This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under Grant Agreement no. 608813

D3.5 Guide on prevention & mitigation, and integration for aging management

Customer:	European Commission			
Project title:	SafeLife-X Safe Life Extension management of aged infrastructures networks and industrial plants		**Costumer order Nr.:**	Grant Agreement: 608813
			Internal project Nr.:	12049
			Project start:	01/09/2013
			Project end:	31/08/2015
Subproject:			**Applicable codes/standards:**	
Work package:	WP3		**Date of order acceptance:**	28/06/2013
Task:	T3.5		**Date of completion:**	
Additional contract info:	Project website: www.safelife-x.eu-vri.eu			
Participants / Distribution:	**Participants in the activity:**		**Distribution (list):**	
			Internal	
Document data:	**Author(s):**	Aleksandar Jovanovic, Bastien Caillard, Stefan Husta		
	File name:	D3.5-AgingPreventionMitigation_v27sh05022015.docx		
	Pages:	174	**Nr. of annexes:**	0
	Status:	Final	**Confidentiality:**	PU
	Keywords:			

Stuttgart, February 12, 2015

Table of Contents

List of Figures

List of Tables

List of Acronyms

A list of acronyms used throughout this document, with the corresponding definitions is given in the table below.

Table 1 – List of acronyms

Acronym	Definition
TRD	Technische Regeln für Dampfkessel [Technical Regulations for Boilers]
MPA	Materialprüfungsanstalt Universität Stuttgart [Materials Testing Institute University of Stuttgart]
ALIAS	Advanced modular intelligent Life Assessment Software System
RL / RLA	Remnant Life / Remnant Life Assessment
ANSYS	Engineering simulation software package
ALGOR	General purpose multiphysics finite element analysis software package
ROHR 2	Pipeline stress analysis computer aided engineering system
RIMAP	Risk based Inspection and Maintenance Procedures
RCM	Reliability Centered Maintenance
O&M	Operation and Maintenance
P&ID	Piping and Instrumentation Diagram
FCA	Failure Characteristic Analysis
MSS	Maintenance and Strategy Selection
HS(S)E	Health, Safety (Security) and Environment
MTBF	Mean Time Between Failure
CBM	Condition Based Maintenance
OREDA	Offshore Reliability Data
iRIS-Petro	Integrated Risk Management System for Petrochemical plants
RBI	Risk Based Inspection
CWA	CEN Workshop Agreement
CEN	Comité Europeén de Normatisation [European Committee for Standardization]
RBIM	Risk Based Inspection and Maintenance

Acronym	Definition
RBLM	Risk Based Life Management
VGB	Vereinigung der Großkesselbesitzer [Association of Large Boiler Owners]
ECCC	European Creep Collaborative Commitee
ALARP	As low as reasonably possible / practicable
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CMMS	Computerized Maintenance Management System
CoF	Consequence of Failure
FME(C)A	Failure mode, effects (criticality) and analysis
HAZOP	Hazard and operability (study/analysis)
HCF / LCF	High Cycle Fatigue / Low Cycle Fatigue
HFF / LFF	High Fluid Flow / Low Fluid Flow
HSE	Health, Safety & Environment
HT	High Temperature
KPI	Key Performance Indicators
LoF	Likelihood of Failure
NDT	Non-destructive testing/inspection
P&ID	Process and Instrumentation Diagram
POD	Probability of Detection
PoF	Probability of Failure
QA	Quality Assurance
QRA	Quantitative Risk Analysis
RBI	Risk Based Inspection: methods to plan, implement and evaluate inspections using risk based approach
RBIM	Risk Based Inspection and Maintenance: methods to plan, implement and evaluate inspections and maintenance using a risk based approach
RBM, RBLM	Risk-Based Maintenance, Risk-Based Life Management
RBWS	Risk Based Work Selection
RC(F)A	Root Cause (Failure) Analysis

1 Introduction

The objective of D3.5 is to provide a guide on prevention and mitigation, and integration for aging management. Mitigation and prevention of aging-related risks requires an integrated approach, combining operating and condition monitoring, and the application of the appropriate analyses and maintenance concepts. This document attempts is to provide guidelines, descriptions and application examples, selected from the list of points given in the description of T 3.5, covering some of these areas.

- Operational and monitoring data – in Chapter 2, current monitoring trends are presented. The importance of monitoring critical components in power plants is stressed, and the various types of monitoring (operational vs. damage, global vs. local) are differentiated and described. The difficulty of selecting the correct monitoring locations for local monitoring, where damage is most likely to appear, is identified as a major issue in the field, and the chapter proposes a solution through the application of Modular Targeted Monitoring, and provides an application example through the use of a software tool at a German power plant. In the conclusions, the importance of monitoring, and specifically targeted local monitoring, is emphasized. It is also noted that monitoring is just one aspect of life management, and that integration with other life management techniques and processes is necessary for the overall management of aging structures.
- Root Cause Failure Analysis (RCFA), as an essential element of Asset Integrity Management and Reliability Centered Maintenance procedures, is briefly described in Chapter 3. Some general steps for performing, documenting and following-up RCFA corrective actions are laid out. Four RCFA investigation techniques:
    - Failure Mode and Effect Analysis (FMEA)
    - Fault Tree Analysis (FTA)
    - Cause and Effect Analysis
    - Sequence of Events Analysis

  are presented, with some advantages and disadvantages of each technique given.
- A logic of aging damage identification is provided, as defined in RIMAP, addressing the point laid out in the description of T 3.5. A flowchart describes a possible way of considering damage in power (and process) plants. For the main types of damage mechanisms defined in RIMAP, tables describe how to look for the damage, with probability of detection (POD) figures for the respective techniques, locations where to look for the damage by component type and analysis methods which can be used to predict the development of a given type of damage.
- Managing Aging by Reliability and Risk Based Methods – in Chapter 3.3, a historical evolution of maintenance strategy is briefly given. Reliability and Risk-Based inspection and maintenance concepts are introduced. These maintenance concepts integrate information obtained from condition monitoring, industry experience with equipment, inspection histories, etc. and provide an optimized maintenance program with an adequate mix of maintenance actions and policies, to safely extend the life of aging structures within the constraints of time, budget and any other considerations. More detailed documents related to Reliability Centered Maintenance (RCM) and Risk Based Inspection (RBI) are provided in Annex 1 and Annex 2, including examples of application cases. The document concerning RBI, CEN CWA 15740 – RIMAP, represents a complete guideline for implementing risk based inspection and maintenance methodologies.
- Chapter 5 briefly describes aging-related KPIs, which can be used to monitor the effectiveness of implemented aging risk controls. A short list of aging related KPIs, with definitions and formulas is provided in Annex 3. In addition, a list of risk factors and indicators of aging is provided.

For additional information on operational, design or monitoring data gathering, please refer to D3.2 – Report on the data collection, where data gathering templates have been provided for process and power industries.

For a comprehensive list of process and power plant related damage mechanisms, containing information such as: units or equipment affected, appearance or morphology of damage, prevention/mitigation measures, inspection and monitoring recommendations… please refer to D3.3 - Report on the analysis of the degradation laws and kinetics (Review of failure mechanisms in industrial processes).

2 Knowing the state: Monitoring Systems

2.1 *Increasing importance of monitoring*

The importance of monitoring of critical components in conventional power plants has been steadily increasing in the recent years due to:

a) the trend of having less people with less qualification in the operation and maintenance (O&M) of power plants (in an unmanned plant the essential importance of monitoring is obvious: the monitoring system in such a case virtually replaces the operator), and due to

b) the fact that monitoring has become more and more connected to the life assessment and management - only with data from monitoring it is possible to assess the past history of the system/component and provide a more reliable basis for future management of the system/component life.

Monitoring "connected to life assessment", must take into account the processes governing component/system life - the damage accumulation processes at the first place. The processes to be monitored depend on type of components, materials operating conditions.

In this chapter an example of monitoring of damage accumulation in high-temperature components caused by creep and fatigue is considered.

2.2 *Monitoring operation vs. monitoring of damage*

"Monitoring connected to life assessment" can be made in two main ways, namely:

a) indirect way: to monitor the operation, i.e. parameters supposed to stay within virtually unchanged ranges during the whole life of the monitored plant or component - e.g. fluid pressures or temperatures ("global monitoring"), and assess the "remaining life" on the basis of these parameters, and

b) direct way: to monitor the damage processes, i.e. parameters the values of which changes with time of operation - i.e. accumulated creep and/or fatigue damage ("local monitoring").

The first case equals to "typical" continuous monitoring, with acquisition of data and their on- or off-line use in life assessment analysis. Most of the technical solutions, available so far, are of this type.

In the second case, with the exception of corrosion, the available technical solutions are far less numerous, and the more direct damage monitoring (e. g. using capacitive strain gauges or displacement transducers – Figure 1, Figure 8) are usually classified as "advanced".

On the other hand, putting an ordered series of inspection results together can sometimes also be considered as "monitoring".

2.3 *Global vs. local monitoring*

Most of currently available systems are essentially global monitoring systems (see e. g. Eckel, Ausfelder, Tenner, Sunder 1996) – i.e. they monitor the operating parameters at a relatively large number of locations, generally not those locations where the maximum damage may/will appear. The "exhausted life" and/or "remaining life" are calculated uniformly for all the monitored locations, on the basis of the monitored global values and using relatively simple algorithms. Comparison with the design life (usually 100.000 or 200.000 hours, see TRD) is in this approach the basis for determination of "exhausted life" and/or "remaining life".

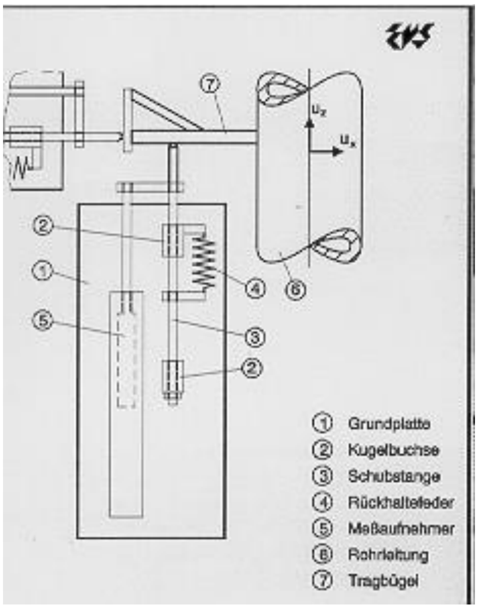

Figure 1: Example of displacement monitoring (Roos, Kessler,Eckel, Ausfelder 1996, see also Kaum and Reiners 1996)

Performing this type of calculation for a large number (say 200+ measurement points), with tight time steps (say 30 sec) over years of plant operation obviously creates a huge amount of data: in itself something that can easily lead to "computerized data cemeteries". Piles of magnetic tapes, printouts, files and similar, in which the important and significant data, if present at all, might easily get lost and/or remain hidden from the user. Furthermore, calculated damage, e.g. creep or fatigue exhaustion in these outputs is often just the repetition of pure inverse design (e.g. TRD), not involving the "real life conditions" like wrong heat treatment, external moments and forces, misalignment, etc. The final result - a huge amount dubious, often useless and/or, in the terms of damage really appearing, "false" results, calculated with "high precision", however, and real damage appearing at locations never spotted as critical by global monitoring.

The wish to improve the situation is therefore understandable and searching for solutions by monitoring the location where damage is more likely to appear. Typically, the goal of this type of monitoring is to catch the "peaks of damage" that may arise on some very particular locations and not, like in the case monitoring of operating parameters, to monitor the "average situation". Damage caused by creep and fatigue in high-temperature components is usually limited to particular zones: e.g. header ligaments, pipe elbow intrados/extrados, crotch or saddle points in T-pieces, safe-ends, transition welds and similar. Monitoring exactly these is very desirable, but, unfortunately, often difficult.

The main difficulty is the choice of monitored locations. The choice is usually a multi-criteria decision problem (Jovanovic, Auerkari, Brear 1996), with many possible outcomes. The rightfulness of the decision can be usually proven only years later. Even if issue of choice is settled, further difficulties arise due to other reasons like:

a) Monitoring instrumentation (transducers) to be used is still labeled as "experimental" or "early commercial version".

b) It is often complicated or even impossible to place the monitoring instrumentation (e. g. temperature or strain) exactly on the most critical/solicited location, even if the locations are known.

c) Even if these locations are instrumented it might be difficult or expensive to calculate stresses and remaining life for them (especially on-line: e.g. in the case of complex geometry a new finite element analysis might be needed for each type of transient, etc.).

d) Even if all the critical locations are known and instrumented, and it is possible to calculate stresses and remaining life on-line, it is often too expensive and time consuming to do it.

2.4 *Modular targeted monitoring*

Searching the way to connect

a) the technical easiness and applicability of the indirect and global monitoring (as defined above) and

b) meaningfulness of the direct damage monitoring

an approach designated here as "modular targeted monitoring", is proposed here. It essentially means that one should

a) use the indirect monitoring for

- checking the overall "health" of the monitored system/component
- (one of the factors) defining where to go for direct damage monitoring, see Jovanovic, Auerkari, Brear 1996

b) use the direct damage monitoring at the places indicated as "critical" by

- global monitoring
- previous experience
- other factors (e. g. safety, economical risk, etc.)

c) combine the two approaches above smoothly and in an optimized way for each particular situation (type and level of actions being part of monitoring should be optimized).

The approach has been developed at MPA and embedded into the MPA System ALIAS (Jovanovic 1997). The chapter presents results from an application of the approach and the system in a German power plant. The emphasis is on the optimization, showing that a lot of knowledge, data, models, software tools and people who can understand are needed for optimized monitoring. Therein, the emphasis is on software tools and practical application of the system in a German power plant

2.5 *Direct application of ALIAS for targeted monitoring in a German power plant*

The concept of modular targeted monitoring is built into ALIAS as an essential part of the overall remaining life assessment concept. The functionality of ALIAS is illustrated here using as the example the piping system in a German power plant (Figure 2).

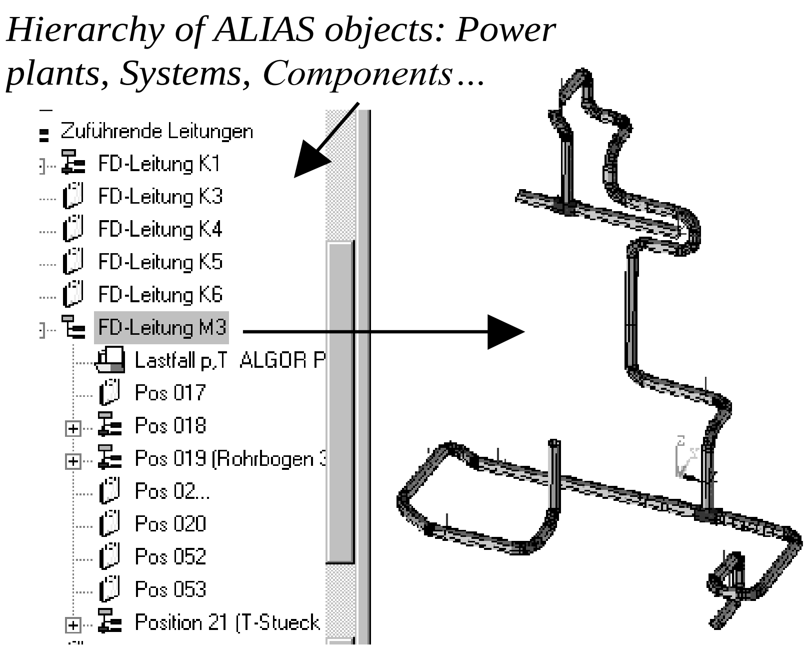

Figure 2: Piping system in a German power plant used as example for targeted monitoring: here as "stored" in ALIAS

Apart from the operational and design data about the objects themselves (Figure 2) – e.g. dimensions, materials used, operating history) analyses performed for these objects (e. g. TRD-analyses) and their results (Figure 3) are linked in a hierarchical model.

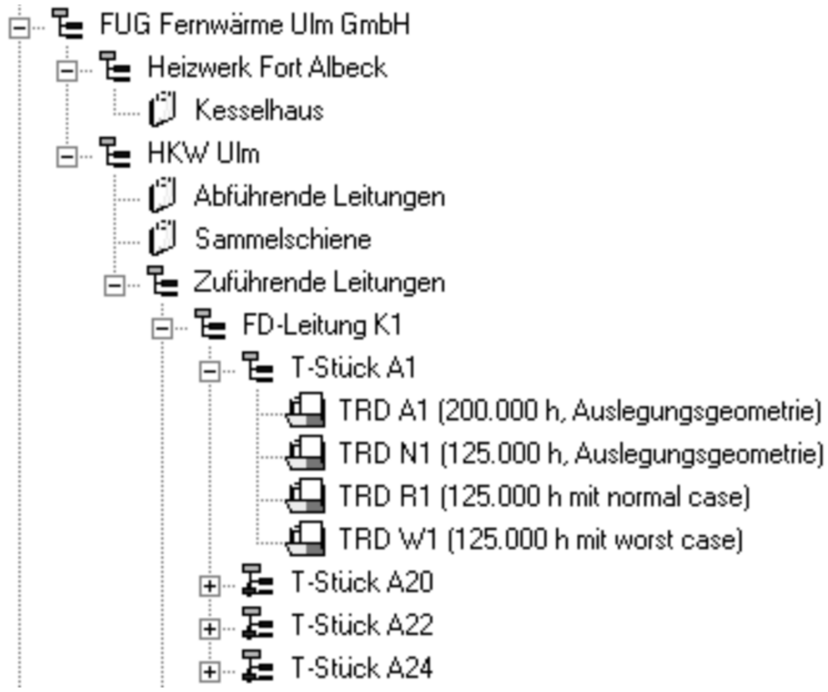

Figure 3: Analyses linked to the objects

Summary of actions

Action 1: All available data about the power plant, systems and components (Figure 2), including geometry materials, fabrications, as well as available calculations (Figure 3, including also the isometry of the piping system), etc. is collected and structured in a hierarchical tree.

Action 2: Monitoring data collected and made available for further analysis (Figure 4)

Action 3: TRD calculations for different nominal, operational and assumed combinations of parameters influencing stress and RL. For different assumed values of pressure, average temperature, wall thickness, diameter and material properties (within standard limits) various "what-if" scenario are analyzed (Figure 3).

Action 4: TRD calculations performed with standard monitoring data (Figure 4) assuming no influence of system stresses.

Action 5: TRD calculations performed with standard monitoring data (Figure 4) assuming influence of system stresses.

Using a finite element model of the piping isometry it is possible to calculate system stresses due to external forces and moments. The analysis was a linear one and before using ALGOR as a tool for parametric analysis its results were compared to those of other codes (ANSYS and ROHR2). The comparison shows nearly identical results in all load cases (Figure 5).

Action 6: Monitoring displacements

The piping system was equipped with the displacement monitoring transducers as shown in Figure 8. Measured displacements deliver, an indication about real system stresses and about the correction to be introduced into the RLA-calculations. Furthermore, comparing the displacements directly to those obtained for the limit design conditions the monitoring delivers an additional indication "is the piping still in the design limits" (Figure 6).

In a similar way as displacements, monitoring of strains was performed on a selected position on the piping (Figure 8) using high-temperature capacitive strain gauges (Figure 7). However, a pre-condition for implementation of strain monitoring is availability of non-linear analysis. In this case it was done by ANSYS finite element code. The analysis enables to (a) reiterate in calculation the stress-strain situation corresponding to the measured one and (b) to perform the component remaining life analysis based on realistic time-dependent creep-fatigue behavior.

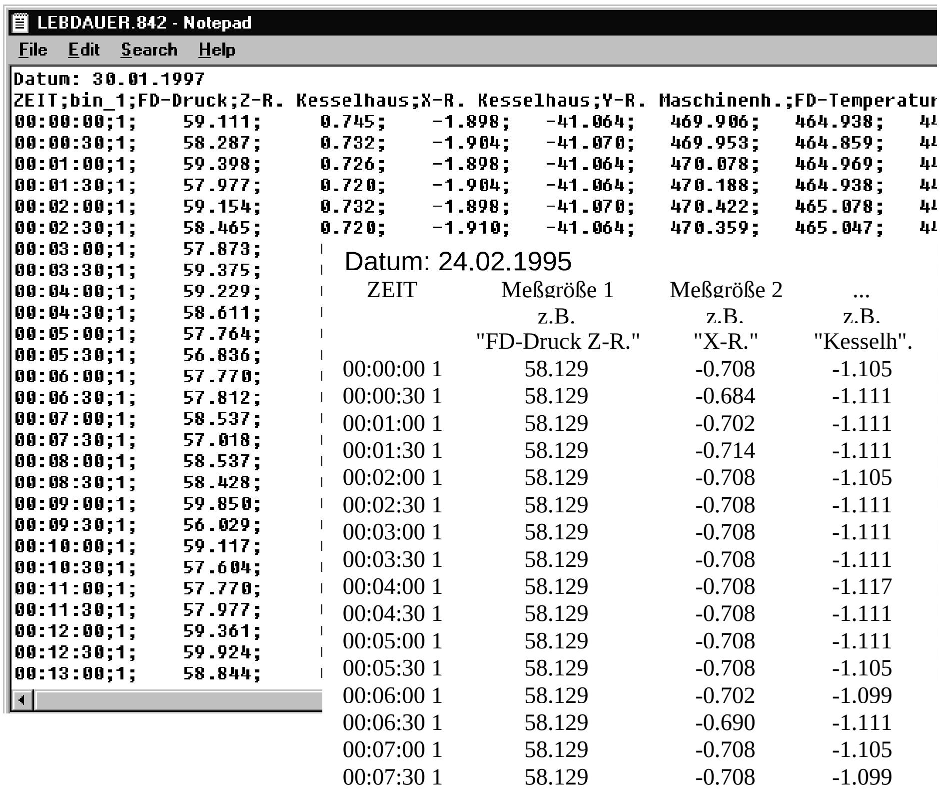
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Figure 4: Data from the monitoring system: time series of temperature, pressure, displacement and strain measurements

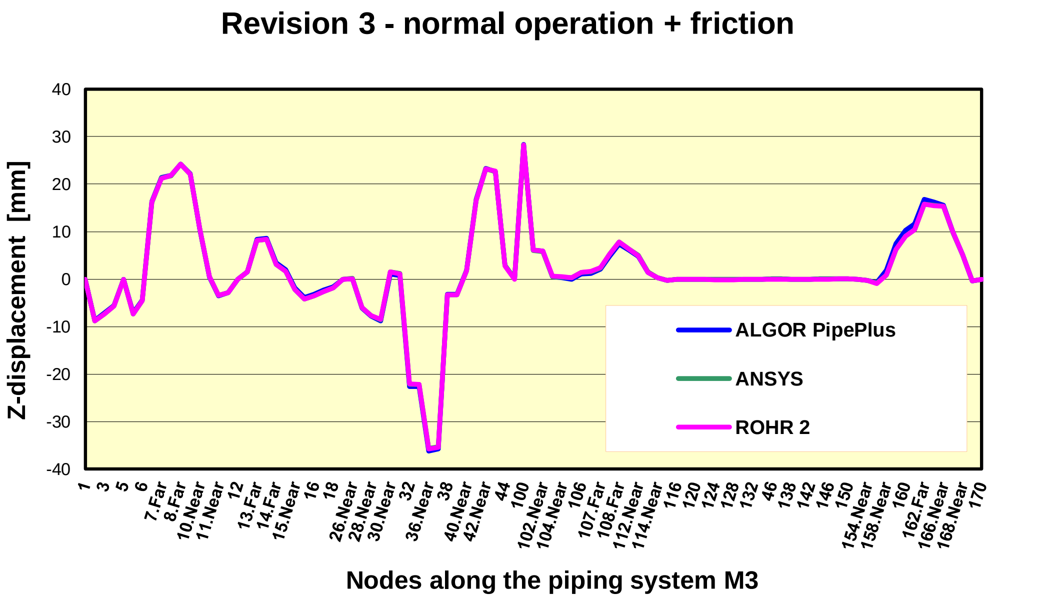

Figure 5: Displacements in z-direction as calculated by different tools for the same piping system in the selected example

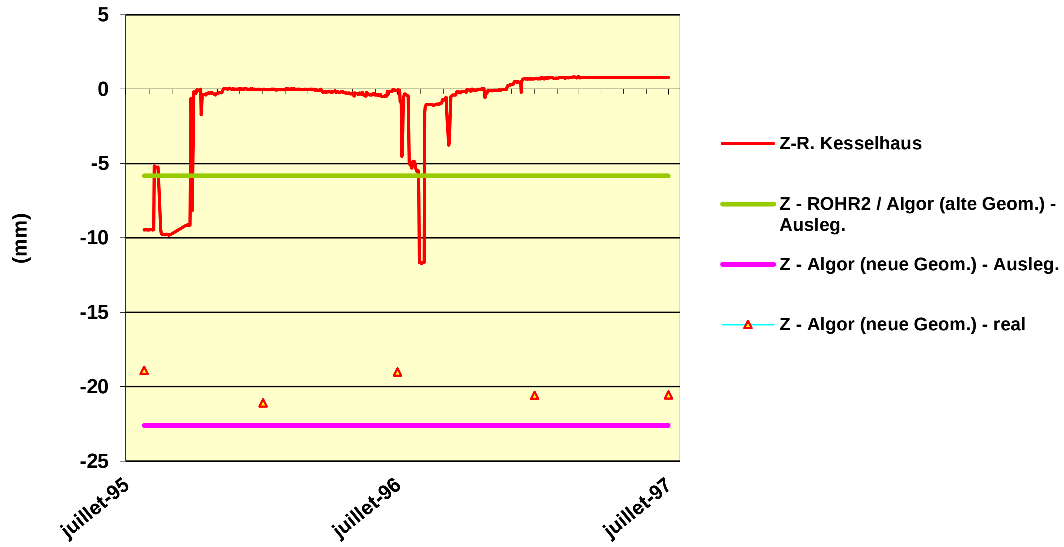

Figure 6: Displacement monitoring (monitoring in z-direction, position 32 as in Figure 8, straight lines displacements for design conditions, triangles displacements calculated for the measured operating conditions): overall result showing that measured displacements are within design limits

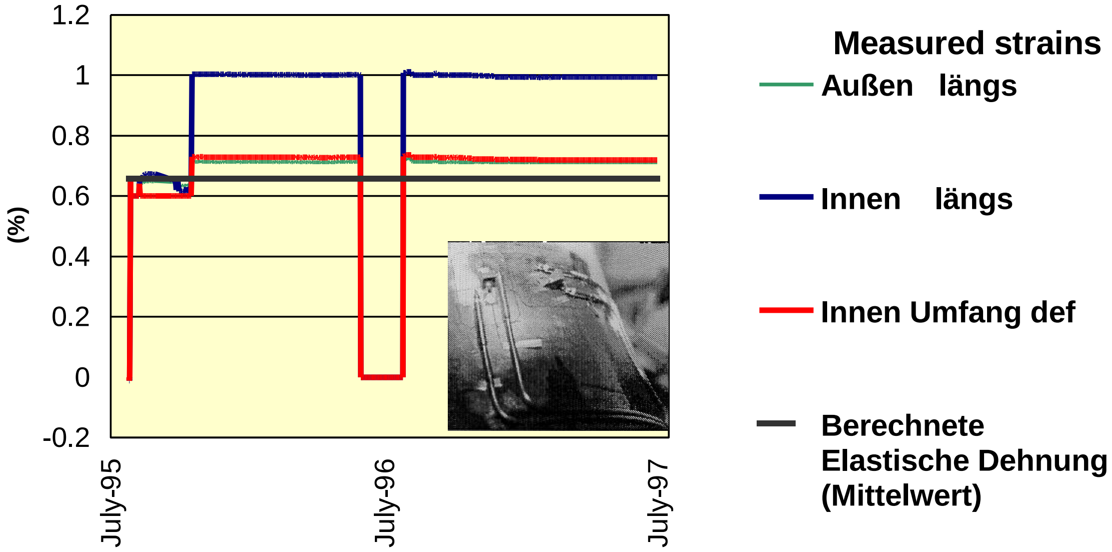

Figure 7: Measured strains using high-temperature capacitive strain gauges (position 36 in Figure 8, out- and inside, hoop, elastic strain)

Action 7: Monitoring strains

Action 8: TRD and RLA calculations performed with advanced monitoring data (displacements and strains)

Comparing the results of damage accumulation and remaining life consumption for the limited time of strain monitoring (approx. 2 years) one can see that in the given example a difference of over 100% was registered (Figure 9).

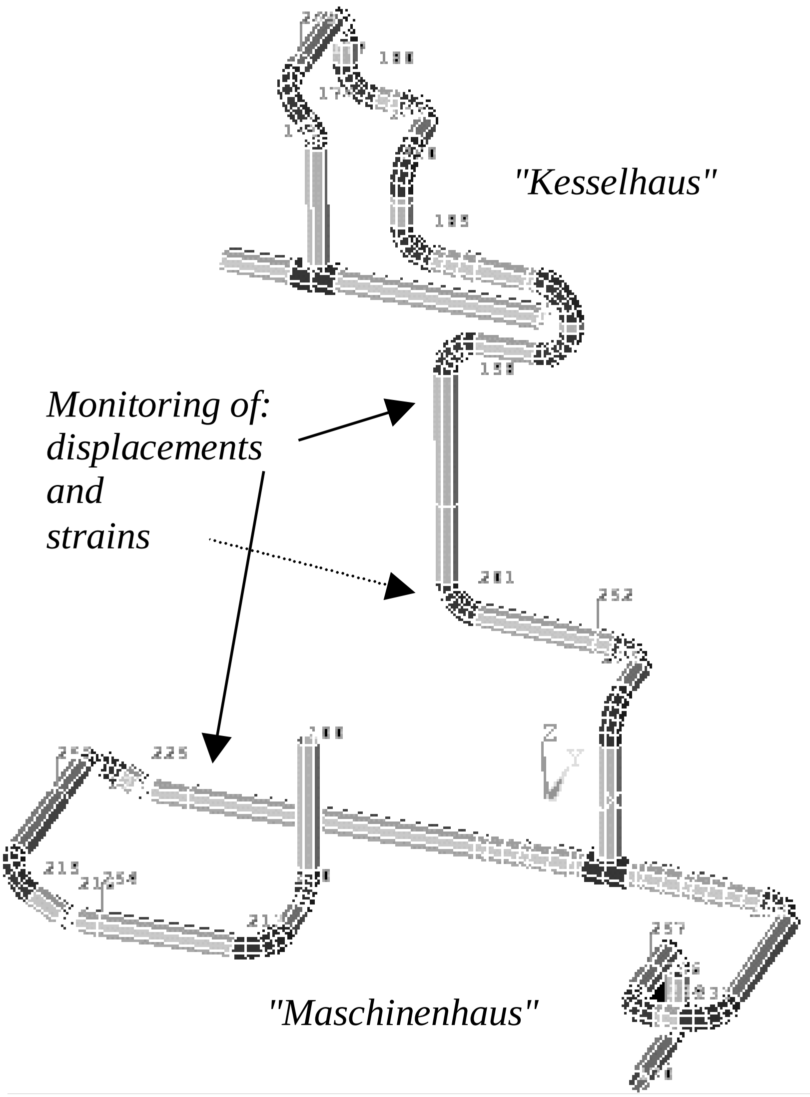

Figure 8: Positions of strain and displacement transducers on the piping (here: the finite element model used for non-linear analysis creep analysis in ANSYS)

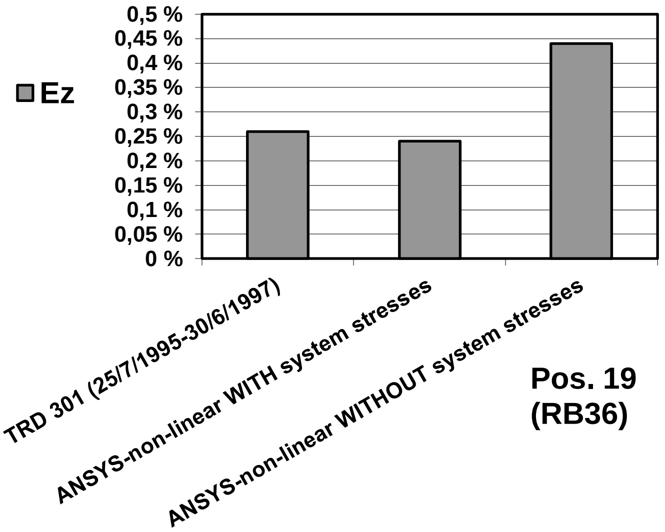

Figure 9: Influence of system stresses onto life exhaustion (Ez - creep) –according to TRD, ANSYS with and without system stresses

2.6 *Conclusions drawn from the selected application case*

1. Life monitoring is essential for the overall life management.
2. Besides the conventional monitoring based on global operational parameters, concentrated "targeted" monitoring should be made.
3. Selection of locations can be made according to experience (e. g. case histories) and results of global monitoring.
4. Monitoring of displacements and strains is essential for the better assessment of actual stress states and, consequently, life assessment.
5. Monitoring of displacements and strains can achieve its goal only if supported by powerful analysis tools, including the non-linear finite element analysis.
6. Monitoring as such just one of the elements of the comprehensive life assessment and management – only a system like ALIAS integrating parallel analyses and enabling permanent cross-checking and linking of monitoring results with other elements (e.g. NDT results and/or case histories and/or detailed off-line analyses), can assure the confidence needed: (a) that no "false alarms" are triggered, and (b) that no real damage location is overseen. Consequences of both can obviously be very serious.
7. Due to many uncertainties involved and the exponential character of the damage development processes it is essential to include risk assessment into the overall evaluation.
8. Virtually every monitoring solution is specific. It is, therefore, difficult to look for a monitoring system that would "fit all". Flexible and modular solutions are required instead (like ALIAS), provided that the corresponding configuration management is available.

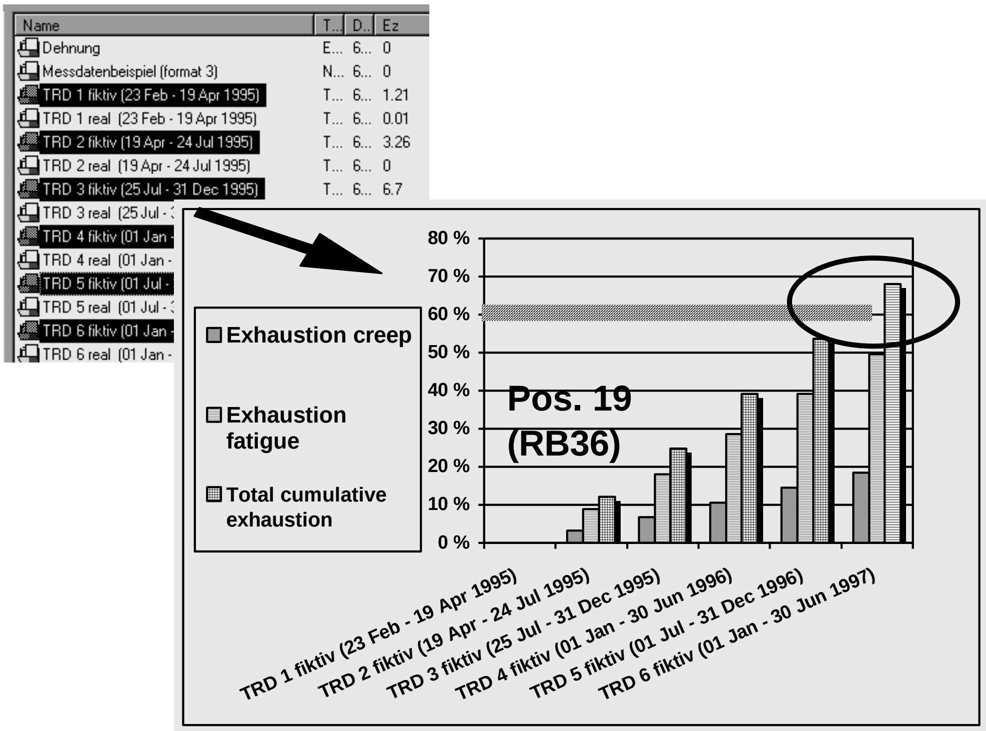

Figure 10: From monitoring data (Figure 4), over single RLA calculations, to the overview of damage development – 60% TRD-limit indicated

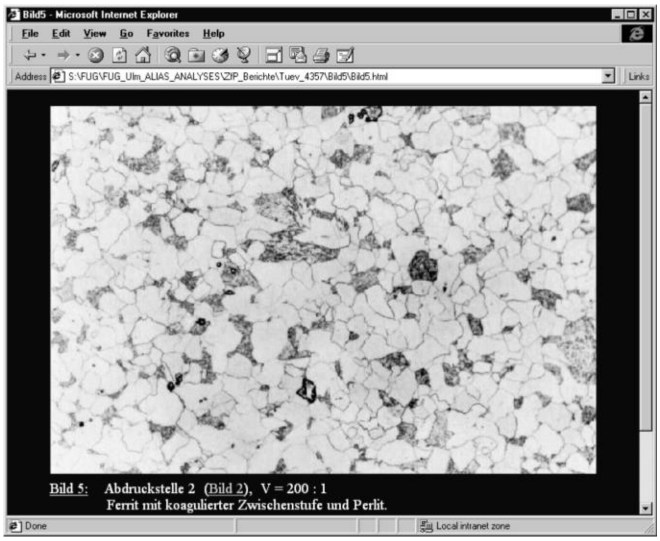

Figure 11: Linking NDT-data (replica) to RLA-calculations in ALIAS

3 Knowing the problem causes: RCFA and the Logic of Aging Damage Identification

Root Cause Failure Analysis (RCFA) is an important part of proactive maintenance strategies, Reliability Centered Maintenance procedures and Asset Integrity Management. It is a structured process which can aid in resolving problems that affect plant performance, by uncovering the causes of undesirable events. It should not be an attempt to apportion blame for the incident. This must be clearly understood by the investigating team and those involved in the process.

RCFA applies advanced investigative techniques to discover the root causes of incidents, and allows us to apply the required correctives. By applying RCFA, we can reduce or eliminate early life failures in components, extend the lifetime of equipment and minimize maintenance. A properly performed analysis should yield the following information:

- Why the incident or failure occurred
- How any future failures can be prevented by:
  - Design modifications
  - Changes to procedures
  - Changes to operating parameters
  - Training of operators/staff
  - Verification that repaired or replaced equipment is free of defects which may cause a shorter service life, which can include adherence to acceptance procedures and identification of additional factors which can adversely affect service life
  - Implementation of mitigating actions for the point above

Effective use of RCFA requires discipline and consistency. Each investigation must be thorough and each of the steps defined must be followed. The general steps for performing and documenting an RCFA based corrective action include the following:

- A definition of the problem or a description of the event to be prevented in the future. The qualitative and quantitative properties of the consequences of failure should be included. In addition, reasonable targets should be set for the action, i.e. reducing the risk of future failure to an acceptable level, as opposed to preventing all future failures.
- Gathering and preserving data related to the problem, and ordering it according to a timeline of events leading to the ultimate failure event. For every behavior, condition, action, and inaction in the timeline that deviates from regular operating parameters or procedures, it should be specified what should have been done, and how it differs from what was done.
- Identification of the causes associated with each step in the sequence towards the defined problem or event, by asking “Why” questions. In this case, "Why" means "What were the factors that directly resulted in the effect?"
- Divide the causes into factors that relate to an event in the sequence and root causes. Root causes are those, which if eliminated, can be agreed to have interrupted that step of the sequence chain.
- Identification of all other factors which can be designated as "root causes." In the case of multiple root causes, all root causes should be discovered for later optimum selection.
- Identification of the corrective action(s) that would prevent the recurrence of each harmful effect. Check whether the pre-implementation of said corrective actions would have reduced or prevented the specific harmful effects.
- Identification of solutions that would prevent recurrence of undesirable events with reasonable certainty. The proposed solutions must be within the institution's control, meet its goals and not introduce other new, unforeseen problems.
- Implementation of the recommended corrections.
- Monitoring the implemented solutions to ensure effectiveness.

A number of named analysis techniques are commonly used within RCFA, including:

- Step Method

- Fault Tree Analysis
- Cause and Effect Analysis (Fish Bone)
- Bow-tie
- Event Tree
- Interview
- Why-why

Each of the techniques has its own strengths and weaknesses, depending on the situation in which it is applied. In the following section, four of these techniques are shortly described.

3.1 *General Analysis Techniques*

According to ISO 31010, a number of analysis tools and techniques, including some RCFA techniques are listed according to their overall applicability for risk assessment. This table is provided below, with the importance of the respective techniques rated from most important (***) to least important (*). The analysis techniques belonging to RCFA are shaded in this table.

Table 2 – Applicability of tools used for risk assessment according to ISO 31010

Tools and techniques	**Risk assessment process**					**Importance**
	Risk Identification	**Risk analysis**			**Risk evaluation**	
		Consequence	**Probability**	**Level of risk**		
Brainstorming	SA 1)	NA 2)	NA	NA	NA	***
Structured or semi-structured interviews	SA	NA	NA	NA	NA	**
Delphi	SA	NA	NA	NA	NA	*
Check-lists	SA	NA	NA	NA	NA	***
Primary hazard analysis	SA	NA	NA	NA	NA	***
Hazard and operability studies (HAZOP)	SA	SA	3)	A	A	*
Hazard Analysis and Critical Control Points (HACCP)	SA	SA	NA	NA	SA	*
Environmental risk assessment	SA	SA	SA	SA	SA	*
Structure « What if? » (SWIFT)	SA	SA	SA	SA	SA	*
Scenario analysis	SA	SA	A	A	A	***
Business impact analysis	A	SA	A	A	A	***

Root cause analysis	NA	SA	SA	SA	SA	***
Failure mode effect analysis	SA	SA	SA	SA	SA	***
Fault tree analysis	A	NA	SA	A	A	***
Event tree analysis	A	SA	A	A	NA	**
Cause and consequence analysis	A	SA	SA	A	A	***
Cause-and-effect analysis	SA	SA	NA	NA	NA	**
Layer protection analysis (LOPA)	A	SA	A	A	NA	**
Decision tree	NA	SA	SA	A	A	**
Human reliability analysis	SA	SA	SA	SA	A	**
Bow tie analysis	NA	A	SA	SA	A	***
Reliability centered maintenance	SA	SA	SA	SA	SA	***
Sneak circuit analysis	A	NA	NA	NA	NA	*
Markov analysis	A	SA	NA	NA	NA	*
Monte Carlo simulation	NA	NA	NA	NA	SA	**
Bayesian statistics and Bayes Nets	NA	SA	NA	NA	SA	**
FN curves	A	SA	SA	A	SA	*
Risk indices	A	SA	SA	A	SA	***
Consequence/probability matrix	SA	SA	SA	SA	A	***
Cost/benefit analysis	A	SA	A	A	A	***
Multi-criteria decision analysis (MCDA)	A	SA	A	SA	A	***

1) Strongly applicable.
2) Not applicable.
3) Applicable.

ISO 31010 also provides a list of attributes for the above listed risk assessment tools, including the RCFA techniques. In the following table, the attributes of the RCFA-specific techniques are given:

Table 3 – Attributes of (RCFA-specific) risk assessment tools according to ISO 31010

Type of risk assessment technique	Description	Relevance of influencing factors			Can provide Quantitative output
		Resources and capability	Nature and degree of uncertainty	Complexity	
SCENARIO ANALYSIS					
Root cause analysis (single loss analysis)	A single loss that has occurred is analyzed in order to understand contributory causes and how the system or process can be improved to avoid such future losses. The analysis shall consider what controls were in place at the time the loss occurred and how controls might be improved	Medium	Low	Medium	No
Fault tree analysis	A technique which starts with the undesired event (top event) and determines all the ways in which it could occur. These are displayed graphically in a logical tree diagram. Once the fault tree has been developed, consideration should be given to ways of reducing or eliminating potential causes / sources	High	High	Medium	Yes
Event tree analysis	Using inductive reasoning to translate probabilities of different initiating events into possible outcomes	Medium	Medium	Medium	Yes
Cause/ consequence analysis	A combination of fault and event tree analysis that allows inclusion of time delays. Both causes and consequences of an initiating event are considered	High	Medium	High	Yes
Cause-and effect analysis	An effect can have a number of contributory factors which may be grouped into different categories. Contributory factors are identified often through brainstorming and displayed in a tree structure or fishbone diagram	Low	Low	Medium	No
FUNCTIONAL ANALYSIS					
FMEA and FMECA	FMEA (Failure Mode and Effect Analysis) is a technique which identifies failure modes and mechanisms, and their effects. There are several types of FMEA: Design (or product) FMEA which is used for components and products, System FMEA which is used for systems, Process FMEA which is used for manufacturing				

	and assembly processes, Service FMEA and Software FMEA. FMEA may be followed by a criticality analysis which defines the significance of each failure mode, qualitatively, semi-qualitatively, or quantitatively (FMECA). The criticality analysis may be based on the probability that the failure mode will result in system failure, or the level of risk associated with the failure mode, or a risk priority number				

In this section, four general analysis techniques are shortly presented:

- Failure Mode and Effect Analysis (FMEA)
- Fault Tree Analysis (FTA)
- Cause and Effect Analysis
- Sequence of Events Analysis

Failure Mode and Effects Analysis (FMEA) was one of the first systematic techniques for failure analysis. It was developed by reliability engineers in the 1950s to study problems that might arise from malfunctions of military systems. An FMEA is often the first step of a system reliability study. It involves reviewing as many components, assemblies, and subsystems as possible to identify failure modes, and their causes and effects. For each component, the failure modes and their resulting effects on the rest of the system are recorded in a specific FMEA worksheet. There are numerous variations of such worksheets. An FMEA is mainly a qualitative analysis.

Fault tree analysis (FTA) is a top down, deductive failure analysis in which an undesired state of a system is analyzed using Boolean logic to combine a series of lower-level events. This analysis method is mainly used in the fields of safety engineering and reliability engineering to understand how systems can fail, to identify the best ways to reduce risk or to determine (or get a feeling for) event rates of a safety accident or a particular system level (functional) failure. FTA is used in the aerospace, nuclear power, chemical and process, pharmaceutical, petrochemical and other high-hazard industries; but is also used in fields as diverse as risk factor identification relating to social service system failure.

Cause-and-effect analysis is a graphical approach to failure analysis. This also is referred to as fishbone analysis, a name derived from the fish-shaped pattern used to plot the relationship between various factors that contribute to a specific event. Typically, fishbone analysis plots four major classifications of potential causes (i.e. human, machine, material, and method) but can include any combination of categories.

