GEOCAP
Geothermal Capacity Building Program Indonesia - Netherlands

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Failure data base report with instruction manual

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1 GENERAL DESCRIPTION OF DEKRA SOLUTIONS B.V.

1.1 INTRODUCTION

This section describes the work and personnel of DEKRA Solutions B.V., formerly part of KEMA (now DNV GL). The work performed by this department evolves around Asset Integrity. There are many definitions of Asset Integrity, and is linked to systems, software and services. What the definitions have in common as that it assures an asset to perform efficiently and when required, while SHE (Safety, Health and Environment) are safeguarded.

In case of DEKRA, Asset Integrity services are supplied by an independent body. This means that DEKRA has no link with material manufacturers, OEMs (Original Equipment Manufacturers), service providers, or any other commercial or political organization. The client is thereby assured that advice or inspection results delivered by DEKRA are not influenced by any organization.

Asset Integrity services are delivered throughout the lifetime of a plant. Examples of services that can be delivered are shown in Figure 1.1. Before a plant is built, a design is made, e.g. by the OEM. A client buying a plant wants to ensure that the design is profound and fulfils the clients requirements, e.g. in terms of electrical and heat output, but also in terms of structural integrity as described in applicable norms (such as ASME).

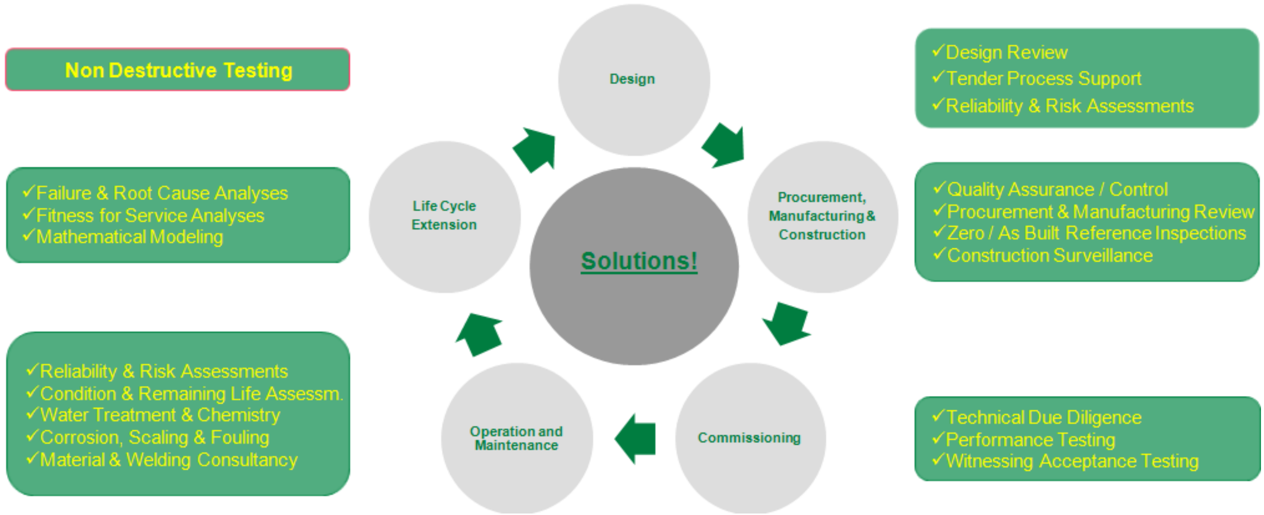


Figure 1.1 Asset Integrity services throughout the lifetime of a plant

A client may wish to ask multiple offers from different OEMs and may start a tender process, evaluation of the pre-design, feasibility study, an advice to the board, setting up functional specifications, market orientation, the tendering process. In this process, the client may be particularly interested in RAMS (Reliability, Availability, Maintainability, Safety). Setting up specifications and give those specifications to the OEM will help to improve the design on RAMS. After an offer has been made by the OEM to the client, the offer must be evaluated, as well as supporting with contract negotiations, supporting with the engineering process, and with quality aspects and procedures. During and after building, inspections should be performed according to the quality handbook. Pre-commissioning, guarantee testing, preliminary and final take over, checking of guarantee and wear parts, checking of documents (project handbook), and final hand over of the plant to production.

In case an installation is not newly designed, but bought, a Due Diligence can be performed. The execution of a due diligence is vital for an investment decision. It gives useful information to be used for negotiations and overcomes surprises. It can lead to an adaptation of price or terms and conditions. A technical due diligence of a power plant gives insight in the existing and future situation regarding operations, maintenance and performance. The scope of a Due Dilligence normally consists of six aspects: organizational structure, condition of assets, operation, maintenance, O&M cost and HSE.

The largest part of the lifetime of a plant is the operation in its design life and after possible lifetime extension. During operation, a number of services are supplied, of which the main are centered around risk and reliability analysis, failure and root cause analysis, condition and remaining life analysis, Fitness for Service, inspections (including QA QC and In-service inspections), corrosion, welding, thermal processes, and NDT. These services are described in more in detail in section 1.2.

1.2 DESCRIPTION OF MAIN SERVICES

1.2.1 QA QC AND INSPECTIONS

QA QC is the abbreviation of Quality Assurance and Quality Control. Quality Assurance focuses on processes to prevent deviations and non-conformances by establishing appropriate quality management systems. Quality Control is a process for maintaining proper standards in manufacturing and construction. Objective is to identify deviations and non-conformances in the product and identifying deviations in the production process that can lead to defects over time. ISO 9000 defines quality control as "A part of quality management focused on fulfilling quality requirements"

As a plant is built you want to attain highest quality standards resulting in highest plant integrity, availability and reliability. Also, you want to prevent poor quality construction resulting in non-conformances and thus project delays and substantial budget over-runs. At the same time, low quality components delivered by suppliers, limited budgets, and ill-organized contractors pose challenges to quality. An independent party supplies QA and QC coordination in (larger) projects, as well as audits of (potential) suppliers, vendor inspections, site acceptance testing, etcetera to assure the required quality level and overcome delays and expanded cost.

A project team is normally formed for building a plant or replacing larger equipment such as a steam turbine or boiler, and a quality manager – or somebody responsible for quality – is appointed. A project team may be formed by the employer's project department, if existing (not every employer builds new plants regularly). It is recommended to appoint a quality manager already upfront of the engineering phase as steering can still be done at this moment.

Knowledgeable experts have decades of experience with QA QC with building new plants and has in-depth knowledge of the equipment and applicable processes. This means they have much practical experience with prioritizing inspections and the impact of performing an inspection too late or not at all and, combined with a pro-active attitude, will timely steer to prevent non-conformances and thus time and budget run-overs.

Knowledgeable experts will supplies following services in the field of QA QC and inspections:
- Organisation and coordination of QA and QC in larger (new build) projects

- Audit of QA system of (possible) suppliers
- Vendor inspections (QC)
- Factory Acceptance Testing (QC)
- Site inspections (QC)
- Site Acceptance Testing (QC)

Coordination of QA and QC in larger (new build) projects

When a new (geothermal) plant is built, a project team is formed and a quality management plan is made. The different roles and responsibilities in the engineering / construction organization must be clear. As an example, a project organization is shown in Figure 1.2.

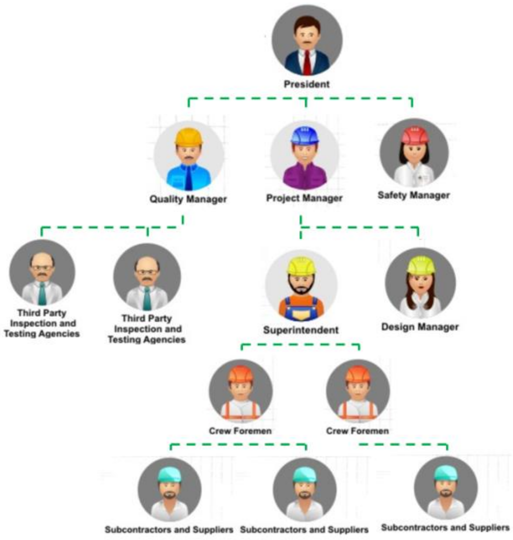


Figure 1.2 Example of possible project organization

Knowledgeable experts can take up the role of quality manager, as it has done so in many projects (for many power plants that have been constructed in The Netherlands). The work starts with the evaluation of the quality plan of the main contractor. This main contractor also supplies QA QC plans (and also specific procedures (inspection and test plans)) of their subcontractors for review and acceptance.

QA QC control during the project is performed by means of regular progress meetings, pre-inspection meetings, inspections, final inspections and contractor evaluation by means of project specific audits.

Also, checking if (national) rules and regulations are followed (e.g. for pressure equipment, the PED (Pressure Equipment Directive) is important in Europe, ASME in the rest of the world) can be part of the task, review PED-classification, as well as communication with the Notified Body. Other important aspects: vendor and site inspections, Factory Acceptance Tests (FAT), Site Acceptance Tests (SAT) and structure and completeness of (final) documentation.

As an example, DNV GL / DEKRA has fulfilled the role of quality manager during the building of the natural gas-fired power station MAGNUM (The Netherlands).

Audit of QA system of (potential) suppliers

To minimise risk of budget over-runs, delivery time, quality issues and life-cycle cost, companies work according an ISO 9001 quality system. However, practice has proven that ISO 9001 is not a single guarantee to overcome the aforementioned risks. Therefore, as a preventive measure, audits can be performed at suppliers. These audits can be:

- Project audits. Audit of a project organization to verify if the required QA/QC-structure, working methods, means and professionalism are present to realise the project within the set goals and requirements.
- Supplier specific. Assessing potential suppliers of (complex) products and services based on the set of requirements set up by the client and assuring all requirements from applicable standards and specifications are fulfilled.
- Product specific. Audit based on purchase specifications of the client while assuring all requirements from applicable standards and specifications are fulfilled.

Vendor inspections (QC)

If an employer (of e.g. a geothermal plant) builds a new plant or performs maintenance and replaces parts, the operator may decide to have vendor inspections performed. This is an activity typically performed by an independent party. A plant is build according to a design and specifications (drawings, materials, fabrication methods, etc.) are attributed to all parts, see Figure 1.3. Smaller, standard parts are inspected on delivery, e.g. valves, pumps or instrumentation. The production of larger parts, however, comprise a larger risk since when they are not according to specification, production of a new part may take longer time causing project delay and increased cost. Therefore, inspections during production are performed. These can be done at the contractor or OEM producing the parts and can include design review, review of material certificates, visual inspection, various Non-Destructive Testing, attendance, supervision or performance of mechanical or functional tests.

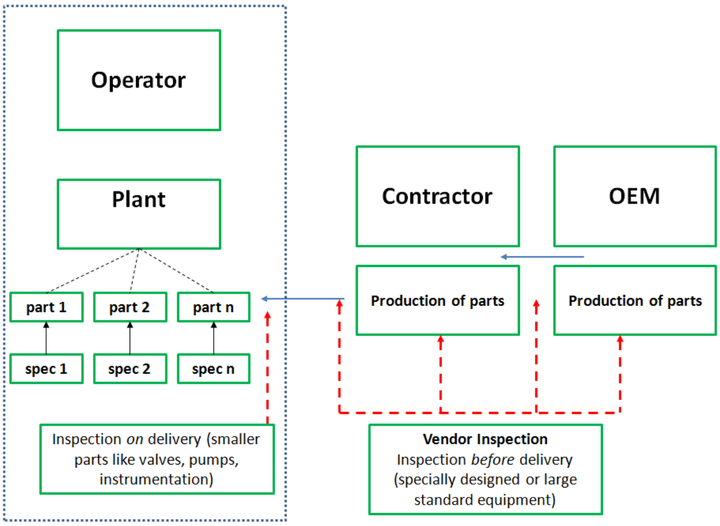


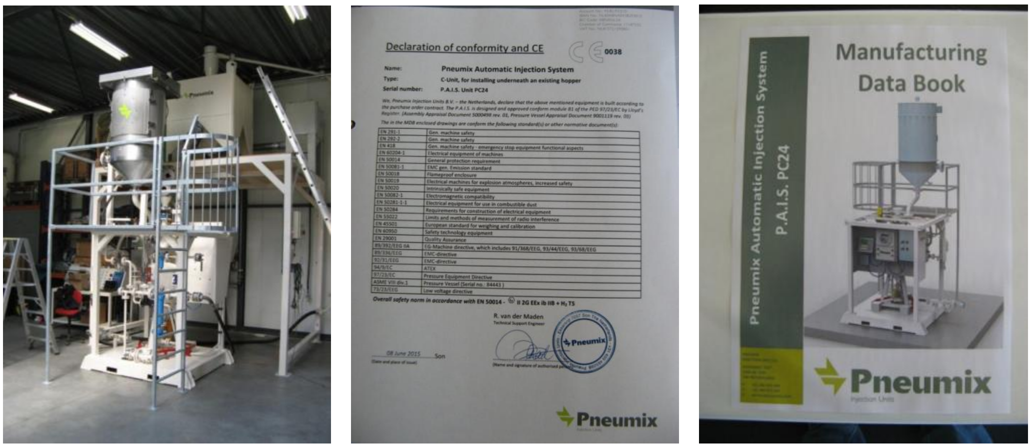
Figure 1.3 The process of part manufacture and delivery including (vendor) inspections

Vendor inspections at the vendors manufacturing site are defined within inspection- and test plans to verify that equipment is being built strictly to the design specifications. Control and management of changes is also an important aspect during vendor inspections.

Factory Acceptance Test (QC)

A FAT or Factory Acceptance Test is usually performed at the vendor prior to shipping to a client. The vendor tests the system in accordance with the clients approved test plans and specifications to show that system is at a point to be installed and tested on site. It is an essential aspect of the whole system lifecycle and should be performed by experienced personnel. Time spent doing a proper FAT will lead to fewer problems when the equipment is installed on your site. FAT can include checking of documentation (manual, maintenance information, material certification, CE, PED and ATEX declarations), witnessing of testing (machine works properly), visual inspection, dimensional checks, checking of preservation and shipment preparation.

As an example, the quality of a dosing installation for a Petrochemical Plant was checked by DNV GL / DEKRA. Mounting and erection should be according good engineering practice and the proper working was tested. All belonging paper works and certifications were checked and were found to be in good order. Minor items were to be improved. Photos are shown in Figure 1.4.



