A Risk Based Maintenance Model for Power Plant Boilers

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Abstract

Deregulation in the electricity supply industry has brought about increased competition to reduce the price of electricity. One of the ways this can be achieved is by ensuring that inspection and maintenance costs are focused on the critical items that experience shows could cause forced outages. This will reduce the inspection levels and associated costs on some components and should reduce the outage duration. The objective is to minimise the inspection and maintenance activities whilst not affecting plant availability or personnel safety.

This paper looks at the philosophy behind risk based maintenance based on an extensive review of maintenance in the power industry in Europe and USA. To be commercially viable the risk-based system has to be robust and simple to apply. This paper presents a practical approach developed by ETD (Waterfall Model) to planning inspection and maintenance-based programmes on a risk basis. Examples of the opportunities for reducing costs and extending runs between outages are also presented.

1. INTRODUCTION

The electricity generation industry has changed significantly throughout the world in the past decade. Deregulation is occurring and is leading to increased competition with a marked change in how the industry conducts its business. Furthermore, the current uncertainty of the market with the potential swings in fuel price, demand etc. together with investor earnings expectations has resulted in unprecedented pressure on station management teams to cut costs at the same time as improving all aspects of plant performance and safety.

In-service maintenance of plant equipment has traditionally been dictated by prescriptive industry practices. Indeed, statutory inspection under the regulator legislation has long been a requirement for boilers, pressure systems and other critical equipment. Prescriptive practices fixed the locations, frequency and methods of inspection mainly on the basis of general industrial experience for the type of equipment. These practices, although inflexible, have on the whole provided adequate safety and reliability. However, prescriptive plant maintenance has a number of deficiencies, as it does not encourage the analysis of the specific threats to plant integrity, the consequences of failure and the risks created by each item of equipment. It also lacks the freedom to benefit from “good” operating experience and hinders from focussing finite inspection resources to the areas of major concern. This has led to an increasing trend towards the use of ‘risk based’ approach particularly when this is now well supported by extensive plant operating experience, improved understanding of material degradation mechanisms, the availability of fitness-for-service assessment procedures. Another supporting factor is the more recent developments in non-destructive testing (NDT) methods, which have increased the scope and efficiency of examinations that can be undertaken. The main objective of Risk Based Maintenance (RBM) is to allow a framework for identifying and measuring the risk areas and thereby allowing optimised focusing of available resources. As such it is a management tool. It is important to recognise that identification of risks does not necessarily require a substantial financial or resource commitment rather, as the Guidelines provided in this paper will show, a simplified system can be developed that readily highlights risk areas for attention. It will also allow a means of choosing what level of risk a station can/will operate with.

In response to the current requirement of the electricity industry worldwide for a RBM methodology for assessing levels of risk, ETD has developed Risk Based Maintenance (RBM) Guidelines based on the *Waterfall Model*, which is simple to apply and is robust and flexible as it can be easily customised for a given station’s requirements. This paper gives a description of the ETD’s RBM guidelines and looks at some of the aspects that should be considered when applying this model. It also illustrates the application of the different steps of the proposed Guidelines through a series of practical examples.

2. ‘FRAMEWORK’ OF MAINTENANCE RISK ASSESSMENT

Risk based maintenance essentially comprises a systematic approach for optimising the operation, maintenance, and integrity management processes by focusing the appropriate level of maintenance resources (both financial and staff) at the highest risk areas of a plant. A review of the current Risk Based Maintenance / Inspection procedures currently being employed or under development [Refs.1, 2] reveals that there are essentially two methods:

- A prescriptive rule based three-stage process e.g. the API approach [Ref. 3].
- A question based specialist assessment system.

Both approaches have their advantages and disadvantages. The former can be overly prescriptive and time consuming whilst the latter can be difficult to consistently replicate without resorting to an excessively large list of questions.

ETD’s RBM Guidelines aim to give sufficient background to allow the introduction of a risk-based approach to the maintenance activities and general management. The Guidelines use some of the aspects of both the prescriptive and question based approaches but emphasis is given to facilitate its application rather than absolute accuracy in determining risk. The principle aim is to be able to quickly prioritise the areas of highest risk in order to allow informed decisions as to the funding and resource commitments. This Guideline differs from the traditional approach adopted by most risk based systems in that it mainly concentrates in identifying areas of high risk emanating from the way the management systems control the technical aspects of the plant. It then looks at how well the control systems are being implemented. It is only at this stage that the condition of specific components is considered. The principle benefit of this approach is the early identification of possible problem areas without excessive detail.