Sequence of events analysis uses a sequence of events diagram (Figure 14) from the start of an investigation and helps the investigator organize the information collected, identify missing or conflicting information, improve his or her understanding by showing the relationship between events and the incident, and highlight potential causes of the incident.

3.1.1 *Failure Mode and Effects Analysis (FMEA)*

A failure mode and effects analysis (FMEA) is a design-evaluation procedure used to identify potential failure modes and determine the effect of each on system performance. This procedure formally documents standard practice, generates a historical record, and serves as a basis for future improvements. The FMEA procedure is a sequence of logical steps, starting with the analysis of lower-level subsystems or components.

Main steps in FMEA are:

1. Identification of failure modes
2. Isolate failure cases
3. Predict failure effects
4. Determine corrective actions
5. Optimize the corrective action decision based on other factors (technical feasibility)

6. Select one of the options:
    a. Eliminate failure effects
    b. Reduce failure effects
    c. Accept failure effects

Some of the advantages that FMEA provides are:

- Improving the quality, reliability and safety of a product/process
- Improving company image and competitiveness
- Reducing system development time and cost
- Collecting information to reduce future failures, capturing engineering knowledge
- Early identification and elimination of potential failure modes
- Reducing the possibility of same kind of failure in future
- Reducing impact on company profit margin

While FMEA identifies important hazards in a system, its results may not be comprehensive and the approach has limitations. If used as a top-down tool, FMEA may only identify major failure modes in a system. Fault tree analysis (FTA) is better suited for "top-down" analysis. When used as a "bottom-up" tool FMEA can augment or complement FTA and identify many more causes and failure modes resulting in top-level symptoms. It is not able to discover complex failure modes involving multiple failures within a subsystem, or to report expected failure intervals of particular failure modes up to the upper level subsystem or system.

Additionally, the multiplication of the severity, occurrence and detection rankings may result in rank reversals, where a less serious failure mode receives a higher Risk Priority Number than a more serious failure mode. The reason for this is that the rankings are ordinal scale numbers, and multiplication is not defined for ordinal numbers. The ordinal rankings only say that one ranking is better or worse than another, but not by how much. For instance, a ranking of "2" may not be twice as severe as a ranking of "1," or an "8" may not be twice as severe as a "4," but multiplication treats them as though they are.

3.1.2 *Fault-Tree Analysis*

Fault-tree analysis is a method of analyzing system reliability and safety. It provides an objective basis for analyzing system design, justifying system changes, performing trade-off studies, analyzing common failure modes, and demonstrating compliance with safety and environment requirements. It is different from a failure mode and effect analysis in that it is restricted to identifying system elements and events that lead to one particular undesired event. FTA is a deductive, top-down method aimed at analyzing the effects of initiating faults and events on a complex system. This contrasts with failure mode and effects analysis (FMEA), which is an inductive, bottom-up analysis method aimed at analyzing the effects of single component or function failures on equipment or subsystems.

This technique is often combined with building of consequence tree on the other side, thus allowing the creation of **"bow-tie" model** (Figure 12), where an adverse event is put in the middle.

Some of the advantages/disadvantages of FTA are given below:

- FTA is very good at showing how resistant a system is to single or multiple initiating faults.
- FTA considers external events, FMEA does not.
- FTA is not good at finding all possible initiating faults. FMEA is good at exhaustively cataloging initiating faults, and identifying their local effects.
- FTA is not good at examining multiple failures or their effects at a system level.

3.1.3 *Cause-and-Effect Analysis*

Ishikawa diagrams (also called fishbone diagrams, herringbone diagrams, cause-and-effect diagrams) are causal diagrams created by Kaoru Ishikawa (1968) that show the causes of a specific event. Causes are usually grouped into major categories to identify the sources of variation. The categories typically include:

- People: Anyone involved with the process
- Methods: How the process is performed and the specific requirements for doing it, such as policies, procedures, rules, regulations and laws

- Machines: Any equipment, computers, tools, etc. required to accomplish the job
- Materials: Raw materials, parts, pens, paper, etc. used to produce the final product
- Measurements: Data generated from the process that are used to evaluate its quality
- Environment: The conditions, such as location, time, temperature, and culture in which the process operates

The advantages and disadvantages of this type of analysis are given below:

This technique of diagramming the potential causes of a specific event provides the structure and order needed to quickly and methodically resolve problems.

This approach has one serious limitation. The fishbone graph (Figure 13) provides no clear sequence of events that leads to failure. Instead, it displays all the possible causes that may have contributed to the event. However, it does not isolate the specific factors that caused the event.

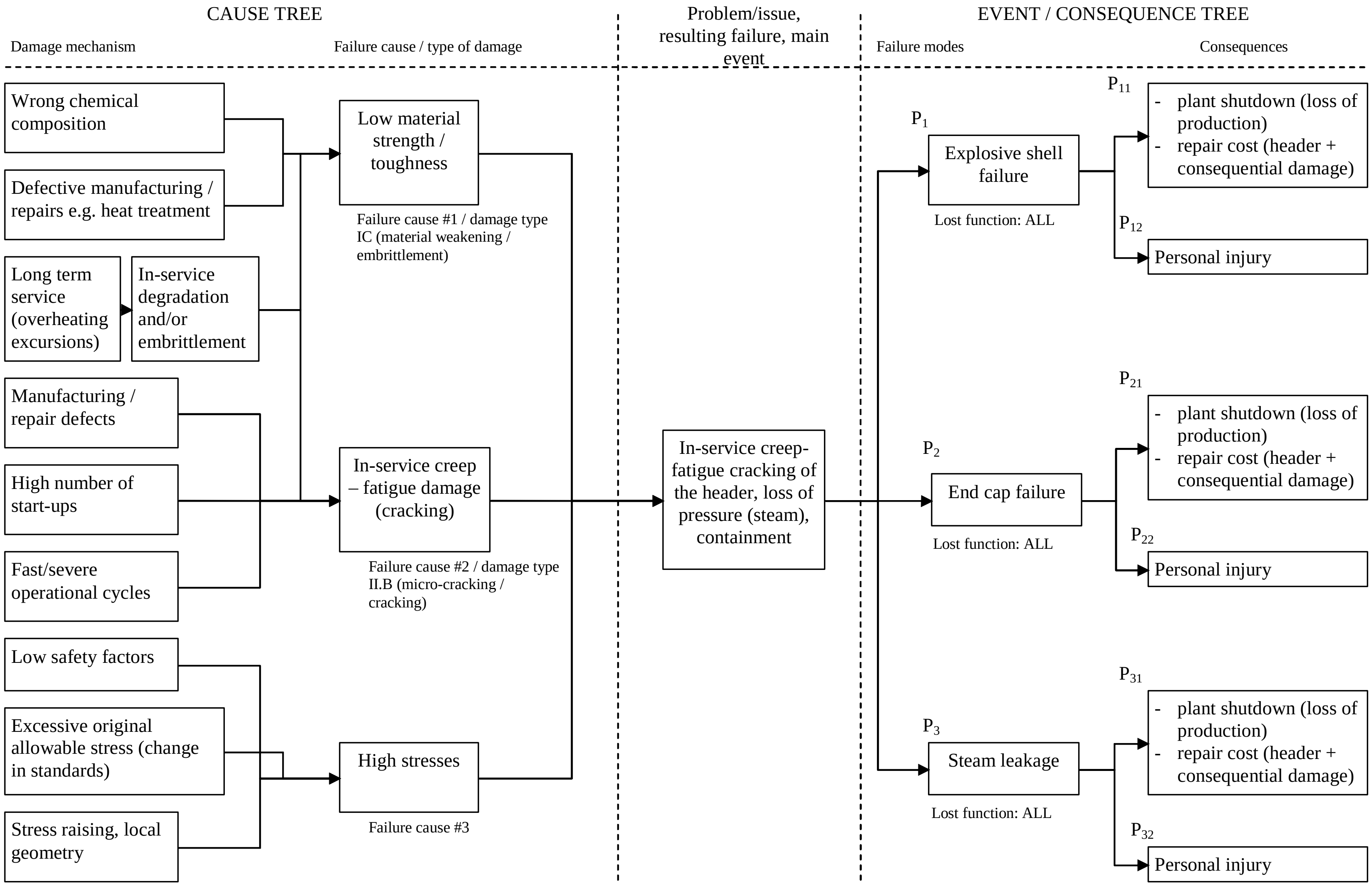

Figure 12: Bow-Tie model

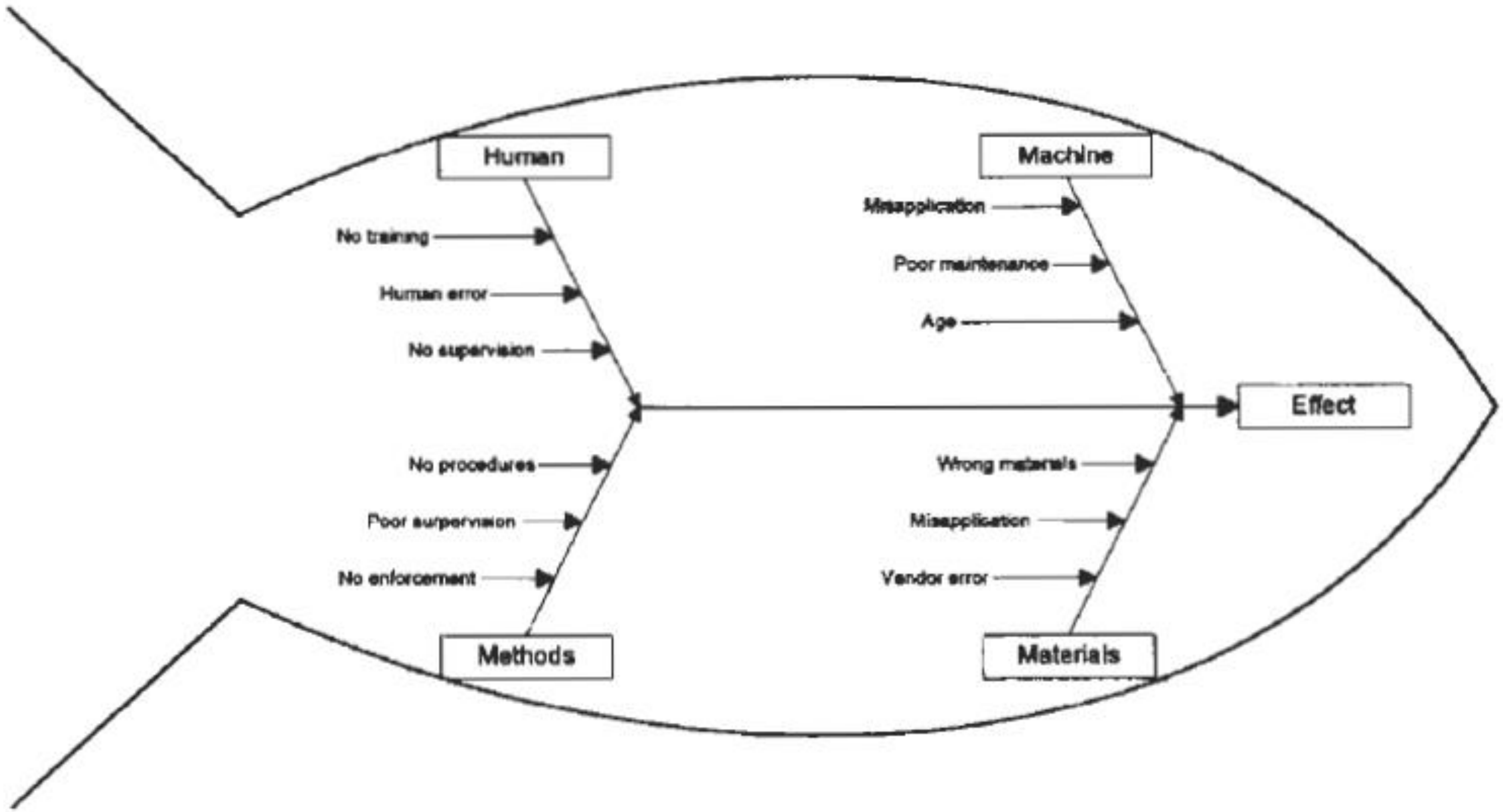

Figure 13: Fishbone diagram

3.1.4 *SEQUENCE-OF-EVENTS ANALYSIS*

Sequence of events analysis is useful for:

- straightforward problems that have a known sequence of events leading to the failure event.
- complex problems where combinations of root causes exist and the approach is to determine which cause(s) must be eliminated to break the chain.
- establishing timelines and identifying which events require some other analysis tool such as a logic tree.

It requires an understanding of what is controllable, and the resulting outcome of the control, action, or response.

In the case of occurrence of an adverse event, the following steps have to be taken:

1. Identify WHAT happened – clearly define the specific event, failure or incident, interview/talk to all personnel directly or indirectly involved in the incident
2. Identify WHERE it did happen – the specific machine, location, system, and try to find out whether such an event has already occurred in the past on the same or similar unit in the plant/company
3. Identify WHEN it did happen – the time and sequence of the events that were bound to the event (before AND after)
4. Identify WHAT CHANGED – whether there was any change in the process, product, procedures, etc.
5. WHO was involved – directly linked to the point 1
6. What is the IMPACT – quantify the damage, injuries, fatalities, reliability, financial
7. Will it happen AGAIN – Determine the probability of recurrence of the similar event
8. Can the recurrence be PREVENTED – determine if the measures exist that might prevent the event from happening again in the future; alternatively try to investigate if the effects might be eliminated or kept under control

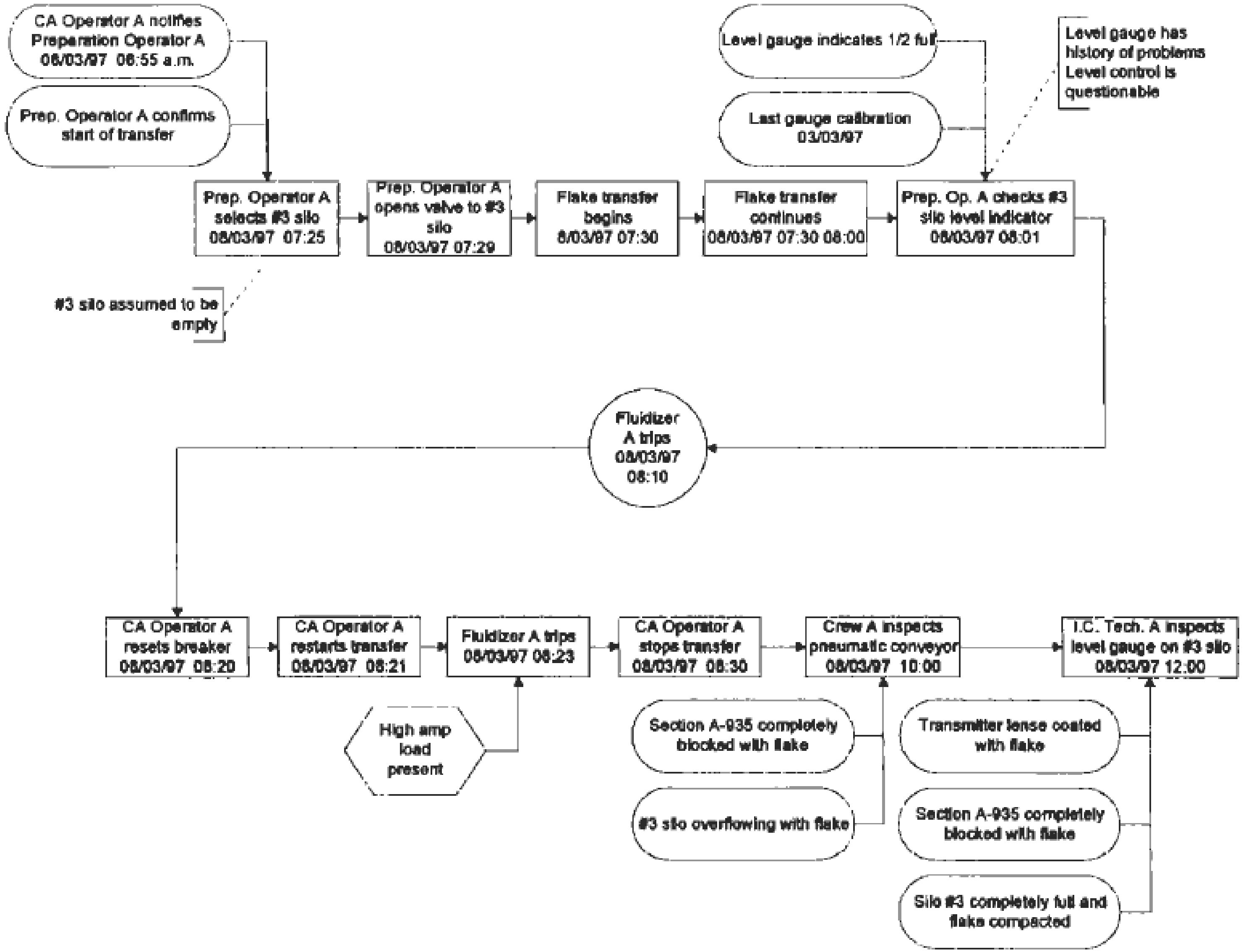

Figure 14: Sequence of events diagram

3.1.5 *Common causes of failures*

The table below gives a list of some typical causes of failures. Some of the information in this table can be used during the construction of a cause and effect diagram.

Table 4: Common causes of failures

<table>
<tr>
<td>1. External causes
a. Earthquake
b. Harsh weather
c. Terrorist attack
d. Incident staring outside the plant/unit boundary
e. Other environmental influences</td>
<td rowspan="2">2. Equipment failure
a. Misapplication
• Operation outside design condition
• Poor design practices
• Poor procurement practices
b. Operating practices
• Procedures inadequate
• No adherence to procedures
• Inadequate training
• No enforcement
c. Maintenance practices
• Procedures inadequate
• No adherence to procedures
• Frequency inadequate
• Lack of skills
d. Age
• Normal wear
• Reached useful life
• Accelerated wear</td>
</tr>
<tr>
<td>3. Procedures
a. Not used
• No procedure
• Difficult to use
• Not available
• Not enforced
b. Inadequate
• Facts or methods wrong
• Poor organization
• Wrong revision used
• Situation not covered
c. Followed incorrectly
• Format confusing
• Excessive references
• Too technical</td>
</tr>
<tr>
<td>4. Training
a. No training
• Task not analyzed
• Decided not to train
• No learning objective
• Training not enforced
b. Inadequate
• No learning objectives
• No lesson plan
• Poor instruction
• No practical application
c. Not learned
• Retention lacking
• Too technical
• Did not attend the course
• Mastery not verified</td>
<td>5. Supervision
a. Preparation
• No preparation
• No work packages
• Lack of pre-job training
• Inadequate scheduling
b. Selection of workers
• Not qualified
• Fatigued
• Upset/personal problems
• Substance abuse
• Poor team selection
c. Supervision during work
• No supervision
• Poor crew teamwork
• Too many other duties</td>
</tr>
<tr>
<td>6. Communication
a. No communication
• No method available
• Late communication</td>
<td>7. Human engineering
a. Worker interface
• Arrangement/ placement
• Excessive lifting/twisting</td>
</tr>
</table>

• Lack of report format b. Turnover • No standard process • Turnover process not used • Turnover process inadequate c. Misunderstanding • No standard terms • Repeat back not used • Long messages • Noisy environment	• Tool/instruments • Controls/displays b. Work environment • Housekeeping • Ambient environment • Cramped spaces c. Complex systems • Knowledge-based decisions required • Monitoring too many parameters • Inadequate feedback
8. Management system a. Policies and procedures • No standards • Not strict enough • Confusing or incomplete • Technical errors • No drawings or prints b. Standards not used • No communication • Recently changed • No enforcement • No way to implement • No accountability c. Employee relations • No audits/evaluations • Lack of audit depth • No employee communication • No employee feedback	9. Quality Control a. No inspection • No inspection required • No hold point • Hold point ignored b. Inadequate quality control • Poor instructions • Poor techniques • Inadequate training/skills

3.2 *RC(F)A Decision making*

In most of the cases the equipment failures might be the result of any combination of the factors listed above.

Some of the issues are to be solved on the higher/managerial levels, such as environmental/external, managerial or human related. Nevertheless, the appropriate source of the problem should be identified and recommendations given.

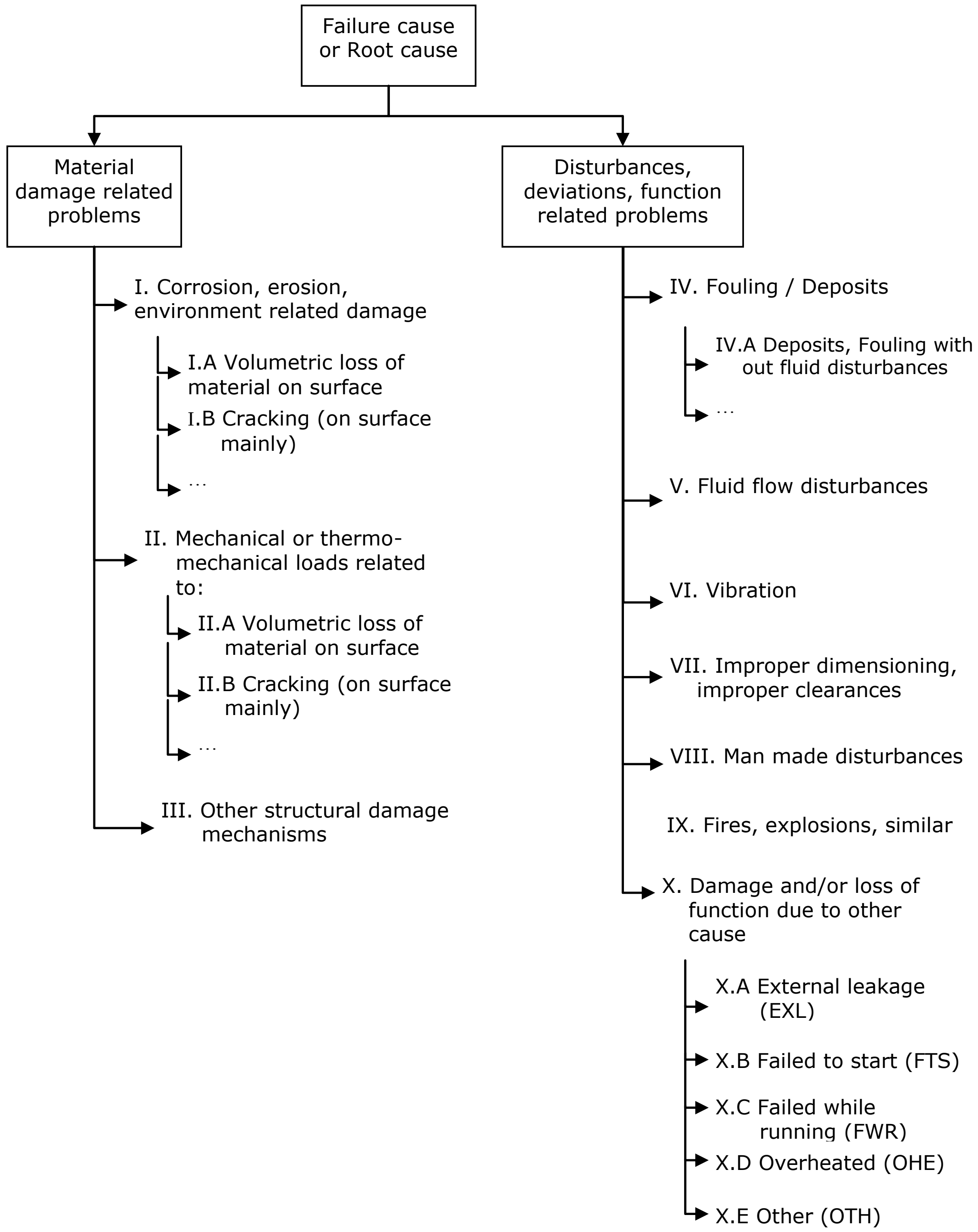

Figure 15: Damage types appearing as failure or root failure causes in RIMAP

For the technical/equipment related issues, it is important to perform the maintenance strategy decision making process, illustrated in Figure 16 below:

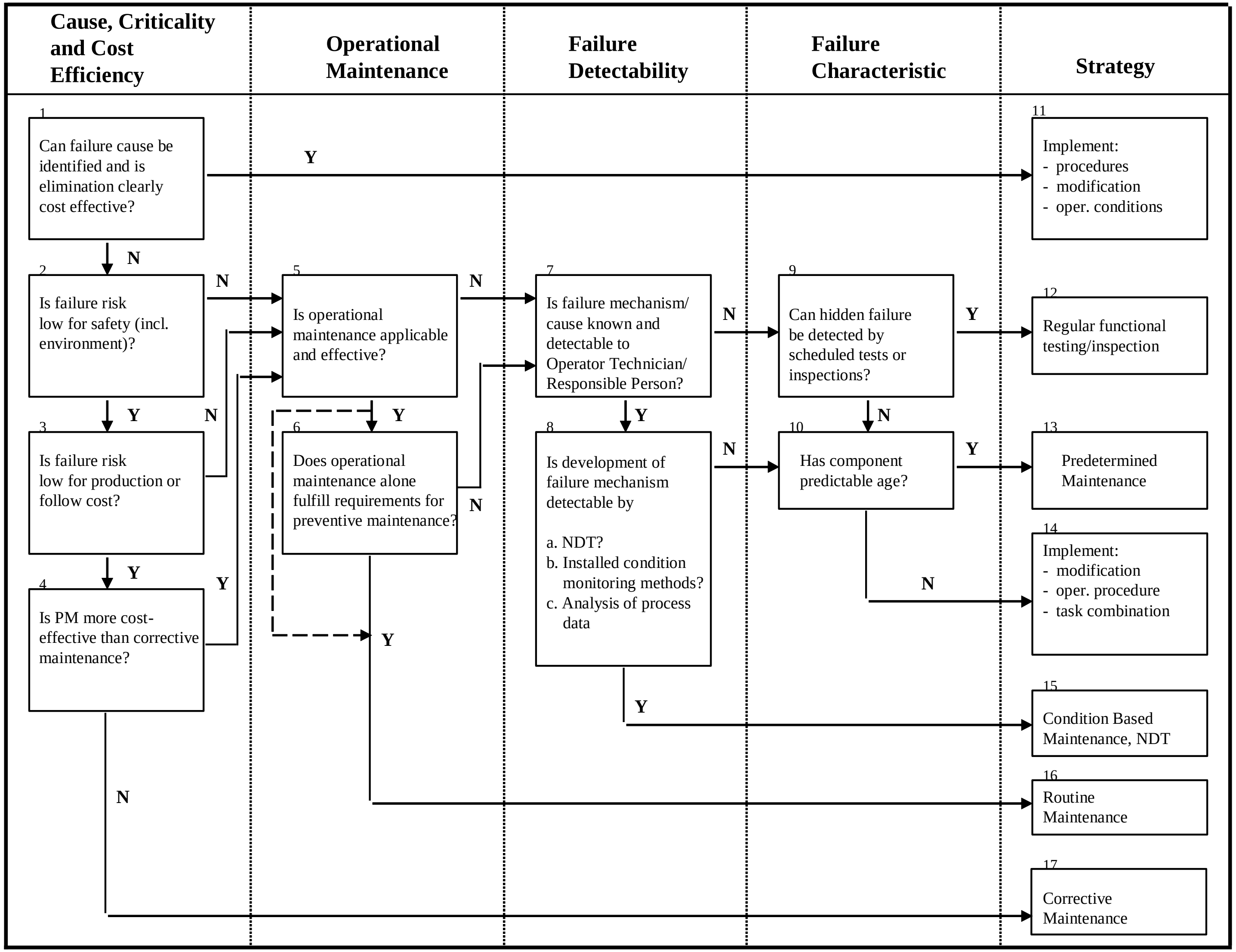

Figure 16: Maintenance strategy decision making

3.3 *Logic of aging damage identification*

This chapter considers the systematics, detection and analysis of damage in power plant systems and components subject to RBI/RBLM analysis. The chapter is adapted from the RIMAP Application Workbook for Power Plants and references to the CEN CWA 15740 Guideline provided in this deliverable, in Annex 2.

The consideration of damage follows the flowchart shown in Figure 17.

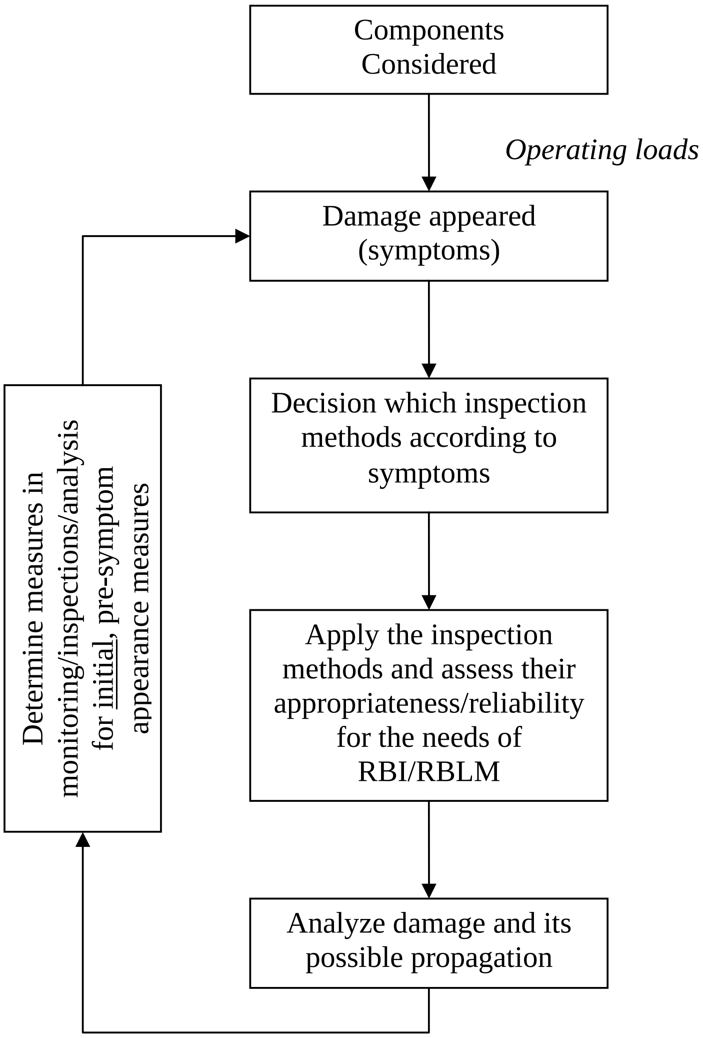

Figure 17: Possible way of considering damage

3.3.1 *Damage systematics*

Based on the different damage mechanisms considered in the approaches of others (e.g. VDI, API) a new approach was proposed in RIMAP. The damage systematics in RIMAP are shown in Table 5.

Table 5 - Types of damage and their specifics mechanisms

What **type of damage**		***How*** **to look for it**		***Measure of uncertainty/risk for selected/preferred method*[1]**				
Identifier and Type of damage	Damage specifics, damage mechanism	best POD[2]	most cost effective	selected method	POD for defect size of or size for			FCP[6]; comments, examples
					1 mm	3 mm	90% POD	
I. Corrosion/erosion/environment related damage, equating or leading to:								
I.A Volumetric loss of material on surface (e.g. thinning)	I.A1 General corrosion, oxidation, erosion, wear solid particle erosion	DiM, VT, ET, UT[3]	UT, (VT), DiM	UT	30÷70%	50÷90%	2 mm	
	I.A2 Localized (pitting, crevice or galvanic) corrosion	UT, DiM, ET	VT, UT	UT	30÷70%	40÷90%	2 mm	see [4]
I.B Cracking (on surface, mainly)	I.B1 Stress corrosion (chloride, caustic, etc.)	MT, PT, ET	MT, PT, ET	ET	max 85%	40÷90%	4±2 mm	<5% [5]
	I.B2 Hydrogen induced damage (incl. blistering and HT hydrogen attack)	UT, MT, PT, ET	MT, PT[6], MT[7]	UT	na	na	na	na
	I.B3 Corrosion fatigue	MT, PT, ET, VT	MT, PT, UT	UT	80÷96%[8] 86÷98%[9]	50÷99%[12],[10] 95÷99%,[14]	3±1 mm[12,11] 0.8±0.4 mm,[12]	
I.C Material weakening and/or embrittlement	I.C1 Thermal degradation (spheroidization, graphitization, etc. incl. incipient melting)	MeT	MeT	MeT	(microscopy) ~100% POD for cracks > 1 mm, 90% POD crack ca. 0.05 mm; main "reliability related problems" linked to wrong sampling, wrong preparation and wrong interpretation of replicas (all numbers are very rough "guesstimates")			
	I.C2 Carburization, decarburization, dealloying	MeT	MeT	MeT				

[1] if not mentioned otherwise all based on re-assessment of data [27]
[2] see Abbreviations in the main list of abbreviations
[3] AE - acoustic emission; PT - penetrant testing; DiM - dimensional measurements; VbM - vibration monitoring; DsM – on-line displacement monitoring; StM - on-line strain monitoring; VT - visual testing; ET – Eddy current testing; UT- ultrasonic testing; VTE - visual testing by endoscope; MeT - metallography, including RpT (replica technique); MST - material sample testing; na - not applicable
[4] the estimate can be affected significantly by local effects (e. g. small-scale pits can remain completely undetected)
[5] ET for non-ferromagnetic materials, sample results in [27]
[6] surface, also
[7] subsurface
[8] crack length
[9] crack depth
[10] for welds as low as 20%
[11] usually more than 5 mm for welds or steels
[12] can be more than 5 mm for welds

What **type of damage**		***How*** **to look for it**		***Measure of uncertainty/risk for selected/preferred method[1]***				
Identifier and Type of damage	Damage specifics, damage mechanism	best POD[2]	most cost effective	selected method	POD for defect size of or size for			FCP[6]; comments, examples
					1 mm	3 mm	90% POD	
	I.C3 Embrittlement (incl. hardening, strain aging, temper embrittlement, liquid metal embrittlement, etc.)	MST	MST	MST	na	na	na	
II. Mechanical or thermomechanical loads related, leading to:								
II.A Wear	II.A1 Sliding wear	VT, DiM, ET	VT, UT					
	II.A2 Cavitational wear							
II.B Strain / dimensional changes / instability / collapse	II.B1 Overloading, creep,	DiM	DiM	DiM	na	na	na	required resolution ≤ 0.1 mm or 0.5 %
	II.B2 Handling damage							
II.C Microvoid formation	II.C1 Creep	MeT	(UT), MeT					
	II.C2 Creep-fatigue							
II.D Microcracking, cracking	II.D1 Fatigue (HCF, LCF), thermal fatigue, (corrosion fatigue)	UT, (MT/PT), ET, VT	MT/PT	PT	max 90%	20÷90%	1.5÷6.5 mm [13]	
	II.D2 thermal shock, creep, creep-fatigue			MT	5÷90%	50÷90%	2.5÷10 mm [14]	
II.E Fracture	II.E1 Overloading	VT, DiM	VT	VT	na	na	na	analysis of causes
	II.E2 Brittle fracture							

[13] typical range; in extreme cases 0.5÷12 mm or more; more uncertainties for welds – but cracks transverse to welds detected easier than the longitudinal ones
[14] typical range; in extreme cases 1÷18 mm or more; applicable for ferromagnetic materials (steels)

3.3.2 *WHERE to look for (inspect / monitor) for which type of damage*

Generally, types of damage defined RIMAP can be found on a very large number of places in a plant depending on its construction, applied materials, operating conditions, etc. For the purpose of a general overview, data on typical locations in different types of plants are given in Table 6.

Table 6: Classification of type of damage vs. systems/components in different types of plants (FPP – fossil power plants, NPP – nuclear power plants, PrP – process plants; weld critical in all components)

Type of damage			**Where to look for it (typical sample components/materials)**			
Iden-tifier	**Type of damage**	**Damage specifics, damage mechanism**	**FPP - steam turbine**	**FPP - gas turbine**	**NPP**	**PrP**
I. Corrosion/erosion/environment related damage, equating or leading to:						
I.A1	Volumetric loss of material on surface (e.g. thinning)	General corrosion, oxidation, erosion, wear solid particle erosion	boiler and superheater tubing, LP blading, and shaft pumps, valves	blading, com-pressor, combustor	pump casings, LP turbine casings, condensers, and shaft	Heat exchangers, pipes, bends, pumps, reactor vessels
I.A2		Localized (pitting, crevice or galvanic) corrosion	Boiler tubing, heat exchangers, condensers, LP-blades, IP-/ LP-shaft	blading	Heat exchangers, steam generators	Heat exchangers, reactor vessels, pipes
I.B1	Cracking (on surface, mainly)	Stress corrosion (chloride, caustic, etc.)	steam drums, LP turbines (disks, blade attachments and blades), bolts		stainless piping, LP turbines (disks, blade attachments and blades), bolts	stainless piping, reactor vessels
I.B2		Hydrogen induced damage (incl. blistering and HT hydrogen attack)	waterwalls		pressurizer	crackers, columns, reformers
I.B3		Corrosion fatigue	waterwalls, drums, dissimilar welds, LP-blading	blading	nozzles, safe-end, sleeves, LP-blading	dissimilar welds
I.C1	Material weakening and/or embrittlement	Thermal degradation (spheroidization, graphitization, etc. incl. incipient melting)	superheaters, hot headers, steam lines, casings, bolts	combustors, hot blading, transition ducts		heat exchangers, reformers, crackers, pipes, reactor vessels

Type of damage			**Where to look for it (typical sample components/materials)**			
Iden-tifier	**Type of damage**	**Damage specifics, damage mechanism**	**FPP - steam turbine**	**FPP - gas turbine**	**NPP**	**PrP**
I.C2		Carburization, decarburization, dealloying				reformers, crackers
I.C3		Embrittlement (incl. hardening, strain aging, temper embrittlement, liquid metal embrittlement, etc.)	forgings, bolts, shafts	disks, cladding	reactor pressure vessel	forgings, hot vessels and piping
II. Mechanical or thermomechanical loads related, leading to:						
II.A	Wear	Sliding wear, cavitational wear	pumps, valves, con-densers, sealing, blading, bearings	blade tips, seals, duct connections	pumps, valves, condensers, bearings	pumps, valves, condensers
II.B	Strain / dimensional changes	Overloading, creep, handling damage	hot steam lines, piping, T-Y pieces, bored rotors, casings (casing joint plane)	blading	fuel rod cladding	hot piping, nozzles, T-Y pieces
II.C	Microvoid formation	Creep, creep-fatigue	hot steam lines (all, incl. welding), headers, bored rotors,	hot blading, combustors, transition ducts		hot piping, reformer tubes, reactor vessels
II.D	Microcracking, cracking	Fatigue (HCF, LCF), thermal fatigue, (corrosion fatigue), thermal shock, creep, creep-fatigue	rotors, bolts, welds in heavy-section pipes, valve internals, turbine shaft and blading, casings	disks, blading, combustors, burner rings	thermal sleeves, safe-end. valve internals, valves, turbine shafts and casings	rotating ma-chinery
II.E	Fracture	Overloading, brittle fracture, foreign object damage	rotors, retaining rings, blading, superheater tubes, gears, disks	blading (foreign-object damage), gears	rotors, disks	vessel failures, pipe bursts, reformer tubes

3.3.3 *HOW to look for (inspect / monitor) for which type of damage*

For the decision which method to apply and for inspection and what kind of result with witch level of confidence can be expected, the data in Table 13 (CEN CWA 15740) can be used.

For early discovery of damage, or decision making on where to look for possible damage Table 7 can be used.

Table 7: Suggested measures for pre-symptom appearance measures leading to early discovery of damage in plants

Indicators coming from:	Typical (specific) indicators:	Suggested approach to monitoring	Suggested approach to intermittent inspections	Suggested approach to engineering analysis
Manufacturing, assembly and quality control (e.g. acceptance records)	deviations from specifications regarding design / dimensions		review of design and QC documents	consider additional engineering analysis
	deviations from specifications regarding integrity (e.g. broken parts), excessive defects		review QC documents	consider additional engineering analysis
	deviations from specifications regarding materials (e.g. incorrect or defective material)		review design and QC documents chemical analysis	
	other deviations from specifications regarding		review design and QC documents	
Operation / condition monitoring	temperature: too high / too low, too high/low rate of increase/decrease	consider additional monitoring measures	consider additional inspections	consider additional engineering analysis
	pressure/loading: too high, too high/low rate of increase/decrease	consider additional monitoring measures	consider additional inspections	consider additional engineering analysis
	vibrations: too high amplitude, noise, other abnormal states	consider additional monitoring measures		consider additional engineering analysis
	flow: leakage, blockage, slagging, etc.	consider additional monitoring measures	consider additional inspections	
	other operational alarms	consider additional monitoring measures	consider additional inspections	consider additional engineering analysis

3.3.4 *How to analyze and predict development of given types of damage*

Once when a given type of damage has been detected and/or supposed, the analysis of the damage consists of:

- Quantification
- Component life consumption (remaining and consumed life), and
- Damage propagation

For the purpose of RBI/RBLM it is desirable that this analysis is done in a probabilistic way. The methods suggested for the damage types are given in Table 8.

Table 8: Suggested methods for the analysis depending on damage types

Iden-tifier	Type of damage	Damage specifics, damage mechanism	Methods of analysis, prediction	Precision of life assessment/prediction, comments
I. Corrosion/erosion/environment related damage, equating or leading to:				
I.A1	Volumetric loss of material on surface (e.g. thinning)	General corrosion, erosion, wear	*GB, CoB, CbC*	*very low, guideline based solutions often very conservative, prediction considered very satisfactory when in range minus 50%÷ plus 100%, often worse results*
I.A2		Pitting	*GB, CbC*	
I.A3		Localized (crevice, galvanic)	*CbC*	
I.B1	Cracking (on surface, mainly)	Stress corrosion	*DA, CbC*	
I.B2		Hydrogen induced (incl. blistering)	*GB*	
I.B3		Corrosion fatigue	*DA, CbC*	
I.C1	Material weakening and/or embrittlement	Thermal degradation (spheroidization, graphitization, etc. incl. incipient melting)	*MetC, RP*	*very low, guidelines and recommendations available only for testing and, partly, interpretation, predictions more qualitative than quantitative*
I.C2		carburization, decarburization, dealloying	*MetC*	
I.C3		embrittlement (incl. hardening, strain aging, temper embrittlement, etc.)	*DA, CbC*	
II. Mechanical or thermomechanical loads related, leading to:				
II.A	Mechanical wear	sliding wear, cavitational wear	CbC	as for I.C
II.B	Strain / dimensional changes	overloading, creep	St, CoB, CbC	*low, guideline/code based solutions often very conservative, prediction considered very satisfactory when in range minus 15%÷ plus 30%, often worse results, depending on e.g. temperature range and material properties*

Iden-tifier	Type of damage	Damage specifics, damage mechanism	Methods of analysis, prediction	Precision of life assessment/prediction, comments
II.C	Microvoid formation	creep, creep-fatigue	RP, AP, CD, HD, CoB, MTh, XYZ, MetC	*low, guideline/code based solutions often very conservative, prediction considered very satisfactory when in range minus 15%÷ plus 30%, often worse results, depending on e.g. temperature range and material properties*
II.D	Cracking	fatigue (HCF, LCF), thermal fatigue, (corrosion fatigue), thermal shock, creep	DA, CoB, CbC	as for II.A, worse for complex loading mechanisms and (often) poorly known material properties
II.E	Fracture	Overloading, brittle fracture	CoB, DA, CbC	

AP – A-Parameter
CD - Cavity-Density
CoB - Code based (e.g. TRD)
CbC - case-by-case

DA – Defect assessment
HD - Hardness based
MTh - Magnetite thickness
MstC - based on metallographic classification/characterization

RP - Replica class based
St - Strain-based analysis
XYZ - other
GB – guideline-based (e.g. EPRI, VGB, Nordtest)

4 Managing aging by reliability and risk-based methods: RCM and RBI

Maintenance strategies and concepts have evolved over the decades, as knowledge is increased and technologies advance (Figure 18). The perception of the "right" type of maintenance action has significantly changed over the previous decades. In the 1950s most maintenance actions were Event-based – the maintenance actions were of a corrective nature, when equipment and machinery broke down. Maintenance was viewed as an unavoidable cost which could not be managed.

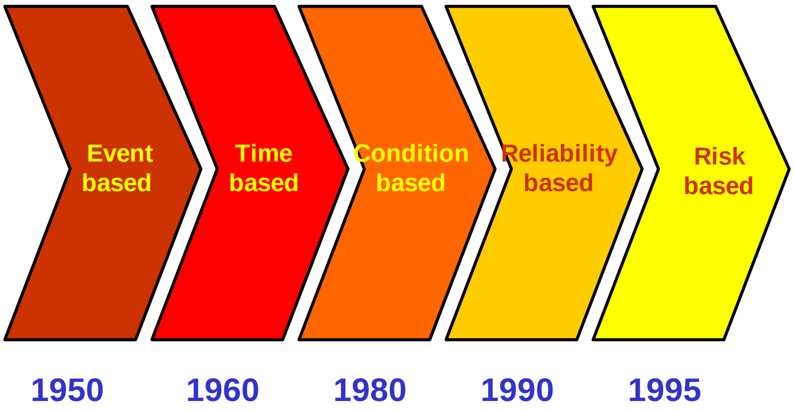

Figure 18: Evolution of maintenance strategies

The 1960s saw a large number of operators of machinery and equipment switch over to preventive maintenance programs. It was believed that some failures of mechanical components were in direct relation to time in use, and this was based on physical wear or age-related fatigue characteristics. The idea was that preventive action could prevent some breakdowns, and lead to cost savings over a long period of time. The biggest challenge was determining the correct time to perform the maintenance, as little was still known about failure patterns and history.

In the 1970s and 1980s equipment was becoming increasingly more complex, and with no clear dominant age-related failure mode. Under these conditions, the effectiveness of preventive maintenance actions was questions and the concerns of over-maintaining grew. At this time, new predictive maintenance techniques emerged, and the emphasis gradually shifted over to inspection and condition-based maintenance actions.

In the 1980s and 1990s, the train of thought evolved again, with the emergence of life-cycle engineering, with maintenance requirements already being taken into consideration during the design and commissioning stages of equipment. Maintenance took an active role in setting design requirements for installations, instead of just having to deal with built in characteristics. This again led to a new type of maintenance strategy – proactive maintenance – where the underlying principle was to be proactive at earlier stages in order to avoid later consequences.