Declaration of conformity and CE 0038

Name: Pneumix Automatic Injection System
Type: C-Unit, for installing underneath an existing hopper
Serial number: P.A.I.S. Unit PC24

We, Pneumix Injection Units B.V. – the Netherlands, declare that the above mentioned equipment is built according to the purchase order contract. The P.A.I.S. is designed and approved conform module B1 of the PED 97/23/EC by Lloyd's Register. (Assembly Appraisal Document 5000498 rev. 01, Pressure Vessel Appraisal Document 9001119 rev. 03)

The in the MDB enclosed drawings are conform the following standard(s) or other normative document(s):

EN 291-1	Gen. machine safety
EN 292-2	Gen. machine safety
EN 418	Gen. machine safety - emergency stop equipment functional aspects
EN 60204-1	Electrical equipment of machines
EN 50014	General protection requirement
EN 50081-1	EMC gen. Emission standard
EN 50018	Flameproof enclosure
EN 50019	Electrical machines for explosion atmospheres, increased safety
EN 50020	Intrinsically safe equipment
EN 50082-1	Electromagnetic compatibility
EN 50281-1-1	Electrical equipment for use in combustible dust
EN 50284	Requirements for construction of electrical equipment
EN 55022	Limits and methods of measurement of radio interference
EN 45501	European standard for weighing and calibration
EN 60950	Safety technology equipment
EN 29001	Quality Assurance
89/392/EEG IIA	EG-Machine directive, which includes 91/368/EEG, 93/44/EEG, 93/68/EEG
89/336/EEG	EMC-directive
92/31/EEG	EMC-directive
94/9/EC	ATEX
97/23/EC	Pressure Equipment Directive
ASME VIII div.1	Pressure Vessel (Serial no.: 84443)
73/23/EEG	Low voltage directive

Overall safety norm in accordance with EN 50014 - Ⓔx II 2G EEx ib IIB + H_2 T5

R. van der Maden
Technical Support Engineer

08 June 2015 Son
(Date and place of issue)

(Name and signature of authorised person)

Pneumix

Figure 1.4 FAT of dosing installation. Left: overview of installation; middle: declaration of conformity and CE; right: manufacturing data book.

Site Acceptance Test (QC)

A Site Acceptance Test can be done on a single machine or a whole (power) plant and is performed to see if the system is according to the approved test plans and specifications, and also to show that the installation works properly, including interfaces with other systems. The completeness of documentation is checked, including as-built documents, handbooks, manuals, spare part lists, data sheets of wear parts, CE-conformity statements and other certificates. Safeguarding tests are performed, including emergency shutdown during full load and test runs to demonstrate performance (including guarantee measurements and reliability runs).

An example of a SAT is of final erection and commissioning inspection of 21 large wind turbines of 3 MWe each. This inspection was necessary for the investment banks regarding the final payments of the project. Some serious irregularities were found as shown in Figure 1.5. For example, it was found that it was possible to try to insert locking pins (preventing the turbine blades to spin) to push into the locking holes while not aligned properly. In effect, the hydraulic pumps pushing the pins exerted an overload reaction force to its fixation with bolts. The part of the thread of the bolts with fixed by the nuts was too small, resulting the pump to come loose and the bolts to be launched with high impulse (imposing risk to people during maintenance).

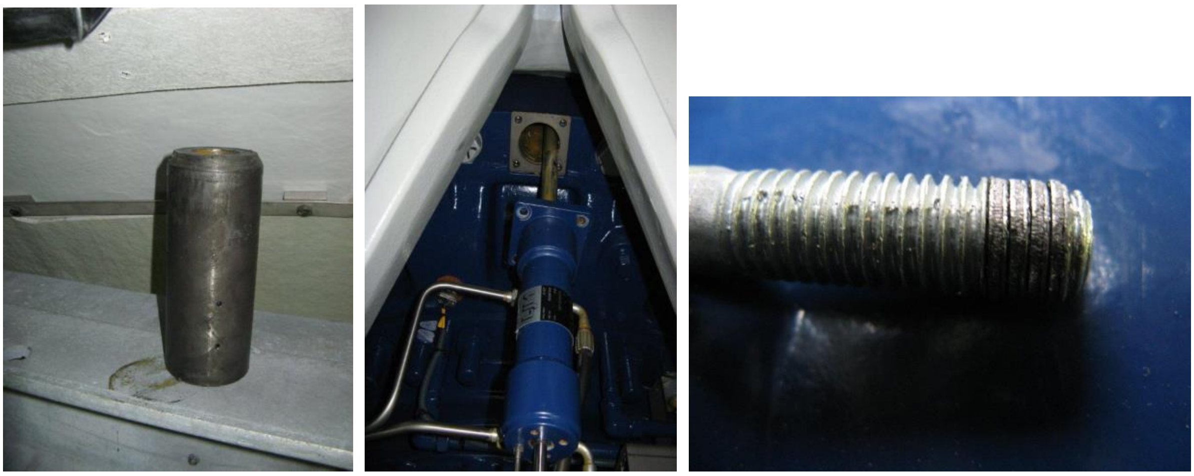


Figure 1.5 Left: locking pin; middle: pump driving locking pin; right: bolt that came loose

1.2.2 RAMS-ANALYSIS

The abbreviation RAM stands for Reliability, Availability, Maintainability and Safety. Based on these aspects, the required quality of primary performance of any product or system can be described, determined and monitored. The terms Reliability, Availability, Maintainability are described in more detail:

- Reliability is the probability that – under given conditions – the product or system can perform its function during a certain time interval. For a geothermal plant, a high reliability means that the plant does not fail often. Reliability is expressed as chance per unit time, for a geothermal plant an indicator is the number of forced outages per year.
- Availability is the ability of a product to perform its function during a certain time interval. It is a dimensionless number, and is the probability that the product or system can perform its function when required. For a geothermal plant, a high availability means that the plant produces when you need it to produce. An indicator of availability of a geothermal plant is the fraction of time that it is able to deliver.
- Maintainability is the probability that active maintenance can be performed within a certain pre-defined time interval. For a geothermal plant, a high maintainability means that it is easy to repair. An indicator of the maintainability of a geothermal plant is the average forced outage duration.

- Safety is the requirement not to harm people, the environment, or any other assets during a system's life cycle. It is reflected by the number of personal incidents caused by failure. A safe geothermal plant means that no serious injuries occur as a consequence of an unwanted event in the plant. An indicator is for example "the individual risk is < X per person per year".

Typical questions that can be solved by data analysis and RAM simulation are:

- The unavailability of a plant is registered. However, is an unavailability of 5-10% a good value or a reasonable value given the layout of the plant or should a project be started for betterment? Which forced unavailability is feasible? How long should one measure to be sure?
- Something happens on a steam turbine causing a 1 month outage. Is this High Impact failure an incident (a Low Probability event) or is the frequency of such incidents at this plant out of bounds? Which components are generally causing HILP failures? Does the probability of a HILP increase with age?
- What is the amount of teething problems that can be expected for a new plant? Which components will cause teething problems? What average value and what range of forced unavailability can one expect? To what extend should redundancy be installed?
- As an alternative to a new built plant it is considered extending the life of the old plant. For what components ageing (increase in failure frequency) and maintainability problems (increase in repair time) will likely occur?
- Spare parts analysis to weigh the costs for spare parts against the financial benefits of shorter repair times. Evidently the distribution of repair times is important to solve this question.

Several tools are available to improve RAM, including RAM-modelling, weak point analysis, betterment of ageing and life extension studies, spare part policy and maintenance optimization. RAM-modelling can be done by making use of Reliability Block Diagram (RBD) analysis. A RBD is a series of blocks that are connected in parallel or in series whereby each block represents a component of the system to which a failure rate is and repair time assigned. An example of the feed water system of a power plant in RBD is shown in Figure 1.6.

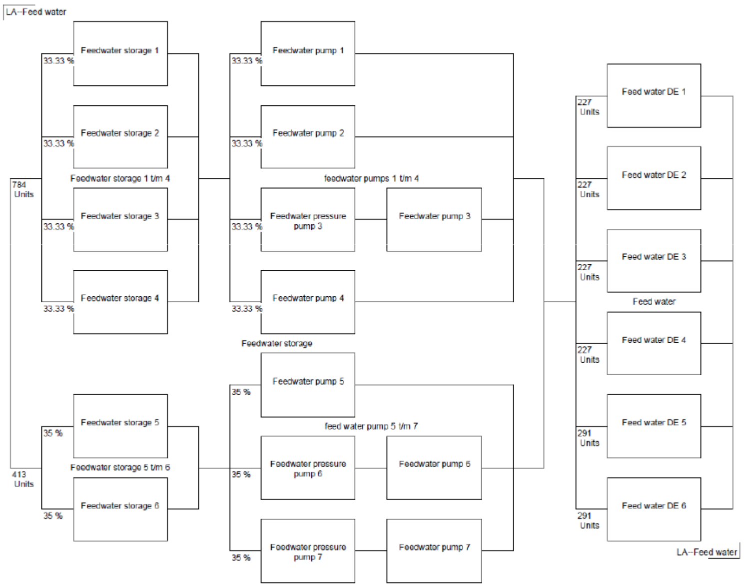


Figure 1.6 Feed water system of a power plant in Reliability Block Diagrams

RAM-modelling can also be done by making use of Fault Tree Analysis (FTA). In general, FTA focuses on one particular "top event", namely total system failure, and is used to analyse the faults and conditions leading to system failure. The various combinations of equipment failures (or events) that lead to system failure are determined. By attributing failure rates and repair times, availability can be calculated. In case of very complex systems, like electrical systems, failure tree analysis is applied. Only one system state (namely system failure) can be evaluated with a fault tree, while using RBD, different states can be evaluated. As an example, a coal plant can be 100% available, fully unavailable ("system failure"), but also partly available, say 75%. A reason can be that one of multiple coal mills break down, that results in a say 25% reduction of power output. An example of a RBD-analysis result is shown in Figure 1.7, showing system state versus time.

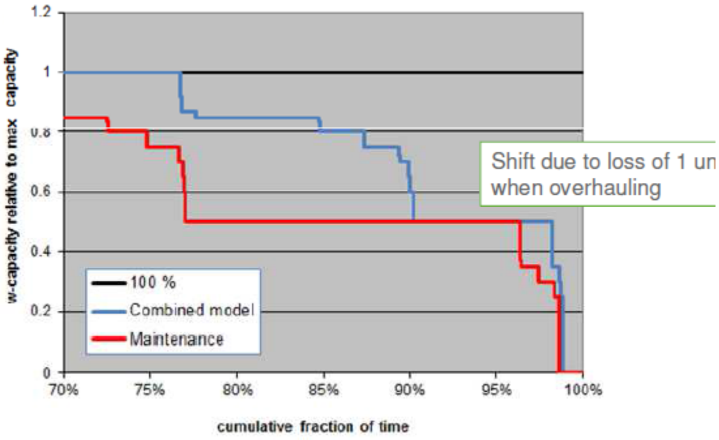
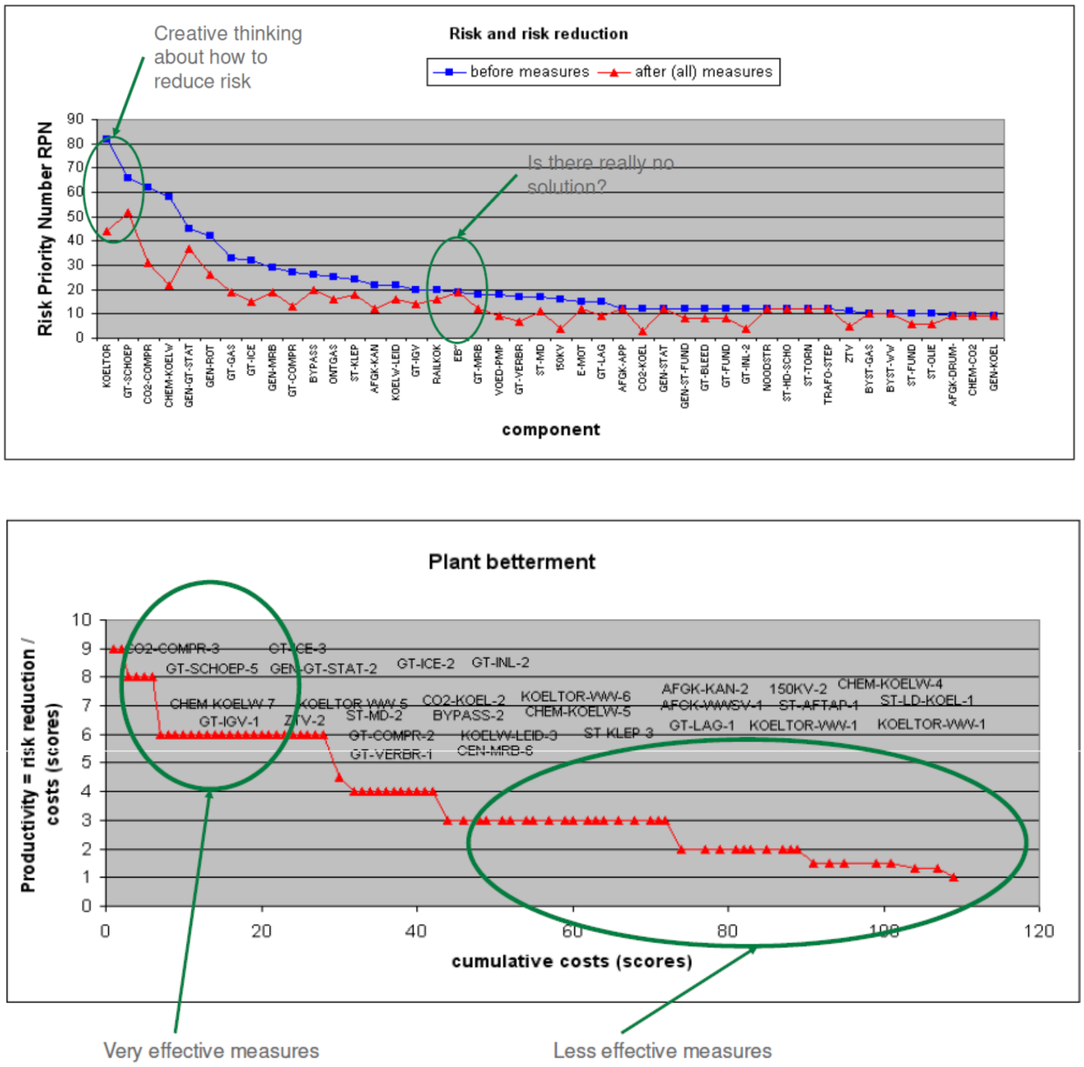


Figure 1.7 Simulation result of RBD-analysis: system state versus time. In this analysis, the delivery of heat by two coal units was simulated in case of two units in operation and an overhaul at one unit.

Failure data (failure rates and repair times) are needed to perform RAM-modeling. This data can be obtained from publically available sources such as OREDA or, for power plants, KISSY. The downside of these data is that the plants are anonymous. It is therefore not known that the plant of interest is identical to the plants in the database. Therefore, DNV GL / DEKRA has gathered their plant specific failure data over the last decades. It is advised to set up such a plant specific failure database (i.e. failure rates and repair times) for geothermal power plants in Indonesia.

