasks will be done and which ones will not. . Finally it must be understood that the tasks not performed are deferred to be analyzed at subsequent outages when probability of failure factors will increase.

1.6
Risk-based Inspection and Maintenance – Industry Feedback and User Needs

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Abstract

This keynote paper considers the current level of industry uptake of risk-based inspection and maintenance (RBI/RBM). The safety and commercial benefits of RBM as an asset management tool are becoming clearer and are gaining acceptance by safety regulators. The needs and perception of RBM however vary across industry sectors. After a review of current regulations and guidelines, a summary of the results of an industry survey carried out as part of a TWI Joint Industry Project is presented. The technical and organisational requirements of RBM are illustrated by reference to a 'best practice' guidance document developed by TWI in association with the UK Health & Safety Executive. The key issues for effective implementation of RBM tools are accordingly identified. The importance of user friendliness and a formal link to inspection periodicity are highlighted. The latter issues are illustrated by application of TWI's RISKWISE™ product.

INTRODUCTION

The assessment of risk forms part of what is increasingly known as 'asset management'. The principle of asset management is to assist companies in adopting a holistic approach to performance improvement which deals not only with the technical or commercial risks themselves but also the context in which they exist.

Regardless of the industry sector, the objectives of the exercise are often related to improvements in: safety, availability, productivity, O&M costs, share holder value, etc. Once the objectives are set, a formal risk assessment of existing systems will reveal those areas where risk mitigation is necessary or where performance can be improved. A risk-cost optimisation process then allows selection of the most cost-effective risk management measures.

In the context of safety as well as economics, risk is a combination of the probability of occurrence of a hazardous or detrimental event and the magnitude of the consequences of the event. Risk is defined by three components: the event, probability of the event occurring, and the undesirable consequences. Perception of risk is often strongly influenced by the consequences rather than probability.

From the viewpoint of integrity management of plant and machinery, the practice of risk-based life management is complex. A balanced approach to life management is to consider all political, economic, commercial, technological and human aspects. In this process, a wide range of pertinent issues should be considered, including:

- The nature and tolerability of risk,
- Principles of management of health and safety at work,
- Process of and methods for risk assessment and management,
- Industry guidelines on risk-based plant safety, availability and inspection,
- Risk related decision making, and
- Fitness-for-service.

Industry is recognising that benefit may be gained from adopting formal risk-based approaches to plant integrity management through improved targeting and scheduling of inspections and maintenance activities. The primary benefits of RBI and RBM are: improved health and safety management; cost savings derived from extending inspection intervals, avoiding unnecessary inspection; increasing plant availability; and optimum repair and replacement scheduling.

REGULATIONS AND GUIDELINES

Overview of Regulations Governing Industrial Risks
The European Commission has introduced a series of European Health and Safety Directives which are law and are becoming implemented by every Member State within the EU. In the United Kingdom, the law requires industries to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all their employees and to conduct their operations in such a way to ensure, so far as is reasonable, that the public is not exposed to risks to their health and safety. The Health and Safety Executive (HSE) in the UK is responsible for drawing up the guidelines on tolerability limits of risk at work[(1)]. The HSE requires the risks within the tolerable limits to be reduced as low as reasonably practical, commonly known as the ALARP principles. Practices of industrial risk regulation and management have been under continuous development over the last three decades. One of the challenges today in industrial risk management is that society becomes less tolerant of risks. Industrial operations are expected to work to a much lower level of risk than that associated with daily life activities. It is therefore crucially important to understand that risk can only be reduced to ALARP.

Risk assessment and management must answer the following questions:

- What can go wrong?
- What are the causes?
- What are the consequences?
- How likely is it?
- How safe is safe enough?
- How can risks be reduced?

There are three generic steps in the risk assessment and management process:

- Identification of hazards,
- Assessment of the risk
- Reduction of risk.

Industry Guidelines on Plant Safety and Risk-Based Methods
Nuclear safety assessment principles in the UK are set within the 'Tolerability of risk from nuclear power stations (TOR)' and the 'Safety assessment principles for nuclear plants (SAPs)'[(2)]. The SAPs require that all potential accidents be identified in a systematic manner. For the analysis of accidents, the SAPs use a three-pronged approach. This requires the deterministic analysis of: (a) both design basis accidents (DBAs); (b) beyond design basis accidents (BDBAs), including severe accidents; and (c) probabilistic safety assessment (PSA). PSA has been used for many years in the UK in licensing and regulation and is now an established feature of safety cases.

A framework of risk-related decision support has been published by the UK offshore oil & gas industry[(3)]. It recognises the need to reach a risk-related decision with a combination of technical and value-based approaches including:

- Engineering codes and standards,
- Good practice,
- Engineering judgement,
- Risk-based assessments, and
- Value based approaches.

The framework provides a means to determine the relative importance of the various methods of assessing risk by referencing the role of standards, quantitative risk assessment (QRA), societal values, etc. Operators are required to judge which combination of these methods is best used to determine whether the risks are tolerable and ALARP.

In 1991 ASME published a general document on the use of risk-based technology for the development of inspection guidelines[(4)]. This document presented an overall risk-based inspection process. It described techniques and tools to be used at each stage of the process. It also presented examples throughout the text to illustrate the use of those tools.

In 1992 ASME published a second document, Volume 2 – Part 1 Light water reactor (LWR) for nuclear power plant components, in a series covering the development of guidelines for risk-based inspection[5]. Volume 2 is an application of the general methodology in Volume 1, for the inspection of nuclear power plant components. Nuclear power plants are different from any other industry installations in that multiple levels of safety protection are designed and built into plant systems on the principle of 'defence-in-depth'. This means that combinations of unlikely events must occur to cause the breach of the defence and to result in a significant public harm. Since the potential consequences of a nuclear release are severe, and the chain of interacting events leading to the final event of core damage is complex, rigorous probabilistic risk assessments (PRA) are required. PRA have been performed in nuclear safety assessments for many nuclear power plants in the UK. The use of this extensive PRA information is a key feature of the methodology presented in Volume 2 in the quantitative risk assessments.

In 1994 ASME published a third document, Volume 3, covering fossil fuel-fired electric power generation station applications[6]. It addresses the in-service inspection (ISI) of components in fossil fuel-fired electric power generating stations. It considers application of a risk-based methodology to all fossil power plant components that contribute to plant unavailability, but the primary focus of inspection is on components that maintain a pressure boundary.

The ASME approach[4] comprises a qualitative risk ranking as well as a quantitative assessment applied to individual components or equipment items. The quantitative approach recommends that a full FMECA (Failure Modes Effects Criticality Analysis) should be conducted. The use of operating experience databases and analytical damage models together with their probabilistic application is also recommended. The latter is required for establishing inspection periods, although detailed examples of the analytical process are not given.

API BRD 581'Base resource document on risk-based inspection' (preliminary draft) was published by the American Petroleum Institute in 2000[7]. It was produce for the oil & gas production, oil refining and petrochemical industry conforming to American regulation and industry practice. It was intended for equipment designed and constructed to the ASME and ANSI codes, as well as the in-service inspection guidelines of API RP 510, RP 653, and RP 570. It was mainly for inspection on pressure maintaining equipment such as pressure vessels and piping, but also for other equipment such as heat exchangers and the pressure-retaining components of pumps.

API BRD 581[7] comprises qualitative and quantitative approaches. The qualitative approach is based on a series of failure likelihood and failure consequence factors and delivers equipment positioning within a five by five risk matrix. For the quantitative method in API BRD 581 the likelihood evaluation process starts with a generic failure frequency for the type of equipment in question. This value is then modified by factors relating to: the specific equipment (F_E) and the safety management regime (F_M). F_E takes account of items such as damage type, inspection effectiveness, condition, design and fabrication, process control and safety management and F_M addresses the potential impact on mechanical integrity of all process safety management issues from API RP 750. The factors F_E and F_M are obtained from an exhaustive scoring system based on questionnaires or workbooks. The quantitative assessment of failure consequence within API BRD 581 is based on a systematic multi-stage process to determine costs relating to explosive release, toxic consequences, environmental clean-up and business interruption.

The API and ASME approaches are similar in that they both advocate progression from a relatively simple qualitative risk ranking method to a far more complex quantitative method requiring significant effort and expertise to execute. Although the ASME approach considers the time dependence of failure probability, neither approach offers clear and formal methods to translate risks into inspection frequencies.

Guidelines on Assessment of Inspection Frequency

The Safety Assessment Federation (SAFed) in 1997 produced a set of guidelines on the periodicity of inspections[8]. The guidelines adopt a basic qualitative risk assessment approach and further state that they should only be adopted after proper consideration of individual circumstances pertaining to each pressure system. The European Confederation of Organisations for Testing, Inspection, Certification and Prevention (CEOC) has developed advisory guidelines aimed at harmonisation within the EU with respect to inspection frequency of boilers and pressure vessels[9]. An approach is proposed whereby likelihood of failure scores are used to establish position on a risk matrix. The maximum period between inspections is then related to the assessed risk. The UK's Institute of Petroleum (IP) has also issued a code of practice for inspection of pressure vessels in the petroleum industry(10). This approach groups equipment into different categories, e.g. process pressure vessels, storage vessels, etc. and uses a grading system to assign inspection intervals. The grade is set by the operator after the first examination. If operational practices are uncertain or if the rate if degradation is expected to be high, then the inspection interval can be reduced by the operator. For cases where the degradation rate is as expected and more predictable the grade achieved allows an extended inspection interval.

In summary, the regulatory environment in the UK is such that where reliable damage rate predictability exists, there is scope for operators to adopt formal methods for determining inspection periods based on risk and remaining life considerations.

INDUSTRY FEEDBACK SURVEY

As part of a major joint industry project, TWI carried out a questionnaire-based survey to gain a better understanding of the needs of plant operators. Approximately 90 of the questionnaires that were distributed worldwide, were completed and returned to TWI.

The majority of respondents were based in the oil & gas refining, fossil power, chemical and petrochemical industries. The nuclear power generation, oil & gas transportation and onshore oil & gas production industries were under-represented.

The majority of respondents classified themselves as producers, operators or manufacturers and engineering service contractors. Engineering insurers, equipment manufacturers or suppliers and safety regulating authorities were under-represented in the survey.

A summary of the indications and directions resulting from the survey is given below(11).

The majority of all respondents' companies (69%) had 'Previously implemented' RBI/RBM, or were 'Currently implementing' RBI/RBM. Several respondents, in all sectors, indicated that they were currently implementing RBI/RBM. Fossil fuel power generation, petrochemical, oil & gas refining, and chemical companies had the largest proportion of respondents that were considering implementation.

- The only sectors in which respondents had indicated that senior management was 'Unconvinced' that an RBI/RBM program would be beneficial to their company' were the petrochemical, offshore oil & gas production and chemical sectors. Approximately 60% of all respondents indicated that senior management was 'Convinced' or 'Very convinced' that an RBI/RBM program will be beneficial to their company.

- Approximately 98% of all respondents (whose company's had previously undertaken a RBI/RBM assessment), indicated that the results of their RBI/RBM program had 'Met expectations' or 'Exceeded the expectations' of their company.

- General pressure vessels, piping and heat exchangers are the types of equipment to which RBI/RBM is more often applied. Structures, safety relief valves and pumps, turbines and compressors are the equipment to which RBI/RBM is least often applied.

- Approximately 20% of all respondents indicated that their company had established and documented a uniform RBI/RBM policy or guidance for application throughout their company. In the fossil power generation sector respondents indicated that their company has not, and is not preparing to, produce a uniform policy or guidance document.

- With regard to how many people were currently responsible for managing the day-to-day introduction of RBI/RBM, 47%, 10%, 28% and 15% of respondents across all sectors indicated that their company had set up a 'Part time – Individual', 'Full time – Individual', 'Part time - Project team', and 'Full time - Project team', respectively.

- Approximately 60% of all respondents whose company is currently using, or intends to use RBI/RBM software, indicated that their software was not linked to any other electronic data management system, or other software system.

- Approximately 24% of all respondents indicated that both the input variables and output results of their RBI/RBM software were linked to another data management or software system.

- Respondents indicated that there is no substantial increase in the accuracy of semi-quantitative compared to qualitative (subjective) RBI/RBM methods. However, respondents believe that qualitative methods were substantially faster to apply than semi-quantitative RBI/RBM methods. Quantitative (probabilistic) methods were considered to be the most accurate of the three methods, but also the slowest of the three RBI/RBM methods to apply.

- Approximately 57% of all respondents indicated that their Safety Regulating Authority accepted RBI/RBM as an alternative basis for determining inspection and maintenance intervals. However, there was no one region of the world in which RBI/RBM was entirely accepted as an alternative basis for determining inspection and maintenance intervals.

For those respondents that had previously undertaken RBI/RBM assessments, the two most important reasons for implementing a RBI/RBM program were: (a) improving the overall safety of critical plant; and (b) reducing the duration of inspection or maintenance outages.

Similarly, for those respondents that were currently undertaking RBI/RBM assessments the two most important reasons for implementing a RBI/RBM program were: (a) improving the overall safety of critical plant; and (b) extending the interval between inspection or maintenance outages.

The two overall least significant reasons for implementing a RBI/RBM program were: Classification of plant in terms of potential for environmental damage; and reducing the duration of inspection or maintenance outages.

For those respondents that had previously undertaken RBI/RBM assessments, the most critical success factors for RBI/RBM implementation programs were: (a) having the ‘right’ people in the assessment team; (b) appointing a suitable assessment team leader; and (c) reliability of the RBI/RBM analysis methodology.

For those respondents that were currently undertaking RBI/RBM assessments, the most critical success factors were: (a) having the ‘right’ people in the assessment team; (b) reliability of the RBI/RBM analysis methodology; and (c) appointing a suitable assessment team leader.

The overall least important success factor was considered to be the ‘speed of undertaking RBI/RBM assessments’.

For those respondents that currently use and intend to use RBI/RBM software, the most important attributes of the assessment software were: (a) overall user-friendliness of the software system; and (b) based on well-known or published model or methodology.

For those respondents that have not and do not intend to use RBI/RBM software, the most important attributes were: (a) based on well-known or published model or methodology; and (b) tracking system for actions.

The overall least important attributes of RBI/RBM software program were the software vendor’s operation and maintenance costs and the incorporation of a help feature based on 'expert rules' or 'knowledge base' within the software.

EFFECTIVE RBI/RBM IMPLEMENTATION

The process of RBI/RBM should form part of an integrated strategy for managing the integrity of all assets and systems throughout the plant or facility. RBI/RBM is a logical and systematic process of planning and evaluation. From the ‘Best Practice Guideline’ developed by TWI in association with the UK Health & Safety Executive the major steps within the process are as follows[12]:

- Establish requirements and clear statement of objectives,
- Define systems, system boundaries and equipment to be addressed,
- Specify the RBI management team and responsibilities,
- Assemble plant database,

- Evaluate failure scenarios, damage mechanisms and uncertainties,
- Perform risk audit based on event probability or likelihood and event consequence analyses,
- Review risk management measures and develop risk-focused inspection plan,
- Implement inspection plan and any associated operational or maintenance measures,
- Assessment of inspection findings in terms of remaining life and fitness-for-service,
- Update and feedback to plant database, risk audit and inspection plan on a continuous basis.

For control purposes and to ensure best practice the plant manager should exercise a 'performance audit' on each of the above steps in the RBI process.

The steps are intended to assist industry to evaluate the processes being used for integrity management and inspection planning of pressure systems and other systems containing hazardous materials.
Some of the main requirements and critical issues for the effective implementation of RBI which should be recognised by suppliers of RBI programmes and software products, are summarised below[13].

User-friendly Software
It is essential that the RBI tool is fully understood and accepted by the user and is easily used without undue complexity. For increased efficiency, the software could be linked with inspection or corrosion data management systems where these are installed such that plant data can be efficiently accessed.

Incorporation of all Damage Mechanisms
The RBI process should take account of all deterioration mechanisms and failure modes to a level of state-of-the-art understanding. Failure databases derived from plant experience together with available material models and associated databases are important input. It should be recognised however, that comprehensive 'expert systems' or prescriptive modules based on knowledge of nominal service conditions, to predict all failure scenarios do not currently exist. Expert judgement in association with technical guidance is the key issue.

Audit Team Approach
The risk audit, the evaluation of risk management options and inspection planning stages requires a multi-disciplinary input covering a range of competences. Therefore, it is best performed by a team of experienced plant engineers. The team should include plant personnel with technical expertise covering the following areas: risk analysis, process hazards and business consequences, local safety management, plant design and materials, operations, inspection and maintenance functions, and inspection and NDE techniques.

The complexity of the plant or facility should determine the size of the team. Safety implications should be addressed by individuals in the team who can demonstrate professional competence. The team leader should preferably be remote from pressures associated with plant production. Consensus is required on all major decisions and a complete record must be kept of all judgements and decisions made. Auditability is essential through all stages from plant data capture to inspection planning rationale.

Further benefits of an interactive audit team approach are the on-the-job training and transference of assessment know-how implicit within the approach.

Risk Management Measures
RBI tools, which only output a relative risk ranking, no matter how comprehensive, do not necessarily provide the solution that operators are looking for. A more holistic approach is increasingly being required whereby the operator is systematically directed through a series of risk management options. These options should not be restricted to inspection or maintenance actions but should also lead the operator to other measures such as, design or engineering modifications, operational changes, etc. The impact of each risk management action should be retained by the software so that cost-risk optimisation can subsequently be undertaken.

Formal Link to Inspection Frequency

RBI tools which only outputs a relative risk ranking, whether qualitative or quantitative, leave the user with the problem of selecting an appropriate and safe inspection period.

Health and safety regulations do not specifically prescribe inspection intervals. In the self-regulating environment in the UK, a competent person is expected to use judgement and experience in deciding inspection and maintenance intervals. The UK's Institute of Petroleum(10) and SAFed(8) have issued guidelines on maximum service intervals between inspections.

In spite of the above, to be effective the RBI tool should offer formal guidance on the inspection frequency based on the risk audit undertaken. The inspection frequency determination must include formal consideration of remaining life for all critical time dependent damage mechanisms. A failure probability route to estimate the remaining life based on established rules (e.g. ASME RBI Guidelines(4)) within a practical user-oriented approach is preferable(13)

RISKWISE™ SOFTWARE

RISKWISE™ is TWI's RBM software for optimising plant maintenance planning. RISKWISE™ has been developed and continuously updated to meet the foregoing requirements of both users and regulators(11,13). Specific outputs are:

- Unit-wide risk audit enables repair and maintenance resources to be risk-focused.
- Safe inspection periods are formerly obtained based on an implicit time dimension of risk.
- Risk mitigation measures are signalled and selected to meet maintenance frequency targets.

RISKWISE™ has the following functionality:

assesses the likelihood and consequence of failure for equipment items and produces an itemised risk and remaining life profile for each plant unit
is convenient to use and can be easily learned as the risk model allows qualitative as well as quantitative input
includes a regularly updated database with all relevant damage mechanisms, as well as guidance on formulating the likelihood or probability and the consequence of failure
allows the user to appraise or focus/defocus the probability and consequence attributes for each component, e.g the level of inspection and maintenance and thus mitigate the risk of loss or optimise the current inspection programme
identifies the most likely damage locations in each component and allows inspection to be properly targeted
determines the risk of failure with time which provides a formal basis for assessing remaining life and hence establishing the maximum period between major inspection outages.

Key features of RISKWISE™ include:

- user friendly software, fully transparent – ensures buy in by users
- uses an audit team approach – accommodates plant experience
- readily interfaces with computerised maintenance management systems
- incorporates a time-based risk auditing module enabling equipment to be ranked by risk and remaining life
- determines inspection/maintenance frequency based on a practical treatment of formal reliability rules - remaining life indicator (RLI) module
- A risk-management or focus/defocus module – facilitates selection of optimum mitigation measures
- fully auditable output – acceptability to insurers/regulators
- suite of products includes application to power generation, pipelines, storage facilities and process plants

The keynote lecture will include a software demonstration illustrating the above features.

CONCLUDING REMARKS

Risk-based approaches are an integral part of holistic asset management aimed at all aspects of improved safety and business performance.

The benefits of risk-based methods for inspection and repair or replacement optimisation are recognised by different industry sectors. However, an industry survey indicates a lack of established and documented uniform RBI policy or guidance for application throughout the industry sectors.

API and ASME guidelines however are based on relatively simple qualitative risk ranking followed by exhaustive quantitative routes, which often involve specialists and significant resource commitment.

Expert judgement is essential in identifying all potential damage mechanisms. In addition to the risk audit itself; RBI/RBM assessment software should lead the audit team to consider all risk mitigation measures, as well as optimal inspection activities.

The requirement to retain application efficiency and user friendliness is an important issue in RBI/RBM software tools. The concept of the Remaining Life Indicator (RLI) incorporated in RISKWISE™ can demonstrate that the single semi-quantitative approach could be sufficient for plant-wide inspection planning as well as establishing risk management measures.

Incorporation of fully quantitative tools in risk-based methods in most cases should be considered only as a refinement in terms of inspection planning although such approaches have their place where the remaining life is critical.

ACKNOWLEDGMENTS

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2.3
Consequence of Failure in the RIMAP[1] Project - Overall Model

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Abstract

This paper will describe the approach to Consequence of Failure (CoF) assessment is performed in the RIMAP project. The CoF method should be a joint approach for risk-based inspection and maintenance. It will cover all consequence aspects, i.e. human safety and health, environmental and business impact. The paper sketches the different CoF elements and how to estimate the different quantities in a practical setting. Furthermore information sources and tools for consequence assessment presented are meant to be used as guidelines/benchmarks to speed up the assessment process in practise. This paper should be seen in conjunction with the Paper "Safety Consequence of Failure for RBMI, concepts from the RIMAP project", ref. /4/ at this seminar.

INTRODUCTION

The RIMAP project (GROWTH Project GRD1-2000-25852 RIMAP) aims to improve current practice to inspection and maintenance planning in European industry and will provide a basis for a European "minimum acceptable" standard for Risk Based Maintenance and Inspection (RBMI). The RBMI approach optimises resource requirement with aspect to improved safety/health and environmental-impact standard and required plant availability. The RIMAP project promotes the risk-concept and communicates the advantages of such a method. The project collects a broad range of industry sectors in order to share experience during the development process, and to hold a cross sectional base for introduction of the European standard.

This paper will address the Consequence of failure (CoF) assessment element of the risk-based methodology. Establishment of Probability of Failure (PoF) and CoF underlies all inspection and maintenance planning using a RBMI approach as the PoF and CoF constitutes the risk for the studied item.

Within the RIMAP project a methodology for assessment of CoF has been generated as well as requirements to the methodology. The RIMAP CoF method should assure Health, Safety and Environmental requirements (legislation) and be able to handle business impact (repair costs, costs due to lost production) in addition. Furthermore should the methodology be applicable to different levels of

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[1] RIMAP is an EU project with the following participants: Det Norske Veritas, Bureau Veritas, Staatliche Materialprüfungsanstalt – Stuttgart, VTT Manufacturing Technology, TÜV Süddeutschland, TNO – Institute of industrial Technology, Hydro Agri (Norsk Hydro), Mitsui-Babcock LTD, ExxonMobil Chemical, Energie Baden-Württemberg AG, Siemens AG, Joint Research Centre of the European Community – Petten, Electricity Supply Board (ESB), Corus, The Dow Chemical Company (DOW), Solvay technology.

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detail of the studied unit and various types of equipment (static (containment), active, safety and instrumental).

The CoF methodology can be used in both screening processes (coarse and conservative) and detailed assessments, where the level of detail can be allowed to be higher. The important thing is however that it is a common methodology for screening and detailed assessment. That ensures a simplified approach to CoF estimation.

CoF method may be built on either descriptive or numerical terms. The proposed RIMAP CoF methodology is mainly numerical as descriptive terms may be misinterpreted and are not as simple to communicate. Numerical values are furthermore less biased from personal judgement and have the same interpretation for one human to another. It is further stressed that the CoF values should be expressed in day to day terms like money, volume, area, etc. that are easy to interpret for the personnel involved.

The objective of this paper is to give an introduction to the RIMAP CoF approach, its requirements and tools and information for assessing CoF.

REQUIREMENTS TO THE RIMAP CoF METHODOLOGY

1. The methodology for assessing the Consequence of Failure should be a procedure applicable (at least) to the industry branches covered in the RIMAP project ((petro-) chemical, steel works, power-industry and offshore oil and gas production). The method should also be applicable for all types of maintainable items (static (containment), active, instrumental and safety) and independent of the item level (plant, system, item etc.) and failure mode detail.

2. Each CoF calculation method that manages consequences that are comprised of legislative requirements, e.g. safety and health, must be validated against an established methodology that is generally being used, accepted and referred to in the open literature. For environmental and business impact there are no overall recognised CoF methodology, even if there are a number of different methods in use. This shows that validation of the CoF methodology for these types of consequences is difficult.

3. It is recommended not to combine SHE and economic consequences as the measure for these are different, and that there are absolute requirements to SHE, whereas economic consequences can be optimised. In any case the consequence assessment must <u>not</u> combine economic and SHE consequences so that the economic consequences leads to reduction in the SHE consequences, i.e. a high SHE consequence must remain high always, even if the economic consequence is low!

4. CoF that are comprised of legislative requirements must always outrank all other consequences. That implies that safety and health consequences comprised by law always are handled first when assessing the risk and working out resulting maintenance and inspection plans.

5. The impact on Safety (acute effects) and Health (long term effects of a short-term exposure) should preferably be expressed in terms of number of injuries and fatalities. Environmental impact should include soil pollution, air pollution as well as pollution of surface and ground water. Business impact should be expressed in monetary values, e.g. Euro.

6. Available CoF methods may differ in level of detail (coarse to detailed) to estimate the consequences. A coarse method should always be conservative compared to a more detailed method.

7. The CoF method should account for initial failure characteristics as well as present circumstances (surrounding population density and ecology, business prerequisites etc.), i.e. should be site specific as opposed to generic.

OVERALL METHODOLOGY

The matrix model of the RIMAP CoF method in Figure 1 describes the outlined consequence classes for which establishment methodologies are explained subsequently. It also defines effect classes for which different tools and information-resources are identified for guidance in CoF estimations. Traditionally SHE issues are dealt with in Risk Based Inspection (RBI), while business impact consequences is usually handled in Risk Based Maintenance (RBM) assessments. That is also illustrated in Figure 2 showing the differences in frequency and consequence magnitude for failures assessed in the different risk based techniques. The RIMAP methodology in Figure 1 provides a complete picture of RBI and RBM CoF considerations in one common view, where both economic and SHE consequences are considered for all classes of equipment in the same decision framework.

HEALTH AND SAFETY METHODOLOGY

The health and safety risk and related consequences are the most important aspects to consider in maintenance/inspection planning. The estimation of consequence effects is thoroughly described and documented in work related to QRA or PSA (Quantitative Risk Assessment & Probabilistic Safety Assessment, see /1/). The basic concept for the consequence part of a QRA is to analyse the event chain;

undesirable event (leak, breakage)

→ dispersion → (ignition) → fire/explosion/toxic (primary) → effect on human/equipment

↘ escalation of the event (secondary) ↗

In the context of maintenance/inspection planning, the aim is to utilise these methods and tools, as well as results, but tailored to the particular need. This has led to the development of *simplified, partly pre-simulated models* ready to use for the practitioners. Examples of such models are described in /2/ and /3/ as well as in the paper "Safety Consequence of Failure for RBMI, concepts from the RIMAP project" /4/ at this conference. A key here is that those models should be more conservative than a more detailed model, and /4/ is setting requirements to the validation of such models. Precaution should be taken when using such models, and the user should know their purpose and limitations. Most of the pre-simulated models do *not* include escalation effects (secondary). Escalation may be important in cases where the equipment is densely packed, and when limited protection systems (segregation) are in place.

The results of the safety assessment will be a quantification of the consequence in terms of either:

- PLL: Potential Loss of life (-)
- Size of the exposed area (m^2)
- A verbally described consequence scale.

Whatever is used, the numbers should be related to the *safety acceptance criteria* applied for the company in question.

ENVIRONMENTAL METHODOLOGY

Environmental consequences include both short-term (cleanup) and long-term effects to the *fauna* both locally and globally. Impact to personnel is covered under the "Health and Safety" part. Environmental effects may receive very high media attention, and result in business impact to the owners more than the "real" value of the damage caused. As mentioned, the purpose of RBMI is to analyse maintenance and inspection, not to do a thorough environmental assessment and it does therefore not replace such assessments. The measure for environmental impact can be monetary values, volumes released, or effect of the spill. As for safety it is believed that environmental consequences modelling in the future may develop into models that in a more precise way rank the true environmental impact - models handy to use for maintenance/inspection planners. The measure should as for safety consequences are related to the acceptance criteria.

The pollution can be divided into the categories presented in Table 1. The cost impact of the pollution is related to:

- Corrective actions that address the consequences of the accident
- Penalty from authorities
- Claims from public parties
- Negative media publicity

A commonly used model to estimate the consequence is to relate the volume of release as the parameter for determining the cost;

$$CoF_{ENV} = C_{FLUID} \cdot V_{\mathrm{Re}lesed}$$

Where the C_{FLUID} is the unit cost considering the remedial actions listed above and V is the volume released.

ECONOMIC METHODOLOGY

The assessments of economic CoF ends in a monetary value as stated in the requirements. The economic consequences can be divided into indirect and direct costs where the operator of the facility controls direct costs while the surrounding business climate and society affect the indirect. Direct costs can be divided in costs due to; production loss (see Figure 3), primary failure (concerning the faulty item) and secondary failures (resulting failures on other equipment). The economic CoF can be assessed by the following formula (parameters explained in Table 2)

CoF_E = Shutdown/start-up costs + Costs of lost production + Repair costs + Costs of spare parts + Costs of secondary repair + Material costs + Indirect cost

$$= C_{sd/su} + C_{LP} + C_{PL} \cdot k_p + C_{PM} + C_{SL} \cdot k_s + C_{SM} + C_{Id}$$

ESTIMATION OF ECONOMIC ELEMENTS:

The estimation of cost items is generally done via cost data from the plant. For cost related to minor repair/events these numbers are readily available from the maintenance and operation department. These will know time for start-up/shutdown, repair time, loss production related to repair for a given failure.

In some cases long-lead items will dominate the time for repair, examples are compressor, turbine parts, large pressure vessels and spare parts for old equipment. In such cases the RBMI assessment should address these issues with the aim to analyse the need for spares of long lead items considering the cost and demand rate.

For larger accidents involving fire, explosions, or large mechanical damage, the costs are outside the normal experience within a plant. These events may require weeks out of service, reconstruction work and maybe redesign of the plant. The costs are obviously plant and event specific. One general model used for estimating cost is Dow Fire and Explosion Index /5/. The model is a correlation between property damage and days outage for a number of cases.

USABILITY

As stated in the requirements the CoF model should always manage items addressed by legislative regulations first. Maintenance and inspection plans are among other things established in order to assure compliance with these regulations. Any of the methods listed in Figure 1 can be used for this as long as the model is validated against a recognised model.

For the assessment of CoF for other maintainable items, with no legislative requirements, it is possible to adapt the CoF estimation models to the purpose. The methods presented above for environmental and business impact assessment defines what should be considered in the assessment. It is, however, evident that also for theses cases a simplified method should convey a higher degree of conservatism.

CONCLUSION/SUMMARY

The RIMAP CoF approach comprises consequence estimation for risk-based inspection and maintenance (RBMI). The consequence estimation is a main theme in the risk-based techniques and a joint methodology will facilitate the establishment of inspection and maintenance plans in the industry. It will also provide a joint terminology bridging the gap between the disciplines. In this paper the RIMAP methodology is presented defining four CoF types; safety -, health -, environmental - and business impact. In the paper usable information-sources and tools for CoF estimation are also presented.

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/4/ Safety Consequence of Failure for RBMI, concepts from the RIMAP project.

J.H.A.M. Heerings, A.J. den Herder, J.E.A. Reinders, TNO Industrial and Safety Technology. 2002.

/5/ Dow Fire and Explosion Index. Hazard Classification Guide, 6th ed. 1987.

Table 1 *Environmental pollution categories*

Pollution category	**Remedial actions**
Soil pollution	Remove polluted soil, implement in situ techniques, insulation of soil pollution
Ground water pollution	Remove polluted soil, implement in situ techniques, insulation of soil pollution
Surface water pollution	Stop intake of (drinking) water, clean floating pollutant, remove polluted sediment, clean polluted water (filtering, oxidation, …)
Seawater pollution	Collection of pollutant, chemical dispersion, cleanup of shore area.
Gas to atmosphere	Stop release.

***Table 2** Explanation of parameters in the economic CoF formula*

Parameter	Explanation
CoF_E	Economic consequence of failure
$C_{sd/su}$	Shut down/start up costs
$C_{DT} = \begin{cases} (t-a) * C_{tu} \forall a \le t \le b \\ 0 \forall t < a, t > b \end{cases}$	Downtime costs
t	Downtime
a	Time from failure to start of loosing production income
b	Time to start-up or Time to insurance, for example, covers cost of lost production
C_{PL}	Primary labour costs/hour
k_P	Amount of hours required for repair of primary failure
C_{PM}	Primary materials costs
C_{SL}	secondary labour costs/hour
k_S	Amount of hours required for repair of secondary failure
$C_{SM} = \begin{cases} \text{Constant} \\ \text{or} \\ v * U_d \end{cases}$	Secondary materials costs
v	Value per destroyed plant unit (m^2, kg etc.)
U_d	Amount of destroyed units (corresponding to v)
C_{Id}	Indirect costs

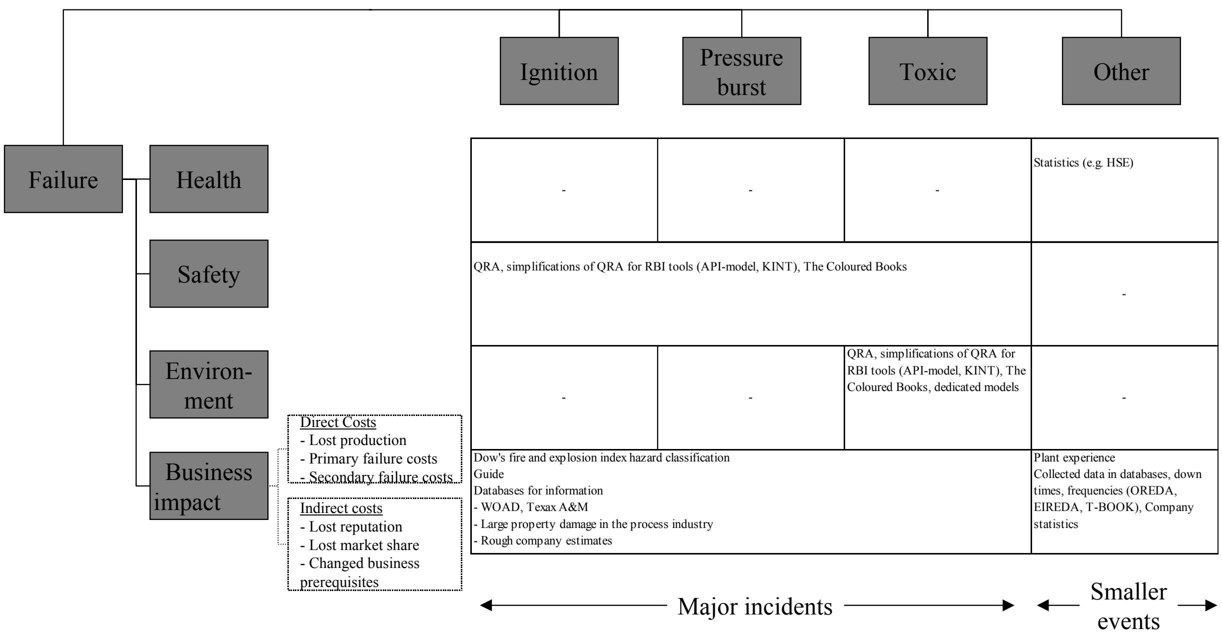

Figure 1 *Matrix model of RIMAP CoF assessment method and with supplementary tools and information sources.*

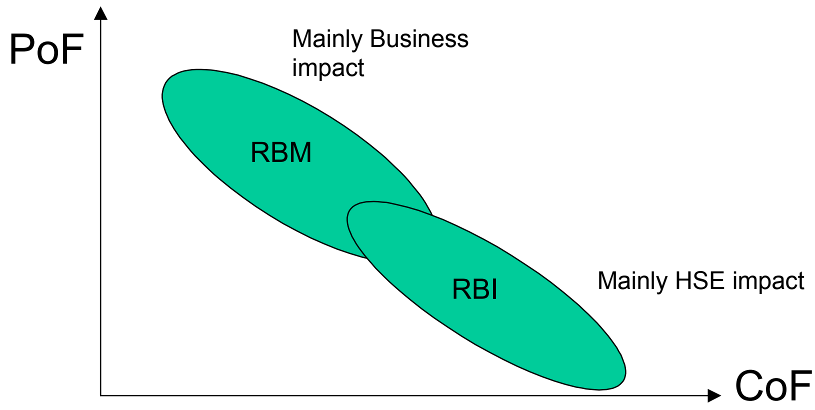

Figure 2 *Differences of RBM and RBI when it comes to failure frequency and consequence magnitude.*

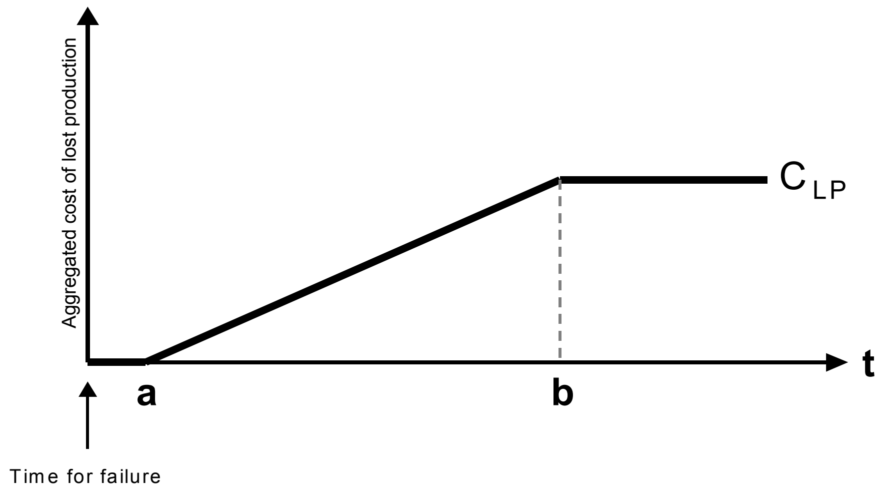

Figure 3 *Schematic illustration of cost of lost production development over time (explanation of parameters in Table 2).*

2.4
Safety Consequences of Failure for RBMI, concepts from the RIMAP project

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Abstract
The RIMAP project is aimed at the establishment of a European RBMI framework including the assessment of the Consequence of failure (CoF). Therefore, a minimum acceptable standard has been defined to set requirements to methods for assessing the CoF. One of the elements of CoF is the impact on safety. The need to validate methods for assessing the safety impact is one of the requirements included in the standard.
In this paper the process of validation is explained. Besides an example of validating the safety aspect is presented and is demonstrated for a number of cases. The demonstration shows that the concept of validation is straightforward and transparent.
Up till now the work in the RIMAP project was limited to containment equipment. In the near future it will be extended to the full range of equipment types, including rotating equipment and safety instrumented functions.

1. INTRODUCTION

The currently running RIMAP project is aimed at establishing a European framework for Risk Based Maintenance and Inspection (RBMI) applicable to all relevant equipment (e.g. containment vessels, rotating equipment, Safety Instrumented Functions) in the chemical, petrochemical, power industry and steel works.

One of the tasks of the project is developing the methodology for assessing the Consequences of Failure (CoF). According to common understanding, the Consequence of Failure is composed of one or more of the following aspects: safety impact, environmental impact and financial impact, e.g. business interruption.

The European methodology is not intended to replace the variety of existing methods and should therefore not be considered as the only acceptable method. On the contrary, the European methodology should allow the use of as many methods as possible. Its main purpose is to set a minimum acceptable standard. A number of requirements have been defined including the need to validate methods for assessing the safety impact. In this paper the process of validation is explained. Besides a worked example of validating the safety aspect is presented and is demonstrated for various cases.

Although other aspects of CoF, like environmental impact and business interruption, will be included in the European methodology, this paper concentrates on the safety consequence. Besides, this paper is directed to containment equipment whereas extensions to other equipment types, including rotating equipment and safety instrumented functions will be elaborated in the RIMAP project shortly.

2. REQUIREMENTS TO CoF METHODS

In order to set a minimum acceptable standard for ‘CoF methods’, the following requirements have been defined:

1. Each consequence calculation method must be validated against a generally recognised (established) methodology, which is generally being used and accepted and referred to in the open literature;
2. At least the aspects Safety, Health and Environment must be included;
3. The consequence rating must be such that the highest rating for one of the individual aspects Safety&Health, Environment and/or Financial consequences must control the final score in order to prevent averaging of the ratings for various aspects.

4. This provides a guarantee that neither the rating for the Business (Financial) impact nor the Environmental impact can lead to a reduction of the ratings for the Safety&Health impact;
5. The validation must be carried out for the Safety aspect only. The Health and Environmental aspect has not to be validated because no generally accepted 'reference method' is available. Besides, business impact does not need to be validated because this aspect has no relation to the assurance of HSE;
6. Both descriptive judgements and numerical analyses may be used. The use of descriptive terms ranging from very high to very low is acceptable providing the meaning of these terms is defined. The impact on Safety (acute effects) and Health (long term effects of a short-term exposure) must be expressed in terms of number of injuries and fatalities. Environmental impact must include soil pollution, air pollution as well as pollution of surface and ground water;
7. Available methods for estimating CoF may differ in the level of detail to estimate the consequences. A simple (less detailed) method must be conservative (yield into higher impact ratings) compared to a more detailed method. So, less detail should always lead to more conservatism (resulting into a higher estimated impact);
8. Methods must not only take account of source aspects (e.g. the fluid characteristics) but also include target aspects (e.g. density of surrounding population).

In this paper the process of validating the safety aspect is explained and is demonstrated for various practical cases.

3. VALIDATION OF CoF METHODS

Process of validation

The validity of a given method is demonstrated by means of a comparison between the results (scores) of the method under consideration and those from the 'Reference method'. The method under consideration is considered valid if the results (scores) of the method prove to be more conservative (the consequences are estimated higher) than those from the 'Reference method'.

The Safety consequence should be calculated for a number of individual components. The group of selected components determine the field of application for which the validation applies to, e.g. offshore, pipelines.

The validation is directed to the aspect of Safety. The Safety consequences (injuries and fatalities) are caused by release of fluid. They depend on the type of fluid and the energy contained in the system. The number of fatalities and injuries is determined for each component assuming various scenario's for the release and dispersion of the fluid.

'Reference method'

The internationally accepted methods, which are generally being used for the calculation of physical effects [1, 2] have a common basis. This basis enables the modelling of scenario's which are composed of the following subsequent events:

a) release of the fluid (Loss Of Containment):
   The release of fluids can be instantaneous, or by leakage through a hole. The release rate is dependent of the pressure, fluid type, etc.
b) dispersion of the fluid:
   The dispersion can be by evaporation, flashing, etc. The dispersion is dependent of the atmospheric conditions, temperature, fluid type, etc.
c) physical effect:
   The physical effect is calculated as a function of time and place. The physical effect can be divided into three types:
   1. flammable effects resulting in: heat radiation, overpressure and a flash fire zone;
   2. toxic effects;
   3. overpressure caused by the release of a non toxic, non flammable fluid.
d) damage to people:
   The probability of death or injury of people resulting from exposure to the physical effect is calculated taking into account the density of the surrounding population.

Various combinations of events as categorised in a, b and c may lead to different so-called 'flammable outcomes'. Typical flammable outcomes are fireballs / BLEVE (Boiling Liquid Expanding Vapour Explosion), jet fires, pool fires, flash fires and explosions / VCE (Vapour Cloud Explosion). Obviously, a scenario may also refer to a pressure release without any flammable or toxic effect, e.g. due to a pressure burst in a steam vessel.

4. Example of validation

For purpose of illustration, a particular CoF method to be validated as well as a particular 'Reference method' have been selected. The CoF method chosen is the 'KINT'-methodology. As a reference the official Dutch guidelines for quantitative risk assessment were used.

4.1 'KINT'-methodology

The 'KINT'-methodology has recently been implemented in the Dutch Regulations for Pressure Vessels [3, 4]. This methodology deals only with the safety aspect and is restricted to the application area of containment equipment.

The 'KINT'-methodology is depicted in the flowchart in Figure 1.
The flowchart starts assessing the flammability effect and the toxicity effect. The assessment of toxicity and flammability are based on the Fire Protection Guide on Hazardous Materials [5] and the Dow Fire & Explosion Index, Hazard Classification Guide [6].
The 'pressure energy effect' is included to assess the potential energy stored in a containment under pressure.
The assessment of flammability, toxicity and pressure energy results into a categorisation in class I to III for the 'Damage distance'. These classes are defined as follows:

- Class I: 100% lethality within 36 metres
- Class II: 100% lethality within 120 metres
- Class III: 100% lethality within 300 metres

In fig. 1b it is shown how the target terms are included and are combined with the Damage distance in order to arrive at a number of fatalities. The resulting number of fatalities is categorised into the classes A-E for the Safety consequence.

<u>Example of how to transfer a Damage Distance class into a Safety Consequence class</u>

- Suppose that based on the toxicity, flammability, etc. the piece of equipment is categorised as Damage distance class I, which means 100% lethality within 36 metres.
- Suppose within a distance of 36 meters 12 persons are present for 25% of a day (being 24 hours). This results into a consequence of 3 fatalities being 100%*12*25%
- Suppose category C represents 2-10 fatalities.
  The Safety consequence is then categorised as C.

4.2 The selected 'Reference method'

The 'Reference method' used is the official Dutch guidelines for quantitative risk assessment, named CPR 18E ("Purple Book") [7]. These guidelines are based on 2 decades of research. Much of this research is condensed in three other 'coloured books', representing different aspects of a Quantitative Risk Assessment (QRA):

- CPR 12E – methods for determining and processing probabilities ("Red Book"), [8]
- CPR 14E – methods for the calculation of physical effects ("Yellow Book"), [9]
- CPR 16E – methods for determination of possible damage ("Green Book"). [10]

Typically a QRA of a facility would contain the following steps:

1. Selection of installations;
2. Selection of Loss of Containment (LOC) events or scenarios and assessing their frequencies;
3. Determination of physical effects (like release phenomena, evaporation, atmospheric dispersion, explosion pressures, heat radiation) and assessing their frequencies;
4. Determination of potential damage (mortality, injury, structural damage) and assessing the corresponding probability.

The coloured books can be considered a standard for QRAs. Many of the commercially available tools (usually software) for QRAs are based on these coloured books. One of these is the software package 'EFFECTS' [2], which is used for most of the calculations reported here. TNO has performed many QRAs based on the coloured books, not only in the Netherlands, but also in Spain, Canada, France, Belgium, Greece (just to name a few) As these books as well as the software are sold to many more countries (at the rate of a few hundred copies a year) it can be assumed that QRAs according to the coloured books are carried out in many more countries. Therefore, this method can confidently be labelled 'Reference method'.

4.3 Results

In the worked examples described in this chapter no attempt for a complete QRA (for e.g. a plant) was made. A limited selection of installations and scenarios was used to demonstrate the validation exercise. Examples from power and process industry are given representing 'pressure burst', toxic and heat hazards.
The following installations were selected:

- LPG (propane) tanker representing a typical flammable hazard
- Chlorine evaporator tank representing a typical toxic hazard
- Steam drum, 1 m^3 content representing a low energy burst (non flammable, non toxic)
- Steam drum, 51 m^3 content representing a high energy burst (non flammable, non toxic).

For each of these cases, the safety consequence is calculated according to both the 'KINT'-methodology and the 'coloured books' (the software package 'EFFECTS').

In Figure 2, the results are only illustrated for the last case, the 51 m^3 steam drum.
Results are presented by means of the following graphs:

a) Percentage mortality-distance: The effects and consequences of each accident scenario will reach a certain distance. Here we have chosen the likelihood of a person (at ground level) a certain distance away from the accident scene to get killed once the accident has occurred.
b) Societal risk curve (fN-curve or group risk curve). This is the probability per year that a group of people of a certain size will be killed as a result of the (industrial) activities under consideration. An fN curve is frequently used by local authorities for (spatial) planning purposes. Population density is a required input for fN-curves.

In the legend of the graphs, the 'KINT'-methodology is referred to as 'CoF method NL'.

It is worth emphasising that a QRA involves the assessment of both the consequence of failure (CoF) and the probability of failure (PoF). The purpose of the current work is the validation of the CoF. However, to create an fN-curve a probability value is required. Therefore a value of PoF was assumed (based on the 'Purple book') for the calculations of the fN curve. The same PoF was used for the 'KINT'-methodology. In essence, though, the value of PoF is irrelevant for the current validation exercise.

Table 1 summarises the results of all cases as far as Consequence of Failure is concerned [11]. Obviously, the absolute value of the number of fatalities is dependent on the selection of various input data. For instance, the population density is selected to be 5 persons/ha. outside a distance of 25 m from the location of release, which can be considered representative for an industrial area with low personnel density. In order to take account of the varying presence of people, it has furthermore been assumed that that (a) for the chlorine and steam cases this personnel density applies for 8 hours a day, and (b) for the LPG case filling will take place during only 4 hrs/week.

In order to demonstrate conservatism in the CoF method to be validated, the scenario with severest consequence should be considered. This would be a total collapse of the vessel resulting in an instantaneous and complete release of the full contents. It should be emphasised that this is an extremely unlikely scenario. In a full risk analysis this factor would be taken into account resulting in actual annual fatality probabilities several orders of magnitude lower than the values reported in table 1.

The results demonstrate that for all selected cases the ‘KINT’-methodology predicts a higher number of fatalities than the ‘Reference method’. This is a strong indication for the validity of the ‘KINT’-methodology when applied to the area for which the selected cases are representative.

However, the work reported here can by no means be considered as a full proof validation. This would be a much more elaborate exercise, in which more aspects would need consideration.

The following considerations are illustrative:

- The use of discrete classes to express the consequence. The discrete character of classes results into a certain conservatism in order to assess the range of cases within each class. This may result in a change from one class to another when only small changes in certain parameters (e.g. volume of substance) are made. The ‘Reference method’ is continuous and incorporates this factor. For this reason the validation should also include cases representing the boundary conditions between the classes.
- The use of a certain population density against distance. In the reported cases an evenly distribution has been used outside a distance of 25 m, which implies that the density is constant against the distance. Yet, in reality the density may increase due to the surrounding population living at a certain distance from an industrial site.

In order to deal with this kind of issues, the number, type and range of cases as well as the input data should be selected with great care.

In general, part of the validation outcome should be the identification of the validity window including the application area or other boundary conditions that need to be taken into account.

Somewhat philosophically one could argue that the larger the application area one wishes to cover with a particular method the larger the level of conservatism one needs to allow for. Therefore, a sound balance should be found between the extent of the application area and the level of conservatism.

5. CONCLUSIONS

From the demonstration of the validation process, the following conclusions can be drawn:

- The prescribed validation process shows clearly the result in terms of a number of fatalities calculated from the methodology to be validated in comparison with the chosen ‘Reference method’;
- The validation can be carried out in a straightforward and transparent way.

The presented demonstration was directed to the application of containment equipment only. However, the objective of the RIMAP project is that the CoF methodology will apply to the full range of equipment types, including rotating equipment and safety instrumented functions as well. In addition, the methodology should be of use to various industry sectors: chemical, petrochemical, steel manufacturing and power industry. Obviously, this paper didn’t cover this full range. In the near future, these extensions will be elaborated to achieve this objective.

6. ACKNOWLEDGEMENTS

The support of the European Commission to the RIMAP (Contract GROWTH Project G1RD-CT-2001-03008 “RIMAP”) is gladly acknowledged and appreciated here. Furthermore, the results presented were also obtained thanks to the help of partners in the RIMAP RTD project: *Bureau Veritas, Corus, Det Norske Veritas DNV (Coordinator), DOW Benelux, EnBW, ExxonMobil, Hydro Agri Sluiskil, JRC, Mitsui Babcock, MPA Stuttgart, Siemens, Solvay, TÜV Süd and VTT.*

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Tables

Table 1 *Results of validation*

	Number of fatalities (1)	
	'KINT'- methodology	'Reference method'
LPG (propane) tanker	7	5
Chlorine evaporator tank	46	31
Steam drum, 1 m^3 content	1	0
Steam drum, 51 m^3 content	14	8

Footnote 1:
Obviously, the values depend on the selected input data. For instance, a personnel density of 5 persons/ha was assumed and a total collapse of the containment was postulated. It is important to realise that the ONLY purpose of this exercise was to demonstrate the relative conservatism in the CoF prediction by the 'KINT' - methodology, even for the highly unrealistic scenario of an instantaneous release of the full contents after a total collapse of the vessel. In reality annual fatality probabilities are several orders of magnitude lower.

Figures

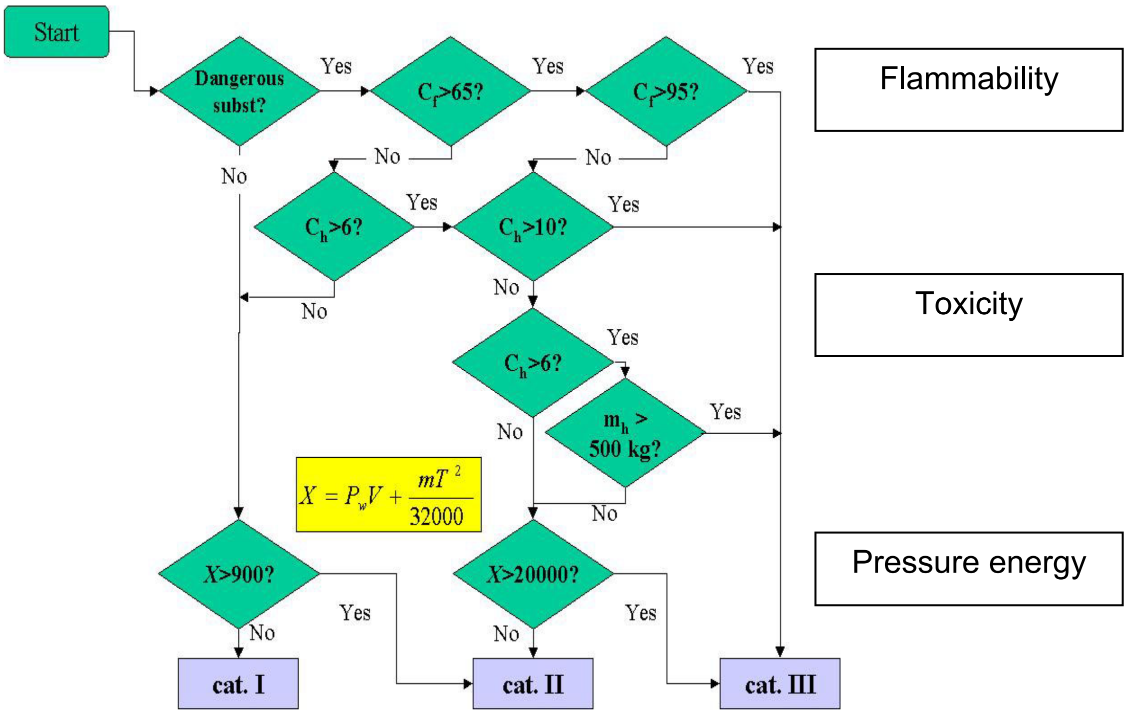
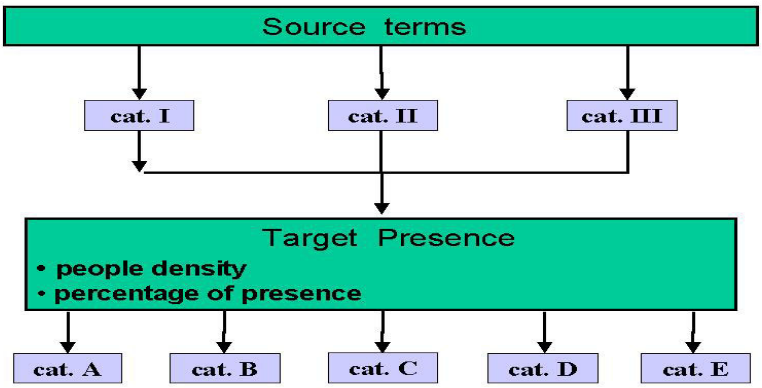


***Figure 1 a**, First part of the 'KINT' method, resulting in categories representing damage distances. **b**, Second part of the 'KINT' method, resulting in categories representing a certain number of fatalities.*



.

In Figure 1a the following parameters and terms are used:

Dangerous substance	*any substance that is combustible (Nf>1), toxic (Nh>1) or extremely toxic (Nh>4) according data on substances, which are mainly taken from [6] and set out in [3].*
C_f	*combustibility number according to the formula below*
C_h	*toxicity number according to the formula below*
P_w	*working pressure in bar*
V	*volume van the quantity vapour or gas in m3*
M	*mass of the liquid heated above the boiling point in kg*
T	*superheating above atmospheric boiling point in °C (Tw - Θ b,a)*
M_h	*mass of toxic substance in kg*

The formula's for the calculation of the toxicity number c_h and the combustibility number c_f are as follows:

combustibility number $c_f = N_m(1+k_e)*(1+k_\vartheta+k_v+k_p+k_c+k_q)$

toxicity number $c_h = N_h(1+k_\vartheta+k_v+k_p+k_c)$

in which the parameters are defined as follows:

N_m	*flammability index; substance data according to the table in [3]*
N_h	*health index; substance data according to the table in [3]*
K_e	*enclosure penalty*
K_ϑ	*temperature penalty*
K_v	*vacuum penalty*
K_p	*pressure penalty*
K_c	*cold penalty*
K_q	*quantity penalty*

More details about calculation and definition of the parameters are available in [3].

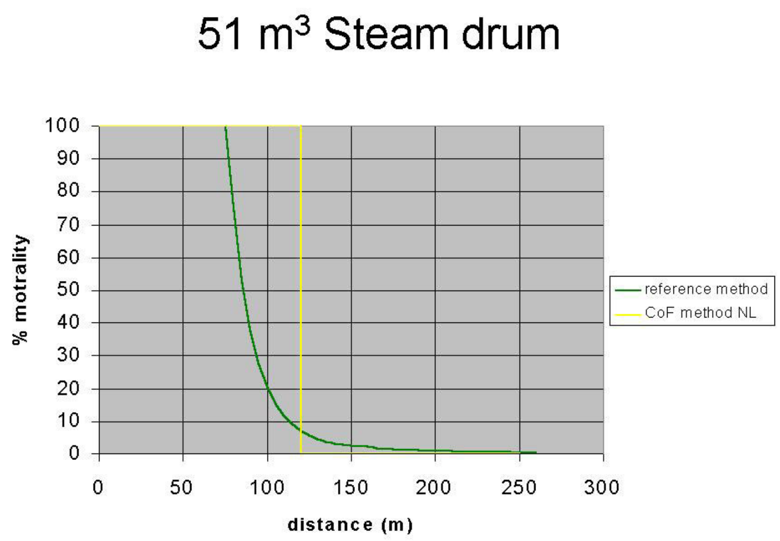
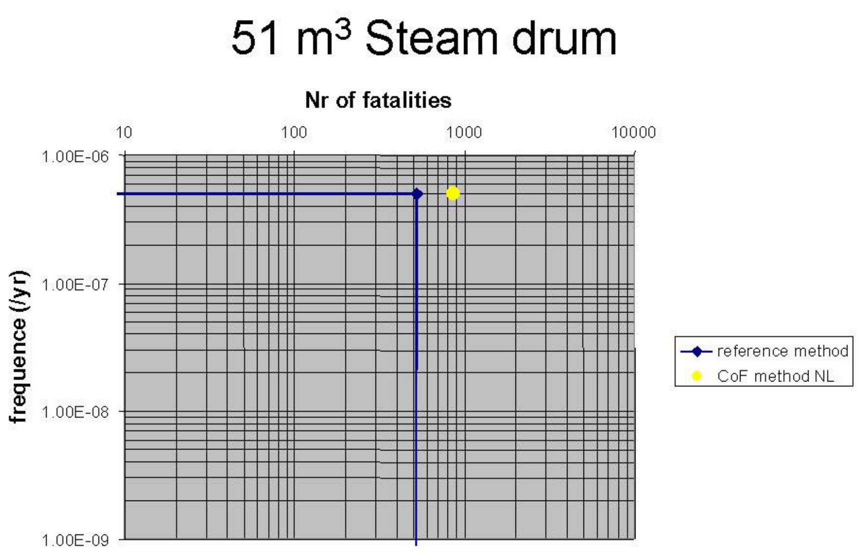


__Figure 2 a__, Percentage of mortality against distance. __b__, Societal risk curve.



2.5 ABSTRACT

Risk Acceptance Criteria and Regulatory Aspects

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Abstract

By applying risk based inspection and maintenance strategies an often asked question deals with the acceptance criteria and the involvement of regulatory aspects.

In the paper several acceptance criteria will be presented. So, risk related acceptance can be driven by SHE-(Safety, Health, and Environment) aspects (consequence related), by failure related issues (reliabilty related) as well as directly by the determined risk. Hence, it is possible to introduce economical aspects.

Due to the fact that it most cases accepted risk values are not given some accepted methods will be presented (e. g. Dutch reference method).

If safety issues are included in the analysis, regulatory aspects will be affected. Here, the influences of a changing European surrounding (PED, new national ISI directives based on PED) as well as the required depth and quality of risk analysis will be discussed.

3.1
Integrated Operational Risk Management in Power Plants

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Abstract

This paper describes the development of an integrated risk management framework for the management of operational risks in power plants. The integrated framework provides a closer linkage in managing various operational risks and business processes, and thereby produces a better decision-making tool. The use of the Scenario-based assessment in the determination of operational risks in the coal-fired Castle Peak Power Station and gas-fired combined cycle Black Point Power Station is also given. The profile represents a simple, straightforward, semi-quantitative template for comparing the magnitude of potential risks and effectiveness of control measures.

1. INTRODUCTION

The worldwide power generation business has gone through significant transformation in recent years into an era of reforms and competition. Improving financial performance and increasing operational efficiency are among the highest priorities during this transformation. Standards of quality control and safety may come under pressure as a result. In the worst-case scenario this could result in major property damage which could impact the Company's financial health, and limit its ability to react to the needs of its customer. Another possible impact is the effect that negative public perception may have on a company. The soft cost can be significant as the perception can reduce investor confidence and offset many years of "goodwill" by the company.

In order to minimise the possibility of the worst scenario happening, the following four key issues need to be addressed well.

i) Safety - the power plant must not pose unacceptable safety risks to its own workforce and the surrounding population.
ii)Environmental - all the legislative requirements on air emission, water discharge, waste management and noise must be fully met.
iii) Security of Supply - the power plant must be able to generate flexibly and reliably to meet demand.
iv) Cost Effectiveness - the electricity must be generated at an attractive competitive price.

Allocation of the most cost effective resources and balancing the risks and benefits on these issues are most challenging. Adoption of systematic and sound risk assessment and management process in the organization becomes essential in managing these risks. Various qualitative and quantitative techniques are available with different degrees of sophistication. Common techniques such as What If, Preliminary Hazard Analysis (PHA), Hazard and Operability Assessment (HAZOP), Failure Mode and Effects Analysis (FMEA), Reliability-central Maintenance (RCM), Risk-based Inspection (RBI) are well known. Each of these techniques has its own merit for a particular application.

As a responsible utility, CLP Power strives to provide cost effective and reliable electricity supply with the highest safety standard and due regard to the environment. An integrated risk management framework combining the engineering risk assessment, business process and management systems were developed. The integration provides a closer linkage in managing various operational risks and business process, and thereby produces a better decision-making process.

This paper describes in detail the integrated framework. The use of Scenario based assessment in the determination of the operational risks in the coal-fired Castle Peak Power Station and the combined cycle gas-fired Black point Power Station is also given.

2. INTEGRATED RISK MANAGEMENT FRAMEWORK

Risk management involves the systematic identification, risk significance evaluation, and control of potential losses that may arise from uncertain problem events, such as fires, explosions, mechanical/electrical failures or natural disasters. Whether resulting losses are measured in terms of direct costs, impacts on employees or the public, property damage, combining the losses and the possibility of experiencing such losses is considered as a risk. The practice of risk management permits contractors, employees and managers to anticipate such losses and to evaluate their potential impacts, so they can be managed in an effective manner. Thus, risk management is a practical instrument, which can assist in business decision-making in the face of uncertainty.

CLP Power's Generation Business Group (GBG) integrated risk management framework, which was developed with a close linkage between the everyday operation of our business, our people and management systems, is shown in Figure 1.

The risk management framework consists of three major levels. The first level includes various department and working group risk assessment activities. Engineering risk assessments such as PHA, HAZOP and FMEA are performed at key stages of power plant creation, utilization and disposal. Participation of operation and maintenance personnel is important in these assessments. Re-HAZOP of plant systems containing hazardous materials is carried out in a periodic basis, with the aim to re-check the mitigation effectiveness of both process and EHS risks. For large projects, high-level project risk assessment is normally carried out during the project planning stage to highlight vulnerable area for a project execution. Job safety analysis is performed on individual operational task or maintenance task. Procedural HAZOP is also applied on changes in unit start-up or shut down operational procedures. Periodic drills are carried out to exercise the effectiveness of emergency team coordination and our means in handling crises.

The second level covers the broader aspect of managing operation risks. The performance of the power plant to generate electricity safely, reliably and cost effectively, at a certain extent, depends on the understanding and the decision making in addressing the following issues:

- how safe is safe
- how environmental control measures are applied
- how well the major fuel input (coals, natural gas) is managed
- how flexible the operation and maintenance strategies and practices are in response to the changes of market conditions
- how effective the equipment changes are managed
- how well a dynamic and flexible workforce is constantly maintained
- how mature the structure behaves as a learning organisation
- how much new investments are placed for new technologies

In GBG, various committees have set up at both middle and senior management levels to steer the direction, approves strategy and periodically review the progress made in addressing the above issues. In the risk-informed process, critical issues are apparent, significant resources can be allocated and the 'best' decision can be made.