Reliability- and risk-based maintenance concepts are centered around providing an optimized maintenance program with an adequate mix of maintenance actions and policies selected to increase uptime, extend the life cycle of the assets and ensure safe working conditions, while taking into consideration constrictions of time, budget and any other concerns (e.g. Environmental legislation).

4.1 *Reliability-Centered Maintenance (RCM)*

Reliability-centered maintenance represents an optimum mix of reactive, time-based, condition-based and proactive maintenance practices. The basic application for each type of strategy is shown in Figure 19 on the following page, where the respective strengths of each individual approach are taken in order to increase facility reliability while minimizing costs. RCM is an ongoing process that gathers data from operating systems' performance and uses this data to improve and design future maintenance.

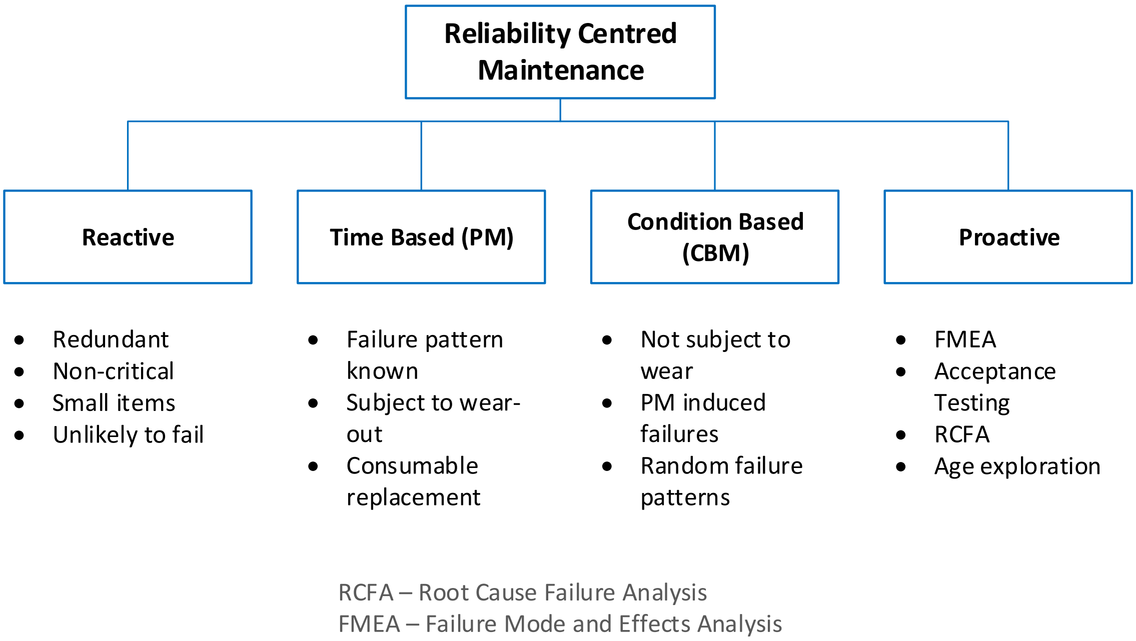

Figure 19: The components of an RCM program

Several ways of implementing an RCM program exist. The program can be based on rigorous Failure Modes and Effects Analysis (FMEA), with mathematically calculated likelihoods of failure based on design or historical data, intuition, expert judgment or common sense, and/or experimental data and modelling. The approaches can be called Classical, Rigorous, Intuitive, Streamlined or Abbreviated. The decision on the type of technique implemented is left to the end user and should be based on:

- Consequences of failure
- Probability of failure
- Availability of historical data
- Risk tolerances
- Availability of resources

Classical/Rigorous RCM

The benefits of classical or rigorous RCM are that it provides the most knowledge and data regarding:

- system functions
- failure modes
- maintenance actions addressing functional failures

of all RCM approaches. The Rigorous method should produce the most complete documentation.

The drawbacks of this approach are that it is based primarily on FMEA with little, if any, analysis of historical performance data. This RCM approach is extremely labor intensive and often postpones the implementation of obvious condition monitoring tasks.

Classical/Rigorous RCM should be applied in the following situations:

- When the consequences of failure can result in catastrophic risk in terms of health, safety, environment and/or complete economic failure of the plant
- The resultant reliability and associated maintenance cost is unacceptable after performing a streamlined type FMEA
- The equipment/systems are new to the organization and there is a lack of corporate maintenance and operational knowledge on function and functional failures.

Streamlined/Intuitive/Abbreviated RCM

The benefits of the Streamlined approach are that it quickly identifies and implements, with minimal analysis, the most obvious, usually condition-based, tasks. This approach eliminates the low value maintenance tasks based on historical data and input from Maintenance and

Operations (M&O) personnel. The idea is to minimize the initial analysis time in order to help offset the costs of FMEA and condition monitoring development.

The drawbacks of this approach stem from the reliance on historical records and personnel knowledge, which can introduce errors into the process that may lead to missing hidden failures with low probabilities of occurrence. This process also requires that at least one individual possesses a thorough understanding of the various condition monitoring technologies – a heavier reliance on expert knowledge/judgment.

The Streamlined approach should be applied in the following situations:

- The function of the equipment/systems is well understood
- A functional failure of the equipment/system(s) will not result in a loss of life or catastrophic impact on the environment or business of the plant

A more in depth description of RCM is given in Annex 1.

4.2 *Risk Based Inspection and Maintenance (RBI)*

Risk Based Inspection (RBI) represents an optimal maintenance concept, using risk as a basis for prioritizing and managing the efforts of an inspection program. RBI can be applied to examine equipment such as pressure vessels, piping and heat exchangers in industrial facilities.

In an operating plant, a large portion of the risk is associated with a relatively small number of components, as shown in a figure obtained from an analysis of a large industrial boiler below (Figure 20). Using RBI, a prioritized inspection plan can be developed, which increases the coverage of the high risk components while providing an appropriate effort on lower risk equipment. This strategy allows for a more rational investment of inspection resources. Inspections typically employ non-destructive testing (NDT).

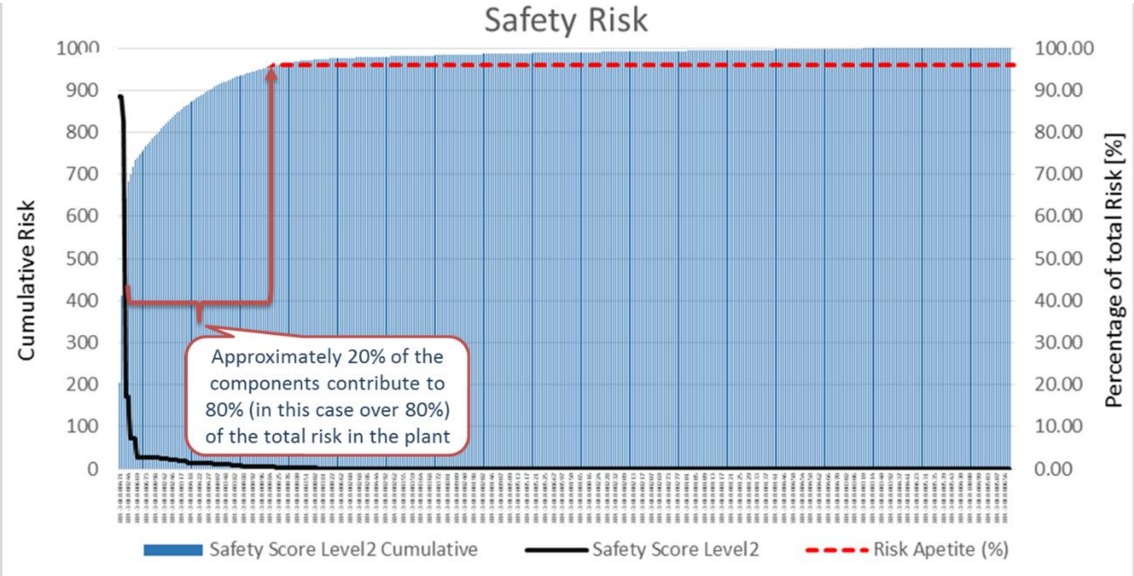

Figure 20: Contribution of overall risk in the plant vs. number of components

RBI assists owners and operators to select appropriate and cost-effective maintenance tasks, increase safety while potentially minimizing effort and cost, produce an auditable system, provide an agreed operating window and implement a risk management tool. The purposes of RBI include:

- Screen operating units of plants to identify areas of high risk
- Provide a holistic approach to managing risks
- Estimate a risk value associated with the operation of each equipment item in a plant, based on a consistent methodology
- Apply a strategy of performing the tasks needed for safeguarding integrity and improving the availability and reliability of the plant by planning and executing the needed inspections
- Systematically manage and reduce the risk of failures

- Provide a flexible technique able to continuously improve and adapt to changing risks
- Provide an appropriate inspection program, ensuring that the inspection techniques and methods consider the potential failure mechanisms
- Prioritize the equipment in a plant based on the measured risk.

In RBI, the risk of the operating equipment is defined as a combination of two separate terms: the likelihood or probability of failure and the consequence of failure.

$$\boldsymbol{Risk = Probability\ of\ Failure \times Consequence\ of\ Failure}$$

The probability of failure can be determined using applicable damage factors, a generic failure frequency (GFF) and a management system factor.

$$\boldsymbol{POF(t) = gff \times Df(t) \times F_{MS}}\ ^{*}$$

Where:

- *gff* represents the generic failure frequency, based on industry averages of equipment failure.
- F_{MS} represents the management system factor which measures how well the management and labor force of the plant is trained to handle the day to day activities, as well as any emergencies that may arise due to an accident.
- *Df(t)* represents the overall damage factor, which is a combination of the various damage factors that are applicable to the particular piece of equipment being analyzed.

The consequence of failure can include both a financial consequence (FC) and an area safety consequence (CA). The consequence of failure, expressed in financial terms, is calculated as the combined values of the consequences for damage to the failed equipment, damage to the surrounding equipment, loss of production, costs due to personnel injuries and damage to the environment.

$$\boldsymbol{CA = \max(CA_{equip}, CA_{personnel})^{*}}$$

$$\boldsymbol{FC = FC_{cmd} + FC_{affa} + FC_{prod} + FC_{inj} + FC_{environ}}^{*}$$

Where:

- CA_{equip} is the area consequence to surrounding equipment
- $CA_{personnel}$ is the area consequence to nearby personnel
- FC_{cmd} is the financial consequence to the failed equipment
- FC_{affa} is the financial consequence to surrounding equipment
- FC_{prod} is the financial consequence due to production downtime
- FC_{inj} is the financial consequence due to personnel injury
- $FC_{environ}$ is the financial consequence due to environmental damage/cleanup

Risk analysis can range from qualitative, semi-quantitative to quantitative, with increasing levels of detail and complexity. Qualitative risk analysis methods use broad categorizations for probabilities and consequences of failure, and are based primarily on engineering judgment and experience. It is a fast approach which may be used to screen large numbers of components quickly, but provides less detailed (and more conservative) results and relies more heavily on expert judgment. Quantitative risk analysis is a detailed approach that quantifies the probabilities and consequences of probable damage mechanisms and identifies and identifies and delineates the combinations of events that may lead to a severe event or other undesired consequence, should they occur. Semi-quantitative risk analysis is, in terms of level of detail and complexity, between the qualitative and quantitative approaches.

When the owner/operator makes a decision to implement RBI, he can justify this decision to regulators based on the work done by several industry committees and experts. Some examples of recognized international guidelines and standards for implementing and applying RBI are listed below:

- CEN CWA 15740:2008 Risk Based Inspection and Maintenance Procedures for European Industry (RIMAP). This is a CEN Workshop Agreement document (CWA),

[*] Source: API581:2008

applicable to the entire European Union. The document is currently in the process of transition to a PrEN, and thereafter to a full European Norm.
- API RP 580:2009 Risk Based Inspection. This recommended practice, produced by the American Petroleum Institute, represents a guideline for implementing RBI program.
- API RP 581:2008 Risk Based Inspection Technology. This recommended practice provides detailed step by step instructions for performing RBI on a qualitative, semi-quantitative and quantitative level.
- DNV-RP-G101:2010 Risk Based Inspection of Offshore Topsides Static Mechanical Equipment. This recommended practice describes a method for establishing and maintaining a RBI plan for offshore pressure systems.
- DNV-RP-G103:2011 Non-Intrusive Inspection. This recommended practice provides guidance to operators for planning and justifying non-intrusive or non-destructive inspection.
- ASME-PCC3-2007 Inspection Planning Using Risk-Based Methods. This standard presents risk analysis principles, guidance and implementation strategies applicable to fixed pressure containing equipment and components.

A complete guideline for implementing RBI (CEN CWA 15740:2008 – RIMAP), including an example case is given in Annex 2.

5 Optimizing aging management: Aging Indicators, Risk Factors and KPIs

5.1 *Aging-related Key Performance Indicators*

In order to better manage the issues of aging, owners and operators can identify key performance indicators (KPIs) associated with aging. These KPIs can be monitored to identify how effectively the risks related to aging are being controlled.

The approaches for different types of plants and different industries may vary, and the number and focus of the KPIs will therefore be different depending on the type of plant being considered. A single universally fitting solution does not exist, and it is the responsibility of management to identify the KPIs which they wish to monitor in relation to aging issues at their particular plant(s). Some example leading and lagging indicators are given below:

Leading Indicators

- Number and frequency of planned inspections
- Effectiveness (of scope/techniques) of planned inspections (with regards to POD of damage/defects)
- Number and frequency of reviews
- Planned replacement schedules for components and systems
- Planned number of tests done on safety critical equipment i.e. PSVs
- …

Lagging indicators

- Number of major failures of components and equipment.
- Number of unplanned outages.
- Number of uncontrolled inventory releases.
- Number of revisions of maintenance activities
- Number of outstanding inspection action items.
- Number of alarms/operation outside of defined normal boundaries
- …

For a more extensive and detailed overview of aging related leading and lagging KPIs, please refer to Annex 3. A number of indicators related to aging, collected and compiled during the iNTeg-Risk project are presented, with definitions and formulas.

A number of safety management and risk control systems can be modified an implemented in order to better manage the aging of plants. The examples of these systems, and some considerations related to each system, are given below:

Plant design and modification

- An Asset Integrity Management Policy is communicated and understood at all levels.
- Design standards and codes of practice are monitored, updated and understood to recognize the potential effect of ageing.
- Performance of assets are monitored and discussed at senior level (Improvements, failures, anomalies etc.) to recognize a potential ageing issue.
- Contractor and third party standards clearly defined and tested

Responsibilities and Communication

- A clear organizational structure in place, with identified roles and responsibilities.
- Clear internal and external routes of communication through regular Engineering/Operational meetings, Contractor/Third Party Management meetings etc.

Procedures

- Technical Safety Reviews on critical equipment.
- Operational procedures that interface with Maintenance Management to avoid repeat maintenance and inspection work.
- Clear leading/lagging KPIs monitored on a regular basis to track performance.
- Proactive approach to identifying potential incidents and near misses which may identify ageing issues.

Risk Assessment/Management processes

- Risk Assessment program related to the impact of failure and the effect of process change
- Hazard identification and fitness for service reviews to identify the effect of ageing mechanisms.
- Risk based inspection program identifying ownership and rational for change.
- Accident/incident investigation procedures with clear action tracking and close out procedures.

Management of Change procedures

- A clearly defined Management of Change procedure.
- Clear lines of responsibility and communication to agree and implement change.
- Consideration of organizational change and its influence on systems and human factors.

Maintenance Management Systems

- A well-structured and understood Maintenance Management and Inspection System that interfaces with operations.
- Replacement policy in place for safety critical equipment.

Asset Integrity Management Systems

- AIMS plan and procedures in place to identify safety critical equipment.
- Clearly identified and accessible Asset Register documentation to ensure action is taken at the correct intervals.
- Reviews at clearly defined intervals to ensure correct data is maintained.

Training and Competence development

- A competency development program for critical staff containing the ability to recognize ageing mechanisms.
- A structured training plan in place.
- Job continuity plans to retain job knowledge and operational skills.

Audit, Review and Operational Inspection regimes

- An audit program is in place to ensure all elements of a management system related to the controlling of ageing plant and equipment issues are maintained.
- An operational inspection regime which highlights the need to identify ageing mechanisms.
- Clearly developed corrective action plans.

5.2 *Risk Factors and Indicators of aging*

Various risk factors can contribute to the promotion or acceleration of degradation of plants and equipment, but by themselves, they are not sufficient for ageing to occur. These risk factors can be specific scenarios, events or occurrences which can suggest that deterioration is occurring or could occur in the future. Some aging-related risk factors are given in Table 9.

Table 9: Examples of aging-related risk factors

Risk factor	**Details**
Equipment age	The symptoms of ageing normally become more apparent with time, and older equipment may be expected to have more damage and deterioration This is especially true with time-dependent damage mechanisms, such as Creep. Equipment age may not necessarily constitute a risk factor in some cases. Older equipment that contained large design margins, operated outside of regimes which promote certain types of damage or has simply been well maintained may be still in an early Stage of life compared with newer equipment that has not been as well

	managed or operates under more difficult regimes (regarding damage initiation and propagation).
Old or outdated materials of construction	Modern steels are cleaner than steels produced prior to the 1970s. The carbon level has dropped over time as a result of the use of more modern production techniques. Older steels have a higher tendency of cracking as a result of welding. Sulphur and phosphorus residuals in older steels can be up to 0.05%, whereas levels of 0.01% can now be obtained.
Low temperature operation	Depending on materials of construction, equipment operated at low temperatures may face an increased risk of embrittlement and brittle fracture, and needs to be assessed against this risk. Lack of low temperature justification is a risk factor for such equipment.
Equipment designed and manufactured to old codes	Equipment designed and manufactured to superseded standards and codes, may be more susceptible to ageing than more modern equipment.
Design creep/fatigue life or corrosion allowance utilized	Once the design creep or fatigue life or corrosion allowance is used up, a thorough inspection and fitness-for-service assessment is normally required to extend life. These inspections may have to include destructive testing.
Welding quality, welding defects and repairs	Poor quality of welding and joint design are key factors promoting the onset of ageing damage. Welding has improved markedly during the last 40 years with better design, improved process control and quality standards. Modern welding consumables can also reduce the potential for hydrogen cracking of arc welds. More effective ultrasonic NDT methods have improved the ability to detect and size weld flaws.
Unplanned shutdowns and recurring service problems	Recurring problems during service can be an indication that conditions in the equipment are not optimized and may make it prone to degradation. Good inventory control is important for detecting these small but recurring faults.
Operation in corrosive environments	A corrosive environment has the potential to cause corrosion to exposed surfaces, if they are not properly protected. Attention should be paid to crevices and stagnant areas and to regions of composition differences, such as at welds. Some materials are susceptible to stress corrosion cracking in specific environments.
Predictable deterioration	Monitoring the extent of predictable deterioration (e.g. thinning rate) through review of inspection reports and service history is important for the determination of the rate of ageing of the equipment.
Change of operating conditions/service	A change of operating conditions of equipment can carry an increased risk of ageing until service history or experience shows otherwise.

External damage	Surface impacts due to collisions with moving equipment or falling debris can result in small defects. These defects can then act as initiators for mechanisms such as fatigue or corrosion. Thermal and fire damage can have an impact on the crystal structure of a material, causing it to lose strength, toughness or corrosion resistance.
Poor condition of paint and surface coatings	Paint or coating failure can be the result of poor maintenance or the use of an incorrect coating. Risk of corrosion is increased.
Prior Repairs	If repairs have been performed on the equipment, the integrity and necessity of repair will indicate the potential for further problems.

Indicators of aging are signs or evidence that damage has already occurred, or is about to occur. Table 10 below provides some example aging indicators.

Table 10: Examples of aging indicators

Indicator	**Details**
Paint blistering or surface damage	Paint blistering or other surface damage indicates that some degradation may be occurring.
Leakage	Leakage may be due to lack of maintenance/functional malfunction (e.g. replacement of seals or gaskets) or it may indicate more serious integrity-related damage such as a through-wall crack.
Common breakdowns	Repeat breakdowns and need for repair suggests that the equipment is approaching the end of its useful service life. It is good practice to establish the underlying reasons for breakdowns and repairs.
Inspection results	Inspection results can give the actual equipment condition and any damage present. Repeat inspection results can be used to establish degradation trends.
Reduction of plant efficiency	Reduction in efficiency (e.g. heat up rates) can be due to factors such as product fouling or scaling.
Process instability	Excursions from the normal process operating envelope may be an indication that the equipment has deteriorated.
Product quality	Impurities detected in the product, composed of plant/equipment materials can indicate corrosion or erosion. An on-going product quality review can detect variations in product quality.
Instrumentation	Anomalies and lack of consistency in the behavior of process instrumentation can indicate a fault with the instrumentation, but can also be an indicator that the equipment has deteriorated.
Industry/operator experience of ageing of similar equipment	Unless active measures have been used to prevent ageing of similar equipment it will be likely that the same problems can occur again.

Poor condition of paint and surface coatings	Poor condition of the coating surface can be an indication of corrosion.
Repairs	May indicate that ageing problems are already occurring.

6 Conclusion

Management of aging structures is a complex issue requiring the integrated application of results obtained through the use of different techniques, so that the risks related to equipment aging and deterioration are successfully mitigated and prevented. The condition of equipment has to be monitored, in the right places and the correct way. If knowledge about the state of equipment is inadequate or incomplete, operators are forced to remain conservative in their assessment of risks and remaining life. When in depth information about the state of the equipment is known, the right kind of inspection and maintenance techniques can be applied, in order to safely maximize equipment life and minimize costs.

The objective of this document was to provide an overview of some of the techniques to be applied in an integrated manner, when facing the issue of aging management of process and power plants. Where possible, detailed descriptions and guidelines for application have been provided.

The gathering of operational and monitoring data is shown in Chapter 2. Current monitoring trends and a real application of modular targeted monitoring at a power plant is given. The importance of striking the right balance between global and local monitoring is stressed in this chapter. The monitoring of strains and displacements needs to be supported by the application of computer-based analysis tools. Due to the uncertainties present and the non-linear nature of some damage mechanisms present in high-temperature components (e.g. creep), a risk assessment should be performed with every condition assessment.

In many cases, problems in plants, related to aging or otherwise, are chronic in nature, meaning that they occur more than once and for the same reasons. Root Cause Failure Analysis is an essential element of Reliability Centered Maintenance methods and can help us determine the root causes of these problems. RCFA is shortly introduced in Chapter 3, and four of the analysis techniques are described: Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Cause and Effect Analysis and Sequence of Events Analysis.

The logic of aging damage identification, addresses one of the key points laid out in T3.5. The systematics, detection and analysis of damage mechanisms in power (and process) plants, based on RIMAP and its accompanying documents, are dealt with, with guidelines on where and how to look for the respective damage mechanisms (through inspections or monitoring techniques, as well as how to analyze and predict the further development of a given type of damage.

The principles of reliability centered and risk based inspection and maintenance concepts are covered in Chapter 3.3. A brief overview of the evolution of maintenance strategies is given, from the era of reactive maintenance to the modern concepts of proactive maintenance, such as Reliability Centered Maintenance and Risk-Based Inspection and Maintenance. These concepts are covered in more depth in Annex 1 and Annex 2. In particular, a recognized European guideline for implementing and maintaining a Risk-Based Inspection program, the CWA 15740:2008/2011 RIMAP is provided. This guideline is currently in the process of transition to a European Norm, the CWA EN. The review of this guideline in CEN will be completed in June 2015.

Applying RBI can allow infrastructure owners/operators to make risk-informed decisions regarding the maintenance of aging plants and provide optimized inspection plans. In order to successfully implement RBI methods and methodologies, an integration of many factors is essential, in order to obtain the most accurate (and least conservative) results. These factors include:

- Gathering and documenting design, operational and monitoring data and inspection records, in order to have a good overview of the operational history of the plant.
- Reviewing and appraising the management system in place, in order to get an idea of how and to which extent it directly or indirectly influences the mechanical integrity of the plant and its systems.

Conducting regular, appropriate quality non-destructive examinations on a well-defined set of components and systems can give operators insight into the true state and rate of aging of a plant, and extend the useful life of many components, when compared to a traditional prescribed replacement program. The modern optimized maintenance concepts, such as RBI and RCM, can provide inspections plans which serve as a basis for regular, quality inspections, which minimize risk and maximize savings by targeting the right components in the right locations.

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Annex 1 Reliability Centered Maintenance (RCM)

A.1.1 Definitions – What is RCM?

Reliability-Centered Maintenance (RCM) is a logical, systematic decision making process for defining optimum maintenance tasks.

RCM is a process used to determine the maintenance requirements of any physical asset in its present operating context.

RCM is the detailed analysis of the functional failures and the failure modes for the development of a maintenance strategy to realize the inherent reliability capabilities of equipment.

RCM is based around answering seven key questions about a system

- What are the functions and associated performance standards of the system/asset?
  Function
- In what ways does it fail to fulfill its functions?
  Functional Failure
- What causes each functional failure?
  Failure Mode
- What happens when each failure occurs?
  Failure Effect
- In what way does each failure matter?
  Consequence
- What can be done to predict or prevent each failure?
  Proactive Tasks
- What should be done if a suitable proactive task cannot be found?
  Default Actions, Maintenance strategies

Functions

The operating context of the asset shall be defined.

All the functions of the asset/system shall be identified (all primary and secondary functions, including the functions of all protective devices).

All function statements shall contain a verb, an object, and a performance standard (quantified in every case where this can be done).

Performance standards incorporated in function statements shall be the level of performance desired by the owner or user of the asset/system in its operating context.

Function — what the owner or user of a physical asset or system wants it to do.

Secondary Functions— functions which a physical asset or system has to fulfill apart from its primary function(s), such as those needed to fulfill regulatory requirements and those which concern issues such as protection, control, containment, comfort, appearance, energy efficiency, and structural integrity.

Functional failures

All the failed states associated with each function shall be identified.

Failure modes

All failure modes reasonably likely to cause each functional failure shall be identified.

The method used to decide what constitutes a “reasonably likely” failure mode shall be acceptable to the owner or user of the asset.

Failure modes shall be identified at a level of causation that makes it possible to identify an appropriate failure management policy.

Lists of failure modes shall include failure modes that have happened before, failure modes that are currently being prevented by existing maintenance programs and failure modes that have not yet happened but that are thought to be reasonably likely (credible) in the operating context.

Lists of failure modes should include any event or process that is likely to cause a functional failure, including deterioration, design defects, and human error whether caused by operators or maintainers (unless human error is being actively addressed by analytical processes apart from RCM).

Failure Effects

Failure effects shall describe what would happen if no specific task is done to anticipate, prevent, or detect the failure.

Failure effects shall include all the information needed to support the evaluation of the consequences of the failure, such as:

a. What is the evidence (if any) that the failure has occurred (in the case of hidden functions, what would happen if a multiple failure occurred)
b. What it does (if anything) to kill or injure someone, or to have an adverse effect on the environment
c. What it does (if anything) to have an adverse effect on production or operations
d. What physical damage (if any) is caused by the failure
e. What (if anything) must be done to restore the function of the system after the failure

Failure Consequence Categories

The consequences of every failure mode shall be formally categorized as follows:

- the consequence categorization process shall separate hidden failure modes from evident failure modes
- the consequence categorization process shall clearly distinguish events (failure modes and multiple failures) that have safety and/or environmental consequences from those that only have economic consequences (operational and non-operational consequences)

The assessment of failure consequences shall be carried out as if no specific task is currently being done to anticipate, prevent, or detect the failure.

Failure Management Policy Selection

The failure management selection process shall take account of the fact that the conditional probability of some failure modes will increase with age (or exposure to stress), that the conditional probability of others will not change with age, and the conditional probability of yet others will decrease with age.

All scheduled tasks shall be technically feasible and worth doing (applicable and effective), and the means by which this requirement will be satisfied as defined under failure management policies.

If two or more proposed failure management policies are technically feasible and worth doing (applicable and effective), the policy that is most cost-effective shall be selected.

The selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure.

Failure Management Policies— Scheduled Tasks

All scheduled tasks shall comply with the following criteria:

In the case of a **hidden failure mode** where the associated multiple failure **has safety or environmental consequences**, the task shall reduce the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner or user of the asset.

In the case of an **evident failure mode** that does not have safety or environmental consequences, the direct and indirect costs of doing the task shall be less than the direct and indirect costs of the failure mode when measured over comparable periods.

In the case of a **hidden failure mode** where the associated multiple failure does **not have safety or environmental consequences**, the direct and indirect costs of doing the task shall be less than the direct and indirect costs of the multiple failure plus the cost of repairing the hidden failure mode when measured over comparable periods of time. In the case of an evident failure mode that has safety or environmental consequences, the task shall reduce the probability of the failure mode to a level that is tolerable to the owner or user of the asset.

ON-CONDITION TASKS — any on-condition task (or predictive or condition-based or condition monitoring task) that is selected shall satisfy the following additional criteria:

- there shall exist a clearly defined potential failure
- there shall exist an identifiable P-F interval (or failure development period)
- the task interval shall be less than the shortest likely P-F interval
- it shall be physically possible to do the task at intervals less than the P-F interval
- the shortest time between the discovery of a potential failure and the occurrence of the functional failure (the P-F interval minus the task interval) shall be long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.

SCHEDULED DISCARD TASKS — any scheduled discard task that is selected shall satisfy the following additional criteria:

- There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration.
- A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.

SCHEDULED RESTORATION TASKS — any scheduled restoration task that is selected shall satisfy the following additional criteria:

- There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration.
- A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.
- The task shall restore the resistance to failure (condition) of the component to a level that is tolerable to the owner or user of the asset.

FAILURE-FINDING TASKS — any failure-finding task that is selected shall satisfy the following additional criteria (failure-finding does not apply to evident failure modes):

- The basis upon which the task interval is selected shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.
- The task shall confirm that all components covered by the failure mode description are functional.
- The failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.
- It shall be physically possible to do the task at the specified intervals.

Failure Management Policies— One-Time Changes and Run-to-Failure

ONE-TIME CHANGES

The RCM process shall endeavor to extract the desired performance of the system as it is currently configured and operated by applying appropriate scheduled tasks.

In cases where such tasks cannot be found, one-time changes to the asset or system may be necessary, subject to the following criteria.

- In cases where the failure is hidden, and the associated multiple failure has safety or environmental consequences, a one-time change that reduces the probability of the multiple failure to a level tolerable to the owner or user of the asset is compulsory.
- In cases where the failure mode is evident and has safety or environmental consequences, a one-time change that reduces the probability of the failure mode to a level tolerable to the owner or user of the asset is compulsory.

- In cases where the failure mode is hidden, and the associated multiple failure does not have safety or environmental consequences, any one-time change must be cost-effective in the opinion of the owner or user of the asset.
- In cases where the failure mode is evident and does not have safety or environmental consequences, any one-time change must be cost-effective in the opinion of the owner or user of the asset.

RUN-TO-FAILURE

Any run-to-failure policy that is selected shall satisfy the appropriate criterion as follows:

- In cases where the failure is hidden and there is no appropriate scheduled task, the associated multiple failure shall not have safety or environmental consequences.
- In cases where the failure is evident and there is no appropriate scheduled task, the associated failure mode shall not have safety or environmental consequences.

A.1.2 RCM Benefits

Implementation of RCM usually is followed by the benefits such as:

- Safety & environmental integrity improvement
- Improved operating performance
- Improved maintenance cost effectiveness
- Maximised useful life of assets
- Maintenance strategy information & decisions fully documented
- Clearly identifies manpower & spares resource requirements
- Helps to build good teamwork

A.1.3 RCM Process overview

- Define The RCM Boundaries and Operating Context
- FMEA – Failure Mode and Effect Analyses
- FCA – Failure Characteristic Analyses
- MSS – Maintenance Strategy Selection
- Task Alignment of Maintenance Tasks
- Task Description & Detail
- Monitor & Update Implementation

Figure 21: RCM Review Team

A.1.4 Information needed for RCM Analysis

Typical Information Needed for RCM Reviews …

- P&ID's
- O&M Manuals
- Flow Diagrams
- Maintenance History Records … If Available
- Previous Maintenance Strategies & Frequencies

The operating context is a definition of the operating parameters within which the system is required to perform.

- Process or product applicable/effected
- Standby or alternative processes available
- Safety/Environmental regulations or standards
- Availability requirements
- Business risk & reliability
- Production downtime economics

A.1.5 Operating context

An operating context statement for a physical asset typically includes a brief overall description of how it is to be used, where it is to be used, overall performance criteria governing issues such as output, throughput, safety, environmental integrity, and so on. Specific issues that should be documented in the operating context statement include:

a. Batch versus flow processes: whether the asset is operating in a batch (or intermittent) process or a flow (or continuous) process.

b. Quality standards: overall quality or customer service expectations, in terms of issues such as overall scrap rates, customer satisfaction measurements (such as on-time performance expectations in transportation systems, or rates of warranty claims for manufactured goods), or military preparedness.

c. Environmental standards: what organizational, regional, national, and international environmental standards (if any) apply to the asset.

d. Safety standards: whether any predetermined safety expectations (in terms of overall injury and/or fatality rates) apply to the asset.

e. Theater of operations: characteristics of the location in which equipment is to be operated (arctic versus tropical, desert vs. jungle, onshore vs. offshore, proximity to sources of supply of parts and/or labor, etc.).

f. Intensity of operations: in the case of manufacturing and mining, whether the process of which the equipment forms a part is to operate 24 hours per day, seven days per week, or at lower intensity. In the case of utilities, whether the equipment operates under peak load or base load conditions.

g. Redundancy: whether any redundant or standby capability exists, and if so what form it takes.

h. Work-in-process: the extent to which work-in-process stocks (if any) allow the equipment to stop without affecting total output or throughput.

i. Spares: whether any decisions have been made about the stocking of key spares that might impinge on the subsequent selection of failure management policies.

j. Market demand/raw material supply: whether cyclic fluctuations in market demand and/or the supply of raw materials are likely to impinge on the subsequent selection of failure management policies. (Such fluctuations may occur over the course of a day in the case of an urban transport business, or over the course of a year in the case of a power station, an amusement park, or a food processing business.)

In the case of very large or very complex systems, it might be sensible to structure the operating context in a hierarchical fashion, if necessary starting with the mission statement of the entire organization that is using the asset.

A.1.6 Primary functions

RCM Question 1 "What are the functions…"

- Define the Primary Function "What It Is Required To Do" - not the Design
- Define the Performance Standards "Quantitative rather than Qualitative"
- Define the Tolerances on the Performance Standard "Minimum, Maximum, Nominal, etc."

PRIMARY FUNCTIONS are the reason why any organization acquires any asset or system is to fulfill a specific function or functions. These are known as primary functions of the asset.

Functional descriptions

Function description - "to be capable of safely transporting people and luggage from A to B"

Protective function statements need special handling. For example, the function of a pressure safety valve may be described as follows: "To be capable of relieving the pressure in the boiler if it exceeds 25 bar."

A.1.7 Performance standards

Owners are satisfied if their assets generate a satisfactory return on the investment made to acquire them (usually financial return for commercial operations, or other measures for non-commercial operations). Users are satisfied if each asset continues to do whatever they want it to do to a standard of performance that they—the users—consider satisfactory. Finally, society as a whole is satisfied if assets do not fail in ways that threaten public safety and the environment.

This means that if we are seeking to cause an asset to continue to function to a level that is satisfactory to the user, then the objective of maintenance is to ensure that assets continue to perform above the minimum level that is acceptable to those users. If it were possible to build an asset that could deliver the minimum performance without deteriorating in any way, then it would be able to run continuously, with no need for maintenance.

However, deterioration is inevitable, so it must be allowed for. This means that when any asset is put into service, it must be able to deliver more than the minimum standard of performance desired by the user. What the asset is able to deliver at this point in time is known as its initial capability. This means that performance can be defined in two ways:

a. Desired performance (what the user wants the asset to do)
b. Built-in capability (what it can do).

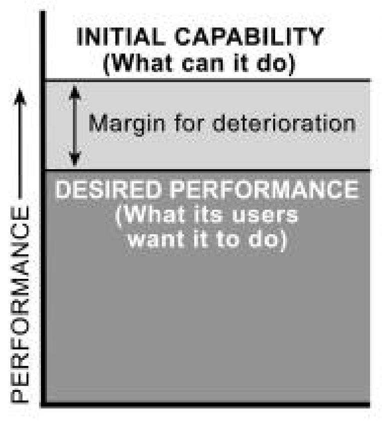

Figure 22: Different levels of performance

The margin for deterioration must be large enough to allow for a reasonable amount of use before the component degrades to functional failure, but not so large that the system is "over-designed" and hence too expensive. In practice, the margin is adequate in the case of most components, so it is usually possible to develop maintenance programs accordingly.

However if the desired performance is higher than built-in capability, no amount of maintenance can deliver the desired performance, in which case the asset is not maintainable.

All this means that, in order to ascertain whether an asset can be maintained, we need to know both kinds of performance: the built-in capability of the asset, and the minimum performance that the user is prepared to accept in the context in which the asset is being used. This minimum performance is the performance standard that must be incorporated in the function statement.

Some examples are performance standards:

- at speeds between 0 and 120 km/h
- maximum weight limit of 500kg
- minimum fuel consumption of 15 km/l

Note that users and maintainers often have significantly different views about what constitutes acceptable performance. As a result, in order to avoid misunderstandings about what constitutes "functional failure," the minimum standards of acceptable performance must be clearly understood and accepted by the users and maintainers of the asset, together with anyone else who has a legitimate interest in the behavior of the asset.

Performance standards must be quantified where possible, because quantitative standards are clearer and more precise than qualitative standards. Occasionally it is only possible to use qualitative standards, for example when dealing with functions relating to appearance. In such cases, special care must be taken to ensure that the qualitative standard is understood and accepted by users and maintainers of the asset.

A.1.8 Secondary functions ("ESCAPES")

- **E**nvironmental integrity
- **S**afety, structural integrity
- **C**ontrol, containment, comfort
- **A**ppearance
- **P**rotection
- **E**conomy, efficiency
- **S**uperfluous

Environmental integrity

These functions define the extent to which the asset must comply with the corporate, municipal, regional, national, and international environmental standards or regulations that apply to that asset. These standards govern such things as the release of hazardous materials into the environment, and noise.

Some examples are i.e. compliance with regulations covering:

- noise
- working temperatures
- pollution discharges to the atmosphere
- effluent discharges
- international, national, local or company standards and regulations

Structural / Safety Functions

It is sometimes necessary to write function statements that deal with specific threats to safety that are inherent in the design or operation of the process (as opposed to safety threats that are a result of a functional failure). For example, the function of electrical insulation on a domestic appliance is "to prevent users from touching electrically live components."

Safety integrity examples

- Pressure Regulations
- HSE

Many assets have a secondary function of providing support for or a secure mount for another item. For example, while the primary function of a wall may be to protect people and equipment from the weather, it might also be expected to support the roof, or to bear the weight of shelves and pictures.

Integrity of structures examples:

- corrosion protection, etc.
- safe working loads
- fixings and mountings

Control Functions

In many cases, users not only want assets to fulfil functions to a given standard of performance, but they also want to be able to regulate the performance. This expectation is summarized in separate function statements. For example, a function of a cooling system may be to regulate temperature at will between one specific temperature and another. Indication and feedback form an important subset of the control category of functions.

Examples of control functions:

- Temperature
- Pressure, flows
- Chemical dosing
- Variable speed

To provide information

- Gauges, dials
- Control panels

Containment Functions

Containment— Systems whose primary function is to store materials must also contain them. Similarly, systems that transfer materials—especially fluids—also have a containment function. These functions must be specified as well.

Some examples of containment functions:

- Storage Containment
- Tanks
- Vessels
- Thermal Insulation

Some examples of transfer containment (fluid, gas, air)

- Pipes
- Joints
- Seals

Comfort Functions

Owners and users generally expect that their assets or systems will not cause pain or anxiety to operators or maintainers. These problems should of course be dealt with at the design stage. However deterioration or changing expectations can lead to unacceptable levels of pain or anxiety. The best way to ensure that this does not happen is ensure that the associated function statements are described precisely and that they fully reflect current standards

Human Discomfort (Ergonomics)

- Adjustable Height
- Glazing Visibility
- Lighting Levels

Equipment Operability

- Quick Release Mechanism

- Swinging Control Panels

Appearance Functions

Appearance often constitutes an important secondary function. For example, the primary reason for painting most industrial equipment is to protect it from corrosion. However a bright color may be chosen to enhance its visibility for safety's sake, and this function should also be documented

Protection Functions

Protective functions avoid, eliminate, or minimize the consequences of the failure of some other function. These functions are associated with devices or systems that:

- Warn people of abnormal conditions
  - sensors, switches, alarms, etc.
- Trip or stop equipment when fault occurs
  - high priority alarms
- Relieve abnormal conditions
  - safety or relief valves, bursting discs, etc.
- Take over the duty role
  - standby equipment or systems
- Prevent dangerous situations from arising in the first place
  - warning signs, protective covers

A protective function ensures that the failure of the function being protected is much less serious than it would be without the protection. The associated devices are incorporated into systems to reduce risk, so their functions should be documented with special care.

Efficiency / Economy Functions

In most organizations, overall cost expectations are expressed in the form of expenditure budgets. However for specific assets, cost expectations can be addressed directly by secondary function statements concerning such things as energy consumption rates and the rate of attrition of process materials.

Some examples are:

- dosing levels
- heating efficiency
- motor drawn current
- fuel economy
- water usage
- recovery, etc.

Superfluous functions

Some systems incorporate items or components that are found to be completely superfluous. This usually happens when equipment or the way in which it is used has been modified over a period of years, or when new equipment has been over-specified.

Although such items have no positive function and are often costly to remove, they can in fact fail and thus reduce overall system reliability. To avoid this, some may require maintenance and so consume resources.

If they are removed, the associated failure modes and costs will also be removed. However, before their removal can be recommended with confidence, their functions need to be clearly identified and understood.

A.1.9 Functional failure

RCM Question 2 “In what ways can it fail”?

A functional failure is defined as the inability of an asset to fulfill a function to a standard of performance which is acceptable to the user

This definition covers complete loss of function and situations where the asset still functions but performs outside acceptable limits (performance standard)

Functional failures can be classified into one of three groups:

- when capability drops below user desired performance after the asset enters service
- when desired user performance rises above capability after the asset enters service
- when the asset is not capable of doing what is wanted from the outset.

The majority of 'maintenance significant' failure modes are associated with the first category. Functional failures are described as "fails to be capable of …"

Partial failures need to be identified separately because they are nearly always caused by different failure modes from total failures, and because the consequences are also nearly always different.

A.1.10 Failure modes

RCM question 3 "What causes it to fail"?

- Zero based – no any maintenance is done
- A failure mode is any event which could cause a functional failure - past, future & currently prevented
- All failure modes which are reasonably likely to cause a functional failure should be identified
- The root cause of failure modes should be identified

Failure effects

Failure effects should describe the following:

- Evidence (if any) that the functional failure has occurred (alarms, indication etc)
- The effects on safety or the environment
- The effect on production/operation (economic or service level)
- Potential secondary damage to other equipment
- Downtime or repair actions with estimated time (loss of function to the restoration of function)

Sources of Information about Failure Modes

Failure modes that have occurred before on the same or similar assets are the most obvious candidates for inclusion in the list of failure modes, unless something has been changed in such a way that the failure mode cannot occur again. Sources of information about these failure modes include people who know the asset well (operators, maintainers, equipment vendors, or other users of the same equipment), technical history records, and data banks.

Failure modes that are the subject of existing proactive maintenance routines should also be incorporated in the list of failure modes. One way to ensure that none of these failure modes has been overlooked is to study existing maintenance schedules for identical or very similar assets and ask, "what failure mode would occur if this task was not performed?" However existing schedules should only be reviewed as a final check after the rest of the RCM analysis has been completed, in order to reduce the possibility of perpetuating the status quo.

Finally, the list of failure modes should include failure modes that have not yet occurred but that are considered to be real possibilities in the context under consideration. Identifying and deciding how to deal with failure modes that have not happened yet is an essential feature of proactive management in general, and of risk management in particular. It is also one of the most challenging aspects of the RCM prospect, because it calls for a high degree of judgment applied by skilled and knowledgeable people.

A.1.11 Failure classification

RCM Question 5: "In what way does each failure matter?"

Failure classification specifies the impact of failures (i.e. the consequence or extent to which each failure matters).

- Hidden or evident under normal conditions
- Safety or environmental
- Operational (economic or service level)
- Non-operational

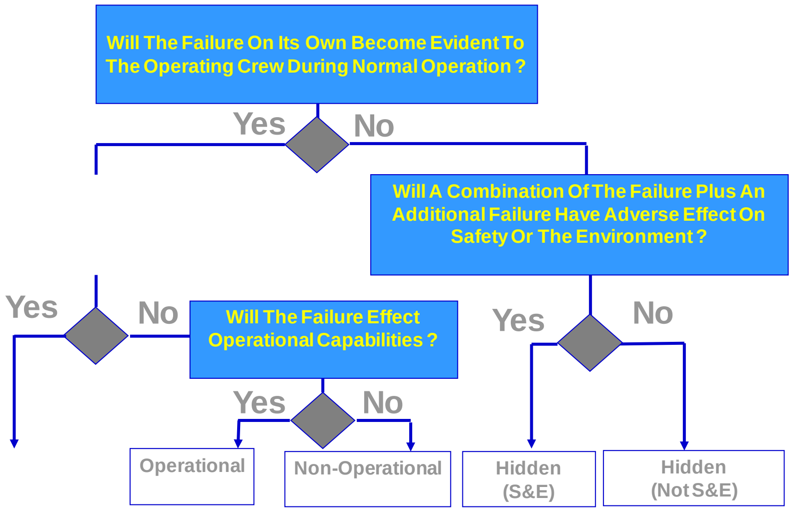

Figure 23: Failure Classification Decision Tree

Hidden & Evident Failures

Hidden failures: a hidden failure is one, which will not become evident to the operating crew under normal circumstances if it occurs on its own, for example protective devices.

Evident failures: an evident failure is one which will on its own eventually become evident to the operating crew under normal circumstances, for example, alarms activate, flow stops.

Safety / Environmental Failures

A failure has safety consequences if it causes a loss of function or damage which could hurt or kill someone.

A failure has environmental consequences if it causes a loss of function or damage which could lead to a breach of any known environmental standard or regulation.

For failure modes which have safety or environmental consequences, a proactive task is only worth doing if it reduces the probability of the failure to a tolerably low level.