Average values of failure data and repair time can be applied in reliability modeling. This gives an average value for the system reliability. Often, however, interest exists for the influence of the probability distribution of failure and repair time data on reliability distribution. For this, probability distributions functions can be assumed (uniform distribution for failure and exponential distribution for repair time). Monte-Carlo simulation is applied, whereby distributions are represented as sequences of discrete random values. A probabilistic model of the system is generated after which a trial run of the model is repeated many times, and each time several indicators for the performance of the model are recorded. After a sufficiently large number of computer runs, the average value as well as the distribution of the value can be used for decision making.

Opposed to FTA, which follows a top-down approach ("what event can lead to system failure"), a FMECA follows a bottom-up approach: "what is the effect of equipment failures on the installation". The method in itself is relatively easy to apply, it is however most important to perform an FMECA with people that are familiar with the components of the system and the system to be analyzed. They must be able to state - either on basis of their experience, or on their engineering judgment - the failure modes of the components and the effects of those failure modes on the system as a whole. By assigning consequences (quantified in classes) and probabilities of the unwanted events, risk classes can be determined. By defining alternative measures to reduce the risks, in addition to present measures, risks can be rated and compared to the situation after implementation of the additional measures. This shows what measures have most impact, see Figure 1.8. Together with the associated cost of an alternative measure, an action list can be drawn up to decrease risks.

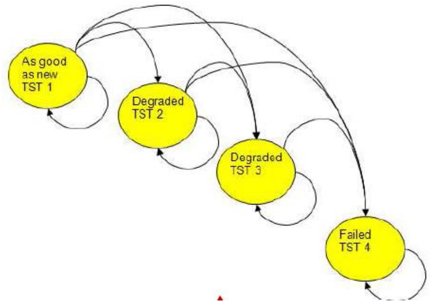


Very effective measures

Less effective measures

Figure 1.8 Top: Risk Priority Numbers of different components in a power plant with existing and alternative measures, following from a FMECA. Bottom: risk reduction versus cost.

Maintenance optimization can for instance be performed using Markov processes. In a Markov-chain, a system is described moving from a certain state to another state (or the same state), whereby moving to a certain state is only dependent of the current state and not the sequence in which that current state is reached. First a state diagram of the system is constructed; see Figure 1.9 (left). The system starts as "As good as new", and can move through several degradation states (or directly) to the final state "Failed". De probabilities of transition are estimated on basis of failure and maintenance data. As an example, maintenance optimization was done for motors driving circulation pumps of a FGD (Flue Gas Desulphurisation) unit of a coal-fired power plant, where bearings of the motors fail (too) frequently. Also, there is a chance of misalignment. Four system states are defined: 1) as good as new, 2) bearing is warm and starts vibrating, 3) large vibrations, noise 4) failure. In addition, cost of maintenance and degradation were estimated, as well as inspection and maintenance time. By simulating the process numerically for four different strategies: 1) periodic replacements of bearings, 2) condition based replacement in state 2 or 3, 3) condition based replacement in state 3, 4) corrective replacement (replace when broken). The condition was measured using vibration measurements, visual inspections (dripping fat) and checking for bearing noise. Multiple optimum solutions for inspection times were found, see Figure 1.9, right for an example (1 out of 5,000 Monte Carlo simulations). The example shows that it is advised to inspect quickly after installation, and re-inspect on basis of the measurements (rather than applying a fixed step inspection interval).



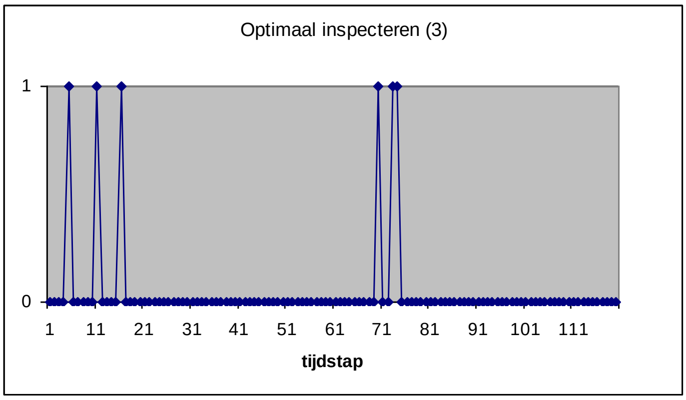


Figure 1.9 Left: state diagram. Right: example of optimum times of inspection.

1.2.3 IN-SERVICE INSPECTIONS

Once a (geothermal) plant is in operation, components are subject to degradation (e.g. due to creep, fatigue, corrosion, steam oxidation, et cetera). Components therefore have a finite life. For some components, the degradation rate is very low (such as warm water transport lines), while for other components, such as waste incineration boilers, the degradation rate is very high. The main purpose of in-service inspections is to assess the condition of components, and to verify whether degradation is according to the expected level. In addition, non-detected failures can be identified and repair measures can be checked for their effectiveness during an inspection.

Depending on the country, periodic inspections (and according inspection intervals) are part of the national legislation, or legislation is such that a plant "must be safe" by which periodic inspections may not be compulsory *expressis verbis*, though are the only way to ensure safety (and in addition, may be required by the insurance). Furthermore, inspections can be performed not only for reasons of safety, but for plant availability.

If degradation is (very) site-specific, e.g. due to various types of corrosion (this is especially true for the chemical industry), an approach for prioritising equipment to be examined can be adopted based on risks, referred to as 'Risk Based Inspections', abbreviated as 'RBI'. Hereby maintenance can be optimized to decrease both risks and cost. For the power industry, it has shown that where periodic inspections are part of the legislation, RBI does not offer much added value (in countries where periodic inspections are not prescribed, RBI may be a worthwhile approach).

Non-destructive testing normally makes up for the largest part of in-service inspections, see section 1.2.8. As mentioned, the main purpose of in-service inspections is to assess the condition of components, and to verify whether degradation is according to the expected level. To perform such an assessment, i.e. to interpret the findings of visual inspections (and to assure completeness of the visual inspection), and to interpret the NDT-results requires knowledge of the components and their degradation mechanisms and "reference" build up by experience.

Specific components where high degradation rates apply, e.g. due to corrosion (and therefore could negatively plant availability if not repaired in time) may require thorough investigation. An example of such an in-service inspection is the inspection of Flue Gas

Desulphurization Units (FGD) of coal-fired power plants. Flue gasses contain SO_2 and some SO_3 that is harmful for the environment and therefore need to be removed in the FGD. In the FGD, water is sprayed and limestone is added, so that calcium sulphate is formed so that the bulk of the sulphur is not emitted through the stack as SO_x. Hydrated calcium sulphate is gypsum which can be applied as construction material. The washing fluid absorbs sulphur and other constituents of the combustion gasses like chlorine and fluorine which is very corrosive at the operating temperature of 45°C. Although materials are used to prevent corrosion (rubbers, stainless steel, Hastalloy, ceramics, (glass fibre reinforced) plastics), corrosion is normally manifest. During an outage, the unit is therefore thoroughly inspected. Typical damages are shown in Figure 1.10.

Figure 1.10 Typical damages observed in a FGD. Left: corroded steel beam with rubber; middle: impeller with radial cracks; right: holes in glass fibre reinforced plastic pipe.

A type of equipment where RBI is often applied (and where high corrosion rates apply) is storage tanks. An independent party can assist with setting up either the time-based periodic inspection, or the Risk Based Inspection, assuring it is in line with local legislation and the required level of integrity. This includes pre and post-inspections. In the pre-inspection, the scope of the inspection is defined based on tank history, actual condition and risk assessments; the inspection strategy and focus points are defined and the correct inspection techniques are defined. In the post-inspection, results are evaluated and are input for a next (pre-) inspection, remaining life of components may be calculated and recommendations are given for maintenance and repair. Specific mechanized inspection techniques can be applied such as wall thickness measurements (see section 1.2.8) using a "crawler" (a robot, crawling up a wall or riding over a roof, see Figure 1.11 (left)) or detecting corrosion using a 'floor scanner' (see Figure 1.11 (right)).

Figure 1.11 Mechanized inspection techniques of storage tanks. Left: wall thickness measurement using a 'crawler'. Right: corrosion detection using a 'floor scanner'.

Another reason for performing a condition assessment – other than for periodic inspections – is for the purpose of determination of the remaining life. This is described in section 1.2.4.

1.2.4 CONDITION AND REMAINING LIFE ANALYSIS

1.2.5

After a plant has operated for a certain time, the condition of a plant may be assessed. It can be that the theoretical end-of-life (i.e. design life) will be reached in some years and the plant would need to close down. However, the actual remaining life can be (much) higher than the theoretical remaining life as calculated upon design. A reason for this can be that design rules are conservative by nature, i.e. actual degradation (e.g. fatigue) is lower than calculated according to design given the operational conditions. Furthermore, operational conditions may have deviated from those for which the plant has been designed. With e.g. less starts and stops, or lower operational temperature, this will result in lower life consumption. Also, (market) conditions defining operation may change: a plant that has been designed for base load operation may require to cycle and a shorter remaining life will have to be accounted for. In these situations, the condition of a plant has to be assessed to define if investments are needed (or can be postponed) for extended life, and if investments are required, it has to be assessed whether these investments are cost-effective.

In order to assess the plant (or component) condition, estimate residual life and give recommendations, most independent parties are working with a staged approach which is best industrial practice and consist of:

- In general: Project Management (organize, co-ordinate and supervise the activities.
- Stage I Plant Review Activities
- Stage II NDT Inspections
- Stage III Final Reporting

1.2.5.1 STAGE I PLANT REVIEW

The goal of Stage I is to determinate the preliminary condition of the plant and to identify critical components in terms of life extension. This is divided in three main areas of expertise: mechanical, civil and electric condition assessment of specified parts. Based on the results of the plant review, an inspection program is defined to assess the condition of components that have been found critical or suspected, and those components which condition is unknown due to lacking historical information or specific operational conditions. This inspection program is part of Stage II. The site activities that are part of Stage I include:

- Gathering and reviewing design data (drawings) and historical data (inspection reports, operational process parameters, maintenance reports etc. An example of reviewing creep life is shown in Figure 1.12 (left)
- Interviews with involved plant engineers
- Break down of installation/assets in components (material identification, design parameters, design or as built dimensions, construction details like welds)
- Evaluation of condition, based on received historical data
- Identification of active damage mechanisms and (root) causes of failures per component
- identification of criticality in terms of safety, reliability, performance
- Identification of critical components based on design, historical data and experience with similar equipment, and weaknesses in design
- During the Stage 1 site visit, an external visual inspection of specified parts will be performed (Walk down). Pictures will be taken in order to register the visual condition of parts and equipment. See Figure 1.12 (right) for an example.

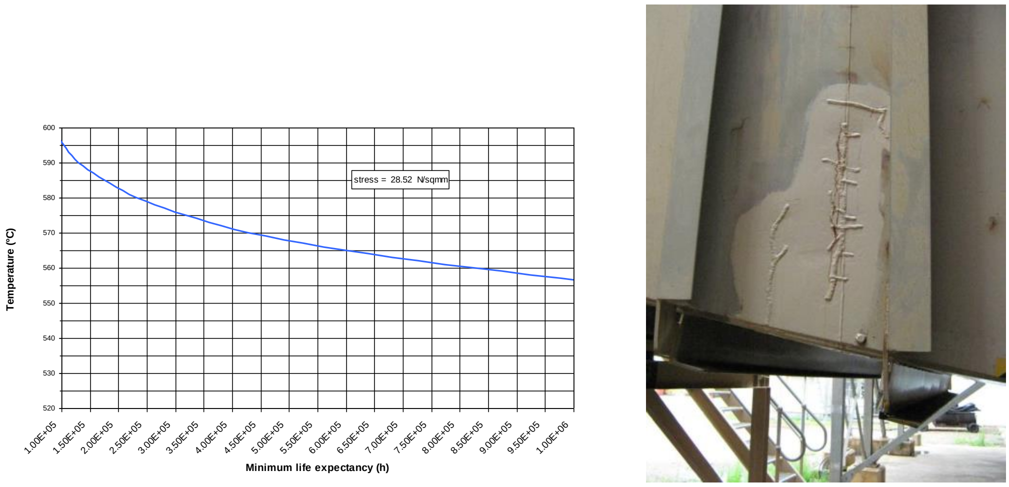


Figure 1.12 Left: Creep life calculation on basis of pressure and temperature. Right: visual inspection of boiler casing showing cracking of repair welds.

1.2.5.2 STAGE II NDT INSPECTIONS

Based on the results of Stage I, a detailed inspection, testing and measuring program can be conducted if necessary, in order to complete the results of Stage 1 inspection. The test program describes which tests or measurements are needed in order to get a complete picture of the assets, based on VT, MT and UT (i.e. non-volumetric) inspection techniques, for determining the condition and estimate remaining life (NDT techniques are described in more detail in section 1.2.8). An example of a test program is shown in Figure 1.13.

Steam line, Unit #4 , #5				
component	**detail**	**inspection item**	**technique**	**interval (yrs)**
turbine stop valves	-spindle -valve mating surface -valve seat -internal surface -strainer	-straightness, wear, surface damage -cracks, wear -cracks, wear -cracks -erosion, wear	VIS MT+VIS MT+VIS MT VIS	4 to 8
turbine control valve	spindles valve mating surface valve seats linkage (cantilever) housing	-straightness, wear, surface damage -cracks, wear -cracks, wear -wear -cracks in internal surface	VIS MT+VIS MT+VIS VIS MT	4 to 8
nozzle boxes (control stage)	nozzles nozzle box	-erosion -cracks	VIS MT	4 to 8
curtis wheel (control stage)	blades balance holes in rotor disk	-rivets of shroud -FOD -cracks -cracks	UT VIS MT/ET MT	4 to 8
diaphragms	diaphragm unit	-guide vanes (FOD, cracks) -welds of guide vanes (erosion) -deflection of diaphragm	MT+VIS VIS VIS	4 to 8
rotor blades	blade	-erosion of leading edge (last stages) -cracks (all blades) -blade foot (last stages)	VIS MT/ET MT	2 4 to 8 4 to 8
labyrinth seals of diaphragms and rotor	labyrinth seals	-wear	VIS	4 to 8
rotor	all diameter transitions	-flange and all other diameter transitions -grooves -seal area -blade grooves (only possible after removal of blades)	MT MT MT + VIS MT/UT	4 to 8
gland seals	labyrinth seals springs below seal teeth	-wear -fixation -check for movement and broken springs	VIS VIS VIS	4 to 8
casing	inner surface outer surface	-wall thickness transitions -diaphragm grooves -gland carrier grooves	MT MT MT	4 to 8
casing bolts	bolts	-cracks in transition thread to shaft -local reduction of area in shaft	MT+VIS VIS	4 to 8

MT = magnetic particle testing
VIS = visual inspection
UT = ultra sonic testing (e.g PE, TOFD, PA)
ET = eddy current testing
all turbine parts should be cleaned by glass pearl blasting prior to NDT

Figure 1.13 Example of test program (NDT activities) resulting from Stage I activities.