The Power Plant Risk Profile, which is shown at the third level of Figure 1, covers the overview of Environment, Health and Safety (EHS) risks and the operation risks that result in the loss of generation. The profile is produced through a series of Scenario-based risk assessments. It is developed with inputs from project engineers, operation, maintenance, SHE practioners and technical specialists. It is a live document that can be used at any time, from asset inception through abandonment (most useful during operating stage). The information represents a simple, straightforward, semi-quantitative template on the magnitude of potential risks and its control measures effectiveness. More details are given later.

Human error can be an important source of risk (see Figure 2), and risk analysis often points to positive changes in overall management procedures and practices. The integrated framework would ensure that the human error would be taken into consideration in the Job Safety Analysis, Engineering Risk Analysis and the Incident Reporting, Investigation and Analysis.

A good management system is required in addition to the equipment and people aspect for continuous risk mitigation process. Operating Integrating Management System (OIMS) originally developed by ExxonMobil was adopted in GBG. The system consists of 11 elements (see Figure 3) with 60 management expectations in the area of safety, environmental and health performance. The system requires a complete set of system document, working procedure and instruction for our daily work in the field. Routine verification and peer review are also carried out to ensure each system is working in line with the management expectations.

3. POWER PLANT RISK PROFILE

The Power Plant Risk Profile (also known as GBG Risk Profile internally) was developed to produce an inventory of EHS and loss of generation risk in Generation assets. It documents the failure scenarios that may or may not happen, together with the corresponding risk mitigation measures. Such information is essential for management and employees to understand the major scenarios that can put the power plant operation at risk, and they could assess the effectiveness of the mitigation measures.

The technique to generate the Risk Profile, which is based on the continuous process, involves few key steps as shown in Figure 4.

The matrix in Figure 4 defines the internal view of acceptability of risk. Unacceptably high risk (H in Figure 4) can be reduced to a tolerable level by improving prevention (reducing probability) or improving mitigation (reducing consequence).

Typical examples for reducing risk by either prevention or mitigation are :

Prevention	Mitigation

• Improve design or provide 'redundancy' in control systems
• Establish/enforce operating practices and procedures
• Tighter control of ignition sources
• Increase testing of critical safety equipment
• Enhance safety awareness and improve communications
• Impose operation constraint: weather, capacity, routes
• Training
	• Facilities/Equipment relocation
	• Improve detection of leaks and fire
	• Reduce inventory of hazardous material
	• Enhance fixed fire fighting equipment
	• Improve spill containment
	  – Add isolation valves
	  – Improve secondary containment
	• Develop and effectively implement emergency response plans

In an extreme case, risk financing by means of insurance is the only alternative. It requires continued operation review until corrective actions are taken. For undesirable medium risk (M in Figure 4), cost benefits can be used to assist the decision-making. No further action is normally required for the acceptable level of low risk (L in Figure 4).

3.1 Castle Peak Power Station

Castle Peak Power Station (CPPS) is situated at Tap Shek Kok in Tuen Mun of Hong Kong. The Station has a capacity of 4,110 megawatts (MW) and has undergone several changes through the years as it moves forward to fulfill its mission of serving the Hong Kong community in the best possible way.

"A" Station, housing four generating units of 350MW each, was built between 1982 and 1985. "B" Station, which houses four larger units generating 677.5MW each, was in operation in phases since 1986.

Figure 5 shows the profile of risk in the Castle Peak Power Station using Scenario-based assessment.

Based upon the method mentioned in Section 3 above, a total of 164 scenarios were identified for the whole station. 61 high, 98 medium and 5 low risk scenarios were prioritised assuming no control measures were in place. After assessing the risk control measures, all high risk items were reduced to zero, 63 medium and 101 low risk items remaining. In each scenario, the type of control measures and responsible parties are documented and their effectiveness are reviewed and updated yearly (see Figure 6 for a typical example). The following bring out two examples of major scenarios considered and the corresponding key control measures.

Boiler tubes leak - Implement the engineering polices for inspection frequency of vulnerable areas and the launch of Boiler Tube Leak Reduction Programme.

Generator gas explosion - Conduct engineering risk assessment as per plan and follow routine gas instruments calibration in preservation of generator seal oil system integrity.

3.2 Black Point Power Station

Black Point Power Station is situated in northwest New Territories, four kilometres north of the nearby CPPS. It is the first natural gas-fired plant in Hong Kong.

With a planned total capacity of 2,500MW, consisting of eight units of 312.5MW each, BPPS is being built in phases. The first unit commenced operation in 1996 and completion is planned in 2006. It is one of the largest natural gas-fired combined-cycle power stations in the world.

The station utilises natural gas - a clean burning fuel that leaves no ash and produces negligible sulphur dioxide - and employs some of the most advanced technology yet developed in the power industry in respect of equipment and operating systems.

Figure 7 shows the profile of risk in the Black Point Power Station using Scenario-based assessment.

A total of 110 scenarios were identified; 39 high, 69 medium and 2 low risk scenarios assuming no control measures were in place. In contrast, with presence of effective control measures, all high risk items were reduced to zero, 34 medium and 76 low risk items remaining. The following bring out two examples of major scenarios considered and the corresponding key control measures.

Gas turbine combustion components failure - In addition to the planned inspection, development of central dynamics monitoring tools to monitor the change in dynamics and temperature spread during mode transfer.

Generator rotor end-winding insulation deterioration - Condition monitoring and outage inspection according to the best practice, formulation of contingency plan to minimize impact of forced outage

4. CONCLUSION

A comprehensive and integrated risk management framework has to include management of people performance, plant and equipment and management systems so as to miminise potential threats to the business and thus controlling risk. Engineering risk assessment, incident investigation and OIMS play important parts in the integrated risk management framework. The success and implementation of the framework is attributed to the commitment and leadership from management, dedication of the work teams and on-going feedback mechanism.

ABOUT CLP POWER

CLP Power is the largest electric utility in Hong Kong serving the business and domestic community in Kowloon, the New Territories, Lantau and most of the outlying islands. Operating a vertically integrated electricity generation, transmission and distribution business, CLP Power provides a highly reliable supply of electricity and excellent customer services to over two million customers in its supply area.
Web site: http://www.clpgoup.com/

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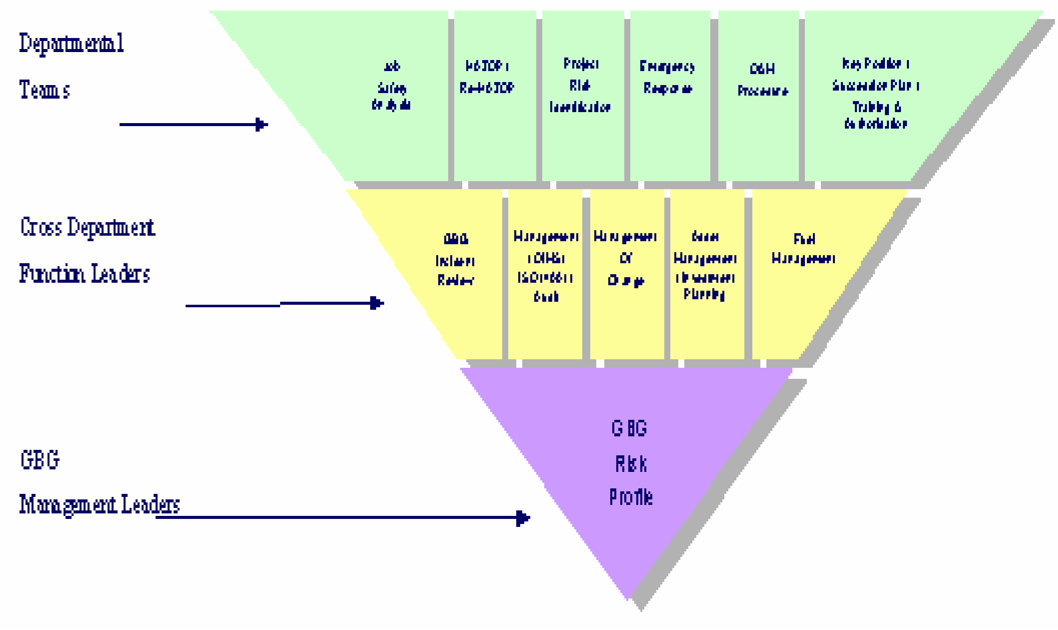


Figure 1 *Integrated risk management framework.*

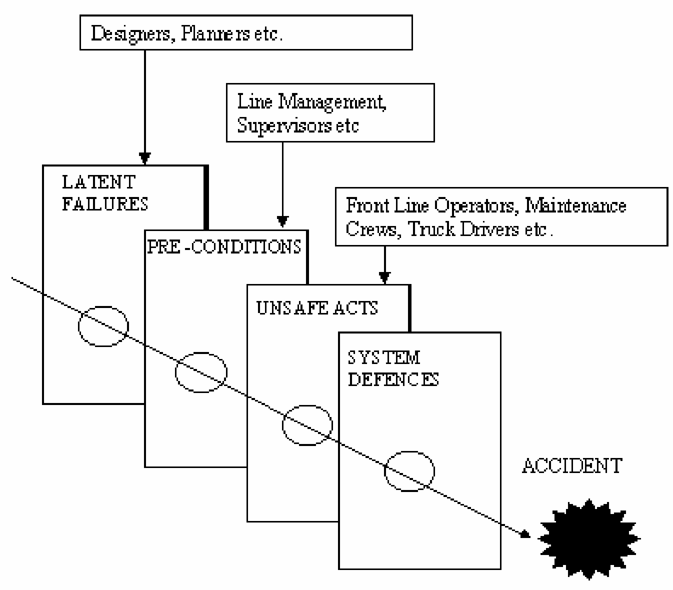


Figure 2 *Human factor contribution to accident.*

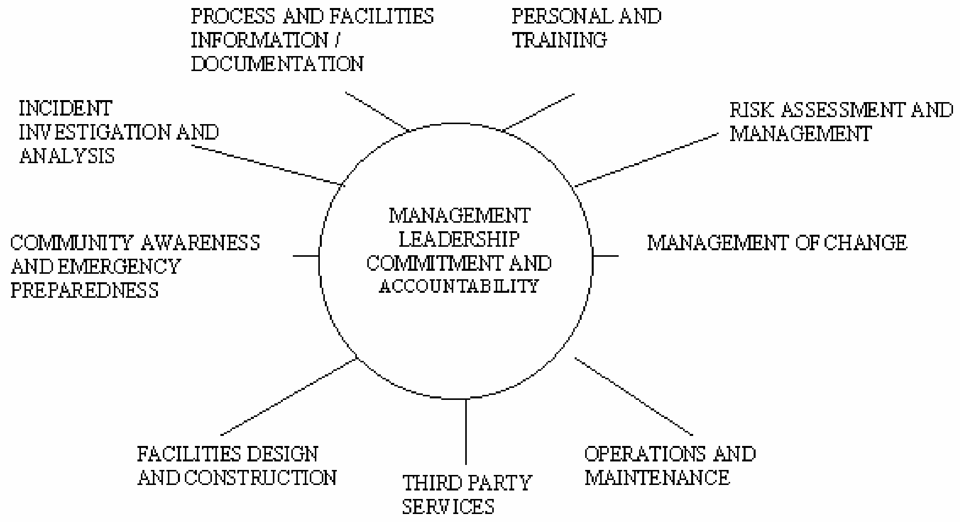


Figure 3 *Operating Integrating Management System (OIMS).*

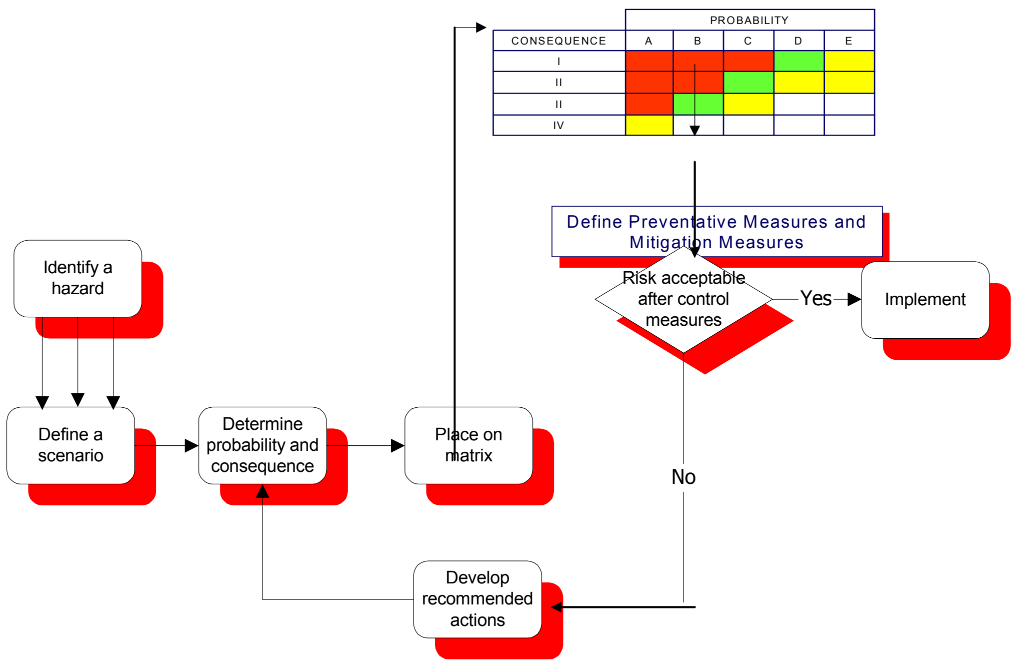


Figure 4 *Process for generating power plant risk profile.*

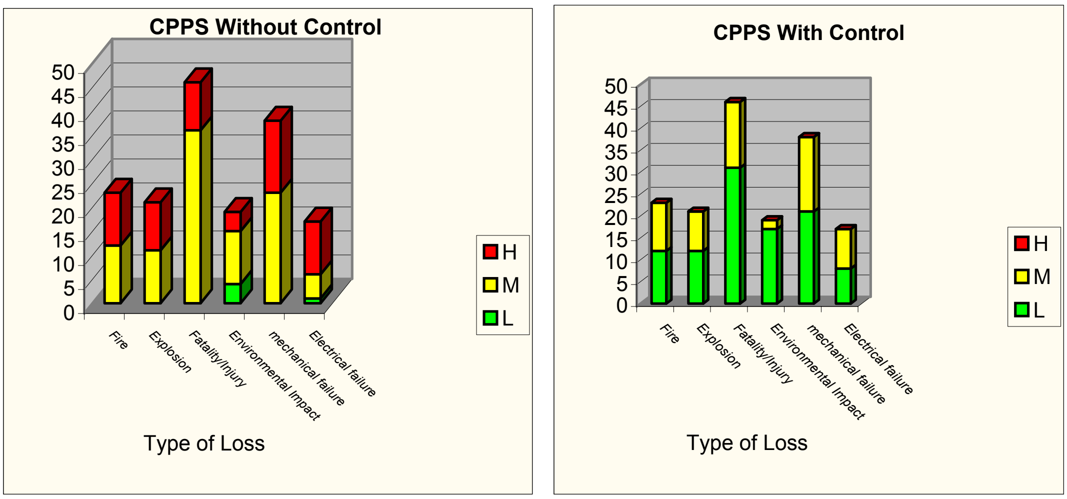


Figure 5 *Distribution of risks at Castle Peak Power Station.*

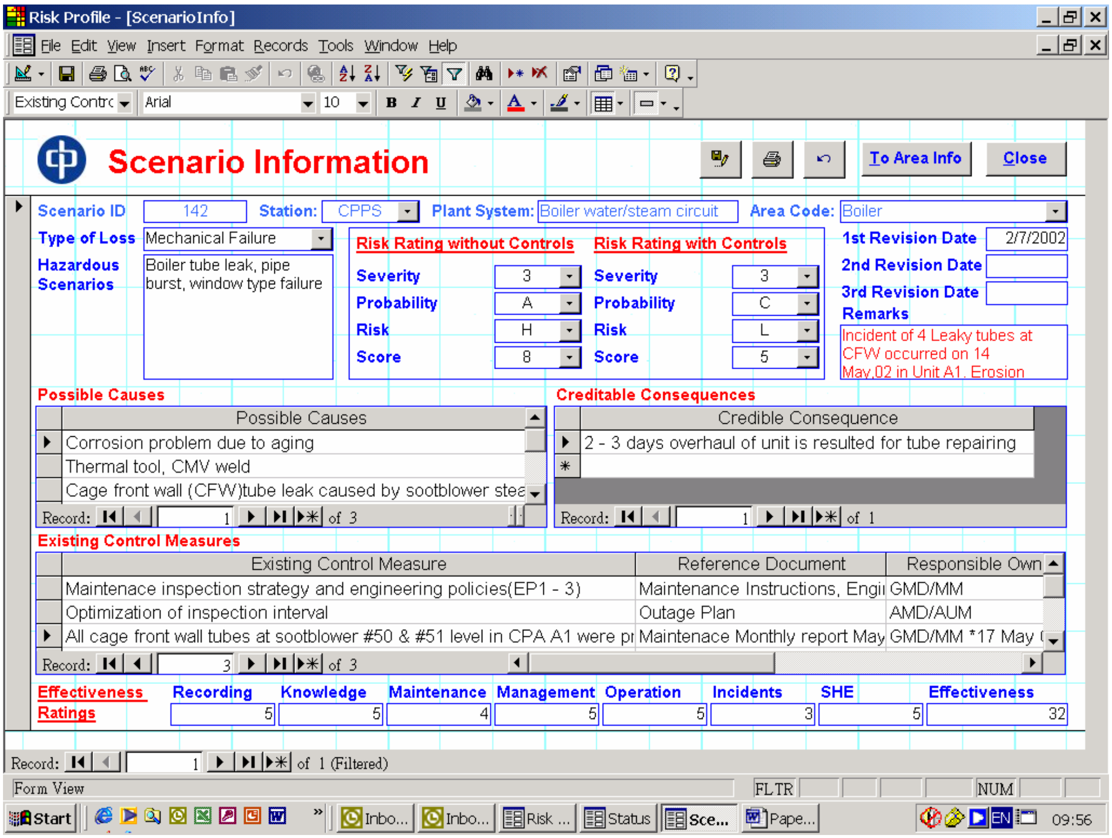


Figure 6 *A typical scenario information extracted from the Power Plant Risk Profile.*

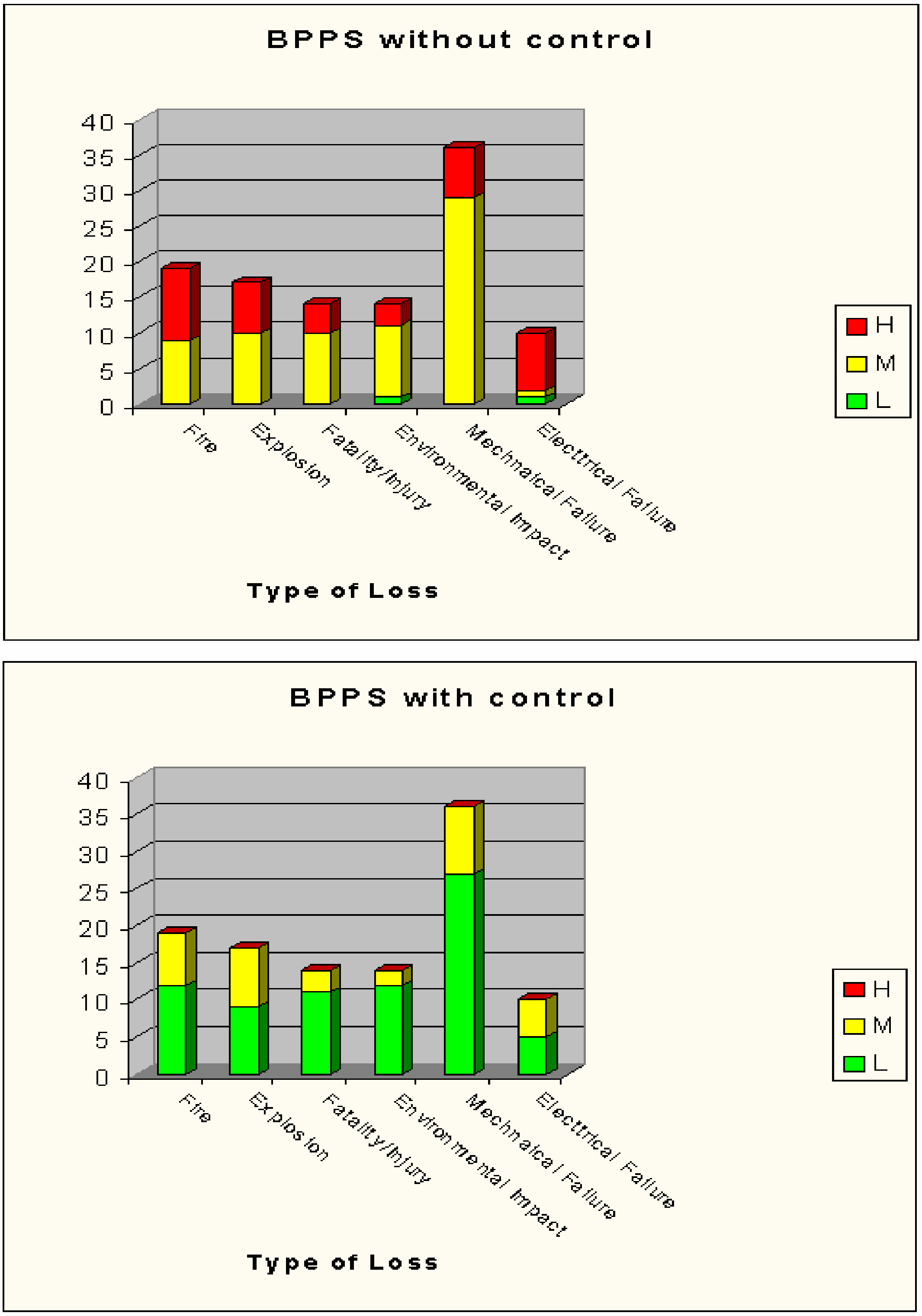
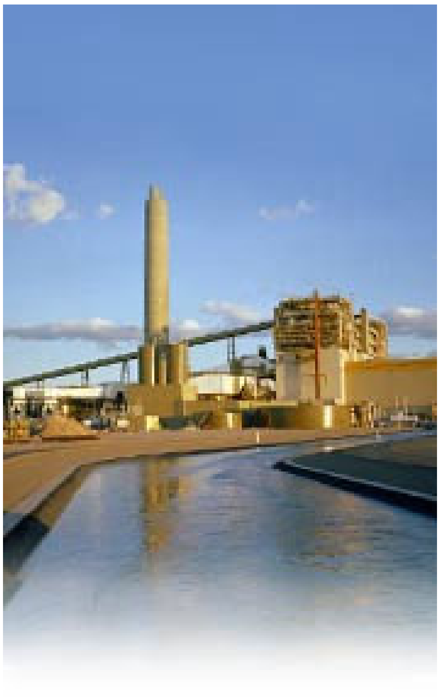


Figure 7 *Distribution of risks at Black Point Power Station.*

3.2
Risk Assessment at a Coal-Fired Power Plant

Mark DeCoster
EPRI, USA
Bill Beck
Salt River Project, USA

Abstract



A pilot project was performed to evaluate a particular risk analysis technique at a coal-fired power plant. The technique, which was previously applied in nuclear power plants, is called Probabilistic Risk Assessment. EPRI sponsored the project, Salt River Project's Coronado Generating Station was analyzed, and ERIN Engineering performed the analysis work. The Coronado Generating Station (CGS) consists of two coal-fired units located in Northeastern Arizona. In this technique, the term risk means the probability of failure, and one result of the analysis is to identify systems and components that contribute significantly to production losses. While the calculated unit reliability approximately matched actual plant performance, the ranking of systems and components is particularly useful to focus limited maintenance resources. The technique uses a scenario modeling approach to aggregate component failure information into system and unit reliability. A particular challenge on this project was obtaining enough component failure information needed for the analysis.

INTRODUCTION

Probabilistic Risk Assessment is a way to evaluate and manage the economic risks associated with power plant reliability. An assessment is done by developing a plant specific model and a supporting plant reliability database. That is used to identify and rank key systems, components, and failure modes contributing to unplanned production losses. Plant operators can review and prioritize leading contributors to generation losses, and quickly investigate the quantitative impact of proposed plant design or operational changes on key plant reliability indicators.

APPROACH

Probabilistic Risk Assessment (PRA) uses a scenario based modeling approach that is already familiar to the nuclear power industry. Scenario modeling decomposes the plant availability and reliability performance problem into one of defining a reasonably complete set of scenarios that can have an adverse impact on plant electrical generation performance. These scenarios include sudden plant trips (including automatic and anticipated operator manual scrams), manual shutdowns (to make repairs that cannot be made on-line and to address regulatory requirements), and unplanned reduced power operation states. This set of events provides the basis for evaluation of the plant performance in terms of the plant availability and capacity factors, and the frequency of events leading to production losses.

SCOPE

The objective of the project was to demonstrate the technical approach without developing a detailed model of the entire two-unit site. To comply with the project budget constraints, the scope of the analysis was limited in several areas. The number of systems modeled in detail was limited to four. Based on input from the CGS staff, the following four systems were selected:

- Coal Conditioning (BAF)
- Coal Handling (JKA)
- Fly Ash Handling (JNA)
- Bottom Ash Handling (JMA)

Others systems were included in the model to ensure that the overall results are reasonably benchmarked against the historical evidence, and that the significance of contributions to production loss from those systems modeled in detail are put in proper perspective. These systems were selected primarily based on a review of Coronado operating experience, and were included as high-level models. Those systems that contribute significantly to production risk indices should be considered leading candidates for detailed analysis in future updates of the model.

RESULTS AND INSIGHTS

A summary of the Unit 1 results and selected insights are presented here. There are two avenues available to gain insights from the model. The first is through direct examination of the model results. This review will identify those systems and components that contribute significantly to production losses, and also, those that have very little risk significance.

The second approach to utilizing the model is to run sensitivity cases to quantify the impact of proposed plant design or operational changes on the costs associated with production losses. This "what-if" capability provides a powerful quantitative tool to investigate and prioritize potential reliability enhancement alternatives.

INSIGHTS FROM UNIT 1 RESULTS

The software used to quantify the model presents high-level reliability performance indicators, and a breakdown of the key contributors to these indicators by systems, scenarios, and components. Some of the key performance indicators calculated for the Unit 1 model are presented below.

Availability Factor	88.1%
Forced Outage Rate	6.4%
Capacity Factor	86.0%
Unplanned Capability Loss Factor	8.6%

These results included the assumption that the planned unavailability of the unit is approximately 6%. The inclusion of specific scenario and system contributions in the model, and the development of selected plant specific reliability parameters, were based on historical plant operating data. Therefore, although the objective is development of a predictive reliability model, the key performance indicators approximate past performance. Other key performance indicators include:

Event frequencies (events per calendar year)

Plant trips (forced shutdown)	8.5
Manual plant shutdown (forced shutdown)	3.6
Reduced power operation (forced)	30.4

Other production risk indicators

Unplanned down time	515.1 Hours/Calendar Year
Unplanned production loss	243,238 MWe-Hours/Calendar Year

The unplanned production loss is a function of forced outage events as well as events leading to a reduction in the power level. Depending on the assumed cost of replacement power, unplanned generation losses are costing tens of millions of dollars per year.

Table 1 presents a ranking of plant systems based on contribution to expected annual production loss. Production loss is reported in units of effective full power hours of lost production per calendar year. The system rank with respect to the frequency of forced shutdown events is also presented in the table.

The results presented in Table 1 clearly indicate that boiler system failures dominate the production risk profile. The boiler was not modeled in detail for this study, but high-level failures, such as failure of the boiler control system, boiler tube leaks, and failure of boiler internals, were included in the model, as a result of the review of plant operating experience. These results indicate that the resources currently spent on boiler maintenance and performance enhancements should be maintained or increased. For example, the results indicate that a factor of 2 reduction in the frequency of boiler control system failures would reduce the expected annual production loss by 55 hours per year. Assuming replacement power cost of $100 per MWe-hr, this reliability improvement would translate into a saving of over two million dollars per year. A detailed analysis of the boiler and boiler control system would provide more definitive insights for improving plant reliability.

In the context of this limited scope analysis, it is particularly interesting to note the risk significance of the four systems that were modeled in detail. None of these systems contributes significantly to the expected frequency of forced outage events, but the Coal Conditioning System is the second ranked system with respect to expected annual production losses. The Fly Ash Handling System makes a small but visible contribution to expected production loss, while both the Bottom Ash and the Coal Handling Systems do not contribute significantly to any production risk indicators. Although three of the four systems contribute little to production risk, the quantitative results can provide insights with respect to managing plant operations.

Table 1 *Reliability Importance of Systems at CGS Unit 1*

FO Rank	PL Rank	System Name (1)	Forced Outage (FO) Frequency		Production Loss (PL)	
			Fraction of Total	Events per cal. year	Fraction of Total	EFP Hours per cal. year
1	1	Boiler Systems	0.57	6.91E+00	0.66	458.00
10	2	Coal Conditioning (2)	< 0.01	2.89E-02	0.10	69.40
13	3	Boiler Fans (FD, ID, PA)	< 0.01	6.57E-03	0.08	55.70
4	4	Feedwater	0.06	7.04E-01	0.05	36.50
2	5	Main Turbine	0.18	2.18E+00	0.03	21.40
6	6	Condensate	0.03	4.08E-01	0.03	21.10
8	7	Fly Ash Handling (2)	0.01	8.33E-02	0.02	11.50
3	8	Generator	0.08	9.09E-01	0.01	7.82
5	9	Human Error	0.05	6.11E-01	0.01	6.48
7	0	Electric Power (general)	0.02	2.03E-01	< 0.01	2.63
9	11	Bottom Ash Handling (2)	0.01	6.58E-02	< 0.01	1.58
15	12	Circulating Water	< 0.01	2.00E-04	< 0.01	0.59
11	13	Service/Instrument Air	< 0.01	1.77E-02	< 0.01	0.37
*	14	Scrubber	0	0	< 0.01	0.35
17	15	480V Electric Power	< 0.01	8.72E-05	< 0.01	0.25
*	16	Soot Blowing	0	0	< 0.01	0.08
12	17	Plant Cooling Water	< 0.01	7.71E-03	< 0.01	0.07
16	18	4160V Electric Power	< 0.01	1.30E-04	< 0.01	0.03
14	19	Coal Handling (2)	< 0.01	2.11E-04	< 0.01	0.01
		Totals		1.21E+01		694.00

[1] The systems are listed in order of contribution to total production loss (PL). Production loss is measured in units of effective full power (EFP) hours per year.

[2] Detailed system model was prepared for this system.

For example, are maintenance resources being allocated amongst systems and components such that the risk of unplanned production losses is minimized? The model generates a component importance list to help answer this question. Table 2 presents a list of the events included in the model for the four detailed system models. The events are grouped by system, and within each system are sorted based on the event contribution to the expected production loss measured in effective full power (EFP) hours lost per calendar year. The events in the table are also color coded and placed into three categories of production risk significance, as defined by the table below.

Color	Production Risk Significance	Production Loss Range (Expected EFP Hr/Year)
Red	High	Greater than 5
Yellow	Medium	Between 1 and 5
Green	Low	Less than 1

Table 2 provides a basis to review where maintenance dollars are currently being spent. It may be possible to reduce maintenance costs associated with those components or events that are coded ”green” in Table 2. A review of Table 2 shows that the majority of component failure events models fall into this category. These components contribute very little to the current production risk profile, and decreasing their reliability is not likely to impact the plant reliability. Items coded “yellow” in Table 2 are small, but visible contributors to risk. Relaxation of current maintenance practices for these components, without significantly impacting plant reliability, may be possible but should be supported with additional analysis. Failures associated with the “red” components are currently making significant contributions to expected production losses, and current maintenance practices should be continued if not enhanced. Any savings associated with reducing maintenance costs associated with these systems could be applied to improving the reliability of systems or components identified as leading contributors to production risk (e.g., Boiler, or others listed in Table 1). For brevity's sake, green events are not shown in Table 2.

Table 2 *Production loss component/event importance*

System	Component(s)/Event ID	Event Description	Production Loss (EFP hrs/yr) and Importance Color Code	
BAF	1BAFPULPUL1C_O_N	Coal Pulverizer 1C Fails to Run	9.3	RED
BAF	1BAFPULPUL1B_O_N	Coal Pulverizer 1B Fails to Run	9.3	RED
BAF	1BAFPULPUL1A_O_N	Coal Pulverizer 1A Fails to Run	9.3	RED
BAF	1BAFFDRF1C1__O_N	Feeder 1C1 Fails to Operate	6.5	RED
BAF	1BAFFDRF1C2__O_N	Feeder 1C2 Fails to Operate	6.5	RED
BAF	1BAFFDRF1B1__O_N	Feeder 1B1 Fails to Operate	6.5	RED
BAF	1BAFFDRF1B2__O_N	Feeder 1B2 Fails to Operate	6.5	RED
BAF	1BAFFDRF1A1__O_N	Feeder 1A1 Fails to Operate	6.5	RED
BAF	1BAFFDRF1A2__O_N	Feeder 1A2 Fails to Operate	6.5	RED
BAF	1BAFCRHCD1C1_O_N	Crusher Dryer 1C1 Fails to Run	1.6	YELLOW
BAF	1BAFCRHCD1C2_O_N	Crusher Dryer 1C2 Fails to Run	1.6	YELLOW
BAF	1BAFCRHCD1B1_O_N	Crusher Dryer 1B1 Fails to Run	1.6	YELLOW
BAF	1BAFCRHCD1B2_O_N	Crusher Dryer 1B2 Fails to Run	1.6	YELLOW
BAF	1BAFCRHCD1A1_O_N	Crusher Dryer 1A1 Fails to Run	1.6	YELLOW
BAF	1BAFCRHCD1A2_O_N	Crusher Dryer 1A2 Fails to Run	1.6	YELLOW
JMA	1JMAHOESERWATE__	Manual Alignment of Service/Fire Water to JMA	1.5	YELLOW
JMA	1JMAAOVFCV15GS_N	Decanting Sump FCV 15G Fails to Open	1.2	YELLOW
JNA	1JNAPRENORTH_O_N	North Precipitators Fail to Operate	1.7	YELLOW
JNA	1JNAPRESOUTH_O_N	South Precipitators Fail to Operate	1.7	YELLOW
JNA	1JNAFANBBLOWAS_N	Ash Conveyor Air Booster Blower A Fails to Start and Run	1.6	YELLOW

***Table 2** Production loss component/event importance*

System	Component(s)/Event ID	Event Description	Production Loss (EFP hrs/yr) and Importance Color Code	
JNA	1JNAFANBBLOWCS_N	Ash Conveyor Air Booster Blower C Fails to Start and Run	1.6	YELLOW
JNA	1JNASYSSILO__S_N	Failure to Remove Fly Ash from Receiving Silo	1.5	YELLOW

ANALYSIS MODEL

The analysis model is comprised of the following key elements:

- An integrated reliability model that reflects the success criteria for maintaining power generation at or near 100% of nominal plant capacity (this model is used for both units).
- Detailed reliability models for a selected group of four systems.
- Simplified reliability models for additional plant systems. These models provide a means of calibrating the integrated model results with plant experience and provide a starting point for future model updates.
- A linked fault tree that integrates the detailed and simplified reliability models. The minimal cutsets for the integrated model are generated using the SAPHIRE program.
- A comprehensive set of scenarios generated for each of the integrated fault tree minimal cutsets that identifies combinations of component failures, unavailability states, procedures, and human errors that could result in an adverse impact on power generation capability. The scenarios are generated using an expert system (i.e., PLANTFORMA-RE) that interprets plant logic, generates scenarios, and quantifies key plant reliability performance indicators. More than forty thousand scenarios were generated and quantified. The vast majority of the scenarios were found to have a negligible frequency of occurrence and were screened from the final model. Nearly 5,000 of these scenarios were included in the final version of the model used to calculate the reliability performance parameters and to evaluate the importance of key systems and components that can be used to set priorities for future enhancements.
- A database of plant specific and generic component failure rates (related to "mean time between failures"), repair times, plant recovery times, human error rates, and common cause failure rates to support quantification of the integrated plant model.

Table 3 *Summary of Coronado integrated reliability model characteristics*

Major Elements of Model	**Model Parameter**	**Value**
Scope of Analysis	Detailed System Models (4)	Coal Conditioning (BAF)
		Coal Reclaim and Converging (JAF)
		Bottom Ash Handling (JMA)
		Fly Ash Handling (JNA)
	High-Level System Models	8
Integrated Linked Fault Tree Modeled in Saphire	Number of Fault Tree Basic Events	360
	Minimal Cutsets of Fault tree	12,684
	First Order *	0
	Second Order	121
	Third Order	1,118
	Fourth Order	6,809
	Fifth Order	3,216
	Higher Order	1,420
PLANTFORMA Coronado Integrated Reliability Model	Scenario Classes Modeled	Planned Outage
		Plant Trips
		Elective Manual Shutdowns (MSD)
		Reduced Power Operations (RPO)
	Scenario Causes Modeled	Component Failures
		Common Cause Failures
		Procedures
		Alignments
		Human Errors
	Scenarios Modeled (through 5th order cutsets)	40,091
	Included in Final Integrated Model	4,980
	Screened out (< $1x10^{-8}$/plant operating year)	35,111

* Due to the use of flags on the fault trees to represent scenario end states, there are no first order cutsets; second order cutsets are actually single failure scenarios, etc.

From the above models and data, a base case set of results was obtained as described in detail in the following sections. These results were obtained for each of the two units at CGS using the PLANTFORMA software and include:

- An integrated assessment of several plant reliability performance measures including plant availability, forced outage rate, frequency of forced outages, expected downtime from forced outages, plant capacity, unplanned capability loss factor, and several additional performance indicators.
- An estimate of the annual frequency and consequences of each modeled scenario in terms of the impact on plant downtime, and production losses, and replacement power costs associated with each modeled scenario. (Replacement power costs are estimated based on an assumed value of replacement power in units of dollars per megawatt-hour of lost production).
- An assessment of the primary contributors to several key plant reliability performance indicators to help determine the importance of plant systems and components.

The technical approach adopted for this analysis was developed to provide not only a rigorous assessment of the overall plant reliability performance, but also a detailed examination of the principal contributors to reliability performance. This approach decomposes the contributors to plant performance in terms of scenarios that could have an adverse impact on plant performance. Each scenario consists of the following elements:

1. An initiating event or trigger event that occurs at some random point in time (e.g., failure of a normally operating component).

2. The occurrence of one or more conditioning events that occur at the same time as the initiating event, which may compound the consequences of the scenario in terms of plant performance (e.g., the failure of another redundant component).
3. A plant transient that occurs as a result of the above that creates an unfavorable end states such as a plant trip, power reduction, or forced outage via manual plant shutdown.
4. A return to plant power operation when the causes of the scenario have been corrected and the procedures to return to power have been accomplished.

The type of scenarios that are included in the model dictates the types of reliability performance indicators that can be addressed as illustrated in Figure 1. A reliability model includes scenarios involving plant trip events.

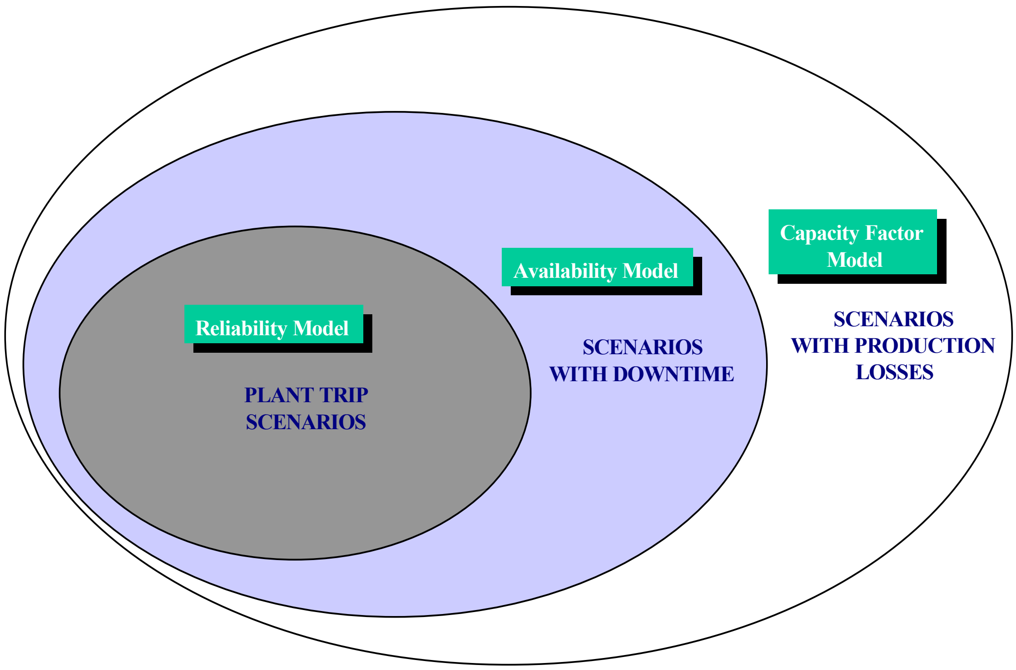


Figure 1 *Relationship of scenario categories to reliability performance indicators*

For an availability model, both plant trips and other scenarios with plant downtime, i.e., with the need to remove the generator from the grid, are included. For a capacity factor model, these events as well as scenarios causing reduced power operation must be included to provide a complete set of scenarios that can impact the capacity factor. By this standard, the model is classified as a capacity factor model as all three of these types of scenarios are included in the evaluation.

The types of scenarios that were modeled in this study fall into three general classes include:

- Sudden Plant Trips (referred to as “Trips”)
- Elective Controlled Shutdowns to perform maintenance (referred to as “MSDs”)
- Reduced Power Operations (referred to as “RPOs” or “RPs”)

”WHAT-IF” CAPABILITIES

An examination of the base case Unit 1 model results provides insights into the sources and magnitudes of production loss events. Another tool available to the reliability analyst is the capability to quantify the impact of proposed plant design or operation changes on plant performance indicators. This “what-if” capability can be used to assess the benefits of proposed changes, or set priorities for a number of potential reliability enhancement projects.

A review of Table 1 shows that Coal Conditioning (BAF) System scenarios contribute significantly to the total risk of generation losses. The specific BAF system component failures that are risk significant are identified as the category red and yellow events in Table 2. The key component failures include the failure to continue running of the pulverizers, feeders, and crusher-dryers on each of the three BAF System trains.

Question: What potential saving, in terms of a reduction in generation losses, could be realized by improving the reliability of these components?

A sensitivity case was quantified to answer this question. The subject failure rates were reduced in the base model by a factor of ten, and the predicted plant performance indicators were requantified. The result of this sensitivity case shows that if the subject failure rates could be reduced by a factor of ten, with all other model inputs held constant, the annual production losses could be reduced by about 25,000 MWe-hr per calendar year. This translates into several million dollars of increased revenue depending on the price of replacement power costs.

FUTURE ENHANCEMENTS TO THE MODEL

The current model demonstrates the capabilities of the predictive reliability modeling approach, and also provides direction for expanding the model. Some potential areas for expanding and improving the current model include:

- Select additional systems for detailed analysis and modeling. Prime candidates based on the current model results include the boiler, turbine, and generator systems and subsystems.
- Review and analysis of production loss scenarios caused by human errors. The current model includes a placeholder in the model to include contributions due to human errors, but the correlation between these production loss events and the specific activities or procedures being performed at the time of the event should be developed and incorporated in the model.
- Detailed data analysis for reliability parameters and scenario impacts. The current model utilizes several generic sources for component reliability data, along with plant specific data taken from the NERC GADS event report database. A more detailed review of plant specific data, and an industry wide search for the best available generic data sources would improve the fidelity of the model.

3.3
Case Studies Illustrating the Use of Qualitative and Quantitative Risk Assessment for Maintenance Planning

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Abstract
The benefits that may be derived from adopting risk assessment as the basis for planning inspection and maintenance programmes have been recognised for the past decade. Risk-based inspection (RBI) is rapidly becoming the norm in the oil and gas industries, take-up being facilitated by the API initiative in this area (API 580 and 581) and by widespread buy-in by the industry regulators. Drivers for RBI are the safety and economic benefits that accrue from a well-considered and implemented RBI strategy.
Although the nuclear power industry has always used probability of failure as a primary consideration in assessing nuclear safety, the fossil power generation industry has been relatively slow to react to the API and ASME initiatives on RBI and the opportunities it offers for optimising maintenance programmes.
This paper illustrates the AEA Technology Risk-Based Maintenance (RBM) planning approach and software for optimisation of maintenance, inspection and refurbishment programmes on power generation plant.
Two applications are described.
The first demonstrates the application of qualitative risk assessment using RBMS (Risk-based Inspection and Maintenance Planning Software) to optimise the inspection programme for a boiler and to prepare a safety case for extending the interval between statutory inspections. In-service degradation mechanisms are first identified for each component, followed by a systematic assessment of the likelihood that they will lead to failure and the consequences were such failure to occur. Where possible, the likelihood of failure assessment is supported by relatively simple inverse-code calculations of remaining life using RBMS.Toolbox. Risk is expressed as a rating that is used to guide the inspection or maintenance response and the risk assessment used as the basis of the safety case.
The second application illustrates the use of fully quantitative probabilistic analysis to determine the optimum programme of tube replacement for a superheater using RBMS.Heater. This software computes all reliability parameters of interest for all sections of tubing in heaters and boilers in a single calculation. The reliability of the whole heater or boiler is thereby determined which enables maintenance programmes to be devised based on the most accurate view of plant integrity.

1. INTRODUCTION

Maintenance of power generation plant can broadly be divided into two categories: routine inspection of static equipment and maintenance of other equipment, and refurbishment and replacement of components. The former is carried out in an attempt to identify impending failure or breakdown or to mitigate deteriorating performance. Refurbishment or replacement of components may be carried out in response to inspection and maintenance observations, the results of predictive life assessment or to upgrade the performance of the plant.

Maintenance programmes constitute a significant proportion of controllable operating costs and enlightened power generators are seeking cost-effective maintenance achieved through a non-prescriptive strategy based on risk rather than a time-based approach. Risk is defined as the product of the likelihood (or probability) that a component may fail and the consequences if it were to fail. Financial, safety and environmental risks are generally evaluated independently using the relevant measure of the consequence of failure.

Risk-based approaches to optimising maintenance programmes have the advantage that maintenance expenditure is focused to plant areas where it offers the greatest benefit in avoiding failure of pressure parts and breakdown of other equipment, thereby increasing plant availability and reducing expected failure costs and/or maintenance costs. Furthermore, establishing rational, effective inspection and maintenance programmes is fundamental to gaining approval from safety regulators for extension of the interval between statutory inspections of plant.

Risk assessment for maintenance planning is invariably carried out at the component level. The assessment may be carried out qualitatively, semi-quantitatively or fully quantitatively, as appropriate to the application.

Qualitative risk assessment generally relies upon the use of questionnaires to force a systematic, consistent assessment of both the likelihood that a component will fail and the consequences if it were to fail. Consequence questionnaires may address the safety, environmental and/or economic impact, either singly or in combination. The likelihood and consequence of failure ratings derived from the questionnaires are then used to categorise the relative risk of failure of each component, generally using a risk matrix.

Semi-quantitative approaches also seek only to categorise relative risk by assigning ratings to the likelihood and consequences of failure. However, here the likelihood of failure rating is determined using models of the degradation process to calculate the susceptibility, rate of deterioration or remaining life, and the consequences of failure rating is determined using the results of failure scenario modelling.

Fully quantitative risk assessment uses statistical analysis of previous failure data or probabilistic solution of degradation models to determine the likelihood of failure as a mathematical probability. The safety, environmental and/or cost consequences of failure are quantified by detailed analysis. Risk is evaluated as a cash value (financial risk), the number of fatalities and injuries (safety risk) and/or the area affected by the release (environmental risk).

Risk-based planning of routine plant inspection and maintenance programmes must of necessity address a large number and wide range of equipment items. To date, a qualitative or semi-quantitative risk ranking approach has been adopted. AEA Technology has developed software for planning routine inspection and maintenance programmes using qualitative risk assessment (Risk-Based Inspection and Maintenance Planning Software - 'RBMS'). Key judgements that must be made in this qualitative approach are supported wherever possible by relatively simple calculations using AEA Technology's deterministic, component life assessment software, RBMS.Toolbox.

The application of fully quantitative methods to risk-based maintenance of complex plant can be limited by adequate descriptions of degradation mechanisms and computational time. However, when adequate degradation models are available large numbers of components can be analysed with efficient numerical procedures to provide a complete probabilistic description of plant reliability; optimum times for refurbishment can then be accurately determined. Such is the case for heater and boiler tubing. AEA Technology has developed RBMS.Heater which computes all reliability functions of interest for all sections of tubing in heaters and boilers in an integrated probabilistic analysis. In particular, accurate forward predictions of the reliability of the whole plant can be made which allows for optimum efficiency in maintenance programming.

This paper describes two applications of risk-based maintenance (RBM) planning. The first demonstrates the use of qualitative risk assessment using RBMS and RBMS.Toolbox to optimise the inspection programme for boilers and form the basis of a safety case for extended run periods between statutory inspections. The second illustrates the use of RBMS.Heater to determine the optimum time to replace superheater tubing.

2. RISK-BASED PLANNING OF ROUTINE INSPECTION AND MAINTENANCE PROGRAMMES

2.1 Risk assessment methodology

2.1.1 Overview

Each pressure part of the boiler is assessed using RBMS to determine the Likelihood of Failure and Consequence of Failure ratings and hence the Risk Category. The need for and extent of inspection required to maintain risk at an acceptable level is then determined.

2.1.2 Rating the likelihood of failure

The Likelihood of Failure rating screen of RBMS is shown at Figure 1. The factors considered in determining the Likelihood of Failure Rating are:

- Would the identified degradation mechanism eventually lead to failure or breakdown of the equipment item at the prevailing operating conditions?
- Would it lead to failure or breakdown within the period of future operation being considered?
- What is the current damage level?
- What is the condition of any protective coating or thermal insulation?
- How effective is the current inspection or maintenance programme in detecting damage in advance of failure?
- What is the condition of the component or pipework supports?
- Was the component manufactured and fabricated according to an appropriate code?
- What level of post-manufacturing and/or fabrication inspection/ testing was carried out?
- If plant cycling is relevant to failure, is this occurring at the anticipated rate?
- Has there been previous beyond design operation?
- What is the potential for future beyond design operation?

For each factor, qualitative assessment is possible. In addition, quantitative methods are available for selected components and relating to specific damage mechanisms. These include remaining life assessments in the context of creep, fatigue and corrosion wall-thinning using RBMS.Toolbox.

Likelihood of failure is rated as:

- **Negligible**: Failure is considered to be incredible within the timeframe considered
- **Low**: Failure is considered to be unlikely to occur within the timeframe considered
- **Medium**: Failure is may occur within the timeframe considered
- **High**: Failure is likely to occur within the timeframe considered.

2.1.3 Rating the Consequences of Failure

The Consequence of Failure rating screen in RBMS is shown at Figure 2. For each component, and each of its identified degradation mechanisms, a number of factors that characterise the severity of the expected failure event are considered and scored.

Safety Assessment

The safety consequence is assessed by a simple question relating to the degree of hazard associated with the failure.

The options are:

- **Insignificant:** no safety hazard
- **Minor**: potential for minor injury to personnel
- **Localised**: potential for major injury or death in a localised area

- **Widespread**: potential for major injury or death over a widespread area.

In order to assign the Safety Severity Rating, the likely mode of failure must first be identified, by considering how damage would accumulate as a result of the degradation mechanism being assessed. Based on these considerations, experienced plant engineers will have little difficulty in categorising safety severity according to the scheme prescribed above. Two illustrative examples are:

- Fast failure (burst) of a superheater tube within the boiler, due to creep and high temperature fireside corrosion, has no implications for personnel safety and the Safety Severity Rating 'Insignificant' would be assigned.
- Failure of a header end-cap weld due to creep could result in the end cap being propelled through the boiler casing with a sudden and massive release of steam. In this situation, the Safety Severity Rating 'Widespread' or "Localised" is appropriate depending on the design of the boiler enclosure.

Financial Assessment

The financial consequence of a failure is assessed by a series of questions which identify the potential outcome in terms of days outage, and direct costs associated with replacement and repair. A financial consequence associated with the safety hazard is also included.

The factors considered are:

- How long would the downtime be to effect repairs or refurbishment and what would be the resulting production loss?
- What would be the cost of repairing or replacing the failed component?
- What would be the cost of repairing or replacing other components damaged by the primary failure?

In addition, the assessors are able to weight the answers according to their confidence that they have bounded the worst case situation using the further factor:

- How predictable is the failure/breakdown event and its consequences?

A response indicating that there was a high degree of uncertainty significantly influences the scoring for financial consequence

2.1.4 Risk ranking matrix

The financial and safety risk matrices in RBMS are shown in Figures 3 and 4 respectively. The Risk Ranking is derived from a Risk Matrix, and can range from "Acceptable" (coded green), through "Acceptable with Controls" (coded yellow) and "Undesirable" (coded amber), to "Unacceptable" (coded red).

The risk categorisations define the requirement for control measures, such as inspection, or access restrictions, as shown below:

Risk rank	Required actions
1. Acceptable	No inspection or other actions are required within the timeframe considered unless to satisfy national legislative requirements.
2. Acceptable with Controls	Define and implement an appropriate revised inspection, assessment or maintenance strategy.
3. Undesirable	Mitigate to Risk Ranking 1 or 2 within the timescale of the next overhaul.
4. Unacceptable	Mitigate immediately to Risk Ranking 1 or 2.

2.1.5 Optimisation of inspection and maintenance programmes

The current inspection and maintenance programme is reviewed for each component in the context of the above framework. In particular, the following are considered:

- the effect of eliminating inspection/maintenance of components categorised as 'Acceptable',
- the optimum programme of inspection/maintenance for components categorised as 'Acceptable With Controls',
- the optimum programme of inspection/maintenance to reduce the risk for components categorised as 'Unacceptable' and Undesirable',
- where the consequences of failure are the predominant risk driver, the need for consequence mitigation, the available options and costs.

The consideration of inspection/maintenance procedures and schedules takes into account the likely location and rate of damage accumulation. These factors determine the sites and features on the component to be inspected, the sample size, the procedure to be employed and the frequency, or the maintenance action required. If the potential rate of degradation is such that inspection or maintenance during plant shutdowns would be too infrequent reliably to detect impending failure, on-line monitoring is recommended. If the likelihood of failure is high because of the possibility of mal-operation or beyond design operation faults, operating practices, plant monitoring and management procedures should be reviewed to determine scope for improved control. Where the risk is driven by the consequences of failure, the scope for reducing this by improving event termination time, limiting the steam release and/or secondary mechanical damage to plant, and engineering modifications to provide improved personnel protection, is considered. The risk-based inspection recommendations are recorded in RBMS, as shown in Figure 5.

2.2 Case study

2.2.1 Background

The project described in this case study was carried out for a power generator in Singapore. The objective was to prepare a safety case to demonstrate to the regulator that safety would not be compromised by extending the statutory inspection interval for the boilers from 12-months to 36-months. The technical approach adopted centred on qualitative risk assessment of the boiler pressure parts using RBMS.

2.2.2 Technical Approach

The risk assessment and inspection planning was carried out interactively by the AEA Technology consultants and power station engineers. The plant scope comprised the boiler (economiser, furnace, steam drum, superheater and reheater), and ancillary vessels including blowdown tank, oil heaters and evaporator.

The aim was to demonstrate that the risk of failure associated with the proposed 36-month inspection interval was no greater than that associated with the then current 12-month interval. If necessary, inspection or other controls were introduced to maintain risk at the previous 'acceptable' level.

The approach adopted was to first assess the risk based on a 12-month inspection interval (the 'primary qualitative risk ranking' or PQRR) and then to revisit it based on a 36-month inspection interval (the 'revised qualitative risk ranking' or RQRR). The assessment utilised the results of inspections that had been carried out in accordance with statutory requirements 12 months after the start of operation.

The process consisted of four stages involving project and RBMS customisation, population of the RBMS plant inventory, risk assessment and inspection planning.

2.2.3 Customisation

(a) Definition of assessment time frame

The "Assessment Timeframe" was taken to be the time to the next outage but one. Operating hours and starts were projected using the expected utilisation factor for the plant. The assessment timeframes for the 12 month inspection interval was therefore (12+12)=24 months, and for the 36 month inspection interval it was (36+36)=72 months. The assessment timeframe is used in when considering such questions "Is failure likely to occur within the timeframe?" and "What is the effectiveness of inspection?"

(b) Financial consequence scaling

The financial consequence of failure was scaled to take account of the particular costs of a day of lost generation at the plant and to provide a reasonable level of discrimination within the consequence categorisation.

2.2.4 Plant inventory

The project team generated a description of the plant, and its inspection history based on a hierarchy of:

- Unit
- System (e.g. superheater, economiser)
- Component (e.g. inlet header, tube bank, outlet header)
- Location (e.g. outlet branch, end cap, tube ligament, tube stub)

The information included:

- Unit: assessment date, time to next outage, the inspection frequency, and plant operating history (operating temperature, operating hours, utilisation and number of starts)
- Component: design and operating conditions, plant reference tag and drawing numbers, operating history (if different from the unit history)
- Location: key dimensions, materials, inspection history, life assessment results, inspection and monitoring requirements, spares holdings.

2.2.5 Risk ranking and inspection planning procedure

The process consisted of the following tasks:

a. **Primary Qualitative Risk Ranking (PQRR)**. The risk associated with the current 12-month inspection strategy was assessed. Each component location was considered in turn. Potential degradation mechanisms for each component were reviewed. If a mechanism was considered tenable, a PQRR was created for the relevant location, and the risk ranking procedure was carried out. Where appropriate, judgements on the likelihood of failure were supported by calculation of remaining life using RBMS.Toolbox (Figs. 6, 7).

b. **Revised Qualitative Risk Ranking (RQRR).** The risk associated with the proposed 36-month inspection period was assessed. Any increase in risk due to the increased inspection interval is typically associated with the longer assessment period (a closer approach to the end of life of the component), and a reduced ability of the inspection techniques to detect an incipient failure because of the increased intervals between inspections. As a result, the RQRR could potentially score more highly on the questions:
    - Will the mechanism lead to failure or breakdown within the assessment timescale?
    - How effective is the current inspection or maintenance programme in detecting damage in advance of failure?

c. **Review Inspection Plan:** If the Revised Risk Ranking was higher than the Primary Risk Ranking, as a result of the extension to the inspection period, the inspection or monitoring control was improved. The Revised Risk Ranking was repeated, taking into account the improvement of the control, until the Risk Ranking was “Acceptable”, or “Acceptable with Controls”.

d. **Record inspection plan:** The inspection or other control requirements were recorded, to form the basis of the written scheme of examination.

2.2.6 Results of risk assessment

Approximately 300 locations were considered, and about 200 risk assessments were carried out. A Risk Ranking of ‘Acceptable’ or ‘Acceptable with Controls’ was achieved for all locations following the introduction, where necessary, of inspection, assessment and other controls.

In many cases, particularly for superheater and reheater outlet headers, a control is required to demonstrate that creep or thermal fatigue damage has not progressed to point where the likelihood of failure increases to a significant level. At this stage in life, the control is a life assessment, which eventually will need to be supplemented by non-destructive examination.

2.2.7 Conclusion

Risk analysis using RBMS and specification of a rational WSE provided the rigorous justification necessary for the safety regulator to approve the extended inspection interval for the boilers. The extension from 12-month to 36-month intervals increased plant availability by 5% or 20 days per year.

3 RISK-BASED PLANNING OF PLANT REFURBISHMENT

3.1 Introduction

Quantitative risk analysis can be applied to determine the optimum, cost-beneficial time to replace or refurbish a wide range of major components of power generation plant. The detailed procedure varies depending on the type of component and the pertinent in-service degradation mechanisms. The following describes the application of AEA Technology's RBMS.Heater software, which is configured to determine the optimum time to replace tubing in steam-raising boilers used for power generation or process applications, and fired heaters used in oil refining and other chemical process industries.

3.2 Risk assessment methodology

3.2.1 Overview

Since the consequence of each tube failure is essentially the same, the risk assessment methodology adopted to identify which tubes should be replaced and when, is based solely on an assessment of the probability of failure.

Two approaches are available for calculating the future probability of failure of the tubes: (a) statistical analysis of previous failure data, and (b) probabilistic solution of a model of the degradation mechanism. The former relies on there being sufficient failure data to provide meaningful results. Since this is often not the case, RBMS.Heater adopts the probabilistic modelling approach to determine failure probability.

The life of evaporator tubing is generally controlled by fireside corrosion which leads to wall-thinning and ultimately tensile rupture of the tube wall. High temperature superheater and reheater tubing also suffers wall thinning due to fireside (principally) and steam-side corrosion; this combines synergistically with creep deformation to cause tube failure. Accordingly, the degradation model incorporated in RBMS.Heater simulates tube failure by the combined effects of fireside corrosion, steam-side oxidation and creep. Input parameters are assigned probability distributions which are randomly sampled in each simulation to determine tube life. The software uses numerical techniques which are significantly more efficient than straightforward Monte-Carlo analysis and lead to more accurate predictions.

Failure probabilities are calculated for individual tubes and these are compounded using a weakest link model to determine failure probabilities for defined sections of the tube bank and the entire bank. The latter is used to calculate the expected number of failures for any defined period of future operation.

3.2.2 Tube bank block model

In order to provide maximum flexibility to accommodate various tube arrangements, RBMS.Heater utilises a block model of the heater whereby it is characterised by rows along the length of the outlet header, legs around the outlet header in each row, and tubes within each leg. Each tube consists of a number of original sections and replaced sections.

3.2.3 Input data

The model requires the following input data:

- Section dimensions
- Section material properties
- Inspection data
- Temperature data
- Internal pressure data

Tube dimensions: Tube dimensions are defined by section diameters, wall thicknesses and lengths. Unless specific measurements are available, diameter is taken to be the as-supplied nominal diameter. Unless specific measurements are available from the manufacturing records, at start of life, wall thickness is taken to be the as-supplied nominal thickness with a normal distribution determined from the specified design tolerance. Section lengths are taken from design data.

Section material properties: The required material properties are wall thinning rate, creep-rupture data and tensile-rupture data.

Wall thinning rate: standard models and data are used to predict the steam side and fireside wall thickness penetrations as a function of time and temperature. Where wall thickness and/or steam-side oxide thickness measurements have been made during inspection outages, these are used to scale the models using parameters determined by fitting to unity the expected ratio of the measured value compared to the predicted value. Here the expected value is the value of the ratio averaged over every inspected position in the tube bank. In this way the scaled parameters are statistical characteristics of the tube bank.

Creep-rupture data: creep rupture properties are represented by parametric equations fitted to standard data. Creep rupture lives are assumed to be Weibull distributed with parameters determined by fitting to life data appropriate to the tube material.

Tensile-rupture data: the critical flow stress for tensile rupture is determined from standard data.

Temperature data: A spatio-temporal distribution of temperature over the heater is required in order to obtain predictions of the reliability of any tube (or section) in the heater. This temperature distribution is inferred from the following four types of data:

- measured steam-side oxide thicknesses (where appropriate)
- header or manifold stub temperature records
- outlet steam (or other fluid) temperature records
- design temperatures.

Rules are defined regarding precedence and use of the various types of data that may be available in order to derive the required spatio-temporal variation of temperature for the heater. In this way, the temporal variation of temperature is defined for each tube.

Internal pressure: This is taken to be the normal operating pressure with an empirical distribution determined from the observed data.

3.2.4 Life assessment methodology

The remaining life analysis calculates the effect of creep in combination with the effects of fireside and steam-side corrosion for each tube in the tube bank. A probabilistic calculation is performed with the uncertainties in material creep-rupture and tensile data, temperature, wall thickness and pressure represented by statistical distributions. Tube creep is assumed to be controlled by the mean diameter hoop stress. Tube behaviour is simulated by the software using numerical techniques that are significantly more efficient than straightforward Monte-Carlo analysis and lead to more accurate predictions. The probability of failure of selected segments of the tube bank, or the entire tube bank, is derived on the assumption that probabilities of failure of individual tubes are fully independent and thus failure is equivalent to a weakest link model.

3.2.5 Presentation of results

Analyses can be performed for any selected tube section, tube or tube bank (a selected set of tubes). The user menu interface for bulk data input is shown in Figure 8 and the analysis menu in Figure 9.

In a section analysis, the following quantities are output graphically as a function of time up to a specified time horizon:

- probability of section failure since installation
- the residual probability of failure with the contributions from creep- rupture and tensile- rupture
- wall thickness.

In a tube analysis, the residual probabilities of failure of the tube and constituent sections are output graphically.

In a tube bank analysis, the output options are:

- tabulation of the heater tube array showing median times to failure
- tabulation of the heater tube array showing ranking of tubes according to residual probability of failure by a specified time and colour-coded according to the value of the failure probability (Fig. 10)
- tabulation of sections ranked according to residual probability of failure by two specified outage times; the source of data from which temperatures are derived is also recorded (Fig. 11)
- graphical output of the expected number of tube failures by a specified time horizon
- graphical output of the residual tube bank failure probability by a specified time horizon.

3.2.6 Maintenance recommendations

The recommended action for tubes/sections most likely to fail takes account of the confidence in the prediction. This in turn largely depends on the temperature data and wall thinning rates used in the analysis. For example, temperatures of superheater or reheater tubing derived from steam-side oxide thickness are assigned high confidence whereas those inferred from mixed steam temperatures are assigned low confidence. Where there is high confidence in the prediction, the recommended action for the outage is to replace those tubes expected to fail in the next run period. Where the temperature data is assigned low confidence, the action recommended is to improve the relevant input data to the model, be this by installing additional thermocouples, monitoring tube wall thickness by measurements during inspection outages etc., and to re-run the analysis.