A selected list of examples includes:

a. Increased risk of fire or explosion
b. The escape of hazardous chemicals
c. Electrocution
d. Vehicle accidents or derailments
e. Ingress of dirt into food or pharmaceutical products
f. Exposure to sharp edges or moving machinery

Operational Failures

Failure has operational consequences if it has a direct adverse effect on operational capability.

For failure modes with operational consequences, a proactive task is worth doing if, over a period of time, it costs less than the cost of the operational consequences plus the cost of repairing the failure which it is meant to prevent.

Non-Operational Failures

A failure has non-operational consequences if it has no direct adverse effect on safety, the environment or operational capability.

For failure modes with non-operational consequences, a proactive task is worth doing if, over a period of time, it costs less than the cost of repairing the failure which it is meant to prevent.

A.1.12 Failure Characteristic Analyses

Information of the asset conditions that give prior warning of the failure mode

- time intervals between the onset of failure and catastrophic failure (for age-related failure)
- time intervals before the onset of failure (indicates periods when failures will be unlikely)
- useful and safe life (for random failure)
- estimates can be used if no other data is available

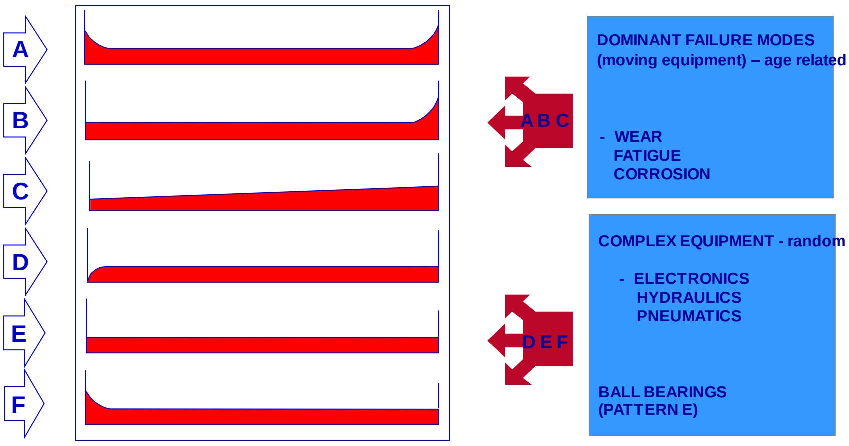

Figure 24: Failure Characteristic Patterns

Relationship between age and failure—The failure management selection process shall take account of the fact that the conditional probability of some failure modes will increase with age (or exposure to stress), that the conditional probability of others will not change with age, and the conditional probability of yet others will decrease with age.

Patterns A and B both display a point at which there is a rapid increase in the conditional probability of failure (sometimes called a "wear-out zone"). Pattern C shows a steady increase in the probability of failure, but no distinct wear-out zone. Pattern D shows low conditional probability of failure when the item is new or just out of the shop, then a rapid increase to a constant or very slowly increasing level, while pattern E shows a constant conditional probability of failure at all ages (**random failure**). Pattern F starts with high infant mortality, dropping to a constant or very slowly decreasing conditional probability of failure.

In general, age-related failure patterns apply to items that are very simple, or to complex items that suffer from a dominant failure mode. In practice, they are commonly associated with direct wear (most often where equipment comes into direct contact with the product), fatigue, corrosion, oxidation and evaporation.

MTBF – is main characteristics of random failures, and represents mean time between failures.

Hidden and evident failures

Some failure modes occur in such a way that nobody knows that the item is in a failed state unless, or until, some other failure (or abnormal event) also occurs. These are known as hidden failures. A hidden failure is a failure mode whose effects do not become apparent to the operating crew under normal circumstances if the failure mode occurs on its own. Conversely, an evident failure is a failure mode whose effects become apparent to the operating crew under normal circumstances if the failure mode occurs on its own.

The RCM approach to the evaluation of failure consequences begins by separating hidden failures from evident failures. Hidden failures can account for up to half the failure modes that could affect modern, complex equipment, so they need to be handled with special care.

Hidden Failures and Protection: the function of any protection is to ensure that the consequences of the failure of the protected function are much less serious than they would be if there was no protection. So any protective function is in fact part of a system with at least two components:

a. The protective function
b. The protected function

The existence of such systems creates two sets of failure possibilities, depending on whether the failure of the protection is evident or not. The implications of each set are considered in the following paragraphs, starting with devices whose failure is evident.

A.1.13 Failure Consequences

The consequence categorization process shall clearly distinguish events (failure modes and multiple failures) that have safety and/or environmental consequences from those that only have economic consequences (operational and non-operational consequences).

Safety consequences—a failure has safety consequences if there is an intolerable probability that it could kill or injure a human being. The distinction between a "tolerable" and an "intolerable" probability is very subjective and has to be defined a-priori for the whole evaluation process.

Beliefs about what is a tolerable level of risk of death or injury vary widely from individual to individual and from group to group. Many factors influence these beliefs. The two most dominant are the degree of control that any individual thinks he or she has over the situation and the benefit that people believe they will derive from exposing themselves to the risk. This in turn influences the extent to which they might choose to expose themselves to the risk. This view then has to be translated into a degree of risk that might be tolerated by the whole population (all the workers on a site, all the citizens of a town or even the entire population of a country).

Environmental Consequences—at another level, "safety" refers to the safety or well-being of society in general. Such failures tend to be classed as "environmental" issues. Society's expectations take the form of municipal, regional and national environmental standards. Some organizations also have their own even more stringent corporate standards. As a result, a failure has environmental consequences if there is an intolerable probability that it could breach any known environmental standard or regulation.

Operational Consequences—the primary function of most equipment in commerce and industry is usually connected with the need to earn revenue or to support revenue-earning activities. Failures that affect the primary functions of these assets affect the revenue-earning capability of the organization. The magnitude of these effects depends on how heavily the equipment is utilized and the availability of alternatives. However, in nearly all cases the costs of these effects are greater—often much greater—than the cost of repairing the failures, and these costs need to be taken into account when assessing the cost effectiveness of any failure management policy. In general, failures affect operations in four ways:

a. they affect total output or throughput
b. they affect product quality
c. they affect customer service (and may incur financial penalties)
d. they increase operating costs in addition to the direct cost of repair.

Non-Operational Consequences—the consequences of an evident failure that has no direct adverse effect on safety, the environment or operational capability are classified as non-operational. The only consequences associated with these failures are the direct costs of repairing the failure itself and any secondary damage, so these consequences are also economic.

A.1.14 Maintenance Strategy Selection (MMS)

The RCM decision making process provides a strategic framework for classifying all failures on the basis of their consequences.

The RCM decision diagram is used to:

- evaluate if proactive maintenance is technically feasible and worth doing.
- or what action should be taken if a suitable proactive task cannot be found.

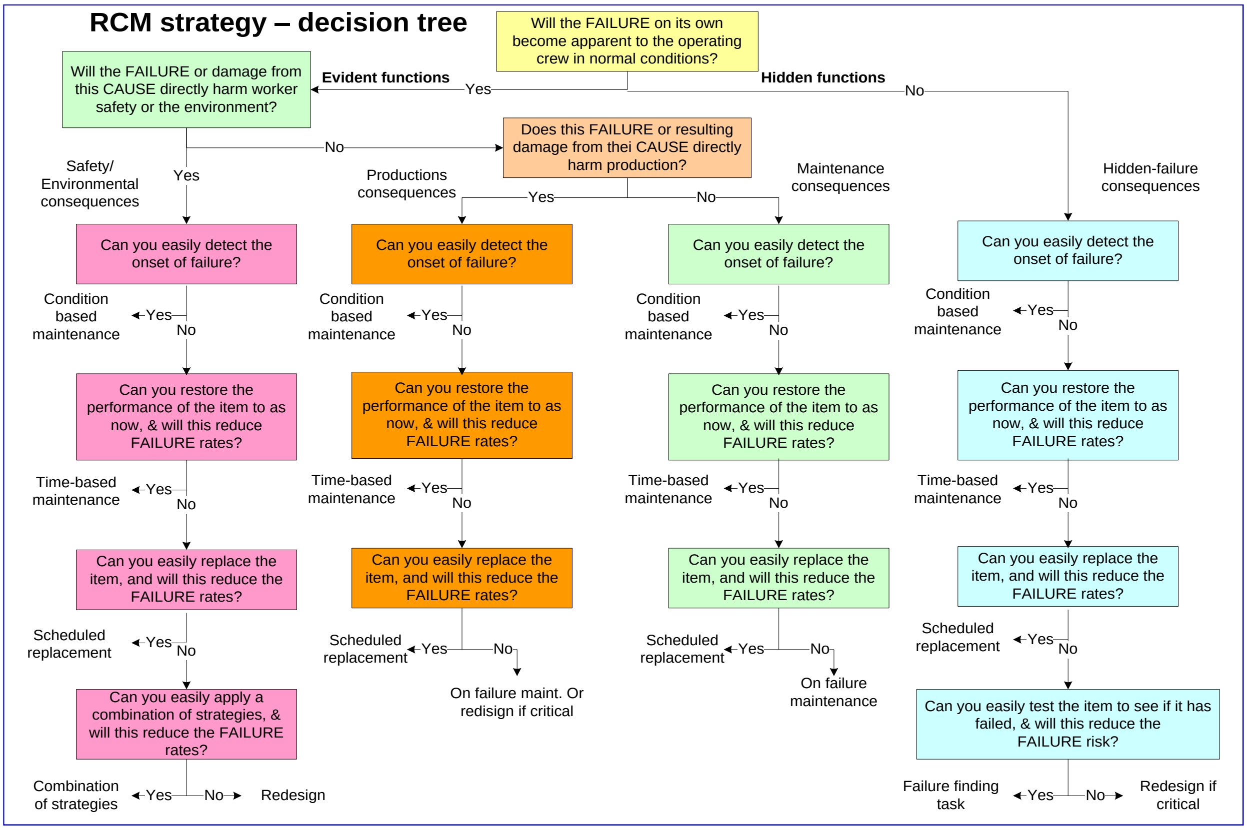

Figure 25: RCM Strategy Decision Logic

	Hidden Safety (or Environmental)	Evident Safety (or Environmental)	Evident Operational	Evident Non-Operational	Hidden Non-Safety (or Environmental)
On Condition	✓	✓	✓	✓	✓
Scheduled Overhaul	✓	✓	✓	✓	✓
Scheduled Replacement	✓	✓	✓	✓	✓
Fault Finding Task	✓				✓
On Failure Maintenance			✓	✓	✓
Re-Design	M	M	✓	✓	✓

Figure 26: Maintenance Strategies

Proactive Tasks

Proactive maintenance tasks are tasks undertaken before a failure occurs, in order to prevent the item from getting into a failed state.

Proactive tasks include both:

- predictive tasks and
- preventive tasks.

Task selection depends upon the following criteria:

- whether the task is technically feasible?
- whether the task is worth doing economically?

Predictive Tasks

Predictive or on-condition tasks are designed to detect potential failures.

A potential failure as an identifiable condition which indicates that a functional failure is either about to occur or is in the process of occurring

On-condition tasks entail checking for potential failures, so that action may be taken to prevent the functional failure or to avoid the consequences.

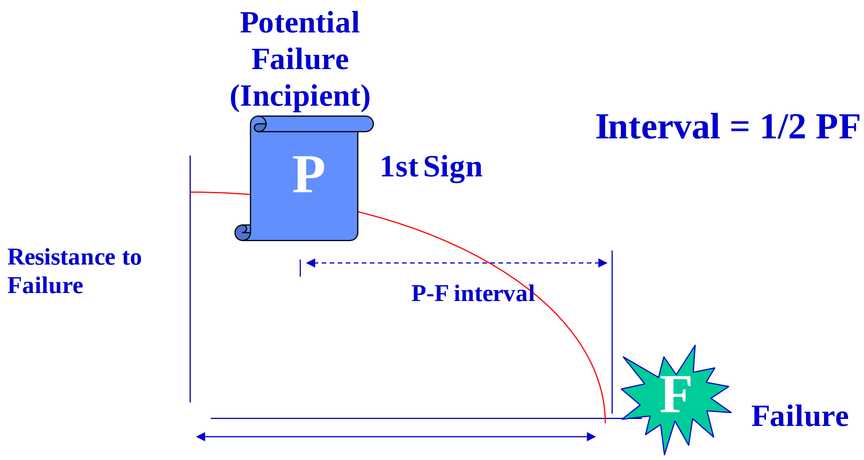

Figure 27: Frequency of Condition Based Tasks

Condition Based Maintenance (CBM)

Condition monitoring does not always mean expensive monitoring equipment

- Human senses (look, feel, hear, smell, taste)
- CM is a rapidly developing technology
- Trend graphs give warning
- Alarms, indicators should be set before the failure point

Condition maintenance techniques

- Dynamic - rotating equipment vibration & acoustics
- Particle - size, shape property changes
- Chemical - elements in fluids
- Physical - ultrasonic, coupon testing
- Temperature - thermograph
- Electrical - potential, impedance tests

CM Technical Feasibility

- do we have any prior warning of the failure?
- what is it?
- how long will it take to fail from the prior warning?
- is it consistent in time?
- will it give us enough time to respond appropriately?

If 'yes' to all the above then the condition monitoring task is technically feasible

Assessment of condition monitoring techniques

For operational & non-operational - over a period of time will the cost of doing the maintenance task be less than letting it fail ?

For safety & environmental - does this task reduce the risk ?

A.1.15 Preventive Tasks

Preventative tasks consist of two categories:

Scheduled restoration tasks entail re-manufacturing a single component or overhauling an entire assembly at or before a specified age limit, regardless of its condition at the time.

Scheduled discard tasks entail discarding an item or component at or before a specified age limit, regardless of its condition at the time.

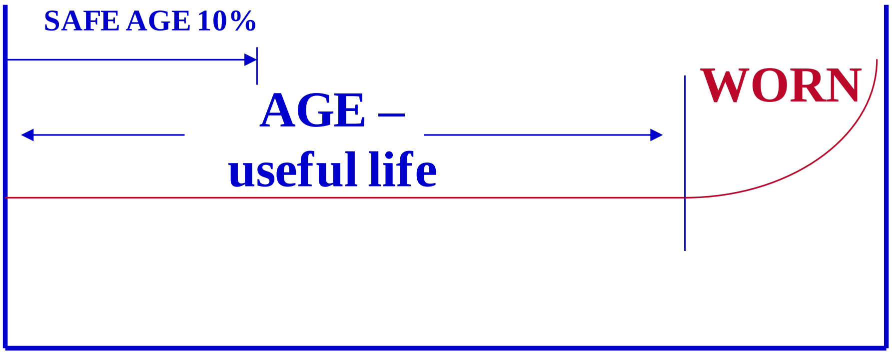

Figure 28: Restoration & Discard Age for age related failures

Restoration/discard technical feasibility

- do we have a reliable age projection ?
- what is the age ?
- will most items reach this age ? (if safety or environmental they must!)
- will we bring it back to as new (restoration) ?

if 'yes' to all the above then the restoration or discard task is technically feasible

Default actions – Evident failure

Redesign is mandatory for safety or environmental consequences

Redesign is optional for operational & non-operational consequences.

If the failure mode can be eliminated by a simple design change this should be considered - e.g. with training personnel, painting etc

Default actions - Hidden failure

The objective of a maintenance program for a hidden failure is to prevent - or at least to reduce the probability of - the associated multiple failure (A multiple failure is when the protected function fails and the protective device is also in a failed state)

If condition monitoring, scheduled replacement or scheduled discarding are not applicable then a failure finding task should be considered

Failure Finding Tasks

Scheduled failure finding tasks entail checking a hidden function at regular intervals to find out whether it has failed.

Failure finding tasks should avoid dismantling protective devices or otherwise disturbing them. It should be possible to carry out a failure-finding task without significantly increasing the risk of the associated multiple failures.

Failure Finding Intervals

To determine the failure finding interval for a single protective device the following information is needed:

- MTBF of protective device:
- desired availability of the device

Generic database MTBF (e.g. OREDA) or failure rate can sometimes be used if no other information is available.

A.1.16 No scheduled maintenance (run to failure)

No scheduled maintenance is only valid if:

- a suitable proactive or failure-finding task cannot be found for a hidden failure, and the associated multiple failure does not have safety or environmental consequences
- a cost-effective proactive task cannot be found for evident failures which have operational or non-operational consequences

A.1.17 Redesign

If a suitable failure-finding task cannot be found:

- redesign is compulsory if the multiple failure could affect safety or the environment
- redesign must be justified on economic grounds if the multiple failure does not affect safety or the environment

Redesign means:

- a change in the physical configuration of an asset or system
- a change to a process or operating procedure
- a change to the capability of a person, usually by training

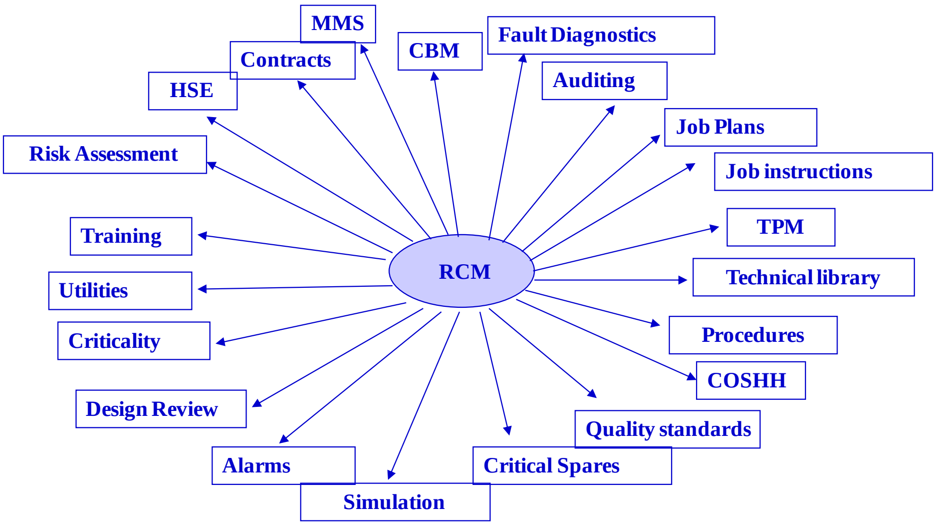

Figure 29: RCM Interactions

RCM and Safety Legislation/Regulations

A question often arises concerning the relationship between RCM and tasks specified by regulatory authorities (environmental legislation is dealt with directly).

Most regulations governing safety merely demand that users are able to demonstrate that they are doing whatever is prudent to ensure that their assets are safe. This has led to rapidly increasing emphasis on the concept of an audit trail, which basically requires users of assets to be able to produce documentary evidence that there is a rational, defensible basis for their maintenance programs. In the vast majority of cases, RCM wholly satisfies this type of requirement.

However, some regulations demand that specific tasks should be done on specific types of equipment at specific intervals. It quite often happens that the RCM process suggests a different task and/or a different interval, and in most of these cases, the RCM-derived task is a superior failure management policy.

However, in such cases, it is wise to continue doing the task specified by the regulations and to discuss the suggested change with the appropriate regulatory authority.

A.1.18 Application of a tool for RCM analysis in the process industry

The iRIS-Petro tool includes an RCM analysis module. The application of this module (Figure 30) in the process industry (Refinery) is shown in the example below. The components for which the RCM analysis is available are organized in a hierarchical tree.

Information such as component design and operational data is provided. Interventions carried out on the component for a specific failure type are indicated by checked boxes in the interventions grid.

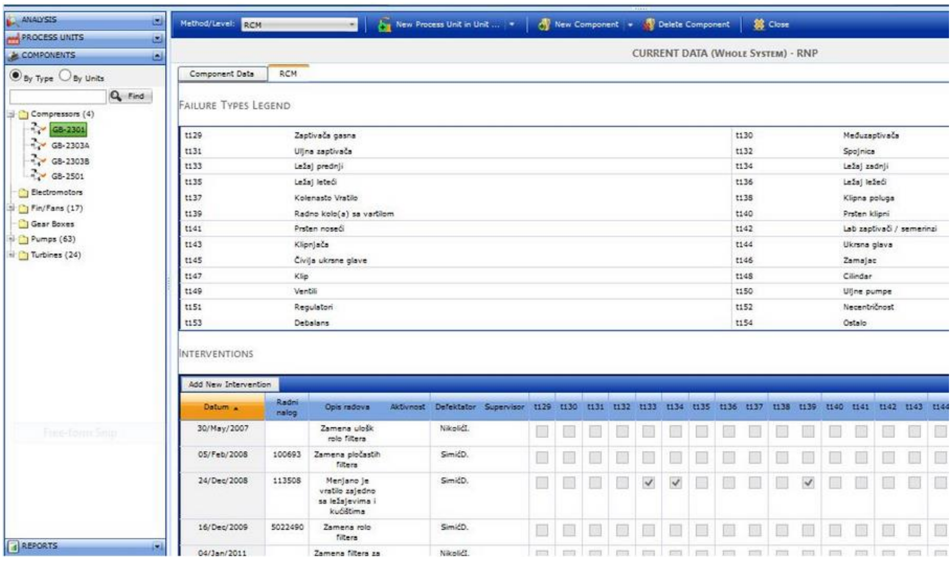

Figure 30: RCM Analysis in the iRIS-Petro tool

Reporting

RCM Analysis Calculation Report – Shown in Figure 31 below displays the current number of failures per month for the selected component type.

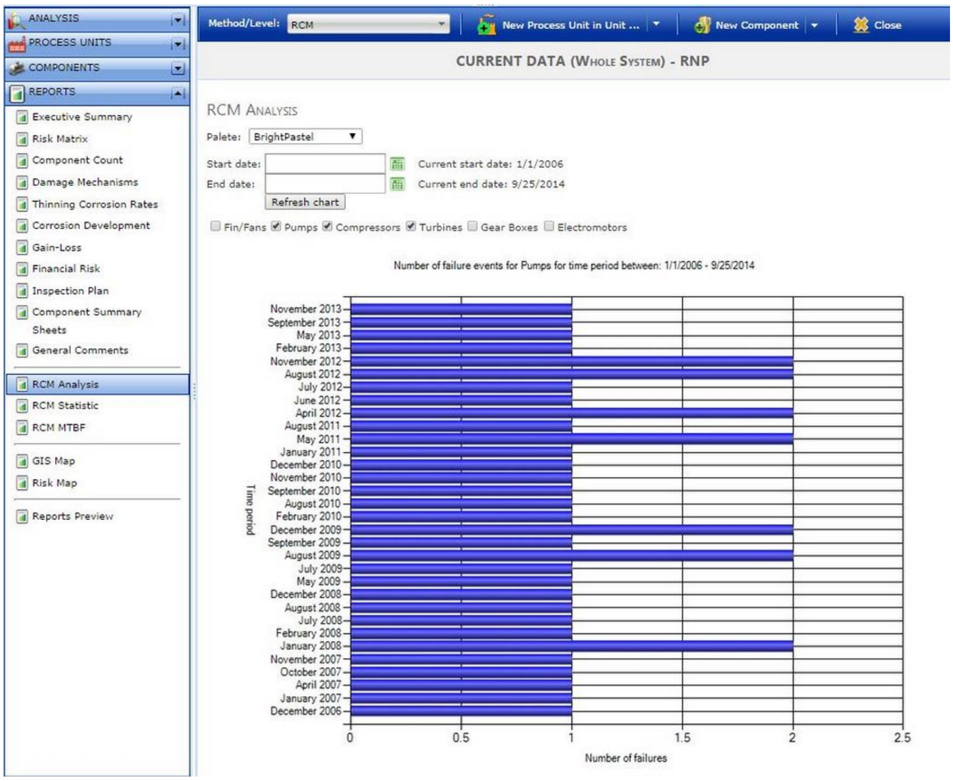

Figure 31: RCM Analysis Calculation Report

RCM Statistic Calculation Report – displays the number of failures regarding a specific component type and failure type, during a selected time period.

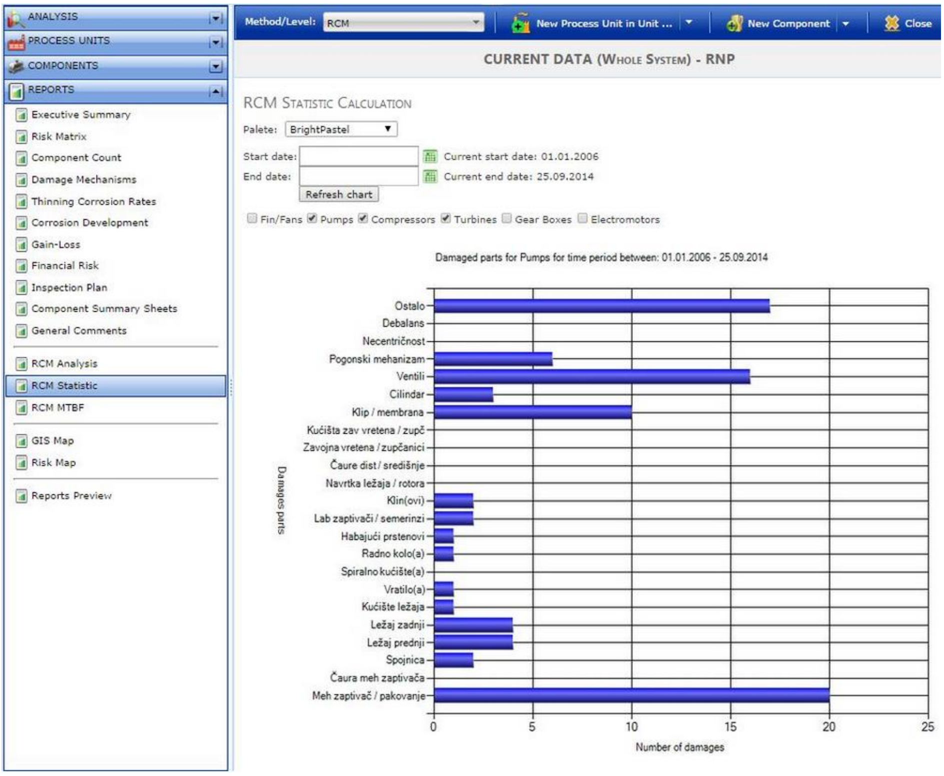

Figure 32: RCM Statistic Calculation Report

RCM MTBF Calculation – component reliability is defined as the probability that a component will be able to perform its function for a specific period of time. This reliability is defined by MTBF (Mean Time Between Failures).

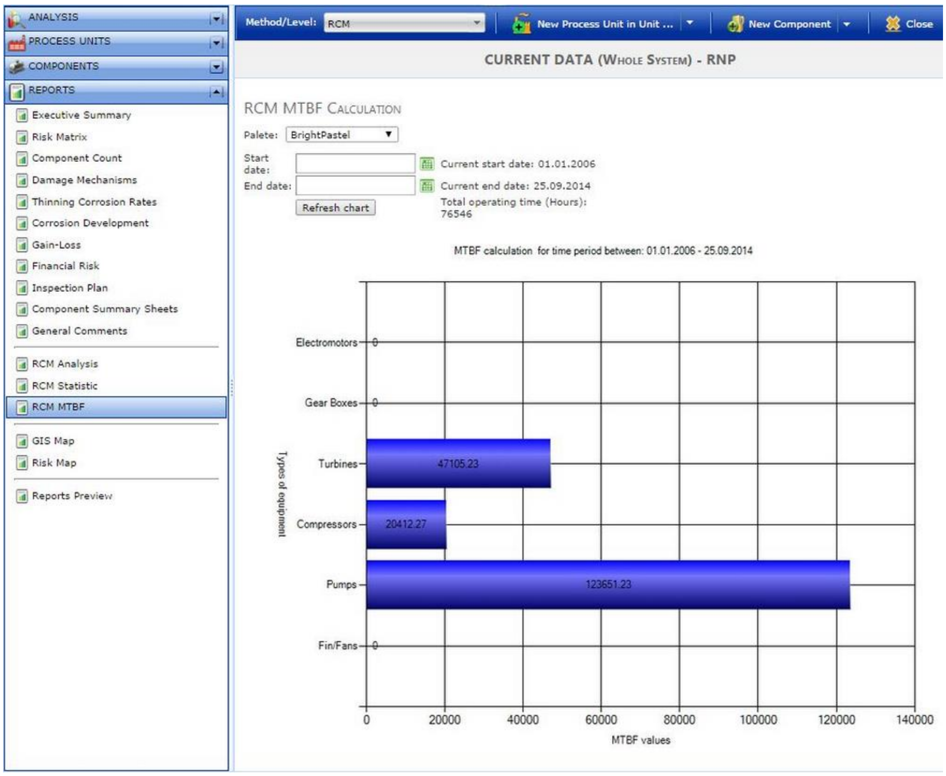

Figure 33: RCM MTBF Calculation

Annex 2 Managing aging by risk-based methods and inspection optimization: RBI – CEN CWA 15740

Introduction

This particular CWA provides the essential elements of risk based assessment of industrial assets according to the RIMAP approach which has been developed and demonstrated in and by the European R&D project RIMAP (GIRD-CT-2001-03008 and the corresponding RIMAP Network: "Risk-Based Inspection and Maintenance Procedures for European Industry"). One of the main goals of the project, as well as of this CWA, has been to contribute to the harmonization of the EU national regulatory requirements related to the inspection and maintenance programs in the industrial plants and make them more cost-efficient while, at the same time, safety, health, and environmental performance is maintained or improved.

The document is intended for the managers and engineers establishing the RBIM (Risk-based Inspection and Maintenance) policies in the companies in power, process, steel and other relevant industries. It is supposed to be used in conjunction with the relevant internationally accepted practices, national regulations and/or company policies. The document is supposed to provide a common reference for formulating the above policies and developing the corresponding inspection and maintenance programs within different industrial sectors, such as oil refineries, chemical and petrochemical plants, steel production and power plants. Each part of this Agreement can be used as a stand-alone document.

The positive impact and transfer of industry practices resulting from the use of this document and from the approach promoted by/in it are expected to be of benefit for the European industry and strengthening of its competitiveness through better inspection and maintenance practices.

A.2.1 Scope

The objective of this CEN Workshop Agreement document is to present a set of transparent and accurate framework for applying / implementing risk-based inspection and maintenance (RBIM) and risk-based life management (RBLM)[15] in industrial organizations

The document formulates the procedure for risk based approach, thereby supporting optimization of operations and maintenance (O&M) as well as asset management.

The purpose of RBIM is to ensure that clearly defined and accepted levels of risk related to:

- safety,
- health,
- environment and
- business/production/operation

are achieved using resource-efficient methods of inspection and maintenance. The methodology for RBIM described here is based on that developed in the European project RIMAP (Risk-based Inspection and Maintenance Procedures for European Industry) [1]. Within the RIMAP project, the RBIM methodology has been developed and validated for chemical, petrochemical, power and steel industries in Application Workbooks [10], [11], but the methodology as such is intended to be industry independent. The methodology addresses the following aspects:

- Inspection and maintenance
- All types of equipment, e.g. pressure containing, rotating, electrical, instruments and safety devices
- Technical and managerial aspects of maintenance and inspection planning
- Asset management related to inspection, maintenance and life assessment for plants, systems and components
- Production and operation

Although RBIM encompasses RBI & RCM, this document focuses primarily onto RBI. The RCM is included only up to the extent to demonstrate the applicability in the overall context of RBIM.

[15] Hence forth, the term RBIM will be used in this document in place of similar terminologies like RBLM, RBMI, etc.

A.2.2 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only cited applies. For undated references, the latest edition of the referenced document (including amendments) applies

[1] "Best practice for Risk Based Inspection as a part of Plant Integrity Management" by J.B. Wintle, B.W. Kenzie, G.J. Amphlett and others, ISBN 0717620905, Health and Safety Executive (HSE Books), (CRR 363/2001); www.hsebooks.com/Books/

[2] EN473 – "Non destructive testing - Qualification and Certification of NDT personnel – General principles", European Committee for Standaradization (CEN)

[3] CEN/TR 14748 Non-destructive testing – Methodology for qualification of non-destructive tests, European Committee for Standaradization (CEN),

[4] IEC 812 – "Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)", International Electrotechnical Commission (IEC),

[5] EN ISO 14224 –"Petroleum and natural gas industries – Collection and exchange of reliability and maintenance data for equipment", European Committee for Standaradization (CEN),

[6] NACE TM0248 – "Evaluation of pipeline and pressure vessel steels for resistance to hydrogen induced cracking", NACE Int. (USA)

[7] SAE JA 1011 – "Evaluation Criteria for Guide to the Reliability Centered Maintenance (RCM) Processes" (1998) – SAE International G-11 Supportability Committee; www.sae.org/technical/standards/JA1011 199908

[8] SAE JA 1012A – "Guide to the Reliability - Centered Maintenance (RCM) Standard" (2002), SAE International G-11 Supportability Committee; www.sae.org/technical/standards/JA1012 200201

[9] EN ISO/IEC 17020 (ISO/IEC 17020) – "General criteria for the operation of various types of bodies performing inspection", European Committee for Standaradization (CEN)

[10] EN ISO/IEC 17025 (ISO/IEC 17025) – "General requirements for the competence of testing and calibration laboratories", European Committee for Standaradization (CEN)

NOTE: Other cited references in the text of this document are presented as reference documents in Bibliography.

A.2.3 Definitions, symbols and abbreviations

A.2.3.1 Definitions

Risk is the combination of the probability of an event and its consequences (ISO/IEC Guide 73:2002 definition 3.1.1 "Risk management – Vocabulary – Guidelines for use in standards")

Risk Management is the systematic application of management policies, procedures, and practices to the tasks of analyzing, evaluating and controlling risk. (ISO 14971:2000)

A.2.3.2 Symbols

The symbols used in this CEN Workshop Agreement and corresponding designations are explained below.

Symbol	Designation	Unit
N_m	flammability index	
N_h	health index	
k_e	enclosure penalty	
k_ϑ	temperature penalty	
k_v	vacuum penalty	
k_p	pressure penalty	
k_c	cold penalty	
k_q	quantity penalty	
C_f	combustibility number	
C_h	toxicity number	
P_w	working pressure	bar
V	volume of the quantity of vapour or gas	m^3
M	mass of the liquid heated above the boiling point	kg
T	superheating above atmospheric boiling point (Tw - Θ b,a)	°C
m_h	mass of toxic substance	kg
C_{LP}	Cost of Lost Production	€
C_{PC}	Cost of restoring Primary failure (faulty item required for original function)	€
C_{SC}	Cost of restoring Secondary failure/ faulty items	€
C_{Id}	Indirect costs	€

A.2.3.3 Abbreviations

Abbreviations referred in the document are given below.

Acronym	Definition
ALARP	As low as reasonably possible/ practicable

Acronym	Definition
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CMMS	Computerized Maintenance Management System
CoF	Consequence of Failure
FME(C)A	Failure mode, effects (criticality) and analysis
HAZOP	Hazard and operability (study/analysis)
HCF / LCF	High Cycle Fatigue / Low Cycle Fatigue
HFF / LFF	High Fluid Flow / Low Fluid Flow
HS(S)E	Health, Safety (Security) and Environment
HSE	Health, Safety & Environment
HT	High Temperature
KPI	Key Performance Indicators
LoF	Likelihood of Failure
MTBF	Mean Time Between Failure
NDT	Non-destructive testing/inspection
O&M	Operation and maintenance
P&ID	Process and Instrumentation Diagram
POD	Probability of Detection
PoF	Probability of Failure
QA	Quality Assurance
QRA	Quantitative Risk Analysis
RBI	Risk Based Inspection: methods to plan, implement and evaluate inspections using risk based approach
RBIM	Risk Based Inspection and Maintenance: methods to plan, implement and evaluate inspections and maintenance using a risk based approach
RBM, RBLM	Risk-Based Maintenance, Risk-Based Life Management
RBWS	Risk Based Work Selection
RC(F)A	Root Cause (Failure) Analysis
RCM	Reliability Centered Maintenance: methods to plan, implement and evaluate maintenance using reliability to rank the importance of targets and measures
RIMAP	Risk based Inspection and Maintenance Procedures

A.2.4 RIMAP Framework

A.2.4.1 RIMAP vs RBIM

The collection of reports on Risk Based Maintenance and Inspection (RBIM) is the deliverable from the European Commission funded project **RIMAP - Risk Based Maintenance Procedures for European Industry [1]**. The documentation provides guidance for risk-based planning and execution of maintenance and inspection. Hence forth the term "RIMAP" used in this document will be synonymous to the RBIM methods as applied in the RIMAP project.

The RIMAP documentation provides also the guidance for quality assurance and follow-up of activities, tasks and work processes within an organisation that is used for risk-based asset management. The need for quality of all the elements in the work process elements and the need for continuous improvement shall be emphasised. Also, it is important to ensure that the link between the engineering planning and the actual execution of RBIM is maintained. RBIM should not be considered as a 'quick fix' methodology for reducing costs but as a comprehensive philosophy for managing asset integrity. The procedure therefore needs to be endorsed and supported by management and its use encouraged accordingly.

A.2.4.2 RIMAP Principles

Since the late 1990's the maintenance approaches in industry have been globally moving from prescriptive/time-based towards risk-based inspection decision making. This trend is driven by the clear objective to increase the on-stream production time to reduce unscheduled downtime due to breakdown maintenance or unknown equipment condition which may ultimately cause a shut down.

In general terms, if a company wants to apply a simple prescriptive maintenance/inspection approach then it is necessary to apply strictly conservative criteria for the decision making process.

A risk-based approach on the contrary needs a detailed multi-discipline engineering analysis to ensure that safety issues are not sacrificed by implementing a maintenance/inspection planning process. An appropriate risk-based methodology covers following principles:

- Plan the primary work products of RBIM assessments and management approach in such a way that risks at system and/or equipment level are managed, highlighting risks from both safety/health/environment (HSE) perspective and/or from the economic standpoint
- Define the RBIM methodology in a framework which meets common sense (such as good engineering practices or industrial reference standards) in handling hazardous materials and situations in industrial equipment
- Address a generic work flow and competencies needed to handle projects in an appropriate manner

Define minimum requirements for performing and documenting RBIM assessments in order to comply with legal or normative regulations and guidelines

A.2.4.3 RIMAP Requirements

A.2.4.3.1 General requirements

The general requirements of RIMAP as applied to RBIM are:

a) The objectives and risk criteria should be clearly defined for the assessment.

b) The assessment and the applied detailed procedure should comply with the locally applicable legal and regulatory framework

c) The required level of input information should be available for the assessment.

d) The assessment should be performed in a multidisciplinary team by personnel with the required competence, and using procedures and tools that can provide the required results on the selected level of assessment.

e) The assessment and the applied procedure should be able to provide results, which are

- safe
- conservative

- representable in risk matrix, auditable and consistent with both the objectives and applied risk criteria
- supporting RBIM planning and decision making on the target system or component.

f) RBIM should be based on a team approach

g) RBIM should reflect the prevailing conditions in the plant, i.e. RBIM needs to reach the “evergreen” status.

A.2.4.3.2 Personnel requirements

Risk based inspection and maintenance management requires experienced personnel at all levels as well as appropriate routines for the execution of the work. Current relevant standards do not set fully comprehensive formal requirements for the qualifications of people that perform inspection and maintenance planning, even if the execution of inspection and maintenance activities is partly regulated through qualification schemes, such as e.g., ISO standards such as 17020 [9], 17025 [10], and European standard EN 473 requirements [2]. RBIM planning requires a multidisciplinary team with engineering competency within:

- Inspection and maintenance
- Specific equipment disciplines (e.g. materials, corrosion, electrical, fixed and rotating equipment)
- Safety and health issues
- Plant operation and process
- Reliability and risk assessment

NOTE: Particular cases may require special competencies. In addition, local rules and legislation, and the type of industry may set detailed requirements to competencies involved. Due consideration should be given to the width of background skills and expertise collated in the team. One or more of the skills may be possessed by one person, but it is emphasized that RBIM planning is a team effort.

A.2.4.3.3 Requirements for performing PoF analysis

General RIMAP requirements for PoF analysis as given in [5] are:

1. General acceptability
2. Conservatism of simplified approaches
3. Audiability of results
4. Performance
5. Multi-level approaches (qualitative-quantitative, in depth of plant)
6. Procedural character
7. No averaging
8. Additional aspects to be considered
9. These requirements is explained in detail below.

General Acceptability

RIMAP describes a methodology for PoF assessment, which can be either used alone, or alternatively combined with established methods. PoF assessment method should be verified / benchmarked against a recognized (established) methodology, which is generally being used, accepted and referred to in the open literature.

Conservatism of simplified approaches

The results from the risk screening may be on average conservative compared to the results from a detailed analysis. Available methods for determining Probability of Failure may vary in the level of detail. Method with less detail (e.g. qualitative analysis) can be conservative, in other words it may yield higher or equal average score of probability of failure compared to a more detailed approach.

Auditability of results

The results should be auditable to similar experts (peer view); therefore the methodology, the input data, the decision criteria and the results may be documented (the results may be recorded in an approved document).

Qualification

The RBIM team may include with written evidence the following areas of expertise: inspection, maintenance, materials technology, process technology, operations and facilitation. For each area of expertise a certain requirement should be defined related to education and experience. The facilitator should have expertise on the methodology and lead the analysis process. Some of the expertise may be combined in one person. An expert should back up the RBIM team on process fluid characteristics and the possible modes for loss of containment.

Multi-level approaches
(qualitative-quantitative, in depth of plant)

Both qualitative and quantitative approaches (ranging from screening to detailed) may be used. The use of descriptive terms, such as “very high” to “very low” or similar can be used only if the meaning (explanation) of these terms is provided. The approach can be multi-level both in terms of “qualitative/quantitative” and in terms of going “in-depth” into plant equipment hierarchy.

Procedural character

The PoF assessment shall be structured as a procedure with well defined boundary conditions (e.g. as provided within the RIMAP procedure).

No averaging

The PoF rating should be such that the highest rating for one of the individual aspects of different damage mechanisms and trigger events should control the final rating score in order to prevent averaging of the ratings for various aspects. Alternatively, probability tree diagrams can be used to model the causes leading to single PoF’s. In such a case, the probability of each branch in the reliability diagram can be combined (parallel/serial – OR/AND) in order to define the final PoF. The same applies to single PoF’s: they can be combined in the same way to avoid averaging and producing consequent unrealistic values of PoF.

Additional aspects to be considered

PoF analysis shall be done in such a way that the following aspects are covered to screen the operation to identify the active damage mechanisms

- identify susceptible damage mechanisms
- establish realistic (“best estimate”) damage rates
- link PoF to the effectiveness of the inspection program in the past as well as in the one planned for the future.
- determine the confidence level in the damage rate
- assess the effect of the inspection program on improving the confidence level in the damage rate
- assess the probability that a given level of damage will exceed the damage tolerance of the equipment and result in failure
- analyze possible interaction or synergy effects for all damage mechanisms.
- determine PoF with respect to the planned interval for the next inspection
- determine PoF with respect to risk acceptance criteria

A.2.4.3.4 Requirements for performing CoF analysis

RIMAP requirements for CoF analysis addresses various types of consequences as [4]:

1. General requirements for CoF assessment
2. Requirements on CoF_{safety}
3. Requirements on CoF_{health}
4. Requirements on $CoF_{enviornment}$
5. Requirements on $CoF_{business}$

Each of these requirements is explained in detail below.

General requirements for CoF assessment

In order to assess the CoF, at least the aspects Health, Safety and Environment should be included. There are two possible ways to deal with CoF (a) real consequences related and (b) potential consequences related (e.g. the RIMAP CoF). If the RBIM process is used for assuring Health, Safety and Environment rather than a financial optimisation, averaging of individual aspects (Health, Safety and Environment and/or business consequences) is not allowed.

Requirements on CoF_{safety}

The CoF_{safety} assessment shall be documented and approved by the responsible authorities recognized by the national regulations, if necessary.

The methods can be based on at least one or more of the following aspects (depending on the type of equipment and fluid):

- released mass flow rate of fluid
- type of release (instantaneous discharge of total contained quantity or by leakage at a specified rate)
- flammability
- toxicity
- energy release (pressure or heat)
- kinetic energy of projectiles

Requirements on CoF_{health}

6. The CoF_{health} assessment shall be documented and approved by the responsible authorities recognized as per the national regulations, if necessary.
7. The methods can be based on at least one or more of the following aspects (depending on the type of equipment and fluid):
    - properties of the fluid that effect health
    - released mass of fluid
    - effect on people in the long term

Requirements on $CoF_{environment}$

1. The $CoF_{environment}$ assessment shall be documented and approved by the responsible authorities recognized as per the national regulations, if necessary.
2. Environmental impact shall include effects on soil, air, surface water and ground water.
3. The methods can be based on at least one or more of the following aspects (depending on the type of equipment and fluid:
    - properties of the fluid that effect the environment
    - released mass of fluid
    - direct and indirect effect on flora and fauna
    - remediation effort

Requirements on $CoF_{business}$

The $CoF_{business}$ assessment shall be documented, if necessary.

A.2.4.3.5 Risk assessment Requirement

All requirements specified for personnel, PoF assessment and CoF assessment are also applicable to Risk assessment requirements [2]. In addition, the following requirements shall also be satisfied for conducting risk assessment:

1. Development of a scenario for each failure mode is a critical step. Even though various techniques are available such as fault tree analysis, event tree cause-effect methods, etc., bow-tie modelling is recommended due to the simplicity of charting different scenarios and the ease with which the result can be understood. When the bow tie model is constructed (the fault and event tree established) different scenarios for the failure modes can be developed by following different paths from root cause/damage mechanism to potential final consequence.
2. It is not allowed to combine PoF's and CoF's related to different scenarios (e.g. different failure modes) even if they refer to the same equipment.
3. Efficiency of the risk mitigating activities shall be connected to identified failure modes and the projected risk reduction shall be quantified.

A.2.4.4 RIMAP within the overall management system

The development and implementation of a RBIM plan requires resources such as personnel, budget, spare parts and documentation. Management should assess the effectiveness of the RBIM by monitoring performance indicators like reliability, costs and risks.

RBIM planning requires a multidisciplinary team with a range of engineering competency. Management should identify and define the objectives related to acceptable levels of risk in inspection and maintenance activities. The objectives should be transparent and support the company's overall objectives, with respect to health, safety, environment, production, quality, etc. The objectives should also be in line with national and other normative requirements, and possible contractual requirements.

The RBIM strategy should ensure that risk mitigating actions are identified and implemented before the health, safety or environmental (HSE) risks associated with an equipment failure become unacceptable. If the HSE risks are 'tolerable'/acceptable, actions to reduce economic and other business risks may still be needed.