Conceptually these Guidelines involve a "Risk Waterfall" as shown in Fig.1, where the level of detailed information about the plant and its condition increases and the accuracy of the assessment improves with the depth of the process i.e. the process initially starts at a high level with identification of risk areas. This involves examining how well the plant is managed in terms of technical programs. The output is a numerical indication of the level of risk in different plant areas. This is followed by a more detailed evaluation of the degree of risk in each area by examining how effectively the technical programs are implemented. The next level examines the level of risk associated with specific components. Finally the maintenance activities to be performed on the component at the next shutdown are examined in terms of their (risk based) value to eliminate the low value tasks.

Fig. 1. ETD's Risk Based Management Waterfall Model

As illustrated in Figure 1, the Risk Based Management process outlined here involves four basic risk calculation and decision-making levels:

a) ***Management Program***: Identifies management program deficiencies in terms of risk.

b) ***Program Implementation***: Highlights where there is inadequate application of the management programs.

c) ***Component Condition***: Provides a simple and quick method of ranking the most critical components while identifying the current condition of the component.

d) ***Risk Based Task Prioritisation***: Risk assessment prioritised in terms of the most critical work.

2.1. Management Program

The aim of technical management programs is to ensure that component integrity and plant reliability are maintained over the plant life. This requires that information about the plant, its design, how it is operated and the impact of operation and maintenance on its condition is gathered and assessed by competent people to ensure safe and reliable operation. Each management program should have a series of ***attributes*** that define the core actions that need to be taken or the procedures that should be present in order to ensure that all safety and reliability requirements are fulfilled. For all plant areas there should be a structured component condition appraisal system, which typically will involve a written procedure detailing:

- Frequency and scope of inspections.
- Basis for deciding the inspection program (e.g. life assessment estimates/degradation mechanisms, known problems for components of similar design, etc.).
- Assessment of the impact of operational factors since the last inspection, e.g. method of detecting operating variations and the effect that the variations will have on the component and the timing and scope of the next inspections.

The above procedure is what should be happening for each major component and plant area. However, in practice these procedures are frequently not adequately applied or can be omitted altogether. The degree of application of such procedures will give some indication of the level of risk of a major failure occurring on that component. It is also apparent that excessive i.e. too wide (and/or too often) an inspection coverage will inevitably waste financial resources. The maintenance/inspection program must therefore take into account the likelihood of the various possible damage mechanisms occurring and the potential failures and associated consequences that could result from the damage mechanisms, in deciding precisely what level of inspection is merited. For each plant area there are a number of activities/processes that should be active within a comprehensive "best practice" plant maintenance and integrity management system. Each aspect or attribute of a particular program, activity or process will have a role to play in controlling the condition of the plant. The effectiveness of a particular technical management program can therefore be measured relative to a comprehensive “best practice” program/plant area attributes and metrics. If for example there are deficiencies in the program – inadequate or omitted attributes – or lack of applicability to a plant area then clearly the likelihood of problems arising will be higher than if all aspects of the best practice program are present.

The risk is defined as the product of the consequence/impact and probability /likelihood of failure and its calculation requires the determination of these two factors. This can be done using linguistic terms or classifications or by using more involved processes relative to a specific threat. However, for the Management Program review this is carried out at a high level without identification of specific component failure scenarios and hence no specific consequence or likelihood assessments are made at this stage, these are rather determined at a "*generic*" level.

Program Attribute Impact (PAI): It is measured in terms of the feasible "generic" impact of significant "failure" events associated with "best practice" attributes for each process, organisational aspect or general plant area. The aim is to provide an indicative value of the significance of a major problem that may result due to the lack of a particular procedure/ attribute associated with the management program. Consequently, a simple severity categorization can be used, which is related to a suitable numerical value e.g. High, Medium and Low (10, 3, 1 respectively) or a scale of 1-5.

Program Attribute Likelihood (PAL): This is assessed indirectly based on the presence or otherwise of particular aspects/attributes of each Management Program. If a "best practice" attribute is not present in the management procedures under examination then its omission will influence the likelihood of a failure occurring. This likelihood can be assessed by ranking the omission relative to a (high, medium, low) or (1-5) classifying system. Alternatively, a slightly more involved assessment can be carried out. Firstly an "**A**ttribute **P**resence" (AP) score can be determined (Yes = 0 and No = 5). The significance of the omission is then evaluated using a "**C**riticality **W**eighting" parameter (CW) (e.g. 1-5) that effectively biases the score towards the most important attributes missing from the program. Example: If 2 attributes were: 1) to have a documented inspection planning process, and, 2) 100% completion of all planned inspections, then having a planning process would be less critical (e.g. CW=1) than having completed 100% of the planned inspections (e.g. CW=4).