3.3 Case study

3.3.1 Boiler information

The boiler is of Babcock and Wilcox manufacture and was commissioned in 1970. From commissioning until 1985, the boiler was oil fired and accumulated 60,967 operating hours. From 1986 until the time of the recent inspection, the boiler has been gas fired and has accumulated an additional 66,346 operating hours.

The superheater is arranged in three passes: first pass rows 20 - 28, second pass rows 10 - 19 and third pass rows 1 - 9. Each row has ten legs (A to J). The tube material is 1Cr0.5Mo steel. The outer diameter of the first and second pass tubes is 63mm; the outer diameter of third pass tubes is 51mm. The original nominal wall thicknesses are 4.9mm for the first pass, 5.4mm for the second pass, and 4.47mm for the third pass.

3.3.2 Operating conditions

Generally, the boilers operate at around 18kg/s output during the winter months (May-September) with occasional rises to 21kg/s. During the summer months (October-April) the boilers operate at around 21kg/s with occasional rises to 28kg/s. During these periods the superheater outlet pressure remains relatively constant at around 4.24MPa-4.26MPa. The steam drum pressure (inlet to saturated tube pass - inlet to superheater) indicatively varies with steam output as follows: 18kg/s (4.425MPa), 22kg/s (4.51MPa), 28kg/s (4.65MPa), 30kg/s (4.67MPa).

The steam outlet temperature from the third stage is typically 455°C.

3.3.3 Inspection results

A specialist ultrasonic technician attended site during the outage in September 1998. Measurements were made of superheater tube wall thickness and internal oxide thickness on each tube element at up to 4 elevations, of several tube rows from the front (depending on accessibility) and bend locations.

The technique used for steam-side scale thickness measurement was a proprietary ultrasonic procedure. An appropriate frequency transducer (typically 20MHz) and suitable gating was applied to achieve adequate resolution and enable the internal oxide interface to be discriminated from the back-wall echo and hence the oxide thickness measured. In practice, the minimum thickness of internal oxide which may be satisfactorily resolved using this method is approximately between 0.16 and 0.20 mm.

Metallographic examination of a tube sample removed from the boiler confirmed that the internal oxide layer was reasonably uniform (towards the tube front surface of the tube) and confirmed the ultrasonic readings obtained in the field.

3.3.4 Wall thinning

Tube wall thinning was based on original nominal wall thickness and thickness data from the 1998 outage.

3.3.5 Stress

The relevant tube operating stress was represented by the mean diameter hoop stress based on steam drum pressure.

3.3.6 Temperature

The effective temperature was calculated from the measured steam-side oxide thickness using a parabolic growth relationship and constants determined from published data.

3.3.7 Material creep-rupture data

Creep-rupture data were taken from AEA Technology's proprietary materials property database for 1Cr0.5Mo steel which is broadly consistent with the International Standards Organisation (ISO) data set.

3.3.8 Results

The median remaining tube lives (that is a 50% probability that the lives would actually be greater than these) showed that, in general, first pass tubes were the most vulnerable to failure. Tubes with the shortest remaining lives were 9A (3 years, the shortest), 21A-28A, 20B-21B and 20C-21C. Most tubes had median lives greater than 17 years. A comparison between the lives of replaced tubes and the predicted lives (since installation) of the new tubes at the same positions is made in Table 1. Agreement is clearly very good giving high confidence in the results of the analysis. The predicted mean number of tube failures as a function of time is shown in Figure 12.

The results were used by the plant owner/operator to determine the timing of tube replacements during scheduled maintenance outages.

3.3.9 Conclusion

The quantitative risk analysis enabled the plant operator to instigate a cost-effective tube replacement programme.

4 CONCLUDING REMARKS

Planning maintenance on the basis of the risk of component failure offers the following potential benefits:

Improved safety: inspection and maintenance actions are focused to components and locations where there is a significant risk of failure causing a safety hazard.

Improved component reliability: maintenance expenditure is targeted to components where it will have the greatest effect in reducing the number and consequence of failures and breakdowns.

Increased plant availability: in addition to a reduction in forced outages to plant failures and breakdowns, risk-based maintenance may be used to justify extended intervals between inspection intervals with an associated increase in plant availability.

Reduced maintenance expenditure: unnecessary and ineffective inspection and maintenance is identified and can be eliminated.

Table 1 *Case study for risk-based optimisation of the timing of component replacement: comparison of predicted and historical tube failure times*

Tube	Historical life (years)	Predicted life (years)
9A	7.0	9.0
24A	7.1	9.7
20A	9.2	-
‘A’ row	9.2	7.7 - 8.8
21A	9.6	8.3

It should be emphasised that the predicted lives are median lives from the probability distribution and so are realistic rather than conservative.

Figure 1 *RBMS: likelihood-of-failure assessment screen.*

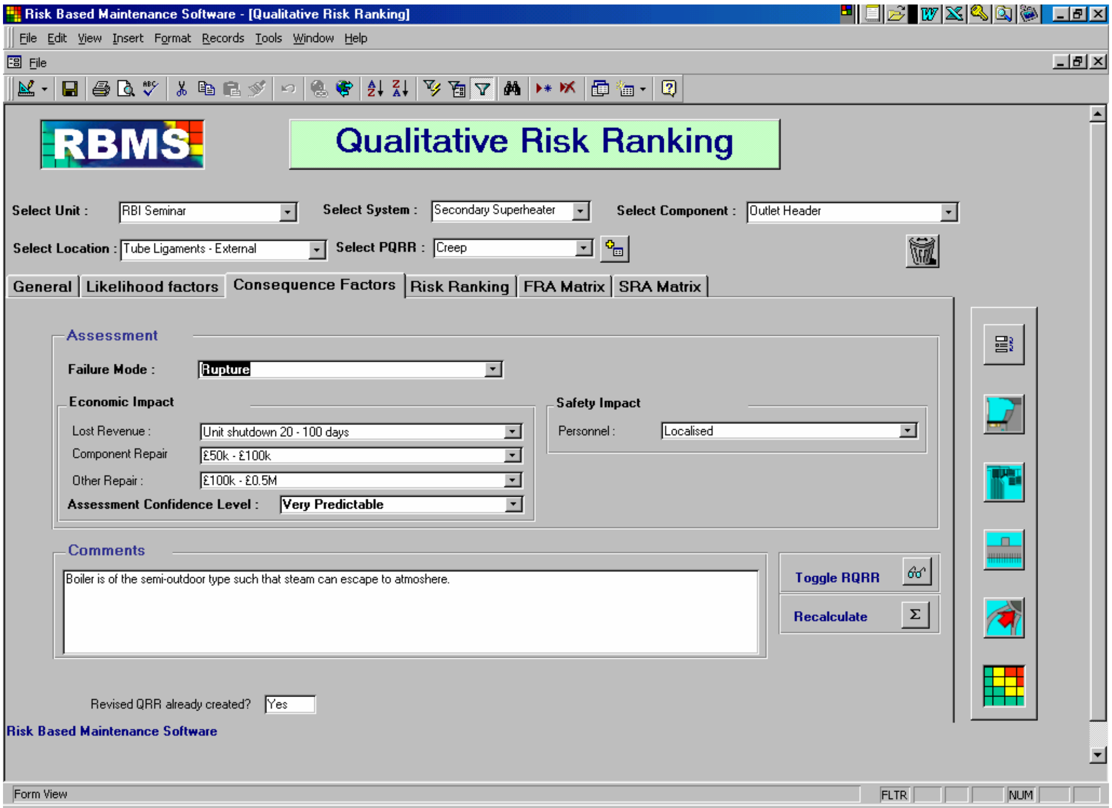

Figure 2 RBMS: consequence-of-failure assessment screen.

Figure 3 *RBMS: financial risk of failure result screen.*

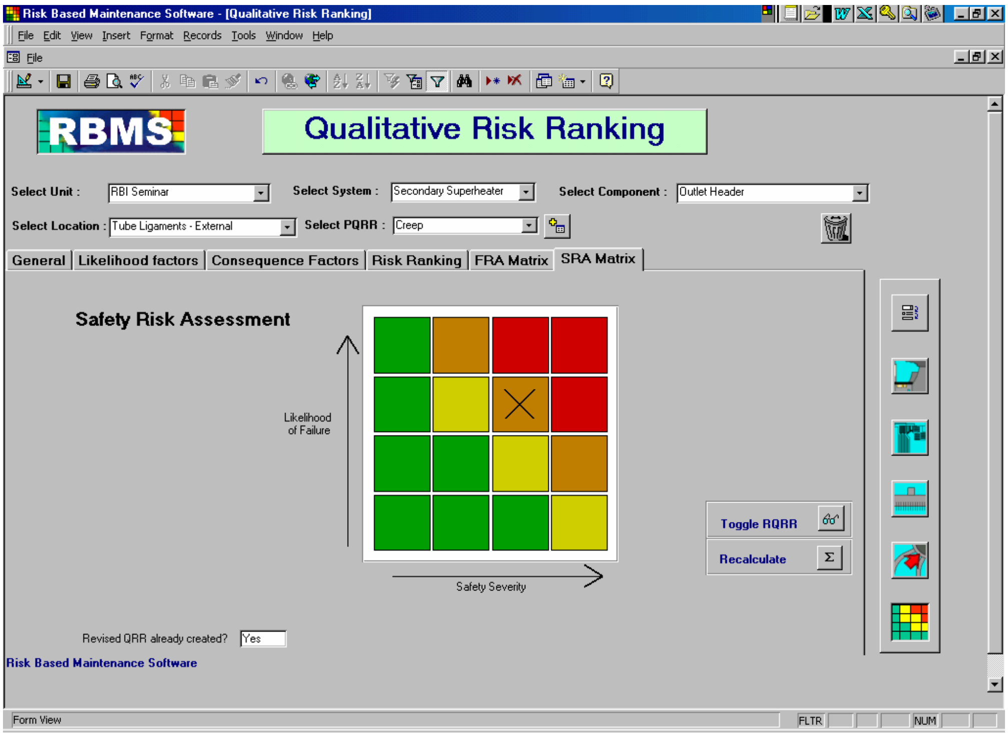

Figure 4 *RBMS: safety risk of failure result screen.*

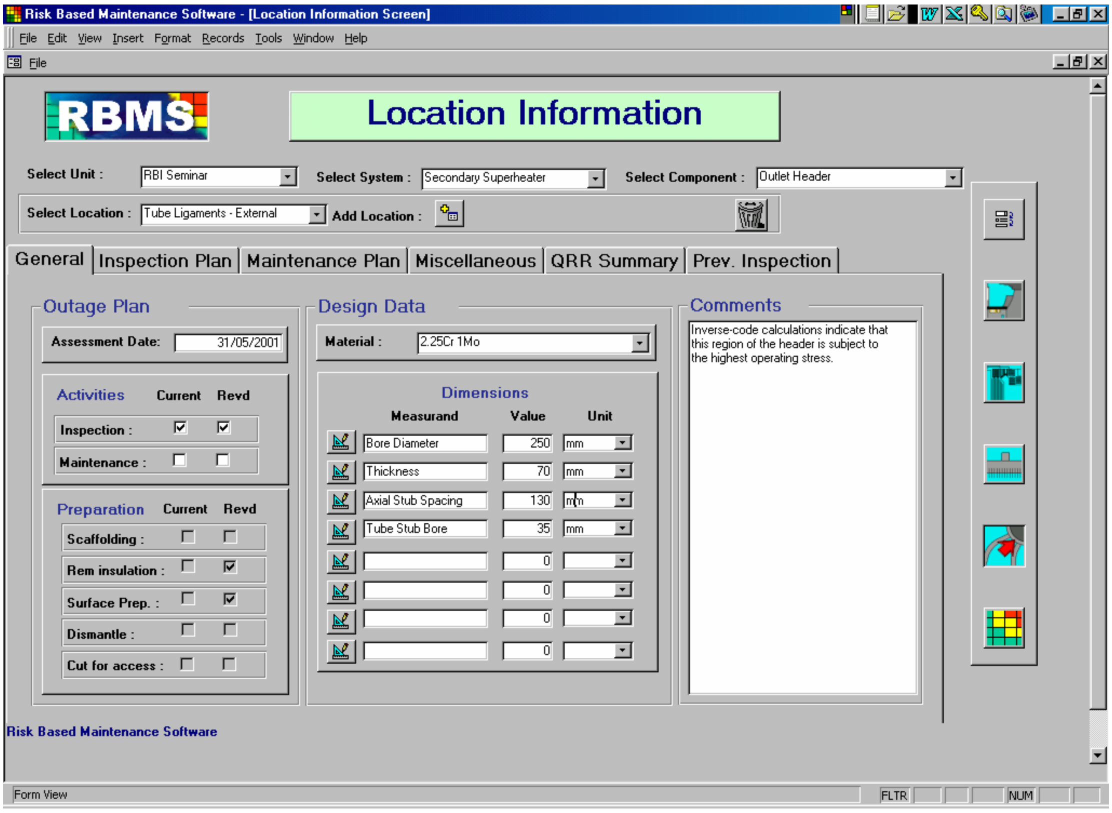

***Figure 5** RBMS: maintenance recommendations screen.*

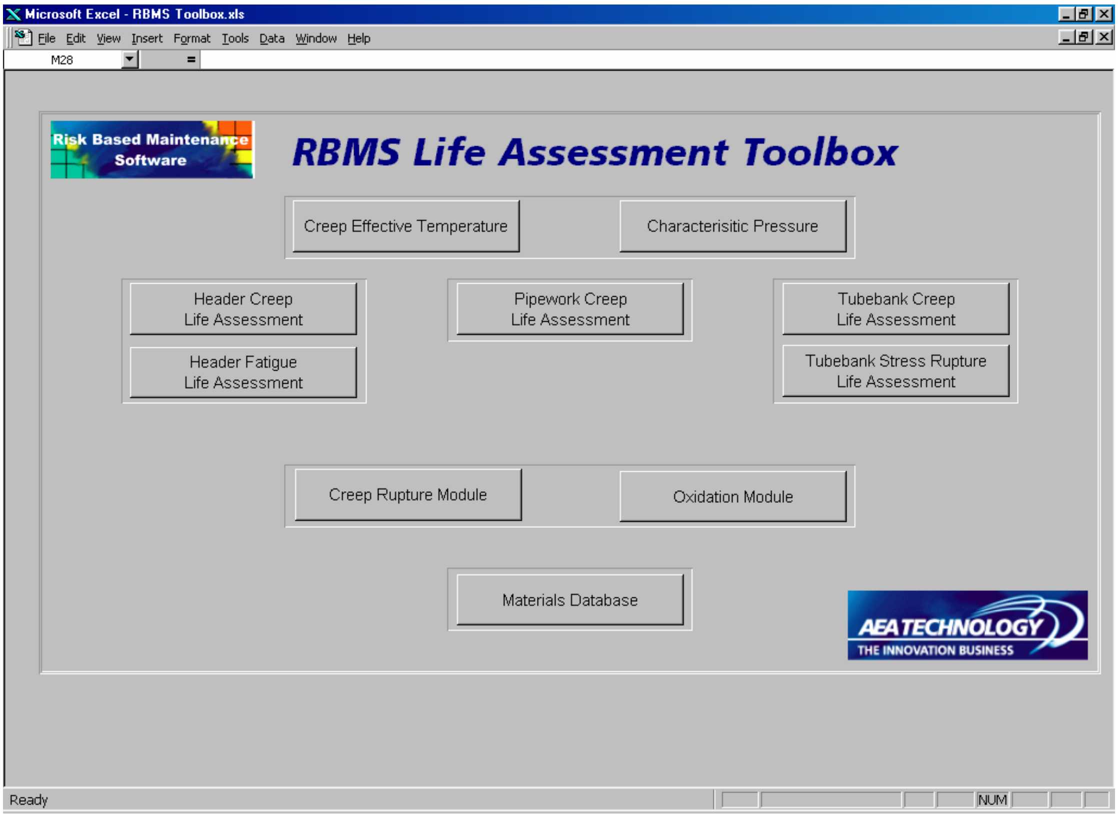

Figure 6 *RBMS. toolbox: analysis selection screen.*

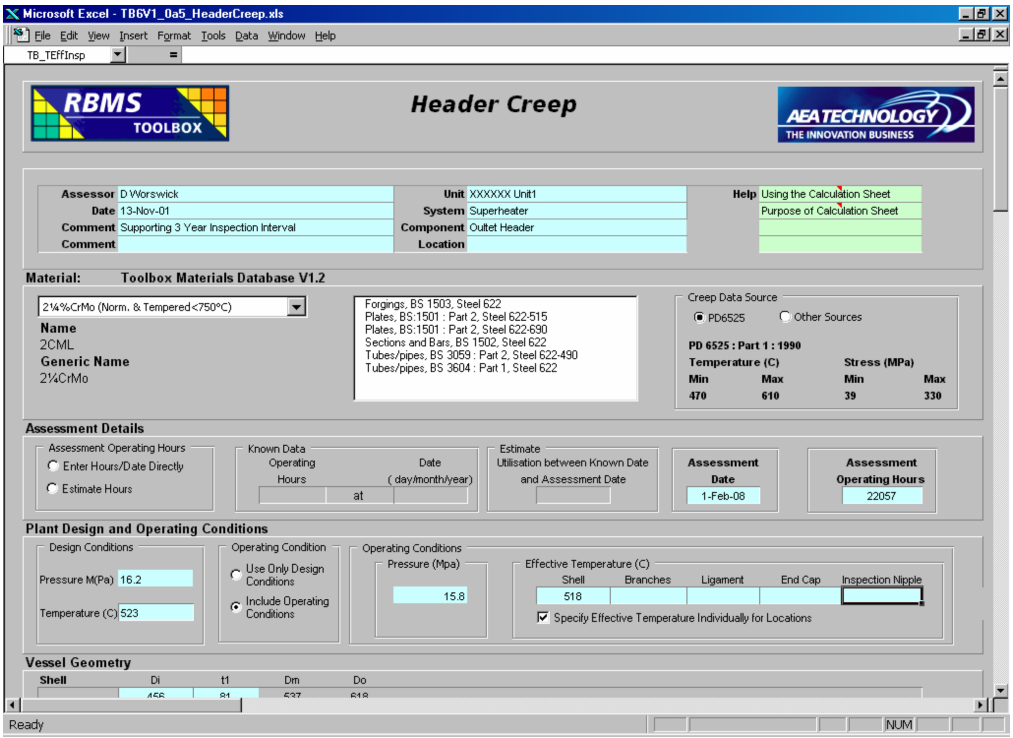

Figure 7 *RBMS.toolbox: header creep assessment screen.*

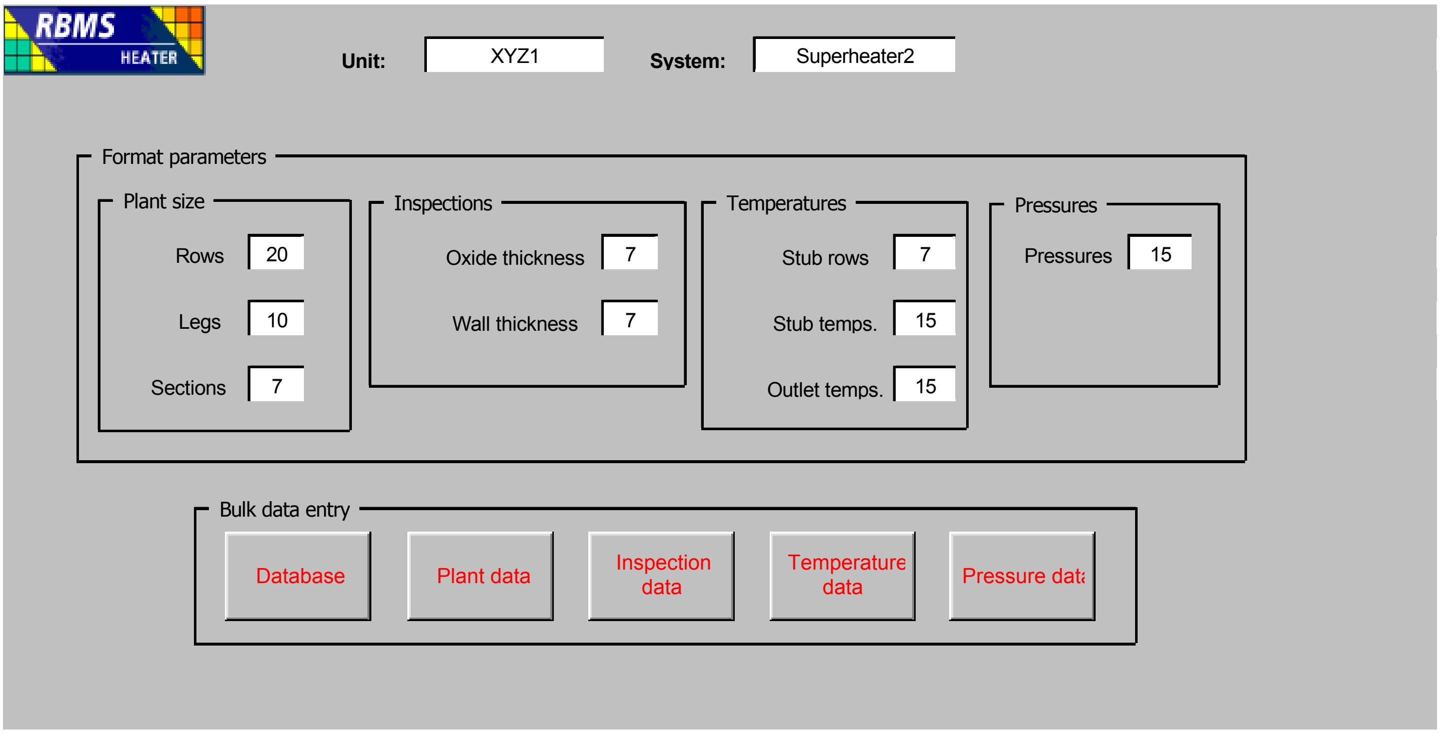

Figure 8 *RBMS.Heater: user menu for bulk data input.*

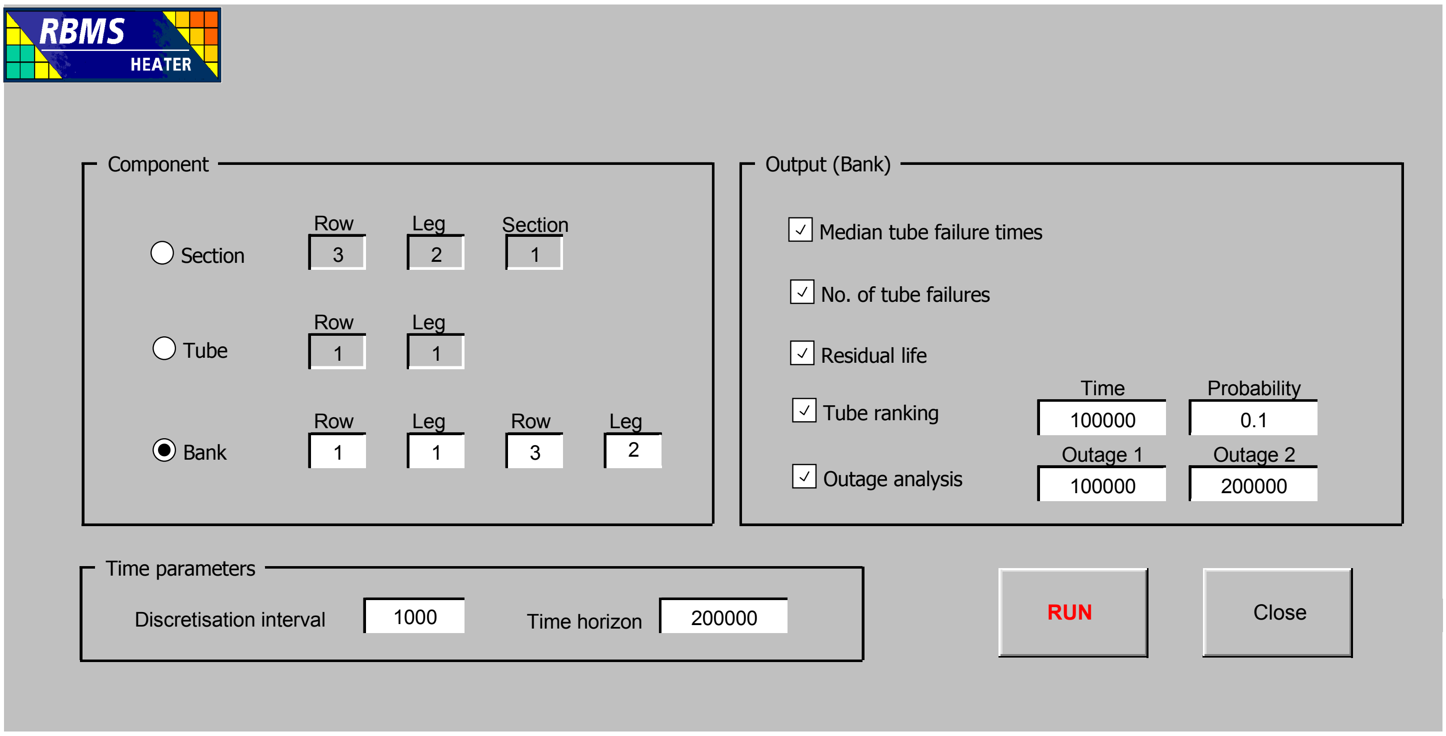

Figure 9 *RBMS.heater: analysis menu.*

TUBE RANK ARRAY Bank (1, 1)-(16, 7) Time 100000 XYZ1 Superheater2

Kev
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}

row / leg	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	6	4	1	25	20	14	7	50	43	36	29	78	71	64	57	85
2	5	2	26	21	15	8	51	44	37	30	79	72	65	58	86	101
3	3	27	22	16	9	52	45	38	31	80	73	66	59	87	102	96
4	28	23	17	10	53	46		32	81	74	67	60	88	103	97	92
5	24	18	11	54	47	40	33	82	75	68	61	89	104	98	93	110
6	19	12	55	48	41	34	83	76	69	62	90	105	99	94	111	108
7	13	56	49	42	35	84	77	70	63	91	106	100	95	112	109	107

Figure 10 *RBMS. heater: tube rank by colour-coded failure probability.*

OUTAGE ANALYSIS Bank (1, 1)-(16, 7) XYZ1 Superheater2

	OUTAGE 1				28/04/2006	OUTAGE 2				27/06/2009
	Row	Leg	Section	Type	Probability	Row	Leg	Section	Type	Probability
10^{-1}	1	2	1	1	5.00E-01	1	1	1	4	1.59E-01
	2	1	1	1	5.00E-01	1	2	1	1	1.51E-01
	1	1	2	1	5.00E-01	2	1	1	1	1.51E-01
	1	1	1	4	4.00E-01	1	1	2	1	1.51E-01
10^{-2}	1	6	1	1	9.00E-02	1	6	1	1	9.41E-02
	2	5	1	1	9.00E-02	2	5	1	1	9.41E-02
	1	5	2	1	9.00E-02	1	5	2	1	9.41E-02
	3	4	1	1	9.00E-02	3	4	1	1	9.41E-02
	2	4	2	1	9.00E-02	2	4	2	1	9.41E-02
	1	4	3	1	9.00E-02	1	4	3	1	9.41E-02
	4	3	1	1	9.00E-02	4	3	1	1	9.41E-02
	3	3	2	1	9.00E-02	3	3	2	1	9.41E-02
	2	3	3	1	9.00E-02	2	3	3	1	9.41E-02
	1	3	4	1	9.00E-02	1	3	4	1	9.41E-02
	5	2	1	1	9.00E-02	5	2	1	1	9.41E-02
	4	2	2	1	9.00E-02	4	2	2	1	9.41E-02
	3	2	3	1	9.00E-02	3	2	3	1	9.41E-02
	2	2	4	1	9.00E-02	2	2	4	1	9.41E-02
	6	1	1	1	9.00E-02	6	1	1	1	9.41E-02

Figure 11 *RBMS. heater: tabulation ranked by failure probability at two specified maintenance outages.*

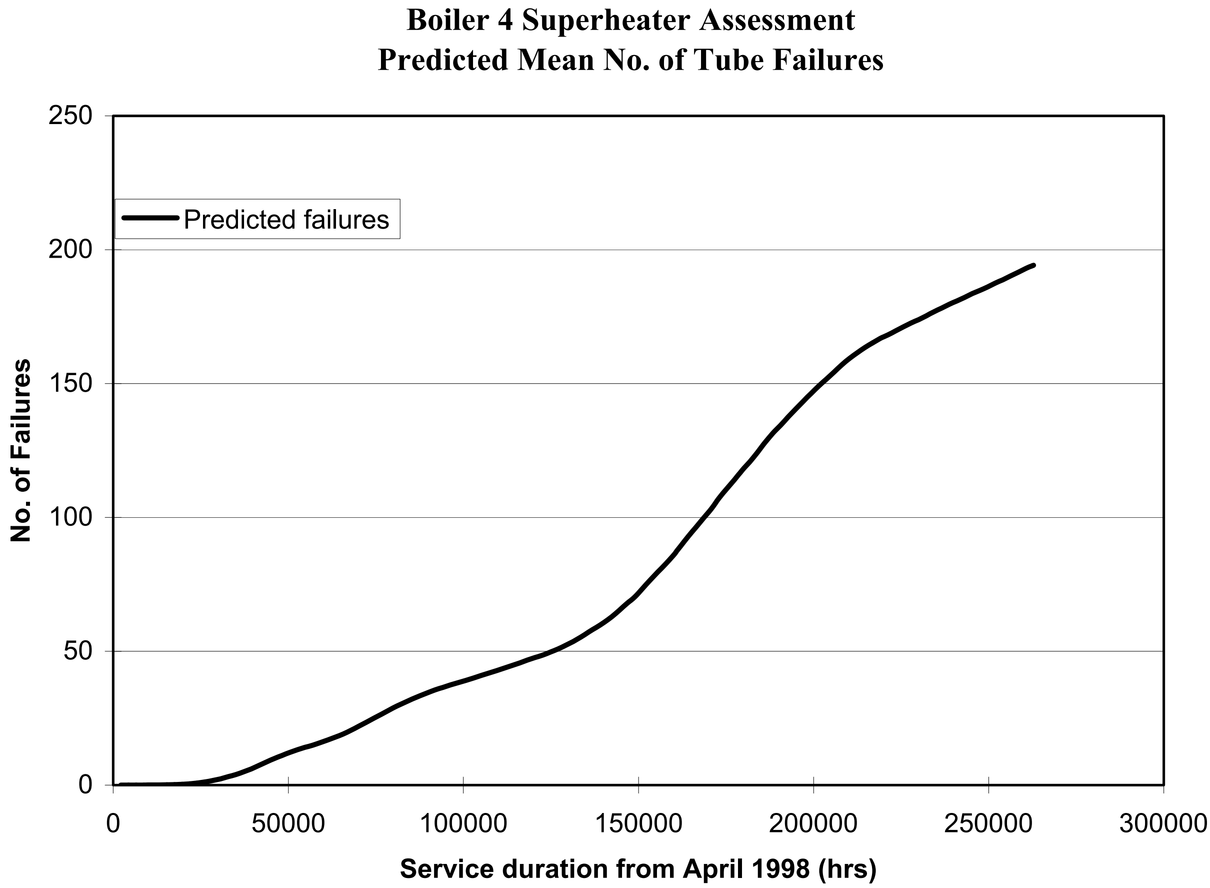

Figure 12 *Predicted number of tube failures as a function of future operating time (in absence of tube replacement).*

3.4
A posteriori Probabilities Application to Inspection Planning of 0.5Cr0.5Mo0.3V Steam Piping

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Abstract
A number of computational quantities exhibit a certain variability. Therefore, these quantities can be considered to be random variables or stochastic processes, and the life-time can be calculated by means of probabilistic procedures. In piping systems operating under creep conditions this involves mainly creep properties and geometrical parameters. The probabilistic assessment of life-time and reliability is based on calculations of the stress redistribution (using the creep constitutive equations) and of the accumulation of creep and fatigue damage (as stochastic process). Failure risk is calculated not only for critical localities but also for the piping system as a whole. The residual life was predicted and the inspection periods optimized by means of a posteriori (conditional) probabilities.

1. INTRODUCTION

Most of current stress analyses and life-time assessments are based on the extreme values method. These extreme values are so defined that it is highly improbable that they could be exceeded. However, accumulation of these extreme values (minimal wall thickness, minimal material properties and maximal load) in every part of the pipeline seems to be unrealistic. As the quantities describing the piping system (the material, the dimensions) can be considered to be random quantities (they have certain variability), they can be described and the life-time can be calculated by probabilistic methods.

As an example, the calculation of the life-time of an outlet steam pipeline made of 0.5Cr0.5Mo0.3V steel is demonstrated. Basic parameters: ∅273/25 mm and 219/20 mm; effective temperature of steam 536.7°C, mean pressure 9.6 MPa.

2. BASIC CALCULATION PRINCIPLES AND STAGES

The integrity and life-time of creep-damaged structures are, in the first place, calculated from the accumulation of creep material damage, and also from the stress redistribution which is a result of the development of permanent time-depending deformations under creep. Therefore, the life-time calculation has the following steps:

1) Working conditions of the piping system assessment - temperature and load spectra.
2) Calculation of primary elastic or elastic-plastic stresses.
3) Calculation of stress redistribution during creep.
4) Determination of stationary state of stress after the stress redistribution and the calculation of the relevant creep damage.
5) Calculation of failure risk (crack initiation) for each critical locality.
6) Assessment procedure of failure risk for the piping system or its parts.
7) Calculation of the residual life-time and optimization of inspection periods.

3. PRINCIPLES OF PROBABILISTIC CALCULATION

The basics of the probabilistic calculation are introduced in the following chapters. The methodical procedure is described in more detail in Report [1]

3.1 Stochastic model of creep - constitutive equation

If we wish to use probabilistic methods, we need a mathematically formulated stochastic description of creep including strain characteristics. This model can be described by the following constitutive equations [1]:

$$\varepsilon_c(t|\sigma,T)=\varepsilon_o.\left[\frac{\varepsilon_m(\sigma,T)}{\varepsilon_o}\right]^{g[\pi(t)]}$$

(1)

$$g[\pi(t)]=[\pi(t)]^N\left[\frac{1+\exp\left[-2[\pi(t)]^{K(T)}\right]}{1+\exp(-2)}\right]^M$$

$$\pi(t)=\frac{t}{\tau(\sigma,T)},\quad K(T)=\exp\left(K_1+\frac{K_2}{T}\right),$$

where $\varepsilon_c(t|\sigma,T)$ is creep strain (creep curve) at time t under constant stress σ and temperature T, $\varepsilon_m(\sigma,T)$ is limit creep strain (ductility) as a random quantity (under stress σ and temperature T), ε_0 is initial strain - may/may not be considered to be random, $g[\pi(t)]$ is damage function, $\pi(t)$ is creep damage in time t as a random process, $\tau(\sigma,T)$ is time to rupture as a random quantity (under constant stress σ and temperature T), N, M, K_1, K_2 are material parameters evaluated from the creep data.

3.2 Material damage accumulation law

The common damage accumulation law shall be modified into a discrete form: the state of rupture shall be characterised by damage value of 1. The pre-rupture state (material damage) shall be characterised by a damage value of less than 1. Then, the damage accumulation law shall be as follows :

$$\pi_c(t)=t.\exp(-\delta_c.\Omega_c).\sum_{i=1}^{n}\frac{{}^r t_i}{t_{ci}}\quad \text{pro}\ \ \pi_c(t)<1 \tag{2}$$

$$\pi_c(t)=1\quad \text{otherwise,}$$

where $\mu_{ci}=\mu_c(\sigma_i,T_i)$ is the mean value of logarithm of the time to rupture at stress σ_i and temperature T_i, $t_{ci}=\exp(\mu_{ci})$ is the delogarithmed mean value of logarithm of the time to rupture, ${}^r t_i$ is the relative temperature spectrum, δ_c is a standard deviation of logarithm of time to rupture, Ω_c is random quantity with unit Gaussian distribution characterising the random nature of the time to rupture τ.

Similar relationships can be derived for the fatigue-damage accumulation law. If we characterise the fatigue-amplitudes spectrum by relative numbers ${}^r N_i$, the fatigue-damage accumulation law shall be as follows

$$\pi_f(N)=N.\exp(-\delta_f.\Omega_f).\sum_{i=1}^{n}\frac{{}^r N_i}{N_{fi}}\quad \text{pro}\ \ \pi_{\rm f}(N)<1 \tag{3}$$

$$\pi_f(N)=1\ \ \text{otherwise,}$$

where $\mu_f(\Delta\sigma_i,T_i)=\mu_{fi}$ is the mean value of logarithm of number of cycles to crack initiation at stress range $\Delta\sigma_i$ and temperature T_i, $N_{fi}=\exp(\mu_{fi})$ is the delogarithmed mean value of logarithm of number of cycles to crack initiation, δ_f is a standard deviation of logarithm of number of cycles to crack initiation, Ω_f is a random quantity with unit Gaussian distribution expressing a random nature of the number of cycles to crack initiation.

The total damage of material, as defined above, is considered to be the state when the damage $\pi(t)$ reaches the value of one. In other studies, however, different values are mentioned for the total material damage under the interaction of creep and fatigue :

$$\pi(t)=\pi_c(t)+\pi_f[N(t)]=D,\ \ D\neq 1.$$

(4)

We can presume, however, that in the coordinate system (fatigue damage versus creep damage) there is a limit curve D_1 defining safe and failure regions. Better than by a relationship (4), the state of material damage can be represented by vector

$$\boldsymbol{\pi}(t) = [\pi_f(t), \pi_c(t)] \quad . \tag{5}$$

The damage shall be defined as a ratio of absolute values of the damage vector $\boldsymbol{\pi}(t)$ and the limit vector $\boldsymbol{p}_1(t)$ on D_1 curve

$$\boldsymbol{\pi}(t) = \frac{|\pi(t)|}{|\boldsymbol{p}_1(t)|} \quad \text{pro} \quad |\pi(t)| < |\boldsymbol{p}_1(t)|$$

$$\pi(t) = 1 \qquad \text{otherwise}. \tag{6}$$

3.3 Failure risk and residual life-time

Applying probabilistic method, failure risks for each critical location are calculated first of all and then failure risk of the whole system is calculated, by means of the following relationship.

$$P_{(m)}(\tau \le t) = 1 - \prod_{i=1}^{m} (1 - P(\tau_i \le t)), \tag{7}$$

where $P_{(m)}(\tau \le t)$ is the total failure risk for a piping system or subsystem - crack initiation before time t, $P(\tau_i \le t)$ is failure risk (crack initiation) for the i-th critical location, $\tau = \min\{\tau_i\}$, $i = 1,2,\ldots m$, m is the total number of critical locations.

The risk (the probability of crack initiation) can qualitatively be divided into:

- a priori risk related to the time from the start of operation, ie., to the operational interval $<0 , t_o>$,
- a posteriori risk related to the time after the time t_o, ie., to the operational interval $<t_o , t>$

The residual life-time is based on the relationship between the a priori and a posteriori (conditional) probabilities

$$P_{(n)}(t_o < \tau \le t \,|\, \tau > t_o) = 1 - \frac{P_{(n)}(\tau > t > t_o)}{P_{(n)}(\tau > t_o)}, \tag{8}$$

where $P_{(n)}(\tau > t_o)$ is an a priori probability of failure occurring after the time t_o, $P_{(n)}(\tau > t > t_o)$ is an a priori probability that the failure occurs after the time $t > t_o$, $P_{(n)}(t_o < \tau \le t \,|\, \tau > t_o)$ is an a posteriori probability that the failure occurs before time $t > t_o$ - on condition that there has been no crack until the time t_o.

4. CALCULATION OF FAILURE RISK AND LIFE-TIME OF STEAM PIPELINE

The life-time was calculated from the project documentation and by using of material properties declared by ČSN 41 5128 (Czech National Standard). As the dimensions were taken from the drawings and as nominal dimensions were used, their variability was also taken into account. The wall thickness was described in a relative form and the state of stress was also corrected, as follows:

– the relative wall thickness ρ of elbow as a random quantity

$$\rho = \frac{s}{s_o} \text{ or in the logarithm form } \log\rho = \log\rho_o + \xi.\delta_s \tag{9}$$

– the stress σ as a random quantity as a result of variability of the wall thickness ρ

$$\sigma = \sigma_o \frac{s_o}{s} \text{ or using the relationship } \log\sigma = \log\sigma_o - \log\rho, \tag{10}$$

where s, s_o is the wall thickness as a random variable and the nominal wall thickness, respectively, ρ_o is the mean value of the relative wall thickness, σ_o is the stress for the nominal wall thickness, ξ is a random quantity having the unit Gaussian probability distribution, δ_s is a standard deviation of the relative wall thickness ρ of the elbow.

The above steps were carried out and the failure risk calculated from the (7) and (8) equations. The results of calculations of the a priori risks of crack initiation in the piping system are shown in Fig. 1

which demonstrates the total risk dependence on the time of operation, see relationship (7). Total risks calculated for all critical localities (BM - base material, elbows and welds) are rather high. From the Fig.1 it can be seen that the welds are the critical parts of the piping system, as the welds exhibit about ten times higher risk than the base material. Therefore, another calculation was carried out - for BM, elbows and a reduced number of welds.

The above calculations make the basis for finding risks of crack initiation during the operational time. After rearranging the relationship (8) the risk of crack initiation during the k-th period Δt (ie., during the time intervals $t_o + (k-1)\Delta t < \tau < t_o + k.\Delta t$)) can be calculated from the relationship :

$$P_{(m)}^{(k)}\left(t_o + (k-1).\Delta t < \tau < t_o + k.\Delta t\right) = 1 - \frac{P_{(m)}\left(\tau > t_o + k.\Delta t\right)}{P_{(m)}\left(\tau > t_o + (k-1).\Delta t\right)}. \quad (11)$$

The relationship (11) can only be used if there was no crack initiation during the operation time $t_o + (k-1)\Delta t$.

The risk of crack initiation during periods of operation is shown in Fig.2 for BM and elbows for different intervals (Δt = 5 000–20 000 hours). It is obvious that if the periods Δt are constant, the failure risk is higher in the following operational periods. The failure risk can be decreased by making the periods shorter (see Fig.2).

Fig.3 shows results of a similar calculation which was carried out for a complete system of critical locations of the steam pipeline (BM, elbows and welds) and Fig.4 represents results for the system of critical localities of BM, elbows and a reduced number of welds. The essential character of dependencies and qualitative changes remain the same in all cases.

5. MORE ACCURATE CALCULATION OF RESIDUAL LIFE-TIME

As some localities show risks of enormous size, it is not always possible to optimize the inspection periods. There are three main solutions to this problem:

- the procedure is the same as above but the inspection period is shorter
- a continuous inspection
- a more accurate calculation.

The first solution can only be used if we have a relatively smaller number of localities inspected. Moreover, it may be difficult to carry out frequent inspections. This problem can be avoided by using the continuous inspection. Very efficient seems to be the third solution where more accurate calculations are carried out. If we look at the most important service-life related factors, they are mainly the creep resistant properties.
The effect of the creep resistant properties can be seen from the time to rupture as a random quantity. The time to rupture as a random quantity can be expressed as follows

$$\log\tau = \mu(\log\tau|\, T,\sigma) + \Omega_c.\delta_{(*)} \ , \quad (10)$$

where τ is the time to rupture as a random variable, $\mu(\log\tau|\, T,\sigma)$ is the mean value of logarithm of the time to rupture at the temperature T and the stress σ, Ω_c is a random quantity having the unit Gaussian distribution function, $\delta_{(*)}$ is a standard deviation of logarithm of the time to rupture.

If the calculations are carried out according to Czech National Standard (ČSN 41 5128), the creep resistance variability of all produced heats must be respected (the standard deviation $\delta_{(S)}$). If the creep resistant properties are more accurate, there shall be a change in the creep resistance mean values $\mu(\log\tau|\, T,\sigma)$, but also in the standard deviation $\delta_{(*)}$. This is why real elbow dimensions (diameters, wall thickness and ovalities) and the real creep strength were found during the inspection of the steam pipeline [3].

The post-operation residual creep rupture strength is based on a correlation between the creep rupture strength and the yield point. The time to rupture of the 0.5Cr0.5Mo0.3V steel was demonstrated to grow with increasing yield point up to about 550 MPa. For this reason the constitutive equations were developed, describing long-term creep rupture strength and strain behaviour of low-alloy creep resistant steel of 0.5Cr0.5Mo0.3V type. The necessary material parameters enabling the realistic modelling of the creep process in dependence on the yield point or tensile strength - considered alternatively as independent variables - were identified [2]. The examples of estimated dependencies of creep rupture strength (for 10 000 hours and temperature 600^{o}C) on the yield point are shown in Fig.5.

Therefore, the creep resistant properties of the steel after creep exposure are fully defined by the current yield point.

New a priori risks for the above mentioned critical-locations systems are shown in Fig.6 (see also Fig.1). They were calculated from the updated creep resistant properties which were determined from the current yield point which was found by the inspection. It is obvious that this is how the objectiveness and accuracy of the crack initiation calculation can be achieved.

6. CONCLUSIONS

The analysis of the steam pipeline life-time is based on:
1. Technical procedures supplied by Nuclear Electric R5 [4].
2. Random interpretation of material damage accumulation laws for creep and fatigue.
3. Stochastic model of the creep process (creep rupture strength, deformation characteristics).
4. probabilistic description of geometrical quantities of the steam pipeline.

The above probabilistic procedure results in the calculation of the crack initiation risks both for the critical localities and for the steam pipeline as a whole (its subsystems, if need be). The residual life-time was calculated from the conditional (a posteriori) probabilities. The risks of crack initiation was calculated for different operating periods (inspections frequency), and the periods were optimized to meet:
- the minimum risk of crack initiation;
- the operation and economy criteria.

The method also involves the calculation of the residual life-time from the updated data (material properties, dimensions).

In the standard service-life calculations there is no difference between the weld and BM, the justification being that the weld is exposed to the axial stress caused by inner pressure, which is one half of the hoop stress.

Thus, the low creep resistant properties of the weld have been ignored, as well as the uneven state of stress and its redistribution. In a number of cases it is the welds that are a weak point and therefore they should be paid great attention.
The probabilistic method of life-time and reliability assessment has been verified on more than 29 piping systems in power and petrochemical plants [1].

7. REFERENCES

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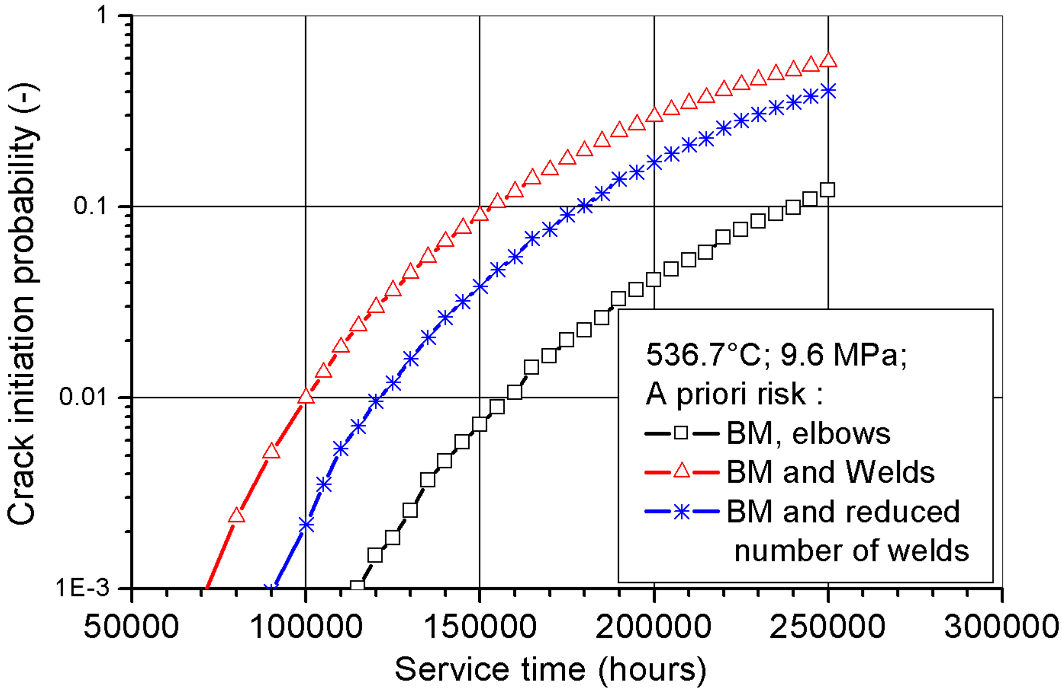

Figure 1 *Comparison of total risks of crack initiation in critical localities.*

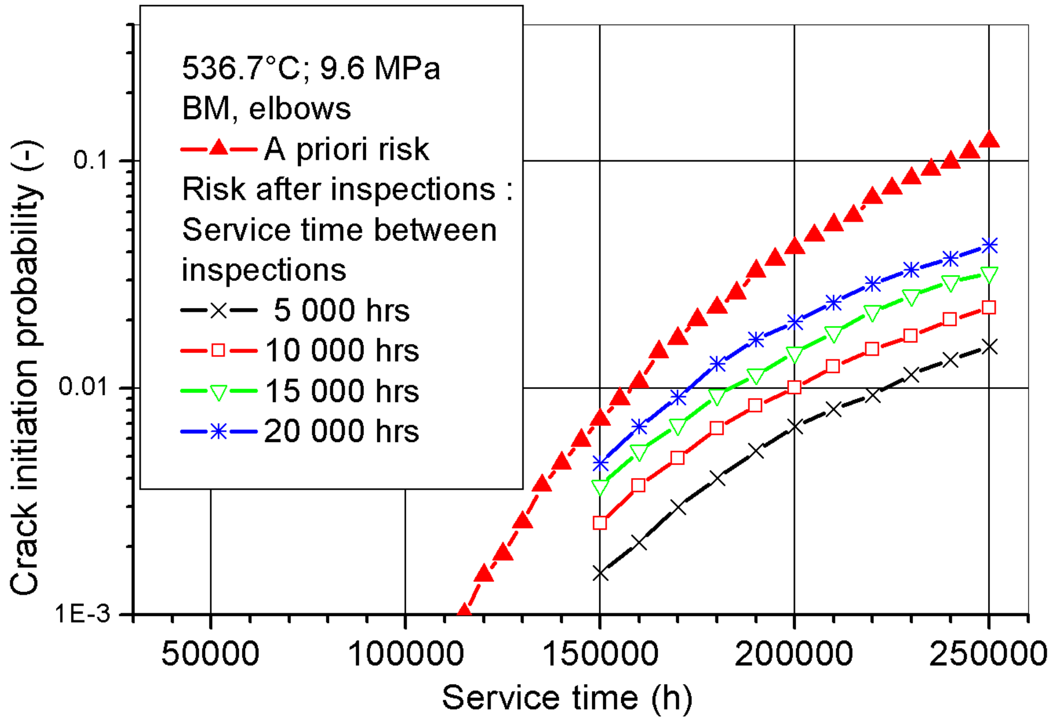

Figure 2 *Total a priori risk of crack initiation in BM and dependence of risk on service time between inspections.*

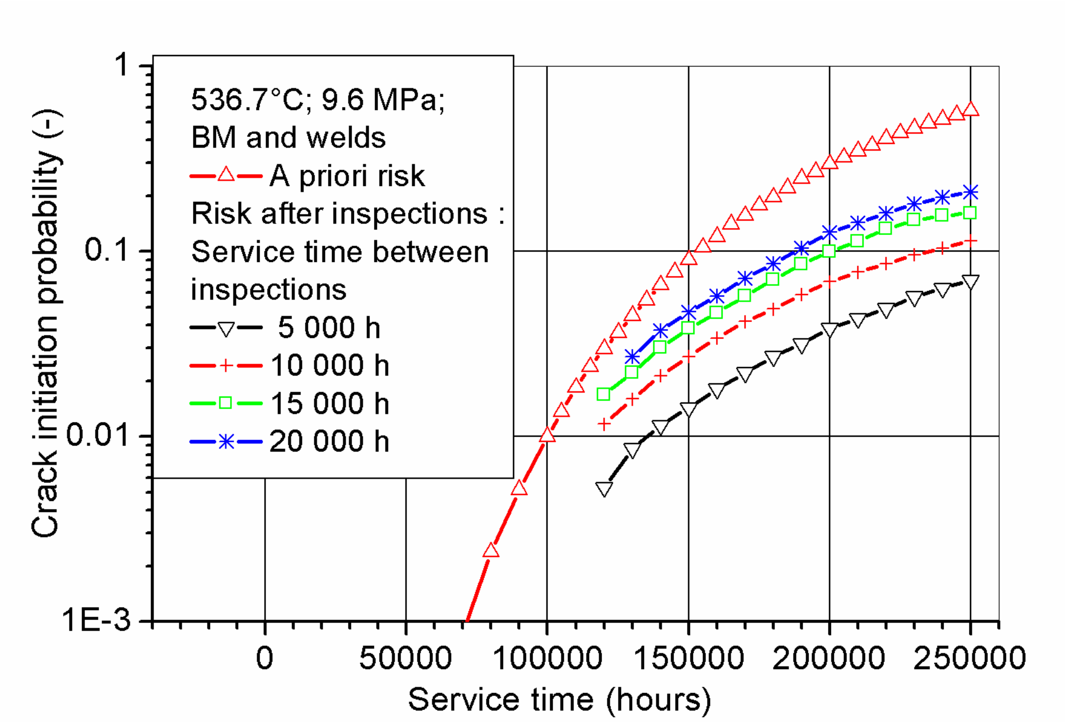

Figure 3 *Total a priori risk of crack initiation in steam pipeline (BM and welds) and dependence of risk on service time between inspections.*

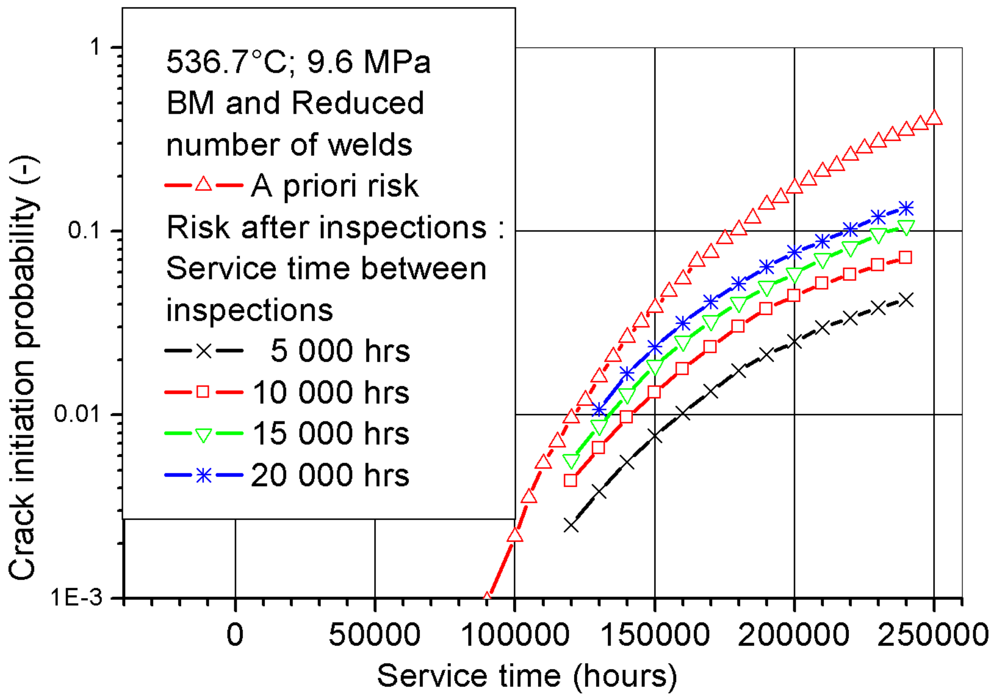

Figure 4 *Total a priori risk of crack initiation in steam pipeline (without externally evaded welds) and dependence of risk on service time between inspections.*

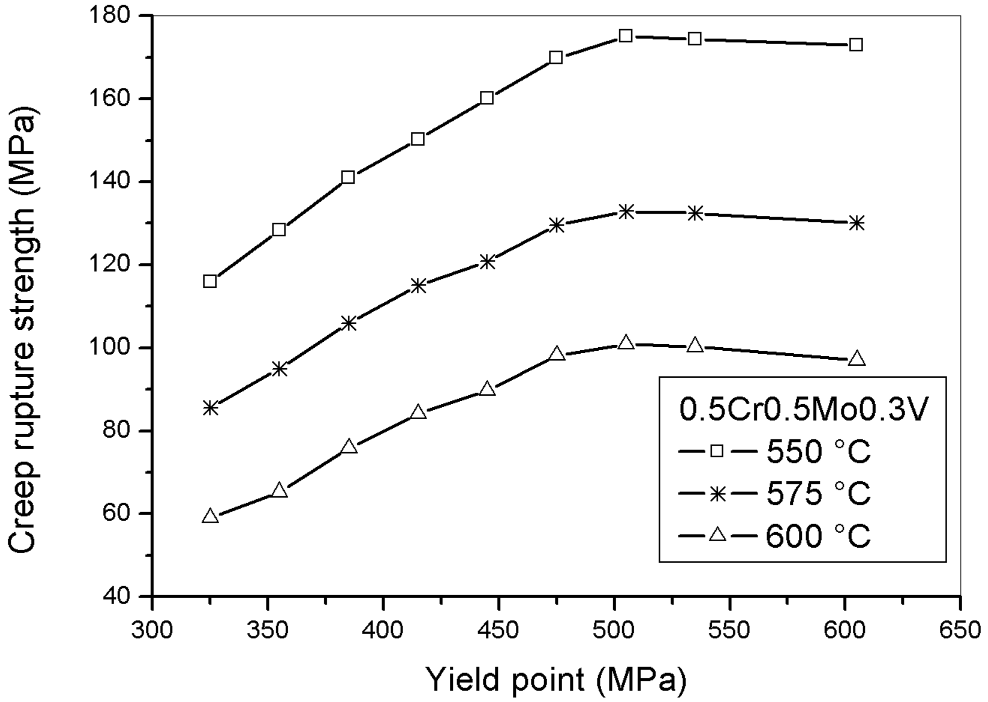

Figure 5 *Dependence of creep rupture strength on yield strength for 0.5Cr0.5Mo0.3V steel .*

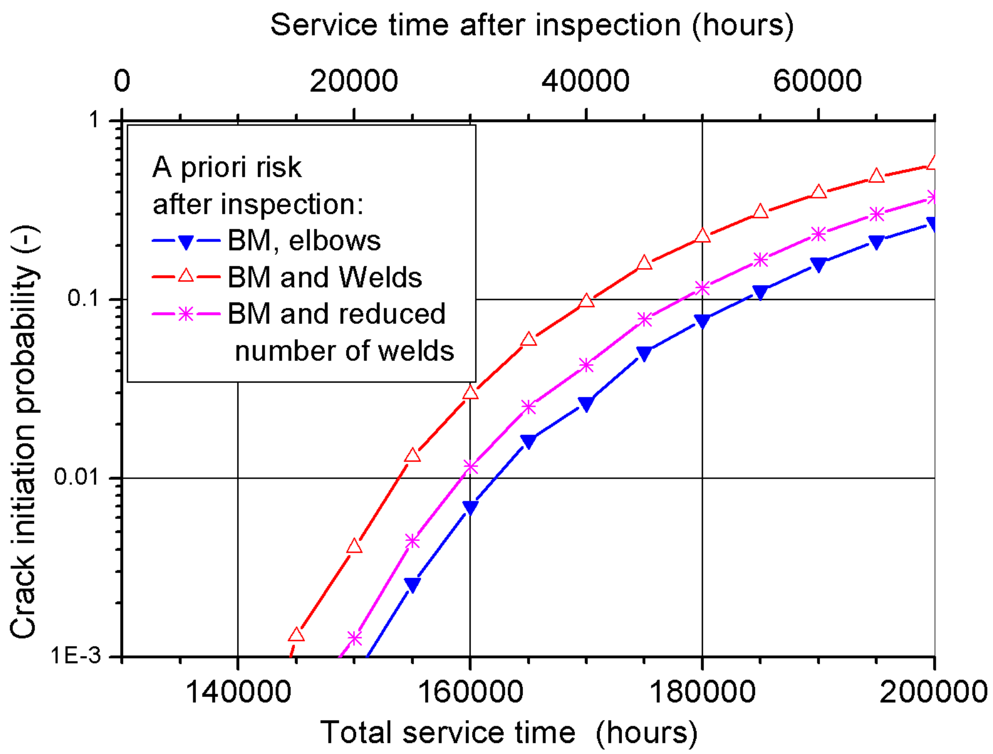

Figure 6 *Dependence of risk of crack-initiation on time of operation (and time after inspection) calculated from residual creep rupture strength.*

4.1

Application of Probabilistic Fracture Mechanics in the Life Assessment of Steam Turbines

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Abstract
Long life endurance and high availability are very important factors in the operation of large steam turbines. The operational safety is ensured by regular inspections in combination with mechanical calculations. Naturally, every operator strives for long inspection intervals, which in turn require a very accurate calculation of damage processes and the corresponding life endurance. Here it is essential to avoid unnecessary high safety factors while at the same time the operational safety has to be guaranteed.

In this context, risk based life assessment approaches, which balance out safety and economic requirements, have become more and more important in the last years. The paper shortly outlines the theoretical background of life assessment with the help of probabilistic fracture mechanics and shows its application for typical heavy-loaded components of large steam turbines.

1. INTRODUCTION

As in many other industrial fields, it is becoming more and more important in the operation of large power plants to balance out safety and economical requirements. So it is essential to identify unnecessary high safety factors in component dimensions, allowable crack sizes or component inspection intervals. Modern calculation methods like the Finite Element Method (FEM) help to further approximate to the actual component limits compared to classical methods. At the same time, this demands to estimate possible risks and impacts of failure as accurate as possible, which in turn increased the application of probabilistic methods in the engineering field. Generally the components are designed by deterministic methods first; based on that, failure probabilities are calculated and assessed (i.e. finally accepted or rejected) with respect to the corresponding failure impacts.

The paper in hand illustrates this area with the example of the assessment of intervals in which the shrunk-on disks of steam turbine rotors are inspected. Section 2 introduces some material failure limits that are typical in mechanical turbine engineering. Section 3 gives an overview of methods to calculate the failure probability. In section 4 the applied probability distributions of material parameters, loads etc. are given, while section 5 shows the obtained results for the above-mentioned disks.

2. FAILURE ASSESSMENT METHOD

The turbine component integrity evaluation uses the well-known failure assessment diagram (FAD) method [2]. This approach enables integrity analyses of components with defects at the same time due to brittle fracture and plastic collapse. The FAD locus divides the area of the co-ordinate frame (S_r , K_r) into “safe” and “unsafe” regions, s. Figure 1.

Once the brittle fracture parameter $K_r = \dfrac{K_I}{K_{Ic}}$ and the plastic collapse parameter $S_r = \dfrac{\sigma}{\sigma_Y}$ for the case under investigation are calculated, the relative position of the evaluation point (S_r , K_r) is considered regarding the FAD locus.

Taking into account the main failure mechanism, three limit state (failure) functions are used:

- Steam turbine rotors and shrunk-on disks (nuclear units) design excludes in wide range of operational speed the plastic collapse occurrence. Therefore the reduced failure assessment is predominantly based on the linear elastic fracture mechanics (LEFM) with small plasticity effect correction at the crack tip (small scale yielding), s. Figure 1 (FAD_{SSY} line). Thus, the resulting limit state function has the following form:

$$\Psi(K_{Ic}, \sigma_Y, a, \xi, \sigma, \text{geometry}) = K_{Ic} - K_I(\sigma_Y, a, \xi, \sigma, \text{geometry}).$$

Low pressure rotors and modern shrunk-on disks are made of materials with high ductility. This leads to the necessity of application the limit state function based on the J-Integral concept (without plastic collapse load criterion consideration, s. Figure 2):

$$\Psi(J_{Ic}, \sigma_Y, a, \xi, \sigma, \text{geometry}) = J_{Ic} - J(a, \xi, \sigma, \sigma_Y, \text{geometry})$$

- Stationary steam turbine components like cylinder casings, valve casings and piping have a common feature – they have a finite geometry (wall thickness) regarding the system "crack – remaining ligament", so that the concept of plastic collapse can be applied to characterise the remaining through-the-wall plastification. Limit state function is based on the failure assessment diagram, s. Figure 1 (FAD line):

$$\Psi(K_{Ic}, \sigma_Y, a, \xi, \sigma) = K_r - \frac{\pi S_r}{\sqrt{8 \ln\left(\sec\left(\frac{\pi}{2} S_r\right)\right)}}$$

3. PROBABILISTIC FAILURE ASSESSMENT

Denote by $(x_1, ..., x_N)$ an N-dimensional random vector, characterising in the frame of the assumed model the uncertainties concerning the geometry, material properties, applied loads and existing/assumed defects which can be modelled as random variables.
The probability of failure is defined as

$$P_f = \int_{\Psi(x_1,...,x_N) \le 0} f(x_1, ..., x_N)\, dx_1 ... dx_N$$

where $\Psi(x_1, ..., x_N)$ is the limit state function (failure surface), $f(x_1, ..., x_N)$ is the joint probability density function of $(x_1, ..., x_N)$.

There are some commonly used approximating methods available for performing the integration of the above multidimensional integral in probabilistic uncertainty analysis.