RIMAP framework shall be seen as a part of the overall "Working process" consisting of

- Definition of objectives, goals and requirements
- Establishing of inspection and maintenance program
- Plan for tasks and activities in inspection and maintenance
- Execution of the work orders
- Reporting about failures and status
- Evaluation of the technical conditions
- Preparing for the improvement tasks
- Performing of corrective action
- Active management
- Management of change
- Operating procedures
- Safe work practices
- Pre-start-up reviews
- Emergency response and controls
- Investigation of incidents
- Training
- Quality assurance

A.2.4.5 Limitations

The RIMAP framework is also applicable to industries other than those directly addressed (petrochemical, chemical, power, and steel), however it is limited to non-nuclear applications. The RBIM framework only applies to systems and equipment in the in-service phase of the operation. For the design or fabrication phase, the relevant legislation and engineering standards shall be followed. If RIMAP principles or procedures are used, it shall be ensured that all measures are in compliance with local and national legislation. While applying RBIM following aspects should be kept in mind

1. An RBIM assessment is only as good as input data provided
2. RBIM is not a replacement for good engineering practices / judgement

A.2.4.6 Compatibility with other known approaches

The overall RIMAP approach is in general compatible with most other major risk-based approaches such as those designed by API [16], VGB [23] or ASME [12] and intended broadly for similar purposes. However, while the principles are largely similar, the user is warned against expecting identical results. There are differences in detail that may result in significant differences when using different approaches on the same plant, case or system. For example, unlike most other known approaches, RIMAP was originally designed to be in principle industry independent and providing seamless transfer between different levels of analysis (ranging from screening to detailed).

A.2.5 RIMAP Procedure

The RIMAP procedure provides guidance for developing and maintaining a risk-based inspection and maintenance program, preferably embedded into a higher level quality or risk management environment. The procedure is applicable to many industries and to different types of equipment (for example static equipment, rotating equipment, safety systems, and electrical/instrument equipment). The steps in the procedure are the same for all cases, even if the models and tools for assessing probability or consequence of failure may vary from one application to another.

The procedure includes the following main steps:

1. Initial analysis and planning
2. Data collection and validation
3. Multilevel risk analysis
4. Decision making and action planning
5. Execution and reporting
6. Performance review / evergreen phase

For each of the above steps the following elements are defined such as:

1. General description and scope
2. Requirements
3. Input
4. Procedure
5. Output
6. Warnings and applicability limits

An overview of the RIMAP procedure is shown in Figure 34.

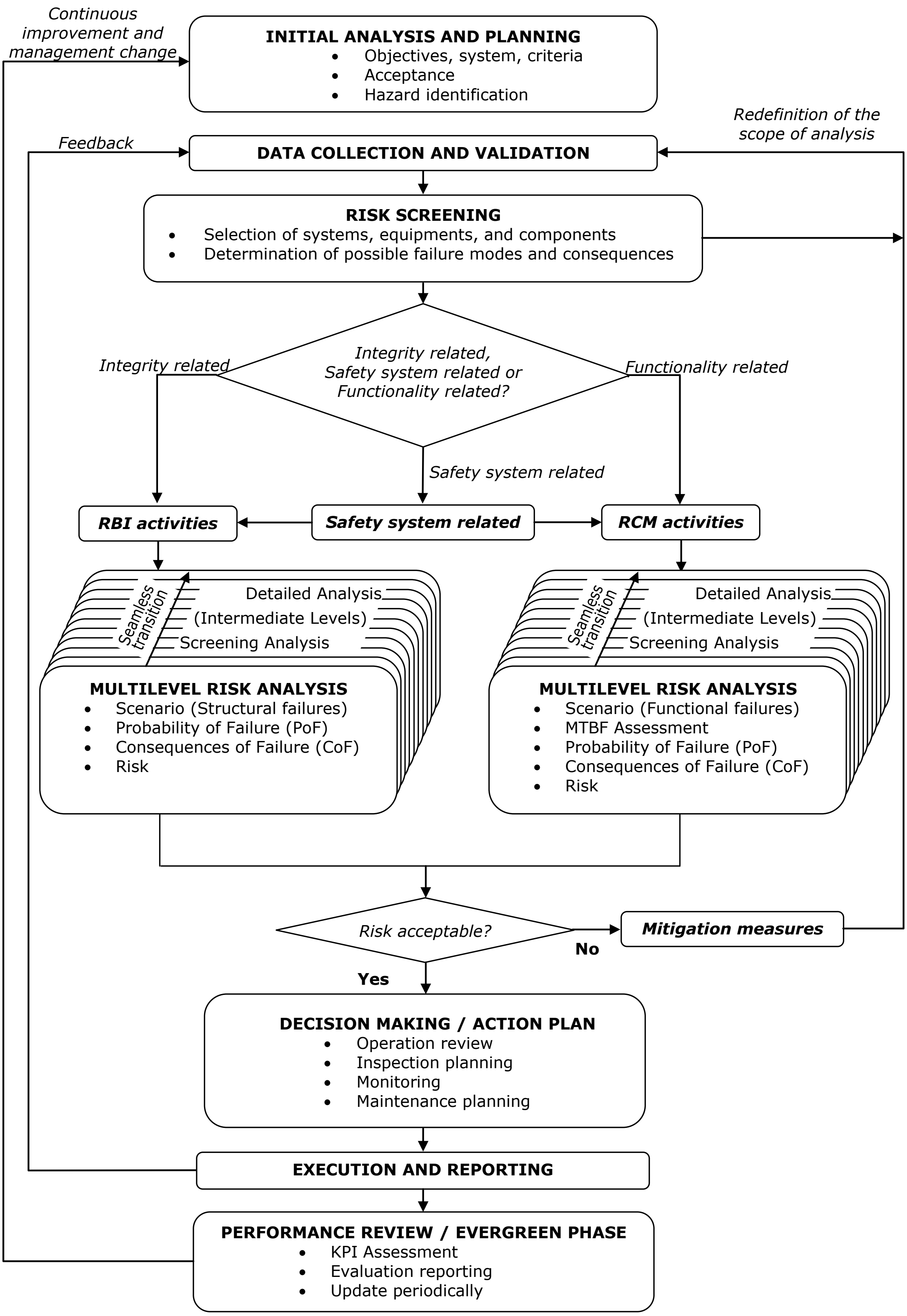

Figure 34 - Framework of RIMAP procedure within the overall management system

A.2.5.1 Initial analysis and planning

After having initiated the decision to establish RBIM using RIMAP procedure, the first step is to start with the initial analysis and planning.

A.2.5.1.1 General description and scope

This stage consists of the following steps:

1. Definition of objectives (e.g.:company Health and Safety objectives, optimise timing and extent of next inspection)
2. Definition of the systems and components to be considered as well as the respective boundaries (example: preheating system from inlet x to outlet y (P&ID No. xyz) including pressure vessels xyz, heat-exchangers xyz, and pumps xyz)
3. Definition of the scope of analysis, including operating conditions and exceptional situations to be covered (e.g. disturbances, accidents etc.), as well as the operating period covered.
4. Definition of data sources available (e.g. design data, equipment history)
5. Definition of regulatory requirements to be considered
6. Setup of the multi-disciplinary team
7. Tools (software) to be used
8. Assurance of the acceptance of the methodology and objectives with relevant institutions concerned (internal e.g.: management and external e.g. approved bodies and authorities)

In the following subsections, these steps will be described in more detail.

Definition of objectives

At this stage the management should clearly define measurable objectives of the assessment and confirm the applied procedure suggested by the assessment team. These objectives are largely defined in terms of health, safety, environment and business impact. In particular, risk based inspection and maintenance when applied to a plant should address one or more of the following objectives:

- meeting the requirements on health, safety and environmental regulations by reducing the corresponding risks to ALARP
- improving the safety and reliability of the plant
- optimising inspection and maintenance (possibly also production and quality) cost
- extending the useful service life of plant, e.g. beyond its design life, and implementing an appropriate end of life strategy.

The final objectives and targets of the implementation project to be initiated shall be fixed in writing.

Definition of systems and components to be considered

A risk-based analysis can focus on a network of plants, a single plant, certain systems (unit operations) of a plant, a certain component or even a part of it. The input step of the preparatory work serves the purpose of defining the systems and/or subsystems of interest.

Systems are generally defined based on the functions they perform. There are many ways to divide a system into sub-systems, i.e. to create a system-component hierarchy. The sub-systems should be easily manageable and meaningful to allow for assessment of specific issues related to them, e.g. according to particular damage mechanisms, a certain fluid, a process function or the same level of inventory. The level of detail on systems, equipment and its components, and their hierarchy may differ on the chosen methodology (RBI/ RCM).

Every system and sub-system should be clearly defined in terms of its boundaries, for example when considering a pump, whether only the impeller and housing or also the drive mechanism, the power source etc. are included. Establishment of boundaries is based on criteria specific to particular needs, such as safety aspects, operational requirements, process interactions, jurisdictional constraints, available data, etc.[16]

[16] For the establishment of boundaries in petroleum and natural gas industries, ISO 14224 [5] recommends rules for the definition of boundaries and also gives further guidance in the

As a general rule, one should remember that there is also a risk in defining the system to be assessed too widely. The complete picture of safety and integrity can be clouded by complexity or too much information, resulting in confusion and misinterpretation. On the other hand, too narrow a definition may lose sight of the impact a failure or process upset in one subsystem may have on another [25].

To establish the system/component hierarchy, every sub-system is further divided into components and/or locations that might relate to a system failure. This 'decomposition' should continue until the smallest components for which sufficient data from inspections, maintenance, and failure history are available or may be collected, are examined.

Definition of the scope

For all defined systems (from the input) the scope of the analysis should be determined including operating conditions, loads and exceptional situations e.g. upsets and the operating period to be covered.

Definition of data sources available

The data sources available shall be identified. It should be ensured that a minimum of information is available, as

- Design data
- Operating data
- Historical data (maintenance and inspection records)

Before collecting the data, the RBIM team should estimate the quality and quantity of the data that are needed to fulfil the requirements stated in the objectives of the assessment. The data should be balanced for the needs of the application (system or component), scope of the assessment, expected level of detail (or acceptable uncertainty) in the results, and foreseen future service.

Definition of regulatory requirements to be considered

Regulatory requirements which apply shall be carefully identified. Requirements may be on the qualification of some team members, software tools to be used (see 5.1.1.6 and 5.1.1.7 below), etc.

Setup of the multi-disciplinary team

Successful risk based assessment, in general, can only be conducted if competent technical input and perspectives from different disciplines are available. This can be achieved only by team effort. To setup the procedure, the required expertise of the team should be defined. Usually a RBIM team should have competencies within

- Inspection and maintenance
- Specific equipment disciplines (e.g. materials, corrosion, electrical, instrumentation & control, fixed and rotating equipment)
- Health, safety and environment issues
- Plant operation and processes
- Reliability and/or risk assessment

Much attention should be paid in the beginning to the selection of the competent team, which is a key element in successful risk based assessment. No sophisticated details in the procedure or other tools can compensate for possible deficiencies in the team, because this would very much affect the quality of input information, foreseen failure scenarios and conclusion of the assessment.

Managing risk based inspection and maintenance requires experienced personnel at all levels, as well as appropriate routines for implementation (See section 4.3.2 on personnel requirements).

Where the needed expertise is not covered by in-house resources, appropriate external experts shall be consulted. This can apply to expertise in reliability and risk analysis, but particular cases may also require special competencies, e.g. in deterioration mechanisms or, statistics.

form of examples. In the case of power plants the most common criteria are plant availability and safety [12].

In addition, local rules and legislation, and the type of industry may set detailed requirements to competencies involved. Due consideration should be given to the depth of background skills and expertise collected in the team. One or more of the skills may be possessed by one person, but it is emphasised that RBIM is a team effort.

Tools to be used

In general it is impractical to perform risk assessment without the support of dedicated computer tools (software) for the purpose. Such tools are used for managing the input data and for performing the operations of risk assessment and related decision making. Computerised systems are also used to store the data, analyse results and other related information for the next time the need for analysis arises. Dedicated software tools are widely used to manage the large amount of input data that will be collected from the systems to be assessed. In such a case, it is convenient if the tool can be integrated with existing data collection systems, such as those used for inspection and maintenance.

The user shall make sure that the software to be used is able to comply with the targets given and that the basic calculation methodologies (if there are any) comply with local legal requirements.

Accuracy of the acceptance

At this stage the assessment team and the management should also have a general idea about the level of commitment and resources required for a successful implementation of the procedure, and about the time available to produce the results.

The responsible team should take all necessary actions to ensure the acceptance of the procedure and its objectives by the essential stakeholders, such as the owner, management, and the authorities/notified bodies.

HSE risk (Health / Safety / Environment)

The metric for risk based decisions should be defined via company standards and/or national legislation. For the process industry in general, three different risk criteria are used:

- Plant worker safety
- 3rd party safety (people outside the plant border)
- Environmental damage, long and short term

The risk acceptance criteria are used to derive the required maintenance activities within the given time frame. For degradation mechanisms developing with time, the degradation rate and acceptance limit provides an upper bound on the time to preventive maintenance or time to inspection. Also the effectiveness of an inspection method for detecting degradation and coverage shall be considered.

Other criteria: Business risk

In case of business impact, no similar absolute limits are provided by the regulatory framework or comparable practices. Instead, the business impact associated with the assessed risk is to be compared with the competing alternatives in monetary terms. To achieve reduction in the allocated resources e.g. through lower cost of inspection and maintenance, may require lower volume but improved targeting of inspections and component repair/replacement, rescheduling of such actions when possible, or changes in the process or operational practices. If necessary, also other quantities such as product quality may be used as additional risk criteria.

Combined criteria

For combined criteria, the HSE criteria should be used to define the limit of unacceptability (between intolerable and ALARP regions), when the HSE criteria arise from mandatory regulatory limits. This may leave other quantities such as economic criteria to define the limit of acceptability towards negligible risk (i.e. 'tolerable if ALARP' to 'broadly acceptable'). Also other quantities such as product quality may enter into the combined criteria, often using quality cost as common monetary basis for the combination.

A.2.5.1.2 Requirements

The responsible team should take all necessary actions to ensure the acceptance of the RIMAP procedure and its objectives by the owner and/or management of the plant and by the responsible authorities.

A.2.5.1.3 Inputs

From an applicability point of view, it may be more useful to perform a relatively thorough analysis of a smaller but well defined sub-system than a very approximate assessment of a much wider system. However, a rough screening level analysis can also be useful to pinpoint the sub-systems for more detailed assessment. There is also a risk in defining the system to be assessed too widely, as the complete picture could be clouded by complexity or a very large amount of information. On the other hand, too narrow a definition may lose sight of the impact that a failure or process upset in one subsystem may have on another [1]. The functional boundaries of a system may depend on the mode of plant operation.

A.2.5.1.4 Procedure

Lacking stakeholder support or even indifference to the objectives and procedure of the assessment can seriously limit the applicability of the effort taken. Such support should be seen as mandatory for meaningful assessment.

For defining credible failure scenarios, the team responsible for the implementation of the procedure should agree what within the context of their industry is considered a failure of an item of equipment. This activity should be a company issue. Moreover, the function of a component may depend on the mode of operation of the plant. For example, a feed water pump system comprising three units (pumps) is fully operational at full power (all three pumps are needed). The same system at less than full power contains one redundant unit (two pumps are needed; the third is a standby unit available on demand).

Therefore, whenever a plant may have more than one mode of operation, it is necessary to define failure criteria that take into account the specifics of each operational mode.

A.2.5.1.5 Output

The expected output from the preparatory work is the following:

- selection of the applied procedure, competent assessment team and supporting tools
- defined system of interest, system/component hierarchy and boundaries for the assessment
- objectives, scope and methods of the effort, as well as confirmation of stakeholder support for these
- collected regulatory requirements to set boundaries to the assessment and decisions affected by the results
- collected risk assessment criteria from foreseen health, safety, environmental, business and other impacts.

A.2.5.1.6 Warnings and applicability limits

The essential parts of planning, including the requirements, inputs, procedure and output all involve items of caution and applicability limits. Some of the most common ones are outlined below, with some specific issues related to static, active and safety equipment.

Specific issues related to static equipment

Many static components are subject to mandatory regulations, e.g. pressure equipment and storage vessels containing fluids with potential hazard of toxic release, fire or other environmental impact. In such a case the competent team should include or have otherwise available sufficient expertise on this regulations. These regulations will often require consideration of HSE criteria in assessment. The underlying potential hazards will frequently set the scenarios to be dealt with in the risk assessment.

Specific issues related to active components

Most active components are not subject to normative regulation, which therefore will not set the criteria of assessment. However, active components such as turbines, pumps, motors, compressors, generators, fans, valves and gears are often subjected to significant loading in service, and form important parts of the critical systems or subsystems to be considered from the risk point of view.

Active components in particular may have more than one mode of operation, and then it is necessary to define failure criteria that take each mode into account.

A.2.5.2 Data collection and validation

A.2.5.2.1 General description and scope

The collection and organization of relevant data and information are mandatory prerequisites to any form of risk based analysis. Much of this data is probably related to design, operation and failure information. The data are used to assess both the probability and consequence (and thus the risk) of a failure scenario with analysis method(s) that meet the requirements of the generic RIMAP procedure.

Information for risk-based analysis may be available or obtainable from many sources. However, the quality of the data can be very case-dependent. Where the data are sparse or of poor quality, the uncertainty associated with the risk assessment will be greater.

Before collecting data, the RBIM team should estimate the data that will actually be needed. This is partly to match the data collection with the analysis, and partly to assess the effort needed considering the data and information that are already available and data that require additional work. The collected data are best stored in a well-structured database, which will not only facilitate the assessment process but also updating and auditing the processes that are an essential part of the RIMAP procedure.

A.2.5.2.2 Requirements

Data should be collected from many different areas including:

- Plant level data
- Design Manufacturing and Construction
- Operational
- Maintenance and Inspection
- Safety systems
- Cost
- Generic or equivalent industry databases

In addition to reviewing documents, such as electrical diagrams, process and instrument drawings, process flow diagrams, maintenance and operating records and procedures, etc. the team should ensure that relevant non documented data are collected.

The team should have access to plant personnel who can provide an understanding of the actual plant configuration and operating conditions, the effectiveness of the plant inspection and maintenance programs, the identification of problems particular to the investigated plant. Involvement of plant personnel will contribute to their acceptance of the outcome of the risk based analysis and its success.

A.2.5.2.3 Input

It is recommended that the established RBIM team follows the data collection and validation procedure outlined below. It should be noted that before this step the team should have initially estimated the rough quality and quantity of data that is needed for the analysis. The collected data should be verified and stored, when used for RBIM analysis and documentation.

1. Collect and validate documented relevant data, which typically includes at least some elements of the following:
   - Technical data on design, manufacturing and construction
     These data are largely plant and component specific, and in the form of numerical data and e.g. diagrams and drawings of the process and systems, components, controls and instruments, as well as safety systems. These background data also describe the functional requirements and intended loadings, and may indicate potential locations of failures. Data validation can be performed by internal cross-comparisons, comparison to physical and technical limits of the process and by cross-comparison to expert opinion (see below on non-documented data).
   - Inspection and maintenance history (including failure analysis)
     These data are plant and component specific, and typically include records of inspection results and of possible corrective actions such as repairs or modifications to the original system or component. The records may also include experience on the mode and causes of failures or other process disturbance. Most recent data updates preceding information, and it may be possible to construct time series from these data. Records of previous engineering and failure analysis, as well as data and results from other procedures (e.g. RCM, QRA, PHA, and HAZOP) can be considered

as input to the RBIM analysis. Data validation can be performed as above for other documented data.

- Operational history
  These data are plant and component specific, and may include at least some records of operator logs to identify operating periods, transients, starts, trips and other shut-downs, and load levels during different phases of operation. These records also indicate to what extent the actual operation may have deviated from that intended in design. For predicting the future performance it can also be important to consider the future mode of operation, if it is foreseen to be different from that in the past. Data validation can be performed as above for other documented data.
- Generic failure and operational data for similar cases or components
  Generic data on failures for similar cases and components is available from various sources [10], [11]. Generic data on operational experience are partly included in these sources, although the available information can vary widely depending on case and component. Data validation can be mainly performed by comparison of such sources and by expert opinion, but also in validation the options may be limited by the availability of information depending on the case or component.
- Cost information on the facility
  These data can in principle be plant and component specific, but are also often taken as generic for each component type and class, and type of action on it. Data validation can be performed by cross-comparisons or by asking for quotations from suppliers. The required information can also include cost of lost production and indirect losses.

2. Collect relevant non-documented data
   Relevant, non-documented data are generally available from most if not all of the sources (listed above) from which documented data should be collected. Non-documented data typically exists as personnel knowledge and opinions, which can be a very important source of information for RBIM analysis. Therefore, the team should have access to the personnel that can provide an understanding of the actual system and component configuration and operating conditions, the effectiveness of the inspection and maintenance programs, and identification of specific problem issues. The recommended interview process of the personnel (e.g. operator, maintenance engineer, instrument technician etc., called "expert" below) to estimate failure probabilities is as follows:

   a) Expert opinion on his/her general experience with the component or system
      In this initial stage of the interview the expert is given the opportunity to describe his/her own experience or feelings about the target component (or multi-component system) and its history.
   b) Expert opinion on the perceived consequences (also personal) of unforeseen component failure
      This opinion can indicate the expected consequences but also potential personal bias when compared with opinions on other issues.
   c) Expert opinion on the earliest possible time of failure
      This question serves as an introduction to opinion-based life assessment of the component or system, first for the short-term end of the perceived scale.
   d) Expert opinion on the longest possible life (for a single component), or (for multi-element components) on a time when it is no more worth repairing
      This question is for the long-term end of the opinion-based life assessment. In case of multi-element component, an opinion on the number of failures per year (or other time period) after which the component is not worth repairing can also be helpful .
   e) Expert opinion on the reasons for the earliest and latest possible failure times.
      This question aims to encourage reasoning and forgetting possible previously memorised numbers and it is suggested that at least two reasons are given for both ends of the timescale.
   f) Expert opinion on reasonable time intervals between shortest and longest failure times
      Agreement on the intervals is important, because too coarse a scale will not reveal uncertainty, and too fine a scale may require excessively detailed thinking. Often 4-5

time increments are sufficient, and for many systems the increments are expressed in whole years. This allows for the establishment of a time scale from earliest to latest possible perceived failure time, with time increments in between.

g) Expert opinion on the likelihood or frequency distribution of failure in time
The expert is given e.g. 50 similar coins or comparable objects, and asked to place them on the above defined time scale intervals, at least one in each interval but otherwise in proportion of his/her feeling on when the failure is going to take place. In the end, the expert is re-queried to confirm or modify the distribution.

h) Recording of the resulting lifetime distributions
The resulting distribution can be normalised by multiplying the number of objects in each category (interval) by 2 and dividing the result by 100. The results are documented and provided for RBIM analysis.

A.2.5.2.4 Procedure

The collected data should be validated and stored, when used for RBIM analysis and documentation. Validation may not always be easy for one-off analyses or measurements, but cross-comparisons, checks for compatibility with physical and technical limits, compliance with calibration requirements or standards/guidelines can be often used for this purpose. Comparison to externally available information may also help, for example data on technical details and cost from the equipment suppliers.

Data and results from other procedures (e.g. RCM, Quantitative Risk Analysis, Process Hazard Analysis (PHA), and HAZOP, previous risk based assessments if available) can be considered too as input to the RBIM analysis.

Documented background data are often available as e.g. diagrams and drawings of the process and systems, components, controls and instruments, safety systems, and maintenance and operating records and procedures. Useful operational and other plant specific data can include severity, mode and causes of failures, and operator records to identify operating periods, transients, starts, trips and other shut-downs, and load levels during different phases of operation.

Relevant non-documented data and information are typically available as personnel knowledge and opinions. For these sources the RBIM team should have access to the plant personnel that can provide an understanding of the actual plant configuration, operational history, maintenance effort, and current/future condition.

A.2.5.2.5 Output

The output of the data collection and validation should be an assessment of all relevant and representative data, which are needed for the risk calculation of the components of interest. This data should be collated in an appropriate way, e.g. by storage in a database.

Depending on the availability of data, a change in the system/component boundaries identified during the initial analysis and planning may be needed. Also, insufficient data may require additional effort to produce new data through engineering analysis or by other means. In such a case, data validation and re-assessment is also needed.

The output of data collation and validation mainly consists of raw technical data and information related (or processed) to failure probabilities and consequences. The defined objectives and the system to be assessed can largely dictate the depth and extent of the output of data collection serving these higher purposes.

Support of the management and involvement of the plant personnel are important and will contribute to their acceptance of the outcome of the risk based analysis, and may also positively influence the quality of the data.

A.2.5.2.6 Warnings and applicability limits

The data related to design, manufacturing and construction (assembly) may not be always updated according to later modifications. This is particularly likely for older equipment that has been used for many decades and originates from the time before modern CAD/CAM documentation. The same may also apply to controls and instrumentation, and to operational and maintenance history records for similar reasons. Expert opinion of the plant personnel about these issues may be essential.

One problem in the data collection is the quality of generic databases – and particularly their failure frequencies to include information related to inspections, maintenance and operating conditions of a component. Thus, these databases should be used with care, and qualified for use in each case. Their applicability depends greatly on several parameters

- Type of plant/component (size and fuel type)
- Manufacturer
- Process fluid (including chemical control, corrosion, erosion)
- Operation parameters (process pressure and temperature, vibration etc.)
- Operating environment (moisture, temperature, etc.)
- Operating constraints (load following vs. steady state)
- Inspection system/program/techniques
- Geographic area (environment and external influences)

This means that in order to obtain a reasonable probability (or likelihood) one has to modify the generic data (i.e. to calculate equivalent data) by taking into account all conditions prevailing to the specific problem of interest (for more information, refer [5]).

Another potential problem is that the method of development of a generic database often screens out specific component failures. For example, the NERC-GADS [19] system is only concerned with derating and forced plant outages; component failures not associated with derating or forced plant outages go unreported [12].

A.2.5.3 Multilevel risk analysis (ranging from screening to detailed)

A.2.5.3.1 General description and scope

Risk analysis consists of the following steps:

a) Identify hazards
b) Identify relevant damage mechanisms and failure modes
c) Determine probability of failure (PoF)
d) Determine consequence of failure (CoF)
e) Determine risk and classify equipment

Multilevel risk analysis defines the risk assessment in terms of (i) complexity of the analysis (e.g. from the simplified/screening analysis to the detailed one), and in terms of and (ii) plant hierarchy level (depth). It can be seen in Figure 35, that complexity of analysis or in other words, the number of components for analysis decreases steadily from screening to detailed analysis in RIMAP approach, whereas it decreases step wise in a conventional approach It can be seen in Figure 36, that depth of analysis increases steadily from screening to detailed analysis in RIMAP approach, whereas it increases step wise in conventional approach

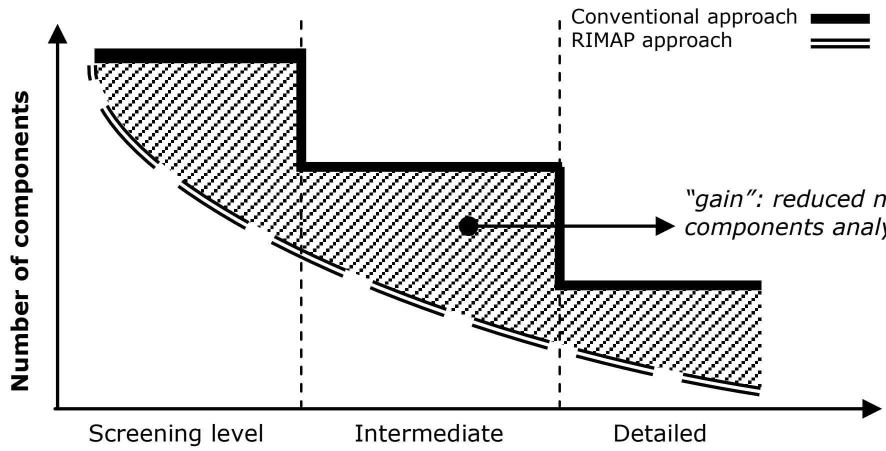

Figure 35 - Multilevel risk analysis: Complexity of analysis

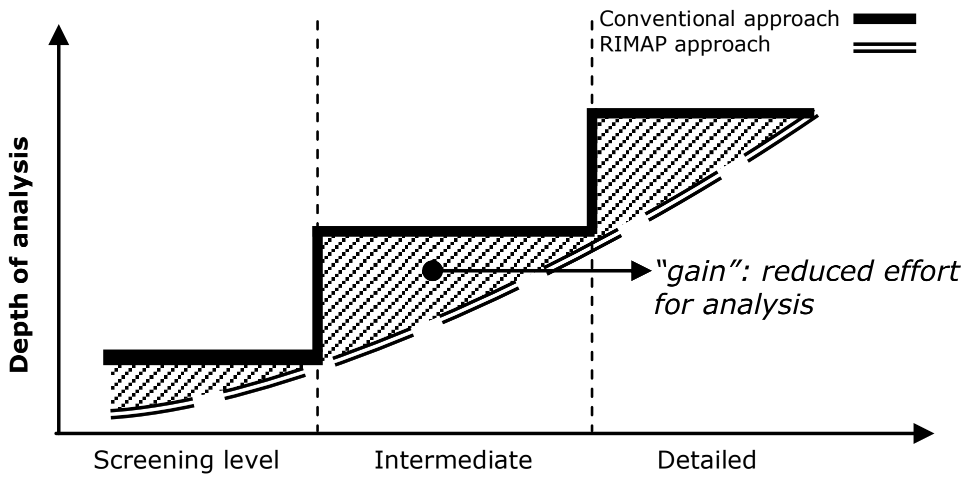

Figure 36 - Multilevel risk analysis: Plant hierarchy level

The inputs usually required for each step of screening and detailed phases of risk assessment are given in Table 11. It can be seen from the table that some inputs are common for both the phases, whereas the detailed phase calls for much more elaborate data for analysis.

Table 11 - Input source for Screening & Detailed risk assessment

Topic	Activities involved in Screening Risk Assessment	Common for both Screening & Detailed Risk Assessment	Activities involved in Detailed Risk Assessment	Specific for Detailed Risk Assessment[17]
A. Identify hazards	• Identify the relevant hazards for each system within the boundaries of the scope of work.	• Input from initial analysis and planning • Identify the relevant hazards for each system within the boundaries of the scope of work	See chapter 7.5.3.3.A	
B. Identify relevant damage mechanisms and failure modes	• Determine the operating conditions, upsets, likely excursions, as well as future process conditions should be taken into account to identify the possible degradation and/or failure likely to occur.	• Review the applicability of Damage mechanism classification (e.g. RIMAP I 3.1[3], OREDA [20], API [15]) and exclude those mechanism which do not apply	See chapter 7.5.3.3.B	• Determine Operating and design conditions, Upset conditions • Determine susceptibility windows of degradation mechanisms. • Characteristics of potential degradation mechanisms, e.g. local or overall degradation, possibility of cracking, detectability (in early or final stage). • Mechanical loading conditions • Geometry and structure of each piece of equipment from the point of view of susceptibility to damage mechanisms
C. Determine probability of failure (PoF)	• For each hazard identified in each system, the PoF should be assessed. • PoF should be determined for the pre-defined time frame. • The estimate should be conservative and based on the available information and expert judgment. • When the PoF has been determined, it should be assessed whether the PoF is high or low. This amounts to determining whether the PoF is higher or lower than a predefined limit. • If this is difficult one may set the PoF equal to 1 and perform a consequence screening	• Predefined time frame (from initial analysis and planning) • Maintenance and inspection history of the item of equipment under consideration. • Specification of the operating window including factors which can be influenced by the operation of the process (e.g. temperature, pressure) as well as factors which cannot be influenced by the operation (e.g. composition of the process medium). • Experience with similar equipment, e.g. average	See chapter 7.5.3.3.C	• Value of expected residual lifetime • Weighing system/factor to take account of the uncertainty of prediction • prediction of lifetime based on measured inspection data, a calculation making use of operating conditions, or expert opinion. Specific analysis tools may be used, e.g. probabilistic (safety) analysis and/or fitness for purpose analysis. • For non-trendable degradation mechanisms for which progress cannot be properly monitored or predicted (e.g. stress corrosion cracking), it should be demonstrated that degradation is prevented or detected early by means of sufficient measures to be taken (inspection, maintenance, operation). A methodology should be available in which the relation between the

[17] Eventhought the methodology is similar to all type of equipments, examples are explained based on static equipments.

Topic	Activities involved in Screening Risk Assessment	Common for both Screening & Detailed Risk Assessment	Activities involved in Detailed Risk Assessment	Specific for Detailed Risk Assessment[17]
		probability data from a relevant database. • Plant specific experience (data or soft knowledge).		effectiveness of measures (type, scope and frequency) and probability of failure is given. • Handling of unknown damage mechanisms.
D. Determine consequence of failure (CoF)	• The worst possible outcome of a failure should be established. The safety, health, environment, and business consequences shall be considered. Other consequences as quality of production and business impact may also be included. • When the CoF has been assessed it should be decided whether it is high or low, depending on whether the CoF is above or below a predefined limit. Possible limits are • Safety consequences: Any failure which may lead to injury of personnel. • Environmental consequence: Release of toxic substances. • Business consequence: any failure leading to loss of production or assets	• Composition of the contained fluid and its physical/chemical properties • Pressure, temperature and total amount of fluid available of release • Depending on national regulations more data, e.g. the final phase of the fluid on release into the atmosphere, the dispersal characteristics of the fluid at the site, mitigation systems such as water curtains, measures for detection of the leak/break. • If it is desired to include the potential leak/break area then the failure mode and the pipe/vessel size should be entered. • If it is desired to include business impact then the financial effect of production loss as well as repair/replacement costs should be entered. • If it is desired to include publicity damage then a financial value should be entered expressing the negative effect on future business. • For hazards with consequences other than fluid release, appropriate information on the nature and extent of the consequence is required	See chapter 7.5.3.3.D	• Characteristics of the relevant degradation mechanisms, e.g. local or overall degradation, possibility of cracking, detectability (in early or final stage). • If containment is considered, the composition of the contained fluid and its physical/chemical properties, the pressure, temperature and total amount of fluid available of release shall be available. To obtain satisfactory CoF assessments may in this case often require to defining a number of scenarios, e.g., small leakage, large leakage, and full rupture. • Credit may be taken for passive mitigating systems. • Consequences should also be assessed for hidden failures and test independent failures • Identify barriers.

Topic	Activities involved in Screening Risk Assessment	Common for both Screening & Detailed Risk Assessment	Activities involved in Detailed Risk Assessment	Specific for Detailed Risk Assessment[17]
E. Determine risk and classify equipment	• Determine the categories in which PoF and CoF are classified using the risk matrix shown in Figure 38. • Determine the risk category of the equipment • Based on the screening results the systems or groups of equipment should be given a low, medium or high risk. • Systems or groups of equipment with a high risk should be considered in a detailed assessment. • Systems of groups of equipment that have medium risk should be considered for maintenance. • Finally, for the low risk systems or groups of equipment the assumptions should be periodically checked. This may amount to verifying that the basic assumptions are satisfied, e.g. coating is satisfactory or that the operating conditions remain unchanged. For low risk systems minimum surveillance is required. • High risk systems should be considered in the detailed analysis. In any case, regulatory requirements should be considered.	Risk acceptance criteria (input from initial analysis and planning)	See chapter 7.5.3.3.E	• Determine risk to people (second and third parts)

A.2.5.3.2 Risk analysis - screening level

Description

Risk screening shall be relatively fast, simple and cost effective compared to more detailed risk analysis. Risk screening is particularly suited for broadly based problems and limited populations of items to consider. Risk screening divides the systems and groups of equipment into two groups: high-risk items and medium/low risk items.

The high-risk items should be analysed in detail. The medium risk items should be considered additionally in order to decide if minimum surveillance or detailed assessment should be followed. The low risk items should only require minimal surveillance to verify and ensure that the assumptions made during the screening process remain true. This could, for example, amount to verifying the condition of a painting, coating, functional compliance or the correct undistorted position of a structure.

If information is missing during the screening so that the risk associated with the equipment cannot be determined, the equipment should be regarded as having a high risk and reassessed using a more detailed assessment.

The work process for risk screening is detailed in Figure 37.

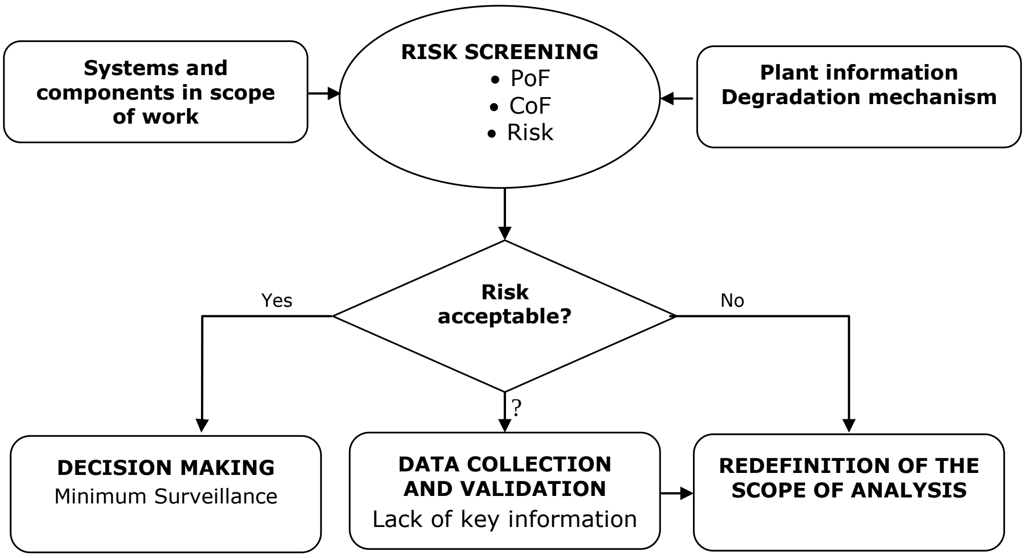

Figure 37 - Work flow for risk screening

Requirements

The following requirements should be fulfilled for risk analysis:

1. The rating criteria should be defined and recorded in writing.
2. The PoF should be established for a given (predefined) time frame based on a prediction of damage development for operation within a specified operating window. The specified operating window should include factors, which can be influenced by the operation of the process (e.g. temperature, pressure) as well as factors which cannot be influenced by the operation (e.g. composition of the process medium).
3. In order to assess the consequence, at least the aspects of health, safety and environment should be included. In addition, the consequence rating should be such that the highest rating for one of the individual aspects (health, safety, environment and/or business consequences) can control the final score (so no averaging of aspects).
4. The methodology should be verified / benchmarked.
5. This task should be performed by the RBIM team (see initial analysis and planning).

The results should be auditable by similar experts (peer review); therefore, the methodology, the input data, the decision criteria and the results shall be documented (the results shall be recorded in an authorized document).

Inputs

Table 11 presents the details required for performing the steps of risk assessment in screening level.

Procedure

Screening level of analysis is often sufficient to highlight areas with highest probability/frequency of failure in the plant (units/systems). The work flow of risk screening is given in Figure 37. The main purpose of the risk screening is to identify the low risk items (see Figure 38) and remove them from further analysis. It is very important that not too many components are placed in category Low risk, therefore it is useful to compare the spectra of assessed PoF, CoF and risk categories with those obtained in other similar assessments.

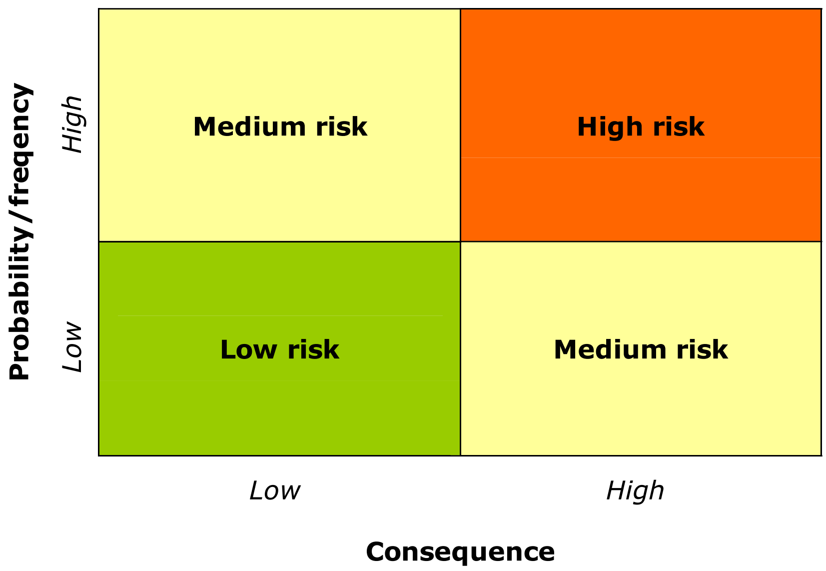

Figure 38 - Screening risk matrix

Output

Typical results from these tasks are:

- PoF value or category for the piece of equipment under consideration
- CoF value or category for the piece of equipment under consideration
- Risk value or category for the piece of equipment under consideration from screening risk matrix shown in Figure 5.

Warnings and applicability limits

Note that PoF assessments usually require more detail and are therefore more cost intensive than CoF assessments. Therefore some prefer to screen systems and groups of components on consequence of failure only. This is also acceptable, even if in this report other types of screening are suggested.

A.2.5.3.3 Risk analysis – detailed assessment

General description and scope

The detailed assessment differs from screening in the depth of detail required for analysis and hence involves considerably higher work effort for the assessment. Detailed assessment should be applied to the high risk systems and groups of equipment identified in risk screening, and to all equipment within the scope of work if no risk screening has been performed.

For each system or group of components, the relevant degradation mechanisms shall be identified and the extent of damage shall be estimated. Furthermore, the most likely damage development shall be determined. Based on this information, the maximum time interval to the next inspection / maintenance activity shall be determined subject to the condition that the health, safety and environmental risks remain acceptable (as defined in the acceptance criteria). This should then be combined with inspection / maintenance cost and inspection / maintenance effectiveness to derive cost optimal maintenance / inspection intervals such that the health, safety and environmental, risks are acceptable, i.e., the acceptance criteria are satisfied

The detailed analysis consists of the following main tasks:

a) Identify hazards.
b) Identify relevant damage mechanisms and failure modes.
c) Determine probabilities of failure (unmitigated and in later runs through the cycle mitigated).
d) Determine consequence of failure (unmitigated and in later runs through the cycle, the mitigated ones).
e) Risk assessment.

Requirements

Rating criteria shall be defined and recorded in writing.

The requirements for identifying and considering damage mechanisms are as follows:

- Identify all the damage mechanisms that can really appear in a given system/component
- The analysis should be performed by qualified personnel and in collaboration with people who know the plant well (e.g. personnel from the plant with good knowledge of the state of the components)
- The plant breakdown, identification of damage mechanisms and the analysis process should be duly documented
- The plant management should ensure that the knowledge about service and maintenance, history and all known degradation mechanisms in the plant, is considered in the analysis
- The responsible person(s) involved in the analysis should ensure that all knowledge about the degradation mechanisms from the available literature is considered in the analysis
- The responsible person(s) involved in the analysis should ensure that all available knowledge about the degradation mechanisms and experience from similar plants is considered in the analysis.
- All emerging damage mechanisms not accounted so far are considered (taken into account) under the category “other” damage mechanisms.

The analysis of failure modes enhances the level of detail used to assess the consequence of failure. If it is not undertaken, a conservative approach shall be followed. A conservative approach may be e.g. the assumption that the complete content of the containment may escape instantaneously.

The likelihood/probability shall be established for a given (predefined) time frame based on a prediction of damage development for operation within a specified operating window. The specified operating window should include both factors which can be influenced by the operation of the process (e.g. temperature, pressure) as well as factors which cannot be influenced by the operation (e.g. composition of the process medium).

For all trendable degradation mechanisms, the assessment of PoF in a detailed analysis shall be based on the value of expected residual lifetime and include a weighting system/factors to take the uncertainty of prediction into account. The prediction of lifetime may result from one of the following options: measured inspection data, a calculation making use of operating conditions, or expert opinion. If so desired, specific analysis tools may be used, e.g. probabilistic (safety) analysis and/or fitness for service analysis.

For all non-trendable degradation mechanisms, for which progress cannot be properly monitored or predicted (e.g. stress corrosion cracking), it should be demonstrated that they are prevented (due to proper design issues) or detected early by means of sufficient measures to be taken (inspection, maintenance, operation). A methodology should be available in which the relation between the effectiveness of measures (type, scope and frequency) and likelihood / probability of failure is given.

In order to assess the consequence, at least the aspects of health, safety and environment shall be included. In addition, the consequence rating shall be such that the highest rating for one of the individual aspects (health, safety, environment and/or business consequences) shall control the final score (averaging of these aspects is not done).

The methodology shall be verified / benchmarked. CoF_{safety} can be benchmarked against recognised methods already available.[18]

The task should be performed by the competent RBIM team (see Initial analysis and planning).

The results should be auditable by similar experts (peer review); therefore, the methodology, the input data, the decision criteria and the results shall be documented (the results shall be recorded in an authorized document).

Inputs

Table 1 presents the details required for performing the steps of risk assessment in detailed level.

Procedure

Detailed assessment is a relatively elaborate procedure involving multiple activities. Numerous activities are envisaged for carrying out the individual steps of detailed risk assessment.

A. Identify hazards

A number of tools can be used for identifying hazards. In this case it is recommended to carry out a system level failure mode and effects (and criticality) analysis, or FME(C)A as per the available standards [18]. There are also a number of software tools that can support FME(C) analyses. In addition other analysis methods such as HAZOP, What-if, or Checklists may be useful.

B. Identify relevant damage mechanisms and failure modes

The purpose of this task is to identify the relevant degradation mechanisms and failure modes. A failure mode is any possible state where a defined function cannot meet the desired performance standard.

The listing of failure modes is made easier if the functional breakdown is well described. All probable failure causes for the identified failure modes should be listed for the function. That could be failures dealt with by current maintenance program, historical failures and possible failures.

The RBIM methodology aims to foresee these and prevent them. The failure cause list should include all events that are likely linked to the identified failure modes. This should include equipment wear/deterioration, human factor impact, asset design etc.

The root cause phase investigates the underlying causes connected to the failure modes. Establishing the root causes increases the possibility of finding the appropriate tasks for preventing these failure modes. The hierarchical breakdown and the root cause phase in Root Cause Failure Analysis (RCFA) can certainly provide insights into relevant damage mechanism.