A key issue for management programs is the timescale over which a program omission will yield a "failure". Hence inclusion of a **T**imescale **F**actor (TF) to take account of this is preferred. For example, lack of a life management procedure for a superheater will not cause problems in the short term but will eventually result in forced outages caused by end of life tube failures. Hence inclusion of a timescale factor (e.g. Short (10), Medium (3) and Long (1)) can be introduced. This ensures that short-term program level risks i.e. ones that should be given priority, will yield high-risk scores and hence will be prioritised for attention. The **P**rogram **A**ttribute **L**ikelihood (PAL) is therefore determined as follows:

$$\text{PAL} = \text{"attribute presence(AP)" x "criticality weighting(CW)" x "timescale factor(TF)"}$$

To measure the risk, the **A**ttribute **I**mpact (AI) severity term is introduced as follows:

$$\text{Attribute Risk Score} = \text{PAL x AI}$$

Adding the risk for each attribute within the designated Program will yield a **P**rogram **R**isk **S**core (PRS). This is therefore simply the sum of each attribute risk: $\text{PRS} = \sum(\text{PAL x AI})$.

An “at risk percentage” can be obtained by taking the ratio of the actual PRS to the maximum possible PRS (i.e. no attributes present in the designated program) and multiplying by 100.

An example of the Program Level risk calculation is shown in Table 1 for boiler and pressure parts, which highlights how the different elements of the process combine to yield a ranking of the highest risk attributes. Based on these results, the priority is to make sure that regular pipework inspections are carried out, followed by improving component condition assessment procedures, then monitoring of main component metal temperatures and procedures for ensuring condition assessment of other pressure components.

The principle benefit of this evaluation process is that when applied comprehensively across all of the plant areas, main processes and other organisational aspects, it will identify (in risk prioritised order) where to focus effort to improving and/or developing management procedures. As procedures are developed or improved, the overall score will reduce. Hence the PRS can be used to monitor improvements in overall technical management. The output of this type PRS can be presented in various forms. An easily recognisable form is shown in Fig. 2, which gives a summary Spider Chart of the Management Program Risk covering 16 management programs or plant areas. Note a higher score corresponds to higher risk hence more concern.

PRINCIPAL OBJECTIVES	ATTRIBUTES	Attribute Presence (Y=0/ N=5)	Attribute Weight (1-5)	Timescale Factor			Attribute Impact severity			Attribute Risk Score	Maximum Attribute Risk Score
				Short 10	Med 3	Long 1	Low (1)	Med (3)	High (10)		
Ownership	Responsibility structure for Station	5	1			1	1			**5**	**5**
Avoidance of main pressure vessels failures headers, steam drums, main and safety valves, attemporators etc.	Procedure for managing component life in creep specifying degradation mechanisms, assessment & inspection intervals, etc. with Competent Person Approval	0	4		3				10	**0**	**600**
	System for monitoring main components metal temperatures & assessing impact on life	5	3		3			3		**135**	**135**
	System for recording component information (material, design etc.), inspection and condition assessment details	0	2			1	1			**0**	**10**
	Procedure for qualifying short and long term repairs	0	2		3		1			**0**	**30**
	Procedure for routine assessment of components **not** in creep range - specifying degradation mechanisms, assessment & inspection intervals, etc. with Competent Person Approval	5	3		3			3		**135**	**135**
	Procedures for ensuring adherence to regulatory requirements	0	5	10				3		**0**	**750**
	System for monitoring dead space tube leaks to avoid external erosion of headers, e.g. acoustic detection	5	1		3		1			**15**	**15**
	Procedure for regular inspection and testing of safety valves	0	5		3				10	**0**	**750**
Avoidance of tubular system failures - e.g. evaporator, economiser, superheaters	Procedure for assessing tubing life taking into account relevant degradation mechanisms & operating conditions	0	4			1		3		**0**	**60**
	Inspection procedures with Competent Person Approval for monitoring condition of tubing systems	5	4			1		3		**60**	**60**

Table 1: Maintenance Program Risk Evaluation Process (Example From Plant Area: Boiler, Pressure Parts)

It can be seen in Figure 2, for example, that the Training Program is lower risk concern while the Turbines & Generators Condition Procedure represents the higher risk item.