Mean value estimation method (MVM)

This method typically involves developing the Taylor series expansion of limit state function $\Psi(x_1,...,x_N)$ about the mean values $\bar{x}_i$ of random uncorrelated variables ($i = 1,..., N$). The first and second moments of resulting approximation are then used to calculate the failure probability [1]:

$$\Psi(x_1, ..., x_N) \approx \Psi(\bar{x}_1, ..., \bar{x}_N) + \sum_{i=1}^{N} \frac{\partial \Psi(\bar{x}_1, ..., \bar{x}_N)}{\partial x_i}(x_i - \bar{x}_i) + \frac{1}{2!}\sum_{i=1}^{N}\sum_{j=1}^{N} \frac{\partial^2 \Psi(\bar{x}_1, ..., \bar{x}_N)}{\partial x_i \partial x_j}(x_i - \bar{x}_i)(x_j - \bar{x}_N)$$

The expectation of this expression or the first moment about the mean is then:

$$\overline{\Psi}(x_1,...,x_N) = E[\Psi(x_1,...,x_N)] \approx \Psi(\bar{x}_1,...,\bar{x}_N) + \frac{1}{2!}\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\partial^2\Psi(\bar{x}_1,...,\bar{x}_N)}{\partial x_i \partial x_j}\left(x_i - \bar{x}_i\right)\left(x_j - \bar{x}_N\right)$$

The same procedure applied to the expression for the second moment or variance yields:

$$V[\Psi(x_1,...,x_N)] \approx \sum_{i=1}^{N} V[x_i]\left(\frac{\partial\Psi(\bar{x}_1,...,\bar{x}_N)}{\partial x_i}\right)^2 + 2\sum_{i=1}^{N}\sum_{j=1}^{N}\mathrm{Cov}[x_i, x_j]\left(\frac{\partial\Psi(\bar{x}_1,...,\bar{x}_N)}{\partial x_i}\right)\left(\frac{\partial\Psi(\bar{x}_1,...,\bar{x}_N)}{\partial x_j}\right)$$

Under assumption of normality of the limit state function $\Psi(x_1,...,x_N)$ an evaluation of the failure probability can be made:

$$\Pr\{\Psi(x_1,...,x_N) < 0\} = \Pr\left\{\frac{\Psi(x_1,...,x_N) - E[\Psi(x_1,...,x_N)]}{\sqrt{V[\Psi(x_1,...,x_N)]}} < \frac{0 - E[\Psi(x_1,...,x_N)]}{\sqrt{V[\Psi(x_1,...,x_N)]}}\right\}$$

$$P_f \approx \Phi\left(-\frac{E[\Psi(x_1,...,x_N)]}{\sqrt{V[\Psi(x_1,...,x_N)]}}\right)$$

where $\Phi(\bullet)$ is the standard normal cumulative density function.

First-order reliability methods (FORM)

This method can be considered as an extension of the mean value estimation method. The first-order approximation of the limit state function (Taylor series expansion about the design point) is considered at the closest surface point (most probable point (MPP) or design point) to the origin of the standard Gaussian space.

First, the original random variables $(x_1,...,x_N)$ are transformed into independent standard Gaussian variables $(u_1,...,u_N)$. The original limit state function is then mapped into the new limit state function $\Psi_U(u_1,...,u_N) = 0$.

Second, the point on the surface (in standard Gaussian space) with the shortest distance to the origin is determined. This point is referred to as design point and the distance from the design point to the origin is called reliability index . The probability of failure P_f is thus approximated by

$$\Pr\{\Psi_U(u_1,...,u_N) < 0\} = \Phi(-\beta)$$

Monte Carlo simulation method

To evaluate the multidimensional integral

$$P_f = \int_{\Psi(x_1,...,x_N)\leq 0} f(x_1,...,x_N)\, dx_1...dx_N\ ,$$

n realisations of the random vector of model variables $\left(x_1^{(1)},...,x_N^{(1)}\right),\ldots,\left(x_1^{(n)},...,x_N^{(n)}\right)$ are generated. Corresponding output samples $\Psi^{(1)}(x_1^{(1)},...,x_N^{(1)}),\ldots,\Psi^{(n)}(x_1^{(n)},...,x_N^{(n)})$ are counted as follows:

$$P_f \approx \frac{1}{n}\sum_{i=1}^{n}\Omega[\Psi(x_1,...,x_N) \le 0]$$

where

$$\Omega[\Psi(x_1,...,x_N) \le 0] = \begin{cases} 1 & \text{if } \Psi(x_1,...,x_N) \le 0, \\ 0 & \text{otherwise} \end{cases}$$

The approximation approaches the exact value of failure probability when the number n of trials approaches infinity.

An enhancement of the crude Monte Carlo method is the Monte Carlo simulation with importance sampling. Using FORM the design or most probable point can be obtained and the samples are taken around the “important “ MPP with importance-sampling density.

4. RANDOM VARIABLES

In this section, the used probability distributions are given. Further for the application example it is assumed that the variables are uncorrelated.

Fracture toughness

The fracture toughness follows a three parameter Weibull distribution with the density

$$f(K_{Ic}) = \frac{\alpha}{\eta}\left(\frac{K_{Ic}-\gamma}{\eta}\right)^{\alpha-1} \exp\left[-\left(\frac{K_{Ic}-\gamma}{\eta}\right)\right]$$

with position parameter γ, shape parameter α and scale parameter η.

Yield strength

For the yield strength values a distribution with a lognormal density is assumed:

$$f(\sigma_Y) = \frac{1}{\sigma_Y \cdot s \cdot \sqrt{2\pi}} \exp\left(-\frac{(\ln(\sigma_Y)-m)^2}{2\cdot s^2}\right)$$

Crack growth rate

A model known as “Westinghouse”-rate with mean value of

$$\ln(\dot{a}) = -1.733 - \frac{4056.7}{T+273.3} + 0.004032 \cdot \sigma_Y$$

and standard deviation of 0.587 is found to describe appropriately a crack growth due to the stress corrosion in nuclear power plants [7] as a lognormal variable.

Crack initiation probability

Based on the field data about the number of indications found during inspections of number of different disk types and different locations, the crack initiation probability q_i can be estimated as a binomial distributed variable.

Crack shape probability

The crack shape description based on the crack depth to crack length ratio is assumed to be distributed normally with mean of 0.4 and with the standard deviation of 0.1.

Applied load

For the description of the applied load randomness a normal distribution with a coefficient of variation of 0.1 is taken. The mean value is calculated based on the results of the two-dimensional Finite Element (FE) modelling [3], s. Figure 3.

5. Application: Probability of disc rupture due to stress corrosion

Disk-type rotors are used in large power plant turbines with large exhaust steam volumes, i.e. generally in nuclear power plants. Figure 3 shows a low-pressure turbine with an exhaust area of 20 m^2 per flow, corresponding to the more recent Siemens/KWU models.

The spindle shaft accommodates 8 shrunk-on disks. Although stress corrosion cracking is conservatively assumed to take place in older-type turbines right from the start, it should be mentioned that it is possible to reduce the danger of SCC initiation in newer turbines almost arbitrarily. Experimental and field investigations [4, 5, 6] have shown that, even under severe steam conditions, no stress corrosion cracks are initiated when the ratio of (tensile) surface stress and yield strength remains below 0.5. This requirement was fulfilled throughout the newer Siemens PG disk-type rotors.

For the service example considered here the possibility of SCC should be conservatively taken into account. Moreover it should be assumed that the disks are made of older type material (with lower fracture toughness and high yield strength values), so that the method based on LEFM will be used.

Thus, failure occurs when the maximum value of stress intensity factor K_I exceeds the fracture toughness K_{Ic} , i.e.,

$$\Psi(K_{Ic}, \sigma_Y, \xi, k, a_0, \dot{a}, \sigma) = \frac{{K_{Ic}}^2}{\left[\sigma(\text{applied load, geometry})\sqrt{\frac{\pi}{Q}} \cdot Y(\text{geometry})\right]^2} - a(t_1, t_2) \leq 0$$

for an operational interval between t_1 and t_2.

For shrunk-on disks the most significant crack growth mechanism is stress corrosion cracking (SCC). Low cycle fatigue due to the starts-ups and shut-downs processes is insignificant because of the low number of starts due to the base-load operation character of nuclear units. For stress corrosion cracking the following evolution equation is assumed:

$$a = a_0 + \int_{t_1}^{t_2} \dot{a}(\sigma_Y, T)\, dt\,,$$

whereby as the cases found in the literature on this topic shows, the assumed stress corrosion cracks grow typically in geometrically self-similar manner, i.e. the “crack depth / crack length” ratio can be ignored.

Figure 4 shows the evolution of the disc rupture probability due to the stress corrosion crack growth during operation estimated with the mean value method (MVM line), first order reliability method (FORM line) and Monte Carlo simulation method with importance sampling (MCSIS line). The MCSIS is assumed to be a method yielding “exact” results.

6. CONCLUSIONS

A methodology was outlined for the evaluation of failure probability of shrunk-on disk rupture due to stress corrosion cracking. The basis is an elastic analysis by FEM to compute the stress distribution in the turbine part, the linear elastic fracture mechanics approach within small scale yielding to formulate the failure surface and standard computational methods of structural reliability theory. The failure probabilities were computed using MVM, FORM and MCS with importance sampling.

The results show a very good agreement between the Monte Carlo simulation method and FORM. The FORM is much less time-consuming compared to the MCS method. Thus, the FORM provides a fast and effective method for computing failure probabilities of steam turbine parts and can be used instead of currently used time-consuming MC simulation for calculation of the turbine inspection intervals.

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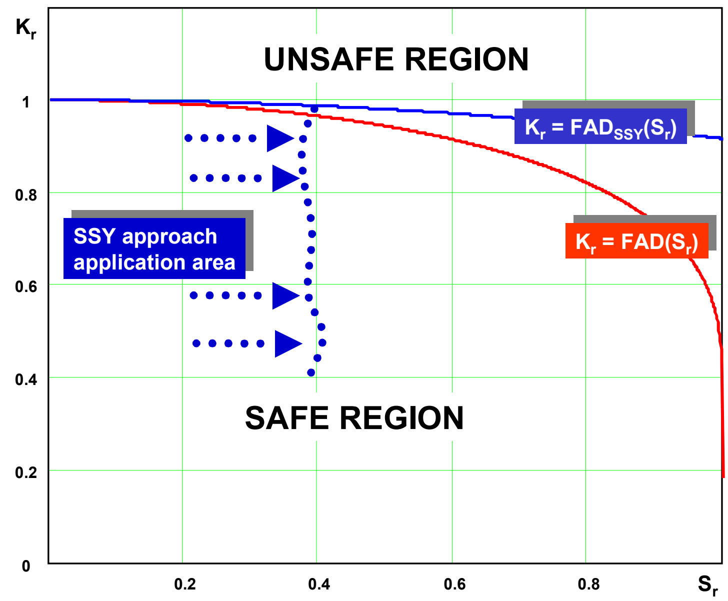

Figure 1 *FAD Diagram.*

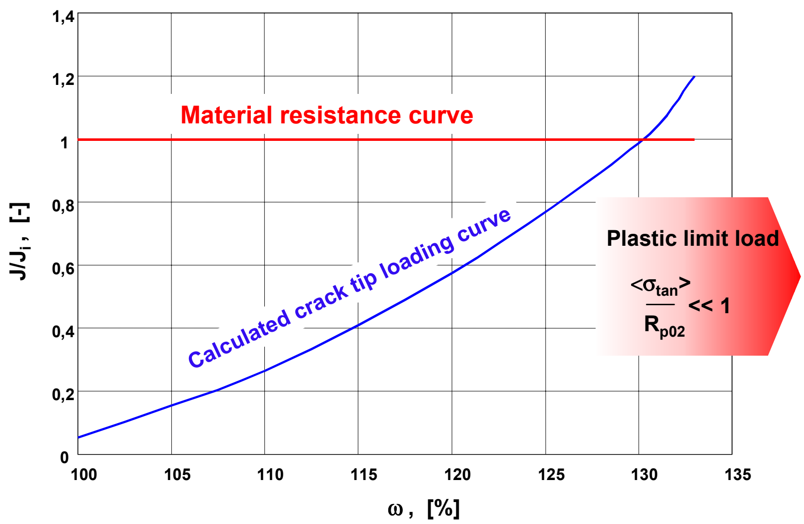

Figure 2 *Failure assessment based on the J-integral method.*

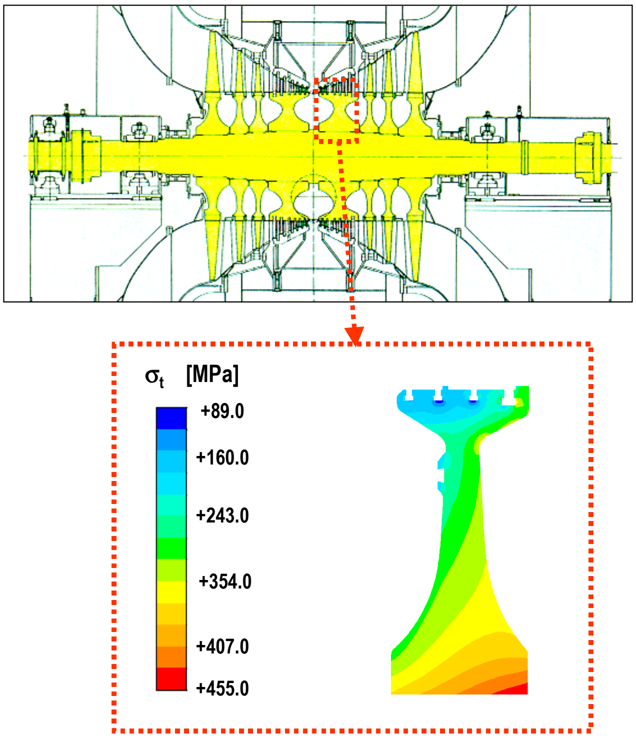

Figure 3 *Low pressure steam turbine and tangential stress distribution in a shrunk-on disk.*

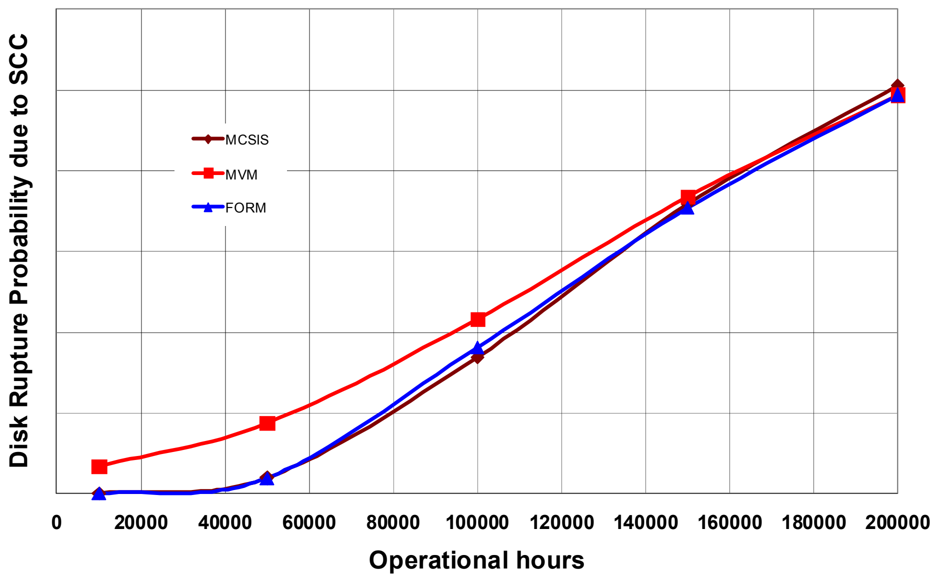

Figure 4 *Effect of operational hours on probability of disk rupture according to different probabilistic methods.*

4.2 ABSTRACT

Steam Turbine Management in a Changing Market

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Abstract

Changes in the UK Electricity Supply Industry since transition from a government owned monopoly 12 years ago, include substantial and – under NETA – increasing commercial pressure for the flexible operation of large capacity utility steam turbine plant originally designed for base load operation.

Flexibility enhancement comes at the price of increases in plant integrity risk, invoked by degradation mechanisms which do not pertain under base load conditions, increased commercial risk associated with failure to supply to contract schedules and the potential for personnel risk if integrity issues are not managed appropriately.

This paper describes the relationship between key aspects of steam turbine plant integrity and flexible operation, and the InnogyOne methodology for safely optimising both.

INTRODUCTION

For steam turbine plant, "flexible operating" capability is primarily defined by the following parameters:

- Maximum number of start up / shut down cycles without incurring unacceptable material degradation.
- Minimum time from barring speed to full MW load for a range of initial HP and IP casing temperatures - typically defined as cold (>30 hrs shutdown) and hot (< 30 hrs shutdown).
- Maximum rates at which MW load can be increased and reduced.

Key design and operating characteristics/constraints associated with these parameters are illustrated in Figures 1 and 2.

Flexibility Enhancement:

- identifies characteristics and constraints which can beneficially be changed
- determines the limiting extent of such changes
- Establishes alterations to plant design and operating practice necessary to implement them.

The application of these principles to key constraints invoked by rotor thermal stress and internal axial clearance is described below:

Figure 1 *Optimisation of rotor integrity risk.*

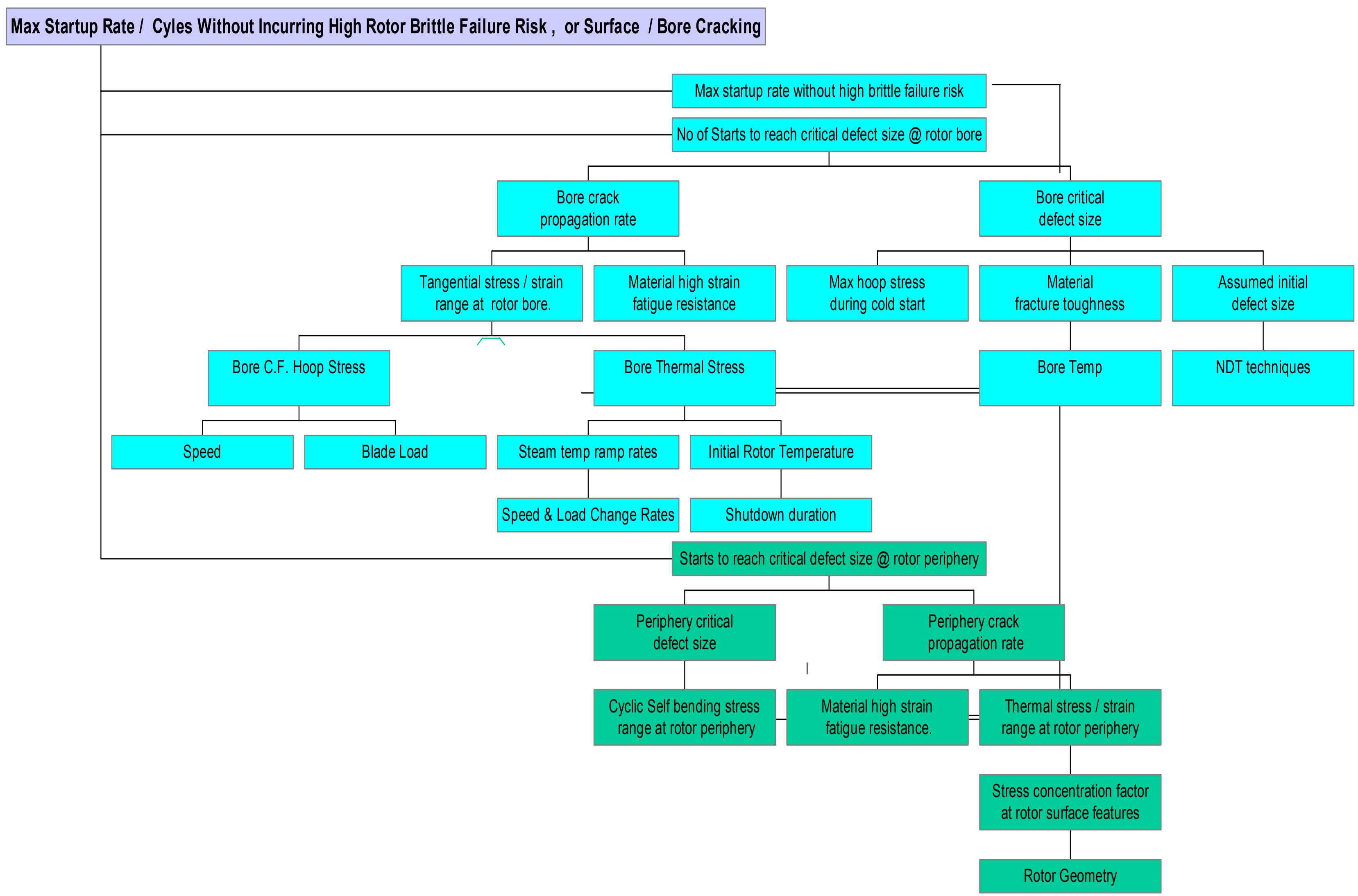
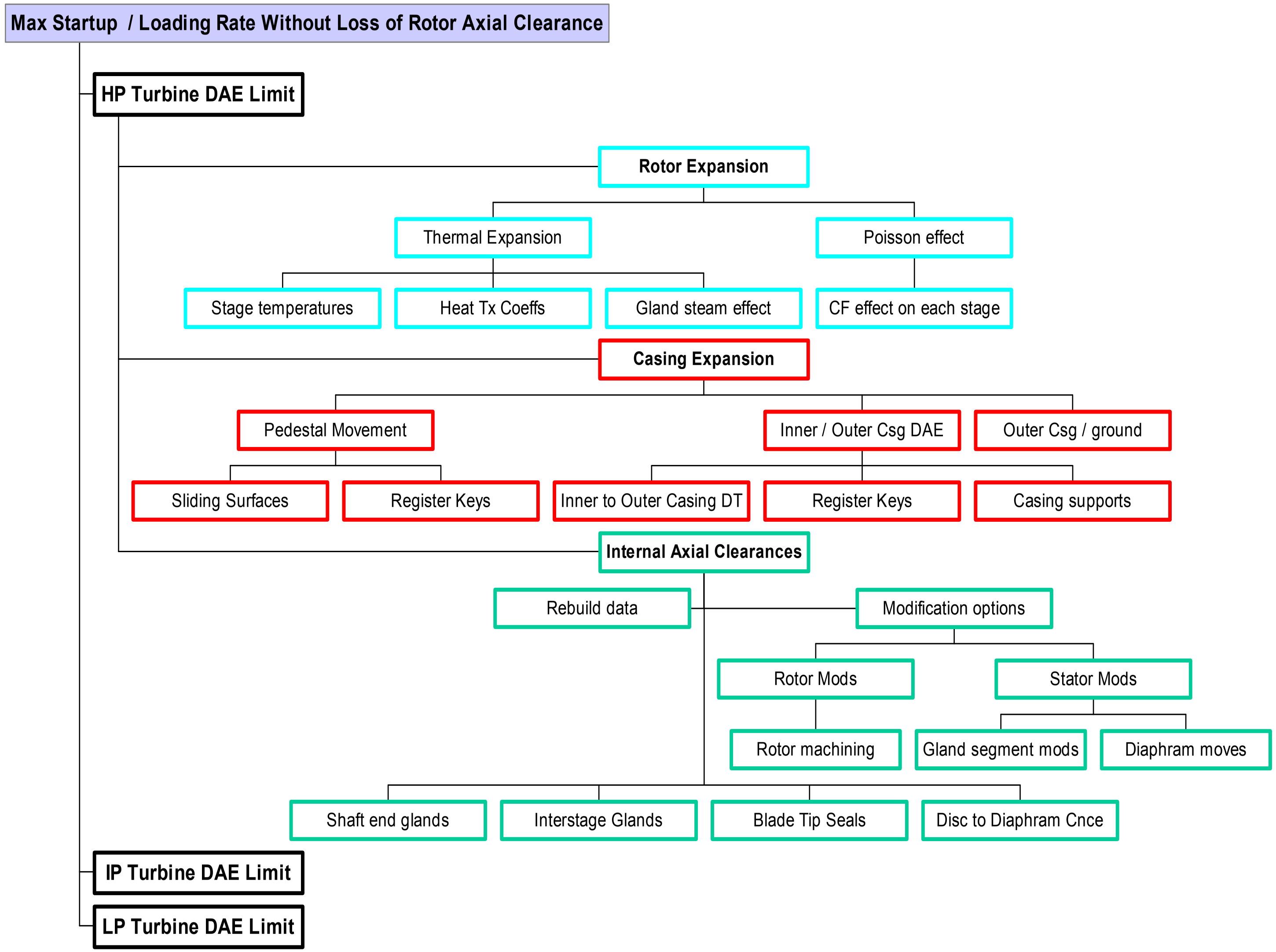


Figure 2 *Optimisation of rotor to casing clearance loss risk.*



4.3 The quantification of the Risks to Steam Turbine Rotors from Stress Corrosion Cracking

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Abstract

This paper outlines a method for quantifying the risks of stress corrosion failures of steam turbines. The method uses probability distributions for all the known uncertainties associated with stress corrosion in this situation. A specific example is given of the way in which uncertainties in the sizing capability of non destructive examination of stress corrosion defects can be used in an assessment of defect size following an inspection. It is also shown how improved values can be obtained for the probability that stress corrosion has initiated in a machine, again based on the examination results. Finally retrospective calculations are made for a steam turbine known to have failed, and the predicted probabilities of failure are shown to be high.

INTRODUCTION

Stress corrosion cracking (SCC) of turbine rotors has been and remains of serious concern to the preservation of the integrity of these components. The key requirements for SCC are to have a material sensitive to stress corrosion cracking, to have a wet environment and to have highly stressed components. Many low alloy turbine rotor steels are potentially susceptible to SCC, although large increases in fracture toughness have resulted in shafts that can tolerate relatively large defects without failure.

High stresses are inevitable in turbine components, particularly in the present competitive electricity markets found in many industrialised countries, where reduced first cost, and hence pressure for maximum efficiency in material use, becomes a significant factor in winning orders for OEMs.

Whether or not a component is wet is determined by the design and operating conditions inside the turbine. Non-reheat machines will run wetter in general. All machines probably experience wetness on starts, but prolonged wetness is likely only in a few stages of a reheat cycle machine. Contaminated steam can make corrosion rates much higher, but ‘pure’ steam can itself be enough to set up corrosion.

SCC is affected by a wide range of variables and it is not a deterministic effect. In this Paper the intention is to outline a method for quantifying the risks of SCC induced failures.

PROCEDURE FOR CALCULATING THE RISKS OF FAILURE

There will be a critical defect size for any specific turbine component that will result in failure at some specified operating condition. There will also be a defect of some size at this location at the time of the assessment-this could of course be zero. The basic assessment of remaining life is that the difference between these two sizes divided by the crack growth rate will give the time to failure. The critical defect size will depend on the configuration of the component, on the stresses acting, and on the fracture toughness of the material. This latter will in turn depend on the operating temperature of the component. The initial defect size can be assessed from the operating hours and crack growth rates, and these calculations can be augmented by the results of non destructive examinations (NDE) of the component. The crack growth rates are essentially empirically based, but will depend strongly on the operating temperature and also on the material proof stress.

Most of the parameters mentioned above have uncertainty about them. The uncertainties can be described, but it is usually impossible to determine for any one component precisely which of the many possible values can be used. Various methods have been used to deal with these uncertainties. An often used method is to evaluate upper or lower bound values for parameters to arrive at pessimistic assessments of the remaining lives. For example lower bound estimates of material toughness can be used with upper bound estimates of initial defect size and crack growth rates to arrive at an estimate of remaining life that is almost certainly lower than the actual value. Actions taken on the basis of such methods will prevent failures in almost all situations. The methods can be too conservative, and on some occasions can predict negative lives.

The method that is to be presented here is based on the retention of all the uncertainties as probability distributions. The SCC crack growth rate, V, is frequently expressed in the form:

$$\ln(V) = A + \frac{B}{T} + C\sigma,$$

where A, B and C are constants, T is the absolute temperature at the component and σ is a yield stress for the material (see, for example, Rosario et al 1998). In the method here this type of expression is taken to define the mean crack growth rate, and it is assumed that the natural logarithms of the possible values for crack growth rate are normally distributed around the mean value with a standard deviation selected to model the available data on SCC crack growth rates.

The operating temperatures of the component being assessed are calculated separately from knowledge of the specific machine, and the relevant steam pressures and temperatures, heat transfer coefficients etc. Ranges of possible metal temperatures result from these calculations, and to reflect these uncertainties a range of possible temperatures is set up, and it is assumed that the actual temperature can be anywhere in this range with equal probability. The material proof stress is modelled by a probability distribution judged to be appropriate to model the available data. In practice normal or uniform distributions were used.

The fracture appearance transition temperature (FATT) is modelled as a Weibull distribution in which the cumulative probability $p(x)$ is represented by:

$$p(x) = 1 - \exp\left(-\left(\tfrac{x}{\beta}\right)^{\alpha}\right),$$

in which α and β are constants selected to provide the best fit for the specific material. The resulting values for FATT from this distribution may have additive constants to improve the fit, and there may be additional corrections to allow for changes in FATT away from the material surface.

The material fracture toughnesses were not available for the work on which this paper is based, so it was assumed that the cumulative probability distribution p was related to the fracture toughness K, by a relationship of the form:

$$K = \left(\frac{D}{E - (T - FATT)}\right)\left(-\ln(p)\right)^{F},$$

where D,E and F are constants.

The critical defect sizes were calculated for each component and were available in a form usually relating the critical defect size to a polynomial expression in the stress intensity; no extrapolation outside the fitted range is valid.

The probability distributions of the times to failure are calculated using a Monte Carlo procedure. In this all the possible combinations of possibilities from the above distributions are retained. To establish an estimate of the remaining life, the probability distributions for all the variables are sampled, and the remaining life is calculated. The process of sampling and calculation is then repeated until stable distributions are obtained. The probabilities of failure in specified future times can then be calculated from the predicted life distributions. Many thousands of independent calculations may be required if accuracy is required at the extremes of the probability distributions. All the calculations were made using the @RISK add in for MS Excel or Lotus 123 spreadsheets. From the probabilities of failure for a single component the resulting probabilities of failure can then be constructed for a complete rotor, for a complete turbine, for a complete power station, or even for a complete machine fleet.

The resulting distributions present the full implications of the information available. The method can be applied to determine the risks of failure during specific operations such as overspeed testing when the components are cold, and potentially have the lowest fracture toughnesses. They can be used to quantify the reductions in risk associated with the avoidance of overspeed testing in this condition. They can also be applied to machines for which NDE results are available. Such approaches are well known, and this paper will present some information on some aspects of the technique that may not be so well known, and also presents the results of an application to a service failure.

Of particular interest in all SCC investigations is the empirical observation that among apparently identical turbine components exposed to comparable operating conditions, some components will initiate SC cracks and some will not. Even in situations where severe cracking has been experienced with in-service failures, some components have been found to be defect free. The reasons for this have been the cause of much speculation, but without much hard explanation being found. This observation can be interpreted as saying that each component has a SCC initiation probability. Some components will initiate defects and some will not, and this appears to be a random event. The actual distributions may vary from component to component, and empirical observation will be required to determine the initiation probabilities in any specific situation.

ROLE AND LIMITATIONS OF NDE

Ideally, the primary role of NDE in the assessment of SCC in turbine components is to detect and on detection, to provide a size measutrement for defects. In practice the geometries that are to be inspected are often of complicated shapes, with features that make detection more difficult, and accurate sizing rather more problematic. For some defect locations the surface where the crack initiates is only accessible with considerable dismantling, involving for example the removal of blade rows. In such situations ultrasonic inspection has to be used for both detection and sizing. Built up low pressure steam turbine rotors may have the discs connected together by dowels located in axially orientated blind holes in adjacent discs. The axial clearances between the discs are small. These blind holes are difficult to inspect from the disc periphery, especially for defects in all possible orientations from the holes. Similarly defects around the disc holes in pin rooted blades with multiple roots are difficult to detect ultrasonically.

In many cases the results of the NDE examinations are more completely expressed as probability distributions. Rather than saying that a component is defect free, it is more accurate to provide a probability distribution showing the probability that various sizes of defect may be present, but are not able to be identified. Such distributions will normally show reduced probabilities as the defect size increases. However, the practicalities of real life rotor inspections are such that the probability of even quite large defects being detected is often short of absolute certainty, see Wall et al, (1998).

The sizing of submerged defects using ultrasonics is an area where considerable progress has been made in recent years, often driven by the needs of the nuclear industry. Once again the geometries of turbine components may act to reduce the accuracy with which defects may be sized. Rather than providing a size estimate, it is often a more complete description of the results if they are expressed as a probability distribution as a function of the defect size.

The representation of the NDE results as probability distributions appears at first glance to be a step back from certainty in the results. It is clearly more comfortable to pronounce a component 'defect free', or to say that a defect is 4.5mm deep, than to report that there is a 30% probability that there may be a defect present even though one has not been detected, or that there is a 20% probability that the defect size is greater than reported. However the simple descriptions normally have hidden baggage in the form of uncertainties or assumptions about threshold levels that are ignored in the simple presentation. It is preferable, for the high risk situations of turbine failures, for these uncertainties to be exposed and included in the assessment of the risks. The ways in which the results can be used in this way is discussed in the next two Sections.

USE OF NDE IN LIMITING POSSIBLE DEFECT SIZE

The previous Section introduced the possibility of expressing the results of NDE examinations as probability distributions. In this Section the application of such distributions for the assessment of defects present in a component are presented. Let us suppose that on inspection a component is cleared of defects. If the component is assumed to have a defect, then it is possible to provide a probability distribution for the possible defect size. This can be done by sampling the probability distributions for the component temperature and material proof stress and then using the sampled values to sample the distribution for the crack growth rate. The sampled rate multiplied by the operating hours will give the required sample of the distribution of the defect size. Repeated sampling and calculations will enable the defect size distribution to be established. Let us suppose that that there are n bands of possible defect size, and then that the probability that the defect is in size band j is p_j.

The inspection results can be represented as n values q_j, where this is the probability that a defect in band j is not detected. The probability that a component that is cleared on inspection has a defect in size band j is the probability that there is a defect of this size present and that it was not detected on inspection. This probability is $p_j q_j$.

The probability that the component is completely cleared on inspection is the probability that for every size band a defect is not detected. This probability is $\sum_{k=1}^{k=n} p_k q_k$.

The probability that there is a defect in band j in a component that has been cleared on inspection is the conditional probability of there being a defect in band j, given that the component has been cleared on inspection. This is the probability that there is an undetected defect in band j divided by the probability that the component has been cleared on inspection. This is given by the expression:

$$\frac{p_j q_j}{\sum_{k=1}^{k=n} p_k q_k} .$$

Figure 1 shows the probability distribution for a possible defect size. Figure 2 shows the NDE capability of detection, expressed in probabilistic form. Finally Figure 3 shows the modified probability distribution for the defect. It can be seen that the upper range of possible defect sizes is effectively eliminated by the inspection, even though the inspection itself in this case is rather a poor one, with only a 50% probability of detecting a 6 mm defect.

PREDICTION OF INITIATION PROBABILITY

As mentioned above, it can be assumed that the number of locations at which SCC initiates can be treated as a random variable. Put another way, there is a probability that any single location will initiate SCC, and this probability will have some distribution. It is known from full scale empirical work that the initiation probability can vary greatly between components and between the same component on different machines, for reasons that are not at all well understood.

In the probabilistic assessment of the risk of failure from SCC on a machine it is vital to include the initiation probability to avoid unnecessary pessimism in the calculations. With the present state of knowledge about SCC initiation, the initiation probabilities will need to be established empirically. This is where NDE can play an important role through the detection of defects, although the uncertainties inherent, as discussed above, need to be accounted for.

For any rotor it is possible to calculate the probabilities of a given number of defective components being present on the assumption that there is a specified initiation probability defined. This can be carried further with the assumptions already mentioned about the probabilities of defects being detected by NDE. In other words for it is possible to calculate the probability that a specified number of defects in a particular location will be detected on a rotor, on a particular turbine, or even on a complete power station for a specified initiation probability.

If an initial estimate is available for the probability distribution of the initiation probability, then these data can then be used with a Bayes analysis to produce a revised distribution, based on the site data obtained by NDE. In the example shown here it was assumed that the possible initiation probabilities are uniform between zero and a value of 0.25, or linearly increasing from zero up to a value of 0.25. Figure 4 shows the predicted probability distributions following the Bayes analysis. It can be seen that broadly similar distributions are obtained for the two initial assumptions.

EXAMPLE OF REAL LIFE APPLICATION

In 1969 a disc on unit 5 at Hinkley Point 'A' Power Station failed during an overspeed test. Subsequent investigation showed the cause of the failure to be SCC in the disc bore keyway, and many other SCC cracks were found. In subsequent work other individual rotors from other machines at the site were subjected to overspeed tests in works overspeed pits, and one of these rotors also failed from SCC defects in the disc bore keyways. Gray, 1972 and Kalderon 1972 present the detailed results of the immediate investigations into this failure, and Hodge and Mogford (1979) give a detailed account of subsequent work. The application of the probabilistic methods outlined above have been applied to these failures to provide a yardstick of the predicted risk levels associated with the failures.

The calculations assume that the machine in question had survived for 20,000 hours in operation, and the calculated probabilities refer to the probabilities of failure of this unit from a defect in a keyway during a cold overspeed. The resulting predicted probabilities of failure are shown in Figure 5 for various assumptions for the probability of initiation of SCC.

Additional calculations were made for the individual LP rotors from Hinkley Point A that were tested at 20% above rated speed in an overspeed pit. Table 1 presents the calculated probabilities of failure for these rotors, based on their known material composition, and the running hours a the times of the tests. Different values for the initiation probability are used, including a set of values derived from the destructive failure of the Unit 5 rotor components.

DISCUSSION

The results presented here are a brief look at some extensive studies that were made into the calculation of the risks of failure of steam turbines from stress corrosion cracking in disc bore keyways, in disc buttons and in different designs of blade root fixings. The approach has the advantage that all the available information and uncertainties about the materials and the cracking mechanism can be included in the prediction of the risks of failure.

The specific details included in this paper are related to the use of the uncertainties inherent in the NDE testing of turbine components. It is possible to use these uncertainties in a probabilistic way as shown here. The application to the production of a post inspection defect size distribution is of great value in any application to real life machines, as such inspections are frequently used as the basis for returning machines to service when it is known that there are defects either present or potentially present. In the application shown here the probability of detecting a defect is taken to drop to zero as the defect size increases. In practice there is always a residual low level probability that even a large defect may not be detected.

The treatment of SCC initiation as a probabilistic event is another area where NDE can be valuably used, despite the associated uncertainties. As demonstrated here, the initiation probability can have an important effect on the predicted probabilities of failure. The method presented enables the distribution of the initiation probabilities to be revised, based on inspection results, thereby avoiding unnecessary pessimisms by the full use of all the available information.

Finally the application of the methods to the Hinkley failure, while of no immediate practical value in itself, does demonstrate the levels of predicted risk that were present prior to the failures. It is clear from the results that the predicted levels of risk of failure for the machine were high. Similarly the predicted risks of failure of the LP rotors also show reasonable agreement with the observed outcomes of the overspeed testing.

CONCLUSIONS

The following conclusions can be drawn:

- It is possible to calculate the risks of failure of individual components or of complete machines or of power stations or even of complete fleets based on a probabilistic assessment of the risks.
- The methods can be used to incorporate the inherent uncertainties associated with non destructive inspection of individual components.
- The non destructive examination results can be used to determine revised distributions for the probability that stress corrosion has initiated.
- The retrospective application of the results to a specific failure has shown broad consistency with the practical outcomes.

ACKNOWLEDGEMENTS

I would like to acknowledge many valuable discussions with Mike Gull, John Mackay and John Ditchfield, all of Magnox Electric, who all made significant contributions to the work described here, and also to Geoff Spink of Innogy and Dave Carr of ERA who provided valuable insights into the stress corrosion of steam turbines. The deficiencies of this paper are, however, all down to me.

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Table 1 *Calculated probabilities of failure for LP rotors in overspeed pit*

Rotor	Initiation probability			Outcome
	1 in 5	1 in 2	Actual	
Ex Unit 3 LP1	0.0054	0.014	0.019	Survived
Ex Unit 3 LP2	0.014	0.034	0.036	Survived
Ex Unit 6 LP1	0.101	0.242	0.361	Survived
Ex Unit 6 LP2	0.131	0.303	0.403	Failed

('Actual' refers to the initiation probabilities inferred from subsequent analysis of components from the failed unit 5 machine)

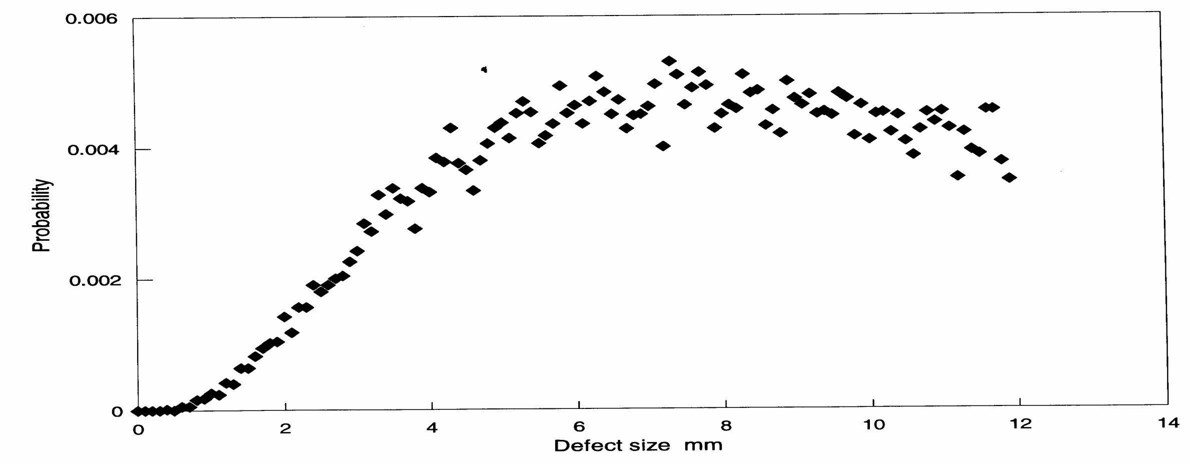

Figure 1 *Probability distribution for defect size.*

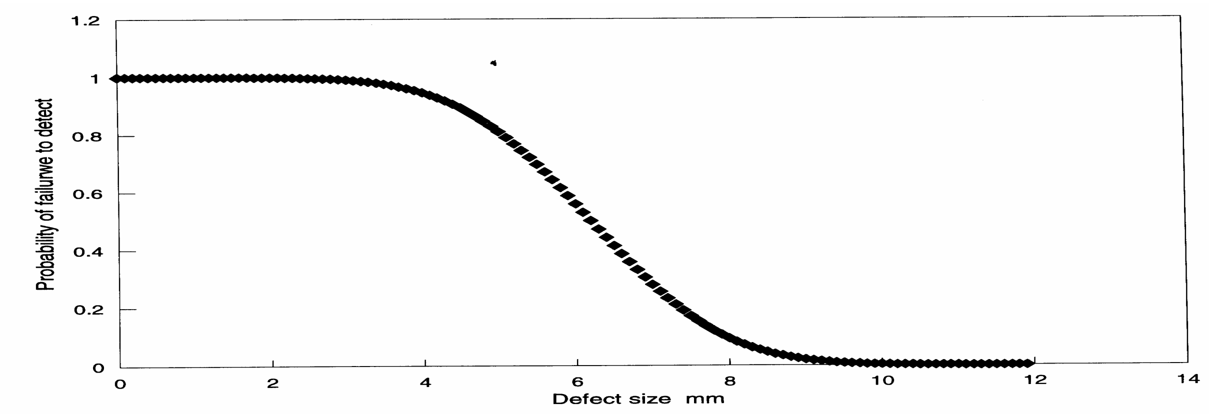

Figure 2 *NDE capability expressed in probability terms.*

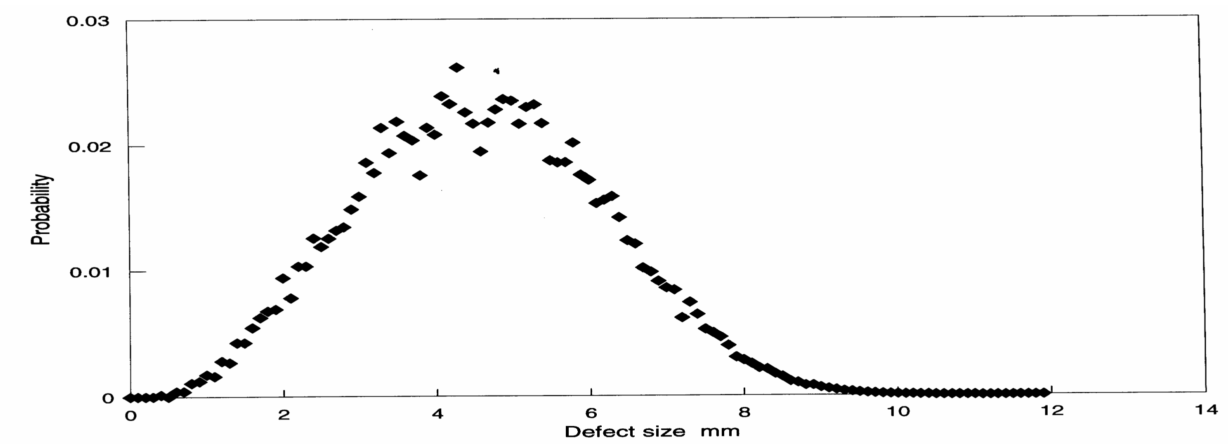

Figure 3 *Modified probability distribution for defect size.*

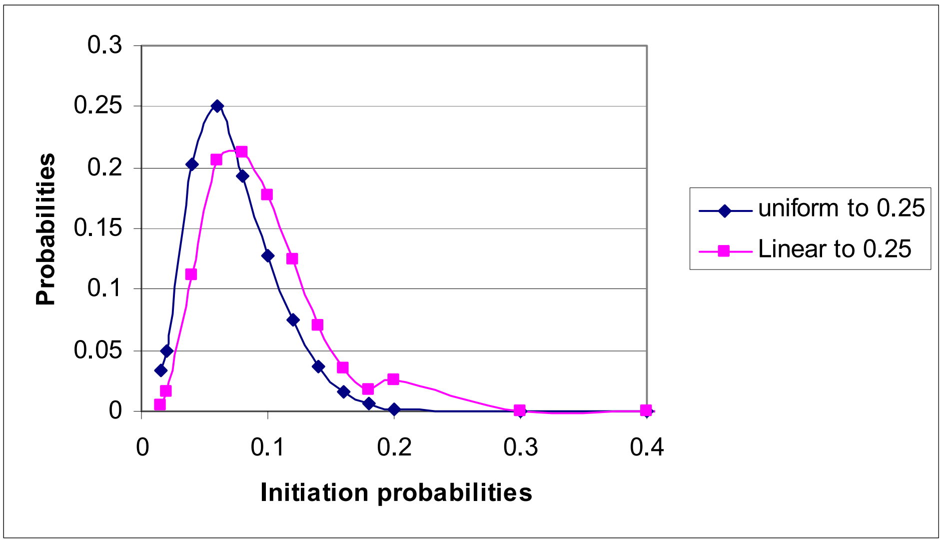

Figure 4 *Distributions for initiation probability.*

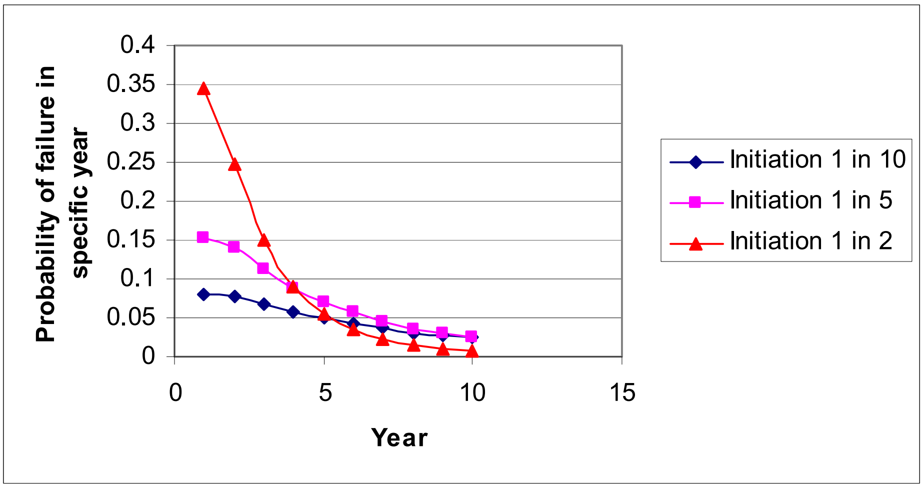

Figure 5 *Hinkley Point Unit 5 probabilities of failure for various initiation probabilities.*

5.1
Generator Management, Balancing Economic Risks and Rewards

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Abstract

Modern CCGT power plants have recently been constructed using functional specifications and at minimum cost. Significant cost savings have been promised by the supplier by using ever larger air cooled generators. Flexible operation in a competitive market has also introduced further demands on the more conventional but ageing machines.

Ensuring that the correct monitoring is carried out and that the risk of cutting costs during maintenance is fully assessed are the subjects of this paper.

INTRODUCTION

Two pole generators directly connected to steam turbines have been used since the early days of bulk power generation. In the UK their rating slowly increased in the first half of the 20th century, reaching 30MW in 1939. Rapid developments in generator design following the Second World War introduced hydrogen and water direct cooling and resulted in the first 500 MW unit in 1966.

After this point was reached development of generators progressed slowly in the UK with 660 MW generators providing the next rating point for a range of nuclear, coal and oil fired units. Although full speed 900MW generators were designed for the CEGB these were not built. However, overseas large nuclear units pushed up the generator rating to some 1500MW with the ultimate goal of 2000 MW seeming possible.

The majority of the major generating plant was operated as part of Nationalised industries and supported by large central engineering organisations. The close working ties between the operators and the manufacturers resulted in a clearly defined operating and maintenance regime being produced. They might therefore be considered to be “risk free”.

Privatisation of the UK Electricity Supply Industry in 1990 coupled with the relaxation of restrictions in burning gas for power generation caused a fundamental review of this strategy. Suddenly the prime mover of choice was the gas turbine and unit rating reverted to approximately 150 – 200 MW. These stations were required to have a very short build time and low maintenance and operating costs. In the European 50 Hz market to achieve this the generator of choice was air-cooled.

In addition to the new types of machines the Privatisation of the UK Electricity Supply industry has resulted in strong commercial pressure being exerted on Power Generators to ensure that their Turbine generators are capable of operating at all points within their design capability. This has resulted in unexpected problems as plant is possibly being operated at its limit for the first time in over twenty years.

These machines are being introduced into a vastly different arena to that which dealt with the major problems in the 1960-70’s. The advent of Independent Power Producers (IPPs), with no engineering support and the consolidation of the generator manufacturers has resulted in a critical situation that cannot be considered to be “risk free”.

Balancing the potential rewards obtainable from the choice of these new generators against the possible risks during operation and maintenance is the subject of this paper.

OUTAGE PLANNING

Outage planning activity has changed considerably with the advent of CCGT plant. Traditionally outages in the UK took place during the period March to October, with the interval between outages determined by statutory boiler inspections, typically four to six yearly.

It was anticipated that steam turbine cylinders would be opened and the generator rotor removed every eight years. Because of the linkage to boiler inspection, there is only a small possibility of turbine generator condition being used to determine outage intervals.

Outages on the CCGT plant are dictated by the requirements of the hot gas path components, with major outages occurring typically every 20-25000 operating hours. Any work on the steam turbine and generator being carried out during this much-reduced window of opportunity.

Modern CCGT plant is usually built to a "standard" design. This may be a single shaft unit, having the generator installed between the gas turbine and the steam turbine. The elimination of the overhead crane and even the building may also be another "cost saving". The cost and complexity of removing the generator rotor introduces pressures to delay or even eliminate the normal generator inspection. Risks can be reduced by using robot inspection techniques although experience of this method is currently limited. At some stage, a full inspection will be required.

Detailed plant status documents are therefore required to allow problem areas to be clearly identified and work planned to remedy any faults. These should be complemented with on-line and off-line condition monitoring.

PLANT CONDITION MONITORING

The introduction of functional specifications and new designs of generators has resulted in a significant reduction in the monitoring that is fitted as part of the original equipment. Vibration monitoring and a few temperature detectors are all that is likely to be supplied as standard. This follows the perception that for the new types of air-cooled machine that maintenance is expected to be not much more than a small amount of cleaning every five years or so.

Evidence to date on the operation of this new plant is that a number of significant deficiencies in the design are becoming apparent after only short periods of operation. Monitoring of machine condition is therefore considered essential and has required the retrofitting of additional equipment. In particular equipment to determine partial discharge occurring in stator windings.

Vibration analysis, generator condition monitors and rotor flux probes are also used to assess the generator condition. All of the information collected from these systems is combined with the knowledge of the machine design and visual inspections to determine the maintenance/repair schedules required during the gas turbine hot gas path inspections.

MAINTENANCE, REPAIR OR SPARES

In 1992 the European Community issued the Utilities Directive. This was introduced to ensure fair competition for plant supply and service contracts having a value above 400000 €. This directive requires the use of common European standards, a declared method of assessing competing tenders and has a major impact on the letting of contracts.

This directive and the commercial demands of the UK electricity supply system have resulted in a drive to reduce costs to an absolute minimum. This means that the supply of a major spare component or a major plant overhaul may end up being carried out by a non-OEM contractor. The Directive has also necessitated a move away from specific to functional specifications with the emphasis on performance guarantees. This type of contract needs to be carefully thought out and it may be necessary to have specific performance criteria for each part of an exercise.

It is expected that the OEM will have the most complete knowledge of the plant design and in theory should be able to provide the best service. Any move away to the lowest cost contractor must be carefully balanced against the "hidden value" obtained by the use of the OEM. OEMs may not help their case by making assumptions on, say the extent of supply, in their tender response. A comparatively high price may ensure work is carried out without question, small additional items being corrected as a matter of course. The lowest price job may require extensive involvement of the Central Engineering Group and subsequent lengthy argument regarding variations and extras. There is also a difficulty in safeguarding confidential manufacturing/design information, assuming that any exists.

Following an initial aggressive attitude towards the OEM Innogy is looking much more carefully for the value of a contract rather than just its price. Tender assessment models that look at all aspects of the bid have been constructed. In particular the design authority / capability plays a significant part. Identifying and managing the potential risk is likely to be the key to achieving a satisfactory project.

RISK ASSESSMENT

In addition to the normal commercial risks, there are other technical risks that need to be considered when placing a contract with a company other than the OEM. It has been shown during recent contracts that the additional engineering support required from within Innogy can be significant. A certain amount of "re-inventing the wheel" is bound to take place when confronting problems and the lack of access to the original design calculations and criteria is a potential problem. A risk assessment procedure has therefore been developed to allow for this "hidden" cost when assessing tenders.

Take for example the rewind of a generator rotor. No spares are available and the work has to be carried out during a normal outage period. Expressions of interest have been received from a number of OEM and non-OEM suppliers.

In the process two elements are considered, firstly factors our experience has shown results in direct or indirect cost increases and secondly the ability of the rewind contractors design to meet the performance requirements of the specification.

DIRECT/INDIRECT COSTS

For instance, the lack of suitable facilities for carrying out rotor rewinds e.g. clean conditions and the availability of local balancing facilities should be considered. It is very difficult to put a cost on these issues but some form of weighting should be applied.

The design capability of the various rewind companies is obviously very important. The company needs to demonstrate a detailed modelling and design competency such that any redesign of the rotor winding will result in the desired cooling performance whilst maintaining adequate clearances, endwinding retaining ring factors of safety etc.

Programme Failure to meet the agreed programme may have repercussions resulting in lost generation. However, if the rewind were of a spare rotor this would be unlikely. The implications of programme overruns are more likely to be greater Innogy involvement, increased chance of problems at the end of the contract and knock-on effects on associated contracts.

Facilities The standard of dedicated repair/rewind workshop areas has an impact on the quality of the resultant work. For instance, poor clean conditions is likely to result in interturn defects when in service which may cause operational difficulties and hence constraints on potential income. Extended guarantees against defects would enable the costs of repair to be recovered but this would not cover lost generation costs or MVAr capability payments.

Balancing Overspeed Facilities for large generator rotors are limited in the UK. The consequences of transporting a rotor overseas for balancing are likely to be the difficulty in controlling or monitoring the work, increased Innogy involvement due to unfamiliarity of balancing techniques, standards etc. and the result of extended travelling times for witnessing.

History The past history of relevant rotor rewinds is an important consideration. Proven experience in this area gives a degree of confidence and should be criteria for tender selection.

Problems Known problems associated with recent rewind work should be considered. Since it is unlikely that a contractor would openly admit to any serious problem encountered as a result of their work, this factor relies on intelligence gathering when the work has been done outside NP.

Each of the above has been assigned a weighting factor dependant upon its overall importance. A score of between 1 and 10 is made for each contractor against each factor which when multiplied by the weighting factor gives a "weighted" score. The total for the five factors gives a total score, which is then used against the "Standard" to give an aggregate score. The adjustment to the Tender prices is then made on a basis that each point is equivalent to "x" days lost generation pIus "y" days increased Innogy engineering support.

"x" and "y" are constantly updated to reflect experience to date and market conditions.
An example of a tender assessment is given in Table 1.

DESIGN

This part of the analysis concerns the design capabilities of the rewind contractors. It focuses on the contractors ability to produce a design capable of addressing any known problems associated with the current rotor. Although significant liquidated damages would be sought if the design fails to meet the specification, it is likely that these would not offset the potential loss of income to Innogy from loss of generation (MW or MVAr).

The example analysis has used the various rewind options and contractor capabilities for a 500 MW rotor. The weighting used is based upon the estimated fault free life of the proposed design. For example taking the two extremes; a re-design only utilising uprated interturn material would have a life of 2-3 years against a full winding re-design life of 10 years. The additional costs incurred, calculated on a Net Present Cost (NPC) basis, for the shorter life is then used as the basis for the weighting factor. Details of an example assessment are given in Table 2.

For the above example, an additional estimated £172,000 should be allowed for when assessing tenders.

CONCLUSION

Modern plant is sold based on saving capital cost. Great care must be taken to ensure that this initial advantage is not lost during subsequent operation and maintenance by choosing the wrong strategy. The correct monitoring and an engineering plant status assessment should be used to obtain this result.

Table 1 *An example of a tender assessment*

		Contractor 1 (OEM)		Contractor 2	
Element	**Weighting Factor**	**Score (1-10)**	**Weighted Score**	**Score (1-10)**	**Weighted Score**
Programme	0.25	1	0.25	6	1.5
Facilities	0.1	2	0.2	5	0.5
History	0.1	2	0.6	5	1.5
Problems	0.3	5	1.25	7	1.75
Balancing	0.25	2	0.2	5	0.5
Total	1.00		2.5		5.75
Aggregate Score			0		3.25
Tender Adjustment			£0		£70,000
Programme		• Two rotors of this design rewound. • 12 Week Programme proven		• Lack of in house facilities, over optimistic programme jeopordising quality of work.	
Facilities		• Dedicated rewind facility - good controls.		• Use of third party facilities. • Lack of control	
History		• Two rotors of this design completed. • Proven operating record		• No rewinds of this type. • Other 500 & 660 Mw rewinds using OEM supplied kit.	
Problems		• First rotor has small non current carrying interturn fault		• Reported problems with 500 MW rotor after rewind.	
Balancing		• Local balancing facilities		• Use overseas pits. • Good facilities but transport and programme implications.	

Table 2 *Details of an example assessment in design*

Design	Description	Costs (on NPC 10 year basis)	Tender Adjustment
1	OEM Proven Design	£684,000	£0
2	Ad-hoc redesign, no modelling confirmation	£786,000	£102,000

5.3
Managing Technical Risk for Pressure Parts

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Abstract
This paper describes the development and application of the Innogy Technical Review Process. The periodic in-service inspections of the pressure systems of large power generating plant are subject to the Pressure Systems Safety Regulations 2000. For these major and complex pressure systems, especially the boilers, it has become established practice throughout the industry for the written scheme to be supported by a technical review. The technical review is a risk management tool and facilitates the required inspections to be identified comprehensively, systematically, and in detail, and takes into account the changing plant condition and operational requirements. The Technical Review Process is linked to the Engineering Risk Assessment Process and the O&M Documentation system.

1. INTRODUCTION

Thermal generating plants comprise major pressurised systems. These systems include the feedwater, steam and boiler circuits in both conventional and CCGT plant. On account of the large amount of stored energy in these pressurised systems, a major failure could result in injury to personnel and commercial penalty. For reasons of safety, pressure systems are subject to legislative control.

The Innogy Technical Review Process is a risk management tool and has been developed to reinforce compliance with the 1989 and 2000 UK legislation on pressure systems (Refs. 1 and 2). The Technical Review Process is concerned primarily with the statutory in-service inspection of pressure system plant. The process is a systematic and comprehensive assessment of all the components within a pressure system. The process identifies the detailed inspections required to justify operation over the planned operating period.

For the large and complex pressure systems associated with main unit generating plant, it has been found to be essential for the written schemes of examination to be complemented by a technical review.

The flexibility of the Technical Review Process means that it can fulfil a variety of duties and can also be adapted for application overseas, on a case by case basis, to supporting the main objectives for the management of pressure system plant. In the UK, the process is accepted by the engineering inspection organisations as industry best practice.

To place the Technical Review Process into context, the relationship between the Technical Review Process and the Innogy Engineering Risk Assessment Process, and the links with the O&M Documentation system, are discussed.

This paper includes a brief review of the development of boiler plant and the statutory requirements relating to pressure systems. The technical review and the process of its periodic updating are described.

2. RISK

2.1 Aim of pressure systems safety regulations

Safety of Pressure Systems (Ref. 2, paragraphs 6) states:
"The aim of the PSSR is to prevent serious injury from the hazard of stored energy as a result of the failure of a pressure system or one of its component parts. The regulations are concerned with steam at any pressure, …"

2.2 Risk equilibrium

Risk can be divided into two categories, commercial, and safety. Commercial risks associated with pressure systems are those that do not have significant implication on safety. Commercial risks may be managed on purely economic grounds.

However, whilst in a power station boiler, the failure of a superheater tube inside the boiler envelope would not normally be judged to present a significant safety risk, at some point (in terms of pressure part size and/or physical position) a failure would present a risk to safety. The identification of the boundary between safety and commercial risks is often a matter of judgement.

Where there are risks to safety, then controls must be applied to reduce or eliminate these risks. The ALARP principle may also apply. There is never going to be zero risk. Statutory compliance is not a fixed threshold, and is likely to be tested only when things go wrong.
The Technical Review can be used to record policy and arguments where it is necessary to exercise judgement with respect to:

- The "grey area" between commercial and safety risk, and
- the appropriate extent of examination, repairs and controls for safety risks.

2.3 Risk management processes

The main process by which Innogy identifies technical risk is the Engineering Risk Assessment Process (ERAP). The ERAP covers all plant areas and all sources of technical risk, and identifies and ranks risk. The ERAP confirms that for power generating plant, the risk from pressure parts is highest. This endorses the need for the detailed Technical Review Process.

In turn, for specific problem areas, the technical review refers to the respective Technical Procedures that are part of the Innogy O&M Documentation system.

Thus there is a fundamental link between the Technical Review Process and the O&M Documentation system, and also a link between the ERAP and the Technical Review Process.

3. HISTORICAL CONTEXT

Table 1 *Development of boilers and periodic inspection*

Boiler development (Refs 3, 4)	**Controls: Periodic boiler inspection (Ref. 5) Legislation**
1725 Haystack Boiler 2 - 3 psig. Waggon Boiler (to 5 psig). 1795 Rolled iron plates available allowing construction of dished ends. Cornish boiler (single internal firebox).	
1844 Lancashire Boiler (two internal fireboxes). (By 1889 operating at 120 psi. In use to present, 250 psi.) 1873 Water tube boiler 1882 First public steam power plant. B&W water tube boilers. 120 psi.	1800 - 1850: Increasing incidence of boiler explosions with increasing drive to higher pressures. 1854 Periodic boiler inspections introduced (Ref. 6) 1858 Insurance linked with periodic inspections (Ref. 6) 1878 Factories & Workshops Act 1882 First Boiler Explosion Act
1957 Supercritical 120 MW unit. 4500 psi.	1901 Factories & Workshops Act 1937 Factories Act 1961 Factories Act 1974 H&SWA 1989 PS & TGC Regs
	2000 Pressure Systems Safety Regulations

3.1 Innovation in boiler design and inspection

During the early part of the Industrial Revolution, around 1700, boilers were essentially kettles as used in Newcomen's atmospheric engines, often used for pumping. Subsequent major innovations were the introduction of the firetube Cornish and Lancashire boilers in 1795 and 1844 respectively, the latter remaining in use today, as the shell boiler.

However, between 1800 - 1850, there was an increasing incidence of boiler explosions, caused by the increasing drive towards higher pressures. From the point of view of boiler safety, the significant innovation was the introduction of periodic boiler inspections. This was subsequently linked to the plant insurance. Hence the present arrangement whereby much pressure part inspections are carried out by the engineering inspection organisations owned by parent insurance companies.

In 1873 the water tube boiler was introduced. This had the great advantage of being inherently safer than the earlier type (fire tube) should a pressure part failure occur.

From the recognition in the 1850s of the huge benefit in carrying out periodic inspection of boiler plant, it was at least a further 30 years before statutory controls were applied to boiler plant. The first legislation introduction was the Boiler Explosion Act of 1882 - interestingly, the Report of the Preliminary Inquiry into the Wakefield header failure in 1969 was made under this Act. It was not until the 1901 Factories and Workshop Act that the requirement for the periodic inspection of boilers by a competent person was introduced. This principle has been carried through in all subsequent legislation, both in the Factories Acts (1937, 1961) and in the recent pressure systems legislation.

3.2 Present legislation

In recognition of the weakness of the 1961 FA (inspection limited to boilers and a limited set of prescribed items) and prompted by the 1974 Flixborough Explosion, the more risk based Pressure Systems and Transportable Gas Containers Regulations 1989 (PS&TGCRegs) were introduced under the Health and Safety at Work Act. In exchange for the deletion of statutory periods, the whole pressure system was included under statutory control. Periods could be set on the basis of a technical review (authoritative is the term used in the PS&TGC Regs.) The present legislation is risk based rather than prescriptive.

This goal setting and risk based legislation has been accelerated by European H&S at Work Directives, made under the Single European Act of 1987.

The PS&TGC Regulations were superseded by the Pressure Systems Safety Regulations in 2000 (PSSRegs), to resolve inconsistencies with the EU Pressure Equipment Directive. The PSSRegs 2000 retain the flexibility of the 1989 PS&TGC Regulations.