[18] Examples of established methods for CoF_{safety} are given as references [29], [30]

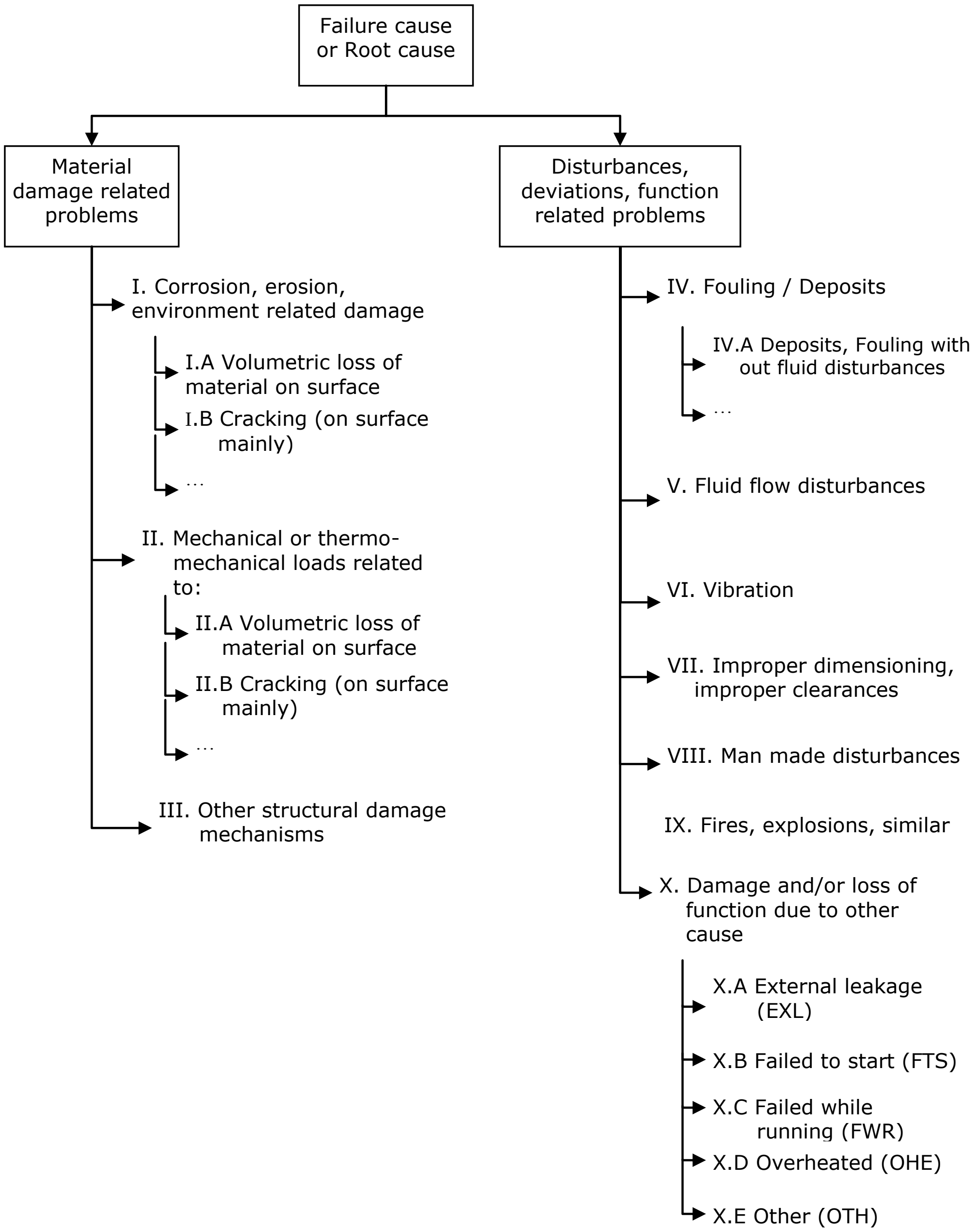

Figure 39 - Damage types appearing as failure or root failure causes in RIMAP

Furthermore, for each type of damage – component combination at least the following "flags" (attributes) should/can be included

S – related to safety ("safety related")

A – related to active components

E – related to/relevant for environment ("environment related")

D – type of damage – component combination that requires detailed analysis per default

Table 12 presents various types of in-service damage and their specification. The hierarchy of damage mechanisms in relation to the corresponding hierarchies of plant components and problems is also shown in Figure 40, with an example case taken of a fatigue problem.

The approach proposed in RIMAP lists the damage mechanism systematics proposed in Table 13 with inspection methods aiming to, yielding reasonable combination of POD (Probability of Detection), effectiveness and FCP (False Calls Probability). This is presented in Table 13.

Table 12 - Types of damage and their specifics mechanisms

Event, problem, issue	Id. and type of damage or disturbances / deviations, functional problems	Subtypes / specifics / further details / examples
MATERIAL DAMAGE RELATED PROBLEMS	I. Corrosion/erosion/environment related damage, leading to:	
	I.A Volumetric loss of material on surface (e.g. thinning)	I.A1 General corrosion, oxidation, erosion, wear, extended thinning
		I.A2 Localized (pitting, crevice or galvanic) corrosion
	I.B Cracking (on surface, mainly)	I.B1 Stress corrosion (chloride, caustic, etc.), cracking
		I.B2 Hydrogen induced damage (incl. blistering and HT hydrogen attack)
		I.B3 Corrosion fatigue
	I.C Material weakening and/or embrittlement	I.C1 Thermal degradation (spheroidization, graphitization, etc. incl. incipient melting)
		I.C2 Carburization, decarburization, dealloying
		I.C3 Embrittlement (incl. hardening, strain aging, temper embrittlement, liquid metal embrittlement, etc.)
	II. Mechanical or thermo-mechanical loads related, leading to:	
	II.A Wear	II.A1 Sliding wear
		II.A2 Cavitational wear
	II.B Strain / dimensional changes / instability / collapse	II.B1 Overloading, creep
		II.B2 Handling damage
	II.C Microvoid formation	II.C1 Creep
		II.C2 Creep-fatigue
	II.D Micro-cracking, cracking	II.D1 Fatigue (HCF, LCF), thermal fatigue, (corrosion fatigue)
		II.D2 Thermal shock, creep, creep-fatigue
	II.E Fracture	II.E1 Overloading
		II.E2 Brittle fracture
	III. Other structural damage mechanisms	
DISTURBANCES / DEVIATIONS / PROBLEMS (not related to structural materials)	IV. Fouling / deposits (without fluid flow disturbances)	
	V Fluid flow disturbances	
	V.A High / low fluid flow (HFF/LFF)	
	V.B No fluid flow (NFF)	
	V.C Other fluid flow problems (OFFP)	
	VI. Vibration (VIB)	
	VII. Improper dimensioning, improper clearances	
	VIII. Man made disturbance (deliberate and unintentional)	
	IX. Fires, explosions and similar	
	X. Damage and/or loss of function due to other causes	
	X.A External leakage (EXL*)	
	X.B Improper start or stop - failed to start/stop (FTS*)	
	X.C Failed while running (FWR*)	
	X.D Overheated (OHE*)	
	X.E Other (OTH*)	

* - acronyms broadly corresponding to those used in OREDA [20]

Hierarchical Structure of the plant: e.g. according to KKS

System: Boiler
└ Equipment: Economiser
  ├ *Component: Header*
  └ *Component: Tubing*

Event, problem, issues	ID and type of damage or disturbances / deviations, functional problems	Subtypes / specifics / further details / examples	*Header*	*Tubing*
MATERIAL DAMAGE RELATED PROBLEMS	I. Corrosion/erosion/environment related damage, leading to:			
	I.A Volumetric loss of material on surface (e.g. thinning)	I.A1 General corrosion, oxidation, erosion, wear, extended thinning	★	★
		I.A2 Localized (pitting, crevice or galvanic) corrosion		★
	I.B Cracking (on surface, mainly)	I.B1 Stress corrosion (chloride, caustic, etc.), cracking		
		I.B2 Hydrogen induced damage (incl. blistering and HT hydrogen attack)		
		I.B3 Corrosion fatigue		★
	I.C Material weakening and/or embrittlement	I.C1 Thermal degradation (spheroidization, graphitization, etc. incl. incipient melting)		
		I.C2 Carburization, decarburization, dealloying		
		I.C3 Embrittlement (incl. hardening, strain aging, temper embrittlement, liquid metal embrittlement, etc.)		
	II. Mechanical or thermo-mechanical loads related, leading to:			
	II.A Wear	II.A1 Sliding wear		★
		II.A2 Cavitational wear		★
	II.B Strain / dimensional changes / instability / collapse	II.B1 Overloading, creep	★	
		II.B2 Handling damage		
	II.C Microvoid formation	II.C1 Creep	★★	
		II.C2 Creep-fatigue	★	
	II.D Micro-cracking, cracking	II.D1 Fatigue (HCF, LCF), thermal fatigue, (corrosion fatigue)	★★	★★
		II.D2 Thermal shock, creep, creep-fatigue		
	II.E Fracture	II.E1 Overloading		
		II.E2 Brittle fracture		
	III. Other structural damage mechanisms			
DISTURBANCES / DEVIATIONS / PROBLEMS (not related to structural materials)	IV. Fouling / deposits (without fluid flow disturbances)			★
	V Fluid flow disturbances			
	V.A High / low fluid flow (HFF/LFF)			
	V.B No fluid flow (NFF)			
	V.C Other fluid flow problems (OFFP)			
	VI. Vibration (VIB)			
	VII. Improper dimensioning, improper clearances			
	VIII. Man made disturbance (deliberate and unintentional)			
	IX. Fires, explosions and similar			
	X. Damage and/or loss of function due to other causes			
	X.A External leakage (EXL*)			
	X.B Improper start or stop - failed to start/stop (FTS*)			
	X.C Failed while running (FWR*)			
	X.D Overheated (OHE*)			
	X.E Other (OTH*)			

Details on fatigue problems in component XYZ including priorities, PoF/ LoF data and references are provided in RIMAP Work books, in this particular case RIMAP Workbook Part I, section 3, page 73.

Note: Overall number of items covered in RIMAP Work book for Power plants approximates to 500, the stars (★) indicate presence of corresponding damage mechanisms. Two or more stars (★★, ★★★) indicate more important or more likely events, problems, issues …

Figure 40 - Types of damage and their specifics in relation to hierarchical structure of the plant according to KKS

Table 13 - Example of classification of type of damage vs. prioritized methods of inspection

What **type of damage**		***How*** **to look for it**		***Measure of uncertainty/risk for selected/preferred method***[19]				
Identifier and Type of damage	Damage specifics, damage mechanism	best POD[20]	most cost effective	selected method	POD for defect size of or size for			FCP[6]; comments, examples
					1 mm	3 mm	90% POD	
I. Corrosion/erosion/environment related damage, equating or leading to:								
I.A Volumetric loss of material on surface (e.g. thinning)	I.A1 General corrosion, oxidation, erosion, wear solid particle erosion	DiM, VT, ET, UT[21]	UT, (VT), DiM	UT	30÷70%	50÷90%	2 mm	
	I.A2 Localized (pitting, crevice or galvanic) corrosion	UT, DiM, ET	VT, UT	UT	30÷70%	40÷90%	2 mm	see [22]
I.B Cracking (on surface, mainly)	I.B1 Stress corrosion (chloride, caustic, etc.)	MT, PT, ET	MT, PT, ET	ET	max 85%	40÷90%	4±2 mm	<5% [23]
	I.B2 Hydrogen induced damage (incl. blistering and HT hydrogen attack)	UT, MT, PT, ET	MT, PT[24], MT[25]	UT	na	na	na	na
	I.B3 Corrosion fatigue	MT, PT, ET, VT	MT, PT, UT	UT	80÷96%[26] 86÷98%[27]	50÷99%[12,28] 95÷99%[14]	3±1 mm[12,29] 0.8±0.4 mm[30]	
I.C Material weakening and/or embrittlement	I.C1 Thermal degradation (spheroidization, graphitization, etc. incl. incipient melting)	MeT	MeT	MeT	(microscopy) ~100% POD for cracks > 1 mm, 90% POD crack ca. 0.05 mm; main "reliability related problems" linked to			

[19] if not mentioned otherwise all based on re-assessment of data [27]
[20] see Abbreviations in the main list of abbreviations
[21] AE - acoustic emission; PT - penetrant testing; DiM - dimensional measurements; VbM - vibration monitoring; DsM – on-line displacement monitoring; StM - on-line strain monitoring; VT - visual testing; ET – Eddy current testing; UT- ultrasonic testing; VTE - visual testing by endoscope; MeT - metallography, including RpT (replica technique); MST - material sample testing; na - not applicable
[22] the estimate can be affected significantly by local effects (e. g. small-scale pits can remain completely undetected)
[23] ET for non-ferromagnetic materials, sample results in [27]
[24] surface, also
[25] subsurface
[26] crack length
[27] crack depth
[28] for welds as low as 20%
[29] usually more than 5 mm for welds or steels
[30] can be more than 5 mm for welds

What **type of damage**		***How*** **to look for it**		***Measure of uncertainty/risk for selected/preferred method***[19]				
Identifier and Type of damage	Damage specifics, damage mechanism	best POD[20]	most cost effective	selected method	POD for defect size of or size for			FCP[6]; comments, examples
					1 mm	3 mm	90% POD	
	I.C2 Carburization, decarburization, dealloying	MeT	MeT	MeT	wrong sampling, wrong preparation and wrong interpretation of replicas (all numbers are very rough "guesstimates")			
	I.C3 Embrittlement (incl. hardening, strain aging, temper embrittlement, liquid metal embrittlement, etc.)	MST	MST	MST	na	na	na	
II. Mechanical or thermomechanical loads related, leading to:								
II.A Wear	II.A1 Sliding wear	VT, DiM, ET	VT, UT					
	II.A2 Cavitational wear							
II.B Strain / dimensional changes / instability / collapse	II.B1 Overloading, creep,	DiM	DiM	DiM	na	na	na	required resolution ≤ 0.1 mm or 0.5 %
	II.B2 Handling damage							
II.C Microvoid formation	II.C1 Creep	MeT	(UT), MeT					
	II.C2 Creep-fatigue							
II.D Microcracking, cracking	II.D1 Fatigue (HCF, LCF), thermal fatigue, (corrosion fatigue)	UT, (MT/PT), ET, VT	MT/PT	PT	max 90%	20÷90%	1.5÷6.5 mm [31]	
	II.D2 thermal shock, creep, creep-fatigue			MT	5÷90%	50÷90%	2.5÷10 mm [32]	
II.E Fracture	II.E1 Overloading	VT, DiM	VT	VT	na	na	na	analysis of causes
	II.E2 Brittle fracture							

[31] typical range; in extreme cases 0.5÷12 mm or more; more uncertainties for welds – but cracks transverse to welds detected easier than the longitudinal ones
[32] typical range; in extreme cases 1÷18 mm or more; applicable for ferromagnetic materials (steels)

C. Determine PoF

The current probability of failure and the PoF development over time should be assessed for all relevant damage mechanisms. The development of the PoF over time is an important parameter to consider when the maintenance/inspection strategies and intervals are determined later in the analysis. The probability of failure should also be linked to the appropriate end event in the bow tie model [5] to ensure that each consequence is assigned the correct probability of failure. In addition the uncertainty in the PoF assessment should be determined.

For introducing the PoF according to RIMAP procedure, three different types of source can be used. One common reference source is taken from statistical analysis of historical data (H/S) on failures in comparable components. A second common source is based on forecasting or modelling (F/M) of the foreseen failure mode in the component considered. The third source is expert judgment (E/J), whereby human expertise is applied to extract the best estimate of PoF (see Figure 41). The individual sources for overall PoF determination are combined as outlined in Figure 41. The elements from different kinds of sources can be modified according to factors related to source reliability and application.

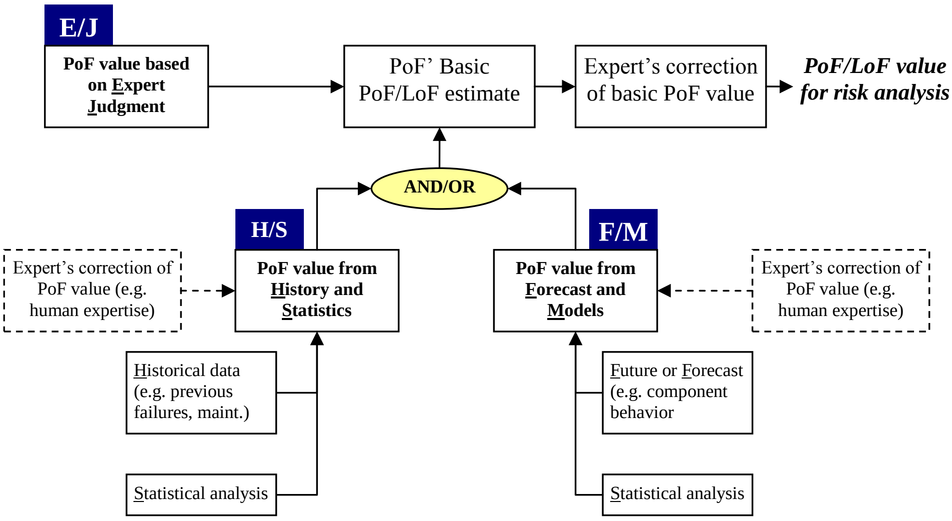

Figure 41 - Elements of PoF determination in the RIMAP concept

The logic involves the following steps:

1. To assess the failure scenarios the user may opt for two types of models:
   - Data-based models considering uncertainties in material data, NDT results, geometry, loads, etc.
   - Life models calculating the remaining life of a component based on the relevant damage mechanisms.

   There are several methods that can be also used when more than one failure scenario is considered e.g.: Monte-Carlo simulation, decision trees, fault-tree analysis, fuzzy rules, etc.

2. Assess, check, calibrate and correct basic failure frequencies by using expert judgment.

   These corrections can include factors like:

   - similar damage already appearing elsewhere in the same plant or in a similar plant
   - any qualitative indications and/or symptoms like irregularities in observations
   - higher loading than planned, unexpected loads (e.g. vibrations), etc.
   - changes in the operating conditions (e.g. operation mode)
   - any known problems with design or manufacturing

This approach allows combining of different levels and methods like expert judgment and probabilistic analysis consistently, also when applied for different or same components. The proposed approach is comparable and consistent with previously established approaches, extending them in several aspects. The extension is done by considering applicability in different industries, first by implementing relations between components in a plant and damage mechanisms, and by associating and suggesting appropriate inspection methods depending on the damage type and assessing the reliability of selected inspection method.

D. Determine CoF

The health, safety, environmental and business consequences of failure (CoF) are assessed for the relevant degradation mechanisms. Other consequences, e.g., image loss or public disruption, may also be considered. There are many approaches for gathering data necessary the CoF analysis. Four typical sources of information that can be used in the analysis of CoF are shown in Table 14.

Table 14 - Sources of CoF for detailed assessment

Source	**Description**
1. Historical data	Estimates are based on historical data of CoF for different failures. The data could be generic in databases, company statistics (from plant), benchmarks or recommended practices. For failures without historical data, similar failures are used for reference.
2. Forecast of future behaviour	Forecasting of degradation and item behaviour to future, to obtain the resulting CoF.
3. Expert judgment	Assess the CoF in co-operation with experts on the studied field (may be in-house experts or persons outside the company).
4. Modulation of behaviour	Modelling the CoF for different failures.

The detailed assessment for CoF for Health, Safety, Environment & Business involves calculations based on material properties, internal energy and the presence of people. Before going into the flowchart, it is necessary to determine toxicity number and combustibility number, which are discussed in detail in reference [4], [28], [29], [30]. The formula for these numbers are:

Combustibility number, $C_f = N_m\,(1+k_e) \times (1+ k_\vartheta + k_v + k_p + k_c + k_q)$ (1)

Toxicity number, $C_h = N_h\,(1+ k_\vartheta + k_v + k_p + k_c)$ (1) (2)

in which;

N_m	Flammability index
N_h	health index
k_e	enclosure penalty
k_ϑ	Temperature penalty
k_v	vacuum penalty
k_p	pressure penalty
k_c	cold penalty
k_q	quantity penalty

Figure 42 depicts the flowchart of a worked example for the estimation of CoF for Safety.

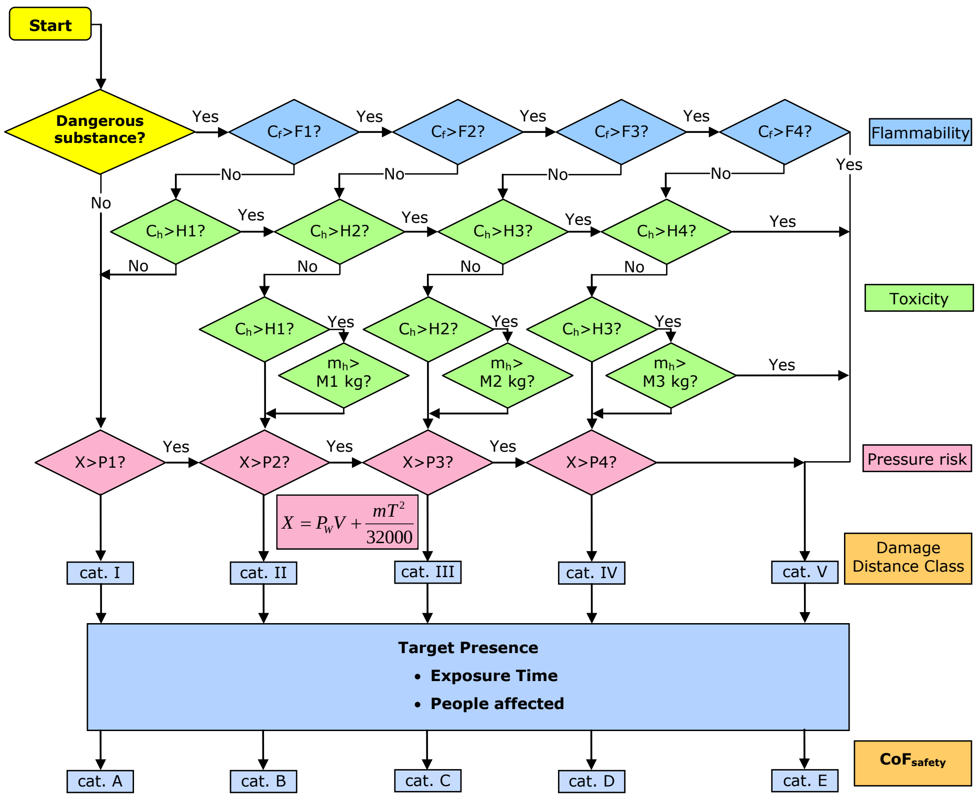

Figure 42 - Example of estimation of CoF for safety in RIMAP

The Safety consequence is classified according to the flowchart in Figure 42**Error! Reference source not found.**.

In the flow chart the following parameters and terms are used:

dangerous substance	any substance that is combustible (Nf>1), toxic (Nh>1) or extremely toxic (Nh>4)
C_f	combustibility number
C_h	toxicity number
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 flowchart uses numerical criteria as explained in Table 15.

Table 15 - Explanation of the numerical criteria given in the flowchart

criteria	Explanation
F1-F4	combustibility criteria being boundary values of the combustibility number. The exact values need to be determined (F1<F2<F3<F4)
H1-H4	toxicity criteria being boundary values of the toxicity number. The exact values need to be determined (H1<H2<H3<H4)
M1-M3	criteria related to the mass of toxic substance. The exact values need to be determined.
P1-P4	criteria related to the stored energy. The stored energy is calculated using the pressure, volume and the mass of liquid overheated above its atmospheric boiling point. (P1<P2<P3<P4)

Values for the criteria from Table 15 are presented in Table 16, both for a flowchart which results into a categorisation in three classes for the 'Damage distance' (this is actually the system included in the Netherlands rules for Pressure Vessels 0) and for a flowchart resulting into five categories. The values for the latter have been derived from those in 0 but should be considered as 'best estimates'.

Table 16 - Values of the numerical criteria in the 3 categories model in “The Netherlands rules for pressure vessels” the estimate criteria for the 5 categories model

criteria	3 categories, as formulated in 0	5 categories, estimated values
F	F1 = 65, F2 = 95	F1 = 35, F2 = 65, F3 = 80 and F4 = 95
H	H1 = 6, H2 = 9	H1 = 2, H2 = 6, H3 = 8 and H4 = 10
M	M1 = M2 = M3 = M4 = 500	M1 = M2 = M3 = M4 = 500
P	P1 = 900, P2 = 20000	P1 = 100, P2 = 900, P3 = 10000 P4 = 20000

Using the flowchart will result in a piece of equipment being categorised as of class I to V, the Damage distance classes. The classes represent the following boundaries for damage distance class is given in Table 17. The criteria of Table 15 shall be determined in such a way that a piece of equipment will be categorised correctly.

Table 17 - Example of class definition of boundaries for damage distance class

Class	boundaries
I	no lethality’s
II	X% lethality within 10 metres
III	X% lethality within 30 metres
IV	X% lethality within 100 metres
V	X% lethality > 100 metres <1000 metres

The Damage distance classes, combined with the target presence result in a categorisation in the CoF classes A-E; Safety Consequence. The categories are expressed in number of fatalities. The procedure to determine the target presence may at least contain:

- the numbers of persons in the area of the Damage distance class
- the percentage of the day they are present in the area of the damage distance class

There is no similar model available for Health impairment and Environment. If a similar model were to be developed for CoF_{health}, the health aspects of the substance should be translated in a health index (a index for the health effectson the long term), mass released, the time of exposure and the area affected. Similarly, environmental consequences can be analysed by looking at the costs. The costs are compiled of fines and remediation costs. The fines could be considered as the measures of environmental damage as viewed by the legislature. The environmental consequences of an event can have serious publicity consequences. These can be considered in the $CoF_{environment}$. In Figure 43, an example is given on decision logic to determine which elements are relevant in determining the cost associated with the environmental consequence analysis.

Similarly, the model for $CoF_{business}$ involves the costs from direct and indirect causes.

$$CoF_E = C_{LP} + C_{PC} + C_{SC} + C_{Id} \quad (3)$$

C_{LP} = Cost of Lost Production

C_{PC} = Cost of restoring Primary failure (faulty item required for original function)

C_{SC} = Cost of restoring Secondary failure/ faulty items

C_{Id} = Indirect costs

The costs determine the severity of the impact which can be categorised to arrive at a rating on the CoF scale, e.g. negligible, contained, etc. whereas the extent of damage distribution, viz. on-site or off-site, may also determine the impact.

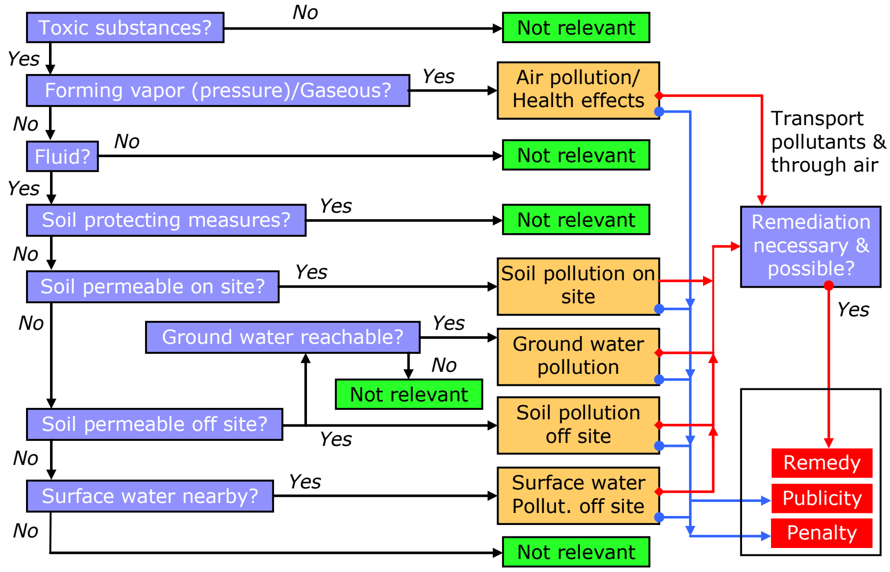

Figure 43 - Example of decision logic for $CoF_{Environment}$ in RIMAP

E. Risk assessment

When the PoF and CoF have been assessed, the health, safety, environment, and business risks are to be determined. The results can be plotted in risk matrices (see Figure 45) for presentation and comparison. Separate matrices should be used for each risk type unless it is relevant to compare the risk types. Note that the risk matrix presents the risk for a predefined time period.

It is generally useful to rank the evaluated components or items by risk level, because this will provide guidance on where to concentrate the inspection/maintenance effort and where such activities can be relaxed. If risks are measured in monetary terms, the expected need for mitigation investment as well as savings by avoided inspection and maintenance become then apparent. This requires that a reasonable cut-off level is set by the evaluated risk criteria.

Risk level	***Decision / Action criteria***
Very high	Define required inspection and maintenance program to reduce risk. Otherwise, consider equipment upgrade/ modification
High	Define required inspection and maintenance program to reduce risk. (Comment: can be acceptable if the driver is economic loss, security, image loss and public disruption)
Medium	Check if it is possible to reduce the risk through inspection and maintenance at low cost. Otherwise, find the optimal cost
Low	If no inspection and maintenance program plan exists, no detailed analysis is required. Otherwise, fine-tune it to find the optimal cost

Figure 44 - Example of decision / action criteria for various risk levels in risk matrix

Output

Typical results from these tasks are:

- PoF value for the piece of equipment under consideration
- CoF value for the piece of equipment under consideration
- Risk value or category from Figure 45

Warnings and applicability limits

Note that PoF assessments usually require more detail and are therefore more resource intensive than CoF assessments. Therefore some prefer to screen systems and groups of components on consequence of failure only. This is also acceptable, even if in this report other types of assessment are suggested.

Examples of PoF scales

Descriptive	MTBF	PoF	PoF category
Very probable	< 1 year	$>1\times10^{-1}$	**5**
Probable	1-5 years	1×10^{-1} to 1×10^{-2}	**4**
Possible	5-10 years	1×10^{-2} to 1×10^{-3}	**3**
Unlikely	10-50 years	1×10^{-3} to 1×10^{-4}	**2**
Very unlikely	>100 years	$<1\times10^{-4}$	**1**

PoF category	A	B	C	D	E
5					**Very high risk**
4				**High risk**	
3			**Medium risk**		
2		**Low risk**			
1	(Very Low, negligible risk)				

CoF category

	A	B	C	D	E
Health (Long term visibility)	Warning issued No effect	Warning issued Possible impact	Temporary health problems, curable	Limited impact on public health, threat of chronical illness	Serious impact on public health, life threatening illness
Safety (Instant visibility)	No aid needed Work disruption	First aid needed No work disability	Temporary work disability	Permanent work disability	Fatality(ies)
Environment	Negligible impact	Impact (e.g. spill) contained	Minor impact (e.g. spill)	On-site damage	Off-site damage Long term effect
Business (€)	<10k€	10-100 k€	0.1-1 M€	1-10 M€	>10 M€
Security	None	On-site (Local)	On-site (General)	Off site	Society threat
Image Loss	None	Minor	Bad publicity	Company issue	Political issue
Public disruption	None	Negligible	Minor	Small community	Large community

Examples of CoF scales

Figure 45 - An example of the risk matrix for detailed assessment, involving HSE and economic risks with four risk limit categories

A.2.5.4 Decision making / action plan

A.2.5.4.1 General description and scope

Conservative inspection and maintenance is an efficient approach when the mitigating actions are cheap compared to developing an optimized inspection and maintenance plan. In order to manage inspection and maintenance on a daily basis, programs with predetermined intervals are established [7], [8]. Based on the deliverables of the project so far, this section describes a proposed decision framework for the determination of an inspection and maintenance strategy.

The need for inspection and maintenance is directly caused by several factors:

- Wear and tear, and unreliability of equipment/machinery
- Unreliability of humans operating, maintaining or inspecting the equipment/machinery
- Legislation and other regulatory requirements
- External factors (earthquakes, harsh weather, etc.)
- Severity of consequence

The action plan consists in particular,

- Operation review
- Condition monitoring

Inspection and maintenance programs are established in response to this unreliability and risks as well as to the legal/regulatory requirements. Maintenance induced by human errors and external factors is not considered as a part of the usual inspection and maintenance program.

The termination of the ability of an item to perform a required function is linked with a failure cause, which could originate from circumstances with use, or maintenance. The inspection and maintenance strategy is the maintenance approach chosen in order to prevent physical and environmental damage, injury and loss of life or assets.

A.2.5.4.2 Requirements

The development of the RBIM plan will be done by a team including experienced personnel with following qualifications:

- Sufficient knowledge of Risk levels, PoF, consequences and inspection expertise depending on local requirements/legislation
- Qualified knowledge of the Maintainable items and experience with the facility (systems, equipment or component) to inspect. Generally, knowledge of reliability engineering practice or several years of familiarity with the operation and maintenance of the facility is required.

The team should have access to all relevant data and risk Analysis. The RBIM plan will contain all relevant details on the strategy level for execution in order to obtain the desired reduction of level of risk as set by the RBIM analysis and process.

A.2.5.4.3 Inputs

The RIMAP project has documented methods for determining and predicting damage mechanisms as well as methods for evaluating consequence of failure (CoF) and probability of failure (PoF). Damage mechanisms identified, CoF, PoF and the related risk are used as input for establishing inspection and maintenance methods in order to safeguard health, life, the environment and assets.

A.2.5.4.4 Procedure

The proposed decision framework is divided into a main level and inspection and maintenance strategy level. The main level is shown in Figure 46 and takes into account the following factors:

- the opportunity to eliminate failure causes
- the risk to personnel during execution of inspection and maintenance strategy
- the risk for introducing new failure causes

In case substituting the inspection and maintenance strategy is not possible, technical (e.g. robotics) or organizational (e.g. training) measures may be introduced to reduce risk for personnel and for introducing new failures.

The decision-logic serves three important purposes:

- to ensure a systematic evaluation of the need for preventive maintenance activities
- to ensure consistency of the evaluation between different plant systems
- to simplify the documentation of the conclusions reached.
-

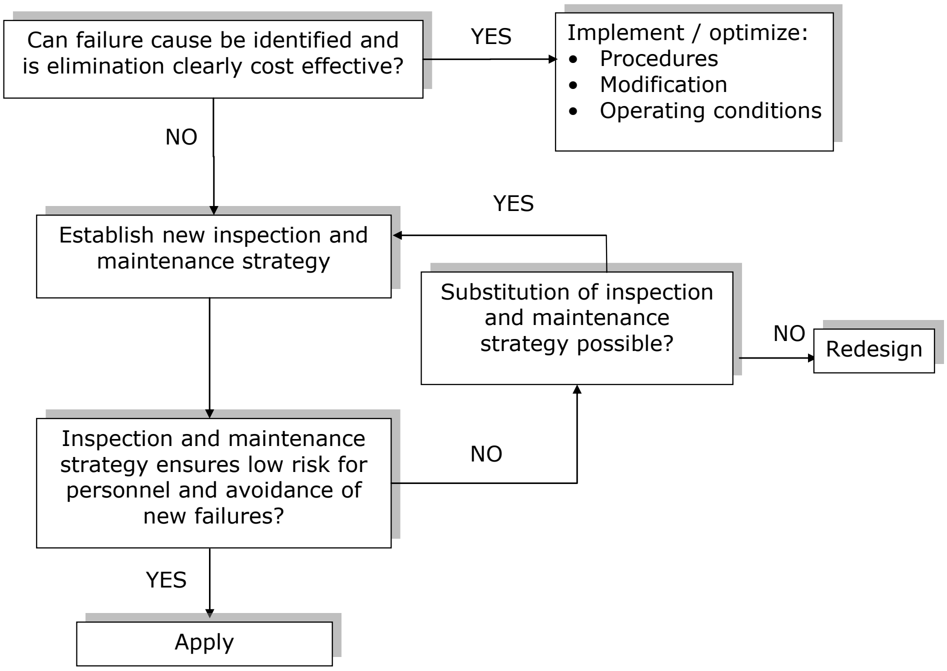

Figure 46 - The main level of the decision-making framework

When the inspection and maintenance strategy has been determined, the method, intervals, and extent of inspection should be determined so that risks remain acceptable and costs are optimised. This is achieved by establishing risk reduction measures for the items that exceed the acceptance limits, and where possible by mitigating measures like inspections and maintenance for items that remain below these limits for the period of assessment. The risk reduction effect of alternative measures as well as the costs of these measures should be determined.

A.2.5.4.5 Output

In principle, the decision logic gives guidance for establishment of the preferred inspection and maintenance strategy on basis of the criticality assessment, detectability of damage and the failure characteristics. The outcomes defined from the decision logic are:

- Elimination of failure cause
- Regular functional testing/inspection
- Time and condition based maintenance
- Operational maintenance
- Corrective maintenance.

A.2.5.4.6 Warnings and applicability limits

The methods of risk reduction should be chosen based on cost optimization subject to the boundary condition that the health, safety and environmental risks satisfy the HSE acceptance criteria.

A.2.5.5 Execution and reporting

A.2.5.5.1 General

The output of an RBIM plan is the input for the planning and scheduling for all involved departments, disciplines and contractors for the inspection and maintenance work for the facility and its maintainable items. The output of the development of the RBIM plan will be based around a maintainable item and will have a broad variety of strategies such as the elimination of the risk through monitoring, performance testing and improvement of procedures for process, operation and/or maintenance, inspection, modification, repair, replacement, or operation to failure. Maintenance work can be split into three main categories shown in Table 18 below.

Table 18 - Principal categories of maintenance

Type of maintenance	Typical procedure	By whom
1. On-stream	No plant shutdown required	Operating/own staff/ specialists
2. Short shutdown	Shutdown up to a week to change worn equipment, or changes called by process (catalysts, molecular sieves, etc.)	Own staff / specialists / contracting companies
3. Turnaround	Larger plant stops for major upgrades, repair, inspection, process upgrades	Own staff and contracting companies

A.2.5.5.2 Input

The main input to the planning and execution is a RBIM analysis including all equipment. From this risk assessment the following results are expected:

1. Risk ranking of the plant(s) / equipment
2. Type of inspection and maintenance
3. Timing for activity – typically by condition based or scheduled
4. Work and skills required, and estimated time per task
5. Need for plant total or partial shutdown
6. Dependencies between work on the evaluated unit and other components
7. Tools and spare parts needed

A.2.5.5.3 Procedure

The maintenance work normally consists of work generated from 3 different sources (Figure 14) and involves activities specified in Table 19.

1. Preventive plans generated by RBIM assessments (condition based and/or scheduled maintenance)
2. Corrective maintenance calls from observed failures, beginning problems

Failures identified via condition monitoring (RBIM recommended Run to Failure)

Table 19 - Activities in execution & reporting

Activity	Description
Risk Based Work Selection (RBWS)	RBWS is used to prioritize the work on a daily or weekly basis, both for the corrective and preventive tasks. Practice has shown that about 40% of the corrective tasks that have been called for can be postponed for several weeks. Thus the RBWS activity deals with the optimum selection and timing of the tasks to be performed. However, RBWS should not replace the RBIM risk analysis, nor postpone maintenance tasks for too long.
Work execution	The work execution involves: • Issuing a work order • Availability of support documentation

	• HSE – tool box talk, risk assessment control of work executed
Tools and databases	A modern maintenance organization will use a computerized maintenance management system (CMMS) as the key tool in managing the maintenance function. The CMMS system will typically contain the following information/modules; • Plant equipment breakdown (hierarchy) • Key technical information • Maintenance plans • Work order management (work flow, signature) • Maintenance reporting • Reporting and analysis module In the context of RBIM information (failure modes, failure rates and associated consequences), a minimum requirement for the CMMS systems is that it should contain or link to the risk information from the risk assessment.
Reporting & documentation of work	The purpose of documentation of the executed maintenance work is: • The condition of the equipment before and after the work. Information on type of degradation, extend of damage – information to be used for future planning. A combination of failure coding, text, pictures are recommended. • Cost & time control – how many man-hours were used, spares used, tools used • Accurate reporting is a key to the analysis and updating of the maintenance plans. Inadequate quality of this part of the work will cause the risk based planning to be non-optimal.
Analysis	The results from the maintenance work done should be analyzed and fed back into the RBIM on a regular basis, typically via monthly, quarterly and yearly maintenance and inspection reports. These reports should typically contain information on: • Backlog – work performed versus the planned work • Overdue pressurized equipment • Breakdown work (non-planned work) • Availability for the main production system, and maintenance related losses • Reliability of the safety systems • Trending of key parameters related to availability ,integrity & reliability

A.2.5.5.4 Output

The output from the maintenance execution work is a plant where the preventive maintenance is based on RBIM analyses, and corrective maintenance is also managed using risk-based principles. As a result, the risk for failure is under control and reduced to an acceptable level. Furthermore, the work is documented and reported so that reports, tools and information for continuous improvement are available.

A.2.5.5.5 Warning/application limits

The quality and capability of an RBIM plan depends on the input. To achieve a successful RBIM plan it is crucial to include input data from operation, process, maintenance and other experts. It is essential to ensure that RBIM plan should adhere to European Union regulations, national regulations and company policies. If required second opinon from independent experts should be sought in reviewing successful execution of plans.

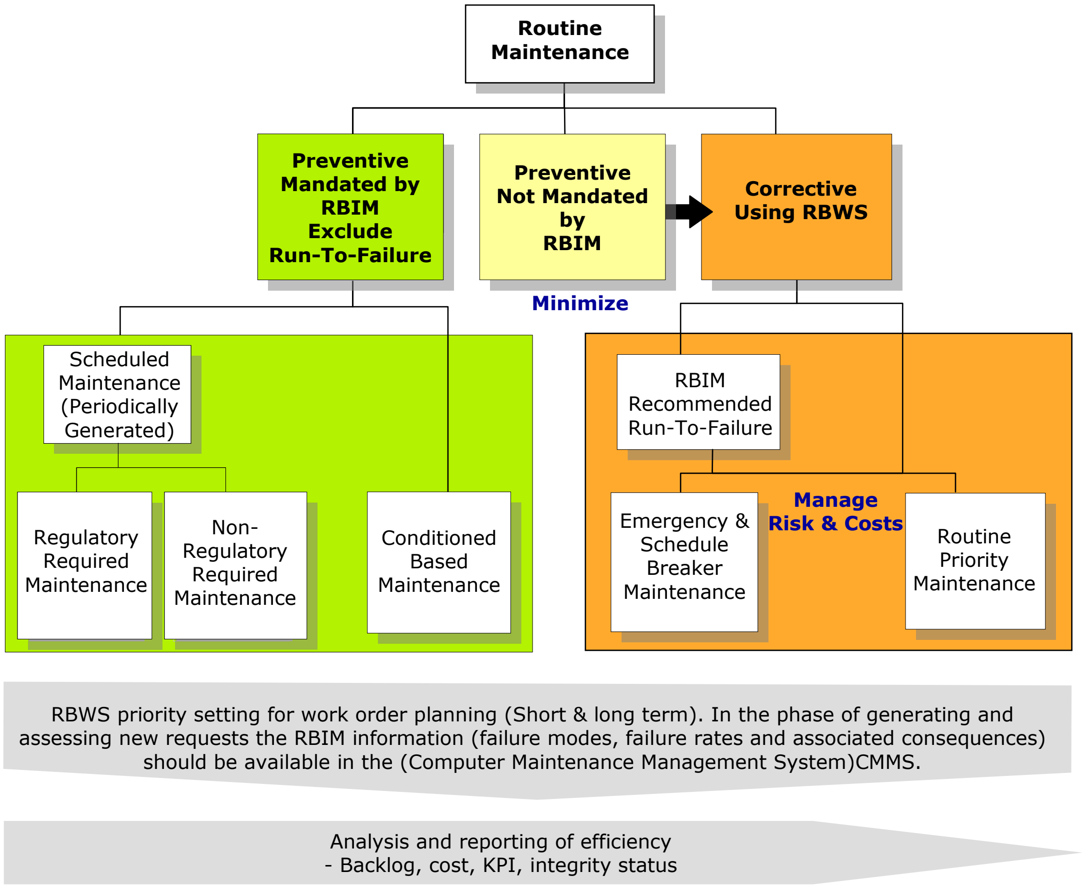

Figure 47 - Detailed planning

A.2.5.6 Performance review / Evergreen phase

A.2.5.6.1 General description and scope

The purpose of the evaluation of the risk-based decision-making process is to assess its effectiveness and impact in establishing the inspection and maintenance programs. This will allow the identification of areas where modifications and improvements are needed. Specifically, evaluation consists of the following tasks:

Assessment of the effectiveness of the risk-based decision-making process in achieving the intended goals (assessment of effectiveness)

Updating the risk-based decision-making process by taking into account possible plant changes and available new knowledge (reassessment of the risk). This should be done periodically.

A.2.5.6.2 Requirements

The evaluation process involves both internal and external assessment conducted by the operating organization and by independent experts, respectively.

The internal evaluation by the plant organization is an integral part of RBIM activity and should be considered as a living process within the overall risk decision-making process. Internal evaluation can take place in any moment of RBIM, especially when:

- discrepancy from any expectation or requirement is found
- new knowledge is available or plant changes occur

In both cases, a detailed analysis of the importance of the involved item (discrepancy or new knowledge/plant change) has to be conducted in order to assess whether it has a significant impact on the RBIM process, and some corrective action should be undertaken. In the latter case a thorough analysis of the causes to discrepancy or of the effects of the new knowledge/plant changes has to be performed.

External evaluation can be executed through independent reviews by external or regulatory organizations (e.g., audits). Independent reviews provide an opportunity to complement the internal evaluation with a different and neutral perspective. A point to note is that the value of information provided by the independent review is directly proportional to the openness and collaboration that the external experts will find in the audited organization. The integration of independent reviews with internal evaluation will allow the identification of necessary actions for improvement.

A.2.5.6.3 Inputs

For assessment of effectiveness, the following can be used, e.g.:

- Definition of risk decision-making process goals (risk may be expressed in one or more of the following terms: safety, health, environment and business impact)
- Definition of Performance Indicators as a measure of the RBM/RBLM process achievements against the above goals. (Note that in order to enable a meaningful evaluation of the performance, consideration should be given to the appropriate time frame applied for the various performance indicators. This is especially when a relation is identified between the performance and potential causes, it may be more meaningful when certain quantities are assessed for a longer period of time. For example, the cost of inspection and maintenance in year X affects the availability in a certain period of time after year X.)
- Reference to existing standards
- Benchmarking with similar operating organizations.