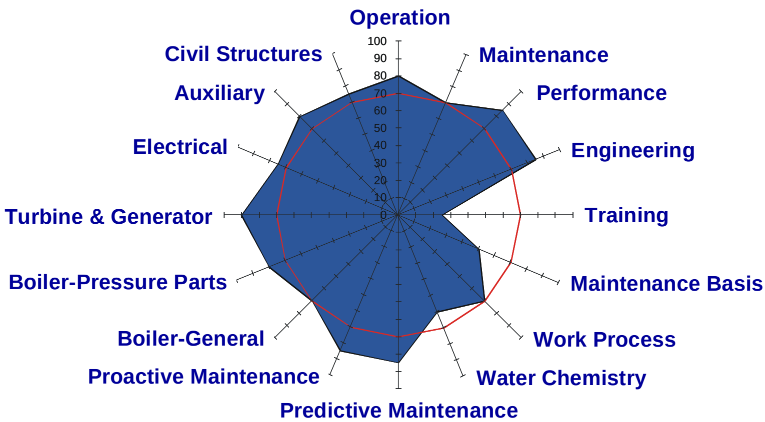

Fig.2: Management Program Risk Spider Chart

2.2. Management Program Implementation

This stage involves looking at how well the existing technical management programs are being implemented. For example, a management procedure may require that a Station should have a written procedure for maintaining or inspecting a particular component. The presence of such a document will yield a satisfactory outcome at the program risk level of assessment i.e. the management control for that component exits, thereby resulting in a relatively low risk. However, the presence of this document does not guarantee that the policy is being implemented. What is required is essentially a “compliance audit".

Compliance Audit Factor (CAF): The compliance audit examines how well the existing management programs are being applied in each plant area. Note Management programs can often concern several different plant areas/aspects of the overall management control procedures. The compliance audit therefore concentrates on components rather than programs to ensure that each aspect of the control structure is being applied where it matters.

Let us take the Superheater tubing as an example. For this type of component a policy may state merely that "*the tubes should be inspected at regular intervals*". Alternatively it may be more comprehensive without being specific e.g. "*that all tubular components should be maintained in a manner to ensure their integrity over the next period of operation taking due account of the effects of any degradation mechanisms*". Neither policy states specifically the scope or type of inspections that should be carried out or indeed their frequency. In either case it is important to ascertain more precisely that all policies e.g. operations, engineering (repairs etc.), that affect the component are being implemented. It is quite clear that if the procedures are not being followed correctly then it is more likely to experience a failure hence the risk is higher. The compliance audit is in essence a series of questions that will highlight whether all the pertinent attributes are being implemented for each component or process. The questions should be designed to illicit "yes" or "no" answers to avoid ambiguity and ease scoring and repeatability of the audit. Examples of the type of questions that can be asked are shown in Table 2. The CAF is then determined as (1 - the ratio of positive answers over the number of questions) as illustrated in Table 2.

Plant Area	Component	Query	Yes	No	Compliance Factor
Boiler	*Superheater Tubing*	Is the inspection policy fully adhered to	a		1
		Is the inspection program drawn up by a competent person	a		1
		Is the inspection program fully completed	a		1
		Are all tube failures recorded		a	0
		Are all tube failures subject to root cause analysis		a	0
		Are the number of tube failures decreasing	a		1
		Are tube repairs/replacements always carried out to documented and approved procedures & engineering standards	a		1
		Are temporary repairs used	a		1
		Are temporary repairs always subsequently replaced with permanent repairs	a		1
		Has a remanent life assessment that considers all feasible failure mechanisms been carried out by a competent person	a		1
		Is the remanent life assessment updated by a competent person after each overhaul	a		1
		Are historical inspection records available	a		1
		Are operating steam temperatures monitored	a		1
		Are METAL temperatures monitored	a		1
		Are significant temperature deviations fed back into life assessment process and inspection plans	a		1
		Is the internal oxide thickness monitored regularly	a		1
		ACTUAL TOTAL			14
		POSSIBLE TOTAL			16
		COMPLIANCE RATIO			0.875
		CAF = 1 COMPLIANCE RATIO			0.125

Table 2: Example Of Implementation "Audit" Questions

If some questions are deemed to have varying degrees of importance then, in a similar fashion to the program risk calculation, a weighting factor can be applied relative to the importance of the question if required.