4. TECHNICAL REVIEW

4.1 What

A technical review is a systematic, comprehensive and detailed assessment, on a component by component basis (or on the basis of groups of components) of all relevant factors, including the current age and anticipated operating regime of the plant, and actual and potential problem areas, to identify the scope of plant inspection necessary to justify the safe operation of the pressure system over the planned operating interval.

4.2 Why

The technical review was originally established in 1991 to justify the increase in periodicity of main power station boiler units from either 30 or 38 months to 50 months, with effect from the 1991 statutory outages. However it was found that the technical review, especially for complex pressure systems, promoted the scope of examination on each component in a pressure system to be determined on a systematic, comprehensive and detailed basis. This function is important for major and complex pressure systems operating at demanding conditions. The technical review is therefore recognised as an essential complement to the written schemes. The technical review has now been in place for 11 years.

4.3 Documentation Structure

The technical review refers to the relevant technical procedures, reports, documents or letters, covering areas such as creep, fatigue and corrosion, and refers to the relevant standard examination procedures.

The technical review identifies any specific operating constraint or limit applicable to an individual component.

5. TECHNICAL REVIEW PROCESS

5.1 Ongoing revision

The Technical Review Process is the ongoing revision of the technical review in advance of each main unit statutory examination. The technical review is maintained as a live document, taking into account the increasing age of the plant and the changing operating parameters. The process is risk based, and is consistently applied at all Innogy Power Stations.

5.2 Timescale

The process of revision of the technical review is initiated approximately 6-12 months in advance of the statutory examination. A key event is the pressure systems review meeting, approximately 6 months in advance of the statutory outage. At this meeting, policy agreement is sought, between the various parties.

5.3 Revision process

The revision process includes ongoing assessment of plant condition, and extensive review of relevant information and plant knowledge, and is summarised in the attached Figure 1. Key meetings are the pressure systems review meeting, held approximately 6 months before the start of the statutory outage, and the post outage review meeting. The purpose of the post outage review meeting is to ensure that any endorsements to be included on the Reports of Examination are clearly understood by all parties.

5.4 Operational model

Several types of activity, by various organisations, are required to be carried out on the plant. For example, in addition to Station staff, the engineer-surveyor fulfils the role of Competent Person for Examination, and the main contractor prepares the plant for NDT. In turn, contractors carry out NDT, with support from metallurgists and other plant specialists. All activities must be carried out correctly for the plant to be operated in statutory compliance, and safely. The Technical Review Process enables coordination to be maintained between the various parties involved.

Whilst the Technical Review process is primarily concerned with in-service inspection, the Technical Review Process may necessarily link to other plant management processes. An example of this is the link to plant operation, where it is necessary to maintain ongoing control of operating temperatures to within safe operating limits.

6. CONCLUSIONS

The Technical Review, and the process of its ongoing revision:

(i) Is an essential complement to the written schemes of examination, especially for the major and complex pressure systems forming main generating plant.
(ii) Has undergone 11 years of evolutionary development.
(iii) Is recognised by the engineering inspection organisations as best industry practice and is becoming the industry norm.
(iv) Is systematic, comprehensive, detailed and is applied consistently.
(v) Is a risk management tool, and can be applied in jurisdictions outside the UK.
(vi) Is flexible, and can be used to make safety cases, for example justifying the postponement of statutory examinations.
(vii) Enables plant history to be recorded.

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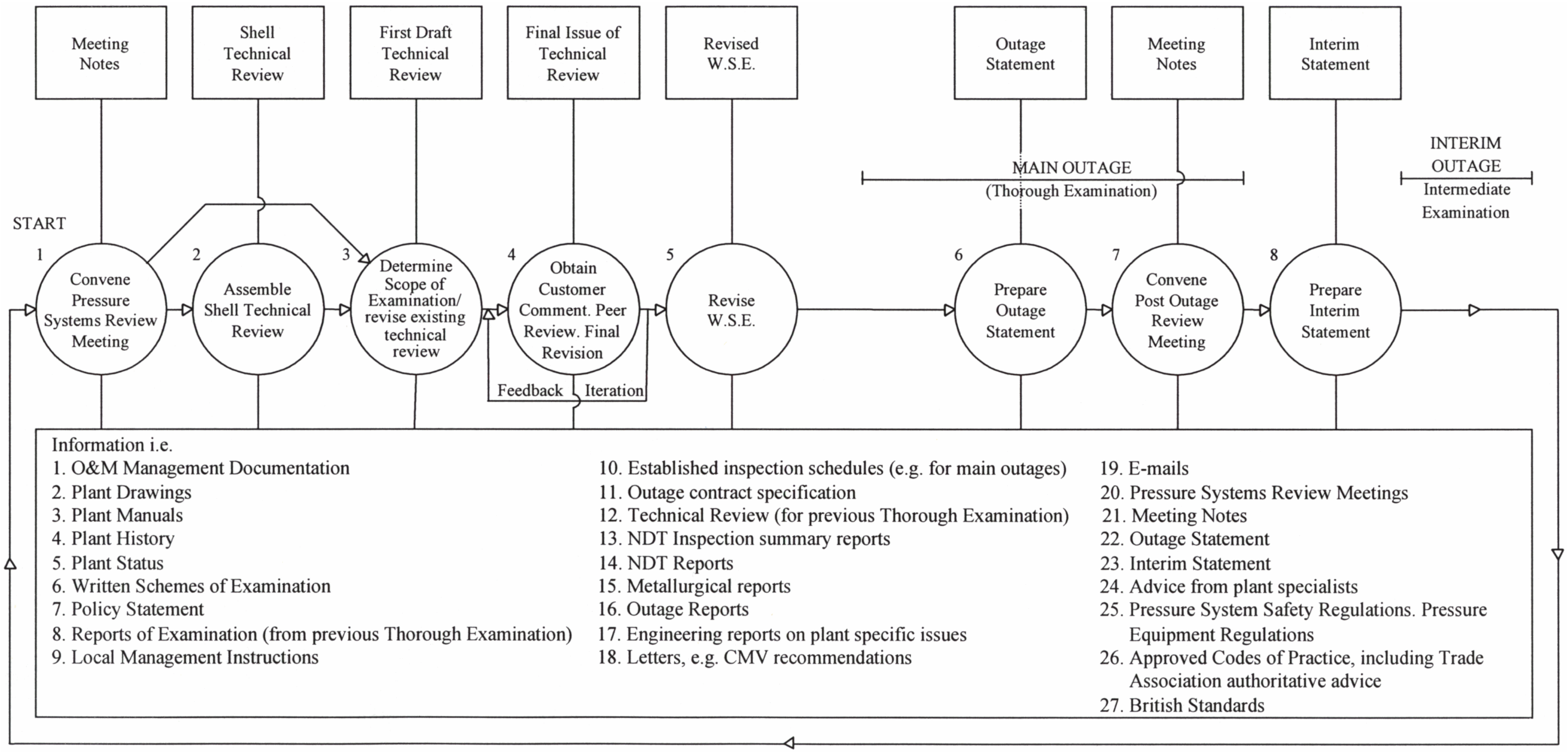

Figure 1 *Innogy technical review process.*

5.4
Redundant Systems Shutdown During Low Capacity Operation

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Abstract
Two possible operation modes of various pumps with redundancy in electric power generating units during low load periods (night) were analyzed. The first mode being when two of three pumps work at night with 25% of the nominal capacity while the third pump being in passive redundancy. The second mode being when one pump works at night with 50% of its nominal capacity while the two other pumps being in passive redundancy. A modified Markov reward model was built for the analysis of these possible operation modes. The model takes into account of all the important factors such as: pumps failure rate, pumps starting availability, cost of alternative energy, penalty cost of energy not supplied and other. It was shown that under current operation conditions the second mode is more effective, e.g. more economical without damaging the power supply reliability but with more risk.

1. INTRODUCTION

Auxiliary systems such as condensing and booster pumps of large generating power units are considered. Redundancy, in these auxiliary systems, is widely used in order to provide the reliability requirements to the power system. This equipment also consumes an essential part of the electrical energy generated by the power station. Usually, the operation mode for the various pumps at night or during low load periods is as follows; two of the three pumps work at 25% of their nominal capacity and the third one is in passive redundancy. We will call this mode as *mode No. 1*. The electric power consumed by the booster and condensing pumps in this mode is $P_B^{(1)} = 774$ KW and $P_C^{(1)} = 334$ KW respectively. In order to decrease the electric consumption at during low load periods the following operation mode was suggested; one pump will work at 50% of its nominal capacity and the two other pumps will be in passive redundancy. We will call this suggested mode as *mode No. 2.* The electric consumption in the suggested mode will decrease to $P_B^{(2)} = 482$ KW (62%) for the booster pumps and to $P_C^{(1)} = 225$ KW (67%) for the condensing pumps.

The suggested mode of operation will lead to a saving of about 30 to 35% of the electric in house consumption but, in the same time, produces a risk of power generation disturbances due to possible starting failures of the passive (cold) redundant pumps when needed (at morning, for example). The starting sequence is provided by a control system and therefore its availability will have a great impact on the operation reliability.

It was assumed that the best operation mode determination should be based on economical criterion, evaluated as follows:

$$M = V^{(1)} - V^{(2)}, \qquad (1)$$

where $V^{(1)}$, $V^{(2)}$ - expected annual cost for operation mode No. 1 and operation mode No. 2 respectively.

The expected annual cost take into account both the operational cost (fuel cost etc.) and possible losses cost due to lack of reliability. The losses cost is composed by the cost of the non-supplied energy and the cost of alternative energy.

A Markov reward model was built in order to compute the economical benefit between the two alternative operation modes. The risk associated with both modes was evaluated using the ordinary Markov model.

2. DESCRIPTION OF THE MODEL

In Figure 1 a state-space diagram for the auxiliary components (various pumps) is presented, describing the operation mode No. 1.

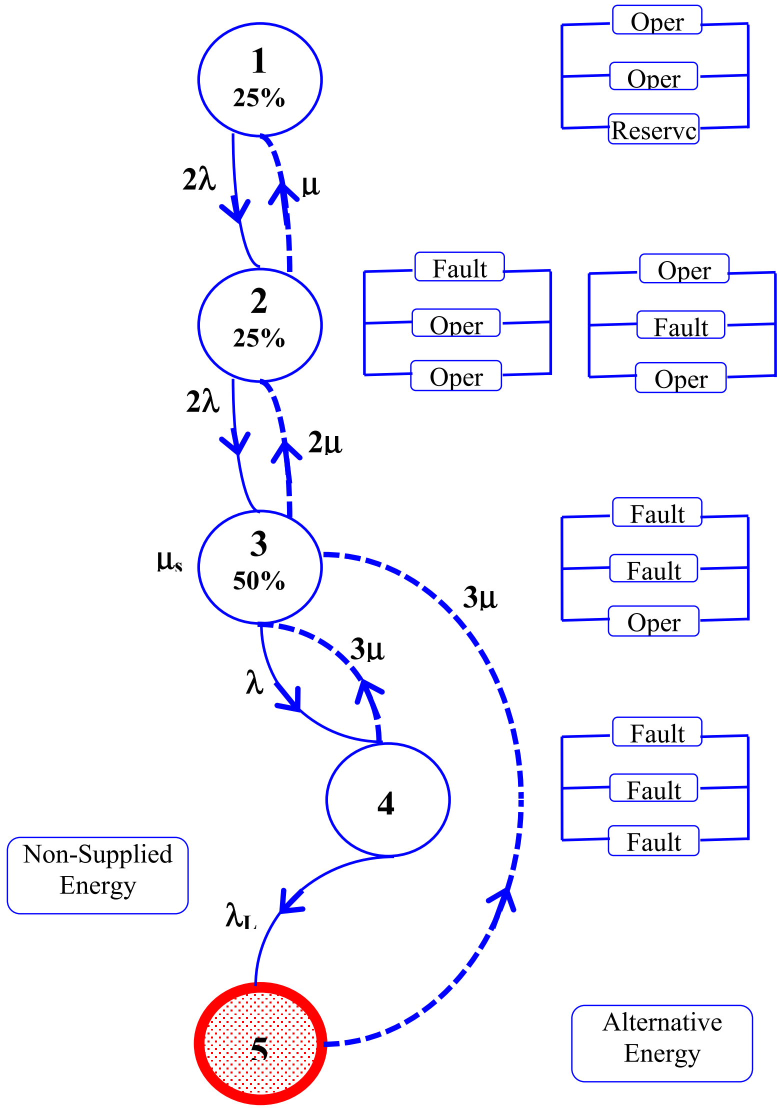

Figure 1 *Operational states of all the three pumps: Two pumps operate at half output rate and supply all the partial unit load.*

In state 1 two pumps are working with 25% of their nominal capacity and the third pump is used as a cold redundant unit. The operation cost in this state is given by:

$$r_{11} = P^{(1)} C_e \frac{T_N}{24} \tag{2}$$

where,

r_{11} – operation cost per unit of time in state 1,

$P^{(1)}$ - electric consumption by the pumps in state 1. For booster pumps $P^{(1)} = P_B^{(1)} = 774$ KW and for condensing pumps $P^{(1)} = P_C^{(1)} = 334$ KW.

C_e - cost of electrical energy, in units of \$/KWh.

T_N - daily low load period, in hours.

If one of two working pumps in the state 1 will fall down because of failure the system will transit from state 1 to state 2 with intensity rate 2λ where λ is pump's failure rate.

In the state number 2 a redundant pump begins to work instead of the failed pump and begins the repair of failed pump. We designate by r_{22} the operation cost in the state 2. Obviously,

$$r_{11} = r_{22}\,. \tag{3}$$

If the repair of the failed pump is completed before an additional failure occurs to the working pumps then the system will transit back to the state 1. The intensity of this transition is μ, where μ is the pump repair rate. If the additional failure occurs before the failed pump is repaired then the system will transit to state 3 with an intensity of 2λ. In the state 3 only one pump works with 50% of its nominal capacity and the other two pumps are under repair. The operation cost in this state is given by:

$$r_{33} = P^{(2)} C_e \frac{T_N}{24} \tag{4}$$

where

r_{33} – operation cost in the state 3,

$P^{(2)}$ - electric consumption by the pumps in state 3. For booster pumps $P^{(2)} = P_B^{(2)} = 482$ KW and for condensing pumps $P^{(1)} = P_C^{(2)} = 225$ KW.

If no other failure happens then the system will come back to the state 2 with intensity rate 2μ, but if the single working pump fails before repair is completed, then the system transits to state 4 with transition rate λ. The system will remain in state 4 up to a vacuum breaking in the condenser leading to a trip of the power generator. In the occurrence of a trip then the generating unit is switch off from the grid and a gas turbine is started to fulfill the demand of electricity.

We designate by T_L the mean time up to the trip. This time is about 30 minutes for the condensing pumps and about 8 min for the booster pumps. Hence, the system will transit from state 4 to the critical state 5 at a rate of $\lambda_L = 1/T_L$. The cost of energy not supplied associated with transition from state 4 to state 5 will be:

$$r_{45} = P_{unit} C_P T_{st} \tag{5}$$

where

P_{unit} – generating unit capacity at night (about 50% of the nominal capacity)

C_p – penalty cost for energy not supplied,

T_{st} – starting time duration of an industrial gas-turbine (about 15 minutes).

In state 5 the cost of the alternative energy (fuel) per unit of time is:

$$r_{55} = P_{unit} C_{gas}\,, \tag{6}$$

where C_{gas} is the cost of alternative energy per KWh.

The system will remain in state 5 up to completion of repair of one of the pumps and then will transit to state 3 at a rate of 3μ.

Such a model is called a Markov model with rewards and according to [1] we can write the following differential equations for computing the expected rewards (or costs) $V_i(t)$ for operation mode No. 1:

$$\begin{cases} \dfrac{dV_1(t)}{dt} = r_{11} - 2\lambda V_1(t) + 2\lambda V_2(t) \\ \dfrac{dV_2(t)}{dt} = r_{22} + \mu V_1(t) - (2\lambda + \mu)V_2(t) + 2\lambda V_3(t) \\ \dfrac{dV_3(t)}{dt} = r_{33} + 2\mu V_2(t) - (\lambda + 2\mu)V_3(t) + \lambda V_4(t) \\ \dfrac{dV_4(t)}{dt} = r_{45}\lambda_L + 3\mu V_3(t) - (\lambda_L + 3\mu)V_4(t) + \lambda_L V_5(t) \\ \dfrac{dV_5(t)}{dt} = r_{55} + 3\mu V_3(t) - 3\mu V_5(t) \end{cases} \quad (7)$$

Solving the system of equations (7) with the initial conditions $V_i(0) = 0$, for $i = 1,2,...5$ will give the annual expected cost $V^{(1)}$.

In order to calculate $V^{(2)}$ the Markov reward model for operation mode No. 2 is built in the same way as presented in figure 2. In state 1 one pump operates with half of its nominal capacity and the other two pumps are in passive redundancy. The operation cost in this state is given by:

$$r_{11} = P^{(2)} C_e \frac{T_N}{24} \quad (8)$$

where

r_{11} – operation cost per unit of time in state 3,

$P^{(2)}$ - electrical power consumption of the pumps in state 3. For booster pumps $P^{(2)} = P_B^{(2)} = 482$ KW and for condensing pumps $P^{(1)} = P_C^{(2)} = 225$ KW.

If the working pump fails then a control system will, automatically, start one of the reserve pumps. The system transits to state 2 with intensity $A\lambda$, where A is the availability of the control system. If the control system is not available or fail to operate then the system transits to state 6 with intensity (1-A)λ and the operator starts manually the reserve pump. In state 2 one pump is working at half capacity, a second pump is under repair and the third one is in passive reserve. The operation cost in state 2 is r_{22} and obviously, $r_{22}=r_{11}$.

The system moves back from state 2 to state 1 at a rate of μ if the repair ends before an additional failure. If the failure happens before, then the system transits to state 3, where 2 pumps are under repair and only one operates at half capacity. The transition intensity is $A\lambda$, because the transition will be executed only if the control system is available. If, on contrary, the control system is not available then the system will transit to state 5 at a rate of $(1 - A\lambda)$, and the operator starts manually the reserve pump. The operation cost r_{33} in state 3 is equal to the operation cost r_{11} and r_{22}. An additional failure will transit the system from state 3 to state 4 at a rate of λ unless one of two pumps beeing repaired is ready to operate, transiting the system back to state 2 with intensity 2μ.

In states 5 and 6 the operator executes all the operations manually in order to start the reserve pump. The mean time required for manual operations is estimated as T_S=90 seconds. If he succeeds before the trip process is triggered then the system comes back to from state 5 to 3 or from state 6 to 2 with intensity $\mu_S = \dfrac{1}{T_S}$. On the other hand If the trip occurs before then the system transits to state 7 with intensity λ_L. In state 4 all the pumps are under repair. Hence the intensity of transition from state 4 to state 3 will be 3λ.

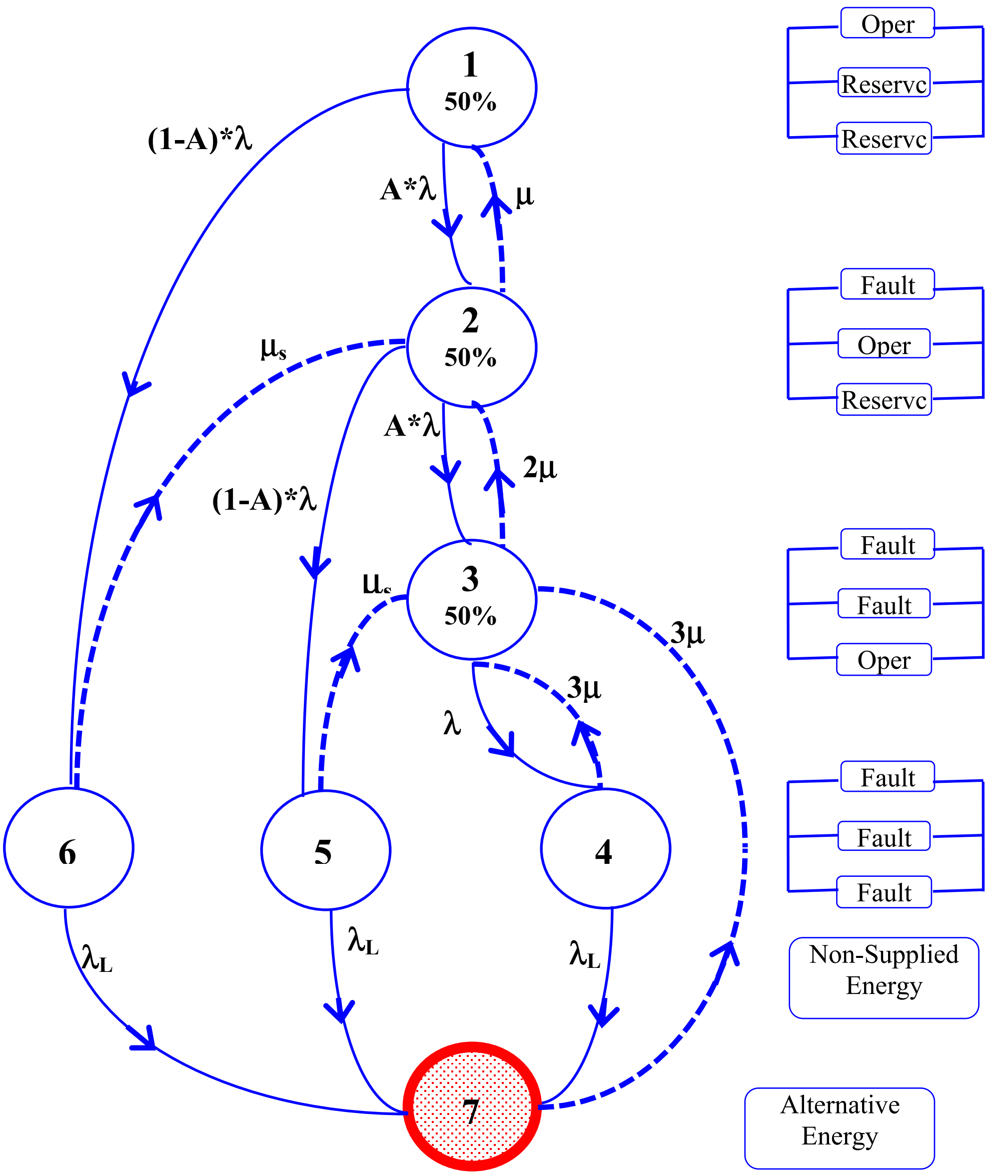

Figure 2 *Operational states of all the three pumps: One pump operates at full output rate and supply all the partial unit load.*

The cost associated with the transitions from states 4, 5, 6 to state 7 is given by:

$$r_{47} = r_{57} = r_{67} = P_{unit} C_p T_{st} \,. \qquad (9)$$

In state 7 a gas-turbine is ignited and the operation cost per a unit of time is:

$$r_{77} = P_{unit} C_{gas} \,. \qquad (10)$$

The following differential equations are used to compute the expected rewards (or costs) $V_i(t)$ for the operation mode No. 2:

$$\begin{cases} \dfrac{dV_1(t)}{dt} = r_{11} - 2\lambda V_1(t) + A\lambda V_2(t) + (1-A)\lambda V_6(t) \\ \dfrac{dV_2(t)}{dt} = r_{22} + \mu V_1(t) - (2\lambda + \mu)V_2(t) + A\lambda V_3(t) + (1-A)\lambda V_5(t) \\ \dfrac{dV_3(t)}{dt} = r_{33} + 2\mu V_2(t) - (\lambda + 2\mu)V_3(t) + \lambda V_4(t) \\ \dfrac{dV_4(t)}{dt} = r_{45}\lambda_L + 3\mu V_3(t) - (\lambda_L + 3\mu)V_4(t) + \lambda_L V_7(t) \\ \dfrac{dV_5(t)}{dt} = r_{57}\lambda_L + \mu_s V_3(t) - (\lambda_L + \mu_s)V_5(t) + \lambda_L V_7(t) \\ \dfrac{dV_6(t)}{dt} = r_{67}\lambda_L + \mu_s V_2(t) - (\lambda_L + \mu_S)V_6(t) + \lambda_L V_7(t) \\ \dfrac{dV_7(t)}{dt} = r_{77} + 3\mu V_3(t) - 3\mu V_7(t) \end{cases} \quad (11)$$

When the initial conditions are $V_i(0) = 0$, for $i = 1,2,...5,6,7$ the expected cost $V^{(2)}$ is calculated.

In order to assess the risk associated with these two operational modes, one must write and solve the differential equations describing the system state probabilities [2, 3]. The probability to fall into the critical state 5 and critical state 7 during the expected lifetime of the equipment (30 years) defines the risk for the operation mode No. 1 and 2 respectively.

3. RESULTS AND CONCLUSIONS

The method presented in this paper permits to calculate the saving and the risk associated with the shutting down of auxiliary redundant systems in a large power plant. The results show that the risk is higher for the mode No. 2 but still insignificant and equal to about 10^{-5} for a time period of 30 years. Although the saving is not very large, about 100K$ per year per generator and about 0.2% of the net power output, yet the risk taken is almost null. More important, is the obtained saving in fuel and pollutants and perhaps the elaboration of an additional other tool to the management of asset in power plants in a changing environment (deregulation of power market).

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6.1
EPRI On-Line Monitoring Activities

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Abstract
EPRI's strategic role in on-line monitoring is to facilitate its implementation and cost-effective use in numerous applications at power plants. To this end, EPRI has sponsored an implementation project at multiple utilities specifically intended to install and use on-line monitoring technology. The goal is to apply on-line monitoring to all types of power plant applications and document all aspects of the implementation process in a series of EPRI deliverables. These deliverables will cover installation, modeling, optimization, and proven cost-benefit.

EPRI will continue to foster continued development of on-line monitoring technology and its application via the Instrument Monitoring and Calibration (IMC) Users Group. Through the IMC Users Group, on-line monitoring as a key technology will continue to be supported technically as its use grows throughout the industry. Finally, the EPRI IMC Users Group will continue to support generic technical issues associated with on-line monitoring, such as providing implementation guidance for calibration reduction of safety-related instrumentation.
The following sections discuss the past, present, and future EPRI on-line monitoring activities in detail.

1 ON-LINE MONITORING GROUP

Because of the large scope of the EPRI on-line monitoring effort, EPRI has formed the On-Line Monitoring (OLM) Group, which operates under the I&C Nuclear Target. There are at present two programs (working groups) under the OLM Group, separately funded under individual subscription programs to address the needs of utilities with regard to instrument monitoring, instrument calibration reduction/extension, and sensor validation. The two working groups are:

- Instrument Monitoring and Calibration (IMC) Users Group, formed in 2000
- On-Line Monitoring Implementation Users Group, formed in 2001

Each working group has oversight authority on the work performed by EPRI. Dr. Ramesh Shankar, rshankar@epri.com, is responsible for the OLM Group. Additional information regarding these groups is available on the EPRI web site, www.epri.com.

1.1 Instrument Monitoring and Calibration (IMC) Users Group

The IMC Users Group performs an oversight role for recommending applications of IMC technology for nuclear power plants; resolving licensing issues for on-line monitoring and calibration reduction of safety-related equipment; and developing implementation guidelines based on the NRC safety evaluation for on-line monitoring.

The IMC Users Group also provides I&C services to EPRI members in technology transfer, training, and implementation of key IMC products. In this regard, the Users Group provides utilities with application support of these key products for improved reliability, lower operations and maintenance (O&M) costs, and safe operation of nuclear plants. Figure 1 shows the general responsibilities of the IMC Users Group.

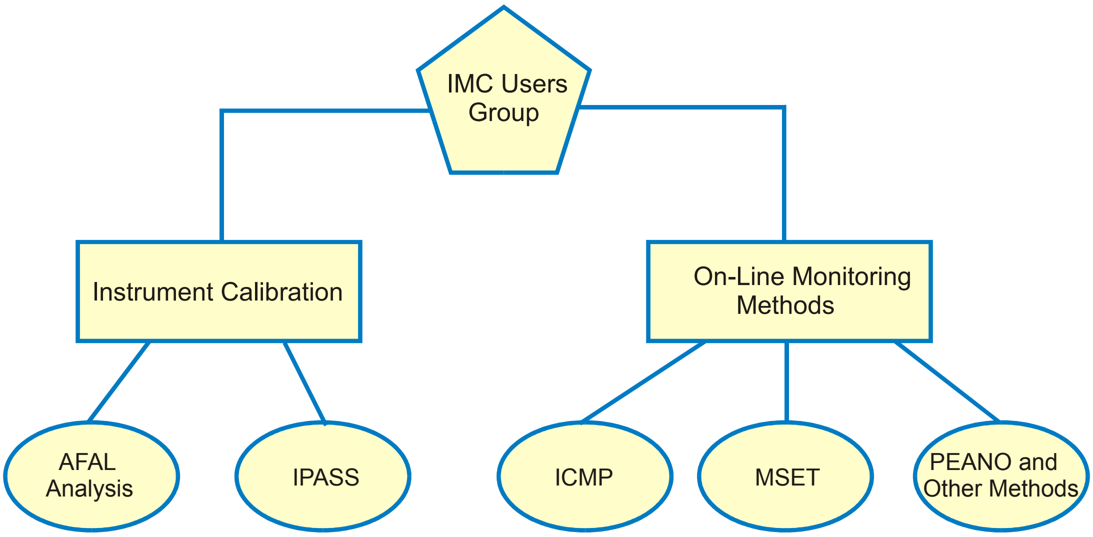

Figure 1 *On-line monitoring and calibration users group.*

The products and services include:

- Evaluation of on-line monitoring technologies and methods. An example is the in-progress evaluation of PEANO (Process Evaluation and Analysis by Neural Operators) for power plant use.
- Technology transfer projects as authorized by the IMC Users Group.
- Instrument Performance Analysis Software System (IPASS) and related documents.
- Instrument Calibration and Monitoring Program (ICMP) software and related documents.
- TR-103335-R1, *Guidelines for Instrument Calibration Extension/Reduction Programs, Statistical Analysis of Instrument Calibration Data*.
- TR-104965-R1 NRC SER, *On-Line Monitoring of Instrument Channel Performance*.
- EPRI Report, *Implementation of On-Line Monitoring for Technical Specification Instruments* (scheduled for issuance in September 2002).

The Users Group meets periodically (at least once per year) to prioritize work defined by the members.

1.2 On-Line Monitoring Implementation Users Group

Overview

During 2000, the IMC Users Group started the transition from product demonstration to product implementation. In July 2000, the NRC issued a safety evaluation (SE) approving the use of on-line monitoring as a means of extending the calibration intervals of safety-related instrumentation. Topical Report TR-104965-R1, *On-Line Monitoring of Instrument Channel Performance*, was revised in September 2000 to reflect the NRC SE.

In 2001, the IMC Users Group started the implementation of on-line monitoring at selected nuclear plants as part of a separately funded program. The project has a planned three-year life in which funding will be provided each year by the participating nuclear plants. Four plants are participating in 2001 and additional plants will join the project in 2002.

This project is organized as a demonstration of on-line monitoring for a variety of applications at multiple nuclear plants, based on the Argonne National Laboratories (ANL) Multivariate State Estimation Technique (MSET) as the on-line monitoring method. The software used for the project has been provided by Expert Microsystems, Inc.

The On-Line Monitoring Implementation Users Group was established in 2001 to coordinate the various activities associated with this project. The group is responsible for the following activities:

- Implementation of on-line monitoring technology in operating nuclear plants for a variety of systems and applications.
- Verification that on-line monitoring is capable of identifying instrument drift or failure under a variety of conditions.
- Demonstration of on-line monitoring cost-benefit.
- Coordination of effort with project partners, including the DOE Nuclear Energy Plant Optimization (NEPO) program and Expert Microsystems, Inc.
- Providing oversight to EPRI on current and future projects.

Each participating plant is actively involved in the implementation effort. The project participants meet periodically for project updates, development of schedules, and conduct of training classes.

Project scope

The EPRI on-line monitoring implementation project is applying on-line monitoring technology in operating nuclear plants for many systems and applications. The principal purpose of the project is to verify that on-line monitoring can identify instrument drift or failure under a variety of conditions, and thereby be used as a tool for calibration reduction. Additionally, several other benefits can be obtained from on-line monitoring:

- Development of long-term trends in instrument performance
- Enhanced instrument troubleshooting capabilities
- Additional resource for historical root-cause analyses and post-trip reviews
- Real-time assessment of instrument health

The on-line monitoring implementation project started in June 2001 with four participating nuclear plants. EPRI is managing the overall effort and the software has been provided by Expert Microsystems. In 2001, the following has been achieved at the participating plants:

- The on-line monitoring software has been installed and is operational at the participating plants. A detailed software and modeling users guide was written specifically for nuclear plant applications.

- Models have been developed, trained, and tested to monitor instrument calibration for a variety of plant systems.

- Development is in progress on the next round of models. The goal is to apply on-line monitoring to as many applications as possible.

- Reviews are in progress to identify the instruments that can utilize on-line monitoring as a method for calibration reduction. The purpose is to quantify the possible financial savings that can be realized solely from calibration reduction.

In 2002, the EPRI on-line monitoring implementation project will continue and significant progress is expected. The following summarizes the planned 2002 activities for the participating plants:

- Model development will continue at each plant to ensure maximum benefit. As many signals as possible will be included within the scope of on-line monitoring.

- Start the calibration reduction implementation process.

- The Expert Microsystems software is being modified in response to comments and requests from the project participants. Expert Microsystems also has received DOE and California grants specifically to tailor their software to the needs of the power industry, and especially the identified needs of the participating plants.

- EPRI and Expert Microsystems will assist each participating plant with making the transition to true on-line monitoring in real time. In 2001, the project developed and tested models using batch files.

- Coordinate the NEPO tasks that directly support this project.

- EPRI will prepare several deliverables that directly benefit the participating plants. The documents to be issued in 2002 include reports covering cost-benefit analysis, modeling guidelines, implementation guidelines, and periodic updates to the software users guide.

The project goal is to provide detailed implementation assistance at each participating plant. This assistance includes safety-related and non-safety-related applications. Figure 2 illustrates the project support for safety-related applications and Figure 3 illustrates the project support for non-safety-related applications.

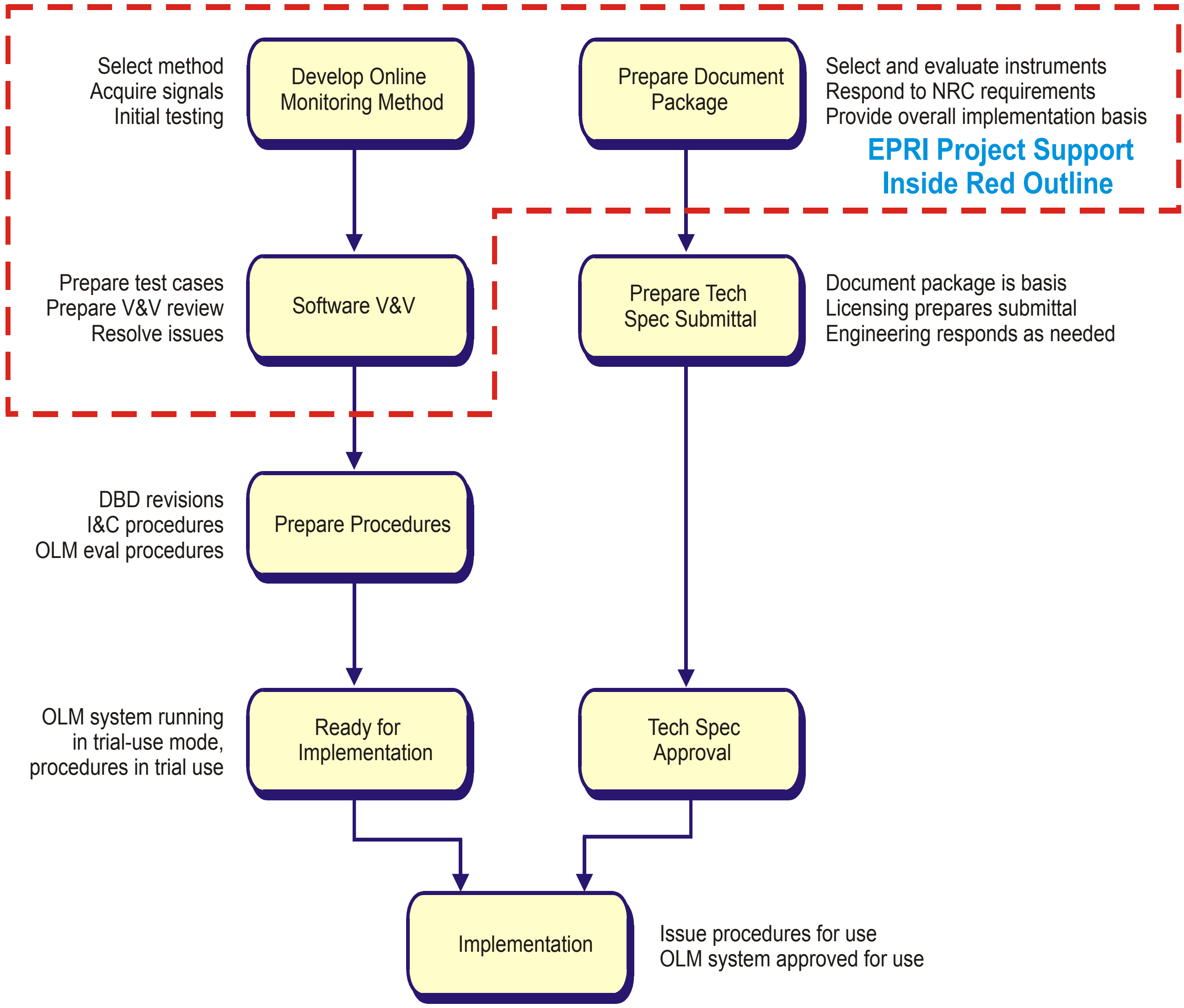

Figure 2 *On-line monitoring implementation for safety-related instruments.*

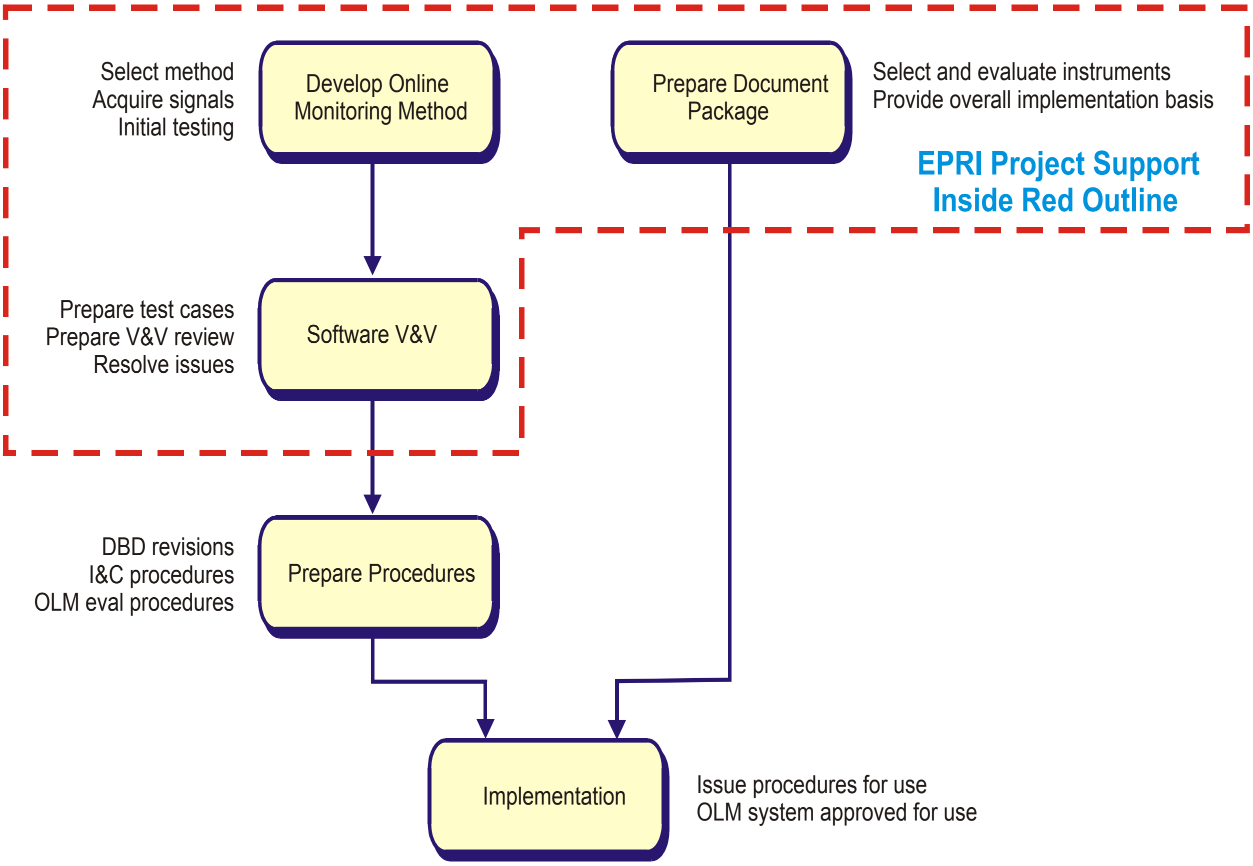

Figure 3 *On-line monitoring implementation for non-safety-related instruments.*

Project partners

The EPRI on-line monitoring implementation project is unusual in terms of 1) its especially large scope, 2) demonstrated commitment from several participating nuclear plants, and 3) project partners that have effectively donated additional funding to the project.

The DOE Nuclear Energy Plant Optimization (NEPO) program has provided funding that directly supports the on-line monitoring implementation project goals. The program was funded for $100,000 in 2001 and has been funded for $250,000 in 2002.

Expert Microsystems, Inc. has provided the MSET software for use in this project. Included in their participation is additional funding from external sources over the period of 2001 and 2002.
This collaboration between various companies and groups is unique, and indicates a willingness to fully implement on-line monitoring in the nuclear industry.

Figure 4 illustrates the total project scope. Subsequent sections discuss the NEPO and Expert Microsystems participation in more detail.

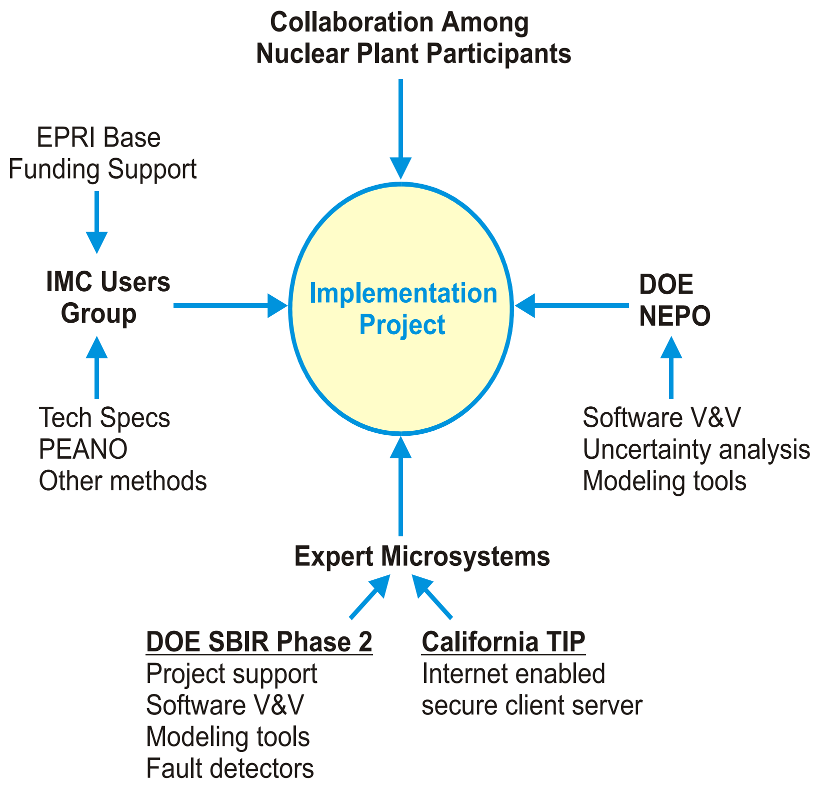

Figure 4 *On-line monitoring implementation project participants.*

Nuclear Energy Plant Optimization Program

The Nuclear Energy Plant Optimization (NEPO) program is a U.S. Department of Energy (DOE) research and development (R&D) program focused on performance of currently operating U.S. nuclear power plants. The primary research areas for the R&D program are plant aging and optimization of electrical production.

The NEPO program is a public-private R&D partnership with equal or greater matching funds coming from industry. The NEPO Program was initiated in fiscal year 2000 and is explained in detail on the DOE web site, http://nepo.ne.doe.gov/.

The IMC Users Group has coordinated NEPO projects that support the continued development of on-line monitoring and directly support tasks associated with the EPRI on-line monitoring implementation project. Argonne National Laboratory was awarded the scope of work for 2001. Additional tasks are planned for 2002 and 2003 for the specific intent of benefiting the on-line monitoring implementation project. The following tasks are in progress or are planned for 2002:

- Verification and validation of the Argonne National Laboratory MSET software – this task started in 2001 and directly supports the on-site acceptance of the associated software.
- MSET uncertainty analysis – this task is planned to start in 2002 and provides the basis needed to demonstrate acceptable uncertainty with respect to safety-related setpoints.
- Additional modeling and evaluation tools – additional research is envisioned to improve MSET and its related fault detection tools.

Expert Microsystems External Funding

Expert Microsystems, Inc. is a California-based company licensed to provide MSET technology to the power industry. The company has considerable experience with signal validation systems and has worked with Argonne National Laboratory for several years on various MSET applications.

Expert Microsystems recently completed a DOE Small Business Innovation Research (SBIR) Phase I project that developed and evaluated new tools related to the MSET estimation process and fault detection capability. In response to the successful Phase 1 project, Expert Microsystems was approved for a DOE Phase 2 project to implement these new capabilities. The project has been funded for $750,000 and has the following tasks:

- Implement MSET model optimization methods.
- Implement fault detector optimization methods.
- Implement numerical signal simulators and create verification test data sets.
- Implement on-line fault classification methods.
- Complete software quality assurance, and verification and validation (V&V).
- Participate in EPRI on-line monitoring implementation project.
- Demonstrate proof of principle for selected applications.

Notice that participation in the EPRI on-line monitoring implementation project is a specific task in the Expert Microsystems project. As part of this participation, Expert Microsystems has provided the software to nuclear plant participants at no cost and is modifying the software to improve its performance for power plant applications.

A California Technology Investment Program has also funded Expert Microsystems to develop internet-based secure client server applications. The results of this project will be useful for companies that intend to access and monitor systems from remote locations, such as corporate offices.

The Expert Microsystems separately funded efforts are complementary to the EPRI on-line monitoring implementation project. Furthermore, Expert Microsystems has deliberately aligned its project goals with those of the EPRI on-line monitoring implementation project.

Planned EPRI report deliverables

The large scope of this program is reflected in the planned EPRI deliverables over the next two years. The following publications are planned to assist users with the implementation and evaluation of on-line monitoring:

- EPRI Interim Report: *SureSense Multivariate State Estimation Studio Users Guide* – October 2001
- EPRI Interim Report: *Plant Applications Guide for On-Line Monitoring* – November 2001
- EPRI Interim Report: *Modeling Guidelines for On-Line Monitoring* – April 2002
- EPRI Interim Report: *Cost-Benefit Report for On-Line Monitoring* – May 2002
- EPRI Interim Report, Revision 1: *SureSense Multivariate State Estimation Studio Users Guide* – June 2002
- EPRI Interim Report: *Implementation Guidelines for On-Line Monitoring* – October 2002

- EPRI Final Report: *Modeling Guidelines for On-Line Monitoring* – March 2003
- EPRI Final Report: *Implementation Guidelines for On-Line Monitoring* – July 2003
- EPRI Final Report: *SureSense Multivariate State Estimation Studio Users Guide* – October 2003
- EPRI Final Report: *Cost-Benefit Report for On-Line Monitoring* – October 2003

1.3 Relationship Between Implementation Project and IMC Users Group

The EPRI on-line monitoring implementation project is a large project with the participation of several nuclear plants as well as additional contributions from external companies and programs. The on-line monitoring implementation project has a specific goal of implementation and technology demonstration at multiple nuclear plants. The participants in this project will directly benefit from the project results, and sufficient documentation and guidance will be developed to provide an adequate starting point for subsequent users of the technology.

The IMC Users Group continues to coordinate EPRI's strategic direction with regard to on-line monitoring, calibration monitoring, and other aspects of O&M improvements associated with instrumentation systems. Generic efforts related to on-line monitoring will continue to be managed by the IMC Users Group.

Figure 5 shows the relationship between the IMC Users Group and the on-line monitoring implementation project. The efforts between the two groups are intended to be complementary with the overall goal of introducing and implementing new methods of evaluating instrument calibration and performance.

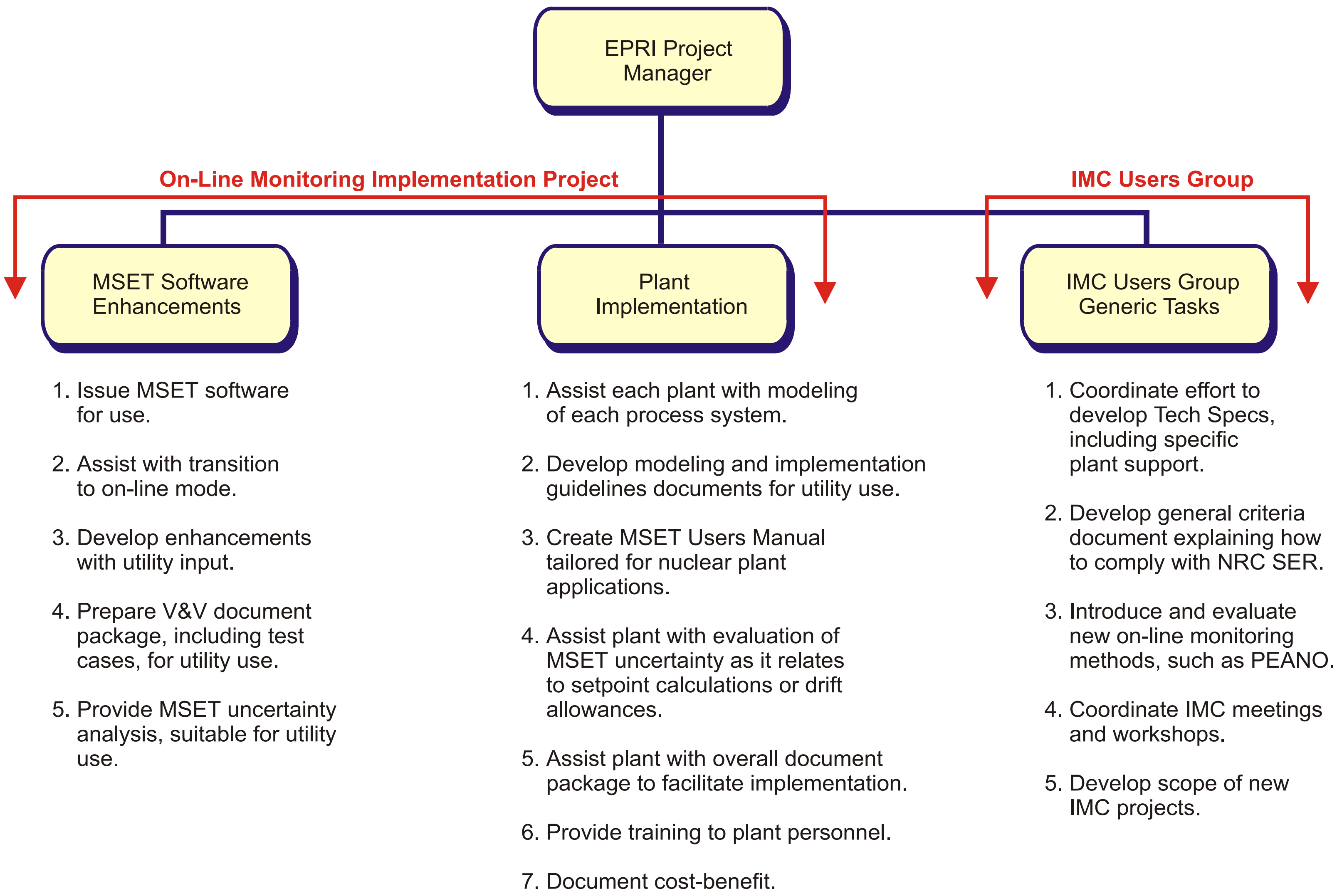

Figure 5 *IMC project relationships.*

2 Past EPRI projects related to on-line monitoring

2.1 Instrument Calibration and Monitoring Program

EPRI developed the Instrument Calibration and Monitoring Program (ICMP) for monitoring applications involving redundant channels. The following EPRI reports describe ICMP:

- EPRI NP-7207-CCML, *Instrument Calibration Reduction Program*, March 1991.
- EPRI TR-103436-V1, *Instrument Calibration and Monitoring Program, Volume 1: Basis for the Method*, December 1993.
- EPRI TR-103436-V2, *Instrument Calibration and Monitoring Program, Volume 2: Failure Modes and Effects Analysis*, December 1993.
- EPRI CM-106822, *Users Manual: ICMP*, August 1999.

The EPRI software and associated documents are available to EPRI members.

2.2 On-Line Monitoring Working Group

EPRI formed the EPRI/Utility On-Line Monitoring Working Group in 1994 with the goal of obtaining NRC approval of on-line monitoring as a calibration reduction tool for safety-related instruments. An initial submittal was made to the NRC in 1995, followed by a detailed submittal in 1998. The NRC Safety Evaluation (SE) was issued in July 2000.

EPRI TR-104965-R1 NRC SER, *On-Line Monitoring of Instrument Channel Performance*, was modified in September 2000 to incorporate the NRC SE. With the issuance of the SE, the EPRI/Utility On-Line Monitoring Working Group completed its mission and evolved into the IMC Users Group.

6.2
The Project on Material Risk Information Platform System

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Abstract
The investigation of the platform system of material risk information and the development project were started in the middle of 2001 by the team including the head of National Institute for Materials Science. The concept of this system is a portal site to be used in the Internet, and it has the function to collect the information related to the material risk from distributed network environment and to provide them for users. "Life test data of the material", "accident or trouble information resulting from material", "standard information", "information related to various evaluations", "other risk information" and etc are assumed as material risk information. This paper reports the overview of our platform system that collects the information related to material risk and the project plan.

1. INTRODUCTION

Recently, the concept or methods of "risk-based design", "risk-based manufacturing", and "risk-based maintenance" are often heard in the field of the mechanical equipment. For the reason of its attention, it is no longer rational to design, manufacture and manage under a specific standard and a specific rule where the environment of mechanical equipment used in the modern society is exposed very variably [1]. This is also supported by plenty of experiences and stock of data. Moreover, from a social point of view, in order to survive in the competitive market, in the basis of deregulation or self-imposed responsibilities, the severe problem of balancing the costs and benefits is also in the background where a concept of risk-based evaluation is adopted.

However, when it is examined the risk of the mechanical equipment from the viewpoint of material, obtaining risk information used as the base of the study is not easy. One of the causes for this is that most of material-related database now are built independently for every special field of study, and are limited to digitalize numerical fact data [2]. In addition, another cause is that these databases don't show enough distributions of parameters to make a risk-based evaluation.

Then the investigation of the platform system of material risk information (henceforth, call "this system") and the five-year development project (henceforth, call "this project") were started in the middle of 2001 by the team including the head of National Institute for Materials Science [3]. The purpose of this project is developing the basis for taking a material risk into consideration. We have focused on the metal material as a main target at the first stage of this project. The concept of this system is a portal site to be used in the Internet, and it has the function to collect the information related to the material risk from distributed network environment and to provide them for users.

This paper reports the overview of our platform system that collects the information related to material risk and the project plan.

2. MATERIAL RISK INFORMATION

Risk is commonly defined as "the probability (or frequency) of an event" and "its consequence (or damage)" [4]. Here the damages often refer a financial loss, a loss of human life, a damage of material value and *etc*. However when "material risk information" is concerned, a specified material cannot usually identify what damage it causes. In other words, the occurrence probability of the damage configuration cannot be estimated unless the environment, the apparatus or the system are selected in which those materials are used.

Then, we reexamined the system of risk focusing on material. Material substance (*e.g.*, stainless steel board or concrete lump) cannot identify a risk, as stated above. So further the circumstances of material use is taken into consideration. For example, it is obvious that a material used for the pillar of a building requires the function to support the weight of a building, and the high-pressure vessel gas requires the function to bear gas pressure. Losing these functions can be defined as risk focusing on material. Therefore, the risk can be understood by its probability of the event, which is the loss of its function. Based on this idea, material risk information is the information related to the events that a material loses its function. The examples of functional losses focusing on material and other related examples are shown in Table 1. In this system, the information related to material risk will be considered on the basis of this concept.

Table 1 *Example of risk information focusing on material*

Application	Required function	Example of loss of function
Structural material	□ Bearing a static load □ Bearing a dynamic load	Ductile fracture, Brittle fracture, Fatigue *etc*.
Pressure vessel	□ Bearing an internal pressure	Ductile fracture, Brittle fracture, Creep, Stress corrosion cracking, *etc*.
Pipe	□ Prevention of leak	Corrosion, *etc*.
Radioactive shield	□ Shields of radiation	Deterioration, Thinning, *etc*.

3. MATERIAL RISK INFORMATION PLATFORM

This system is named "Material Risk Information Platform System." In the field of information system, a term of "platform" is sometimes used as the general term for computer system of hardware and software, but it has been used in a quite large meaning recently. Ono et al. consider the concept of "information platform" as "a common foundation, which serves common place for information to be collected and systematized (collection, construction), to be archived (storage), to be circulated (circulation), and to be extracted to use (utilization) [5].

A "platform" in this system is not a mere computer system but similar to the definition of Ono et al. It is regarded as the system, which satisfies the conditions shown in Table 2.

Table 2 *Concept of the platform system*

(1)	The base system, which can widely provide the information relevant to material risk.
(2)	The open system, which can add the various tools relevant to material risk.
(3)	The standard system, which can link with other tools and information system relevant to material risk.

4. FUNCTIONS OF THIS SYSTEM

The feature of this system is to estimate the risk focusing on materials and to systematize the information of those on the basis of the concept of a platform. The following three are the core functions for this system.

- The portal function of material risk information
- The additional function of material risk information and Web service
- The presenting function of material risk evaluation information

4.1 The portal function of material risk information

The first function of this system is the improved function on the basis of the function equivalent to the portal site in the Internet. The image of the portal function in this system is shown in Figure 1. The portal function in this system specializes in the information related to material risk. The information is grouped into six and those sources of the information can be reached as shown in Figure 1. Figure 1 also shows that it can move to other group from each information group intentionally. Moreover, this system is not a closed system, which can only operate on a particular server. It can be linked and cooperative with various kinds of servers that store the material risk information in the Internet.

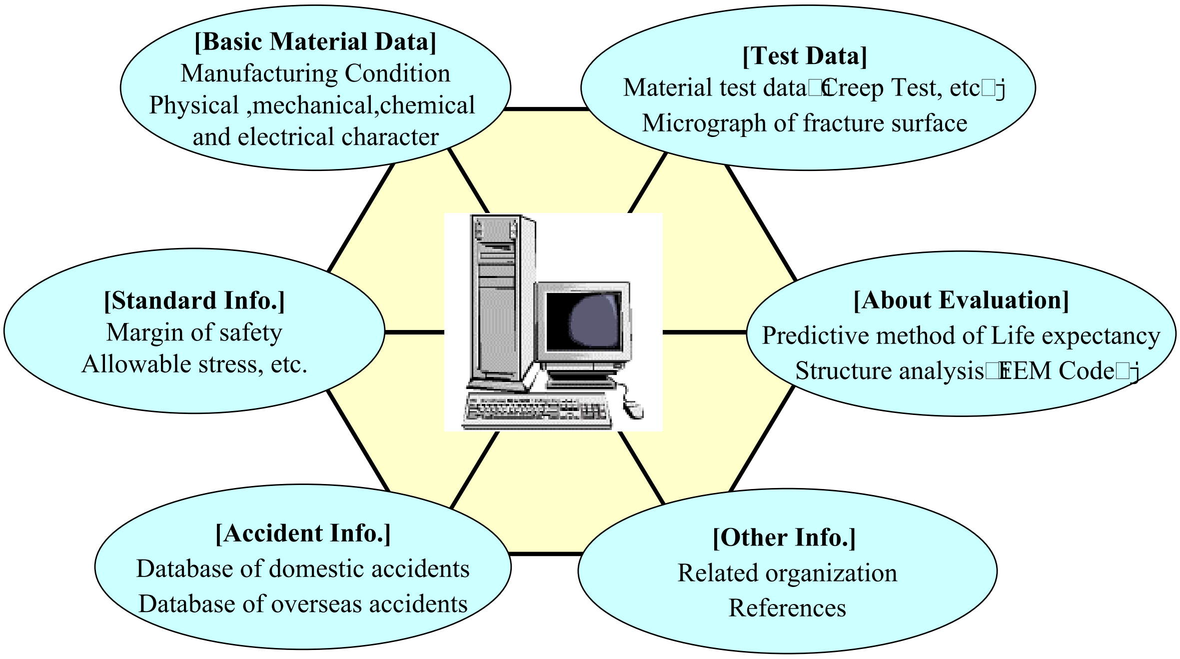

Figure 1 *Image of portal function of this system.*

4.2 The additional function of material risk information and Web service

Realizing the additional function of material risk information and Web service means this system offers an interface that the information is addable and extensible over the future. It is desirable to simplify the systems of both contents providers and the main server of the platform in order to exercise the additional function. The following two points are important to implement the system configuration.

- The systems configuration by unified architecture
- The systems configuration according to the standard

It means that the former makes interconnection easy and later makes developing new service easy for provider.

The specification design for the architecture, which covers two points, mentioned previously, is summarized in the next sub-section.

4.2.1 Description and registration of meta-information about Web service

The structure to control information about Web service systematically is indispensable in this system. This is for the mutual use of the distributed Web service and for providing new Web service. Therefore we think that the meta-information about the contents of Web service is necessary to this system. And it is ideal to provide the standardized specification for this system, and each server defines meta-information based on this specification. Moreover, those defined information should be controlled and registered, in order to enable users of this system to refer to.

In order to realize the structure, we note “Universal Description, Discovery and Integration (UDDI)” and “Web Service Description Language (WSDL)” to define meta-information. UDDI and WSDL have been the standards since mid 2000 and it is expected to become the standard technology for Web service of the next generation. This system also adopts UDDI and WSDL as for the fundamental architecture to refer mutually and register information. The contents of the service and the access points will be registered and maintained by adopting UDDI. This information will be maintained in the main server. WSDL defines the contents of the service (a providing site, an access interface, a running method, *etc*), which is provided by a service provider itself. In another word, it is to standardize the format of meta-information.

4.2.2 Image of UDDI and WSDL use in this system

The example of using this system based on UDDI and WSDL is shown Figure 2. The main server is corresponded to a service broker that supervises the whole contents of information about this system, and also servers that provide service as this system are positioned as service providers, and terminals of users who want to use service is regarded as service requester in Figure 2.

As the first step, the service provider “A”, which offers elementary service, registers the contents of service in service broker (main server). Next, the service provider “B”, which intends to offer new service, accesses service broker and searches the existing service. Since the contents of service which service provider “A” offers, and its interface can be known from UDDI and WSDL information, service provider “B” develops new applied service, which also utilized service of service provider “A.” This is the third step. As the forth step, the service provider “B” also registers the contents of service in service broker. Then a user who wants to acquire certain material risk information, accesses the main server, and knows applied service of service provider “B.” As the sixth step, a user uses the service, which service provider “B” offers. In this case, the user also uses the service of service provider “A” indirectly.

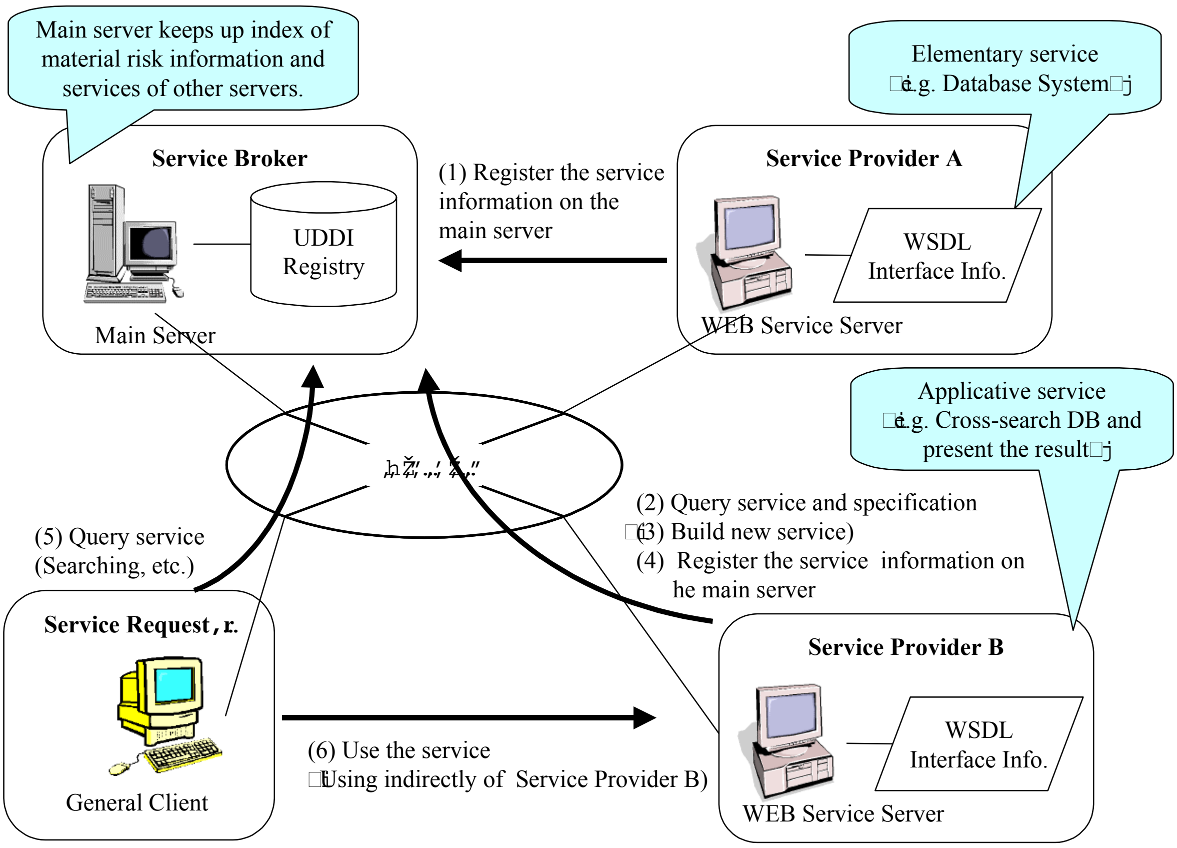

Figure 2 *Example of UDDI and WSDL.*

4.3 Presentation function of the evaluation result of material risk

As a presentation function of the evaluation result relevant to the material risk, various services may be offered with operation of this system. Here, the presentation function of the evaluation result focusing on the information for generating of the functional loss accompanying the variation in fundamental material data is shown. The variation said here is the distribution of the tensile strength, fatigue life, and creep strength which assumes metal material and originates in being of “the chemistry ingredient of material”, “uneven heat treatment conditions", “difference in the processing method" and *etc*.