As an example, Figure 1.14 shows a selection of wall thickness measurements and the locations where they have been performed. Protocol reports are supplied for all measurements.

4th inlet header LH side			
location	wall thickness (mm)	design wall thickness (mm)	minimum required wall thickness (mm)
J (Fig. 22)	3.6	3.2	1.2
K (Fig. 22)	3.6	3.2	1.2
L (Fig. 22)	16.9	14.3	--

Figure 1.14 Top: photos of location where wall thickness measurements have been performed. Bottom: results of wall thickness measurements (column 2), design values (column 3, result of Stage I), and minimum required values (column 4, calculated in Stage I)

1.2.5.3 STAGE III FINAL REPORTING

The report will contain the following:

- Present condition of inspected components with details of tests done, and results to justify the conclusion
- Recommendation for refurbishment of parts including method and further test that are required to be done in the future
- Recommendation for replacement of parts, which have to be done immediately
- Recommendation for renewal of parts for improvement of performance
- Recommendation for regular tests recommended to be done in the future and the time schedules for these tests

- Material required being ready for replacement, to enable destructive tests, which are needed to be done to evaluate condition of parts, should be informed in advance in your program schedule.
- Recommendation for parts required to be ready for replacement as an insurance spare
- Suggestion regarding modification and replacement schedule, as well as renovation proposal.

As an example, a summary of the assessment and recommendations for a high pressure steam line to the steam turbine is shown in Figure 1.15.

HP-steam line from unit #4 & #5 to steam turbine (#6)

Technical condition: good

The creep life expectation of the steam line is ample and the condition as found during inspection appears to be good. The steam line is regarded as fit for an extended period of another 15 years.

Issues:

Condensate traps in relation to reported steam hammer

Details:

- The exposure to creep in the steam line is low and offers no problem in terms of life extension
- Supports of the steam line have been found in acceptable condition
- Main steam valves, Y-pieces and bypass T-pieces have been found free of surface breaking defects
- Reported steam hammer requires a thorough check of the condensate traps and drain valves
- Y-piece and welds in main steam line by pass were found free of surface breaking defects

Note: in the PWC-CIPS Project Packages Life Extension a project is defined for 2013 in which separation of the steam and water system between units #4 and # 5 is carried out. This would allow a possibility for inspection and/or modifications.

Recommendations:

- Periodic, visual inspection of all steam line supports for damage (e.g. broken pipe clamps or clamp bolts, bent guide bars, dislocated support shoes, constant load hangers not blocked and within travel etc.) with a frequency of 6 – 12 months based on best practice.

- Overhaul of condensate traps and drain valves in steam line system to prevent recurrence of steam hammer

Figure 1.15Example of summary of assessment and recommendations of a specific component of a power plant (in this example, the component is the high pressure (HP) steam line to a steam turbine.

1.2.6 FITNESS FOR SERVICE

When a (mechanical) component is inspected and flaws, damage or other deviations are found, this means that the condition of the component is not as required according to the original design. Three options are then possible (3R options): Run, Repair or Replace. The options should be evaluated in terms of cost, time and effectiveness. While in many countries immediate repair is the preferred option, it must be born in mind that there are several issues to consider with repair. Aside from the fact that a repair may be difficult to carry out, there is a risk that material is degraded by welding. Effectively, the condition of the component may be worse after repair than before. Also, a repair can be costly due to preparation, implementation and standstill. The replace option has the same disadvantages and can be even more expensive due to the cost of replacement parts. Furthermore, delivery time of replacement parts can be long, especially for non-standard parts. The third option is "Run when proven to be fit for service". This prove can be delivered by a Fitness For Service (FFS) analysis, whereby safety is ensured until next re-inspection. If proof of Fitness for Service can be delivered, repair can be postponed or avoided, delivery time of non-standard replacement parts can be bridged and cost are saved by continued service. A fourth option, Run without proving FFS, should never be considered.

Typical flaws that can be analysed with a Fitness for Service analysis are thin spots, weld cracks or planar flaws, shape distortion, misalignment, and cavities or inclusions. Typical components that are considered are expensive to repair or replace, subject to damage mechanisms such as fatigue, creep, et cetera are inspected on a regular basis. Examples of such components are pressure vessels or steam headers (nozzle welds, axial and circumferential welds), piping (welds of form pieces), valve bodies, generator rotors and retaining rings, turbine rotors and turbine discs.

An overview of the FFS analysis is shown in Figure 1.16. After inspection, a significant flaw or deviation can be found and FFS assessment can be performed. There are various standards / guidelines for FFS assessment. These include for example BS7910, API 579-1 ASME FFS-1, R6, R5, FITNET.

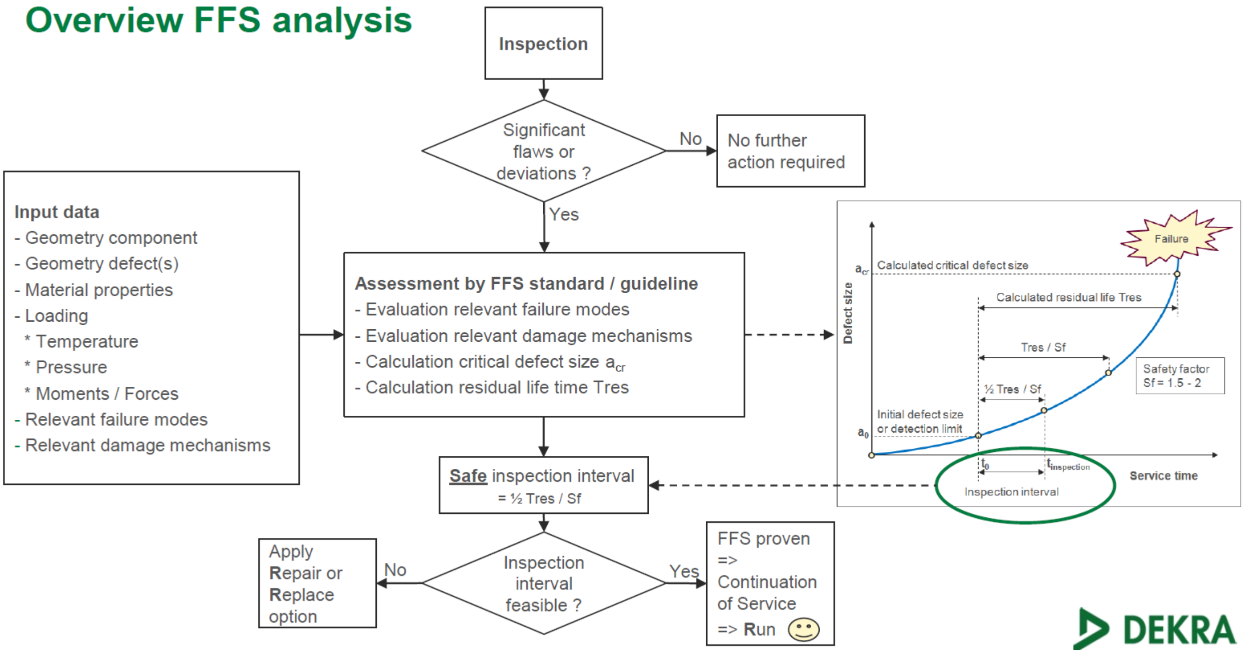


Figure 1.16 Overview FFS analysis

A first question that needs to be answered is: "how does a component fail?" To answer this question, the failure mode needs to be determined. Basic failure modes are plastic collapse (or rupture), creep rupture, brittle fracture and ductile fracture. A second question that needs to be answered is "in how much time does the failure mode occur?" To answer this question, the damage mechanism needs to be determined. Basic damage mechanisms are fatigue, creep, environmentally driven processes (such as stress corrosion cracking), or wear / erosion. The calculation result (using FEM and fracture mechanics) is a residual life time. This residual life time is multiplied by a safety factor (e.g. a factor of 0.5). A safe inspection interval is then determined, by multiplying with a factor (usually also 0.5). An example of a case of a high pressure bypass valve is described in the following.

Case HP bypass valve

During inspection of a high pressure bypass valve of a power plant unit (see Figure 1.17), a craquelé like type of cracking was discovered. The inside wall surface of the valve in the spherical part contained multiple cracks with maximum depth of 4 mm and maximum length of 900 mm. The cracks were most likely caused by thermal fatigue due to thermal shocks induced by contact of relative cold injection water with the inside wall surface of the valve during start-up. The valve is designed to reduce steam pressure and temperature from 180 to 53 Bar and 548 to 400 °C. The wall thickness is 43 mm in the spherical part with an inner radius of 250 mm.

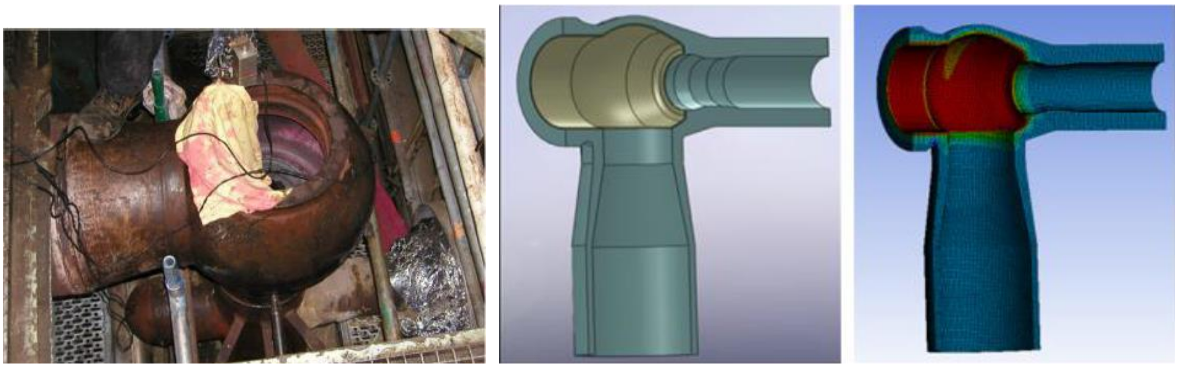


Figure 1.17 Left: Photo of valve during inspection. Right: Stress distribution in valve.

The customer's aim was to continue service for 2 years until the unit would be shut-down permanently. In order to investigate whether this is safely possible according to the appropriate standards, a fitness for service analysis should answer the following questions:

- Is the pressure wall of the valve containing multiple cracks still strong enough? Also when the cracks grow deeper in the wall until finally the critical crack size is reached?
- What is the dimension of the critical crack size causing high risk of unstable crack growth?
- How long does it take before the current cracks have grown to the critical size?
- If service can be continued when should first re-inspection take place?
- When cracks grow through the wall, will leakage- or immediate collapse

With a finite element model of the valve, the strength in the damaged condition is evaluated by a limit load analysis and stresses due to internal pressure load and thermal shocks have been calculated, see Figure 1.18.

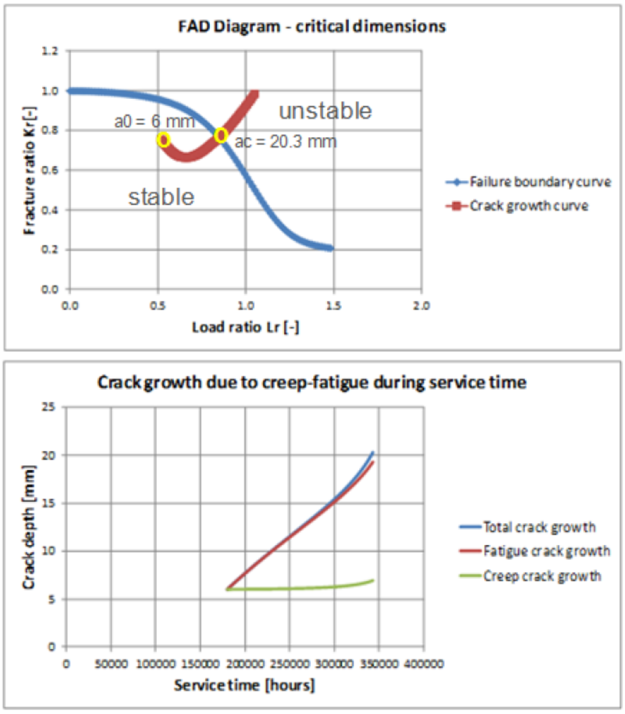


Figure 1.18 Limit load analysis

Based on the stresses derived from the finite element model, the crack behaviour has been evaluated according to the BS 7910 standard. The calculations have shown that beyond 20 mm depth the crack could become critical, i.e. causing fast unstable crack growth.

The critical crack depth is calculated to be reached after 79 starts (82,000 hours of service) due to crack growth by creep and dominantly fatigue. An appropriate safety margin is hereby taken into account. The crack growth rate is nearly constant (instead of increasing as in most cases) due to strong reduction of thermal stress further away from the inside wall surface. The occurrence of leak before break could not be proven for this case.

1.2.7 FAILURE AND ROOT CAUSE ANALYSIS, INCLUDING DESTRUCTIVE TESTING LABORATORY

Assets can experience unexpected failures that lead to extra costs due to repair or replacement, but also due to unplanned downtime of the installation or component. About 30% of the failures of many components have a repetitive character, and failures may even lead to unsafe situations for people and environment. Failure investigation is appropriate in those situations. In some cases the cause of the failure might be clear enough to take adequate preventive measures but in many cases a root cause assessment is required to understand the unexpected problem and prevent reoccurrence.

Failure and Root Cause Analysis will help you to eliminate recurrent failures, thereby increasing the reliability of the plant or rolling stock. As a consequence, cost of lost production and maintenance decrease and safety increases.

As an example, DNV GL / DEKRA has several dedicated labs and experts who can generate vital information available in the material and the fracture surface of the failed component using visual and microscopic techniques. Our labs are specialized in investigation and testing of metallic materials, plastic and rubber. We can perform (hot) tensile testing, hardness testing, fatigue testing, Charpy impact testing, bending testing, replication, Scanning Electron Microscopy, corrosion analysis, corrosion testing in climate chambers, in-service corrosion testing, UV weathering, determination of glass transition area, detection of solvents, fibres and fillers, identification of materials, and more. Some examples of frequently used test devices, sample preparation and microscopes are given in Figures 1.19 and 1.20.

Figure 1.19 Left: universal testing machine (for tensile testing). Middle: Optical Emission Spectroscopy (OES) for accurate determination of metal composition. Right: Charpy Impact testing machine.

Figure 1.20 Left: sample preparation for microscopic investigation. Middle: stereo microscope (magnification 8-100x) and metal microscope (magnification 25-1000x). Right: Scanning Electron Microscope (SEM).