Likelihood of Failure (LoF): At this stage fairly detailed questions are being asked on specific components, hence it is appropriate that some indication is given of the generic likelihood of failure (LoF) of the component. The conventional way of estimating the **P**robability **o**f **F**ailure (PoF) is by reference to actual failure statistics and applying modification factors. This is the preferred route of for example the API methodology. This is facilitated by the fact that since the 1980's many petrochemical and refining companies pooled their failure information to create relatively comprehensive failure rate databases. Whilst some data are available, they are insufficient to allow this approach to be applied to all of the main components in a power station. To get round this problem a classification system can again be used. The "generic LoF" can be divided into different classes using linguistic terms – possible, probable, very probable etc. or a classification system e.g. Class A = a failure probability of say 10^{-4}, Class B = 10^{-5}, Class C = 10^{-6}, Class D = 10^{-7} etc. This is essentially a ranking method based on industry experience. An example of this approach is shown in Table 3. If specific failure rate data are available for some components then clearly they should be used. In time, as reliable data for power generation components are gathered recourse to classification systems should not be required.

Plant Area	Component	Failure Event	Consequence		Generic LoF
			Safety Category	**Cost Category**	
Boiler	*Outlet Header*	Catastrophic Failure due to creep	4	3	F
	Inlet Header	Catastrophic Failure due to creep	4	3	G
	Superheater Tubing	Major replacement	2	2	D
	Reheater Tubing	Major replacement	2	2	D
	Attemporator	Failure due to fatigue	3	2	D
	Attemporator Piping	Catastrophic Failure due to creep	4	2	E
	Interconnecting Pipework	Catastrophic Failure due to creep	3	2	E
	Steam Drum	Catastrophic Failure due to brittle fracture from fatigue crack	5	4	G
	Downcomers	Catastrophic Failure due to corrosion fatigue	3	2	D
	Risers	Catastrophic Failure due to low temperature creep crack growth	4	2	E
	Furnace Tubing	Major replacement	2	2	C
	Tube Support	Catastrophic Failure due to fatigue	2	2	D
	Header Support	Catastrophic Failure due to corrosion	2	3	E
	Boiler Support	Catastrophic Failure due to fatigue/corrosion	4	5	F
	Boiler Stop Valve	Failure to operate when required	4	5	E
	Economizer Headers	Failure due to fatigue	2	2	C
	Economizer Tubing	Major replacement	2	2	D
	Safety valve	Failure to operate	4	4	F
	Safety valve piping	Catastrophic failure of pipe	3	2	F
	Fans	Catastrophic Failure brittle fracture from fatigue crack	4	3	E
	Burners	Furnace explosion due to Failure	4	4	D

Table 3: Example of failure types in a boiler with estimated generic consequences and LoF Classifications

Table 3 also provides an example of classification of the "failure" consequence, which is broken down into safety and cost criteria each with an appropriate scale 1-5. Examples of some possible scales and definitions are given in Table 4 below for both cost and safety impacts. The consequence or impact of the failure event is simply the product of the safety and cost classifications. Say for example the generic failure event being considered is the catastrophic failure of a header. It would be reasonable to expect that the incident would cause major injuries and even a fatality. Hence the safety impact could be "**4**" if the scale in Safety given in Example 1 above is used. The incident would result in significant damage and would require a long outage to repair. Using the scale in Cost Example 2 above a total cost impact of "**3**" would probably apply for a small unit. This yields a consequence value of "**12**". If some asbestos is suspected to be present in the insulation then the cost value may increase to the next level, as may the safety classification.

Example 1 for Consequence Classification				Example 2 for Consequence Classification			
Cost		*Safety*		*Cost*		*Safety*	
Class	**Definition**	**Class**	**Definition**	**Class**	**Definition**	**Class**	**Definition**
1	<0.1M	1	No Impact	1	0-1M	1	Minor accident
2	0.1- 0.5M	2	Minor Injuries	2	1-5M	2	Intermediate accident
3	0.5-1M	3	Major Injuries	3	5-10M	3	Reportable accident
4	1-2M	4	Single Fatality	4	10-50M	4	Severe injury
5	>2M	5	Multiple Fatalities	5	50-100M	5	Fatality