The flow, which included material risk information presentation and evaluation function, is shown in Figure 3. Three evaluation steps or the evaluation support function constitutes the flow. The first step is a function, which consolidates or separates the material data involved this system as a database (include the distributed database on the Internet) and the user's data, supports grasp of the variation state of material. Then the system provides the function of interpolation or extrapolation about the read data with the information of manufacturing condition and so on. In the second step, critical level is led by combining with the standard information and the life-expectancy prediction technique in the material data (and operating condition). This means that a standard line is shown to the variation in material data. In the third step, taking into consideration including the variation in an operating condition derives the information corresponding to probability of fracture. If the Web service evaluated in consideration of the distribution of external force is offered, probability of fracture is computable by piling up with the distribution curve of the material characteristic.
Moreover, we think that using the FEM structural analysis of the "equipment diagnostic support system" developed as part of this project in Central Research Institute of Electric Power Industry can estimate a more detailed fracture state (or soundness) [6].

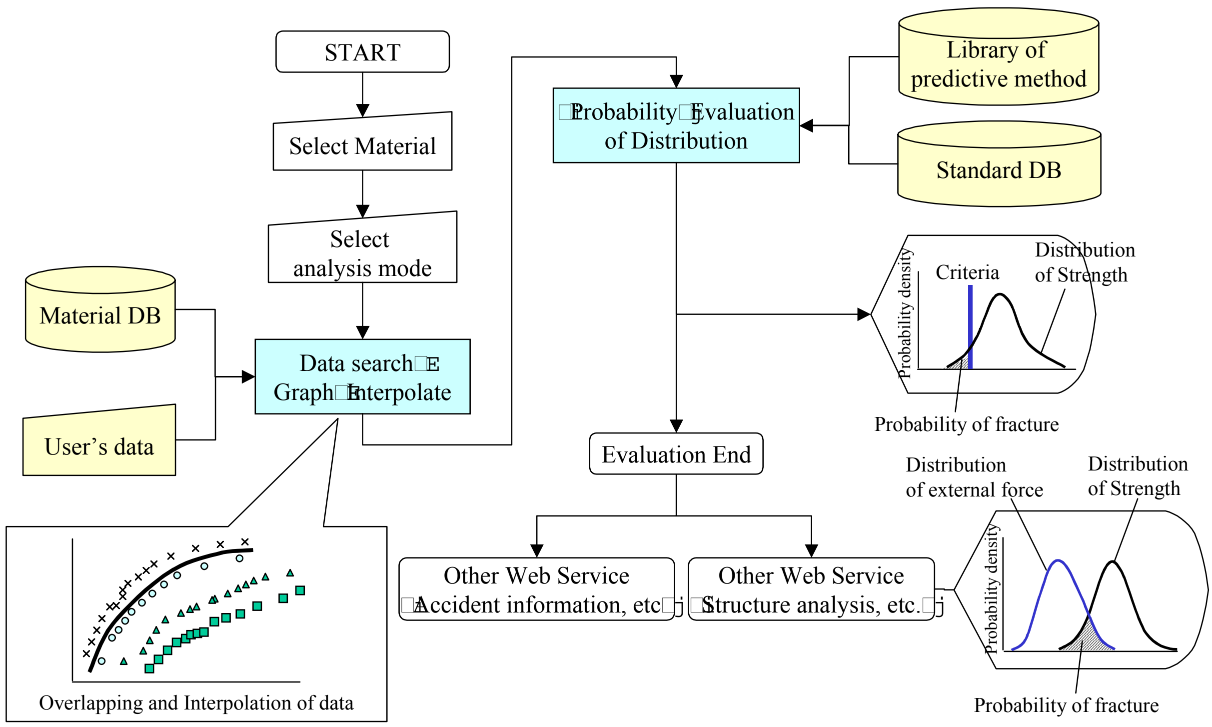

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Figure 3 *Flow of presentation and evaluation function of material risk information.*

5. PROJECT OVERVIEW

Eight organizations are engaged in this project, and National Institute for Materials Science is a leader. Each organization concerning this project and the main work are shown in Table 3. While these research results are stocked as information at this system and a part will be offered as Web service.

A candidate using the information about material is various (*e.g.*, material developer, material user, student and beginner, general citizen, *etc*.). However, target user of this system is the "material user" who designs some kinds of apparatus, because this system is focus on the material risk information. Moreover, if the target users expand to apparatus maintainer and material designers, we think that the profitability of this system will increase.

Table 3 *Organizations of this project and main work*

Organizations	Main work
National Institute for Materials Science	• Project Management • Development of Platform • Test of High Cr Ferritic Creep Resistant Steels and Research of High precision life prediction formula • Micrograph of fracture surface of metals • Extreme environmental Test (cryogenic temperature)
The Iron and Steel Institute of Japan	• Study of rational configuration of safety margin
High Pressure Institute of Japan	• Development of allowable stress database
Central Research Institute of Electric Power Industry	• Development database of domestic accidents • Development Web based equipment diagnostic system and knowledge based system, *etc*.
Mitsubishi Heavy Industries., Ltd.	• Charge test of real equipments • Development database of overseas accidents
Safety Research Institute	• Research on “Technology and Society”
Mitsubishi Research Institute, Inc.	• Design and Development of Platform • Research on “Materials and Society”
The Society of Non traditional Technology	• Adjustment of research and the secretariat

6. CONCLUSIONS

We discuss the overview of material risk information platform and the project of system development of a material risk information platform, which were started from the 2001 fiscal year, and now, systems development is performed aiming at realization of the function shown in this paper.

We think there are two issues about this system at present. One is about the material risk. In this system, we treat the functional loss of material itself is the risk. However, in the definition of general risk, not only the functional loss assumed at the beginning but also other consequent damage may occur. For example, the destruction produced by wetting of the rainwater, which was not assumed at the time of a design corresponds. These are damage scenarios, which cannot be identified from only consider the material use. Another is registration of new Web service. It is meaningless if service unrelated to material risk information is registered. Therefore, we think that the measure and the function to judge how useful information is offered as Web service are needed in operation.

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6.3
RiskScore: A 'Best Practice' Software Package for Quantitative Risk Assessment and Ranking

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Abstract

Powergen has employed a variety of risk-based approaches to maintenance prioritisation on its stations from privatisation. A review of these approaches identified a number of features considered 'best practice', which are briefly reviewed here. Following that work, a software tool has been developed which is designed for use by power station engineers, to assist in assessing and ranking risks. It is not an expert system, but rather is designed to capture the available knowledge, and put it on a common basis. It is simple and flexible, but includes a quantitative ranking scheme for commercial (cost) risks, and also rankings for safety, public relations and environmental risks. This year, for the first time, it is playing a key role in Powergen's annual Plant Status Review process and is also being marketed externally.

BEST PRACTICE

Until recently, a common risk assessment methodology was only applied in the management and prioritisation of safety hazards at Powergen's UK stations, with only some stations using formalised risk assessment procedures to manage commercial and other aspects of engineering risk. Where formal engineering risk assessments were used, the scope and assessment methodology differed at each location. Power Technology was therefore commissioned to review the range of practices used to manage engineering risk on Powergen sites, and those recommended by external consultants / insurers with the aim of identifying 'best practice'.

It became apparent that some risk assessment approaches were more effective than others and also that the more effective schemes shared a number of common characteristics. These 'best practice' characteristics are described below:

- **Site-led:** Individual Powergen locations have functional responsibility for the management of their engineering risk and are most aware of the operational, safety and detailed plant issues.

- **Part of the planning process:** To be useful, risk assessments need to affect the station's future work plans, otherwise they can simply become a paper exercise to justify existing activities. They should affect the prioritisation of monitoring, inspection and maintenance work and alert management to the level of risk. Assessments add most value where they form an integral part of the station annual planning process, with the results feeding into the allocation of tasks and budgets so that the higher-ranking risks are dealt with first. This approach necessitates an annual review or updating of risks.

- **Simple to use:** Risk assessment procedures must be straightforward to ensure consistency between different staff and to encourage risk identification on a common basis.

- **Clear definitions:** For risk assessments to provide sound prioritisation of risks across different plant areas (and different sites), they must be consistent irrespective of who conducts them. Therefore, the implication of risk severity (e.g. high/medium/low) must be clearly and unambiguously defined.

- **Use of task/plant area engineer's expertise:** Within Powergen, the responsibility for individual components rests with the relevant plant area engineer. He/she manages the maintenance, receives all the relevant reports, deals with problems etc. He/she will also need to implement the recommendations of the risk assessment process. Powergen's experience, therefore, is that the plant area engineers should be involved in the risk assessment process. Where this is not done, either the quality of the assessment, or the implementation of the recommendations tends to suffer. The ideal is obviously a team effort, with input from other relevant engineers, including specialists and consultants where appropriate, complementing the knowledge and plant familiarity of task/plant area engineers.

- **Broad scope:** The procedure must be capable of catering for a broad range of risks, covering commercial, safety and where appropriate, environmental and public relations risk categories.

There are two further issues where best practice is more dependent upon the exact circumstances and ultimate use of the risk assessment process.

The first of these is the trade-off between having a uniform procedure that can be applied across an entire portfolio or whether to tailor procedures to suit the needs of individual sites. The former approach allows comparison between sites, gives an indication of overall company risk and allows the company to prioritise investment effectively by having risks for the entire portfolio evaluated on a common basis. The latter has advantages for individual sites in prioritising work. It was therefore necessary for any software evaluation package to be flexible enough to cater for either of these routes.

The second point is the scope of the risk assessment process. This can be comprehensive and incorporate all possible risks or more streamlined to include certain types of risk only. The optimum approach depends on the purpose of the assessment, and to some extent on site-specific factors such as the commercial value of plant availability or the age (and hence experience) of the plant in question. Again, it was critical that any software package would be able to handle and allow practical comparison between the two extremes of risk assessment scope.

RISK SCORING METHODOLOGY

The software aims to meet a number of conflicting requirements:
- the ability to handle a wide spread of risks from cheap and common (eg. tube leak) to expensive but rare (large earthquake).
- to capture the available knowledge, which for some risks will include a well understood likelihood, and for some risks will be quite a crude guess
- it does not give the illusion of accuracy, but nevertheless handles the calculations in a mathematically rigorous way.

In conventional risk assessment theory, the overall level of risk is equal to the product of likelihood and impact. The ranking scheme chosen for the software uses a simple scoring categorisation for frequency per annum (Table 1) and cost (Table 2). In this banding structure, there is an order of magnitude difference between the range of values attributed to each score. A frequency score of 2 is therefore an order of magnitude more likely than a frequency score of 1. In effect, the frequency score corresponds to the frequency on a logarithmic scale. The product therefore becomes an addition of scores:

$$\text{Risk Score} = \text{Frequency Score} + \text{Impact Score}$$

This logarithmic approach allows very infrequent and very frequent events to be accommodated on a simple scoring scale ranging from 0 to 8 (Table 1). The mid-point of the frequency range for the score of 1 is 1×10^{-6}, which represents the lower ALARP (as low as reasonably practicable) safety threshold. Similarly, the scoring system for cost impact can accommodate very inexpensive and very costly risk events on a simple scale ranging from 1 to 5 (Table 2). The use of scores to represent ranges of values increasing in orders of magnitude also helps to make the risk assessments more objective, as two engineers assessing the same risk are more likely to arrive at the same risk score even though their input data is likely to be slightly different. The broad bands should also make the engineer more confident to guess – he/she is only being asked if the frequency is closer to one in ten or one in a hundred. The increased degree of objectivity afforded by this scoring approach makes the risk ranking process more sensible and helps to mitigate the illusion of accuracy that the use of absolute frequency and cost values could produce.

For the other impact categories under consideration (safety, the environment and public relations), the same formula is used for simplicity, even though the relationship is no longer mathematically exact. However, it has been ensured that the impacts attributed to scores of 2 are substantially worse than those attributed to scores of 1 and so on (Tables 3, 4 and 5). The categorisation therefore gives realistic behaviour. Note that the risk scores are calculated separately for each risk category; there is no attempt to produce an overall combined risk score and it is assumed that station/company management will resolve the prioritisation between risk categories.

It is important to recognise the need to recalculate the frequencies of occurrence for safety, the environment and public relations, as not all risk events result in impacts in these categories. For example, the likelihood of a steam turbine blade failing in a manner that results in a fatality (safety impact) is much lower than the likelihood of it causing a breakdown outage (cost impact).

RiskScore: SOFTWARE STRUCTURE

The RiskScore software package has been developed to incorporate the best practice characteristics and risk scoring methodology described above. It provides a structured, uniform approach for the assessment, comparison and ranking of potentially very different risks, whilst remaining simple and flexible in its application. Although it was originally envisaged for use in power station risk assessments, its flexibility means that it can equally be used in other industries with similar asset-based risks.

The software comprises a database in which all data is stored and an executable which acts as the user interface. Flexibility is achieved through the use of a 'Risk Tree'. Each risk added to the tree is uniquely identified by a combination of six 'descriptors' displayed from left to right, with descriptors which are common to more than one risk grouped appropriately. In the example shown (Figure 1), a risk event entitled 'major fire' has been highlighted on the tree, with the complete set of descriptors for this risk being 'Station A\All Units\Boiler\Fuels\Fuel Oil System\Major Fire'.

Also shown in Figure 1 is the 'descriptors' page of the Risk Calculation Form. This can be used to edit descriptors and add/delete risks to/from the Risk Tree. When any of these changes are made, the database updates automatically and the Risk Tree is reconfigured. Note that the descriptor labels shown ('Station or Plant Name', 'Unit or Stream Number', etc.) are default labels only and can be user-defined if required.

RiskScore: DATA INPUT AND SCORING PROCESS

The Risk Calculation Form contains a page for each risk category and an example of the cost page is shown in Figure 2. A brief description of the cost impact can be entered towards the top. The Frequency Score area allows the user to enter either an absolute or a derived frequency, the latter of which may be based on historical (preferably fleet) statistics if available and appropriate. The frequency data is converted to a score automatically using a function based on the ranges given in Table 1. The Cost Impact Score area adds the estimated repair cost to the product of downtime, lost generation capacity and value of generated electricity. The resultant cost is automatically converted to a score using a function based on the ranges given in Table 2. The total cost score is simply the sum of the frequency score and cost impact score and is displayed on the top right-hand side of the form.

The scoring calculations for safety, the environment and public relations are performed in a similar manner, except that the absolute or derived frequency specified on the cost page is modified by one or more factors. For safety (Figure 3), these factors are the probability of a safety impact (should the risk event take place), the percentage of time that staff are in the vicinity of the incident and the number of staff likely to be in the vicinity during that time. This accounts for the fact that a risk event does not necessarily result in a safety incident. Similarly, the frequency scores for environment and public relations are modified by the probabilities of environmental and PR impacts respectively, should the risk event take place.

The Risk Calculation Form also contains a text page where further details relating to the risk being viewed can be entered. Typical entries might include the results of inspection programmes, relevant plant history, spares availability, references to technical reports, details of control measures in place to mitigate risk, assumptions made and so on. Such information is needed to ensure reliable and repeatable risk evaluation and, over time, it can build into a useful knowledge resource. As some data may only be the result of educated guesswork, the text page also allows users to express the level of conviction that they have in their data. As long as this is documented, further guidance from other staff or external consultancies can be sought when reviewing the results.

RiskScore: RISK RANKING AND ANALYSIS

As risks are added to the database, it becomes impractical to view risk scores via the Risk Calculation Form, particularly if there are a large number of risks. The Risk Array (Figure 4) provides a more manageable way of viewing scores for all risks or groups of risks simultaneously. The risks can be ranked alphabetically or in descending score order for any risk category. Scores can also be displayed in number, 'blob' or bar chart format. Aggregate scores for groups of risks can also be calculated by checking the 'sum area' check-box (Figure 5). In the example shown, this allows direct comparison between the total level of risk on different parts of a boiler.

The scores for all risks or groups of risks in any risk category can also be displayed graphically on a Likelihood Consequence Plot (Figure 6). Impact is plotted against frequency with the lower left-hand corner of the plot representing infrequent, low impact risks and the upper right-hand corner representing very frequent, high impact risks. The plot can be used as a means of risk prioritisation.

RiskScore contains two further plots commonly used in the insurance industry (Figure 7). The first shows the distribution of repair and lost generation costs for all risks or groups of risks selected on the Risk Tree. The second shows the frequency per annum with which individual failures will exceed a given cost and can be used to predict the frequency of valid claims if the cost is the excess in the insurance policy.

All risk descriptors, data and scores can be exported to other applications such as Microsoft Excel via a spreadsheet. The currency used throughout the software can also be changed. Standard printing functionality and a comprehensive help system are also included.

RiskScore: ROLL-OUT AND USER EXPERIENCE

The risk scoring methodology was initially tested as a paper-based activity on two of Powergen's international stations. As this proved successful, RiskScore was subsequently developed and has been refined over the last 18 months. It has since been rolled out to Powergen's black fossil and CCGT stations and is forming an integral part of the company's internal annual Plant Status Review process. In the first year of application, it is being used to assess and rank risks previously evaluated using individual station schemes. This enables the comparison of risks across the fleet on a like-for-like basis and facilitate prioritisation of investment. In subsequent years, the scope and depth of risk assessment will be increased, with the results again being used to feed into the stations' annual planning round. The large text field with each risk allows the user to build up a plant history within the database. It is also hoped to apply the software in other parts of the Powergen business.

As explained previously, RiskScore has been designed to be as flexible as possible. This was considered vital if stations were expected to accept, populate and take ownership of the risk database. The organisation of the Risk Tree and the scope of the risk assessment process differ between sites. However, this does not prevent comparison of risks across the portfolio. For example, one site may have one risk to cover the failure of a steam turbine with the frequency taking account of all possible failure modes, whilst another station may prefer to evaluate these failure modes individually (blade failure, water ingress, etc). The logarithmic scoring methodology automatically allows this breakdown of risks to be compounded and so the aggregate score would equal that of the equivalent single risk for an identical machine in similar condition.

In response to customer feedback, the descriptor levels in the tree structure were made interchangeable. This functionality allows (for example) scores to be sorted by unit first and plant area second or vice-versa, depending upon the needs of the station management.

It is vital to ensure that the frequency always corresponds to the severity of the impact chosen. For example, if death is chosen as the impact in the safety risk category, the probability of safety impact specified must be the probability of one or more deaths occurring as a result of the risk event in question (i.e. it should be a low figure). If, on the other hand, the chosen impact is an injury with up to three days lost time, the probability of safety impact is likely to be much higher. This sounds obvious, but it is surprising how often a mismatch between likelihood and impact occurs in practice.

Further feedback from users should be available at the time of the seminar and will be presented.

RiskScore: A FULLY COMMERCIAL PRODUCT

Risk Score is now available to external clients as a commercial product on a license basis with full software support from Power Technology. Power Technology also has substantial experience in risk assessment of power plant in the UK and abroad for both internal and external clients and can advise on technical issues as required.

It is also important to note that a conscious decision was made not to make the software an expert system, or component specific. In this respect, it is quite unlike some other risk assessment packages used in the power industry, which adopt a structured, component-based approach. In these, certain data is prompted from the user. An example might be a boiler header, where the material, operating hours, starts, and inspection data are all put in by the user. The software then uses pre-determined rules (an "expert system" type algorithm) to deduce a risk level.

The approach used by RiskScore allows a wide spread of components and risks to be handled. This offers the scope to capitalise on the breath and depth of expertise that Power Technology and other specialists can offer, if the user wants to, or to allow the user to do the assessment themselves. The downside is that the software gives the user no assistance in quantifying frequency or impact data. There is currently no in-built expertise, although a database of risks assessed historically is growing, and can be used by Power Technology for comparison. The software simply acts to capture the available knowledge, and allow comparison of risks in a consistent way.

CONCLUSION

RiskScore is a risk assessment and ranking software package to help evaluation and comparison of potentially very different risks on a common, repeatable basis. It can be used equally well in prioritising investment at individual sites or across a portfolio. This is achieved by using a clear scoring methodology that reduces potentially extreme frequency and cost values to a simple, sensible scale. Safety, environmental and public relations risks are treated in a similar manner. RiskScore has been successfully rolled out to Powergen's fleet of black fossil and CCGT power stations, forming an integral part of its internal annual Plant Status Review process. It is also commercially available as an external product with full support provided by Power Technology.

***Table 1** Score banding for frequency of occurrence*

Frequency Score	Description	Frequency Range (per annum)		
		Low Limit	**Mid-Point**	**High Limit**
0	Negligible: typically once in ten million years	0	1.0×10^{-7}	3.2×10^{-7}
1	Extremely low: typically once in a million years (lower ALARP safety threshold)	3.2×10^{-7}	1.0×10^{-6}	3.2×10^{-6}
2	Very Low: typically once in a hundred thousand years	3.2×10^{-6}	1.0×10^{-5}	3.2×10^{-5}
3	Low: typically once in ten thousand years	3.2×10^{-5}	1.0×10^{-4}	3.2×10^{-4}
4	Low/Medium: typically once in a thousand years	0.00032	0.001	0.0032
5	Medium: typically once in 100 years	0.0032	0.01	0.032
6	Medium/High: typically once in 10 years	0.032	0.1	0.32
7	High: typically once a year	0.32	1	3.2
8	Very High: Typically more than once a year	3.2	10	No Limit

***Table 2** Score banding for cost impact*

Cost Impact Score	Description	Cost Range		
		Low Limit	**Mid-Point**	**High Limit**
1	Very low	No limit	10,000	32,000
2	Low	32,000	100,000	320,000
3	Medium	320,000	1 million	3.2 million
4	High	3.2 million	10 million	32 million
5	Very high	32 million	100 million	No limit

***Table 3** Score banding for safety impact*

Safety Impact Score	Criteria	Description
0	Not Applicable	The risk considered does not have any possible impact on safety
1	Very low	Minor injury with no lost time (e.g. a scratch, bruise, cut or slight burn)
2	Low	Injury with medical treatment required and up to three days lost time (e.g. a larger cut or sprain)
3	Medium	Reportable injury with more than 3 days lost time (e.g. fractures, serious burns)
4	High	Major injury resulting in long term absence
5	Very high	Death to one or more individuals

Table 4 *Score banding for environmental impact*

Environmental Impact Score	Criteria	Description
0	Not Applicable	The risk considered does not have any possible impact on the environment
1	Very low	Minor impact confined to site
2	Low	Significant impact but still confined to site
3	Medium	Minor impact off-site
4	High	Environmental incident (e.g. discharge) which must be notified to the relevant authorities
5	Very high	A serious breach of site authorisations, and could lead to fines or restriction of operating licence

Table 5 *Score banding for public relations impact*

Public Relations Impact Score	Criteria	Description
0	Not Applicable	The risk considered does not have any possible impact on public relations
1	Very low	Negligible
2	Low	Complaints from public (e.g. letters)
3	Medium	Minor adverse comment in local media
4	High	Major adverse comment in local media, minor comment in national media. Location only is implicated.
5	Very high	National adverse comment, impact on whole company.

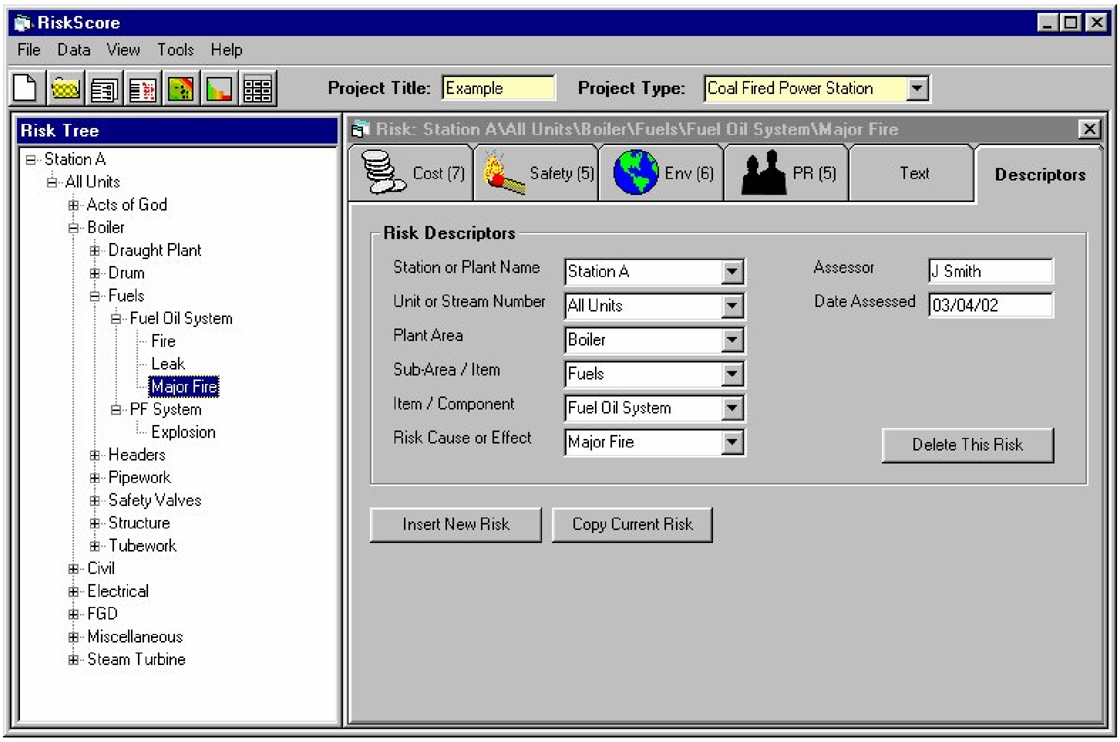


Figure 1 *An example Risk Tree (partly expanded) and the descriptor page of the Risk Calculation Form for the risk selected on the tree.*

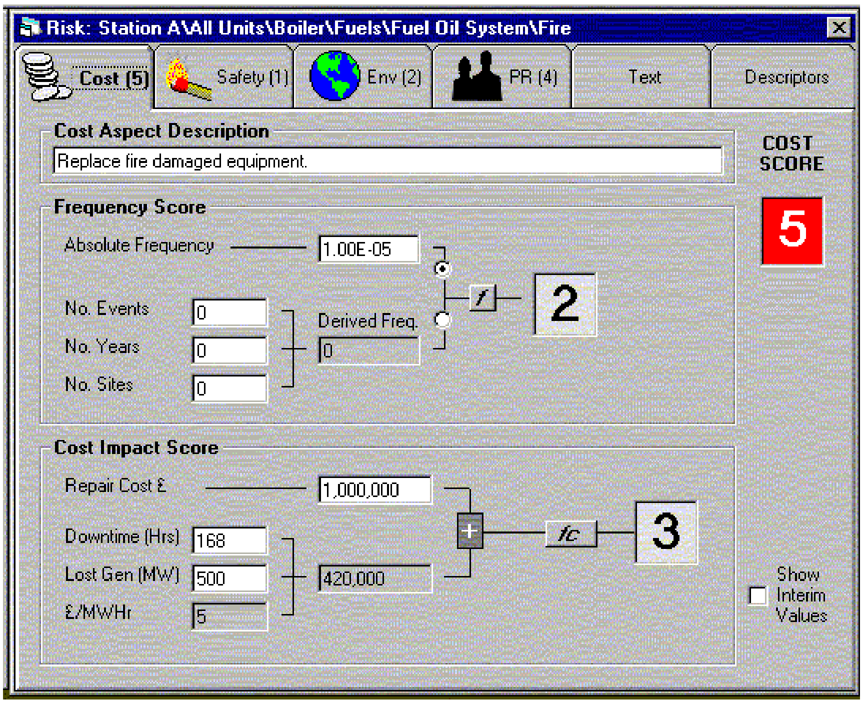


Figure 2 *A typical cost page of the Risk Calculation Form.*

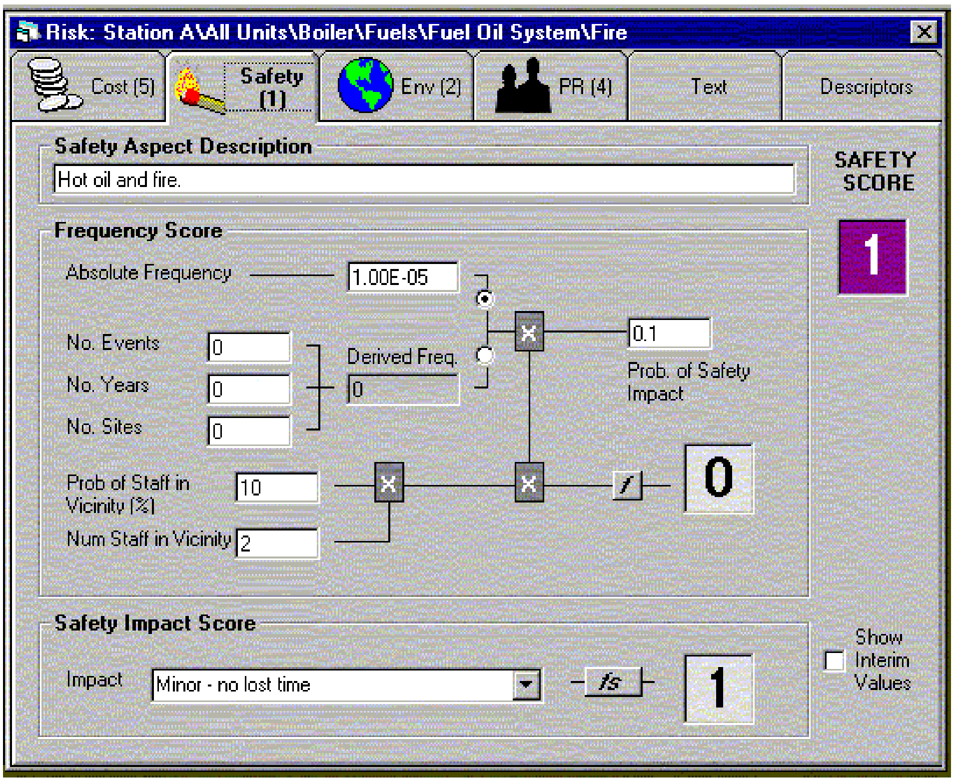


Figure 3 *A typical safety page of the Risk Calculation Form.*

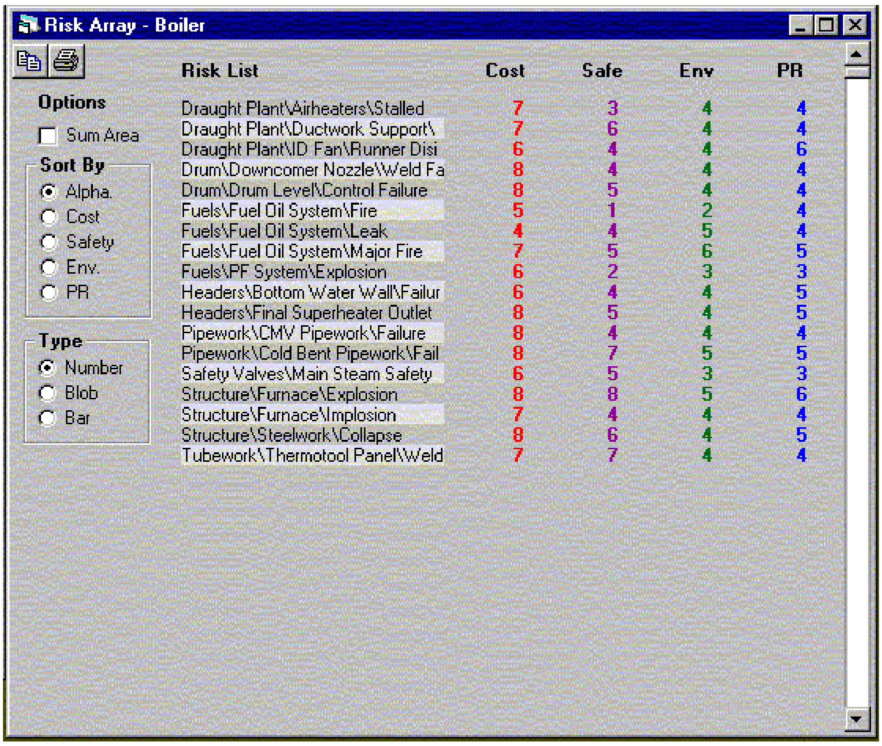
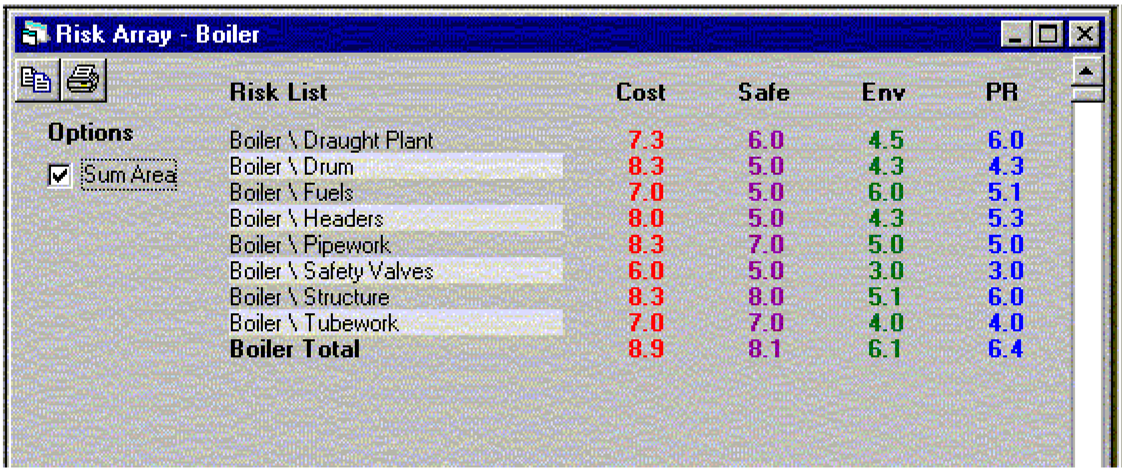


***Figure 4** An example Risk Array showing 'Boiler' risks ranked by cost score.*



Risk List	Cost	Safe	Env	PR
Boiler \ Draught Plant	7.3	6.0	4.5	6.0
Boiler \ Drum	8.3	5.0	4.3	4.3
Boiler \ Fuels	7.0	5.0	6.0	5.1
Boiler \ Headers	8.0	5.0	4.3	5.3
Boiler \ Pipework	8.3	7.0	5.0	5.0
Boiler \ Safety Valves	6.0	5.0	3.0	3.0
Boiler \ Structure	8.3	8.0	5.1	6.0
Boiler \ Tubework	7.0	7.0	4.0	4.0
Boiler Total	8.9	8.1	6.1	6.4

Figure 5 *Aggregate scores for groups of risks under the 'Boiler' descriptor.*

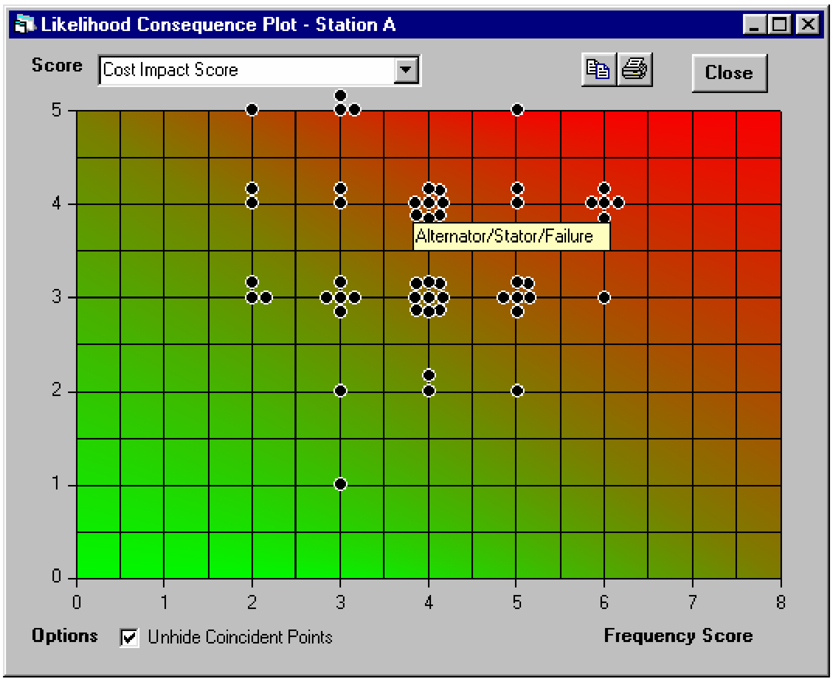


Figure 6 *A Likelihood Consequence Plot displaying cost impact score against frequency score. Coincident points can be shown as clusters for ease of identification.*

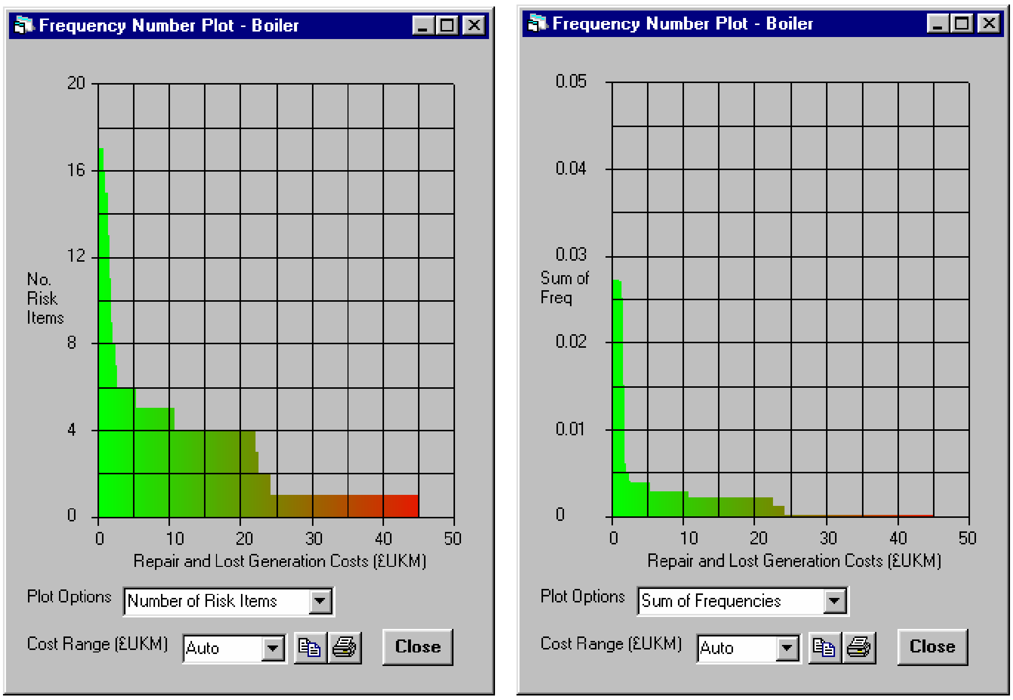


Figure7 *Two forms of Frequency Number Plot. The first shows the spread of costs for the risks considered whilst the second shows the frequency per annum with which individual failures will exceed a given cost.*

7.1
Risk Based Management of Power Plant Equipment Insurer, Inspector and Competent Person

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Abstract
The roles of the engineering plant insurer, inspector and competent person may be seen as three vastly differing roles, especially in respect to the provision of risk based management, with each role being undertaken by separate organisations independent of each other.

This paper looks at these three roles and discusses how they interact with each other giving substance, rigor and confidence to a risk based approach to the continued safety and operation of pressure systems.

INTRODUCTION

Within the engineering world Royal & SunAlliance, like a lot of other similar companies, provide our clients with three very different, and yet closely linked, key services:

1) ***Insurer*** – We offer many and varied products to suit the individual needs of our customers. From sudden and unforeseen damage, including breakdown, explosion and collapse, to undetected defects in building services plant. From deterioration of stock in refrigerated storage to some of the financial consequences of plant failure.

2) ***Inspector*** – There is a requirement under various UK and European Health & Safety legislation for employers to ensure that any work equipment is suitable for its stated purpose and that it remains in a safe condition throughout its life. If the equipment is exposed to conditions causing deterioration, which is liable to result in a dangerous situation, then it should be inspected at suitable intervals. Royal & SunAlliance provide inspection services covering a variety of plant including electrical installations, lifting equipment, power presses, machinery and pressure equipment.

3) ***Competent Person*** – Within pressure related UK legislation the role of Competent Person has two distinct functions, the first is to draw up or certify schemes of examinations and the other is to carry out those examinations as detailed in the certified scheme. The aim of the written scheme is to detail the scope, extent and frequency of an examination to ensure that any deterioration or malfunction is identified at an early stage. The content of the written scheme will therefore vary, depending on the degree of risk associated with each separate part of a pressure system. The attributes of the competent person carrying out these activities will also vary according to the perceived risk of plant failure. Royal & SunAlliance can provide this service across all categories of system including large steam generating systems.

As can be seen, from the foregoing, these are very different and distinct yet all three activities have a crucial role to play in the development and introduction of a risk based management philosophy throughout industry.

Insurer

As previously detailed, the type of cover generally provided by Engineering Insurance Companies is wide ranging, however, there remain many losses which are uninsurable.

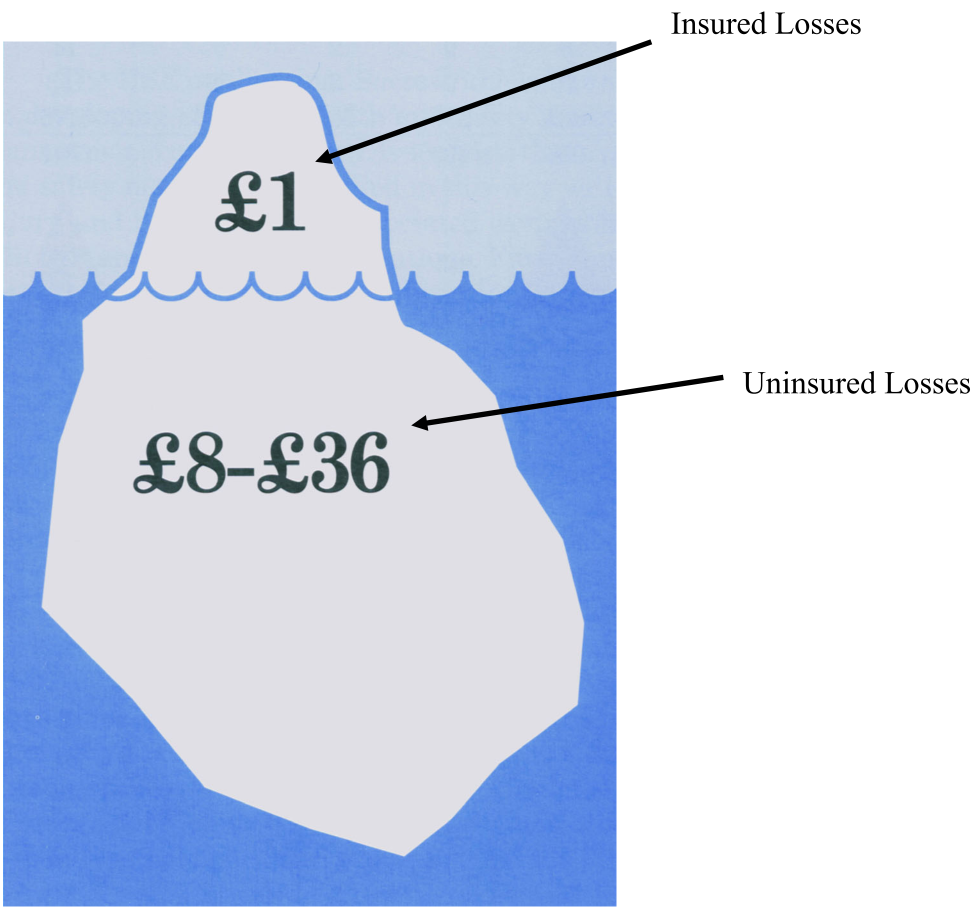
For instance –

- Policy excesses – The amount that the policy holder pays before any insurance claim is paid.
- Losses due to normal wear and tear - Any damage gradually occurring which is predictable and inevitable from normal operation or usage.
- If an employee is injured during an incident, there is a loss of that individual's productivity. There is also the associated cost of training the replacement staff before they become fully productive.
- The psychological impact on the workforce. Incidents can generate negative employee opinion against the company, which can have a significant impact on future productivity and profit.
- Losing public confidence can also have a negative impact, affecting sales and reducing company share value.

In an attempt to understand the cost of these losses, a detailed study was carried out in the UK, on behalf of the Health & Safety Executive between 1990 and 1991, in the area of accidents at work with specific attention being paid to the associated costs incurred as a result of accidents. The study then went further and looked at the differences between the insured and uninsured costs to the organisations concerned. This analysis concluded that, based on a conservative estimate of avoided accidents and serious incidents, the direct cost of inspection is much less than the avoided insured losses. Insured costs can be taken as the cost of all insurance premiums such as employers liability, business interruption, damage to buildings etc. whilst uninsured costs may include such aspects as sick pay, lost product, loss of goodwill or corporate image.

Included in the case studies were comparisons of the ratio of insured to uninsured costs. Many employers mistakenly believe they are covered by insurance for most of the costs arising from accidents. The results of the study showed that uninsured costs far exceed insured costs, in fact they were between 8 and 36 times greater than the costs of insurance premiums paid. It is unwise, therefore, to rely purely on insurance without any attempt to quantify and manage risk.

The main business of Insurance companies is to provide a service where a customer can transfer a certain amount of their own risks over, and so it has been a logical progression for the Engineering Insurance Business, within the UK, to move from the more rigid calendar based approach imposed by the Factories Act to one that enables the specific risks to be targeted and actioned.



Inspector

Pressure vessels and systems do fail and the reasons for those failures are many and varied and include:

- Defects, which were not identified or rectified during manufacture.
- Design issues, which may be due to users not understanding the operational limits of their plant, a feature that may be compounded by the increasing use of second hand plant.
- Lack of a structured, planned approach to the maintenance of protective devices and their routine testing.
- Operator error is known to be a primary cause of failure. Lack of adequate training or the move towards multi-skilling of staff, where plant operation is only one small part of their responsibilities, are considered to be the main issues.
- In-service failure and degradation are generally addressed by the application of various inspection techniques specifically developed to identify the initiation and extent of those defects.

Looking at each of these issues in greater detail can help us understand how changes in the approach can lead to the reduction in plant failures.

❖ The involvement of a third party, or notified body, during the design and manufacturing stage of an item within a pressure system can give increased confidence in the structural integrity of that item. Under the Pressure Equipment Directive there may not be a requirement for independent verification and so the user may need to specifically request such involvement.

- Construction of new pressure equipment in accordance with the requirements of the Pressure Equipment Regulations requires a risk assessment to be carried out. Under the compulsory 'Essential Safety Requirements', the manufacturer is under an obligation to analyse the hazards that may exist when the pressure equipment is used under all foreseeable operating conditions. The pressure equipment should be designed, manufactured, checked, equipped and installed as to ensure its safety. This can be achieved through elimination or reduction, as far as practicable, of identified hazards. Where total elimination is not possible then appropriate protection measures against hazards should be applied or the user should be informed of any residual hazards and indicate whether it is necessary to take special measures to reduce the risks either at the time of installation and/or use.

- A maintenance system that takes into account such plant related issues as the age of the plant, the operating/process conditions and the working environment should be in place. This system would be expected to cover issues such as the correct operation of safety related devices.

- The utilisation of adequately trained staff is essential. It is a requirement of the Provision and Use of Work Equipment Regulations that all staff responsible for the operation and maintenance of the plant should be suitably trained and competent to ensure safe operation of the plant. All staff should also be aware of the procedures to be followed in the event of an emergency.

- In service degradation can be detected through the application of a suitable inspection technique. This inspection may vary from just a visual examination to one that involves the application of specialist techniques such as metallurgical examinations, appropriate non-destructive testing or continuous monitoring. The definition of an examination is given as "a careful and critical scrutiny of a pressure system or part of a pressure system, in or out of service as appropriate, using suitable techniques, including testing where appropriate, to assess its actual condition, and whether, for the period up to the next examination, it will not cause danger when properly used if normal maintenance is carried out". The person or body carrying out the examination is referred to as the Competent Person.

Competent Person

The Pressure Systems Safety Regulations define the attributes of the Competent Person, carrying out the examination, as having sufficient practical and theoretical knowledge and actual experience of the type of system under examination to enable defects or weaknesses to be identified and an assessment made of their significance with respect to plant integrity and safety.

Due to this increase in the demands placed on this role, especially in the more complex and high-risk pressure systems, it is unlikely that the Competent Person is an individual. The role of Competent Person is often taken by an organisation that has all the necessary skills and expertise required within its workforce.

As explained in the introduction, the Competent Person fulfils two roles under the Pressure Systems Safety Regulations: To certify a written scheme of examination and to carryout that examination. These roles do not need to be the same Competent Person however, where they are shared, there is always the potential for confusion over responsibilities and misunderstanding or misinterpretation of the information within the scheme of examination.

Both of the above activities require an understanding and appreciation of the risk of plant failure:

- In identifying those items of plant that should or should not be subject to regular examination requires an assessment of the risk of failure to be carried out.

- In setting the period between examinations requires the Competent Person to understand the in-service degradation mechanism and the rate at which deterioration occurs.

- The choice and application of the inspection technique should be made on the anticipated failure mode and an understanding as to which technique is appropriate according to the type of degradation that is expected.

- When an examination has been carried out, the competent Person is required to make a judgement as to the ongoing safety of the pressure system and to certify that the plant is considered suitable for a stated period of time.

- Should a defect or other evidence of degradation be found during an examination then the Competent Person is required to make a decision as to the remedial action necessary to ensure the plant continues to be safe.

RISK BASED MANAGEMENT

So what can a company do to reduce the losses incurred as a result of an accident? The most obvious way is to stop having accidents in the first place. Things will still go wrong and plant will continue to fail, so insurance continues to play an important role when addressing any aspect of plant failure. Risk management goes one step beyond the mere provision of insurance cover, it involves analysing a companies processes and operations, identifying hazards and devising management procedures. The likely incidence of breakdown and consequential claims for business interruption are thereby reduced.

However, plant operators and users can become proactive in tackling the underlying causes of accidents by introducing a health and safety management strategy that involves addressing the risks associated with any piece of plant. This shift in emphasis towards risk should not be based just on risk protection it should involve risk prevention as well, while the former is still important, it is the latter which has become the ultimate objective as a safeguard against any threat to the earning capacity of an enterprise.

Through effective inspection, which involves providing and acting on feedback with respect to the root causes of any accident or failure, engineering insurance companies have had a dramatic impact on the reduction in the number of plant failures. Current legislation, within the UK, requires those companies carrying out inspection of pressure equipment to notify both the user and the enforcing authority of incidences where there is a risk of imminent failure of a system if immediate action is not taken. Appropriate remedial work can then be carried out on the item of plant thereby avoiding a failure of that system.

In all but the simplest situations, risk analysis and inspection planning require a wide range of technical inputs and perspectives from differing disciplines, risk based management is therefore best undertaken by a team of individuals, the number and composition of which will vary according to the complexity of the system, however the team should be able to demonstrate adequate technical knowledge and experience in all relevant areas such as risk assessment, process hazards, plant safety, operation and maintenance and inspection methods.

In practice, the user and the regulatory authorities rely, to a great extent, on the independence and the breadth of knowledge and experience of the Competent Person, as it is this role, especially the third party bodies, that brings balance to the risk analysis process as it is recognised that they ensure that any decisions made, as part of the risk assessment, do not compromise safety.

The plant user must also take a proactive role if all risks are to be reduced. Through effective training of personnel, consistent safe operation of the plant, implementation of a maintenance regime based on prevention of failure as well as breakdown and finally, by ensuring that the plant is inspected by a company who understands the risks that the plant faces, the user can play a very important part in reducing the number of failures.

In the light of this it is ironic that a key disincentive for a company to carry out risk assessment is the perceived cost involved. Obviously, a company facing financial hardship will wish to avoid any costs that it believes will bring in little return. Far better, some may think, to risk accidents occurring, and deal with them if and when they do.

CONCLUSION

In any successful Risk Based Management approach it is vital that full and open co-operation exists between the various organisations and bodies that provide input into the process. The discrete departments within the users organisation, the Competent Person, the insurer and other independent experts should all communicate freely throughout.
Managing the safety of a complex, high integrity installation should be a rigorous undertaking, one which will stand up to detailed scrutiny. The quality of information, feedback, decision making, competence and planning will reflect in the overall quality and success of the process and it would be advised that such a process is subjected to regular auditing. This audit should establish that the process has been properly designed, is being applied and operated properly and is shown to be effective at meeting its objectives.

The role of any participant in a risk based management approach to plant integrity should not be underestimated, the involvement of the insurer, the inspector or the competent person has often been overlooked to the detriment of the process and it is hoped that this paper has highlighted why they should be seen as being integral to that process and being able to provide valuable contributions to its success.

REFERENCES

'Safety of pressure systems' Pressure Systems Safety Regulations 2000 Approved Code of Practice, HSE Books L122
'Best practice for risk based inspection as a part of plant integrity management' HSE Contract research report 363/2001

7.2 Application of a Justification Factor to a Safety Improvement Program Using Hazard and Operability Analysis

Gordon W. Cowan, P.Eng[a]., Jim Prince, P.Eng.[b] and J. Allan Arnott, P.Eng.[b]
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[b]*Ontario Power Generation, Canada*

Abstract

Ontario Power Generation has undertaken a Safety Improvement Program at one of its large coal fired plants, the Nanticoke Generating Station on Lake Erie in Ontario, Canada. Phase I of the Safety Improvement Program focussed on identifying equipment safety hazards, and consisted of seven Hazard and Operability reviews performed on various critical and non-critical plant systems. The Safety Improvement Program HAZOPs employed a detailed risk evaluation matrix, which was used to provide data for calculation of a Justification Factor. The Justification Factor combines HAZOP session derived risk rankings with order of magnitude cost estimates. The resulting calculation provides an expression of HAZOP Action item benefit that incorporates both risk improvement, and the cost of risk improvement. The Justification Factor provides an additional HAZOP Action evaluation tool for the decision-maker.

This paper outlines the data elements which make up the Justification Factor calculation, and their application to the Nanticoke Generating Station Safety Improvement Program HAZOP studies. Comments concerning the contribution of the Justification Factor to the Safety Improvement Program are provided.

INTRODUCTION

Ontario Power Generation (OPG) embarked upon an extensive Safety Improvement Program at the Nanticoke Generating Station. Nanticoke GS is a coal fired power plant with 8 units rated at 500 megawatts each. It is the largest fossil generating station in North America.

In 2001, Nanticoke GS initiated a Safety Improvement Project in order to develop an action plan for controlling health and safety hazards for various aspects of plant operation and maintenance. The approach adopted for evaluating hazards related to plant systems and equipment, was to employ Process Hazard Analysis techniques, specifically HAZOP analysis. The intent was to use these tools as a formal assessment method for identification these hazards and suitable controls.

HAZOP ANALYSIS

Process Hazard Analysis (Ref. 1) is recognised in most legislative jurisdictions of the world, one example being the OSHA 1910.119 regulation in the United States. There are six types of Process Hazard Analysis cited in OSHA legislation. Of these, two were used for the Nanticoke Safety Improvement Program analysis - “HAZOP,” and “What-if?” Analysis. The term “HAZOP” comes from “HAZard and OPerability” Analysis and it is often used generically to refer to Process Hazard Analysis. This paper uses the term “HAZOP” to describe the studies, and uses the terms “Guideword HAZOP” and “What-if?” to describe the two Process Hazard Analysis techniques used for the plant equipment analysis in the Safety Improvement Program. Both analysis types break a main topic area into smaller parts or components, which are then examined in a systematic manner. For Guideword HAZOP, a main topic is broken into various “nodes” (the topic areas for examination). These nodes then have Guidewords and Parameters attached to them. “Guide Words” are used in combination with “Parameters” to outline the “Deviations” to be considered. To illustrate, the following could be used to evaluate a node such as a portion of a piping system:

Guide Word	Parameter	Deviation
High	Pressure	High Pressure
High	Temperature	High Temperature
High	Flow	High Flow
Low	Pressure	Low Pressure
Low	Temperature	Low Temperature
Low/No	Flow	Low/No Flow
Reverse/Misdirected	Flow	Reverse/Misdirected Flow
As well as	Composition	Contamination
As well as	Flow	Leak

Each Deviation is examined to determine the Causes of the Deviation, the Consequences of the Deviation (effect on plant or personnel), the Safeguards (which are in place to avoid or control the upset situation) and Recommendations (also referred to as “Actions”) - which are the suggested corrections to reduce or eliminate the hazard.

The “What-if” methodology also breaks down the main topic into various discrete items for examination. These are called “Systems” and “Subsystems.” Instead of using set combinations of Guidewords and Parameters, “What-if” methodology postulates upsets to the system through the use of “What-if” questions. “What-if there is a fire in a pulveriser mill?” is an example question, which is then explored in a similar manner to the Guideword HAZOP - consideration and note is taken of Consequences, Safeguards, and Recommendations (Actions).

Another common point of the methodologies is the composition of personnel used for HAZOP sessions, which should be a representation of expertise including operations, maintenance, and engineering. Nanticoke HAZOP personnel included at minimum:

- HAZOP Session Leader
- Nanticoke “System Owner” – an individual who is responsible for the performance of the system under study
- Operations staff familiar with the system
- Controls Maintenance representative
- Mechanical Maintenance representative
- Nanticoke GS Health & Safety Committee representative

Additional session members were present as the demand for expertise dictated.

The principal advantage of using HAZOP Analysis for the Safety Improvement Program was in the generation of Actions from the various sessions. These Actions provided a comprehensive list of recommendations ands suggestions, from a skilled Nanticoke Generating Station stakeholders, for potential improvements in safety and operations in the plant. The list of Actions and other session records was recorded by the Session Leader, using Dyadem PHA Pro 5.0 HAZOP software. Phase I of the Safety Improvement Program generated 486 Actions for the seven systems studied.

THE SAFETY IMPROVEMENT PROGRAM

This paper primarily deals with HAZOP Action management, however the Safety Improvement Program encompassed more than HAZOP Analysis. For example, a separate part of the program examined and improved plant maintenance procedures. The concerns of the plant Health and Safety Committee[1] were important to the main program design. Phase I HAZOP systems identified for

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[1]The Joint Health and Safety Committee is a Committee required by Provincial (Ontario) legislation. At least half of the Committee is composed of employees who are not managers.

analysis were proposed by the Joint Health and Safety Committee of the plant, although total program design considered full coverage of the plant. The issues raised by the Joint Health and Safety Committee were related to the following systems:

1. Bottom Wet Ash System
2. Pulveriser Systems including coal bunkers and feeders
3. Flue Gas Conditioning
4. Dry Fly Ash Systems (Power House)
5. Fly Ash Handling and Unloading Systems
6. 4.6 kV & 600 V Switchgear
7. Hydrogen System
8. Heating, Ventilating, and Air Conditioning Systems
9. Powder River Basin Coal Use

All of the above issues were recognised to warrant analysis within the Safety Improvement Program. The first seven analysis topic areas were chosen for immediate analysis, with the last two items being considered for Phase II program coverage.

Regardless of when the various plant area examinations would take place, it was quickly realised by the Safety Improvement Program project team that a large number of Actions for plant improvement could be expected to arise in the course of the program. Early Safety Improvement Program design anticipated a potential of ten HAZOP studies being done, which could conceivably lead to a total of 700 Recommendations.[2] For the seven Phase I HAZOPs, similar reasoning implies that approximately 350 Phase I Actions would be generated (in fact, there were 486 Phase I Actions). Even allowing for the fact that not all Recommendations would be accepted for implementation, the resulting total would still be more than could be adequately budgeted for within the Safety Improvement Program, and other budgets available over a period of years. The challenge was therefore to provide plant management with a tool that could be used to prioritise the actions and guide expenditure allocation.

To some extent, expenditure allocation guidance can be provided by risk matrices commonly used for HAZOP examinations. An example risk matrix is shown in Figure I. The Safety Improvement Program project leaders were aware of previous work done by Kinney and Wiruth (Ref. 2), which proposed a "Justification Factor" calculated using risk considerations. A similar approach was required for the Nanticoke GS Safety Improvement Program, so that guidance might be provided for value gained from expenditure, as well as risk mitigated.

HAZOP PROGRAM DESIGN

Elements of HAZOP program design were:

- Relation of individual HAZOP studies to the overall Safety Improvement Program
- Risk Matrix Design
- Justification Factor Design
- Overall Reporting
- Anticipation of Phase II work.

The first point acknowledges that HAZOP studies must be useful as stand alone items. At OPG, this means that recommendations from each individual HAZOP study, would be used by the person with system performance responsibility (System Program Owners, in the terminology employed at OPG). The HAZOP outputs must also be useful to plant management, by providing a more global view of the priorities across the plant regarding those systems included in Phase I of the project. This program

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[2]Using an anticipated average of 20 Recommendations per session day, for 10 HAZOPs averaging 3.5 session days for each HAZOP.

requirement was met by risk matrix design, Justification Factor design, and by HAZOP reporting. All were designed to provide useful data on an individual system basis, and for the total program.

The second point refers to risk indication. Risk Matrices had already been used in a previous HAZOP at the Nanticoke Plant and there were numerous other risk ranking methodologies available within OPG. Some of these were created within OPG for specific work, and many were introduced from outside consultants who had contributed to various projects. For the Safety Improvement Program, the various matrices used within corporate OPG were examined. One of these existing matrices was a Business Risk Identification matrix, which was adapted for the use of the Safety Improvement Program. The adaptation is referred to as the OPG HAZOP Risk Matrix, and it is shown in Figure II.

There were several features of this risk matrix which were desirable for the SIP HAZOPs. The matrix was already in use within OPG, and as a Business Risk Matrix. It was familiar to OPG management in general, including executive management. The matrix was detailed, more detailed than risk matrices commonly used for HAZOP Analysis, and therefore better suited to Justification Factor work than a standard HAZOP risk matrix. An additional factor was that the descriptions for the various risk values were very good. They were more clear than other matrices commonly used for HAZOP sessions and these descriptions were more suitable for power plant use than many chemical process oriented risk matrices might be.

The third point refers to the Justification Factor, which provides the means for a qualitative judgement concerning overall value of a HAZOP recommendation. The Justification Factor calculation described by Kinney and Wiruth was unchanged for the Safety Improvement Program:

$$JF = \frac{Risk \times RiskFactor}{\sqrt[3]{\dfrac{TotalCost}{100}}}$$

where:	JF	= Justification Factor
	Risk	= Risk value before mitigation action
	Risk Factor	= An expression of risk solution (0 - 1)[3]
	Total Cost	= Order of magnitude cost estimate for the Action.

Although the Justification Factor calculation was unchanged from Kinney and Wiruth, the OPG HAZOP Risk Matrix values mean that different values for the Justification Factor would be calculated compared to the literature example. The key reason for this was the desire to adhere to a risk matrix, which was already accepted within OPG, which ideally could be used for other work. Other considerations of note for the calculation of the Justification Factor using the OPG HAZOP Risk Matrix were:

- Values assigned for frequency, probability, and consequence, were not restricted to whole numbers
- The top value for frequency presented in HAZOP sessions was 5.5 - "every shift"
- The top value for probability presented in HAZOP sessions was 5.5 - "it is going to happen every time"
- Separate consequence rankings were given in sessions for "Safety," "Environment," "Production"
- Each Action identified during HAZOP sessions was fully rated for the five numerical parameters, for the situation prior to Action implementation, and anticipated rating after Action implementation
- Budget costing was done outside of HAZOP sessions, primarily by the OPG System Owner, with some assistance from the HAZOP Sessions Leader if requested
- A value of "1" was the least value assigned for any parameter - there was no "zero" value

Overall reporting for Phase I HAZOP studies combined all of the Actions for all of the HAZOPs into a general list for the purpose of initial identification of high priority Action for implementation. Testing was done to check the usefulness of the OPG HAZOP Risk Matrix and Justification Factor calculation. This was done by assigning calculated risk values from the Kinney and Wiruth system, and the proposed OPG system, to Actions which had been proposed from the first HAZOP sessions of the program

(Bottom Wet Ash). It was found that the OPG Risk Matrix and Justification Factor calculation did not give identical results to the system proposed by Kinney and Wiruth. The OPG system tended to provide more weight to less expensive Actions, compared to the literature model, and the two systems did not always rank Actions in the same relative order. These differences were explored by both the HAZOP leader and some OPG technical staff. The end result was that the OPG method was judged to be suitable for OPG application, and in some instances, superior to that provided by literature. This subjective conclusion was based upon comparing ratings derived by the two systems, and testing to see which system more closely resembled OPG technical staff judgement concerning the proposed Action.

The last point concerning HAZOP Program Design concerns Phase II of the Safety Improvement Program. Two phases were used for the program so that budget allocations could be made, and progress achieved, without waiting for a comprehensive plant wide result, and in the first budget year of the program.