Furthermore, mechanical and chemical engineers can estimate the mechanical and/or chemical load (e.g. using (finite element) modelling, vibration analysis or in-service force, strain, or stress measurements) which has resulted in the failure. As independent party we can help asset owners to operate safely by determining the root cause of a failure and to make you understand what went wrong.

Figure 1.21 Left: first stage stationary gas turbine blade; middle: failed rail; right: broken bull and pinion gear

An investigation typically starts with an on-site inspection, microscopic investigation of the failed component and gathering process data. Possible causes are listed and a downselection is made to the most plausible failure mechanism or root cause, e.g. by applying the Kepner-Tregoe method. An investigation is often executed by one expert in a few days, but larger root cause may be performed by a team consisting of experts of the client, OEM and an independent party, expanding over multiple weeks. Examples of failed components analyzed by experts are steam lines, heat exchangers, gas turbine blades, (exploded) knock-out vessels, short-circuited HV-cables and transformers, rail switches, train axles and pantographs.

1.2.8 CORROSION ANALYSIS

Corrosion analysis is a very specific type of failure investigation for which specialized knowledge is required. Many different degradation mechanisms apply in (geothermal) power plants. In combustion boilers, High-Temperature Corrosion can be an issue that is difficult to control, and depends on the applied materials, the fuel diet (i.e. combustion gasses and deposits that are formed), temperature and operation (oxygen content, flame impingement, et cetera). For geothermal plants, High-Temperature Corrosion is not an issue. The tools for analysis are however applicable. Also other types of corrosion take place in power plants. An example will be given in section 1.2.7.2 that may apply for geothermal plants.

1.2.8.1 HIGH-TEMPERATURE CORROSION

High-temperature corrosion can take place in combustion boilers fired with e.g. coal, biomass or waste. A typical graph showing HT-corrosion in coal boilers is shown in Figure X. In different temperature zones, where different deposits and gasses are (thermodynamically) stable, different types of corrosion take place. Risks related with high-temperature corrosion, are related to temperature of the metal and flue gas, as well as flue gas composition, i.e. oxidizing or reducing conditions, and presence of sulphur and chlorine, and formation of molten salts that – when deposited – can rapidly increase corrosion rates.

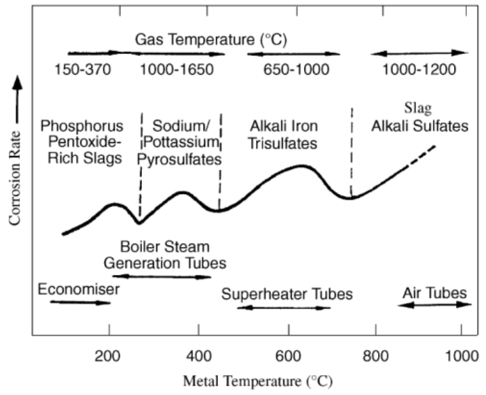


Figure 1.22 Corrosion rate in coal-fired boiler depending on metal and flue gas temperature.

As an example, Figure 1.23 (left) shows a Ni-alloy (A263) in a coal-combustion environment. The type of attack can be seen: a combination of Intergranular and transgranular attack. Micro-analyses are made using SEM-EDS (Electron Dispersive X-ray Spectroscopy), showing the concentration of the present chemical elements. To explain the chemical substance, thermodynamic equilibrium software is used. Figure 1.23 (right) shows an example of the system Ni-O-S at 700°C where the activities of SO_3 and O_2 are plotted on the axes. The activities of those gases is lower material inward and indicate what phases may be formed, corresponding with the SEM image.

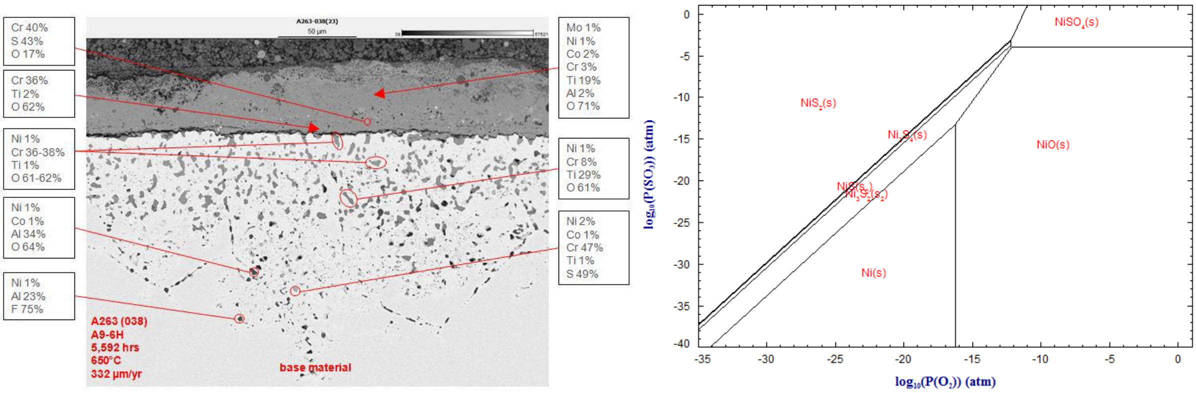


Figure 1.23 Left: Back Scatter Electron image with micro-analyses using EDS. Right: Calculated thermodynamic stability diagram of system Ni-S-O at 700°C using FactSage thermodynamic software.

On basis of the result, of which an example is shown in Figure 1.23, the corrosion mechanism can usually be derived. It has to be born in mind that material that has been exposed for a long time has a 'history' and not all relevant corrosion mechanisms may be derived on basis of long-time exposed material only. The use of corrosion probes that are exposed for a shorter period of time may therefore be of interest additionally (see section 1.2.10.2).

1.2.8.2 LOW-TEMPERATURE CORROSION

Geothermal plants source steam that may contain sulphur that can cause corrosion. As an example, the investigation of corrosion under influence of sulphur in a blast furnace gas fired power plant (CHP, Combined Heat and Power) is shortly described in the following. After compression of the blast furnace gas and combustion in a gas turbine, the flue gasses (>500°C) are supplied to a HRSG (Heat Recovery Steam Generator). The HRSG contains finned tubes for optimal heat exchange. However, the finned tubes corrode heavily and as a result the temperature of the generated steam (the steam is fed back to the blast furnace) cannot be maintained at the required level. Also, the corrosion causes increased pressure drop over the finned tubes, increasing the back pressure of the gas turbine and therewith decreasing plant efficiency. It was initially thought by many that the cause would be dew point corrosion. Given the fact that the dew point of sulphuric acid lies in this case below 100°C (a temperature only reached in the stack under conditions that seldom apply) and pipes operating well in excess of 200°C are heavily corroded, dew point corrosion could be excluded as cause. Samples were taken from the tubes and were analysed using SEM and XRD (X-Ray Diffraction). In addition, thermodynamic stability diagrams and Pourbaix diagrams were calculated, see Figure 1.24.

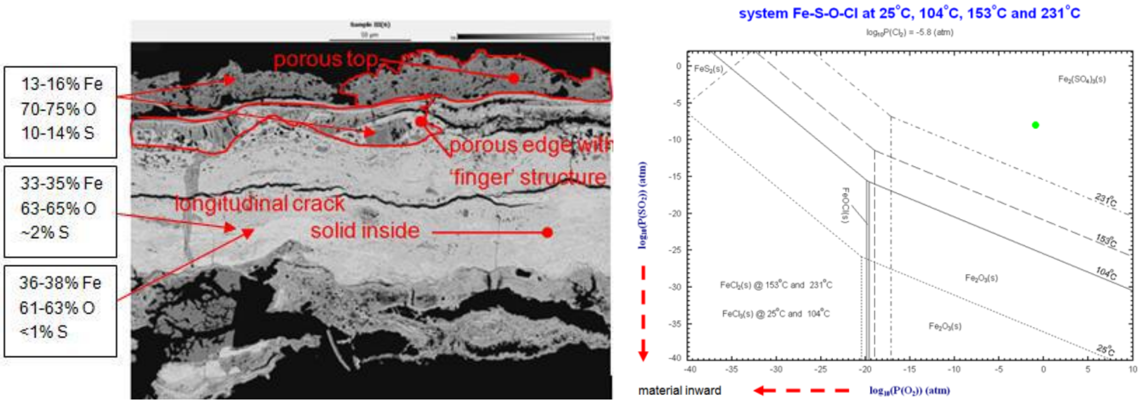


Figure 1.24 Left: Back Scatter Electron image with micro-analyses using EDS. Right: Calculated thermodynamic stability diagram of system Fe-S-O-Cl at 25 - 231°C using FactSage thermodynamic software.

Iron sulphate and iron oxide are formed during operation and standstill. Hygroscopic iron sulphate forms iron sulphate hydrates, and crystal water is re-leased due to load changes, during start-up, or standstill, creating an aqueous environment. The corrosion process during operation cannot be overcome while use of dryers and sealing of the boiler as much as possible during standstill is regarded beneficial. Explosive cleaning of the finned tube boiler pipes was successful while CO_2-ice blasting only showed partly effective due to the boiler design.

1.2.9 NDT

1.2.9.1 NDT TECHNIQUES

Visual Inspection (VT)

Visual inspection is many cases sufficient for screening on surface defects or corrosion. This can be performed with the naked eye, if needed with optical aids. These aids include e.g. magnifying glasses that can have a magnification of up to 20 times or microscopes can have a magnification of roughly 20 – 100 times. If an area that needs to be inspected using VT is difficult to reach (such as the inside of pipes), a borescope can be used (though strictly speaking incorrect, a borescope is often referred to as an endoscope). A borescope is an optical device consisting of a rigid or flexible tube with an eyepiece on one end, an objective lens on the other linked together by a relay optical system in between. Normally, the borescope is equipped with illumination. Often, a borescope is used for inspection of heat exchangers, steam headers or steam turbine parts. Most important is the interpretation of the inspection results afterwards, e.g. judging pitting corrosion in heat exchanger piping. An example of a result of an inspection of a header performed by DNV GL / DEKRA is shown in Figure 1.25, showing severe oxide layer spallation at the inside of a steam header.

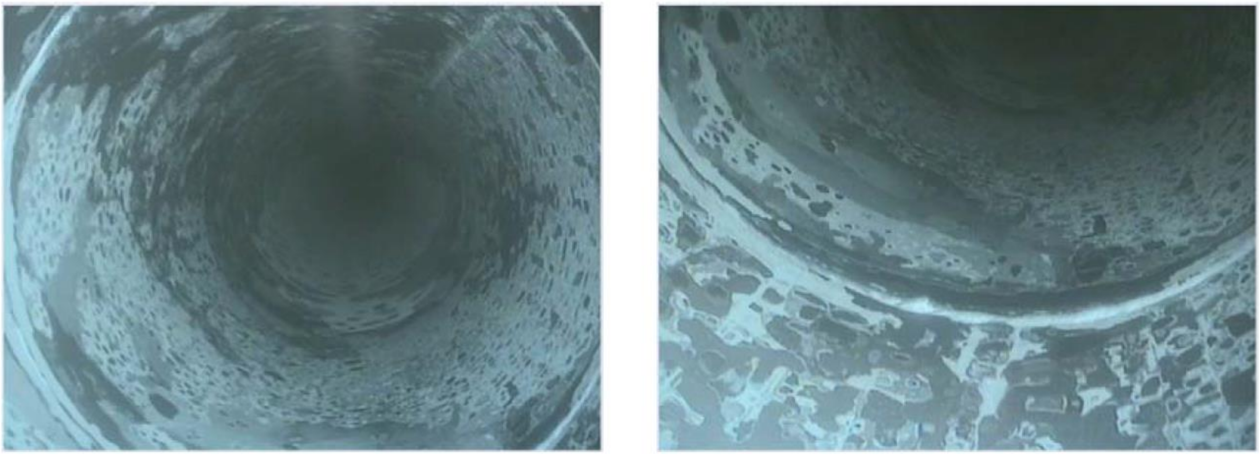


Figure 1.25 Severe oxide layer spallation at the inside of a steam header

An example of a borescope used by DNV GL / DEKRA is shown in Figure 1.26, left. This type of borescope is equipped with a video connection (allowing checking images later) and equipment for sizing (to get an impression of actual size of an observation).

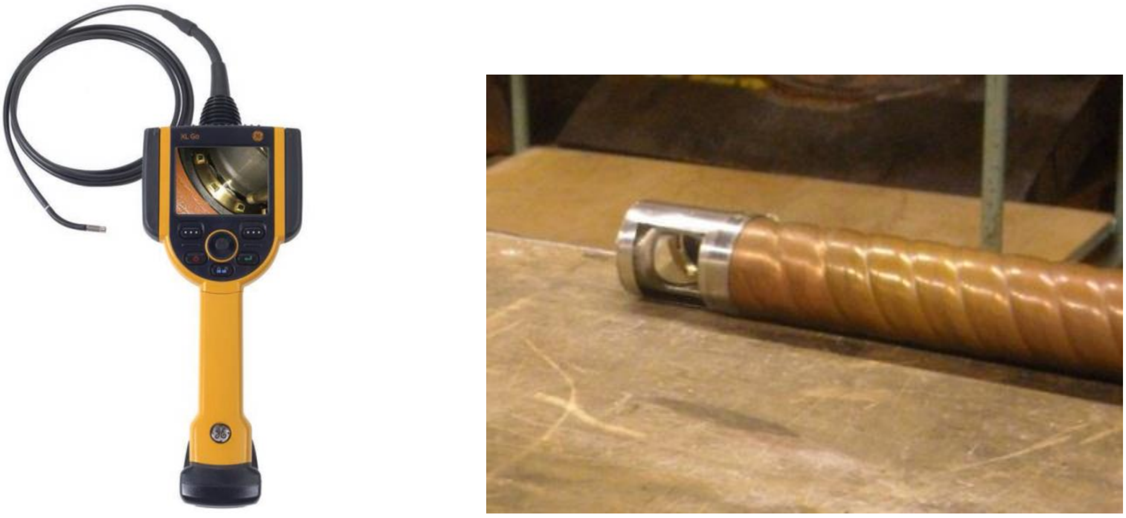


Figure 1.26 Left: commercial borescope. Right: in-house developed water-cooled borescope for inspection of combustion chambers (boilers)

Different borescopes have been developed by DNV GL / DEKRA to perform VT in combustion rooms with temperatures of > 1200°C. As an example, a water-cooled borescope is shown in Figure 1.26, right. Typically, this borescope is used for checking start-up behaviour of burners and deposit formation on burners. Additionally, an air-cooled video camera has been built which has been installed at boilers permanently where a video signal is sent to the operation room of the plant. The plant operators use the video screen to monitor deposit build-up and efficiency of soot-blowing actions.