Table 4: Examples of scales and definitions of the failure impacts

These failure impacts can be refined further. The "cost" impact can be expanded into several sub categories if required e.g. lost income or replacement energy cost, repair cost, legal cost etc. In a similar fashion a "health" dimension can be included, that would cover the possible longer-term aspects of an event, for example exposure to asbestos, PCB's etc. The "Safety" impact can be refined to take account of location dependent factors. An example of this would be a pipe failure. If the pipe is located near a personnel high traffic area, failure would be much more likely to cause a serious injury or fatality than if it were located at the top of the boiler in an area where personnel rarely visited. It is at this point that Station preferences start to significantly influence the nature of RBM. They may decide to accept operating with higher risk for specific components or locations where the possibility of high safety consequences is low in order to gain some commercial advantage from lower maintenance costs.

The assessment of implementation risk is carried out for each component. An **I**mplementation **R**isk **S**core (IRS) can then be calculated using the compliance ratio of positive answers, the generic impact and likelihood of failure (LoF) values i.e

IRS = (1- Compliance ratio) x (generic impact score) x (generic LoF)

Using for illustration the Superheater Tubing compliance ratio in Table 2, and the safety and cost impact and LoF classifications for the Superheater tubing in Table 3, an IRS of $5x10^{-8}$ is determined. If however, only 2 positive answers had been given the score would have been $3.5x10^{-7}$.

This process highlights the components most at risk from inadequate implementation of the management programs and hence provides a focal point for targeting local procedural improvements. However, since we are now looking at the component level it is important to consider the effect that the condition of the component will have on the level of risk.

2.3. Component Condition Risk

The risk emanates principally from the specifics of a component, in particular its design and condition. Indeed, the management procedures only ensure that the condition of the components is known and being monitored by competent persons. Furthermore, it is important to be able to prioritise components when time/resources are limited or where reductions have to be implemented. This aspect of risk assessment is generally the domain of the specialists and detailed evaluation procedures e.g. probabilistic assessment of tube failures. This is the most accurate way of determining the probability of failure but unfortunately it is also very expensive for widespread application in order to establish a criticality ranking. The alternative is to establish the ranking using a risk-influenced methodology. The main or key component risk drivers are:

- *Age*: Many of the damage processes affecting components are time dependant. Hence, the older the component the higher the risk of failure from a variety of degradation processes - creep, corrosion, fatigue, etc.
- *Materials & design*: Properties, degradation, design weaknesses and modifications, the method of fabrication and the heat treatment condition can have a significant influence on the likelihood of failure.
- *Operating factors*: Identification and impact of operating conditions, e.g. changes to operating mode, constant and transient temperatures, number and type of cycles.
- *Inspection:* Technique, frequency, scope, efficiency and reliability.
- *Expected Condition*: Determined from available information.

Each of these factors should be considered together with the probable failure frequency of different types of component to allow estimation of a component specific condition factor. This will highlight some simple facts e.g. if a component is old, of poor design, has experienced high temperatures and many starts but has rarely been inspected then the failure likelihood is expected to be high. Conversely if the component is fairly new with a good design, operated at design temperatures with few starts and is regularly subjected to comprehensive inspection then it is unlikely that a failure will occur. In order to get a reliable indicator of the component condition a simple scaling process is again used. There are various options that can be used for ranking e.g. using a simple generic scale, or indeed using templates specific to individual component types as shown in Table 5.

Factor	1	2	3	4	5
Age	< 50Khrs	50-90Khrs	**90-130Khrs**	130-170Khrs	>170Khrs
Cycles	< 200	200-500	**500-1000**	1000-2000	>20000
Temperature	Constantly below design conditions	Generally at design	Occasionally above design	Frequently above design or poor monitoring	**Generally above design/ unknown**
Environmental Conditions	Benign service conditions	**Minor corrosion or wastage possible**	Corrosion or wastage possible	Corrosion or wastage probable	Very aggressive corrosion or wastage / unknown
Generic Design/ Component type	**No known design related failures**	Very few failures with this design	Occasional failures with this design but different operating mode	Occasional failures with this design and operating mode	Known design weaknesses - subject to frequent failures
Inspection	Comprehensive inspection within last 4 years	Partial inspection within last 4 years	Comprehensive inspection within last 8 years	**Partial inspection within last 8 years**	No inspection within last 8 years
Expected Condition	Good	Average	**Poor**	Condition unknown	Very poor