HAZOP SESSION APPLICATION

A key uncertainty in applying a Justification Factor to a wide ranging HAZOP program is the potential effect on session efficiency. Risk matrix use in HAZOP sessions is generally acknowledged to extend session time. It was found that session team members quickly adapted to the OPG Risk Matrix. The HAZOP leader introduced the Risk Matrix at the beginning of sessions by providing a copy of the matrix to the participants and briefly describing it. Ratings, however, were not done until the middle of the first day, in order to allow each new group to adapt to HAZOP sessions without concern for risk ranking. This practise is felt to be important for program success.

The total amount of session time required for the detailed OPG HAZOP Risk Matrix ranking system is greater than that of ordinary risk matrix use, but it is interesting to note that the time increase is not significantly more. Perhaps this is because the rating definitions are clearer than a standard risk matrix. Justification Factor calculation was referred to in session introductions, but only to briefly explain why the detailed ranking was being done. Justification Factor calculation was dealt with totally outside of sessions for both cost estimation, and Justification Factor presentation in session reports.

Informal testing was done to determine how risk ranking using the OPG HAZOP Risk Matrix would vary between HAZOP groups. This was done by asking each group to risk rank a local automobile driving situation on local highways. It was found that each rating element varied between groups by 7 - 25%, depending upon the element. The environmental ranking varied the most. Overall risk expression standard deviation over six session groups amounted to ~45% of the average risk expression (the product of 5 element ratings). In general, the groups were consistent in either providing above or below average readings for the individual elements, although there were exceptions (i.e. - a group which provided a below average overall risk expression might provide a Safety rating higher than the average over the six groups).

JUSTIFICATION FACTOR - REPORTING AND RESULTS

All of the Actions generated in Phase I, were combined into a single listing of Action Items. The Justification Factor was reported in the final report for each HAZOP system, which some of the System Owners felt was useful within their own plant equipment responsibilities. The main use of the Justification Factor reporting was to provide guidance for the Safety Improvement Program action prioritisation. The Justification Factor sorting quickly identified high value Actions, or those Actions which apparently provided maximum value for immediate implementation, based upon expenditure required, and safety or operability improvement anticipated. For example, there were 24 Actions identified which had essentially no cost for implementation. Only one of these Actions had a Justification Factor less than 10. An example of this would be a simple operations or maintenance procedure change that would have no incremental cost impact.

Kinney and Wiruth provide guidance for their system of Justification Factor results, advising that a Justification Factor of greater than 20 indicates a highly worthwhile Action to undertake, and less than 10 being of doubtful value. Although the risk matrices used to calculate Justification Factors are quite different between the two systems, the total values are similar. OPG results indicate that a value of 10 is worth consideration. The highest Justification Factor value calculated for Phase I HAZOP Actions was 752, with only eleven Actions having a Justification Factor greater than 100. The distribution of Justification Factors over 486 Actions was:

Justification Factor	Number of Occurrences
JF > 300	1
200 < JF < 300	3
100 < JF < 200	7
50 < JF < 100	16
25 < JF < 50	20
10 < JF < 25	75
5 < JF < 10	102
1 < JF < 5	189
JF < 1	73

The above values show that the OPG Risk Matrix does encompass a range of Justification Factor values, which is wide enough to provide guidance to the decision maker. An important aspect of Justification Factor use in this application, however, is that it is viewed simply as another tool for improved decision making. The Safety Improvement Program did not substitute Justification Factor use for engineering and management judgement. While there are many valid reasons for this, perhaps the most obvious is the test performed for risk ranking variance between groups. While the total Justification Factor presentation over almost 500 Actions does present worthwhile relative value information, the variance of risk expression shows that a qualitative judgement is being expressed, and not a quantitative one.

CONCLUSIONS

1) Process Hazard Analysis (PHA) techniques such as Guideword HAZOP, and "What-if?" Analysis can be useful successfully for thermal power generation applications.

2) Kinney and Wiruth examples of value analysis in the risk field can be adapted to specific power generation project uses; qualitative guidance can be provided concerning the amount of safety, environment protection, production improvement presumed to occur for changes made, and money spent.

3) The OPG HAZOP Risk Matrix provides enough risk ranking detail that it can be used for Justification Factor calculation, using the formula outlined by Kinney and Wiruth.

4) Justification Factor calculation can provide an estimation of value achieved for Actions Resolution in a HAZOP study.

5) Justification Factor calculation is a tool for Action/Recommendation evaluation, but it is not a substitute for engineering and management judgement.

ACKNOWLEDGEMENTS

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Figure 1 *An example risk matrix.*

CONSEQUENCE ASSESSMENT			***FREQUENCY RATING***	
1	Fatality, severe injury; OR over 6 months production loss; OR whole unit and adjacent unit(s) damage, production loss.		1	Could occur on an annual basis (or more often).
2	Moderate injury/health impact; OR production loss in months; OR whole unit production loss.		2	Could occur several times during facility life.
3	Minor injury/health impact; OR production loss in days; OR several major components production loss.		3	Could occur once during facility life.
4	No injury/health impact; OR production loss in days; OR single major component production loss.		4	Not expected to occur during facility life.

CONSEQUENCE		**FREQUENCY**			
		1	**2**	**3**	**4**
	1	1	2	3	4
	2	2	4	6	8
	3	3	6	9	12
	4	4	8	12	16

Figure 2 - *OPG HAZOP Risk Assessment Matrix*
(for Ontario Power Generation Justification Factor Calculation).

Likelihood Assessment

Frequency Ranking	**Rank**	**Frequency**
How frequently does the hazardous event occur?	**5**	1 Day
	4	1 Month
	3	1 Year
	2	5 Years
	1	20 Years

Probability Ranking	**Rank**	**Probability**
When the hazardous event does occur, how probable is it that a loss will occur?	**5**	Almost Expected
	4	Quite possible
	3	Could happen
	2	Only remotely possible
	1	Practically Impossible - One in a million

Consequence Assessment

Rank	**Safety**	**Environmental**	**Production Losses**
5	• Multiple Fatalities • Off site impacts	• Immediate and lasting environmental impact, potential for: • Legal impact, charges • Death of Wildlife • 1 or more very serious spill • Clean up costs > $10m	• Loss of one unit for a year • Total production loss for month or more
4	• Fatality • Severe injury causing permanent disability • Injuries resulting in more than 3 lost days	• Exceeded limits resulting in charges • 1 or more serious spill • Air emissions exceeding targets • > 8 reportable events	• Loss of one unit for month(s) • Loss of major equipment for months
3	• Injuries resulting in about 1 - 3 lost days	• No charges • No very serious or serious spills • Emissions meet target • 3 - 8 opacity events • 3 - 8 other reportable incidents	• Loss of one unit for a week or more • Major equipment outage for a week or more
2	• • Accidents, but no off site care • No lost time	• • No charges • No very serious or serious spills • Emissions below target • <3 opacity events • <3 other reportable incidents	• Production losses for days • Major equipment outage for 1 - 3 days
1	• Incidents • No lost time	• Non-recordable events	• Short equipment outage • Minor equipment outage for days

7.3
Risk Based Determination Of Reinspection Intervals Of High Temperature Pressure Vessels And Boilers After 100000 Service Hours

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Abstract

The determination of reinspection intervals of pressure components working at high temperature and under creep load is affected by a large number of uncertainties. One of the most important factors that can be taken into account for the determination of reinspection intervals is the residual life, which can be evaluated by calculation or experience. Another important information is given by the result of metallographic replicas which can detect the level of creep damage. Moreover useful information on defects of nature other than creep such as corrosion, fatigue, erosion etc. come from the results of NDT examinations. All this information, combined with risk assessment related to the specific component, can help the designer and the inspector to determine the reinspection intervals which allow a safe operation of the component. A research on this subject has been carried out by ISPESL - the Italian Authority in charge of the safe operation of pressure vessels and boilers - and has brought interesting results.

We propose a new method for the determinations of reinspection intervals based on ISPESL experience in this field. The proposed method has been tested using ISPESL database on plant working under creep load giving interesting results for practical application and encouraging further research in this direction.

1. INTRODUCTION

The Italian legislation on pressure vessels and boilers working under creep load [1] states that when service life exceeds design life (100000 or 200000 service hours) the component under examination must be "re-certified" by ISPESL (Italian Institute for Work Safety). This procedure includes the following main steps: calculation of life consumption due to creep, performance of in-field non-destructive examinations and investigation of material deterioration by metallographic replicas.
The first part of this paper describes a methodology for defining the inspection plan considering the influence of the type of weld, the category of the equipment according to ascending level of hazard (PED Directive) and the level of expended life fraction.
In the second part of this work a new risk based method for the determination of reinspection intervals is proposed; this procedure is divided into three steps, the first one being the assessment of the global damage level, the second one the evaluation of the corresponding risk level and the third one the determination of the reinspection intervals.
Each step is associated with a specific matrix which correlates different variables: class of defect, class of microstructural damage, type of weld and extension of NDT.
Reinspection intervals defined with this procedure are a function of the accuracy of the inspection performed on the component allowing greater flexibility in the decision policy.
The methodology presented has been implemented for pressure vessels and boilers working under creep load but can be applied to a broader variety of pressure equipment.

Determination of the inspection plan

When service life reaches design life it is necessary to perform – according to the Italian legislation - a wide inspection campaign which includes NDT and replicas. Type and extension of NDT examinations are the basic variables of the inspection plan and can be defined, for a given weld, introducing a new parameter, function of expended life fraction, hazard category and type of welded joint.

Expended life fraction

ISPESL experience has shown that it is extremely difficult to assess - only by calculation - the real situation of the component under investigation.
According to the Italian legislation on life extension of pressure vessels and boilers working under creep load (ISPESL Circular n. 15/92), life consumption must be assessed using time vs. stress log-to-log straight lines as in TRD and Euronorm Codes. For the determination of $\sigma_{r/200.000/T}$ (from $\sigma_{r/100.000/T}$) Larson-Miller parameter (LMP) can be used.
In some cases, instead of using time vs. stress straight lines, LMP vs. stress or temperature vs. stress lines have been used. In all the methods curves are locally approximated to straight lines and a safety factor of 0.8 on the working stress in applied.
Simple comparisons of the numerical results of the various methods applied to a practical situation show that life consumption estimation is not univocal yet subjected to great variations according to which of the above methods is used. In-field experience confirms this result: very seldom the result of calculation agree with the real aging of the component.
However, a statistical investigation conducted by ISPESL has shown that when the result of numerical life calculation shows a high life consumption then the probability of finding defects during in-field investigations increases. This means that in this case it is advisable to increase also the extension of NDE methods in order to have a better insight of the real situation of the component.
For the present application the expended life fraction calculated has been divided into four ranges according to Table 1. To each of these ranges a corresponding level is defined (Level of Expended Life fraction = LEL).

Table 1 *Level of Expended Life fraction = LEL*

	α	**B**	**γ**	**δ**
LEL	0 ÷ 25%	25% ÷ 50%	50% ÷ 75%	>75%, <100%

Determination of extension and type of NDE examinations

In order to determine the extension of NDT to be performed on a given weld during inspection a new risk based parameter has been defined. This parameter is a function of the following quantities:

- Level of Expended Life fraction, as previously defined;
- Hazard category, according to PED Directive (the category of the equipment is defined according to ascending level of hazard I-IV).

The new parameter must count for the necessity to increase NDT extension as the Level of Expended Life fraction and the Hazard Category increase (see Table 2).

		Level of Expended Life fraction			
		α	**β**	**γ**	**δ**
Hazard category	**I**				
	II				
	III				
	IV				

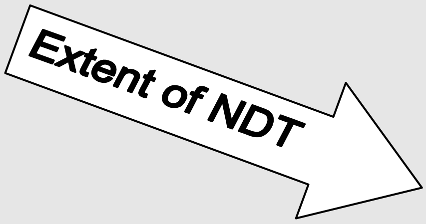

Table 2 *Extension of NDT*

The Extension of NDT Parameter (EXT) ranges between 1 and 5 according to the following table (Table 3):

Table 3 *Extension of NDT Parameter (EXT)*

EXT	Extension of NDT
1	Limited
2	Low
3	Medium
4	High
5	Very high

In order to determine the type of NDT technique to perform it is advisable to refer to the type of weld. For this purpose a new parameter has been introduced, called *criticality of the welded joint.*
This parameter is strictly correlated with the consequences of a failure of a given welded joint and can be classified as very low (A), low (B), medium (C), high (D). Base material is classified as very high (E).
For example, welded joints of headers can be classified as follows (Figure 1):

- A: header/non-pressure parts
- B: header/small nozzles (De<100)
- C: header/big nozzles (De≥100)
- D: circumferential or shell/flat heads

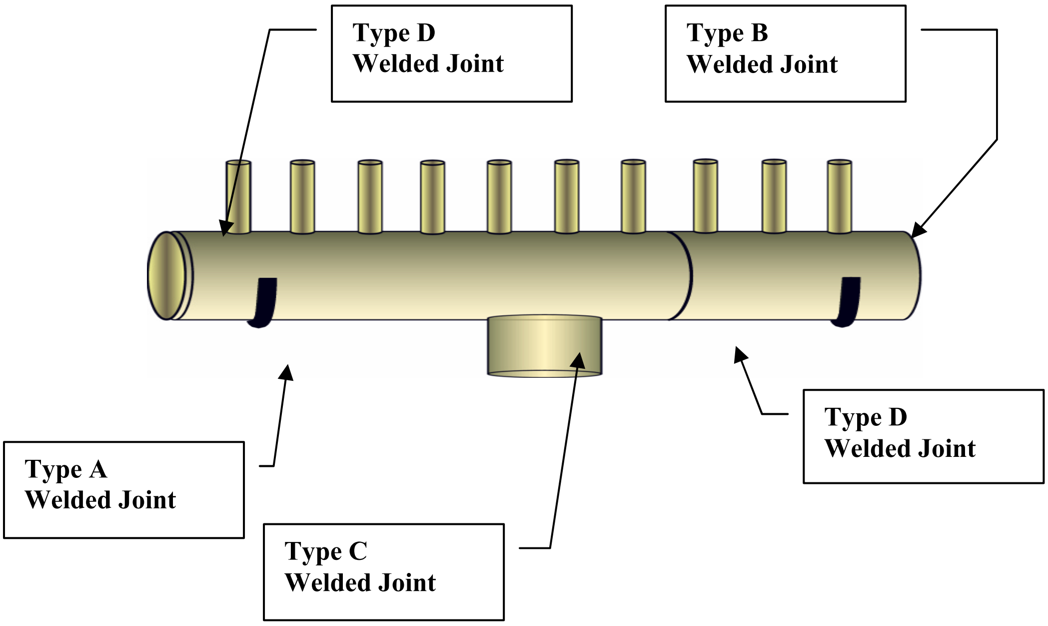

Figure 1 *Criticality of welded joints.*

The NDT technique to be performed must be correlated to the *criticality* of the weld, according to Table 4:

Table 4 *NDT technique according to the criticality of the weld*

Criticality of the weld	Types of NDT Techniques to Perform	
	Compulsory	**Additional**
A	VT, PT (or MT)	ST
B	VT, ST, MT (or PT)	ET
C	VT, ST, UT, MT (or PT)	RT
D	VT, ST, UT, MT (or PT)	RT
E (base material)	VT, UTS	DM

where the following symbols apply:

UT ultrasonic	MT magnetic particles
RT radiographic	UTS thickness
PT dye penetrants	ST replication
VT visual testing	ET eddy currents
DM dimensional	

Additional NDE examinations according to Table 4 are to be performed whenever higher accuracy is needed.

2. DETERMINATION OF REINSPECTION INTERVALS

After the first inspection performed at 100'000 or 200'000 working hours a great amount of information regarding the state of the component is available. In many cases the previously calculated expended life fraction often disagrees with the real situation detected by in-field NDT and replication.
Anyway for our practicle application it is not important to assess precisely the level of life consumption. It is more important to define reinspection intervals in a quick and direct way.

The first step of this procedure is to establish an index of damage of the welded joint which combined with the its *criticality* gives a precious information about the level of risk.
From this information it is possible to define reinspection intervals as a function of the NDT performed with the aid of a probability/consequences matrix.

Classification of NDT results

It is extremely difficult to assign a numeric value to the result of the non-destructive examinations. A complete and precise quantitative classification cannot neglect fracture mechanics and practical experience.
As an example Table 5 shows a possible quantitative schematization of defect detected by non-destructive evaluation methods. Each class of defect (low, medium, high, etc.) includes a specified range of defects of certain size and nature according to ISPESL in-field experience [3, 6].

Table 5 *Quantitative classification of defect detected by NDE methods*

Class of Defect	*Detected Defect*
1	No defect
2	Low defect
3	Medium defect
4	High defect
5	Irreversible defect

Classification of creep damage

Conventional NDE methods fail to detect incipient damage which can degenerate into crack initiation and eventually rapid failure. Metallographic replicas are the basic tool for determining material deterioration and creep damage evolution on the component. Several approaches attempt to determine qualitatively and quantitatively the level of creep damage and estimate life consumption (i.e. Neubauer classification [4]).

Determination of the index of damage

The level of damage of a given welded joint of a given equipment must be determined combining the result of NDT with the result of replication. Once a defect on a welded joint is detected, it is necessary to assess its nature: if it is a creep crack it might develop quickly and eventually lead to failure. For this purpose a new inspection/repair procedure has been implemented by ISPESL [8] for surface cracks:

1. Detection of surface cracks by NDT
2. Grinding till crack disappears up to depth<limit depth (function of type of welded joint)
3. If crack still exists at limit depth perform replication at crack tip to detect crack nature, otherwise simple repair
4. Grinding till crack disappears
5. Repair according to specification

Step 3 gives an important information on crack nature. With the result of replicas it is possible to enter table 6 and eventually assess the global damage level of the welded joint.

Class of defect						
	5	V	V	V	V	V
	4	IV	IV	IV	IV	V
	3	III	III	III	IV	V
	2	II	II	III	IV	V
	1	I	II	III	IV	V
		1	2	3	4	5
		Creep Damage				

Table 6 *Global Damage Level (GDL) of the welded joint*

Determination of the risk index

After having detected the Global Damage Level, which is strictly correlated to the probability of failure, it is necessary to take into account the consequences of a possible failure.
This parameter is dependent on the type of welded joint (*criticality*). For example the failure of a circuferential weld of a SH header can cause more serious consequences than the failure of a nozzle/header weld. Using a risk matrix it is possible to correlate the Global Damage Level with the *criticality* of the welded joint, giving as a result a Global Risk Level (GRL – Table 7).

Table 7 Global Risk Level (GRL) as a function of Global Damage Level (GDL) and criticality of welded joint

Global Damage Level (GDL)					
	V	5	5	5	5
	IV	4	4	5	5
	III	3	3	4	5
	II	2	2	3	4
	I	1	1	2	3
		A	B	C	D
		Criticality of the Welded Joint			

Reinspection Intervals

From the Global Risk Level it is possible to determine the reinspection intervals. The procedure is the following: Entering Diagram 8 with the value of GRL and moving horizontaly we first find the value of the reinspection interval correlated with the minimum extension of NDT (EXTmin). Going on horizontally we find the values of the reduced intervals obtainable by increasing the extension of NDT.

GRL	5					T_{V}
	4				T_{IV}	$T_{IV}/0.8$
	3			T_{III}	$T_{III}/0.8$	$T_{III}/0.7$
	2		T_{II}	$T_{II}/0.8$	$T_{II}/0.7$	$T_{II}/0.6$
	1	T_{I}	$T_{I}/0.8$	$T_{I}/0.7$	$T_{I}/0.6$	$T_{I}/0.5$
		1	2	3	4	5
		EXT				

Table 8 *Reinspection intervals as a function of Global Risk Level (GRL) and Extent of NDT (EXT)*

The type of NDE examination to perform depend on the *criticality* of the welded joint as previously described (see Table 4).

It is important to notice that the value of EXT from Table 8 may not agree with the initial value of EXT from Table 2. This is due to the fact that Table 2 refers to the inspection plan at design life (100’000 or 200’000 hours) while Table 8 refers to the inspection plan at the following plant stops.

The main steps of the methodology for the determination of reinspection intervals are summarized in the following flow-diagram (Figure 2).

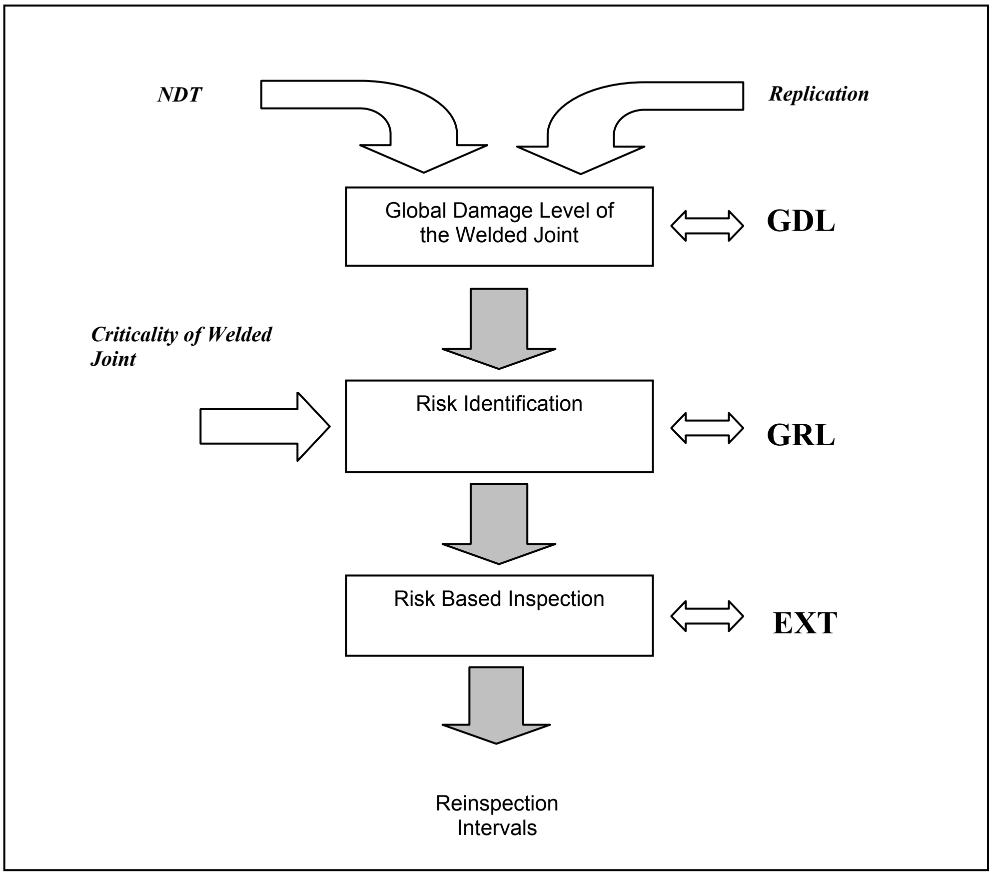

Figure 2 *Determination of reinspection intervals.*

3. CONCLUSIONS

In this paper two procedures are presented: the first one for the determination of the inspection plan (extension and type of NDT), the second one for the determination of reinspection intervals.
Both procedures refer to pressure vessels and boilers working under creep load which have exceeded 100,000 hours and need to be further implemented to become more practically applicable.
This is the first step to define a repeatable procedure for the determination of reinspection intervals for this type of equipment which may support the decision policy of ISPESL, the Italian Authority in charge of the safe operation of pressure vessels and boilers working under creep load.

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8.1
Identification and Management of Engineering Risk

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Abstract
The identification and quantification of Engineering Risks is no longer an optional extra in the successful management of modern power plant. The Engineering Risk Assessment Process (ERAP™) described in this paper, is a methodology widely used by Innogy for the Identification and Management of Engineering Risks at all its power stations. It has been successfully used with external clients on power plant across the world.

INTRODUCTION
Engineering risk is a reality. It is an unfortunate fact of life that major plant failures do and will continue to occur.

It is fair to say that the CEGB were risk averse. Power stations were built under the old adage "When in doubt, make it stout using things you know about". This resulted in an expected life of twenty five years or more. Substantial designs were used in the construction of power station plant with significant margins. The CEGB remit was to keep the lights on at all costs.

Following privatisation of the industry, competition and market forces made successor companies adopt more cost effective policies in procuring and maintaining power plant. Risk awareness was necessary to ensure the continued success of the business. In determining the best Engineering solution to a problem, payback on improved plant operation needed to be demonstrated over an ever-reducing timescale.

Further pressures on traditional "sound engineering practice" have been applied under the New Energy Trading Arrangement (NETA), where the opposing requirements of cheap and high reliability plant have to be provided to ensure the commercial survival of the remaining generating companies.

A methodology for identifying engineering risks and managing these risks was developed within National Power during the late 1990s. As the largest of the successor generator companies formed from the CEGB, the process was developed to assess the level of engineering risk that the Company was potentially exposed to across its operating plant portfolio. At that time National Power owned or part-owned and operated 17,000MW of coal, oil and gas power stations across the UK (+90MW of wind turbine capacity and 11 cogeneration schemes) and a further 7000MW of power stations overseas[1].

Traditional methods of determining risk employed by other organisations were considered to be too subjective and qualitative to perform the task. A process was required which would:

- Give an overview of the degree of engineering risk across all power station plant areas.
- Provide the focus for more detailed technical assessment of identified high-risk areas.
- Maintain an informed and up-to-date view of engineering risks across a portfolio of power stations.
- Produce a means of quantifying and scoring risks, and enabling comparisons of the magnitude of risks between plant areas and similar power stations.

The Engineering Risk Assessment Process (ERAP™) was developed to meet all the above requirements and be applicable to all forms of power plant regardless of location. The process has now been completed on many power plants around the world. In addition, the process has grown to compliment the management of engineering risks and broader business risk assessments (see Figure 1).

THE PROCESS
Engineering Risk is defined as a measure of the likelihood and the impact of technical faults or plant failures occurring during normal plant operation. Innogy's specialists have compiled a handbook with

hundreds of man-years of experience of potential engineering risks that have occurred or might occur on power station plant, based on their past experience and general knowledge [(2)]. This knowledge is now encapsulated into a central database.

A team of accredited specialist engineers visit the site to meet local plant personnel; explain the risk scenarios addressed; and agree safety/commercial/environmental consequences and likelihood scores for each area of concern.

The ERAP™ report provides detailed risk assessment results, highlights top priority areas for action, benchmarks the plant against comparable sites, and makes recommendations on how to implement risk reduction measures

APPROACH TAKEN
Bottom-up processes (such as HAZOP) consider every eventuality of a plant / system failure but are very time consuming and costly. To avoid high level of resource expenditure, the ERAP™ process takes advantage of existing knowledge of plant area experts to filter out low risk areas. There is a danger of missing some areas but cost savings are an order of magnitude lower. In most applications a full bottom-up approach is impractical for a total plant study unless money is no object.

AREAS OF CONCERN
Each expert identifies "Areas of Concern" for their plant area. These "Concerns" are typically generic problems that have been seen somewhere in Innogy's past history. In order to ensure that the process is kept within a manageable size, each expert is asked to ensure that the risks within their plant area can be characterised by no more than about six areas of concern, unless it is absolutely essential to include more.

IMPACTS
A risk is significant if it has a material impact in one or more of the following categories, which are treated independently:

- Safety The possible number of fatalities and/or serious injuries
- Repair Cost The cost to repair any plant damage in £ millions (converted from local currency)
- Availability The loss of plant availability in days; reduced plant performance

The Impacts are the "size" of the consequence in the event that the "concern" actually occurred. The "size" of the Impact is not based on a "Doomsday Scenario" (for example a party of visitors is present, leading to a high number of fatalities), but rather on the circumstances which would prevail on a normal operational day. For most Concerns there is a range of potential outcomes. The Impacts have been sized on the largest credible outcome.

The size of the impacts may change with the type of power station, or they may vary from unit to unit, from station to station, or from country to country. For example the manning levels and availability of plant spares with short lead times in various plant locations may vary significantly from those that are the norm in Europe.

It should be noted that the accuracy that can be reasonably expected for these estimates of the impacts is not high. Estimates of within a factor of ten have been taken as a minimum requirement, whilst those within a factor of two have been considered as good as necessary for this work.

FREQUENCY
Concerns can have very different probabilities of occurrence and magnitudes of impact. As an example, the catastrophic failure of a high temperature steam turbine rotor is a low probability event, but carries a high impact with potential fatalities plus two years loss of generation. By comparison a boiler tube failure is a very frequent event which is normally accompanied by low impacts, typically a relatively small loss of availability. To avoid the potential for the risk assessment being dominated by low probability high impact events, the Concerns are put into one of the following broad categories, which are measured on a per unit basis:

Rare The Concern is not expected to occur at all during the design lifetime of the Unit under assessment, but may be experienced under exceptional circumstances.

Occasional The Concern is expected to occur on the Unit on average once or twice in a five-year period.

Frequent The Concern is expected to occur on the Unit once or more per year.

LIKELIHOOD IN OPERATION

It is necessary to estimate the Likelihood that the Concern will take place. The "likelihood" is a number representative of the relative possibility that one concern will occur during plant operation when compared with another. It is derived by a scoring process, such that an expert can record their judgement of the level of risk posed by a concern in a numerical way rather than in words.

Three parameters have been identified for scoring Likelihood, namely "Extent", "Control" and "Resource".

EXTENT

The extent score is a measure of the underlying size of the problem at the particular unit. It is an inherent characteristic that could be a function of basic design, operational history, and past O&M practice.

CONTROL

This is the set of management processes applied by the Owner that are sufficient and necessary to ensure that the Concern is kept under control such that the risk of the Concern occurring is kept as low as reasonably practicable.

RESOURCE

The Resource parameter answers the question "Are there sufficient personnel, who have adequate competency, to carry out the necessary controls, and are there sufficient funds available?"

CALCULATION OF OVERALL RISK SCORE

The next step is to derive a number that may be used as a measure of overall risk. For each Area of Concern, each of the Impacts is multiplied by the Likelihood to give the overall safety risk; repair cost risk; and availability risk respectively:

$$Risk_{Concern} = Impact \ x \ Likelihood$$

This process is repeated for each Area of Concern in each Plant Area under consideration.

THE SCORING PROCESS

Innogy maintains a database, which includes Reference Sheet data for every Area of Concern. These provide a definition of each concern, generic values for the Impacts, together with written descriptions of the upper and lower bounds for the three components of Likelihood, Extent, Control and Resource. Generic data on stations, plant types, accreditation of specialists and historic data from previous assessments are also maintained within this database.

At the commencement of a new ERAP™, datapacks are generated from the central database and disseminated to a team of specialists who are accredited in each of the required plant areas. These datapacks are populated with data during the discussions with the power station engineers and then returned to the central database.

Features contained within the central database enable the generation of tables of risk scores, radar graphs showing plant area comparisons (see Figures 2 and 3) and an overall structure for the ERAP™ report.

Further assessments add value to the process, enlarging the database and providing specialists with a broadened experience and reference list. Client confidentiality is maintained by keeping reference comparison plant anonymous, to allow generic comparisons between power stations.

CONCLUSIONS

Identification and Management of Engineering Risk by ERAP™ has proven to be applicable across a broad range of plant. To date it has been successfully applied at over 35 stations in the UK and world-wide and there has been good customer feedback. In assisting the development of cost effective plant management strategies, the risk of plant breakdowns and forced unplanned outages have been reduced by this process.

REFERENCES

1. The Electricity Supply Handbook (1998)
2. Engineering Risk Assessment (1997) - J R Gilden / C J Rees

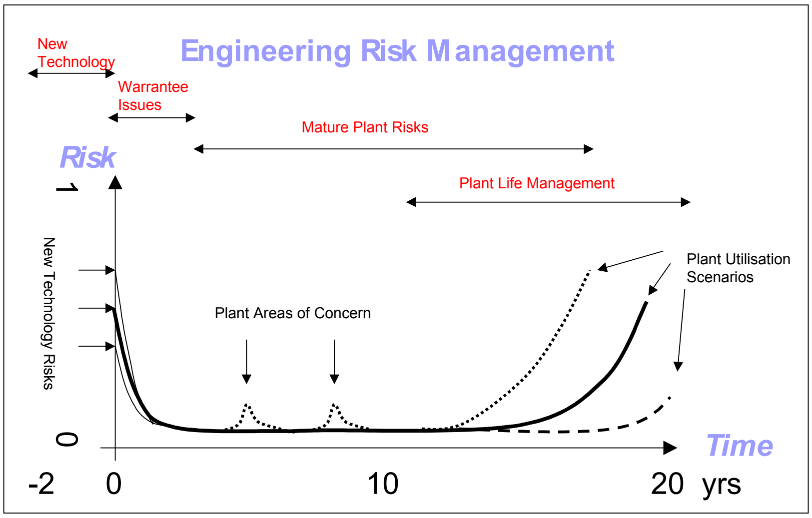

Figure 1 *Engineering risk management processes.*

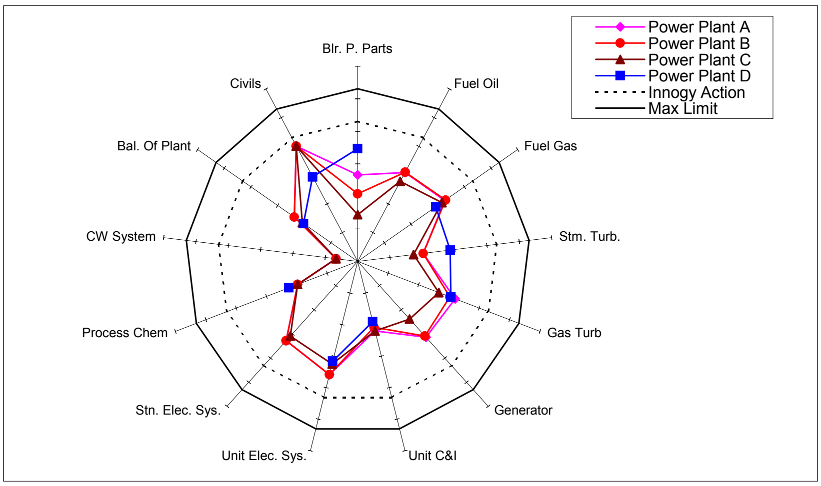

Figure 2 *Safety risk radar diagram.*

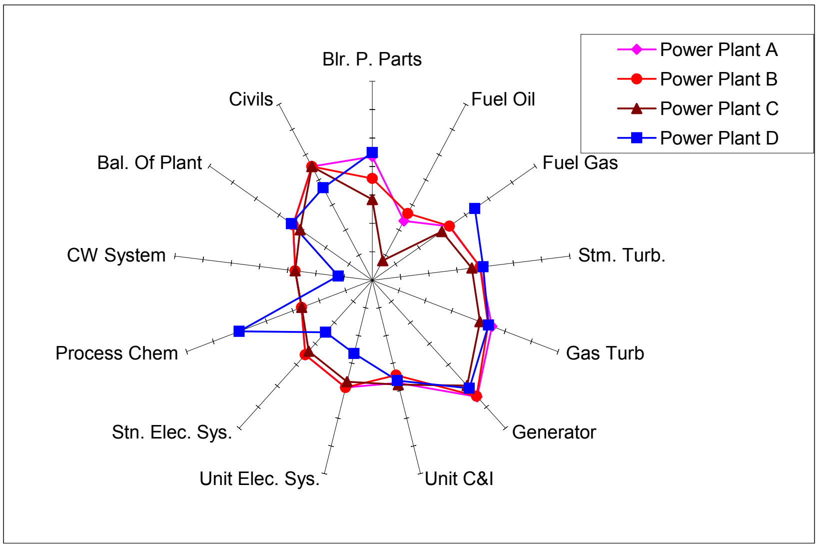

Figure 3 *Availability risk radar diagram.*

8.2
Commercial Application of the Plant Life Usage Approach to Damage Rate of Power Plant

Chris Harris
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Abstract

This paper describes the application of plant life and condition formulae to the asset management process for power plant, including cost of capital, investment planning, and short term operational decisions. The approach taken is that of "plant life usage", which has much similarity to the equivalent operating hour approach commonly used for the blades in combined cycle gas turbines.

1. INTRODUCTION

My purpose today is to demonstrate the usage of metallurgical component life formulae in the practical management of a power station business. It is an interesting application of science-meets-commerce. In terms of commercial application, the science is rough indeed, but daily utilisation of the basic formulae does ensure the live provision and capture of data that we can then use to examine and test in a metallurgical sense.

The concept of using up available life has been around for as long as people have. We age with elapsed time no matter how easy life is, and are conscious that overwork or insufficient repair reduces our life expectancy. The analogy to human life has coloured our thinking on component life through the use of the well known but largely over-emphasised[1] "bath-tub" curve shown in the Figure below, that even has rather vivid anthropological terminology.

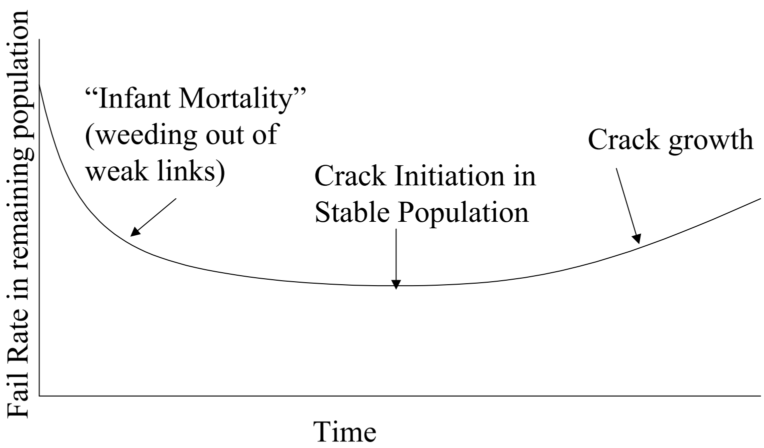

Figure 1 *The "bath tub" curve for age related failure rate.*

The use of the reliability and component life formulae really grew out of the aircraft industry in the 1960's[2], with the next major protagonist being the nuclear power industry. The reasons for the attention in these industries are obvious – condition based failure probability prediction must prevail

[1] Of the six most likely age related failure profiles, this mechanism accounts for less than 10% of failures
[2] Nowlan and Heap. 1978

over a reliability based optimisation of residual life, since the consequence of aircraft failure in flight or of large scale radioactive release from a power station can be catastrophic in human terms. Even one failure is too many.

The commonest practical use of component life formulae in the power station business is the "equivalent operating hour" (EOH), in which the metallurgical damage incurred by a start is recognised and treated as so many equivalent operating hours. This allows the simple addition of the actual operating hours and equivalent operating hours from starts to arrive at a single figure that can be used for percentage of component life used.

The EOH approach has entered the power station business for commercial reasons. The original equipment manufacturers (OEM's) of components of combined cycle gas turbines (CCGT's) have concentrated on the items in the "hot gas path" as the most critical, particularly the rotating turbine blades , and most particularly the first row of blades near the turbine inlet where the gas is hottest. In power station terms, a front row turbine blade failure is particularly damaging because the shards will inevitably follow the hot gas path through all of the blades and vanes (static blades), doing damage along the way, as well as damaging casing, with possible safety consequences if the casing is breached. Up until the late 1990's the need to create high thermodynamic cycle efficiency through a high turbine inlet temperature has ensured that the blades have experienced high attention and frequent advances in metallurgy, coating and internal shape (for cooling) and external shape. The strong focus on the blades has added to the similarity in view between power station life and aircraft life.

EOH is used to define a blade replacement criterion, and for the OEM's, ongoing provision of blades is an important business. An 8000 EOH cycle is common, in which there is a boroscopic inspection after 8000 EOH, and more thorough inspections followed by refurbishment/replacement after further 8000 EOH periods. It is no accident that the 8000 EOH threshold has been broadly equivalent to 8760 hours (i.e. 1 year) of elapsed time, as this makes planning easier. In effect, the EOH threshold is fixed and either the turbine inlet temperature or the blade metallurgy and design is adjusted .

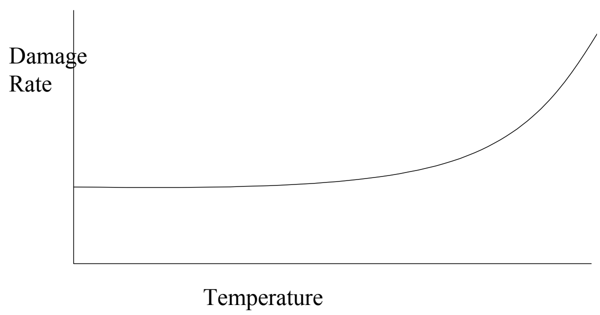

Figure 2 *Damage rate versus temperature for a gas turbine blade.*

At Innogy, we use the term "Plant Life Usage". While broadly similar to the EOH approach, it applies to whole plant of any type, and does not assume that hours and starts need to be added in a linear manner.

In this presentation, I will take a top down approach from the corporate level, to describe the framework for risk and reward, and then describe how commercial management can ensure that a metallurgical understanding of damage accumulation and fracture probability is correctly fed into the asset management process. We will see how the metallurgical science of crack growth is useful both in its own right in establishing the interactions of damage mechanisms, but also as a metaphor for failure at "whole plant" level.

The descriptions of the corporate capital management process and the internal market between power generation and trading will of necessity be brief. More in depth descriptions of these are covered by my colleagues in this conference and in the references.

2. THE CORPORATION

The corporation provides capital to the businesses that it owns, and demands a return on capital in the form of a dividend. In a sense, the corporation is not particularly interested in the activity of the business, but takes a great interest in i) the expected return, ii) the risk of the return, iii) the “worst case” return to a confidence of around 95% and iv) the correlation of the returns to the returns of other business owned by the corporation. Each of these four items can be described in statistical terms, as mean, standard deviation, skewness and correlation.

Depending of the particular viewpoint, we can condense the last three factors under the general category of “risk” , and we can quantify the cost of risk. When doing the actual calculations, risk is defined and calculated in very precise ways that need not concern us here.

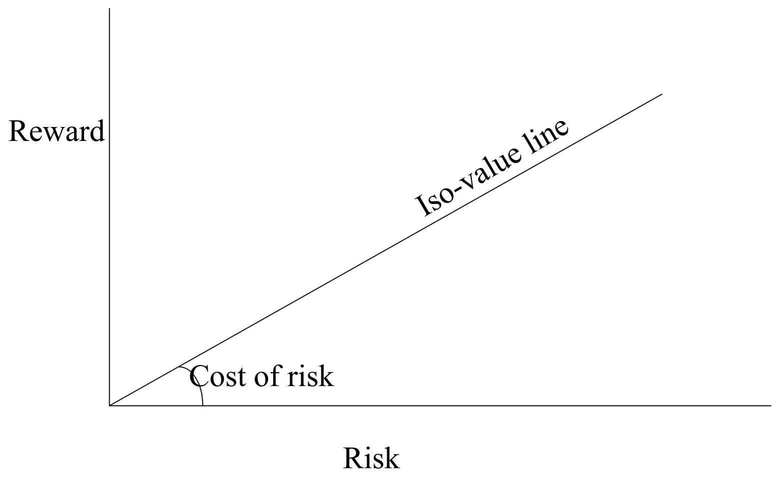

Figure 3 *The cost of risk at corporate level.*

For our “on the ground” power station operations to connect to the asset management process and for the asset management process to connect to the corporate capital allocation process, we must be able to use the corporate language.

In particular, for power station reliability we must be able to;

1) Assess the “prior” mean technical losses in terms of MWh/year, MWh/EOH, MWh*£/MWh etc. (the expectation of loss)
2) Assess the “prior” standard deviation of technical losses (the risk of loss)
3) Assess the degree of uncertainty in the “prior” statistical measures (the uncertainty of the risk of loss)

Actuarial analysis is used to compare the ex post results to the prior estimates.

Ideally we also;

4) Assess the “prior” probability distribution for large losses (the value at risk from loss)

Items 1,2, and 4, called the “Greeks” at Innogy, are actually the rarified language that is used to communicate vertically up and down the corporation. If an asset owner knows these three, plus the fourth “Greek” (correlation), then actually he/she has all the information he/she needs in order to allocate capital.

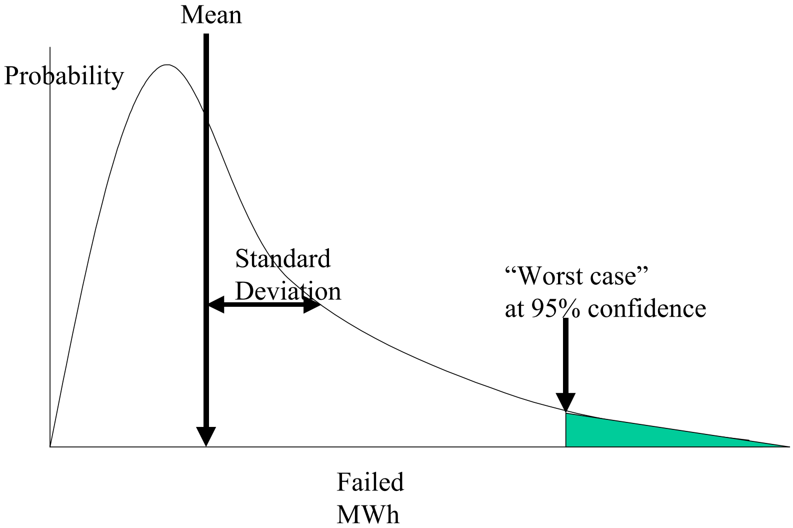

Figure 4 *Forward looking statistical characterisation of failure in MWh.*

The whole concept of "prior" is a difficult one, and I will not attempt to delve into this philosophical area. To take an example, if we quote the prior probability of throwing a five with a die as 1/7, then this prior is likely to be updated with increasing experience of die throwing. In a sense, the "true" probability of throwing a five was 1/6, and our lack of knowledge caused an error of 1/6-1/7=0.023. This would be revealed if we had enough time to do a lot more tests. To the corporation, uncertainty of prior counts as risk and therefore costs money. So, characterising the reliability of power stations has value in its own right. Particularly for the large events, we will never have enough information to use observation to construct our statistical distributions and we must instead rely on prediction.

Nothing sharpens the mind, or encourages the proper capture of data, like a financial incentive, and the segregation of a "reliability account" can achieve this. The figure below is a mapping of the Innogy internal market model that shows this segregation. The ellipse named "reliability risk" is a profit centre owned by the head of operations, and acts as an internal insurer.

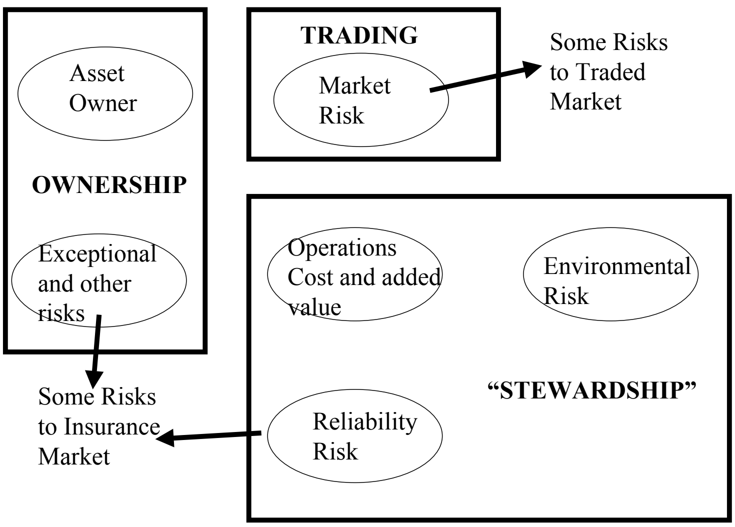

Figure 5 *The Innogy internal market showing the position of the financial measurement of reliability performance.*

The three key risk areas as we can see are market, reliability and environmental. The development of the traded markets and therefore the ability to reduce market risk has increased the focus on reliability risk, both because it increases in relative importance and because it is increased in absolute terms by market hedging[3] actions.

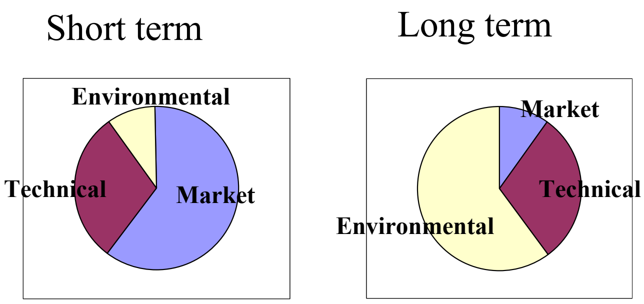

Figure 6 *Mix of risks for an unhedged asset.*

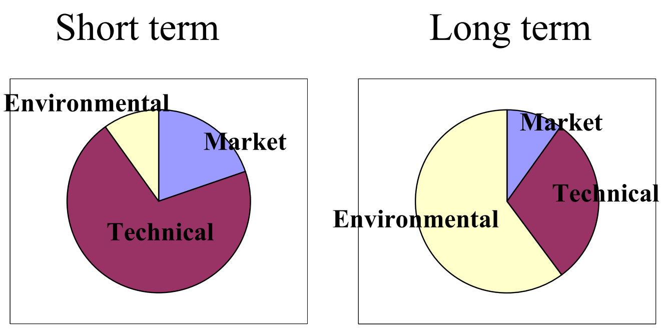

Figure 7 *Mix of risks for a partially hedged asset.*

The relevance here is that an operating unit has a direct *forward looking* value for reliability increase in the form of reduced internal premium. The forward looking aspect is very important because power market structures are in a state of great flux, and the past is not a good indication of the future. The figure below shows how the significance of reliability alters according to market prices. This has an important effect on the setting of plant usage envelopes that we shall be studying today.

[3] A hedge is a contract in the traded markets that has the effect of offsetting the future risk of the company to prevailing market prices at the time of production.

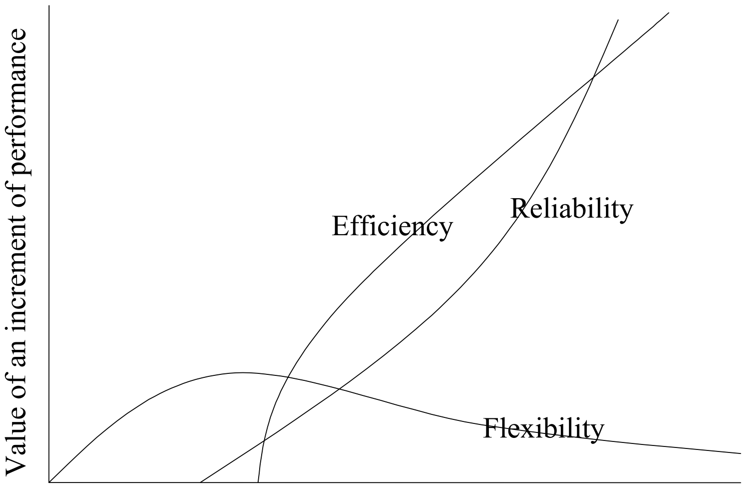

Figure 8 *Variation of relative importance of plant characteristics[4] as market prices change.*

Reliability is related to plant condition. Since we can evaluate the value of a percentage increment in reliability, our challenge is use plant condition measures to assess forward looking reliability.

Note here that we have monetised the value of a probability increment. This is of high importance when we come to consider plant life operating envelopes.

We must now start to relate plant reliability to plant condition and plant condition to some plant life usage formula. Note that plant condition must of practical necessity by a one dimensional numbers, but in reality has at least three principal dimensions-

1) *High confidence reliability*. This refers to the low probability high impact end of the reliability spectrum. The events are ideally not observed at all. This was the focus on the early work on aircraft engines and nuclear plant. Note that it is the *prior* probability that is the key factor, and this is barely testable.
2) *Plant residual life* is also not something that is observed in real time, but is "consumed" as if it were a cost. So, for example, a header with short ligament cracks has no performance loss and minimal risk of failure, but experiences life consumption as eventually the cracks will grow to levels that give rise to unacceptable failure risk.
3) *Other plant performance factors* such as low confidence reliability, plant flexibility, maintenance cost rate, efficiency, cost of environmental performance. These are all observable. For example, a degraded air heater or cooling tower packing gives rise to efficiency loss but little acceleration of degradation or loss of reliability. Oxidised boiler wall tubes give rise to observed reliability loss but no other significant losses.

Merging these into a single measure is inevitable, although we often find that we need to unravel the different components of plant condition in asset management analysis.

Our two key objective sources of data relating to plant condition are i) the energy meter and the associated "money meter[5]" from market contracts and ii) the spend on operations and maintenance. Our two key subjective sources of data are i) operational practice and ii) plant condition examination.

[4] Here the efficiency gain is assumed to impact both fuel consumption and power output
[5] This operates at halfhourly resolution for UK power

3. PLANT CONDITION AND PLANT USAGE RATES

Conceptually, we are looking for a formula that can give us a simple relationship between plant operation and condition decline. Our five key factors are i) elapsed time, ii) operating hours on load, iii) megawatt hours on load, iv) starts (of various warmths), v) on load cycles and load variations. Ideally we have a graph as is shown below. Note that the maintenance spend also has a direct relationship to plant condition enhancement.

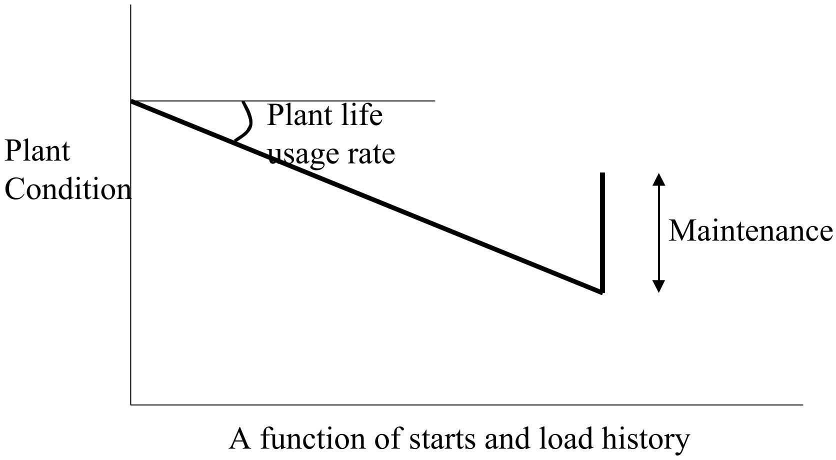

Figure 9 *Idealised plant life usage diagram.*

As mentioned earlier, reliability is but one dimension of condition and hence we cannot truly expect a linear reliability/condition line, but the idealisation is shown below. For asset management we need to quantify the scales of the graph.

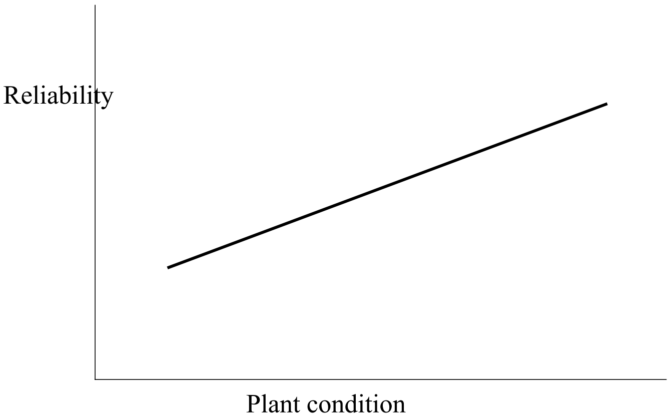

Figure 10 *Idealised reliability versus condition line.*

Now if we have these two relationships, we can financially optimise our asset condition over a many year period[6]. A common optimum condition line for the deregulating power markets is shown below. We see an initial upgrade in order to provide reliable flexibility during the volatile period of market deregulation, followed by life consumption as investment in the asset declines as it is overtaken by new technologies (primarily more efficient in terms of fuel consumption).

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[6] This is done with an iterative model that calculates plant profit and loss over a many year period which a particular maintenance spend, and then optimises the spend by iteration. Plant life usage is handled through the "business risk assessment process" (BRAP).

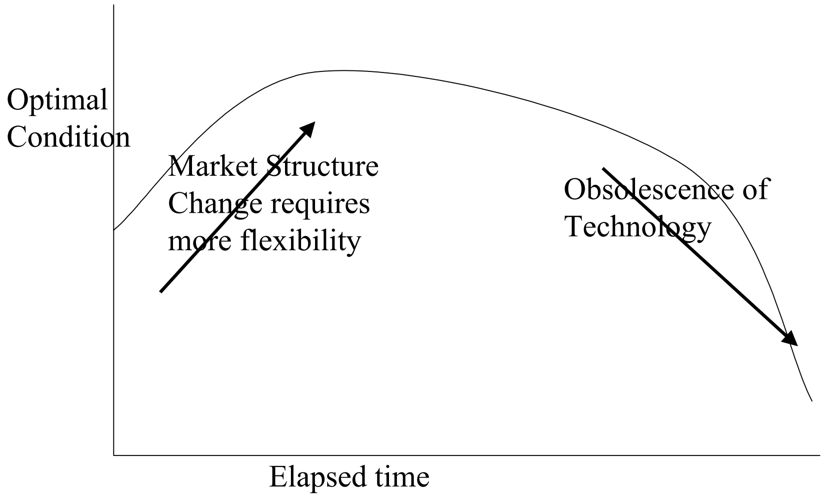

Figure 11 *Example of optimum asset condition plan over a many year period.*

The attraction of a simple plant damage formula to an asset manager is obvious. Below we see a family of iso-condition lines for a particular assumed plant damage rate.

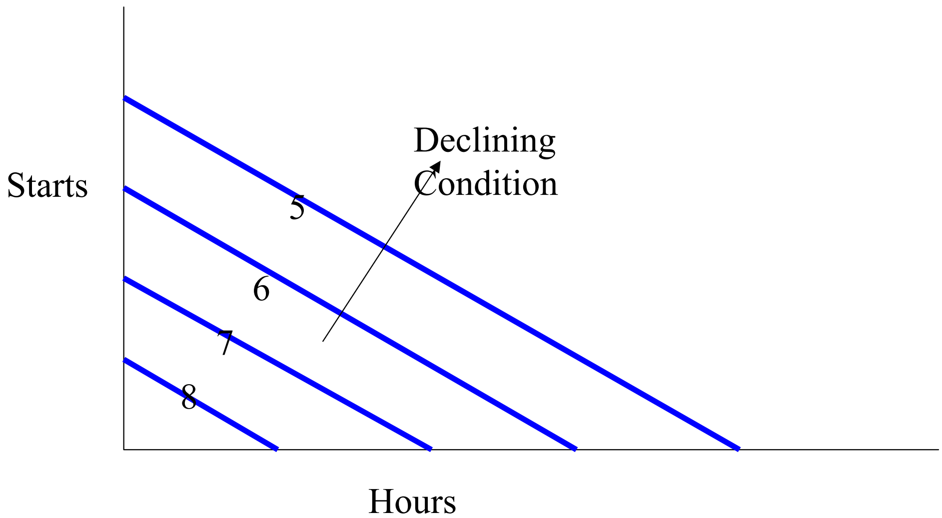

Figure 12 *Iso condition lines showing condition degradation for one plant usage formula.*

Here we used the standard EOH formula. In practice it is a threshold formula, and we are stretching its use in turning into a family. The formula is S*starts + H*Hours = constant.

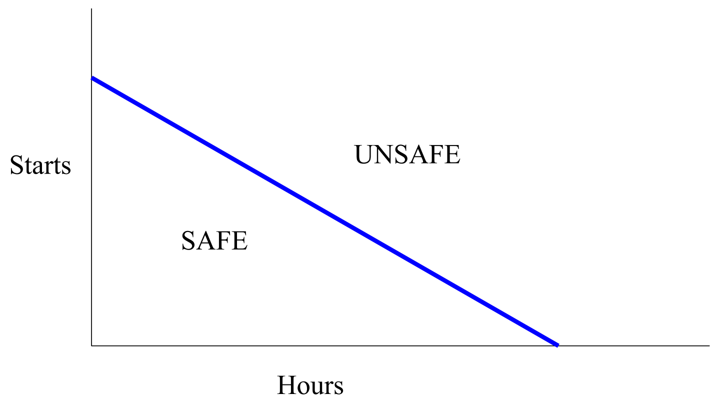

Figure 13 *The standard equivalent operating hour (EOH) formula for plant life usage.*

The formula is an excellent starting place, as it recognises the two principle actions that cause plant damage. However it contains a strong implicit assumption on the interaction between start related damage and hours related damage. If interaction is high, then we would see a diagram of the general form of the one below.

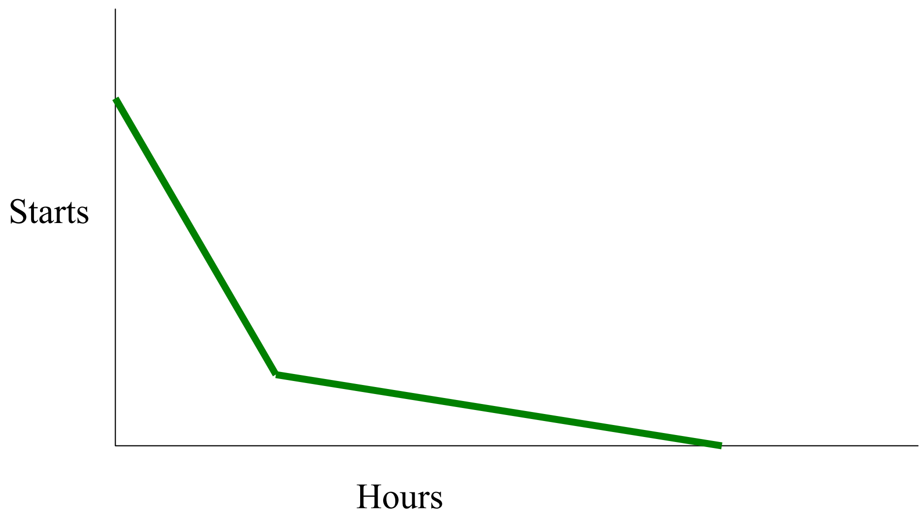

Figure 14 *Plant life usage formula for high hours/starts damage interaction.*

At the other extreme, there is no interaction between the two damage mechanisms as we see below;

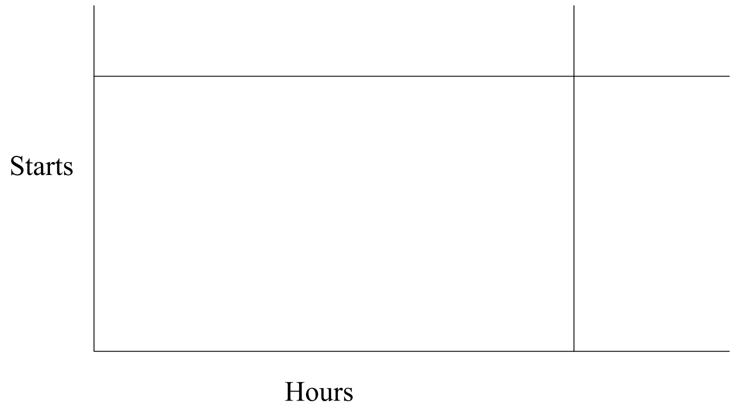

Figure 15 *Plant life usage formula for no damage interaction between hours and starts.*

In between the EOH formula and the "no interaction" formula are a range of limited interactions. All those in the diagram below use simple formulae.

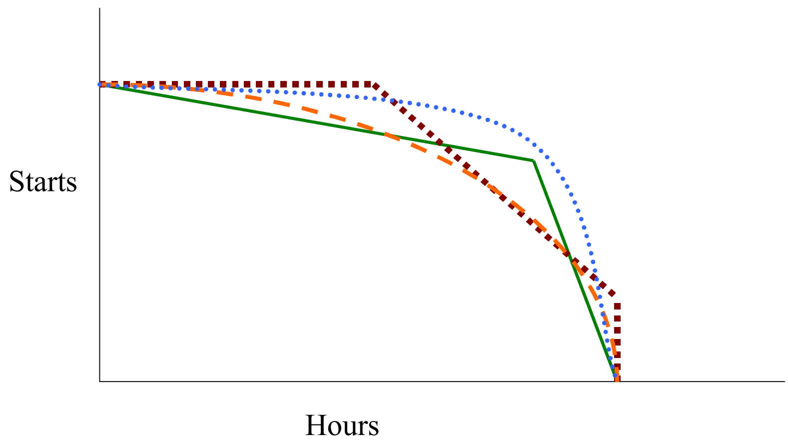

Figure 16 *Plant life usage formulae for limited damage interaction between hours and starts.*

The question of course is, which is right. In practice, the curve depends greatly on the situation and even then is in fact known only in exceptional circumstances. All we can do is to take the information and approaches that are available to us and form an opinion. Since the majority of plant failures arise from cracks in metal, and the science of metallurgy tells us a lot about that, then we should look for some rules of thumb from metallurgical experience.

4. PLANT DAMAGE FROM A METALLURGICAL PERSPECTIVE

Practical metallurgy, amongst other activities, uses the examination of testpieces to simulate behaviour of components in the operating environment. Since the testing environment is restricted in terms of physical size, complexity of loading structure, temperature, atmosphere, waiting time, flow conditions and others, there are limitations on the degree to which the test environment can simulate the local and large scale operating environment.

Our challenge is to find some high level and generic formula that encapsulate the whole world of theory and experiment into some rules of thumb that can be used in practical operation. The most useful technique that we have access to is the threshold approach to critical damage on a component from two different but interacting effects. The process is shown schematically below.