Magnetic Testing (MT)

Magnetic Testing (MT) is also often referred to as Magnetic Particle Inspection (MPI). MT is a method for detecting surface defects and defects that are slightly subsurface in materials that are ferromagnetic. A magnetic field is formed in the object of interest, normally by applying electrical current. In flawless material, the magnetic field lines are mainly below the surface, whereas a defect (air instead of metal) causes the magnetic field lines to appear above the surface (see Figure 1.27), referred to as flux leakage. The reason is that air cannot support as much magnetic field per unit volume as metals. Flux leakage can be made visible by putting on ferrous particles on the surface (dry particles or a wet suspension) that are drawn to the area, or with a measuring probe.

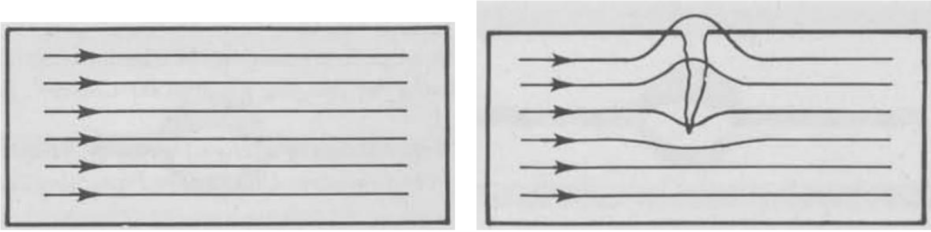


Figure 1.27 Magnetic field lines in a flawless object (left) and in an object with a surface defect (right)

To ease visibility of the particles, and hence the indications of defects, they may be coloured using a dye, and the surface may be stained white to raise colour contrast. Alternatively, particles may be coloured with a fluorescent dye that fluoresces under a UV-light. An example of both colouring techniques is shown in Figure 1.28. Defects must be perpendicular to the magnetic field to be best visible – a defect oriented 45 degrees to the magnetic field can still be detected, while no leakage flux is created when a defect is parallel with the magnetic field, rendering it undetectable.

Figure 1.28 Examples of indications found using MT. Left: colour contrast ("black and white") applied at steam turbine part. Right: UV-fluorescence, applied at gas turbine disc.

Penetrant Testing (PT)

Penetrant Testing (PT) is also referred to as Dye Penetrant Inspection (DPI) and Liquid Penetrant Inspection (LPI). PT is suited for detecting surface breaking defects in non-porous materials. The principle of PT is that a low-surface tension dye penetrates a surface-breaking defect on basis of capillary action. After the fluid has had sufficient time to penetrate, the remainder is removed from the surface, after which a developer is applied (e.g. white chalk). The developer helps to draw penetrant out of the flaw so that an invisible indication becomes visible to the inspector. Inspection is performed under ultraviolet or white light, depending on the type of dye used.

PT is a relatively cheap and quick method to detect surface breaking defects. However, there is some sensitivity to pre-treatment of the surface. The surface must be clean and smooth, metal smearing from power wire brushing, or grit blasting should be removed while surface finish and roughness can affect examination sensitivity and grinding prior to PT may be necessary. Examples of application of PT are shown in Figure 1.29.

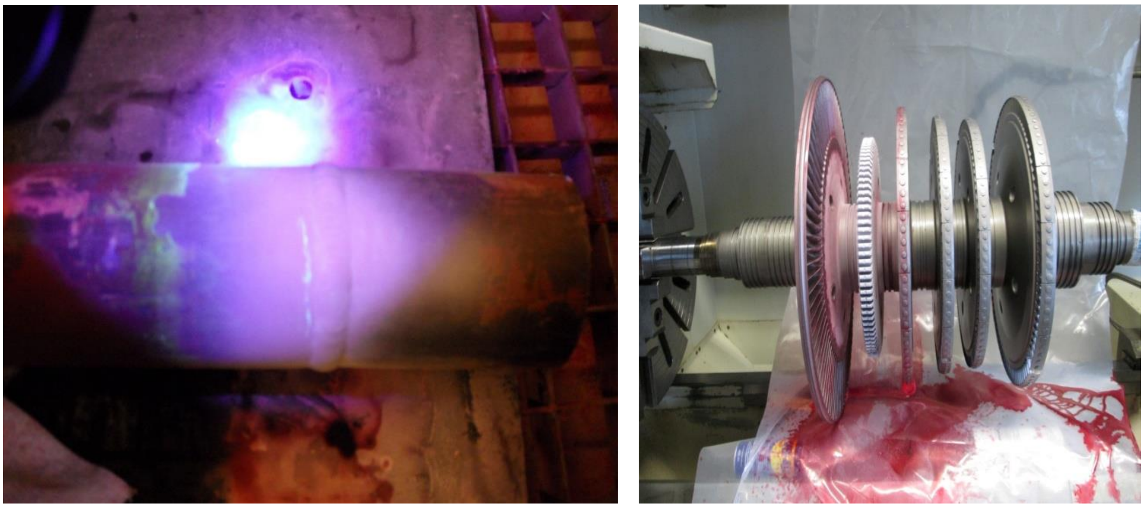


Figure 1.29 Left: Crack in austenitic HR3C boiler pipe in Heat Affected Zone (HAZ) of weld made visible using PT. Right: PT applied at rotor body of turbine.

Eddy Current Testing (ET)

If an alternating current is applied to a coil, the coil induces a (alternating) magnetic field. If an electrically conductive material is brought close to the coil, the alternating changing magnetic field induce eddy currents in the conductive material. The eddy currents, on their turn, induce a magnetic field that is opposed to the magnetic field of the coil. As a consequence, the current flowing through the coil changes as the impedance of the coil changes. If now the conductive material contains a defect, the magnetic field induced by the eddy current is deviating from that of the sound material and as a consequence the magnetic field of the coil is counteracted differently, and the impedance of the coil increases. The current through the coil also changes differently at the flawed and the unflawed part. To put it more precisely: phase and amplitude of the coil impedance change. The induction voltage V = current I x impedance Z, where $Z = R + J\omega L$. The impedance (amplitude $(=V/I)$ and phase angle φ between V and I) can be measured and R vs. jωL can be plotted, see Figure 1.30 and analyzed rendering information on crack geometry, position, type and size. The crack size is determined by comparison with the signal with that of a signal produced with a calibration block. By changing the AC frequency, the penetration depth into the material can be changed, i.e. flaws (extending) deeper under the surface can be detected.

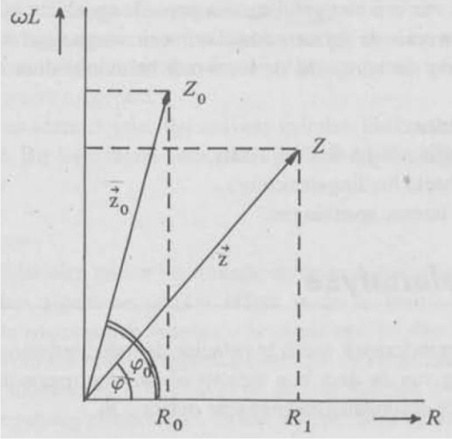


Figure 1.30 Phase angle φ and amplitude (V/I) define the vector Z (impedance)

An independent party should frequently applies ET at heat exchangers (see Figure 1.31), gas turbine discs, generator retaining rings, etc.

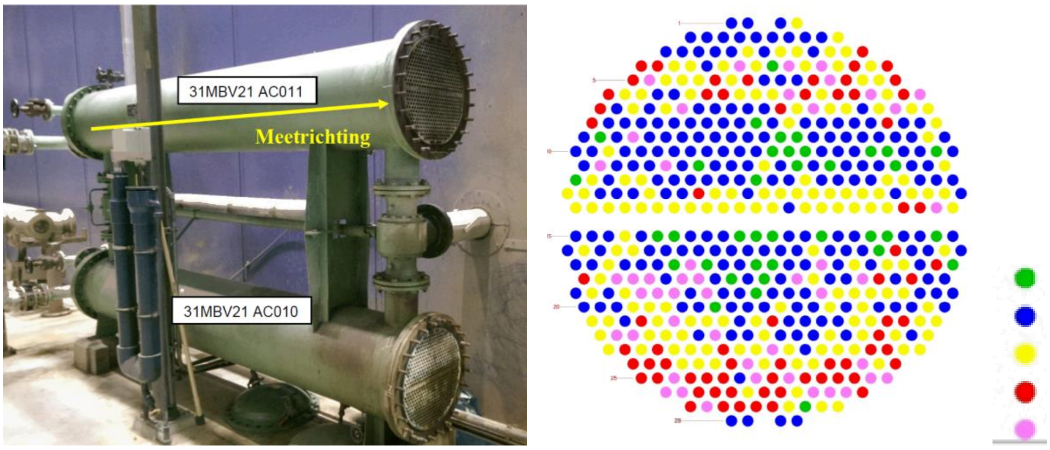


Figure 1.31 Heat exchangers (for lubrication oil of a GT) inspection using ET. The graph shows the results for on of the two heat exchangers with a colour indication for the amount of damage (green = least damage, pink = most damage).

Ultrasonic Testing (UT)

Homogeneous materials with a not too course structure are good conductors for sound. If the sound frequency is high, the sound bundle can be created that is small, and it appears that approximately above 50 kHz (ultrasound), bundles are sufficiently small for application in finding flaws in materials. Pure transversal and longitudinal waves are applied, while for specific applications, surface waves can be used (e.g. Rayleigh wave, creep wave) or Lamb-waves (only in materials of a few wave lengths thick).

The ultrasound is created using a piezo-electric crystal: if a voltage is applied to the crystal, it deforms; when the voltage is released, the crystal will vibrate with its natural frequency. Probes, i.e. transmitter and receiver, both work on basis of this principal, where a receiver picks up the vibration, generating a voltage. Probes exist that both hold a transmitter and a receiver (transducers). Straight beam probes generate longitudinal waves only and angle beam probes (that are place on the work piece on an angle using a wedge) generate both longitudinal and transversal waves. Couplant (e.g. glycerine) is used to ensure that the (by the probe) generated ultrasound is transmitted to the object of investigation, as sound is not effectively transmitted in air. For specific applications, vibration can be created by using EMAT (Electro Magnetic Acoustic Transducer) where eddy current is generated in the material where already a magnetic field is created; the resulting Lorentz force creates a sound wave where the sound frequency is equal to the frequency of the alternating current in the coil (used to create the eddy current, also see preceding section). No couplant is needed which is useful for high-temperature applications.

As a (simple) example, as shown in Figure 1.32, a straight probe (transducer) is placed on a flawless work piece. The generated pulse sent into the work piece is made visible on the UT device. The pulse reflects against the back wall, yielding and echo (lower in amplitude than the pulse sent into the material), indicated in Figure 1.32 (top) as the first back wall echo. That process repeats, yielding a second, third, etc. back wall echo, until the echoes have decayed. When knowing the sound velocity in the material of investigation, the wall thickness can be determined in this way, which finds useful application for combustion boilers or chemical reactors that suffer from wall thickness loss.

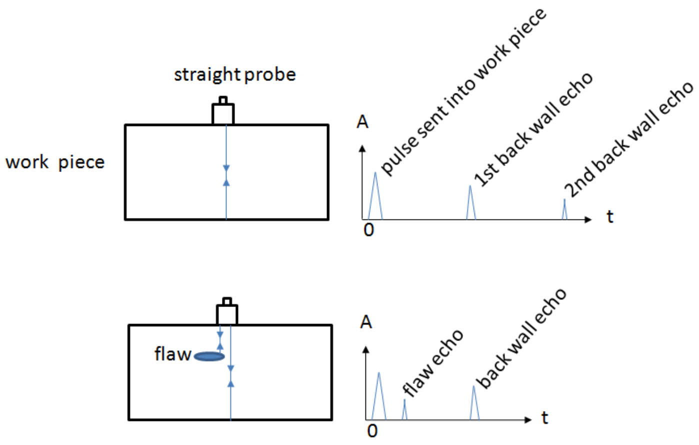


Figure 1.32 Straight beam probe on a flawless work piece (top) and work piece with flaw (bottom)

When the work piece contains a flaw, the generated pulse will reflect against that flaw, generating an echo that appears on the screen between the peaks of the pulse sent into the work piece and the back wall echo. The time between pulse and flaw echo determines where in the work piece the flaw is (by comparing the signals with a calibration piece with flaws with known distances) and the amplitude of the echo determines the flaw size. As the flaw echo's are normally small, the signal needs to be amplified, where amplification is expressed in dB.

To increase focus of a beam the diameter of the probe should be large and sound frequency should be high. Lenses can also be applied to increase beam focus.

As an example, an in-house developed method is shown in Figure 1.33 for determining wall thickness of combustion boilers at high temperature where a straight beam probe is applied. A KEMWAT-sensor is shown: a transducer is mounted on a stud that is welded on the strip of a boiler. The inside of the boiler (i.e. the fireside of the pipes) contain a Ni-alloy cladding. The combination of pipe material and cladding generate a range of reflections which are difficult to analyze. However, as the stud is welded at a fixed point, the change of reflections in time is a consequence of reduction of cladding thickness reduction. The cladding thickness reduction can be determined on basis of these changes.

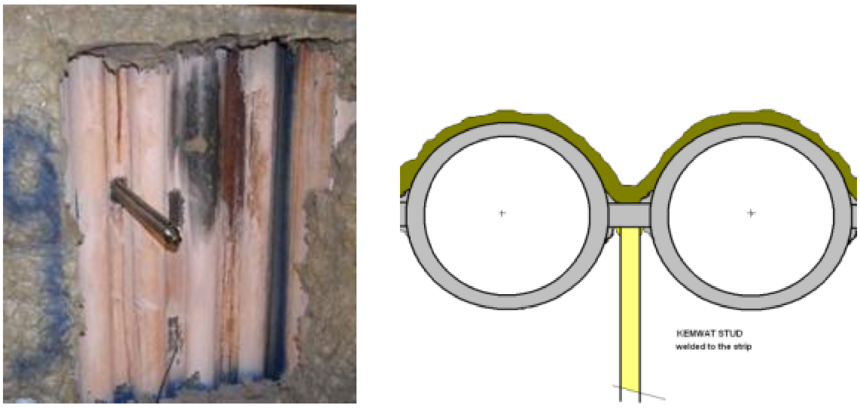


Figure 1.33 Applications of pulse echo at high-temperature to determine wall thickness (KEMWAT).

Figure 1.34 shows an angle beam probe (transducer). In this picture, the sound beam maximum is perpendicular to the defect, in this case a weld defect. The probe has to be moved to obtain this (optimal) situation, and for testing multiple welds, this method is time consuming.