Table 5: Examples of Condition Factor Ranking for Tubing

The component risk is a function of how well the technical management programs are being implemented and the condition of the component. It follows that introducing the **C**ondition **F**actor (CF) into the Implementation Risk Score will yield the Component Risk. Taking as an example superheater tubing in a gas fired unit that has been in service for 100,000 hours with 600 starts with no temperature monitoring but had a limited inspection after 80,000 hours. Using the scaling provided in Table 5, a Component Factor value of 21 (i.e. CF = 3 + 3 + 5 + 2 + 1 + 4 + 3 = 21) can be derived. The Component Risk is calculated by combining this CF with the IRS as follows:

Component Risk = CF x (1- Compliance ratio) x (generic impact score) x (generic LoF)

Using the CF determined above with the IRS example in Section 2.2 gives a Component Risk value for the Superheater tubing of $1.05x10^{-6.}$ As with the other steps of these guidelines, it is possible to refine the CF by expanding the categories to include susceptibility levels for such factors as materials (properties, heat treatment, degradation), specific design aspects such as solid rotors, seam welded piping etc. These will increase the accuracy of the condition factor but perhaps the most important consideration is with the ***inspection***. The accuracy with which one detects, monitors and trends the rate of degradation is a function of the ability to look for and find nascent damage. A summary of some of the main inspection techniques is shown in Table 6.

TECHNIQUE	APPLICABILITY	LIMITATIONS
DPI	All materials	Surface only
MPI	Ferromagnetic materials,	Surface or up to 2mm subsurface, surface preparation required
UT	Most materials, surface or subsurface	Can be operator dependent, prone to defect sizing errors
RADIOGRAGPHY	All materials, surface or subsurface	Defect orientation/size limitations, need access to both sides of component
EDDY CURRENT	Mainly non magnetic materials, surface and limited subsurface, also crack sizing	Operator dependent, sizing limitations
POTENTIAL DROP	All steels, surface crack sizing	Limited accuracy and reliability
REPLICATION	All steels, surface, early stages of creep damage, identification of damage type	Highly operator dependent and interpretation expertise required

Table 6: Summary of the main inspection techniques and their limitations

There is an inherent assumption that the regions inspected are representative and that the inspection will always detect any damage present. Unfortunately human error can have a major influence not only on the accuracy of the inspection but also the reliability. Despite numerous major projects aimed at defining the accuracy limitations and reliability of various techniques the industry still can only quantify these factors for fairly simple geometries. Account of this can be taken qualitatively using API approach type given in Table 7.

QUALITATIVE INSPECTION EFFECTIVENESS CATEGORY (API)
***Highly* Effective:** Correctly identify the anticipated in-service damage in nearly every case
Usually Effective: Inspection methods will correctly identify the actual damage state most of the time
Fairly Effective: Inspection methods will correctly identify the true damage state about half the time
Poorly Effective: Inspection methods will provide little information to correctly identify the true damage state
Ineffective: Inspection method will provide no/almost no information to correctly identify the true damage state

Table 7: Example Of Inspection Classification (after API)

This step gives a simple but effective method of prioritizing the components in terms of risk. The question now is “How do I save money” This is answered in the next section which presents a method for prioritizing tasks based on risk and comparing this task risk relative to the task cost

2.4. Risk Based Task Prioritisation

Risk based task prioritisation is 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 prioritisation of tasks are the calculation of risk and the associated cost of performing the task. The ultimate goal of decision-making is to cover the most risk with the minimum of budget costs. One method of risk based task prioritisation is the model known as Risk Evaluation And Prioritisation (REAP). This model enables to make business decisions on task activities such as outage work or budget item prioritisation. These decisions are derived from information on the condition of equipment, the task to be performed, the equipment’s failure consequences and probabilities, and information on the task’s financial impact. This 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, which represents the amount of risk eliminated by performing the task, is then plotted against the cost of performing the task. From this plot an optimised decision can be made that identifies those combinations of tasks that result in the most value derived for the plant at a given cost. Figure 3 gives an example of the results of the Risk Evaluation and Prioritisation analysis covering 119 maintenance outage tasks to be scheduled for a boiler maintenance outage. This plot can be presented in a more exploitable format by building the outage task scope from the high risk value, low task cost to the low risk value, high cost items as shown in Figure 4. Note that the graph in Fig.4 integrates all tasks such that each point on the curve builds from the previous points. Furthermore, the task cost was changed from $ to required hours for achieving the tasks. Clearly, Figure 4 shows that the 32,700 relative cost level (mostly labour hours), 3.6E+09 risk value is captured with 95 of the 119 outage tasks. Hence, with 40% of the outage task hours (cost), 90% of the outage task value (risk) can be captured with 80% of the tasks being performed.