For reassessment of risk

A. Plant information
   - Changes in design
   - Changes in plant operation (mission, operational regime, production rate, capacity, internal & external environment)
   - Time dependent operating conditions (e.g., fatigue, cracks)
   - Changes in plant management
   - Change in level of personnel training
   - Feedback from industry-wide operational experience
   - Inspection results (rate of relevant damage/degradation mechanisms)
   - Maintenance records

B. New knowledge:
   - Applicable research and development results
   - Newly improved risk processes
   - Advanced inspection methods
   - Failure history of actual systems/components
   - Newly discovered degradation mechanisms (absence / presence of unanticipated degradation mechanisms)
   - New data on inspection and testing effectiveness

A.2.5.6.4 Procedure

Assessment of efficiency is a combination of good reporting including the aspects with respect to the business targets, and external audit of the plant. This audit can be done by internal resources (typical for large organizations), by the owner, or by an independent third party. There are four main methods or approaches applied in such an assessment, are described below.

Reporting of Key Performance Indicators

Key Performance Indicators (KPI) are in this context used for measurement of the business performance of a plant. The KPI's should reflect important goals for the plant, company or owner, and may change with time. For example, a plant in its post start up period may focus on availability and at a later stage more on maintenance cost. An example of a set of KPI's from the owner’s point of view is shown in Table 20.

Table 20 - Examples of KPI's and objectives for selecting them

Objective	KPI
Improve safety and environmental conditions	Number of overall safety and environmental incidents
Increase asset utilization	• Overall equipment effectiveness • Utilization rate by unit % • Plant utilization
Increase return on investment (ROI)	Return on capital employed (ROCE)
Increase revenue from assets	Production throughput
Minimize safety and environmental incidents	Safety and environmental incidents
	Accident by type, time of day, craft, personnel age, training hours attended, supervisor, unit, area
Reduce production unit cost	Cost per unit
Reduction of controllable lost profit	Lost profit opportunity cost
Reduction of maintenance expenses	• Annual maintenance cost / asset replacement cost • Maintenance cost • Work order cost, bi-monthly average • Cost of Preventive Maintenance by equipment type • Maintenance costs per barrel of product produced • Cost of Predictive Maintenance by equipment type • Unplanned cost as a % total maintenance cost

Work process efficiency benchmarking

The validation/ bench making method used in RIMAP procedure uses a scorecard/ check list method. The RIMAP Methodology Feature List (Figure 48) was produced to serve as a tool for validation of RIMAP methodology as well as validation of other methodologies. The resulting validation results gained from this analysis can be used to compare different methodologies. This list is based on review done by Mitsui Babcock [9] for the RIMAP project. The benchmarking/validation method suggested here provides more information to validate methodologies (e.g. chapter/paragraph were certain information resides in the documentation, rating of the specific feature etc.) as well as comments/suggestions for further improvement.

The rating (scoring) of individual features to the methodology or the workbook is based on a scale 1 – 5 where:

Score1 - Low level and/or quality of data, knowledge, confidence, accuracy, control, information, and industry practice. Or a No answer

Score5 - High level of quality of data, knowledge, confidence, accuracy, control, information, industry practice. Or a Yes answer

In more detail: Score 5: excellent, exceeding the requirements; Score 4: compliant with the requirements; Score 3: needs improvement; Score 2: partly fulfilled, not acceptable; Score 1: not fulfilled, addition needed

Internal review

The internal evaluation by the plant organization is an integral part of RBIM activity and should be considered as a living process within the overall risk decision-making process.

External review

External evaluation can be executed through independent reviews by external or regulatory organizations (e.g. audits). Independent reviews provide an opportunity to complement the internal evaluation with a different and neutral perspective. A point to note is that the value of information provided by the independent review is directly proportional to the openness and collaborative environment that external experts will find in the audited organization. The integration of independent reviews with internal evaluation will allow the identification of necessary actions for improvement.

a) Overall management system
b) Reporting
c) Quality of work (need for rework)
d) KPI definition and reporting
    - Safety system status
    - Production
    - Quality
e) Efficient use of expertise

A.2.5.6.5 Output

Assessment of effectiveness

From this step of RIMAP procedure, following outputs are envisaged as a measure of assessment of effectiveness of inspection / maintenance strategy:

1. Periodical reports from internal reviews
2. Reports from external audits
3. List of discrepancies from requirements and expectations
4. Methodical analysis of discrepancy causes, when applicable
5. Proposal for improvement actions

Reassessment of risk

From this step of RIMAP procedure, following outputs are envisaged as a measure of reassessment of risk:

1. Periodical reports from internal reviews
2. Reports from external audits
3. Monitoring and feedback from operation
4. Feedback from new knowledge
5. Proposal for improvement actions

A.2.5.6.6 Warnings and applicability limits

Modifications in the process as well as modifications and/or repairs to the installation should be designed and carried out in accordance with a written procedure reflecting appropriate standards and agreed in advance. This procedure may include an evaluation of the possible consequences of the change with respect to the integrity of the installation as well as the way in which authorisation shall take place. All information should be included in the plant database and be available to the RBIM-team for review.

Feature / Subject / Aspect		**Explanation**	**Ref. to Document/ Chapter/ Paragraph**	**Rating (1-5) or N/A**	**Justification (if <=3)**	**Improvement suggestions**
1. REQUIREMENTS FOR RISK BASED MAINTENANCE & INSPECTION						
1.1	Have references to published information been made?	The requirements for integrity management and risk based inspection of potentially hazardous plant can be determined by reference to Health and Safety regulations, industry standards and guidelines, and other literature. These can provide valuable information on hazards and control measures as well as covering compliance with Duty Holder's statutory obligations.	See reference [1], p.73; See reference [2], p.24	3		More references in D3-documents
1.2	Have reasons/drivers for the Risk Based Approach been explained	The main objective of risk based integrity management is to understand and manage the risks of failure of potentially hazardous plant to a level that is acceptable to the organization and the society within which it operates. Risk based inspection should aim to target finite inspection resources to areas where potential deterioration can lead to high risks. All the objectives of the risk based approach need to be clearly stated at the outset of the process. Duty Holders may wish to consider a wide range of consequences of failure, but as a minimum these should include the Health and Safety of employees and the public, effects on the environment, and implications for their business. It is important that the risks associated with each of these consequences are considered separately and that measures are taken to manage the risks in each case. Duty Holders should ensure that inspection resources are adequate to manage all the risks, and that limited resources do not compromise Health and Safety or environmental risks	All RIMAP documents [1] - [13]	5		This is the main aim of all the RIMAP documents to focus on risk drivers and how to mitigate risk
1.3	Is the availability and accuracy of information given, sufficient	The assessment of risk depends on the availability and accuracy of the information relating to the systems and equipment to being assessed. Good information may enable a low risk to be justified, but does not in itself guarantee that the risks are low. Where information is lacking, unavailable, or uncertain, the risk is increased since it cannot be shown that unfavourable circumstances are absent. The type of information required to assess the risk will vary depending on the type of plant, but should be identified at this early stage. The essential data needed to make a risk assessment should be available within the plant database. If it is obvious that the essential data does not exist, action to obtain this information is required or prescriptive inspection procedures should be applied.	See reference [1]; sec.4.3	4	The need for good data is stressed in many sections. See in particular Preparatory analysis.	

Figure 48 - Example of validation feature list in RIMAP [9]

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A.2.6 RBI example: Multilevel risk analysis in the power industry

Note: German technical rules for boilers (TRD) and German standards used in this example are now European Standards (please see references). The following table shows the correlation between the documents.

Table 21: Overview of TRD documents and their EN designation

TRD / DIN Document	EU Standard – EN
TRD 300	EN 12952-1
DIN 17155 and DIN 17175	EN 12952-2
TRD 301	EN 12952-3
TRD 508	EN 12952-4

The PoF determination in this example is based on creep exhaustion (based on material uncertainties) and fatigue exhaustion. Creep exhaustion is determined using TRD creep curves (EN 12952-1, EN 12952-3), based on material data as shown in Figure 49. Fatigue exhaustion is based on low-bound TRD curve as shown in Figure 50.

The creep curve is usually derived from the experimental data, according to recognized procedures, i.e. ECCC WG1 - Creep Data Validation and Assessment Procedures (ECCC WG1 1995).

Fatigue curve is derived depending on the design temperature and using *min[N/20, 2σ_a /2]*, where N is the number of cycles to crack initiation, and 2σ_a is stress amplitude.

Inputs:

Component geometry according to TRD codes 300/301 (EN 12952-1, EN 12952-3), please see Figure 51.

Design temperature and pressure (see Figure 52)

Material data – average creep rupture strength for the component material and fatigue strength at given temperature

Service time of the component – operational hours (see Figure 53)

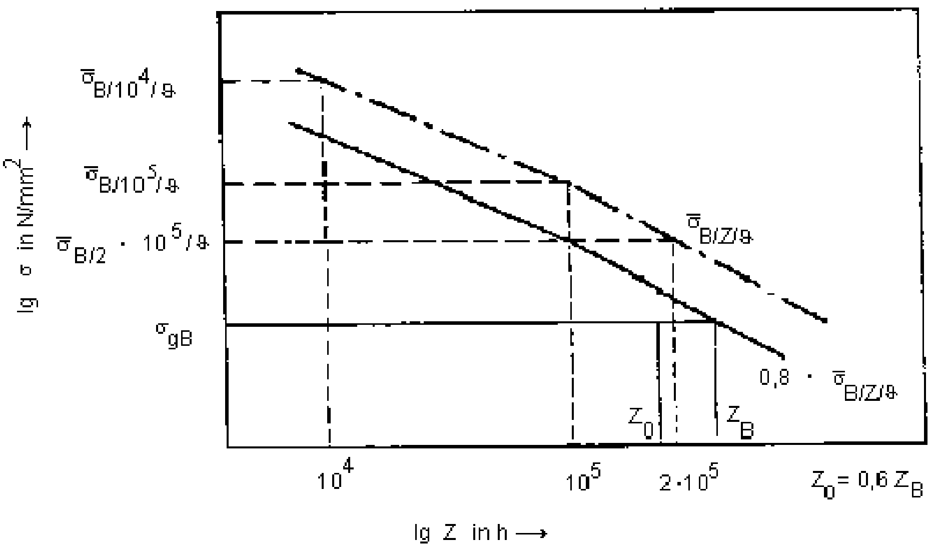


Figure 49 Creep exhaustion calculation based on TRD (now EN 12952)

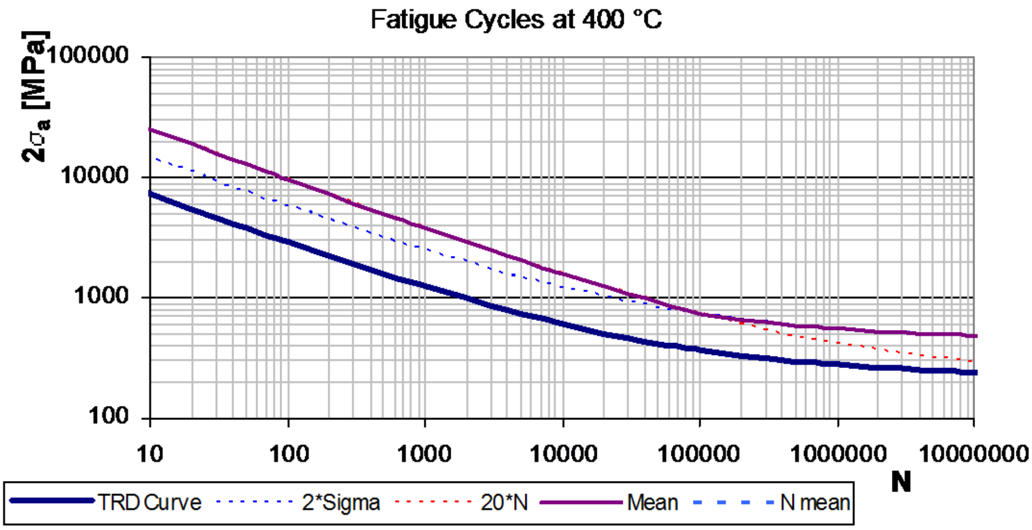


Figure 50 TRD Fatigue curve (with derived mean value curve) at 400°C

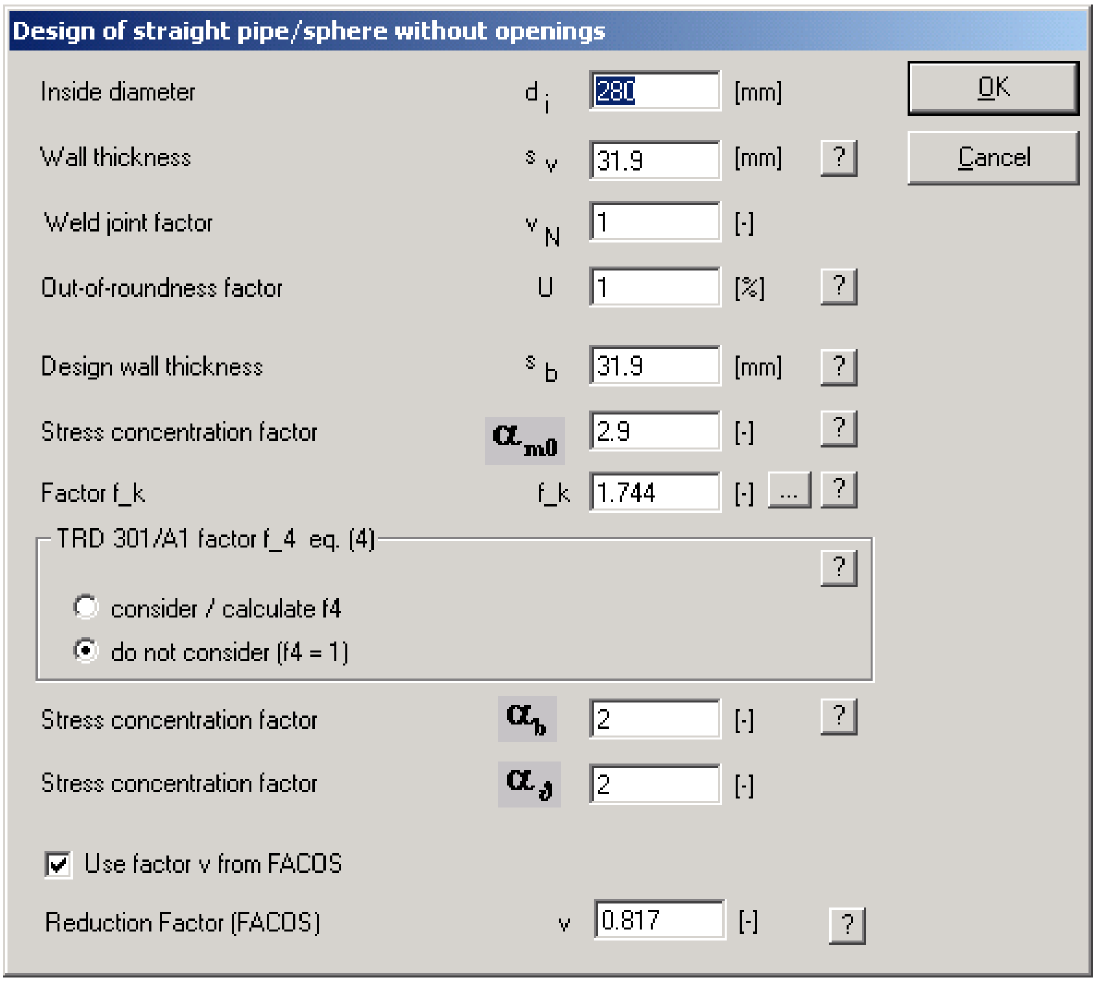


Figure 51: Component geometry data

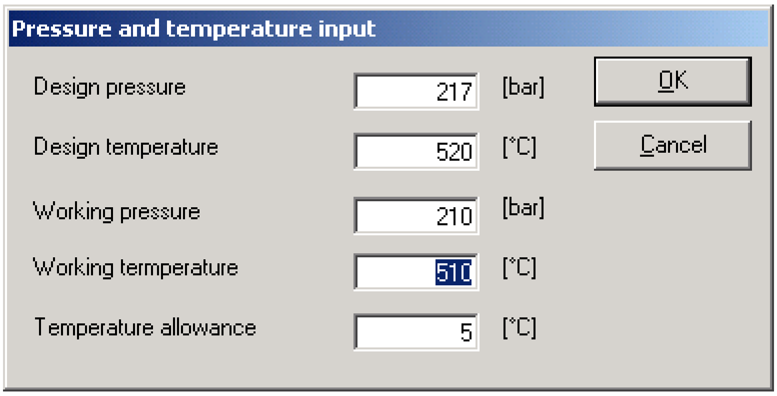


Figure 52: Design and operating temperature and pressure

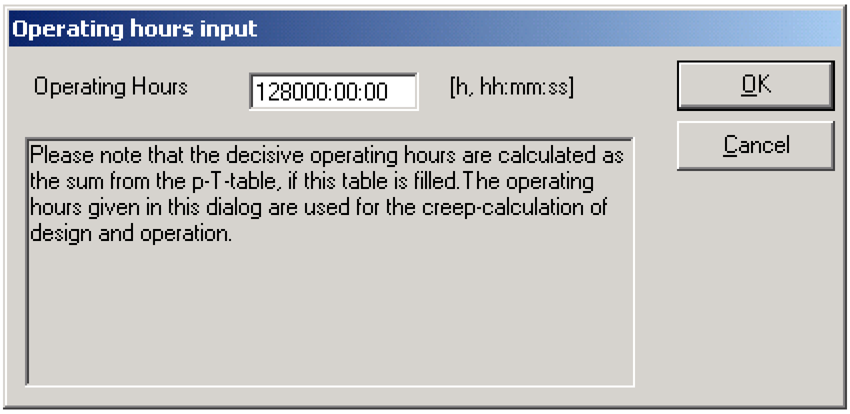


Figure 53: Service time of the component

Based on data inputted and TRD rules exhaustions are calculated:

e_z – creep exhaustion

e_w – fatigue exhaustion

It is assumed that average creep rupture strength and fatigue strength have a log-normal distribution, with $2\sigma_1$ (about 97.5% confidence level) at the lower (TRD) curve, and mean value μ on the mean curve as given by material data for creep.

$$f(t) = \frac{1}{t\sqrt{2\pi\sigma_1^2}} e^{\left(-\frac{(\ln(t)-\mu_1)}{2\sigma_1^2}\right)}$$

where:

$$\mu_1 = \ln\left(\frac{\mu^2}{\sqrt{\sigma^2+\mu^2}}\right), \sigma_1 = \sqrt{\ln\left(\frac{\sigma^2+\mu^2}{\mu^2}\right)}$$

σ and μ values are the values in the “real” (non-log scale), whereas σ_1 and μ_1 are values (parameters) of the normal distribution in the log scale.

Since we assume that the distribution is normal in the logarithmic space, we can calculate the parameter σ_1 using the above equation as:

$$\mu = MeanTimeToFailure$$

$$\sigma_1 = \frac{\ln(MeanTimeToFailure) - \ln(TRDTimeToFailure)}{2}$$

Which gives:

$$\sigma = \mu \cdot \sqrt{e^{(\sigma_1^2)} - 1}$$

For example, using parameters defined as described above we calculate probability of failure based on creep, e.g.

PoF(t≤ServiceTime=128000hours) = 4.31E-04%
PoF(ServiceTime=128000hours ≤t≤ServiceTime=200000hours)=
PoF(t≤ServiceTime=200000hours) - PoF(t≤ServiceTime=128000hours) =
5.84E-03% - 4.31E-04% = 5.41E-03%

Examples of distribution for creep and fatigue can be seen in Figure 54 and Figure 55, respectively.

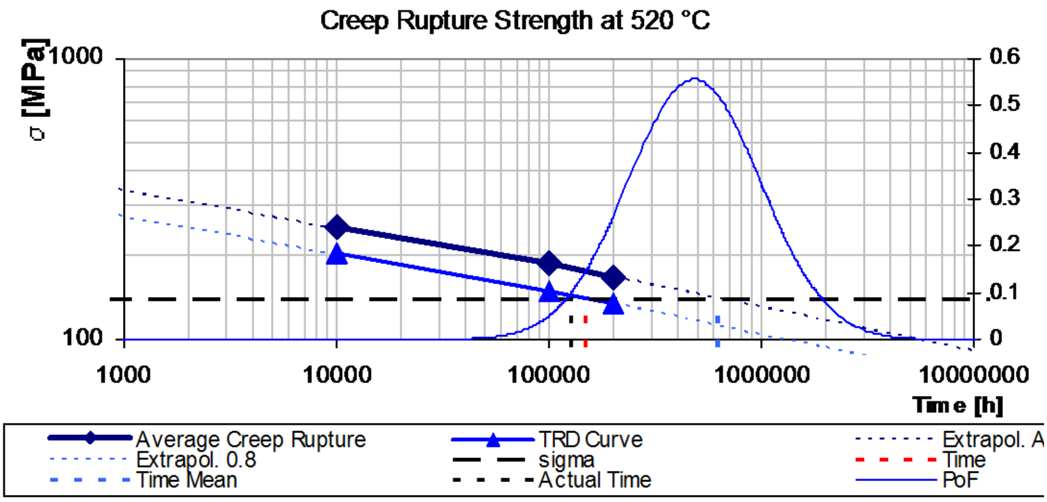


Figure 54 Example of distribution for creep rupture strength at 520°C

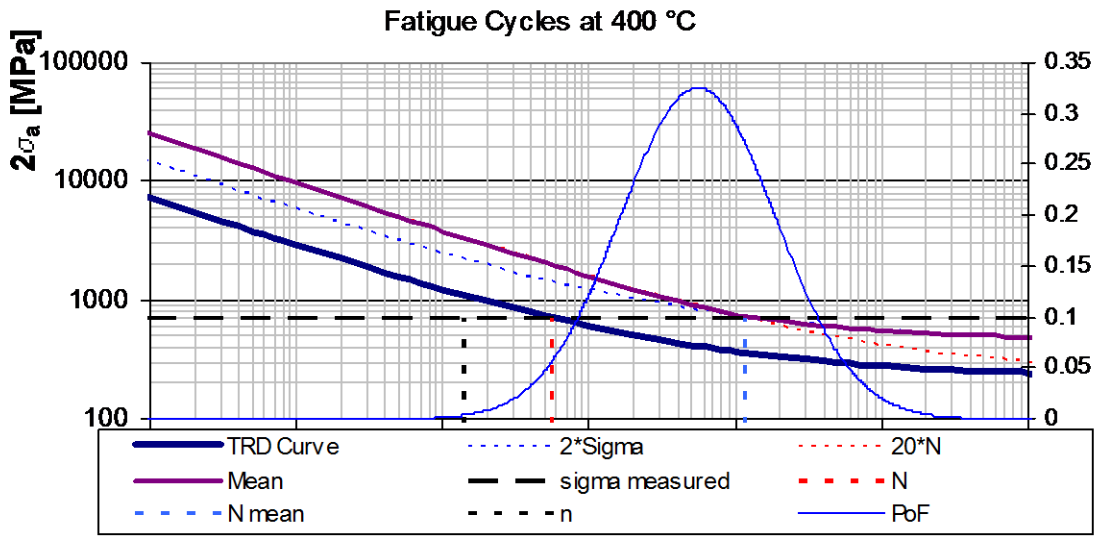


Figure 55 Example of distribution for fatigue strength at 400°C

A.2.6.1 Sample case

For the case of this example we will consider 8 components from a power plant. General information about the sample case plant:

gas turbine 35 MWel and 60 MW of district heating with a coal-fired steam generator (195 MWel and 150 MW of district heating)

commissioning 1982

gross output 230 MW

net output 210 MW

steam generating capacity 576 t/h

district heating 210 MW

fuel:

low-grade coal

methane gas

converter gas

operating hours: 126168

Table 22: Components considered in this example

Name	**Type**
Mix-HEADER	Header
Water Separator	Separator
SUPERHEATER 4 LI	Superheater
SUPERHEATER 4 RE	Superheater
HP-OUTLET	Header
SUPERHEATER	Header
SUPERHEATER-OUTLET	T-Piece
Attemperator	Attemperator

From this 8 components 10 cases will considered (for 2 components additional failure mode will be considered)

A.2.6.2 Screening level

For the screening level of the analysis only the component design data is available. Additional the number of operating hours is also known.

The following table shows the data available for the components.

Table 23: Component design data

Component-Failure mode	**Type**	**Material**	**Service temperature**	**Service pressure**	**Operating hours**
Mix-HEADER - Leak	Header	15NiCuMoNb5	280	238	126168
Water Separator - Leak	Separator	15NiCuMoNb5	390	225	126168
SUPERHEATER 4 LI - Leak	Superheater	X20CrMoV121	483	205	126168
SUPERHEATER 4 RE - Leak	Superheater	X20CrMoV121	483	205	126168
HP-OUTLET - Leak	Header	X20CrMoV121	540	205	126168

Component-Failure mode	Type	Material	Service temperature	Service pressure	Operating hours
SUPERHEATER-OUTLET - Leak	Header	10CrMoV910	542	44.5	126168
T-PIECE RA00 - Leak	T-Piece	X20CrMoV121	540	205	126168
Attemperator - Leak	Attemperator	X20CrMoV121	540	205	126168
SUPERHEATER 4 LI - break	Header	X20CrMoV121	483	205	126168
T-PIECE RA00 - Break	T-Piece	X20CrMoV121	540	205	126168

Based on available data and using TRD codes (now EN 14952), using e.g. ALIAS-TRD, service stress and exhaustion factors (e_z – creep exhaustion, e_w – fatigue exhaustion) were calculated (see Table 24)

Table 24: Calculated component exhaustion values

Component-Failure mode	Type	Service stress	Ez [%]	Ew [%]	Etot[%]
Mix-HEADER - Leak	Header	135.796	0	11.9	11.9
Water Separator - Leak	Separator	110.189	5.52E-08	16.98	16.98
SUPERHEATER 4 LI - Leak	Superheater	108.709	1.6	26.49	28.09
SUPERHEATER 4 RE - Leak	Superheater	88.408	0.3	19.73	20.03
HP-OUTLET - Leak	Header	65.209	20.9	22.67	43.57
SUPERHEATER-OUTLET - Leak	Header	26.996	8.6	8.188	16.788
T-PIECE RA00 - Leak	T-Piece	63.146	18	24.98	42.98
Attemperator - Leak	Attemperator	92.32	53.9	24.98	78.88
SUPERHEATER 4 LI – break	Header	108.709	1.6	26.49	28.09
T-PIECE RA00 - Break	T-Piece	63.146	18	24.98	42.98

Data was then inputted into RIMAP software (ALIAS-Risk, see ref. RIMAP 2002d), like shown in Figure 56.

The following step is to define PoF and CoF classes. Following PoF classes were defined (see also Figure 57)

PoF Ez – probability of failure based on creep exhaustion

PoF Ew – probability of failure based on fatigue exhaustion

PoF E – combined probability of failure for PoF Ez and PoF Ew

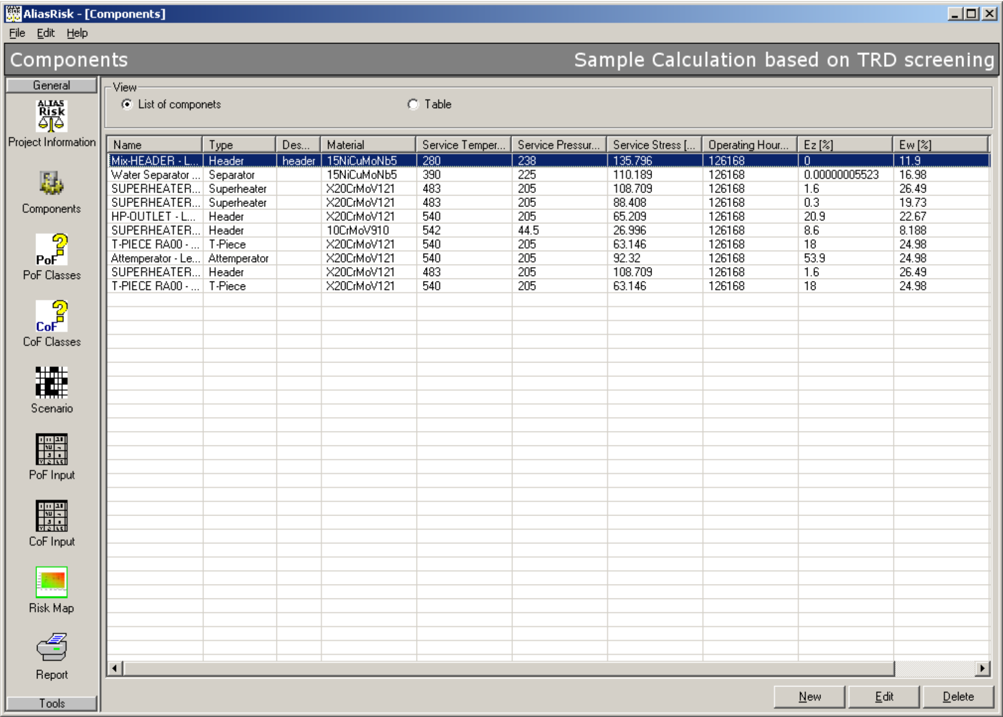


Figure 56 Screening level PoF analysis in ALIAS-Risk

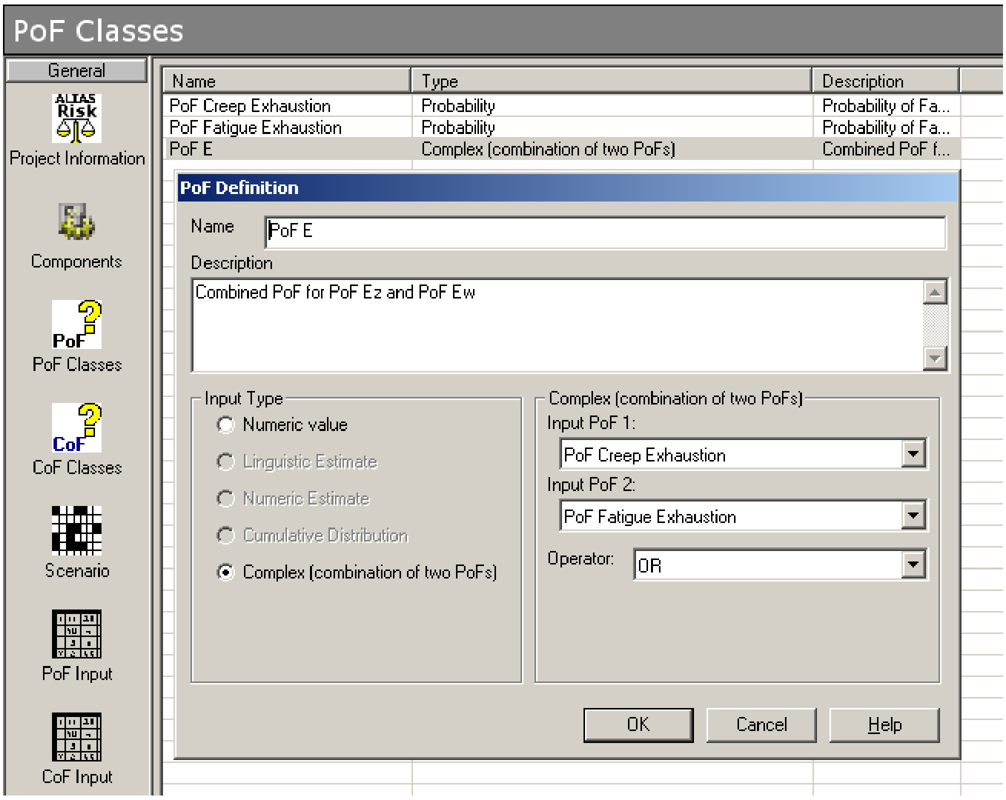


Figure 57 Defining PoF classes using ALIAS-Risk

After defining PoF classes, consequence of failure classes were defined as following (see also Figure 58):

Additional replacement cost (€)

Typical repair cost (€)

Production loss by failure (€)

Overall replacement cost (€)

CoF by leak – combined repair/production loss costs (€)

Additional damage to other equipment cost (€)

Combined replace/damage to other equipment cost (€)

Replacement value (€)

Current value (€)

Overall damage by leak costs(€)

CoF by break (€)

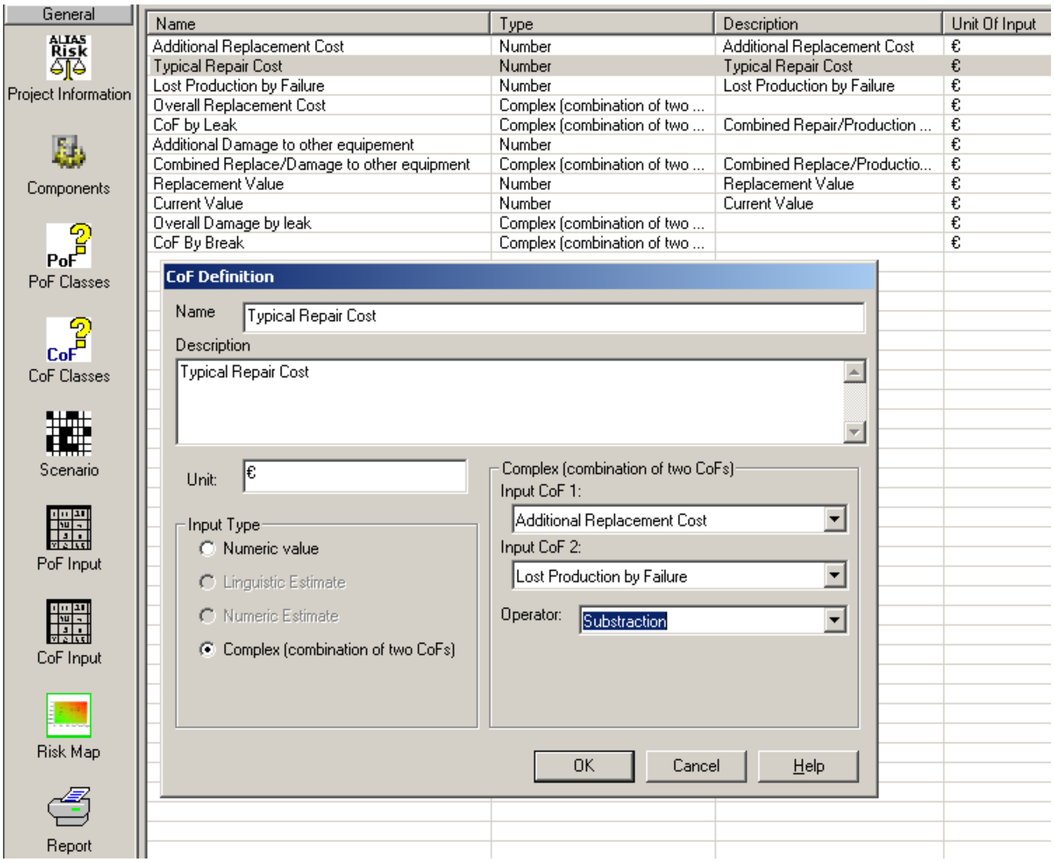


Figure 58 Defining CoF classes using ALIAS-Risk

When the PoF and CoF classes were defined the failure scenarios ("Bow Tie" diagrams) for each component were made (see Figure 59). Example of a failure scenario for the superheater component can be seen in Figure 60.

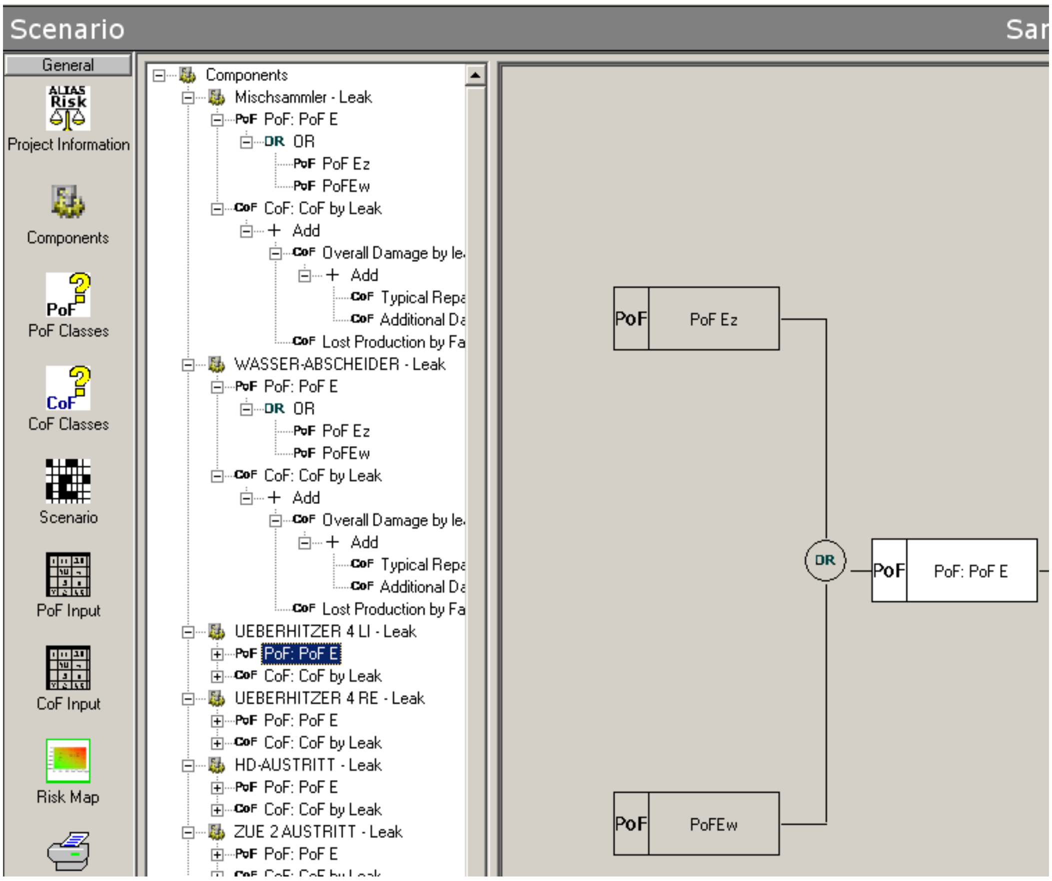


Figure 59 Building failure scenarios using ALIAS-Risk

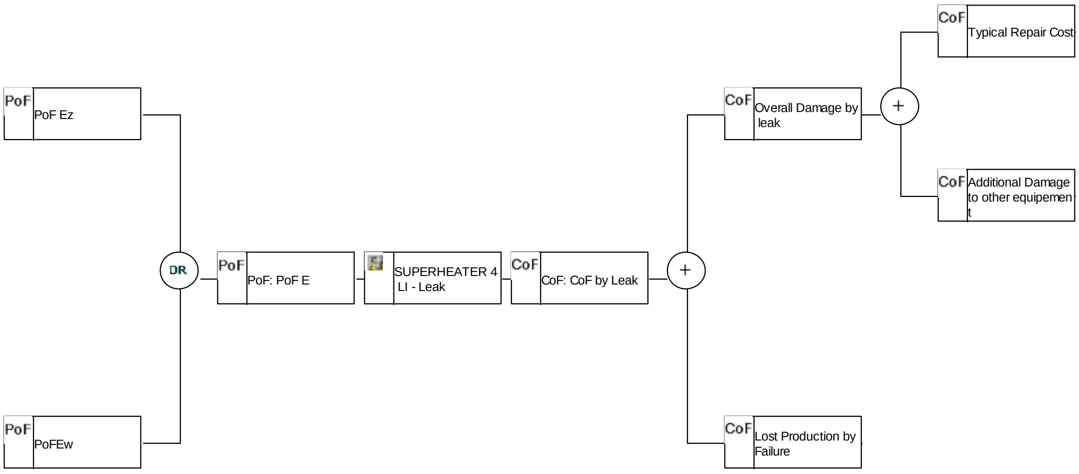
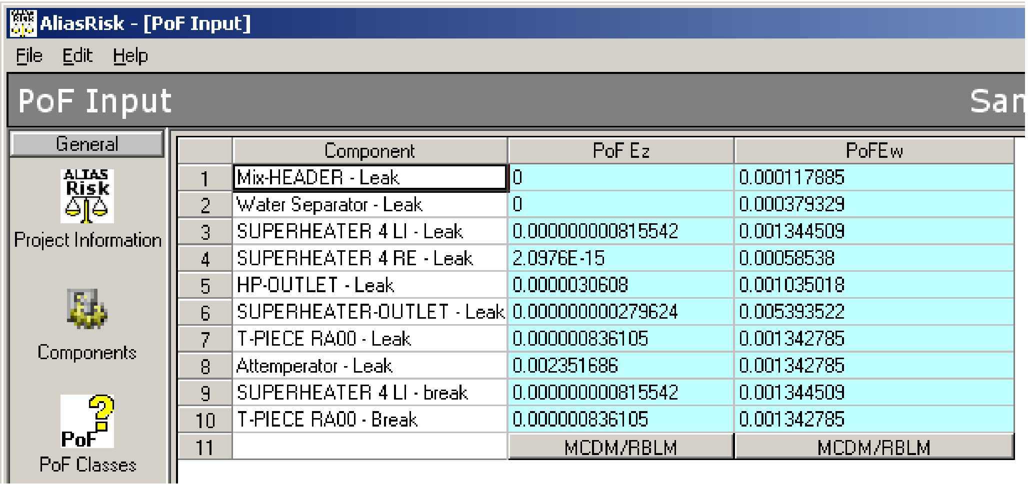


Figure 60 "Bow Tie" for supeheater component

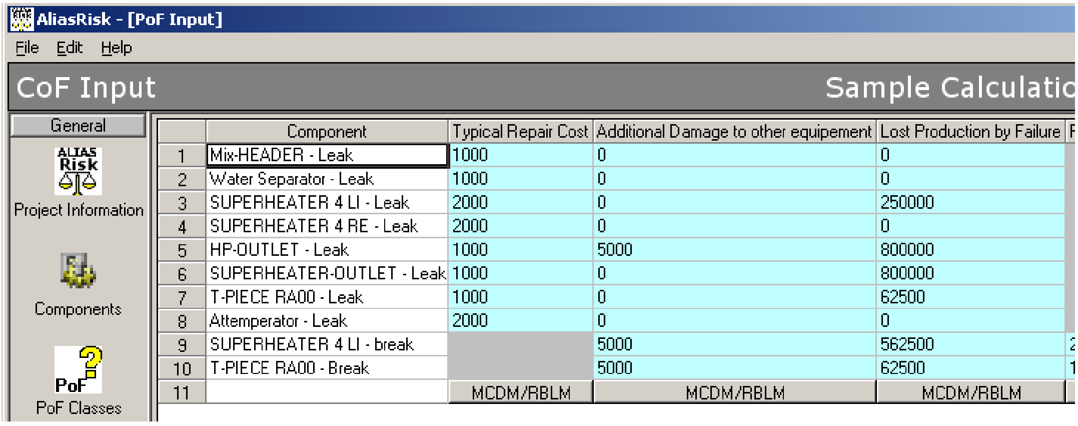
In the next step PoF values were calculated based on inputted data and using ALIAS-TRD. The procedure was done like explained previously in this chapter (see Chapter A.2.6). Afterwards the calculated PoF values were imported into ALIAS-Risk (see Figure 61) and CoF values for each defined CoF class were inputted.



AliasRisk - [PoF Input]
File Edit Help
PoF Input
General | Project Information | Components | PoF Classes

	Component	PoF Ez	PoFEw
1	Mix-HEADER - Leak	0	0.000117885
2	Water Separator - Leak	0	0.000379329
3	SUPERHEATER 4 LI - Leak	0.000000000815542	0.001344509
4	SUPERHEATER 4 RE - Leak	2.0976E-15	0.00058538
5	HP-OUTLET - Leak	0.0000030608	0.001035018
6	SUPERHEATER-OUTLET - Leak	0.000000000279624	0.005393522
7	T-PIECE RA00 - Leak	0.000000836105	0.001342785
8	Attemperator - Leak	0.002351686	0.001342785
9	SUPERHEATER 4 LI - break	0.000000000815542	0.001344509
10	T-PIECE RA00 - Break	0.000000836105	0.001342785
11		MCDM/RBLM	MCDM/RBLM

Figure 61 Imported calculated PoF values



AliasRisk - [PoF Input]
File Edit Help
CoF Input
Sample Calculatio
General | Project Information | Components | PoF Classes

	Component	Typical Repair Cost	Additional Damage to other equipement	Lost Production by Failure	F
1	Mix-HEADER - Leak	1000	0	0	
2	Water Separator - Leak	1000	0	0	
3	SUPERHEATER 4 LI - Leak	2000	0	250000	
4	SUPERHEATER 4 RE - Leak	2000	0	0	
5	HP-OUTLET - Leak	1000	5000	800000	
6	SUPERHEATER-OUTLET - Leak	1000	0	800000	
7	T-PIECE RA00 - Leak	1000	0	62500	
8	Attemperator - Leak	2000	0	0	
9	SUPERHEATER 4 LI - break		5000	562500	2
10	T-PIECE RA00 - Break		5000	62500	1
11		MCDM/RBLM	MCDM/RBLM	MCDM/RBLM	

Figure 62 Input of CoF values

Based on PoF and CoF values, following the previously defined scenarios ("Bow Tie" diagrams) for each component, risk is determined. Risk map (full report as well) are then automatically generated by ALIAS-Risk. The risk map for this example can be seen in

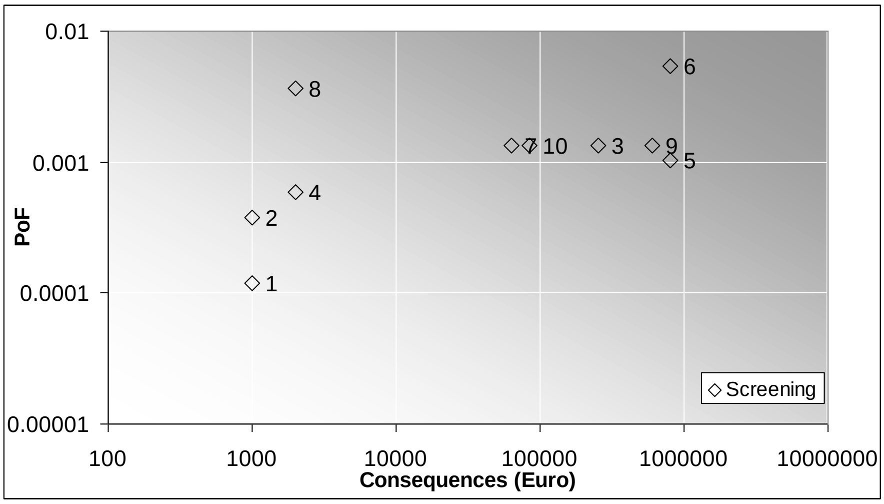


Figure 63 Risk map after screening level

A.2.6.3 Intermediate level

After screening, next level of analysis is intermediate. Since monitoring data was available for this sample case it was decided to perform intermediate analysis for all 8 components/10 cases.