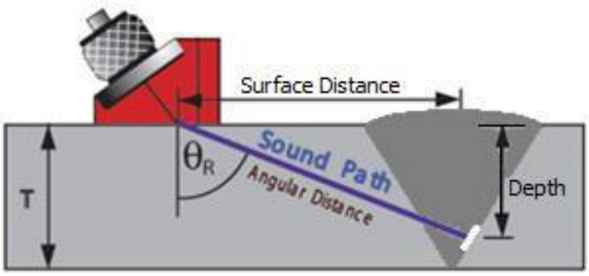


Figure 1.34 Angle beam probe applied at weld with flaw on flank

In Figure 1.35 (right), the principle of KEMBUS is shown where an angle beam probe is applied. If a straight beam probe (transducer) would be applied (see Figure 1.35 (left)), there would be a range of reflections generated by the pipe wall. Hence, a separate transmitter and receiver are used. The difference between the travel time (or "sound path") of the interface echo (IE) and back wall echo (BWE) is a measure of the wall thickness.

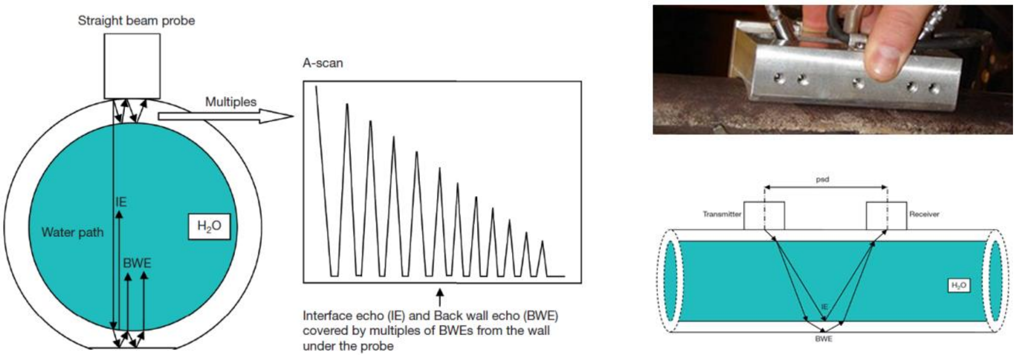


Figure 1.35 Application of for high-temperature application (up to 300°C): KEMBUS

With the use of calibration blocks, it is possible to discriminate between wall thickness reduction at the steamside and fireside of the pipe. Measurements can be performed only when water is in the pipes to ensure transmission of sound. The measurements can be performed up to 300°C when special couplant and wedges are used. This allows for measurements during operation, or during an outage when scaffolding is not in place.

As mentioned, using an angle beam probe is time consuming. If multiple transducers are put in an array, and each transducer generates a pulse delayed with the previous transducer in the array (i.e. phased), a wave front is created (see Figure 1.36, left). By adapting the phasing (i.e. the time delay between pulses), the wave front angle can be adapted. Note that an angle beam probe has one fixed angle.

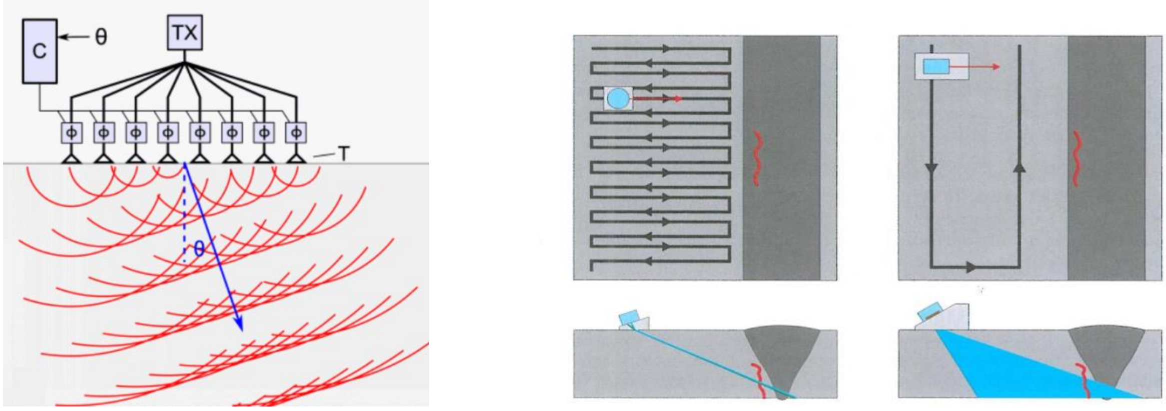


Figure 1.36 Left: Wave front created using phased array. Right: comparison between conventional UT in raster vs. multiple line sequence using UT-Phased Array

This means that an area (actually: a volume) can be scanned by electronically adapting the phasing (the result is referred to as a "sector scan"). A well-known application is the "echo device" used in medical applications such as investigating an unborn child.

An example of application of Phased Array is with checking new build welds as alternative for RT (Röntgen Testing). Another example of application is for complex geometries, see Figure 1.37, left, for a blade root of a gas turbine or steam turbine. In this example, an echo would be generated using an angle beam probe that can hardly be distinguished from the geometrical (back wall) echo. With Phased Array, however, this can be seen with a scan. A practical example is shown in Figure 1.37, right.

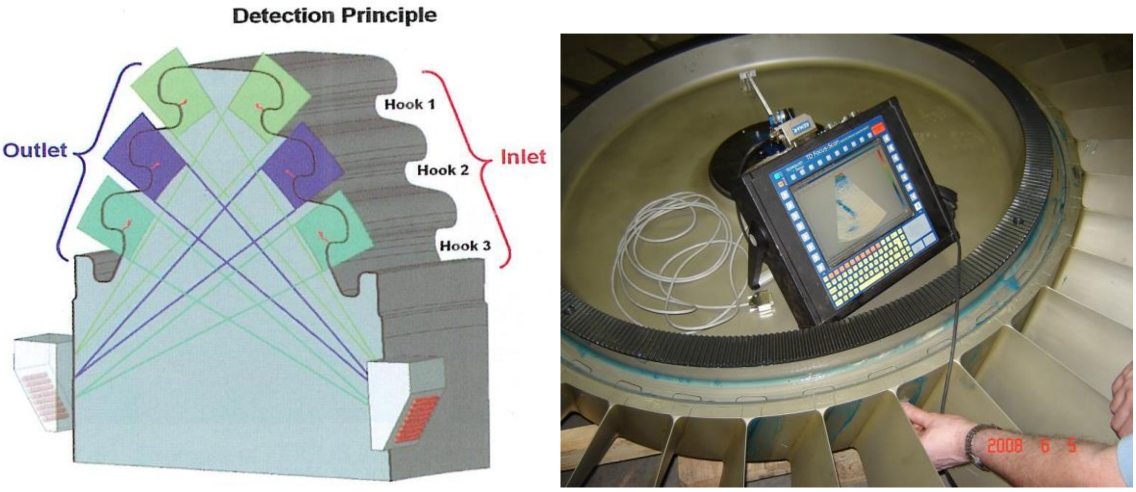


Figure 1.37 Left: blade root with cracks that can be investigated using UT-Phased Array; right: inspection of gas turbine using UT-Phased Array.

A method frequently used to inspect welds is TOFD (Time Of Flight Diffraction) which is based on the principle that the tips of a crack, when struck by a wave, will diffract the signal back to the other location of the surface. The signals can be picked up therefore by place an angle beam transmitter at one side and an angle beam receiver at the other side, see Figure 1.38.

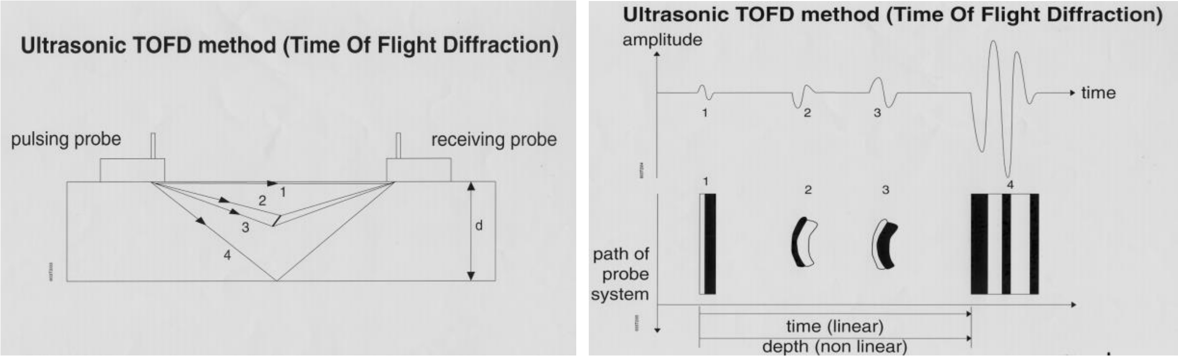


Figure 1.38 Principle of TOFD. Left: crack tip diffraction. Right: Amplitude of wave

Measuring the amplitude of the reflected signal (see Figure 1.38, right) is relatively unreliable since the amplitude largely depends on the orientation of the crack. However, by measuring the time of flight of an ultrasonic pulse, the size and position of a reflector (e.g. a flaw) can be determined.

1.2.10 MECHANISED INSPECTIONS

Mechanised inspections are getting more and more popular. In the past, mechanised inspections were mostly used at nuclear power plants as many places in nuclear power plants are hazardous due to radiation. Nowadays, mechanized inspections are applied everywhere in the power industry. The benefits are that they are repeatable (well documented where exactly measurements have been done), they are quick, they can be applied at places that are difficult to reach and different NDT-techniques can be combined in one inspection. Main mechanised inspections performed are turbine and generator inspections and are described in following sections.

1.2.10.1 TURBINE INSPECTIONS

Rotating equipment such as steam and gas turbines rotate with high frequency and given the rotating mass, cracks leading to failure can yield catastrophic results. As an example, a low pressure steam turbine, manufactured in 1970, exploded after 16 years of operation, see Figure 1.39. The requirements for UT inspection at manufacture were limited compared to nowadays standards. Although the indication leading to the failure was detected, it was interpreted wrongly as non-metallic inclusion while post-mortem metallurgical investigations showed a volumetric defect.

Figure 1.39 Low-pressure steam turbine failure

Also an earlier accident had happened in 1974 after 17 years of operation. The accidents led to the introduction of boresonic inspections and the use of angled beam probes. Inspections can be performed as part of a lifetime assessment. Boresonic inspection is ultrasonic inspection from the (rotor central) bore hole to search for flaws at different locations and orientations within the rotor material. In the following, an overview is given of the different inspections that can be performed on steam turbine (ST) and gas turbine (GT) components consisting of a combination of VT, MT, ET, UT, UT-PA and UT-TOFD.

Rotor body testing (ST, GT)

Boresonic inspection can be performed at larger axial rotor bores (see Figure 1.40, left) and at smaller radial bores (see Figure 1.40, middle). Radial bores are kernels bored out for material research, and mainly present at somewhat older turbines as ultrasonic examination has improved so that kernel boring is not necessary anymore. Boresonic inspections are performed together with our former KEMA colleagues in the US. Cracks can have different orientation and often a high amplification is used. The downside is that many smaller and possible irrelevant indications are detected. Trending (i.e. comparison in time) is therefore worthwhile, but the individual evaluation of possible hundreds of indications is not effective. Traditionally, UT is applied in combination with MT for detection of surface defects. Although a (theoretical) somewhat higher detection is possible with MT compared to ET, there are important downsides of performing MT at a rotor bore. Firstly, a smooth surface is necessary for MT and power honing is necessary e.g. to remove oxide layers. Power honing is time consuming and large devices must be shipped to the test location. Secondly, the complete rotor must be magnetized so a large transformer is necessary, adding to transport cost. ET is therefore becoming more popular to replace MT. Additionally, VT is performed. The external of the rotor body can be investigated with MT, PT, UT, UT-TOFD (crack depth sizing), UT–PA, ET (serrations, cooling holes), replication (see Figure 1.40, right) and Hardness Testing.

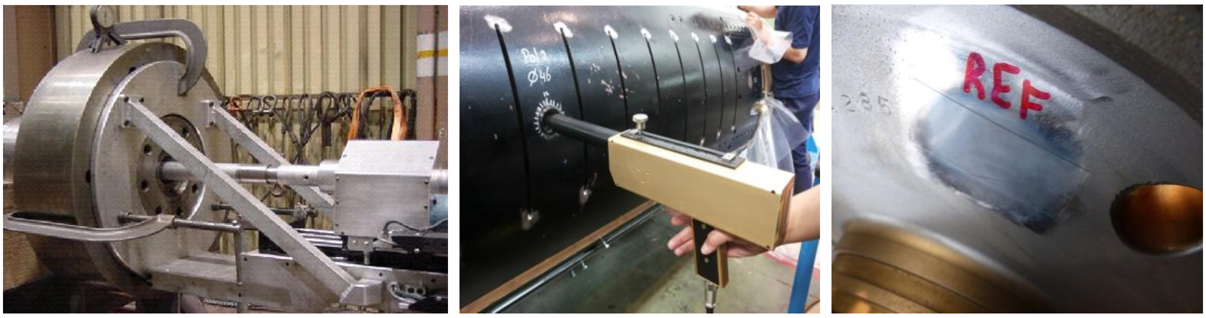


Figure 1.40 Left: axial boresonic inspection; middle: radial rotor bore inspection with ET; right: surface prepared for replication.

Gas turbine disc inspections

Gas turbine discs, especially the discs operating at the highest temperature (turbine discs and last stage compressor disc) are subject to examination in life-time studies. UT focuses on finding volumetric cracks at different orientations at ET focuses on surface defects. Manipulators have been developed to perform mechanized inspections. Following manipulators have been developed (also see Figure 1.41):

- CUEBIS: bore (UT)
- GROTEC: spiral scan (ET)
- DISKEM: automated UT systems: (UT)

In fact, CUEBIS combined with GROTEC is the boresonic investigation for short length bores. DISKEM is a manipulator whereby straight beam probes – 'looking' in different directions to find radial defects and application of DISKEM is therefore very useful.

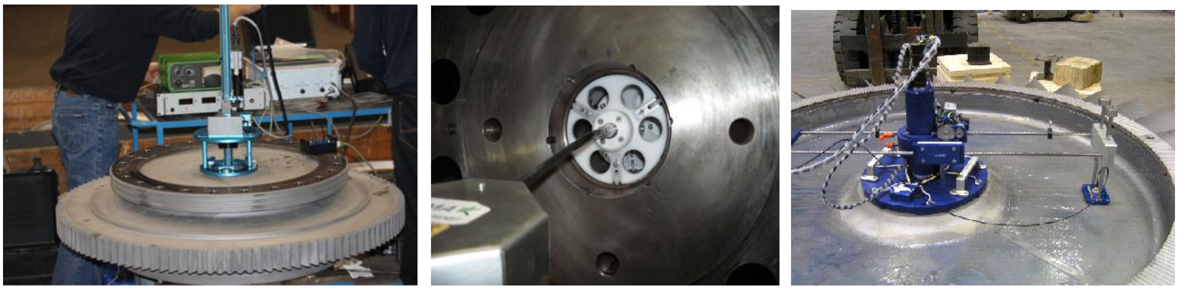


Figure 1.41 Left: CUEBIS. Middle: GROTEC. Right: DISKEM

Currently, a manipulator is under development at DEKRA that combines UT and ET and is suited for a range of geometries (different type of gas turbines – frame 5 – 9 - have different geometries).