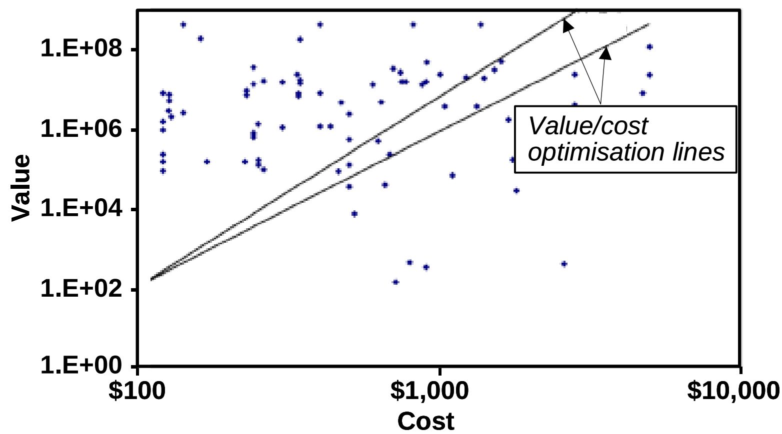

Fig. 3: Example of the plot "Risk Value versus Task Cost"

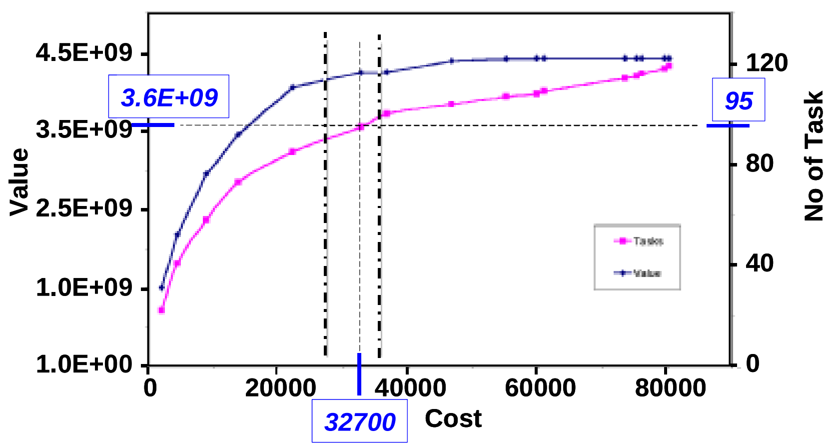

Fig. 4: Example of the plot showing the Accumulated Value versus Cost and No. of Tasks

The Risk Evaluation and Prioritisation analysis enables one to quickly determine the tasks that minimize risk with the minimum of costs. Most of the experience with this approach/model shows that Paredo's rule applies. That is, 80% of the risk can be covered with approximately 20% of the cost.

3. CONCLUDING REMARKS

Although 'Risk' is a new concept to most power generators, it is becoming now more pertinent with increasing commercial pressures. As a tool, Risk Based techniques have a solid basis in other industries such as petrochemical and nuclear plants and hence it should have promising potential for the thermal power generation industry. The ETD Guidelines presented here describe how to apply Risk Based Approach to many aspects of power plant management and maintenance, from day-to-day decision-making to outage scheduling.

The main purpose of ETD risk assessment Guidelines is to provide a risk informed approach to management programs and everyday decision-making. Information details and assessment accuracy increase with the depth of the process. As illustrated in this paper, these Guidelines are simple to apply while being robust and flexible. They can be customised to individual station for planning maintenance and inspection activities. When applied adequately, they should yield industry potential benefits in terms of:

- **Improved component reliability**: Targeting the maintenance expenditure to the most critical components will significantly reduce the number of failures and thereby their consequences.
- **Increased plant availability**: Risk-based maintenance not only results in a reduction in forced outages to plant failures but may be used to justify extended intervals between inspection intervals thereby increasing plant availability.
- **Improved safety**: Targeting the inspection and maintenance actions to components and areas of significant risk of failure causing a safety hazard will enhance the plant safety.
- **Reduced maintenance expenditure**: The risk-based approach enables to identify unnecessary and ineffective inspection and maintenance activities, which can be thereby eliminated.

4. REFERENCES

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