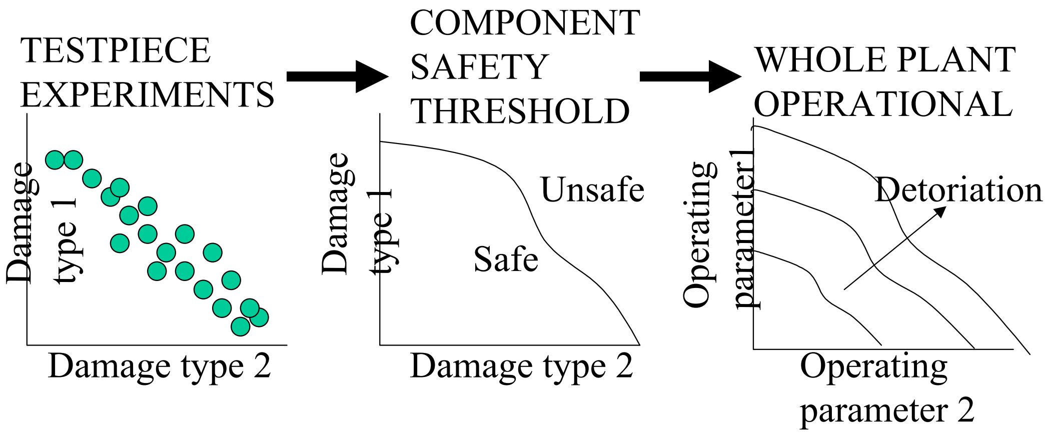

Figure 17 *Damage diagrams with some similarities.*

We have seen in this paper that the most reliable form of information at plant level is the operating hours and starts. Since running power plant is a business, then there should be an audit record of the power flow at the settlement resolution of the market. This is halfhourly in the UK and therefore is a rich data source. This enables us at a later stage to use five data items for our plant; i) elapsed hours, ii) hours on load, iii) megawatt hours on load, iv) starts (of various warmths) and v) on load variations at half hourly resolution.

In order to know which metallurgical threshold map to use, then we must understand the damage mechanism that matches the operating parameter. Broadly speaking, starts incur low cycle fatigue , and hours incur creep (for the high temperature components) and high cycle fatigue[7]. Corrosion and the various corrosion interactions (stress corrosion, flow assisted corrosion, corrosion fatigue, etc.) occurs according to the specific mechanism. For example dew point corrosion occurs if the back of the steam turbine is too cold, hot corrosion of superalloy by salts occurs only at medium temperatures, and oxidation increases with temperature. Corrosion interactions depend for example on the extent to which crack opening allows ingress, cracks originate in the oxide coating, time and temperature reduce environmental resistance by diffusion effects such as denudation, etc.. We will today not concentrate on other fail mechanisms such as wear, loss of thickness from oxidation, minor leaks, damage to civil structures etc. as these can be considered after the "hours and starts" analysis has been done for cracks.

Let's start with the concept of damage accumulation.. A common creep diagram is shown below.

[7] The time dependence of high cycle fatigue is primarily at microcrack initiation stage. Once a crack has initiated, failure tends to be rapid. The dominant failure mechanism in power stations at high temperatures is creep.

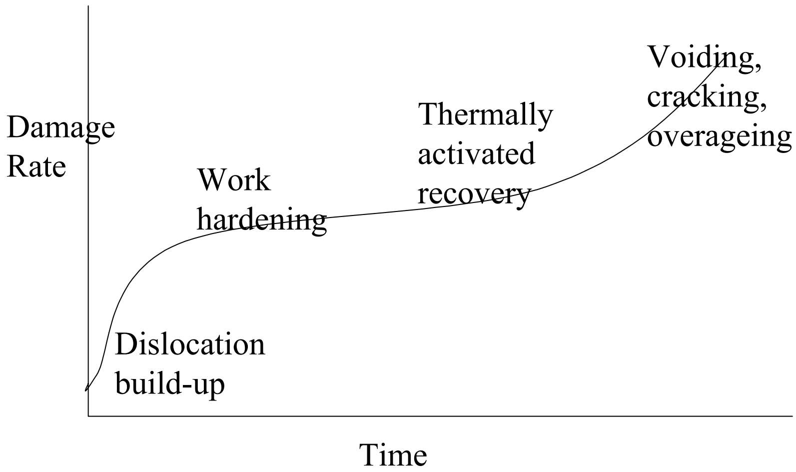

Figure 18 *Common diagram for creep damage accumulation.*

It is clear that this is non linear with time. Similarly, pure fatigue damage above the fatigue threshold (if present for the material) has a similar form to stage 3 and 4 creep, constantly accelerating.

The "R6[8]" diagram goes some way to providing probability thresholds and looking at the susceptibility to two different failure mechanisms. If we know the fracture toughness of the material, we can plot the vertical axis intercept for a testpiece, and if we know its yield stress then we can plot the horizontal intercept. The R6 curve tells us the failure threshold for mixed failure regimes, so if we load a testpiece to, say, half of its fracture toughness and half of its yield stress we can see if the testpiece will fail or not.

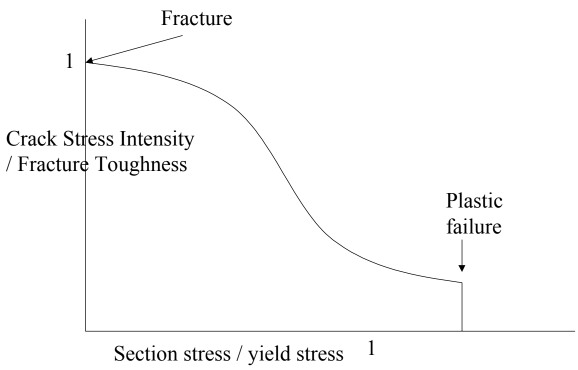

Figure 19 *The "R6" threshold damage accumulation diagram.*

Note the shape of the curve. In general, we would expect both intercepts to strike the axes at right angles since it is common for most mechanisms to exhibit thresholds below which there is no damage from one effect. Fatigue thresholds are the best examples as they can be discrete, but the same logic applies to creep, for example. The angle of the interception of the axes means that there will be two points of inflexion on the curve.
The family of curves is shown below.

[8] R6 is a failure threshold approach to cracked bodies that began as a collaborative research project about 20 years ago and still continues as an affiliation of members.

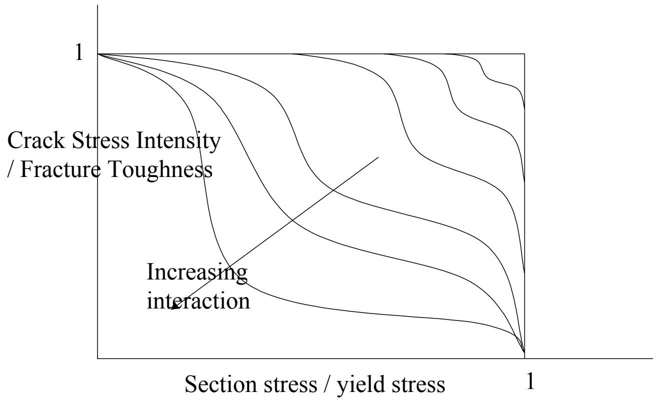

Figure 20 *Family of curves to which R6 belongs.*

While the R6 diagram defines failure (the parting of the material), it is amenable for the application of safety factors for operation. The R6 safety factor is not objective and incorporates some inbuilt non metallurgical judgements about failure consequence. Here are the features that adjust "reserve factors", where reserve factor is taken here to mean margin of threshold over the mean failure (failure being defined in terms of loss of function) of an infinite sample of test experiments.

Features causing an increase in reserve factors are;

1) The non-destructive examination difficulties are indistinct
2) Flaw characterisation is difficult or uncertain
3) The assessed loading condition if frequently applied or approached
4) Little pre-warning of failure is expected
5) There is a possibility of time-dependent effects
6) Changes of operational requirements are possible in the future

Features causing a decrease in reserve factors are;

1) The true loading system has to be simplified or assumptions have to be made in order to analyses the component and these can be clearly shown to result in upper bound values
2) Forewarning of failure is expected. This is more likely in case of ductile failure and in particular a leak-before-break condition.
3) Consequences of failure are acceptable
4) The assessed loading condition is infrequently applied
5) Variability in material properties is well characterised and lower bound values have been used in the assessment.

So the threshold approach has the following features;
- Threshold construction for two interacting damage mechanisms
- The potential for a time axis (increase factor 5)
- Accomodation for insufficient or inadequate data (increase factors 1 and 2)
- Over-simplification of formulae (decrease factor 2)
- A third damage mechanism (increase factor 5)
- Determinants of safety margin (increase factor 4, decrease factor 2)
- Statistical variation (decrease factor 5)

These features are valuable in commercial planning. It is extremely tempting to take a threshold diagram such as R6, convert the vertical axis to "starts", the horizontal axis to "hours", and then use it at plant component level to determine component replacement and at plant level to determine scheduling and overhaul spend. Broadly speaking, this is the approach taken by the original equipment manufacturers in the equivalent operating hour approach.

Our task is to arrive at a formula that can relate optimal replacement time / refurbishment extent to simple operational parameters such as hours and starts, and the commercial signals such as market prices and the cost of reliability risk.

We know what the main damage mechanisms arising from hours and starts are. Starts incurs low cycle fatigue, and hours incur mainly creep. An example of a creep-fatigue[9] interaction threshold curve is the ASME[10] threshold below.

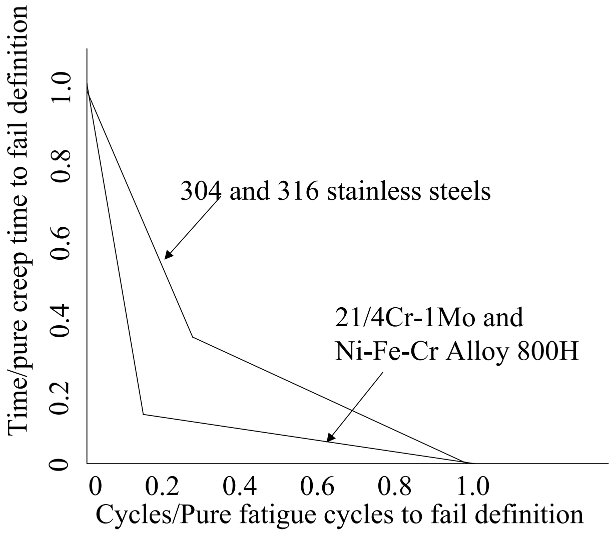

Figure 21 *Creep / fatigue interaction example.*

Clearly there seems to be a high interaction. There are however some words of warning. The damage mechanisms in steels and in the nickel alloys often used in turbine blades are different. The creep and fatigue sensitivities and interactions are different for equiaxed, directionally solidified and and for single crystal blades. The interactions differ according to temperature, to stage of life[11], atmosphere, surface material and condition, etc.. Also, the damage threshold here is slightly differently defined to the R6 curve. Here the threshold refers to crack initiation rather than fast fracture from crack propagation. So an operating component with a ligament crack would be categorised as "failed" under this description[12].

We must use the formula specific to our precise circumstances.

We must also be careful to define our damage or damage threshold criterion. There are five most important criteria for power stations;

1) Experienced loss of commercial function (e.g. frequent failures, efficiency loss etc.)
2) Unacceptable commercial probability of event (fail cost * fail probability > repair/replace cost+lost load cost)
3) Unacceptable health and safety event probability according to internal rules
4) External threshold from regulator, insurer, supplier guarantee, or other.
5) Consumption of residual life

The term "probability" enters into two of these, and one must assume that the external imposer of threshold must also use probability.

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[9] Creep and fatigue interactions are covered by "R5" – a sister to R6.

[10] American Society of Mechanical Engineers Figure T-1420-2.

[11] For example, during early life, corrosion is most important and in late life stress is most important. Creep and fatigue sensitivities to corrosion and stress are different.

[12] Note that ductility exhaustion and cracking from creep induced cavitation are interlinked mechanisms but have different susceptibilities for different temperatures, load geometries, corrosion environments etc.

5. THE PROBABILITY BASED APPROACH TO THRESHOLD

Although there are other failure mechanisms such as loss of material from corrosion or wear, blockage, etc., most failures involve the parting of material, and it is much more common for this to be from cracks than for rupture. Even for failures not resulting from cracks, cracks are a useful metaphor for probability analysis of failure. The discussion below uses a crack as a metaphor for the whole power station.

Let's start by assuming that if we know the length of a crack, that its growth rate is a deterministic function of time on load (or of "PLU time"). We assume that non destructive testing (NDT) will find cracks larger than the NDT limit with certainty and with certainty not find cracks smaller than the NDT limit.

If we cannot see a crack, then our most conservative assumption is that there is one just below the NDT limit, and if we want a fail probability of 0%, then our inspection frequency is shown by the figure below.

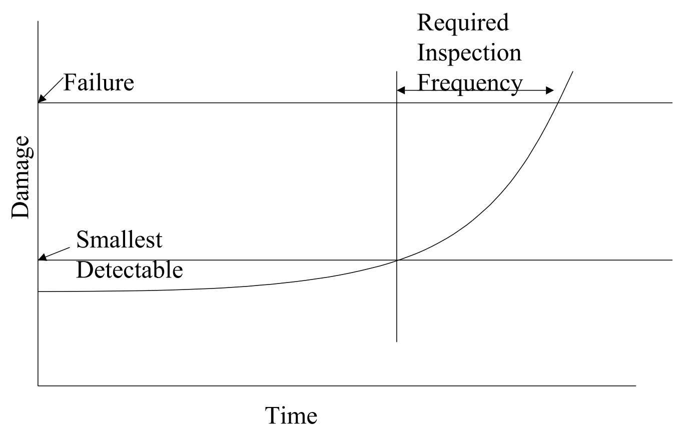

Figure 22 *Required inspection frequency for 0% failure probability in the perfect measurement, deterministic world.*

In practice, uncertainties and variations are endemic.

If we know something about our material, then we can estimate the prior distribution of defect (crack) size. From the observation of zero cracks, we can estimate our mean (largest) crack size, conditional on it being less than the NDT limit, and we can also estimate its distribution. For a crack of given length, there is also a probability distribution of growth rate (arising for example from its position in the loaded section).

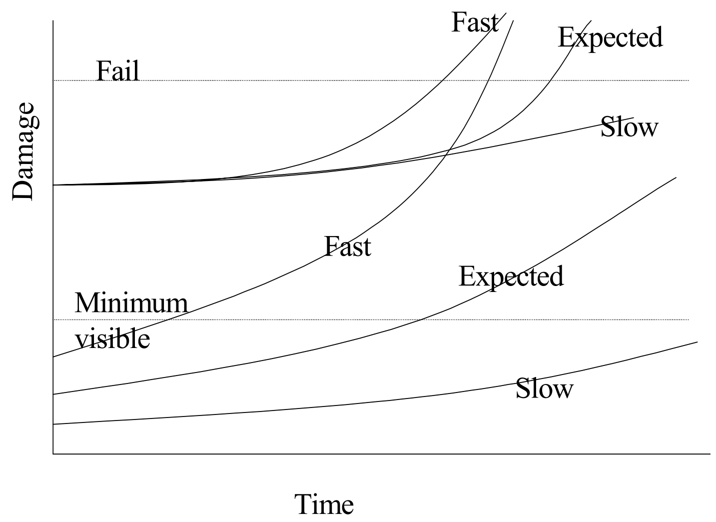

Figure 23 *Variable growth rates from a visible crack of known size, and an invisible crack of unknown size.*

Then we can calculate the probability of failure before the next inspection. The figure below shows this for a visible crack.

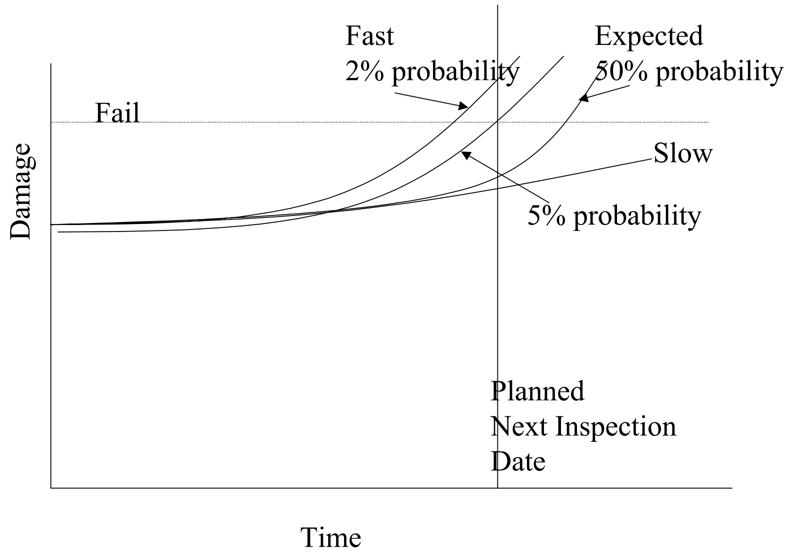

Figure 24 *Probability of failure from known crack before the next inspection date.*

We can use this to determine the safety or commercial criterion for component replacement or for inspection frequency.

As mentioned earlier, crack growth has been used as a metaphor to introduce the use of probability as a management tool. In practice, we are interested in whole plant or at least whole plant area (such as hot gas path), and data tends to be empirical[13].

[13] We can apply empirical observations to the high confidence (non observed) events through a Bayesian application of Extreme Value Theory, which is a theory commonly used in the reinsurance business.

The empirical nature of the data is apparent when we consider that our interest is in whole plant, and that each area (typically civil, electrical, cooling water, control and instrumentation, gas turbine and hot gas path, steam turbine, boiler[14], auxiliaries and balance of plant) has very different failure characteristics.

Of great importance also is the operation of the plant. With the benefit of hindsight, most failures could have been avoided with more knowledge and different operation. This is particularly true with respect to the boiler, in which one way or another most non catastrophic boiler failures are due to water acting (or not acting) on material it contacts in a way that was not designed/intended. Thermocouples and other instrumentation can reduce material damage, but at a cost.

6. MANAGEMENT OF THE CRITICAL THRESHOLD ENVELOPE

We have shown that there is no generic formula for material damage, and that even if we have a good idea of the formula for the particular material and plant area, that we must consider extra influencing factors. It is generally possible to do this.

Let us suppose that we have two identical combined cycle gas turbines (CCGTs) and at plant level, the CCGT exhibits a high hours/start interaction for plant damage. In this circumstance it is best for the two units to have completely different running regimes. To avoid the interaction, one unit would tend to run continuously ("baseload") and the other would tend to have very short runs.

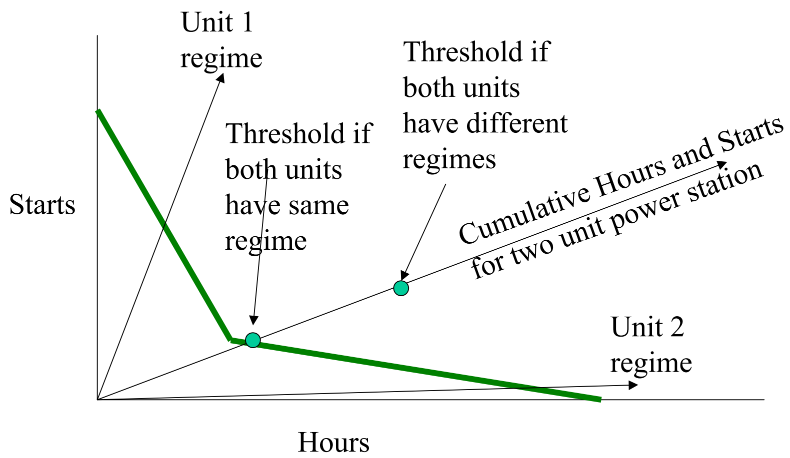

Figure 25 *Life optimisation from running two identical units at different schedules.*

The effect is opposite if there is more than one envelope operating. This may be because a threshold is imposed externally, or if two plant areas have very different hours/start interactions. The need to use the minimum envelope will tend to reduce the effective hours/start interaction and encourage a running regime with an hours/starts mix. The figure below shows how the imposition of the most conservative of two PLU curves gives an overall curve with less hours-starts interactions with either of the individual curves.

[14] Called heat recovery steam generator for combined cycle gas turbines

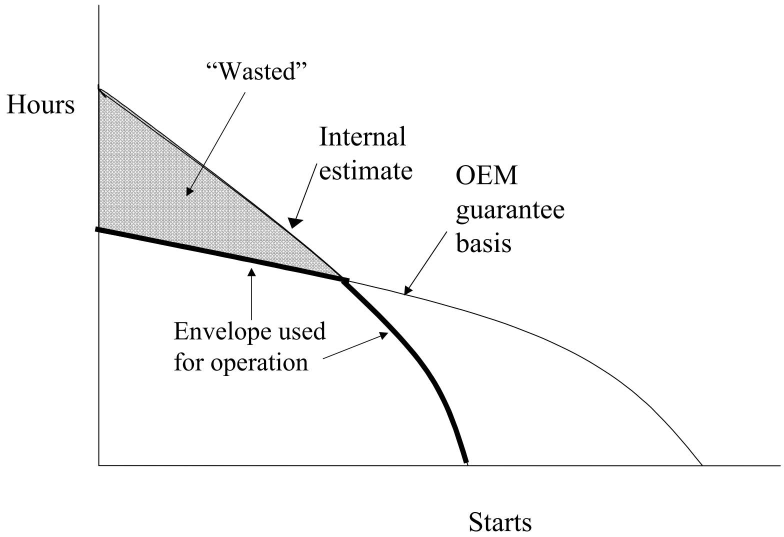

Figure 26 *Two coincident damage thresholds, one from the original equipment manufacturer and one internally estimated.*

More complicated diagrams are possible as we see below, which is two thresholds, one with high hours/start interaction and one with low interaction. The net outcome is much like the common EOH formula.

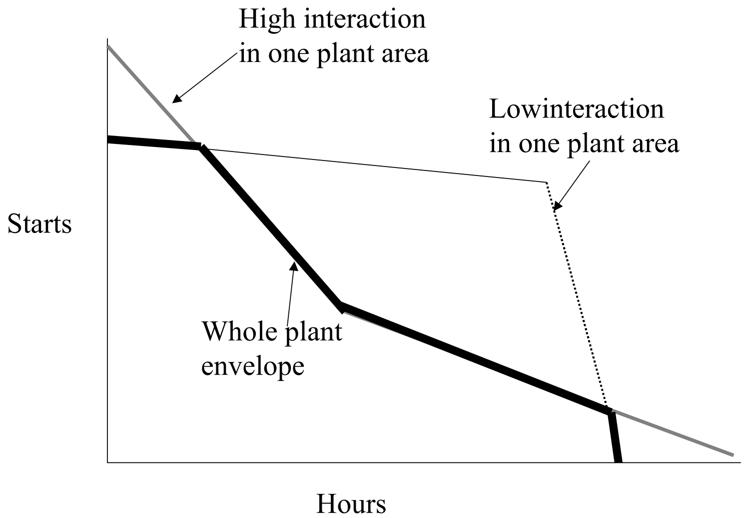

Figure 27 *Operating envelope for whole plant with different hours/starts interactions in different areas.*

Commercial analysis is dispassionate. The asset manager assumes an asset condition plan over a many year period and calculates the optimal schedule indicated by forward prices in the traded market. Investment in plant condition is then optimised to maximise commercial revenue subject to constraints such as safety and guarantees. The asset manager must also run scenarios with defined probabilities in order to assess the risk (which has a defined cost).

Suppose that market prices are high, and therefore that plant reliability has a higher relative importance than maintenance cost. The component replacement threshold, based on the commercial criterion, will in this case indicate early replacement when condition (on which fail rate is dependent) is high.

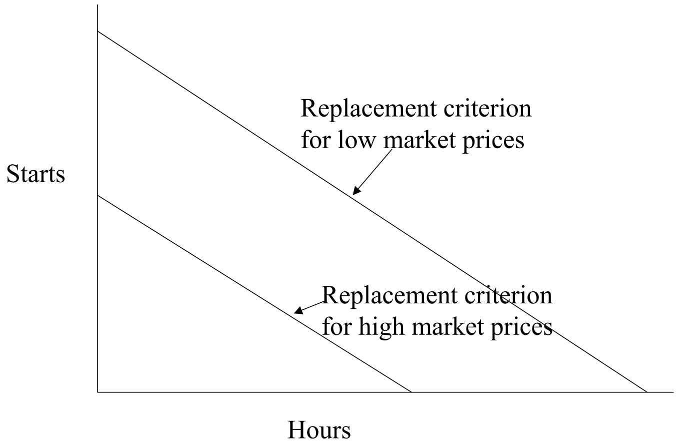

Figure 28 *Condition threshold depends on commercial conditions.*

Here, we are not really using the diagram in threshold mode at all. The criterion arises from a commercial breakeven (in this case, rate of change of business interruption loss likelihood with hours and starts versus rate of change of total maintenance cost at equilibrium condition versus hours and starts). Note here, that "condition" explicitly maps to failrate here, rather than a mix of factors including efficiency, residual life etc.

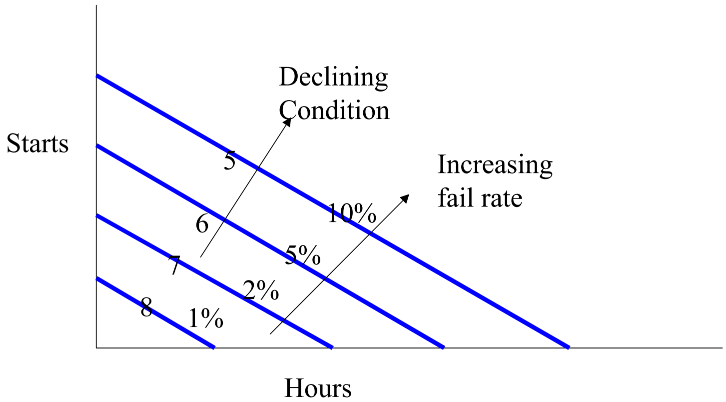

Figure 29 *Mapping reliability to condition and plant life usage.*

We have assumed here that the plant usage rate is a linear function of net (after maintenance) cumulative use to date (i.e. condition). In practice, there is a condition dependence. High condition plant is expensive to maintain since replacement rate is high. Low condition plant is expensive to maintain since failures cause collateral damage.

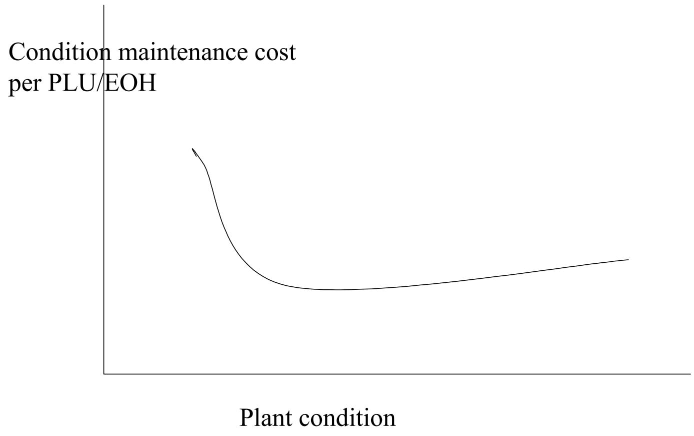

Figure 30 *Commercial cost of plant life utilisation as a function of plant condition*.

Assume that we can quantify the PLU costs in the figure above, the relationship between condition and reliability and the cost of reliability loss, then we can estimate our optimum equilibrium for our plant. This is shown in the figure below.

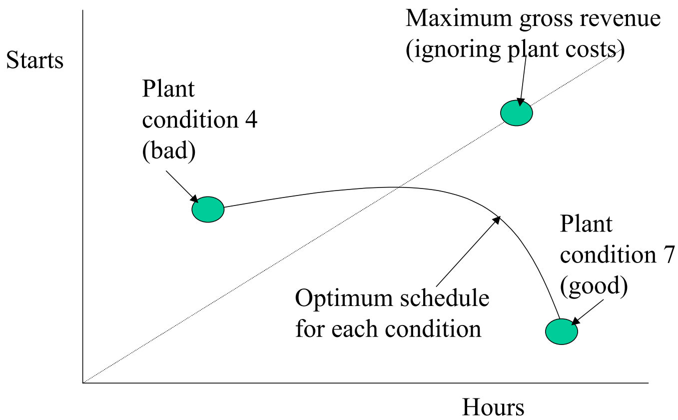

Figure 31 *Optimum schedules for plants of different conditions*.

The optimum schedule lies on the line between the two condition points, and the precise point can be calculated using information from figure 30.

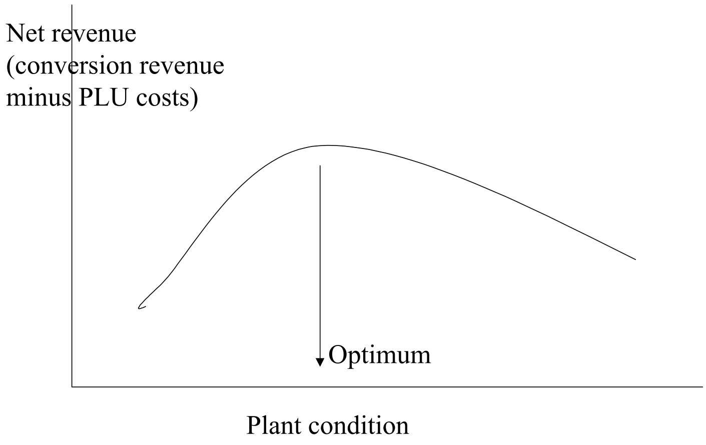

Figure 32 *Optimal plant condition for market in long term equilibrium.*

There are more ways in which the hours-and-starts damage rate diagram can be used in relation to the hours-and-starts optimum condition diagram when we consider the various dimension of plant condition such as non visible major failure rate, residual life optimisation, outage timing, negotiation of externally driven thresholds etc.

To this point, we have concentrated on the visible commercial condition of the plant (i.e. the performance actually witnessed). As described in the section on the corporation, variation of income/loss is another very important dimension of stakeholder welfare, and hence we are interested to know the likely variation of income/loss at both normal and extreme level. Different conditions and operating regimes have different risk levels, and hence the line figure 32 will be different if risk is taken into account. The estimation process is beyond the scope of this paper, but involves the specific cost adding a measured increment of a defined risk.

7. CONCLUSION

Power plant management in deregulated markets is a commercial venture that must be commercially optimised. The various sciences of risk capital management, plant engineering and financial derivatives are individually complex and must be drawn together in simplified form. This requires a formal and fit for purpose quantification of plant condition (PLU score), reliability in relation to condition, plant life utilisation rate in terms of operating history, and maintenance spend in relation to operating history and condition.

A metallurgical approach to plant life usage and to failure (and other performance measures) in relation to plant condition is useful both as metaphor for the whole plant, and in relation to an estimation of the interactions between the two key operating parameters of hours and starts.

Quantification is necessarily rough, but in power plant management commercial decisions must be made and it is better to make this decisions with some analytic foundations than by just guessing !

9.1
Spares - Risks, Options and Cost Benefits

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Abstract

All electricity generating plants suffer failures that result in loss of availability and thus business losses as well as repair costs. Some extended outage times are caused by the long lead times to manufacture spare parts, a business loss that can be eliminated by carrying a suitable spare. However the holding of spares is itself a costly exercise.

This paper reviews the issues behind a decision to purchase a spare. It also looks at other options apart from direct ownership of spares including spares contracting, virtual spares and other risk management strategies.

1. INTRODUCTION

Power Stations carry a wide and extensive stock of stores and spares, from low cost consumables such as nuts and bolts to high value rarely used spare parts such as large motors. Some of these items are required for routine maintenance, others are associated with planned major overhauls and some are kept for unplanned failures.

All power stations have failures, some of which incur a plant outage. Fortunately most such as boiler tube failures, although relatively regular events, only involve loss of 2 or 3 days operation. However occasionally a "high impact low probability" event will occur which causes significant plant damage and can involve the plant in an extended outage. Some of these extended outage times are caused by long lead times on the manufacture of spare parts, rather than significant time spent in site work. The availability of a "strategic spare" will significantly reduce this outage time, making large savings in business losses. However such typically high cost spares will tie up significant amounts of working capital, incurring revenue costs that can be ill afforded in today's competitive electricity generation business.

Effective decision making on its spares portfolio and overall cover is a key issue for a generating company. What and how many strategic spares should be held? What alternatives are there to holding spares? Are capital outsourcing approaches used in other industrial sectors applicable here?

A classic high cost, low failure rate spares problem relates to generator transformers and this will be used for all examples in this paper.

2. SPARES AND STORES

All power stations hold stocks of spares and stores and there is benefit in the optimisation of holdings of both these types of items. There is some similarity in the mathematics of the optimisation of the holding of spares and stores, the main difference being usage rates, reorder quantities and lead times, however this paper only deals with spares and then predominantly with particularly high value strategic spares.

Generally stores have the following characteristics:

Relatively low value items;
At least several and normally tens used per year;
Reordered in multiples of tens or more;
Usage levels high enough to be easily measurable.

Correspondingly spares are:

High value items;
Less than 1 used per year;
Reordered singly;
Limited failure data from any one site.

Site based spares may include large pumps, fans, large motors, electrical switchgear etc. Some of the comments in this paper apply to such items, but will it concentrate on very high cost spares (> £0.5m). Generator transformers, where a 400 kV primary voltage 600 MVA example costs about £2.5m, clearly fits in this category.

Historically the large state owned European Utilities like EdF, ENEL and CEGB built families of similar power plants. This enabled spares, especially large value infrequently used spares such as large transformers, generator rotors and stators, turbine spindles etc to be shared by several stations. Often families were large enough that several spares could be justified across a fleet of similar units running well into double figures.

Privatisation, the move to liberalised markets and the emergence of a few large multinational power plant suppliers has completely altered the ordering patterns for power plant. A level of commonality now exists, but especially for CCGT plant is based upon manufacturing standardisation. Any commonality is largely between sister stations built by one supplier, rather than owned by one company, and is particularly focussed on generator transformers, generators and gas turbines.

3. NEED FOR A SPARE

Decision making on spares ownership is normally based upon an assessment of the costs and benefits. The costs are relatively simple, including:

Interest on capital committed;
Reduction in the capital value of the item if the useful life is being consumed;
Maintenance and storage.

The benefits are however more difficult and have to be evaluated using statistical methods to quantify the expected savings in business losses. In simplistic terms:

Benefit = Probability of Failure x Savings from having Spare

Several methods of evaluating this can be used including that employed historically in the UK Electricity Supply Industry based upon a Poisson distribution and documented by Hodges (ref. 1.). Another approach is derived from Economic Order Quantity (EOQ) models (ref. 2) with the reorder level set to 1.

However all these methods require data on the failure probability of the in-service item or items that the spare is covering. This data will not be easily available to most power plant operators for items used in small numbers and with low failure rates. Only large generators, major OEMs and Insurance Companies have data on generator transformer failure rates, which they treat as commercially sensitive. Innogy with its long corporate memory has significant amounts of transformer failure data, but even this is only indicative when applied to new transformers from new suppliers.

Practically a Poisson model is a satisfactory model for generator transformer failures. Although we believe that a Weibull or non-homogenous Poisson model would be slightly more accurate, with the failure risk increasing as the transformer nears the end of its design life, in practice there are advantages in using a simple Poisson model. It is the only distribution which has the “no memory” property, so that failure amongst a population of many items can be found without referring to the history of each item. Also the Poisson distribution is the best starting point for any item which is a complex maintained system. Failure probabilities for new transformers are then estimated from manufacturer, type, design parameters, past performance and benchmark historic data.

Another problem with historic generator transformer data is that best practice transformer life management with appropriate condition monitoring has significantly reduced failure rates. Our judgement is that corporately 50% of what historically would have been catastrophic failures are now identified early enough to be repaired at site. The division between failure and non-failure is blurred by this increasing ability to anticipate and mitigate what would previously have been a failure.

Failure rate values used not only need to take account of plant item losses caused by the failure of that item, but also losses that are consequential damage from another failure or nearby incident. We are aware of at least one incident where a generator transformer was destroyed by a fire resulting from the failure of the unit transformer.

However despite these problems, the answer as to optimum spares holding levels is often one. Obviously spares can only be held in integer numbers and where any spare covers a small number of in-service items, the answer will generally be 0, 1 or just possibly 2. The same answer can be valid for a wide range of failure rates. As an example using the Hodges model, 1 spare is the optimum number for covering between 2 and 11 components with a 2% failure rate, a 1 year lead time and a lost business cost of £5500/day/component. These values are similar to those one might find for generator transformers on 500 MW units.

4. DISTRESSED PURCHASE

One approach to spares management is the "ostrich approach": do nothing until the problem arises. Most large items of plant have long lead times which forces the distressed party to attempt to buy a spare off another generating company, who may be a competitor. Other parties who have spares are normally willing to enter into negotiations. Surprisingly a concept of fairness exists in such negotiations, with the supplier often looking for half the net benefit of the transaction. However this can still be a very high price:

Price = ½ (Distressed part benefit + Lost supplier benefit) + Long cycle replacement cost

where the lost supplier benefit is based upon his risk from no longer having access to the spare.

Using such a formula the price can be easily 3 to 5 times the replacement cost for a generator transformer.

The real threat here though is that no one has a spare available and the plant is left carrying the whole business loss. The generator's business interruption insurance may cover this after a deductible period (typically 120 days) and a given excess (perhaps losses of £2m). However, insurance premiums are a major component of a generator's fixed cost base, and a claim will be followed by significant rises in premiums for that generator and others. Additionally insurance claims follow an economic cycle, with premiums following a similar but delayed cycle. As the insurance market hardens (as at present) the desired business interruption cover can become unobtainable, and the available cover extremely expensive. This can make the generator uncompetitive when electricity prices reward only the lowest cost generators, and capacity is being pushed out by fierce competition.

The nature of the England and Wales electricity market under NETA has also changed, to strongly penalise lack of reliability. As prices have fallen, and relative volatility increased, the proportion of profits coming from being available, from flexing, and being reliable have shifted to the last of these. The magnitude of losses from failures has steadily risen.

Under NETA it is not sustainable for independent generators to reduce spares holdings, manning and maintenance, and to rely on insurers to cover increasing losses. The generator needs to find an efficient and cost effective way of mitigating these losses.

5. SPARES CONTRACTING

Access to a spare does not always require direct ownership of a spare. Ownership requires investment of capital; in other sectors this is sometimes avoided by leasing of high capital cost equipment which may be required for only a limited period. Such capital outsourcing means the company hires items such as vehicles, plant or air conditioning, which it does not wish to own, but needs at short notice. A good example of capital outsourcing is TLS vehicle rental, now a GE Capital company. They lease or hire lorries to companies who do not wish to own some or all of the lorries they need; this requirement may vary unpredictably, and leasing provides flexibility, efficiency and cost effectiveness given the capital outlay saved.

There are several arrangements by which a power station can arrange to have access to a spare:

Contract with OEM (Original Equipment Supplier) or other supplier;
Shared ownership of spare;
Contract with spares business or club.

Some OEMs are in the spares business and will contract to provide spare parts. However historically OEMs have shown minimal interest in the rapid provision of complete spares such as transformers or generators.

Some examples of shared ownership exist, although they are primarily hangovers from or where unliberalised markets exist.

The third option is to contract with a third party who will provide access to a spare at a pre-agreed cost in return for an annual payment - effectively an option contract. Innogy is currently establishing a business in strategic power plant spares to do this. Currently we are exploiting spares that we have acquired historically to support our own business plus others from decommissioned and mothballed plant. However we anticipate this will naturally expand into specifically acquired items. We already hold a selection of generator, station and unit transformers and are investigating generator stators and rotors and gas turbine parts. Another part of Innogy already produces and refurbishes gas turbine hot gas path components and can also provide a spares service for these components.

6. VIRTUAL SPARES AND RELIABILITY RISK MANAGEMENT

Innogy has extended many of the risk management concepts evolved within its trading activities into operations, and established a sophisticated internal market to measure transfers in terms of prices and risks. Reliability on its generation fleet is managed using an internal vehicle called "Brimshaw" to carry the risk of failure, financed by an annual charge on each generating unit. The charges or “premiums” are calculated from the unit’s historical failure data, planned running schedule and market data (the forward curve). The stations see an average cost of their unreliability through premiums, but are protected by "Brimshaw" covering the cost of each failure. "Brimshaw" in turn utilises the cheapest means of mitigating the failure either by generating with other units in the Innogy fleet or using trading activities to buy in lost generation. Innogy’s captive insurance company Electra reinsures "Brimshaw" for losses exceeding a given level. Electra in turn reinsures in the external market. Innogy is thus able to efficiently minimise the cost of unreliability through exploiting its internal market.

Building on its portfolio of strategic spares Innogy has evolved the concept of Reliability Risk Management as a service to other generators. Reducing risk, by transferring it to the counterparty best placed to mitigate it, at least cost, is a part of the evolution of all business sectors. Risk reduction is a key element of increasing shareholder returns given the close relationship between risk and reward. Through taking on technical risk from smaller generators, Innogy can focus on mitigating this via a combination of portfolio generation, physical spares, skilled staff, trading capability, financial strength and close relationship with reinsurers.

As an illustration, consider Innogy’s spare generator transformers, such as a universal CCGT spare. A number of independent generators (IPPs) can gain access by belonging to the Reliability Risk Management (RRM) service, paying an annual membership fee. The first IPP to call on this then pays a lease fee to use it for the period until a replacement becomes available, and RRM is restocked at their expense. However, several units are served by one physical spare; what happens if a second IPP suffers a failure? RRM provides monthly compensation payments, approximately in line with expected lost profit, throughout the deductible period until an IPP's insurer starts to cover business interruption losses. This capital, set aside for the purpose, can be called a virtual spare. Where RRM finds it is optimum to replace a virtual spare with an additional physical spare this is done, so that as the number of IPP customers rises so will the fleet of strategic spares. How is the total liability involved handled? RRM closely monitors its exposure beyond its physical and virtual spares, and takes out reinsurance with the external market to cover liabilities above a given level. This leaves RRM able to focus on managing moderately probable, medium cost events, while the reinsurer covers very low probability high cost events. This is what each does best and optimises the relationship between IPP, RRM and the reinsurer in a manner that minimises cost and allows each to focus on doing what they do best without exposure to excessive risk.

Failure risks need to be analysed for all the units covered, in order to measure, manage and price the risks that are being taken on by RRM. Once accurate estimates of the failure rate of each unit have been made, the complete population of units is modelled. This can be done by using state space methods and transition matrices to model the transient and steady state probabilities of the different failure scenarios. Markov diagrams are normally used to build up the transition matrices. Assuming adequate modelling of failure scenarios, the profit and loss probability distribution needs to be modelled, so that the low probability, large loss events can be determined. Extreme Value Theory is important in accurately modelling the very long tails of low probability events that occur, and Bayesian analysis is used to update the model and to incorporate further information as it arises from failures or claims. Both frequency and severity distributions are considered and models using the principles of actuarial risk theory built to establish the true cost of covering potential claims. The results enable the best estimate of potential losses to be deduced, and the correct number of strategic spares, capital provisions and reinsurance put in place to meet these potential liabilities.

7. CONCLUSIONS

All privately owned power plant carries insurance, which will include some form of business loss cover. However insurance companies have increased premiums, increased excesses either in amount or in initial time periods not covered, following a large number of claims. The technical press has reported stations having difficulties meeting insurance premiums and cases exist of insurance companies making apparently excessive demands on stations to carry spares. This is inefficient and unsatisfactory for both IPP and the insurer.

Our stations contract internally for business loss insurance with an internal insurance fund. This fund then contracts for replacement power with our traders who then cover part of their risk through contract options with our own peak lopping plant. Large business loss incidents and major plant damage events are then reinsured with the insurance market.

However, the business loss due to plant unavailability in a liberalised market is uncertain, as the wholesale electricity price can be extremely volatile. Additionally the unavailability of plant can be a contributor to increasing the wholesale price. The level of risk can be managed by having RRM contracts in the event of loss of availability. Such contracts put a ceiling on losses in the event of loss of availability, and are cost effective.

Portfolio players like Innogy have opportunities in this situation, and can share the created value with IPP customers through innovative solutions and new relationships.

8. REFERENCES

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9.3
What Shutdowns, Why and When? The Cost/Risk Optimisation of Shutdown Strategy

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Abstract

The establishment of anything that can claim to be an optimal shutdown strategy requires the incorporation of four elements of technology:
1. *The interpretation of the cost implications of altering the intervals at which particular work is carried out.*
2. *The development of a parameter of merit, by which it may be assessed that one strategy is better than another.*
3. *An interpretation of the direct costs and the outage or downtime costs for a particular combinations of tasks.*
4. *A search engine to find the best strategy.*

The parameter of merit in this case will be expressed in costs per year. This technology is now all available, and the concepts are in a form where the technology is usable by the Engineering and Operations Departments.

1. WHAT IS SHUTDOWN OPTIMISATION?

The word 'Optimisation' is widely used, and usually misused. To describe a process as optimisation implies some kind of parameter of merit, and the means of finding the strategy or decision that gives the best value for this parameter. If one considers the 'Weighted score' methods of decision making, then the parameter being optimised is normally the overall score achieved by a given solution.

Shutdowns have their advantage in requiring a single period of outage, and perhaps single incursion of some of the 'overhead' costs, to allow a number of tasks to be undertaken. If it were not for this concept of 'Shared Outage' then there would be no advantage in having a consolidated shutdown – each task could be carried out at its own optimum interval. A chart showing the form of such a strategy is shown in Figure 1.

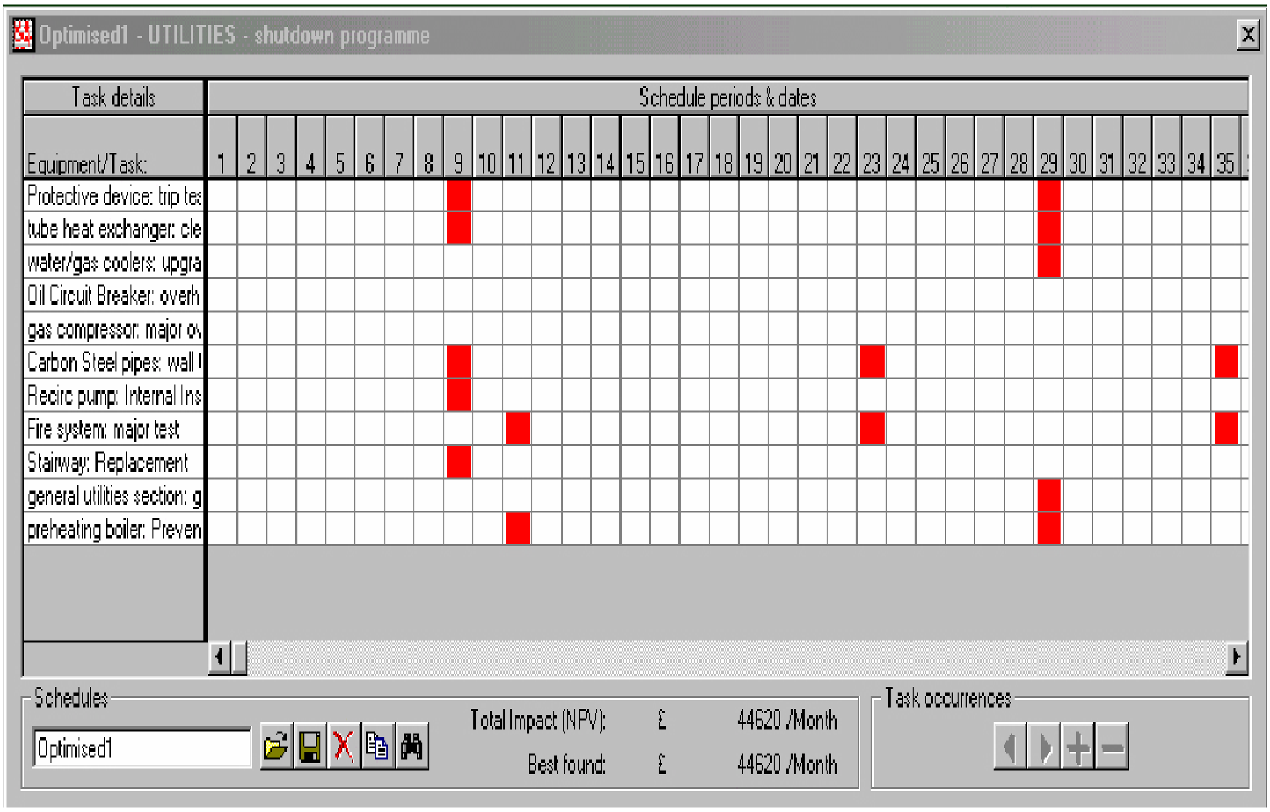

Figure 1 *A graphic view of a shutdown strategy.*

But the disadvantage of the shutdown is that several of the tasks will be being carried out at points which would not be optimal, if they were consider on their own merits alone. The generation of a shutdown strategy will therefore involve adjusting the intervals at which particular tasks are undertaken, in order to achieve the best combination.

The process of optimisation does not mean that the schedule pattern is predefined. If we are going to describe it as optimisation, then the process itself has got to determine whether the best strategy consists of doing all the tasks at a 3-year shutdown, or whether there is a better strategy consisting of doing all of the tasks at 4 years, and also doing some of them at a 2-yearly 'mini-shutdown'. In other words, the optimiser has got to construct the pattern as well as determining the optimum intervals.

This brings us onto the first element of technology that is required to do it.

2. THE INTERPRETATION OF THE COST IMPLICATIONS OF ALTERING THE INTERVALS AT WHICH PARTICULAR WORK IS CARRIED OUT

The shutdown strategist is going to be adjusting the intervals at which particular tasks are to be undertaken. He must therefore be able to interpret in financial terms how that adjustment affects the finances of the operation.

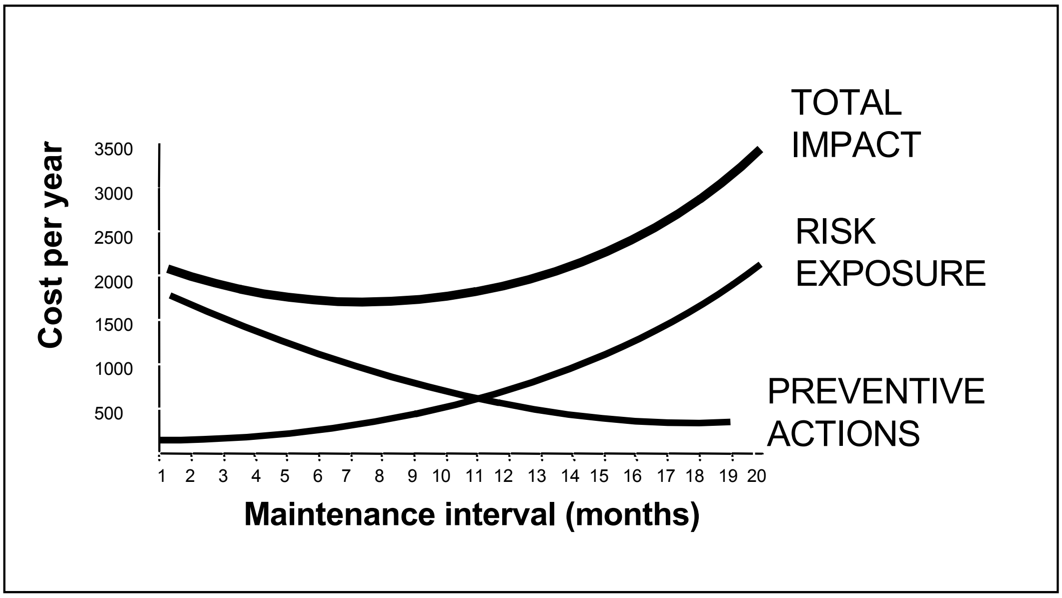

Figure 2 *The typical 'trade-off' or optimisation problem.*

The typical 'trade-off' diagram shown in Figure 2 is a representation of this problem, but sadly, such diagrams are of no use unless the axes are scaled. The majority of times that one sees this diagram, the axes are unscaled, and the most that can be communicated is the nature of the problem. Unscaled graphs provide no assistance in getting to better decisions.

Starting probably with operational research during the second world war, much work has been done in the field of determining on a cost basis the optimum time at which to carry out particular tasks, though, it must be admitted, relatively little of this technology has actually reached the workface. Because the mathematics of reliability are pretty intractable, and the majority of shutdown tasks affect reliability, most of the theoretical work could not have been implemented until computer programs were developed to handle the maths. The first such programs appeared in the late 1970s, but there are still very few programs to tackle this area. APT-MAINTENANCE, APT-INSPECTION and APT-LIFESPAN tackle various of these problems. An output graph from APT-MAINTENANCE is shown at Figure 3. Outputs of this type for each of the tasks being considered are input for the Shutdown Optimisation Process.

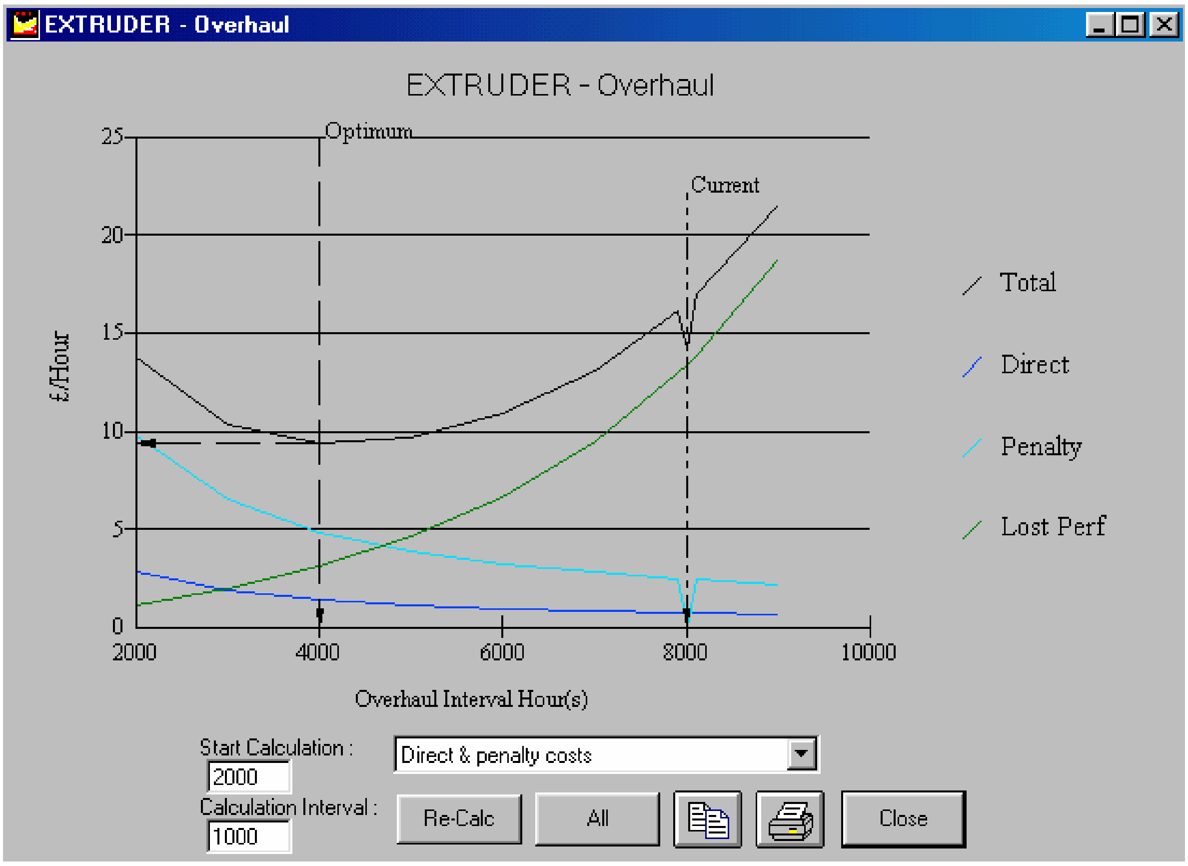

Figure 3 *An optimisation output from APT-MAINTENANCE.*

3. PARAMETER OF MERIT
(or Just How Good is a Particular Strategy?)

To talk about optimisation, we must have a concept of measurement, such that we can show whether one strategy is better than another. It is no use concluding that one strategy is fairly good, another is not too bad, and a third one looks hopeful. We need an actual numerical parameter, and the parties to the strategy decision-making must obviously all be working to an agreed parameter of merit.

The parameter of merit employed in this approach is an actual cost per year, but that cost has to take account of all the elements of cost influenced by the strategy. This may sound an ambitious objective, but in fact most of the work is done in developing the individual analyses. Although it must be studied in more detail, it takes account of the following costs:

3.1. The cost of carrying out the respective tasks. The actual cost may or may not vary with the maintenance interval, but the cost per year most certainly will.
3.2. The cost of outage or lost production incurred by the shutdowns (expressed per year).
3.3. The costs incurred through deterioration with time since last application of the task. This will vary with the task interval adopted, and may include elements of reliability and efficiency.
3.4. The overheads associated with particular work.
3.5. The effect on amortised asset life cost of any delay in ‘housekeeping’ type maintenance (e.g painting).

In addition, the calculation will require the percentage rate at which cash flows are to be discounted.

The resulting parameter of merit is then calculated and appears as a simple 'cost per year' for that particular strategy. The simple form of the result belies the comprehensiveness of the costs that generate it.

4. AN INTERPRETATION OF THE DIRECT COSTS AND THE OUTAGE OR DOWNTIME COSTS FOR A PARTICULAR COMBINATION OF TASKS

As was stated in Section 2, the optimising program must be able to evaluate strategies that involve different combinations of tasks being done during a particular outage. To do this, it must have the information and a rule-set to allow it to determine the direct costs of the work and the costs of the outage that would be involved in any given combination of tasks.

The outage costs for any given combination of tasks will be affected by any statement that particular tasks within the schedule are incapable of being performed simultaneously. e.g. Certain tasks may have to be carried out with electrical power applied, and certain others with the plant isolated. Within a given shutdown, there may be more than one such 'channel' of sequential work. For instance, in addition to the power constraint indicated above, there might be some other area of plant where part of the work must be carried out with the system pressurised, and part with the system ventilated, or it might be that the same team have to undertake several tasks.

The outage is then calculated as the longest sum of sequential tasks, or the longest single task, whichever is greater.

The direct costs of a particular combination of tasks are also not simply a linear summation of the direct costs of the individual tasks. Frequently, an element of overheads may be shared. e.g. The costs of shutdown and restart will only be incurred once, no matter what combination of tasks is undertaken.

5. OTHER CONSTRAINTS

In addition to the constraints outlined above, there may be limits on the maximum or minimum intervals at which certain tasks must be undertaken. It is no use showing an optimum strategy that involves inspecting a pressure vessel at 5 years, if the law requires that it be inspected at 3 years – the whole analysis is invalidated. Such constraints must be entered for each task. The form of entry is shown in the next section.

6. A SEARCH ENGINE TO FIND THE OPTIMUM STRATEGY

The number of different strategies that might be evaluated is very large, and increases rapidly as the number of tasks included in the evaluation rises. For a case involving 20 tasks, this can be in the order of 10^{17} combinations, and it is not practicable to evaluate every combination. At this stage, a search engine is required to home in on the best strategy.

There are several types of search engine that might be considered. Terms such as genetic algorithm, simulated annealing, and neural network, form part of the jargon in this area. But what we need is a means of searching the large number of possible strategies, and homing in on the best strategy (that with the lowest cost per year, as set out in Section 3).

A graphic view of the performance of an optimising search is shown in Figure 4.

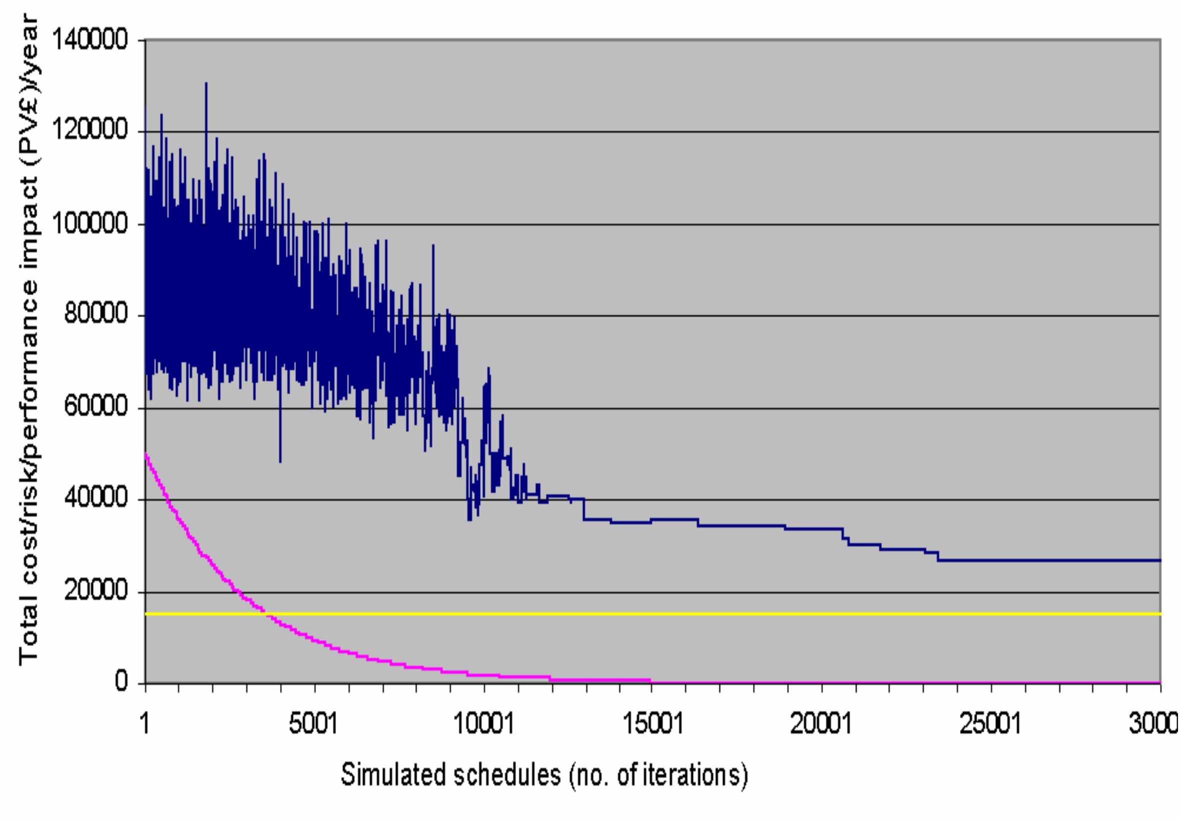

Figure 4 *An optimising search.*

7. IMPLEMENTATION

The process is started by determining the tasks which are likely to influence the shutdown pattern. Although a large number of tasks will normally be included in any shutdown, there are usually only a small number which are of a magnitude such that they significantly influence the strategy.

For each of the tasks defined, individual analyses are then made using the appropriate analytical tools (APT-MAINTENANCE, APT-INSPECTION and APT-LIFESPAN). Each analysis creates the information set out in Section 3 above, relating the overall costs to the company to the interval at which the individual task is carried out.

The individual analyses are imported into APT-SCHEDULE, and additional information entered in the following input form.

Task Type	Equipment Description	Task Description	Of which, Overhead (£)	Outage Duration (Hours)	In Series Within Group?	Group	Preferred Interval (Months)	Minimum Interval (Months)	Maximum Interval (Months)	Last Performed
M	Plant business unit	general work	5000	40	☐	1	24	12	48	10/07/2001
M	unit 1 in area a	Control valve mtce	200	12	☐	1	12	6	36	10/07/2001
M	unit 2 in area a	Clean ht exchange	200	16	☐	1	24	22	24	10/07/2001
M	Emergency bypass	bypass system	400	16	☑	1	36	22	36	10/04/2001
M	unit 3 in area A	Compressor overh	5000	36	☑	1	60	48	60	13/11/2001
O	compressor 6	modify controls	200	20	☐	1	6	6	6	
O	chiller units	replace lining	300	20	☑	2	20	12	30	
C	ht exchanger c3	clean	400	8	☑	2	6	3	18	01/06/2001

Figure 5 *Entry of information additional to the individual analyses.*

The optimiser is then run, and the results might look as in Figure 6. Note that the full display cannot be shown since it is accessed by scrolling across.

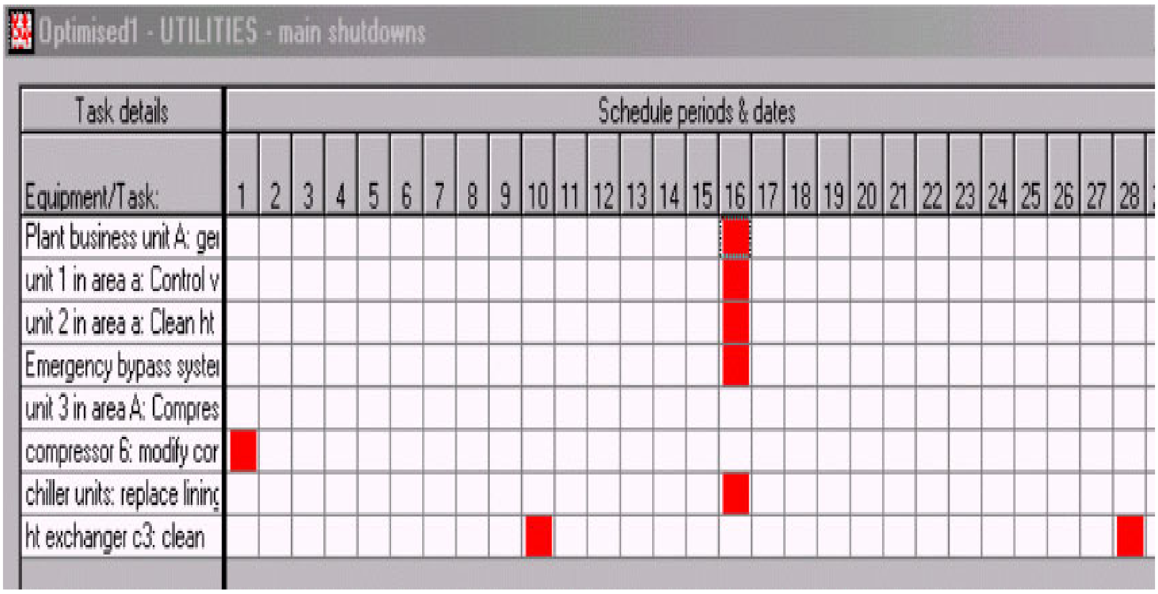

Figure 6 *The optimised schedule.*

The schedule can then be amended by hand, if so desired, and the parameter of merit for the resulting schedule is displayed.

8. CONCLUSION

Genuine shutdown strategy optimisation is now fully practicable. The results achieved so far demonstrate substantial savings over manually composed schedules.