Because of seamless transition between analysis levels in proposed RIMAP approach it is not necessary to perform all steps performed already in previous (screening) level. Based on monitoring data, new values of exhaustion based on creep and fatigue (according to TRD, now EN 14952) could be calculated. Since PoF and CoF classes, as well as the scenarios were already done in the previous step, the only necessary step in this level is to calculate again the PoF values based on updated values of exhaustion (the methodology is the same like in the screening level, only more data is available).

Table 25: The following table shows new calculated values of PoF:

Component-Failure mode	**Type**	**PoF**
Mix-HEADER - Leak	Header	2.03E-11
Water Separator - Leak	Separator	2.03706E-05
SUPERHEATER 4 LI - Leak	Superheater	0.001345622
SUPERHEATER 4 RE - Leak	Superheater	0.000587421
HP-OUTLET - Leak	Header	0.000448781
SUPERHEATER-OUTLET - Leak	Header	0.002393522
T-PIECE RA00 - Leak	T-Piece	1.28E-04
Attemperator - Leak	Attemperator	8.35896E-05
SUPERHEATER 4 LI – break	Header	0.001345622
T-PIECE RA00 - Break	T-Piece	1.28E-04

Newly calculated values were input into ALIAS-Risk and new risk map was generated automatically (see Figure 64). In order not to make the risk map overcrowded, only few components are shown in the figure.

Interesting thing with Figure 64is that it clearly shows the conservatism of low-level (screening) analysis when compared to intermediate. The arrows show how the components moved into the areas of lower risk from those determined in the screening level.

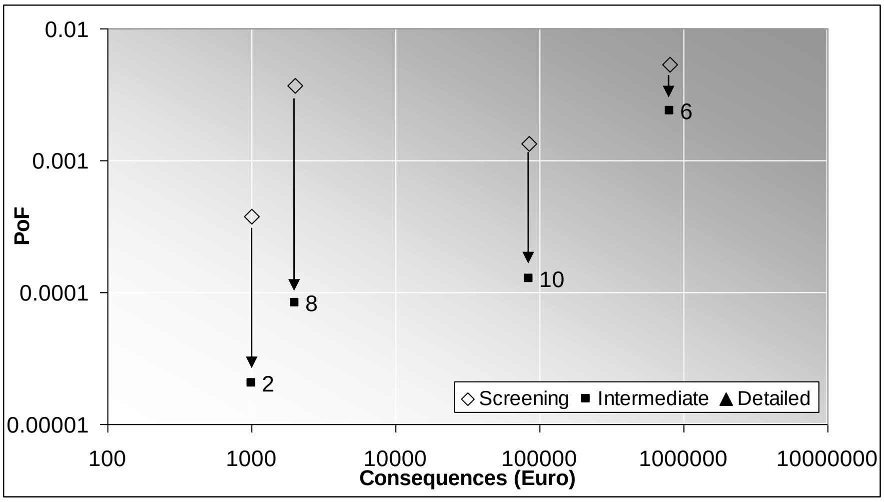


Figure 64 Risk map after intermediate analysis

A.2.6.4 Detailed level

For the most critical component (in our sample case, component 6 – SUPERHEATER Outlet, Header) it was decided to perform detailed analysis.

The analysis was performed according to the schematics shown in Figure 67.

All obtainable data for the component was gathered (including geometry, properties of the material used etc.) and the analysis was performed for several load cases (so called "worse cases"). The detailed analysis included:

Stress calculation for the "worse cases"

Creep analysis

Fatigue analysis

Critical crack size calculation

Creep crack growth (see Figure 65)

Fatigue crack growth

Corresponding details about this analysis are given in the work of Jovanovic, Maile 2001 (see references).

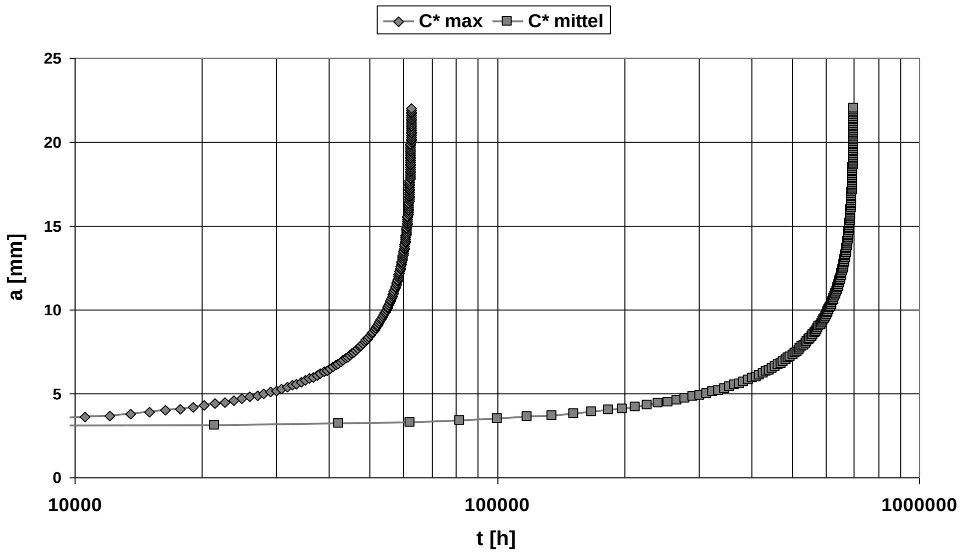


Figure 65 Creep crack growth with C* (form factor 2.5) (Jovanovic, Maile, 2001))

After performing the detailed analysis and applying the statistical models (like shown in Figure 67), new value of PoF for the component was determined and plotted on the risk map (see Figure 66)

Again it can be seen that the conservatism was preserved and that the detailed analysis moved the component on the risk map in the region of lower risk from those after screening and intermediate analysis.

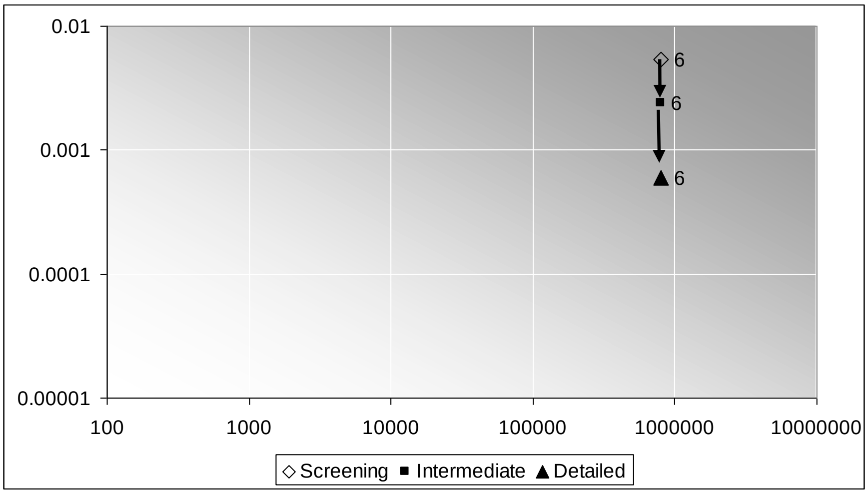


Figure 66 Superheater component on a risk map after detailed analysis

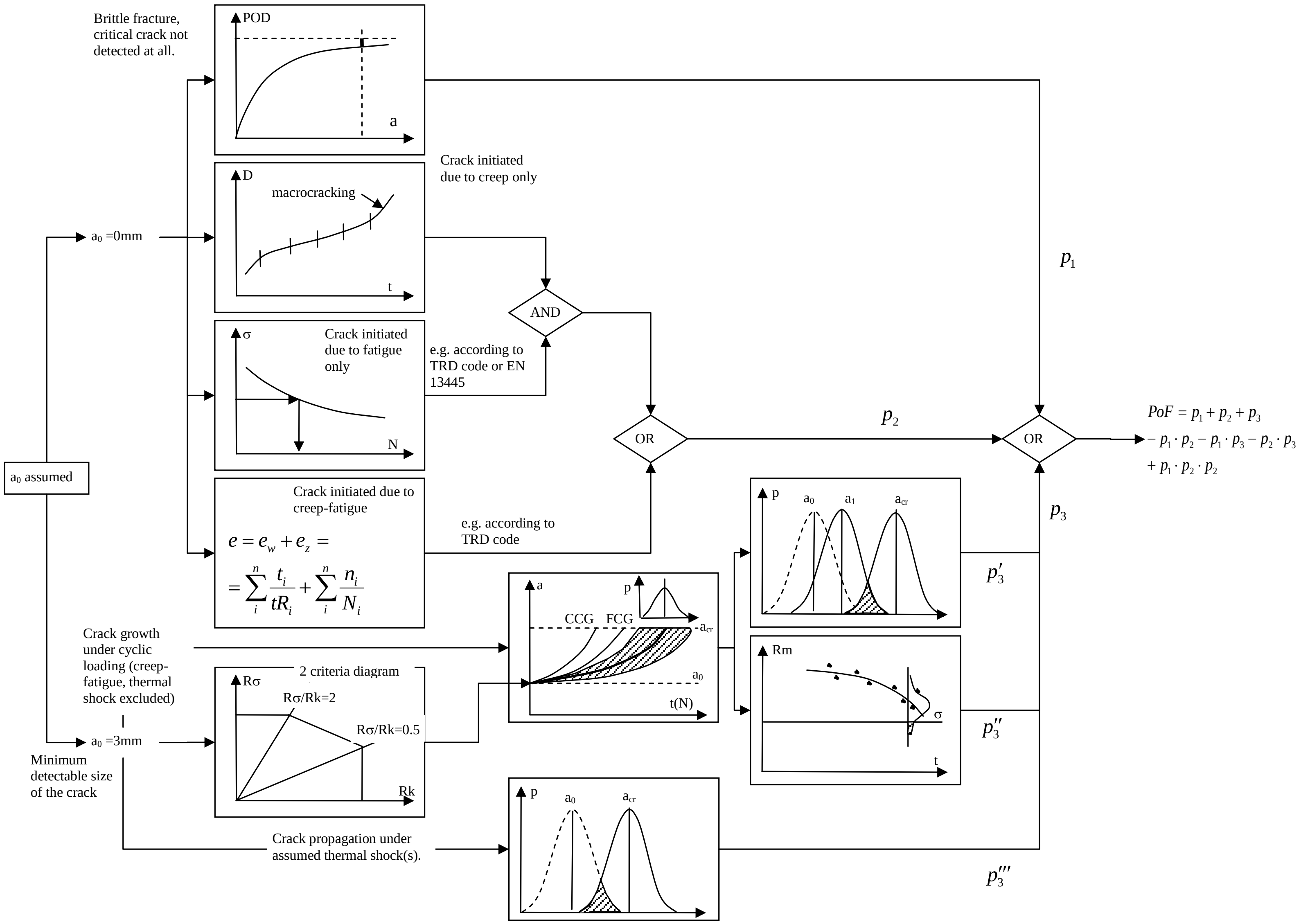


Figure 67 Example of calculating PoF for the sample case considered

Annex 3 Aging Related KPIs

<table>
<tr><th colspan="8">ERRA Key Performance Indicators (KPIs)</th></tr>
<tr><td>Name of indicator</td><td colspan="7">Increasing/emerging internal corrosion rate factor of a UNIT- for group of static equipment and piping</td></tr>
<tr><td colspan="8">KPI classification</td></tr>
<tr><td>Leading KPI</td><td>X</td><td>Organizational</td><td></td><td>Action</td><td></td><td>Other</td><td></td></tr>
<tr><td>Lagging KPI</td><td></td><td>Frequency based</td><td>X</td><td>Consequence based</td><td></td><td>Mixed based</td><td></td></tr>
<tr><td>Local indicators</td><td></td><td>Global indicators</td><td>X</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="8">Definition</td></tr>
<tr><td colspan="8">Portion of static equipment and pipes where the probability of failure due to internal corrosion has increased with at least one category (resulted from RBI analyses e.g. according to API 581) during the last investigated period.</td></tr>
<tr><td colspan="8">Formula (e.g., mortality rate / 1000*hour work)</td></tr>
<tr><td colspan="8">$$\mathrm{KPI} = \left(\frac{\mathrm{N_{inc}}}{\mathrm{N_{all}}}\right) \times 100\%$$
where:
N_{inc} – Number of equipment and/or pipes, where the probability of failure has increased with at least one category during the last investigated period, e.g. 6 months.
N_{all} – Number of equipment and/or pipes in a UNIT. Minimum 5 equipment and pipes are necessary to be involved in the calculation in order to get realistic result.</td></tr>
<tr><td colspan="8">Comment</td></tr>
<tr><td colspan="8">Increasing of the internal corrosion rate can increase the probability of leakage or other structural failure of static equipment or piping.

This is a damage mechanism related KPI at unit level.</td></tr>
<tr><td colspan="8">To which system it appeals to</td></tr>
<tr><td colspan="8">All static equipment and piping in a unit.</td></tr>
<tr><td colspan="8"></td></tr>
<tr><td>Name of indicator</td><td colspan="7">Increasing/emerging external corrosion rate factor of a UNIT- for static equipment and piping</td></tr>
<tr><td colspan="8">KPI classification</td></tr>
</table>

ERRA Key Performance Indicators (KPIs)							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							
Portion of static equipment and pipes where probability of failure due to external corrosion has increased with at least one category (resulted from RBI analyses e.g. according to API 581) during the last investigated period.							
Formula (e.g., mortality rate / 1000*hour work)							
$$KPI = \left(\frac{N_{inc}}{N_{all}}\right) \times 100\%$$ where: N_{inc} – Number of equipment and/or pipes, where the calculated corrosion rate factor has been increasing with at least one risk category during the last investigated period. N_{all} – Number of equipment and/or pipes of the UNIT. Minimum 5 equipment and pipes are necessary to be involved in the calculation in order to get realistic result.							
Comment							
Increasing of the external corrosion rate can increase the probability of leakage or other structural failure of static equipment or piping. This is a damage mechanism related KPI at unit level.							
To which system it appeals to							
All static equipment and piping in a unit.							
Name of indicator	**Increasing/emerging internal cracking susceptibility factor of a UNIT- for static equipment and piping**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	

ERRA Key Performance Indicators (KPIs)							
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							
Portion of static equipment and pipes where internal cracking sensitivity has increased with at least one category (resulted from RBI analyses e.g. according to API 581) during the last investigated period.							
Formula (e.g., mortality rate / 1000*hour work)							
$$\mathrm{KPI} = \left(\frac{\mathrm{N_{inc}}}{\mathrm{N_{all}}}\right) \times 100\%$$ where: Ninc – Number of equipment and pipes, where the calculated cracking sensitivity has been increasing with at least one risk category during the last investigated period. N_{all} – Number of equipment and/or pipes of the UNIT. Minimum 5 equipment and pipes are necessary to be involved in the calculation in order to get realistic result.							
Comment							
Increasing of the susceptibility to internal cracking (due to e.g. stress corrosion cracking) can increase the probability of structural failure of static equipment or piping. This is a damage mechanism related KPI at unit level.							
To which system it appeals to							
All static equipment and piping in a unit.							
Name of indicator	**Increasing/emerging external cracking susceptibility factor of a UNIT – for static equipment and piping**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	

ERRA Key Performance Indicators (KPIs)							
Local indicators		Global indicators	X				
Definition							
Portion of static equipment and pipes where external cracking sensitivity has increased with at least one category (resulted from RBI analyses e.g. according to API 581) during the last investigated period.							
Formula (e.g., mortality rate / 1000*hour work)							
$$KPI = \left(\frac{N_{inc}}{N_{all}}\right) \times 100\%$$ where: N_{inc} – Number of equipment and pipe, where the calculated external cracking sensitivity higher with at least one category during the last investigated period (e.g. 6 months). N_{all} – Number of equipment and/or pipes in a UNIT. Minimum 5 equipment and pipes are necessary to be involved in the calculation in order to get realistic result.							
Comment							
Increasing of the susceptibility to internal cracking (due to e.g. stress corrosion cracking) can increase the probability of structural failure of static equipment or piping. This is a functional failure related KPI at unit level.							
To which system it appeals to							
All static equipment and piping in a unit.							
Name of indicator	**Failure factor of static equipment - UNIT level**						
KPI classification							
Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							

ERRA Key Performance Indicators (KPIs)
Ratio of actual number of failures of static equipment to average number of failures in the previous period in a unit.
Formula (e.g., mortality rate / 1000*hour work)
$\mathrm{Failuresfactorofstaticequipment} = \frac{\mathrm{NumberoffailurereportsNumberoffailurereports}_{\mathrm{average}}}{\mathrm{Numberoffailurereports}_{\mathrm{ref}}}$Failure factor = (Number of failures - Number of failures_ref)/Number of failures_ref*100% where: Number of failures - actual number of failures of static equipment in the last period (e.g. last month) (e.g. that are recorded in SAP) Number of failures_ref - number of failures of static equipment in the previous period (e.g. previous 6 months) (e.g. that are recorded in SAP)
Comment
Increasing number of failure of static equipment and piping is an indicator of decreasing the reliability and availability of a unit or a plant. This is a functional failure related KPI at unit level.
To which system it appeals to
All static equipment and piping.

Name of indicator	**Increasing of the number of failure cases of different parts of rotating equipment - UNIT level**						
KPI classification							
Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							
Ratio of the increasing of the number of the failure cases of different parts of rotating equipment in the last investigated period compared to the previous period.							
Formula (e.g., mortality rate / 1000*hour work)							

ERRA Key Performance Indicators (KPIs)

$\Delta N\% = (N - N_{ref})/N_{ref} * 100\%$

where

N - Actual number of failure cases of different parts of rotating equipment in the last investigated period (e.g. 6 months). This number can be taken e.g. from an on-line diagnostic system of rotating equipment.

N_{ref} - Number of failure cases of different parts of rotating equipment in the previous investigated period (e.g. previous 6 months). This number can be taken e.g. from an on-line diagnostic system of rotating equipment.

Comment

Increasing number of failure of different parts of rotating equipment is an indicator of decreasing the reliability and availability of a unit or a plant.

This is a functional failure related KPI at unit level.

To which system it appeals to

All rotating equipment in a unit.

Name of indicator	**Failure factor of rotating equipment - UNIT level**

KPI classification

Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				

Definition

Ratio of actual number of failed rotating equipment in the last period to average number of failed rotating equipment in the previous period in a unit.

Formula (e.g., mortality rate / 1000*hour work)

$\text{Failuresfactorofstaticequipment} = \frac{\text{NumberoffailurereportsNumberoffailurereports}_{\text{average}}}{\text{Numberoffailurereports}_{\text{ref}}}$Failure factor of rotating equipment= (Number of failed rotating equipment -Number of failure rotating equipment_ref)/Number of failed rotating equipment_ref*100%

ERRA Key Performance Indicators (KPIs)
where: Number of failure rotating equipment - actual number of failed rotating equipment in the last period (e.g. last month), reported e.g. through an on-line diagnostic system or SAP. Number of failed rotating equipment_ref - number of failed rotating equipment in the previous period (e.g. previous 6 months), reported e.g. through an on-line diagnostic system or SAP.
Comment
Increasing number of failed rotating equipment is an indicator of decreasing the reliability and availability of a unit or a plant. This is a functional failure related KPI at unit level.
To which system it appeals to
All rotating equipment in a unit.

Name of indicator	**Increasing of the number of unsuccessful calibrations of instruments - UNIT level**

KPI classification							
Leading KPI		Organizational		Action		Other	X
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				

Definition
Ratio of actual number of unsuccessful calibrations of instruments in the last period to the number of unsuccessful calibrations of instruments in the previous period in a unit.
Formula (e.g., mortality rate / 1000*hour work)
KPI = Number of unsuccessful calibration of instruments in a unit in the last period (e.g. last 6 month) /number of unsuccessful calibrations in the previous period (e.g. 6 months) *100%
Comment
The increasing number of unsuccessful instrument calibration mean that the conditions of the instruments are getting worse, thus the probability of operational failure related to any malfunction or failure of an instrument may increase. This is a functional failure related KPI at unit level.

ERRA Key Performance Indicators (KPIs)
To which system it appeals to
All instruments in a unit.

Name of indicator	**Decreasing of the number of calibrations of instruments - UNIT level**

KPI classification							
Leading KPI		Organizational		Action		Other	X
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				

Definition
Ratio of the actual number of calibrations of instruments in the last period to the number of calibrations of instruments in the previous period in a unit.
Formula (e.g., mortality rate / 1000*hour work)
KPI = Number of calibration of instruments in a unit in the last period (e.g. last 6 month)/number of calibrations in the previous period (e.g. 6 months) *100%
Comment
Decreasing of the number of instrument calibration can indicate the decreasing reliability of the instruments, so the probability of instrument failure can increase. This is a functional failure related KPI at unit level.
To which system it appeals to
All instruments in a unit.

Name of indicator	**Failure factor of instruments - UNIT level**

KPI classification							
Leading KPI		Organizational		Action		Other	

ERRA Key Performance Indicators (KPIs)							
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							
Ratio of actual number of failures of instruments to average number of failures in the previous period in a unit.							
Formula (e.g., mortality rate / 1000*hour work)							
$KPI = \frac{Number\ of\ instrument\ \ failures - Number\ of\ instrument\ \ failure\_ref}{Number\ of\ instrument\ \ failure\_ref}$ where: Number of instrument failures - actual number of instrument failures in the last period (e.g. last month), e.g. that is recorded in SAP. Number of instrument failures_ref - average number of instrument failures in the previous period (e.g. previous 6 months), e.g. that is recorded in SAP.							
Comment							
Increasing number of instrument failures is an indicator of decreasing the reliability and availability of a unit or a plant. This is a functional failure related KPI at unit level.							
To which system it appeals to							
All instruments in a unit.							

Name of indicator	**Failure factor of remote control valves - UNIT level**

KPI classification							
Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	

ERRA Key Performance Indicators (KPIs)							
Local indicators		Global indicators	X				
Definition							
Ratio of actual number of failures of remote control valves in the last period to average number of failures in the previous period in a unit.							
Formula (e.g., mortality rate / 1000*hour work)							
$\mathrm{Failuresfactorofstaticequipment} = \frac{\mathrm{NumberoffailurereportsNumberoffailurereports_{average}}}{\mathrm{Numberoffailurereports_{ref}}}$Failure factor of remote control valves= (Number of failures -Number of failures_ref)/Number of failures_ref*100% where: Number of failures - actual number of failures of remote control valves in the last period (e.g. last month) that is recorded e.g. in SAP. Number of failures_ref - average number of failures of remote control valves in the previous period (e.g. previous 6 months) that is recorded e.g. in SAP.							
Comment							
Increasing number of remote control valves failures is an indicator of decreasing the reliability and availability of a unit or a plant. This is a functional failure related KPI at unit level.							
To which system it appeals to							
Remote control valves in a unit.							
Name of indicator	**Failure factor of equipment – UNIT level**						
KPI classification							
Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							
Ratio of actual number of failures of all equipment to average number of failures in the previous period in a unit.							

ERRA Key Performance Indicators (KPIs)
Formula (e.g., mortality rate / 1000*hour work)
$$KPI = \frac{Number\ of\ equipment\ \ failures - Number\ of\ equipment\ \ failures\ \_ref}{Number\ of\ equipment\ \ failures\ \_ref}$$ where: Number of equipment failures - actual number of failures of all equipment in the last period (e.g. last month), e.g. that is recorded in SAP. Number of equipment failures_ref - average number of failures of all equipment in the previous period (e.g. previous 6 months), e.g. that is recorded in SAP.
Comment
Increasing number of equipment failures is an indicator of decreasing the reliability and availability of a unit or a plant. This is a functional failure related KPI at unit level.
To which system it appeals to
All equipment in a unit.

Name of indicator	**Decreasing of the management system factor**						
KPI classification							
Leading KPI	X	Organizational	X	Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							
Decreasing of the management system factor that is determined according to API 581.							
Formula (e.g., mortality rate / 1000*hour work)							
KPI=actual calculated management system factor/last determined management system factor x 100%							

ERRA Key Performance Indicators (KPIs)								
Comment								
The determination of management system factor is based on API581. The decreasing of the management system factor is an indicator that the quality of the unit/plant management has been decreased, so the safe and reliable operation of the plant could be decreased due to not proper management.								
To which system it appeals to								
Whole unit or plant.								
Name of indicator	**Increasing/emerging internal corrosion rate factor - for static equipment and piping**							
KPI classification								
Leading KPI	X	Organizational		Action		Other		
Lagging KPI		Frequency based	X	Consequence based		Mixed based		
Local indicators	X	Global indicators						
Definition								
Increasing of the average internal corrosion rate calculated or measured for the last investigated period (e.g. 6 months) compared to the corrosion rate calculated at last RBI analysis.								
Formula (e.g., mortality rate / 1000*hour work)								

$$\Delta RATE = RATE_{average} - RATE_{Ref}$$

where:

$$RATE_{average} = \frac{\sum_{i=1}^{n} RATE_i \cdot \Delta t}{T \cdot 1440}$$

$RATE_{Ref}$ - internal corrosion rate calculated at last RBI analysis in mm/year (API 581)

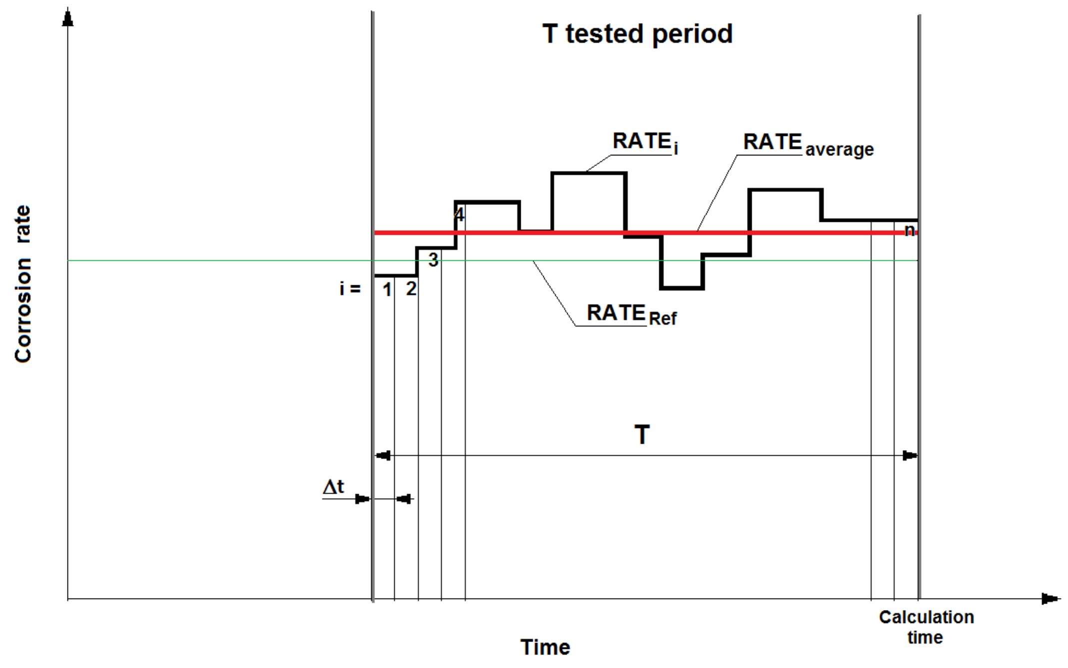
$RATE_{average}$ – calculated or measured average internal corrosion rate for the last period (T) in mm/year

T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.

Δt – the sampling interval of the on-line measured parameter that is used for calculation of the corrosion rate(e.g. T, p) in minutes

n – number of samples

ERRA Key Performance Indicators (KPIs)
$RATE_i$ – calculated (API 581) or measured corrosion rate at sampling in mm/year



Comment
The corrosion rate calculation is based on API 581. The potential damage mechanism (corrosion type) can be determined using the screening questions defined in API 581, e.g. this screening could be implemented into the on-line monitoring software code itself. Increasing of the internal corrosion rate is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.
To which system it appeals to
Static equipment and piping, i.e.: Heat exchanger, Reactor, Absorber, Desorber, Separator, Storage tank, Filter, Piping

Name of indicator	**Decreasing of the remaining life time (year) - static equipment**

KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	

ERRA Key Performance Indicators (KPIs)							
Local indicators	X	Global indicators					
Definition							
Decreasing of the remaining life time of equipment or piping calculated based on the actual corrosion rate (in the last period) in % compared to the life time calculated using the corrosion rate determined at last RBI analysis.							
Formula (e.g., mortality rate / 1000*hour work)							
$$T\% = \left(\frac{Tr - Tc}{Tr}\right) \times 100\%$$ Reference remaining life time: $Tr = \frac{V - Vs}{Rate_{ref}}$ Calculated actual remaining life time: $Tc = \frac{V - Vs}{Rate_{cal}}$ where: v – measured thickness of the equipment or pipe at last RBI analysis v_s – minimum required wall thickness $RATE_{ref}$ – corrosion rate determined at last RBI analysis (API 581) $RATE_{cal}$ – calculated or measured average corrosion rate for last 6 months							
Comment							
Decreasing of the remaining lifetime calculated based on the corrosion rate is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.							
To which system it appeals to							
Static equipment and piping							
Name of indicator	**Increasing/emerging external corrosion rate factor-static equipment**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					

ERRA Key Performance Indicators (KPIs)							
Definition							
Increasing of the average external corrosion rate calculated for the last investigated period (e.g. 6 months) compared to the corrosion rate calculated at last RBI analysis.							
Formula (e.g., mortality rate / 1000*hour work)							
$$\Delta RATE = RATE_{average} - RATE_{ref}$$ where: $RATE_{ref}$ - corrosion rate calculated at last RBI analysis in mm/year (API 581) $RATE_{average}$ – calculated or measured average corrosion rate for the last investigated period (T) in mm/year T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.							
Comment							
The corrosion rate calculation is based on API 581. Increasing of the external corrosion rate is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.							
To which system it appeals to							
Static equipment and piping in a unit.							

Name of indicator	**Increasing/emerging internal cracking susceptibility factor-static equipment and piping**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					

ERRA Key Performance Indicators (KPIs)
Definition
Increasing of the average internal cracking sensitivity calculated for the last investigated period (e.g. 6 months) compared to the cracking sensitivity calculated at last RBI analysis.
Formula (e.g., mortality rate / 1000*hour work)
$$\Delta S = S_{average} - S_{Ref}$$ where: S_{Ref} - cracking sensitivity calculated at last RBI analysis (1: low, 2: middle, 3: high) (API 581) $S_{average}$ – calculated average cracking sensitivity for the last investigated period (T) T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.
Comment
The susceptibility to internal cracking calculation is based on the API 581. The potential damage mechanism (cracking type) can be determined using the screening questions defined in API 581, e.g. this screening could be implemented into the on-line monitoring software code itself. Increasing of the susceptibility to internal cracking is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.
To which system it appeals to
Static equipment and piping.

Name of indicator	**Increasing/emerging external cracking susceptibility factor – for static equipment and piping**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					
Definition							

ERRA Key Performance Indicators (KPIs)
Increasing of the average external cracking sensitivity calculated for last investigated period compared to the external crack sensitivity calculated at last RBI analysis.
Formula (e.g., mortality rate / 1000*hour work)
$$\Delta S = S_{average} - S_{Ref}$$ where: S_{Ref} - sensitivity calculated at last RBI analysis (1: low, 2: middle, 3: high) (API 581) $S_{average}$ – calculated average sensitivity for the tested period (T)   T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.
Comment
The susceptibility to external cracking calculation is based on the API 581.   Increasing of the susceptibility to external cracking is an indicator that the probability of structural failure has been increased.   This is a damage mechanism related KPI at equipment level.
To which system it appeals to
Static equipment and piping.

Name of indicator	**Increasing/emerging mechanical fatigue susceptibility – for piping**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					
Definition							
Susceptibility to mechanical fatigue of piping can be derived from the vibration of piping. Ration of the increase of the vibration amplitude measured with on-line monitoring technique on piping connected to rotating equipment – to a reference level of vibration.							
Formula (e.g., mortality rate / 1000*hour work)							

ERRA Key Performance Indicators (KPIs)
KPI = $(A-A_{ref})/A_{ref}*100\%$ A_{ref} – measured vibration amplitude after maintenance or replacement of connected rotating equipment under normal operating condition. A – actual measured vibration amplitude
Comment
Increasing of the susceptibility to mechanical fatigue of piping is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.
To which system it appeals to
Piping connecting to rotating equipment.

Name of indicator	**Increasing/emerging HTHA susceptibility factor changing – static equipment**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					

Definition
Increasing of the average HTHA sensitivity calculated for the last investigated period (e.g. 6 months) compared to HTHA sensitivity calculated at last RBI analysis.
Formula (e.g., mortality rate / 1000*hour work)

$$\Delta S = S_{average} - S_{Ref}$$

where:

S_{Ref} - sensitivity calculated at last RBI analysis (1: low, 2: medium, 3: high) (API 581)

$S_{average}$ – average HTHA sensitivity for the last investigated period (T)

T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.

ERRA Key Performance Indicators (KPIs)
Comment
Calculation of HTHA sensitivity is based on API 581. Increasing of the susceptibility to HTHA is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.
To which system it appeals to
Static equipment and piping.

Name of indicator	**Increasing/emerging brittle fracture susceptibility factor – for static equipment and piping**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					

Definition
Increasing of the average brittle fracture sensitivity calculated for the last investigated period (e.g. 6 months) comparing to the brittle fracture sensitivity calculated at last RBI analysis.
Formula (e.g., mortality rate / 1000*hour work)

$$\Delta S = S_{average} - S_{Ref}$$

where:

S_{Ref} - sensitivity calculated at last RBI analysis (1: low, 2: medium, 3: high) (API 581)

$S_{average}$ – calculated average sensitivity for the last investigated period (T)

T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.

Comment
Calculation of brittle fracture susceptibility is based on the API 581.

ERRA Key Performance Indicators (KPIs)							
Increasing of the susceptibility to brittle fracture is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.							
To which system it appeals to							
Static equipment and piping.							
Name of indicator	**Increasing/emerging erosion rate factor – for static equipment and piping**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					
Definition							
Ratio of the increase of the measured erosion rate determined from on-line wall thickness measurement in the last investigated period to the erosion rate considered in the last analysis.							
Formula (e.g., mortality rate / 1000*hour work)							
$KPI=(RATE-RATE_{ref})/RATE_{ref} * 100\%$ RATE = (V-V0)/T (mm/year) T=investigated period (e.g. 6 months) V – on-line measured wall thickness (end of the investigated period) V_0 – on-line measured wall thickness at the begening of the last investigated period $RATE_{ref}$ – erosion rate calculated at last RBI analysis							
Comment							
Increasing of the erosion rate is an indicator that the probability of structural failure has been increased. This is a damage mechanism related KPI at equipment level.							
To which system it appeals to							
Static equipment and piping.							

ERRA Key Performance Indicators (KPIs)							
Name of indicator	**Number of faults of rotating equipment parts**						
KPI classification							
Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of the number of error messages at different severity level which are provided by the rotating equipment on-line diagnostic system, in the last investigated period compared to the previous period.							
Formula (e.g., mortality rate / 1000*hour work)							
$N = N1 + 2*N2 + 3*N3 + 4*N4 - N_{ref}$ where: N1 - Number of error messages related to low severity level deviation in the last month. N2 - Number of error messages related to medium severity level deviation in the last month. N3 - Number of error messages related to high severity level deviation in the last month. N4 - Number of error messages at extreme severity level deviation in the last month. N_{ref} – total number of error messages in the previous period (e.g. previous 6 months)							
Comment							
The definition of parameters is based on the on-line diagnostic system used at MOL. Increasing of number of error messages related to the different parts of rotating equipment is an indicator that the probability of process or structural failure has been increased. This is a functional failure related KPI at equipment level.							
To which system it appeals to							
Rotating equipment.							
Name of indicator	**Increasing of the number of emergency stops of rotating equipment**						

ERRA Key Performance Indicators (KPIs)							
KPI classification							
Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					

Definition
Increasing of the number of emergency stops of rotating equipment in the last investigated period compared to the previous period.
Formula (e.g., mortality rate / 1000*hour work)
$\Delta N = N_2 - N_1$ where: N1 - The number of emergency stops of rotating equipment in the last investigated period (e.g. 6 months). This number can be taken from the diagnostic system of rotating equipment. N2 - The number of emergency stops of rotating equipment in the previous investigated period (e.g. previous 6 months). This number can be taken from the diagnostic system of rotating equipment.
Comment
Increasing of the number of emergency stops of rotating equipment is an indicator that the reliability and availability of the equipment has been decreased. This is a functional failure related KPI at equipment level.
To which system it appeals to
Rotating equipment.

Name of indicator	**Increasing of the number of failed parts of rotating equipment**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	

ERRA Key Performance Indicators (KPIs)							
Local indicators	X	Global indicators					
Definition							
Increasing of the number of rotating equipment failed parts of rotating equipment in the last investigated period compared to the previous period.							
Formula (e.g., mortality rate / 1000*hour work)							
$\Delta N = N_2 - N_1$ where: N1 - The number of failed parts'reports of rotating equipment in the last investigated period (e.g. 6 months). This number can be taken from the diagnostic system of rotating equipment. N2 - The number of failed parts'reports of rotating equipment in the previous investigated period (e.g. previous 6 months). This number can be taken from the diagnostic system of rotating equipment.							
Comment							
Increasing of the number of failed parts of rotating equipment is an indicator that the reliability and availability of the equipment has been decreased. This is a functional failure related KPI at equipment level.							
To which system it appeals to							
Rotating equipment.							
Name of indicator	**Temperature increase of rotating equipment parts**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of the maximum temperature of rotating equipment determined from on-line temperature measurement.							
Formula (e.g., mortality rate / 1000*hour work)							

ERRA Key Performance Indicators (KPIs)
$\Delta T\% = (T-T_{ref})/T_{ref}*100\%$ T_{ref} – reference maximum temperature measured after maintenance T – actual maximum temperature of rotating equipment
Comment
The reason for the temperature increasing of rotating equipment could be the fault (e.g. wearing) of any part, degradation of the lubrication system or problem with the cooling system. The temperature increase can be an indicator that the probability of failure has been increased. This is a functional failure related KPI at equipment level.
To which system it appeals to
Rotating equipment.

Name of indicator	**Operating time factor of rotating equipment**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					

Definition
Time elapsed from last inspection compared to the average time between failure of the rotating equipment.
Formula (e.g., mortality rate / 1000*hour work)
KPI= Time elapsed from last inspection/Average time between failure*100%
Comment
The probability of failure of rotating equipment may increase with the time elapsed from the last inspection. This is a functional failure related KPI at equipment level.
To which system it appeals to
Rotating equipment.

ERRA Key Performance Indicators (KPIs)							
Name of indicator	**Decreasing of the average mean time to instrument repair (between failures)**						
KPI classification							
Leading KPI		Organizational		Action		Other	
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators		Global indicators	X				
Definition							
Ratio of the average mean time to instrument repair in the last period compared to the average mean time to instruments repair in the previous period.							
Formula (e.g., mortality rate / 1000*hour work)							
KPI= average mean time to instruments repair in the last year/ average mean time to instruments repair in the previous year*100%							
Comment							
Decreasing of the average mean time between instrument failures is an indicator that the reliability of operation has been decreased and the probability of instrument failure has been increased. This is a functional failure related KPI at equipment level.							
To which system it appeals to							
Instruments.							

Name of indicator	**Failure level of remote controlled valves**						
KPI classification							
Leading KPI		Organizational		Action		Other	

ERRA Key Performance Indicators (KPIs)							
Lagging KPI	X	Frequency based	X	Consequence based		Mixed based	
Local indicators	X	Global indicators					
Definition							
Fingerprint curve deviation compared to the reference curve.							
Formula (e.g., mortality rate / 1000*hour work)							
Percentage average deviation (D) between the fingerprint curve recorded after inspection and the actual curve recorded at functional test.							
Comment							
This curve is recorded by the Advanced Maintenance Monitoring system at MOL for remote control valve. Increasing of the deviation of the fingerprint curve from the reference one is an indicator that the probability of failure of remote controlled valves has been increased. This is a functional failure related KPI at equipment level.							
To which system it appeals to							
Remote controlled valves.							

Name of indicator	**Increasing of consequence category for static equipment or piping failure based on API581 analyses**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based		Consequence based	X	Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of the consequence category of static equipment or piping based on RBI analysis, e.g. API RBI or RIMAP CEN WA.							
Formula (e.g., mortality rate / 1000*hour work)							

ERRA Key Performance Indicators (KPIs)
$$\Delta CoF = CoF_{average} - CoF_{ref}$$ where: CoF_{ref}: calculated consequence of static equipment or piping failure at last RBI analysis (1-5). $CoF_{average}$: calculated average consequence of static equipment or piping failure for the last investigated period T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.
Comment
Increasing of the consequence category of a potential failure is an indicator that the risk level has been increased. Consequence of failure related KPI - at equipment level.
To which system it appeals to
Static equipment and piping.

Name of indicator	**Increasing of consequence of static equipment or piping failure based on criticality analysis**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based		Consequence based	X	Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of the consequence score for static equipment determined with criticality analysis.							
Formula (e.g., mortality rate / 1000*hour work)							
$$\Delta CoF = CoF_{actual} - CoF_{ref}$$ where: CoF_{ref}: consequence score of static equipment failure at last criticality analysis (1-5).							

ERRA Key Performance Indicators (KPIs)							
CoF_{actual}: actual consequence score determined with criticality analyses of static equipment or piping							
Comment							
Criticality analysis can be based on specific qualitative method at a company. Increasing of the consequence category of a potential failure is an indicator that the risk level has been increased. Consequence of failure related KPI - at equipment level.							
To which system it appeals to							
Static equipment and piping.							
Name of indicator	**Increasing of consequence category of static equipment or piping failure based on risk based organisational work assessment**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based		Consequence based	X	Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of the consequence category of static equipment or piping failure determined during risk based organizational of work assessment.							
Formula (e.g., mortality rate / 1000*hour work)							
$\Delta CoF = CoF_{actual} - CoF_{ref}$ where: CoF_{ref}: minimum consequence category of static equipment or piping failure during the last investigated period (T) CoF_{actual}: actual consequence category of static equipment or piping failure determined during the last analysis. T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.							

ERRA Key Performance Indicators (KPIs)							
Comment							
The CoF determination is based on risk based organization of work assessment (used at MOL). Increasing of the consequence category of a potential failure is an indicator that the risk level has been increased. Consequence of failure related KPI - at equipment level.							
To which system it appeals to							
Static equipment and piping.							
Name of indicator	**Increasing of consequence of rotating equipment failure based on criticality analysis**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based		Consequence based	X	Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of consequence of rotating equipment failure score determined with criticality analysis.							
Formula (e.g., mortality rate / 1000*hour work)							
$\Delta CoF = CoF_{actual} - CoF_{ref}$ where: CoF_{ref}: consequence score of rotating equipment failure at last criticality analysis (1-5). CoF_{actual}: actual consequence score determined with criticality analyses of rotating equipment							
Comment							
Criticality analysis can be based on specific qualitative method at a company. Increasing of the consequence category of a potential failure is an indicator that the risk level has been increased. Consequence of failure related KPI - at equipment level.							
To which system it appeals to							

ERRA Key Performance Indicators (KPIs)							
Rotating equipment.							
Name of indicator	**Increasing of consequence category of rotating equipment failure based on risk based organisation of work assessment**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based		Consequence based	X	Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of the consequence category of rotating equipment failure determined with risk based organization of work assessment.							
Formula (e.g., mortality rate / 1000*hour work)							
$\Delta CoF = CoF_{actual} - CoF_{ref}$ where: CoF_{ref}: minimum consequence category of rotating equipment failure during the last investigated period (T) CoF_{actual}: actual consequence category of rotating equipment failure determined during the last analysis. T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.							
Comment							
The CoF determination is based on risk based organization of work assessment (used at MOL). Increasing of the consequence category of a potential failure is an indicator that the risk level has been increased. Consequence of failure related KPI - at equipment level.							
To which system it appeals to							
Rotating equipment.							

ERRA Key Performance Indicators (KPIs)							
Name of indicator	**Increasing of consequence of instrument failure based on criticality analysis**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	
Lagging KPI		Frequency based		Consequence based	X	Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of consequence of instrument failure depends of the connected equipment consequence of failure. This can be estimated from the criticality analysis of the equipment.							
Formula (e.g., mortality rate / 1000*hour work)							
$\Delta CoF = CoF_{actual} - CoF_{ref}$ where: CoF_{ref}: consequence score of instrument failure at last criticality analysis (1-5). CoF_{actual}: actual consequence score determined with criticality analyses of instrument							
Comment							
Criticality analysis can be based on specific qualitative method at a company. Increasing of the consequence category of a potential failure is an indicator that the risk level has been increased. Consequence of failure related KPI-- at equipment level.,							
To which system it appeals to							
Instruments.							
Name of indicator	**Increasing of consequence category for instrument failure based on risk based organisation of work assessment**						
KPI classification							
Leading KPI	X	Organizational		Action		Other	

ERRA Key Performance Indicators (KPIs)							
Lagging KPI		Frequency based		Consequence based	X	Mixed based	
Local indicators	X	Global indicators					
Definition							
Increasing of consequence of instrument failure depends of the connected equipment consequence of failure. This can be estimated from the risk-based organization of work of the equipment.							
Formula (e.g., mortality rate / 1000*hour work)							
$\Delta CoF = CoF_{actual} - CoF_{Ref}$ where: CoF_{ref}: minimum consequence category of instrument failure during the last investigated period (T) CoF_{actual}: actual consequence category of instrument failure determined during the last analysis. T – last investigated period in days (default value is 180 days, but it can depend on the stability of the process parameters. If the process parameters (temperature, pressure, fluid composition, etc.) are relatively stable, this period can be longer. If the process parameters may change relatively often (for example: frequent stock change) this period can be shorter. In each case it must be assessed individually.							
Comment							
The CoF determination is based on risk based organization of work assessment (used at MOL). Increasing of the consequence category of a potential failure is an indicator that the risk level has been increased. Consequence of failure related KPI - at equipment level.							
To which system it appeals to							
Instruments.							