Rotor body fire tree testing: with blades in place (ST)
The "Banakem system" has been developed for fir tree testing with UT-PA. The probes (here the UT- PA, with curved extension piece) are moved along the curved fir tree, guided along the small blade edge, magnetically attached to its surface and are manually propelled (see Figure 1.42).

Figure 1.42 Left: blades in place. Right: UT-PA inspection of fir tree

Blades & vanes testing while mounted
Blades and vanes can be tested while mounted at the rotor body. Examination can be done using PT, MT, ET (trailing and leading edges) and UT surface (Rayleigh) waves (blade foils). The advantage of a Rayleigh wave is that the wave travels along the surface, also when the surface is curved. Fillets (see Figure 1.43) are of particular interest and while mounted this are area can be checked with these type of surface waves.

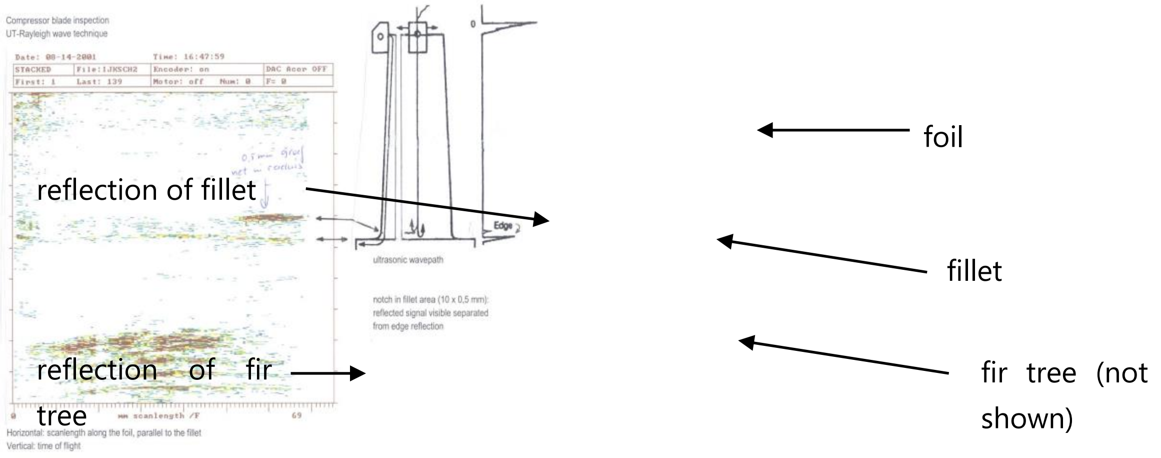


Figure 1.43 Application of Rayleigh waves for inspection of blade surfaces

Blades & vanes testing while dismounted

While dismounted, blades and vanes are much easier to inspect. Usual applied techniques are PT, MT (yoke, coil), VT, UT and ET.

Custom-made inspections

As an example: DEKRA was asked to inspect a repair weld at outside of an inner steam turbine housing. The housing was made of ferritic cast material. The outer housing and shrunk ring were in the way. As a result, a manipulator needed to be build to measure from toroidal cavity inside inner housing (elliptical cross-section), see Figure 1.44.

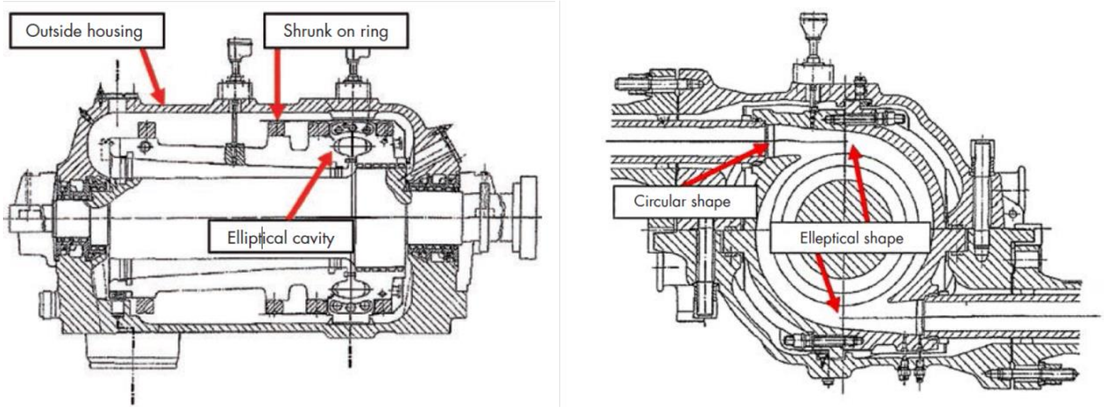


Figure 1.44 Left: Side view of turbine housing. Right: Lateral view of turbine housing

The solution was to build a manipulator (see Figure 1.45, left) entering through the inlet nozzle (circular shape), see Figures 1.44 (right) and 1.45 (right).

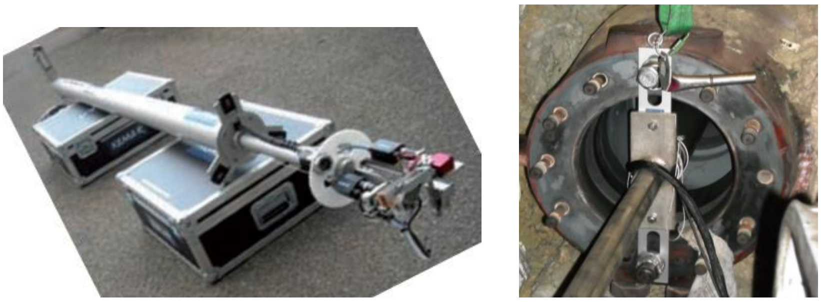


Figure 1.45 Left: manipulator. Right: manipulator entering through circular shaped inlet nozzle of the steam turbine.

Test piece manufactured with spark eroded slots (depth: 5 mm and 10 mm). Critical crack depth: 10 mm. UT Phased Array with beam steering / flexible beam focus appeared to be most suitable for this geometry and (course grained) material. A mock up was built to test handling of the manipulator, see Figure 1.46, right. Probe positioning and placement was checked with a built in camera in the manipulator.

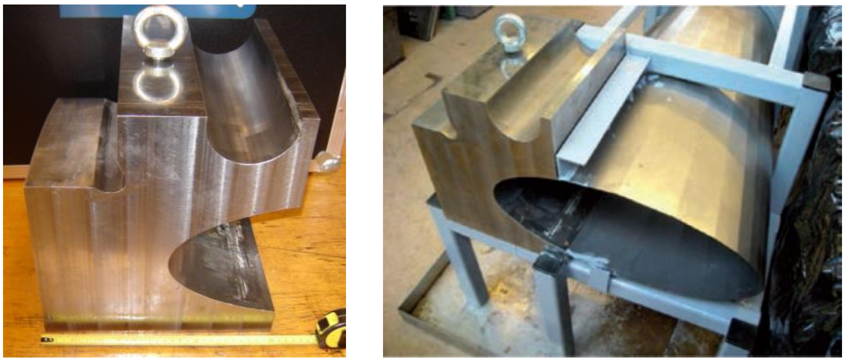


Figure 1.46 Left: test piece with spark eroded slots. Right: Mock up for testing handling of the manipulator

1.2.10.2 GENERATOR INSPECTIONS

KIRR

The generator is one of the most crucial parts of a power plant, since it is where the mechanical energy is converted into electric energy. It is therefore essential that the generator is always in optimum condition. Among the critical components are the retaining rings at each end of the rotor. These are susceptible to damage as a result of specific chemical influences and mechanical or electrical forces. However, replacing the rings involves substantial costs. The DEKRA inspection system for retaining rings (KIRR) – see Figure 1.47 - represents a cheaper yet equally effective alternative. The system has already been used to inspect over 1,600 generator retaining rings in 25 countries worldwide.

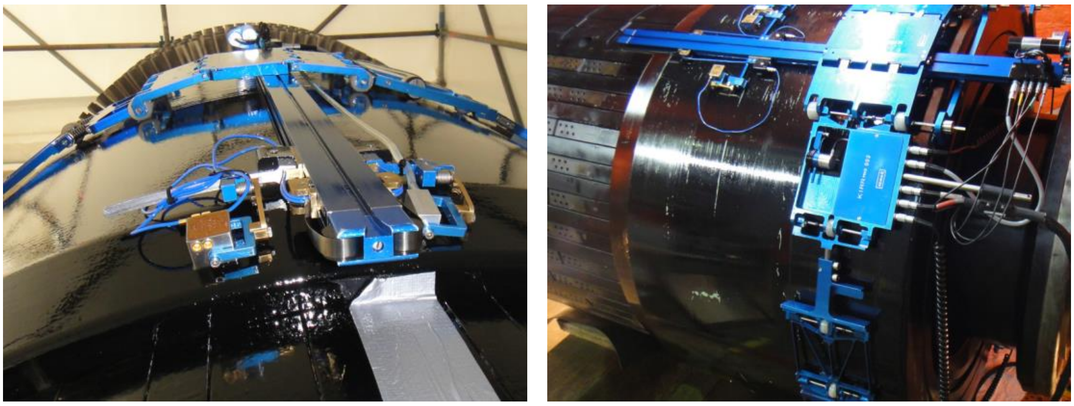


Figure 1.47 DEKRA's KIRR system for inspection of generator retaining rings

A retaining ring has a long lifespan and often lasts for the entire life of the generator. However, the smallest of cracks in the retaining ring poses a risk to safety and could result in extremely costly damage. To avoid such disastrous consequences, many manufacturers recommend that the retaining rings are replaced periodically – an expensive exercise which can cost up to a million euros. DEKRA’s KIRR offers a cost-effective alternative. The system detects and analyzes flaw indications in the retaining ring, enabling you to determine whether the retaining ring needs to be replaced. Furthermore you can keep a close eye on newly detected flaw indications in retaining rings which do not yet need replacing and monitor their condition during future operation. One crucial advantage is that it is no longer necessary to disassemble the rotor and the retaining rings for inspection purposes, which in turn yields cost savings of up to EUR 200.000.

The KIRR system is adjustable to fit virtually all generators and large motors. This flexible system combined with our extensive experience in this field allows us to draw up the inspection plan on site, without detailed information being required beforehand. If required, the inspection can be performed within 24 hours.

Ultrasonic crack detection is focused on the shrink-fit areas and wall thickness steps. Damage, such as stress corrosion cracking and top tooth cracking, is detected. In addition, eddy current scanning is added to accurately map the outer surface. The ring's coating is left in place. If cracks are discovered, ring geometry and flaw data are used in an FEM computer model to calculate the residual lifespan. Furthermore, we establish the inspection interval for monitoring purposes.

The KIRR system can be applied on generators with a ring diameter of 600mm and upwards. In-situ test characteristics: minimum gap between retaining ring and stator: 8mm; technique: UT-TOFD, UT-TRL and ET; scanning Surface: 360° circle and 1-10mm pitch; defect heights of 0.5 mm and upwards are detected. Typical test duration for two rings in-situ: 24 hours

ARGIS

Generators are crucial components in an industrial power plant and are designed to operate reliably for many years. The most expensive part of a 3-phase generator is the stator, which is where the energy from the magnetic field is converted into electrical energy. The condition of the generator and its core deteriorates over time, increasing the likelihood of failures. Quantitative testing and periodic inspections of the generator core are necessary to avoid unplanned outages. ARGIS enables inspections to be carried out not only when the rotor has been removed, but also with the rotor still in place, thus saving you time, effort and money.

Condition testing normally requires the rotor to be removed from the generator. Not only could this possibly damage the generator, but it is also time-consuming work that can only be performed during a major shutdown. However, thanks to the Advanced Robotic Generator Inspection System (ARGIS), removal of the rotor can be avoided. The ARGIS system is a unique concept for in-situ mechanical inspections which can be performed on many brands of generators.

A chain containing motor drives and a docking station for the Generator Inspection Vehicle (GIV, see Figure 1.48, left) is mounted around one of the retaining rings of the generator. The chain is positioned accurately in front of each slot so that the GIV can be inserted into a gap as small as 17 mm and up, see Figure 1.48 (right). The GIV then moves to the other end of the stator core and back in order to perform the ELCID, wedge test and visual inspections all in the same run to save time.

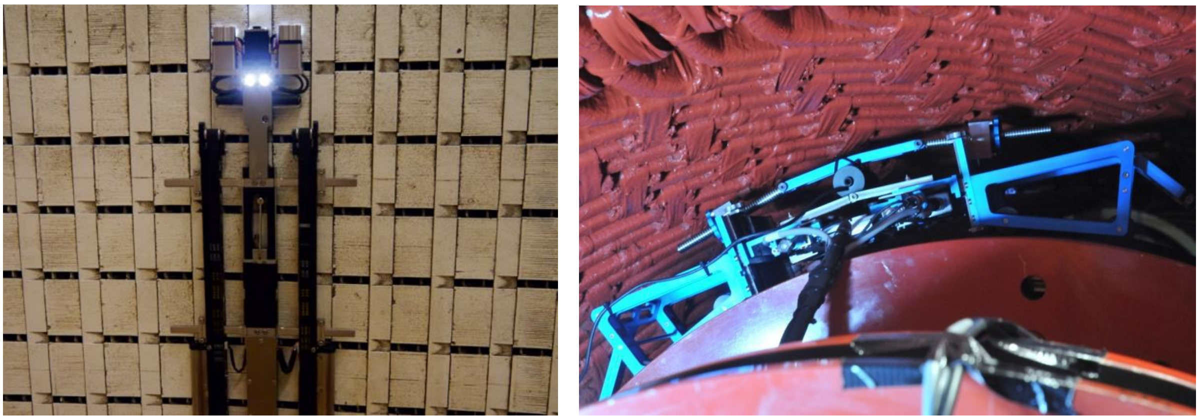


Figure 1.48 ARGIS system. Left: GIV (Generator Inspection Vehicle). Right: GIV between rotor and stator.

Three different tests can be performed by ARGIS, the low flux leakage test, the wedge tightness test and visual testing. Regarding the low flux leakage test, the Electromagnetic Core Imperfection Detection (ELCID) is a standard feature. The step irons are measured by a separate module. The GIV is provided with a stator wedge tap tester that determines the wedge tightness based on spectral analysis of the sound response. The GIV is equipped with 4 camera modules: a forward-viewing camera is used for general inspection of the stator teeth and wedges, another camera inspects the rotor body and cooling slots, and 2 further cameras inspect the stator cooling slots.

Regular testing increases reliable operation and prevents potentially costly downtime and repairs. Our experts can provide you with information and recommendations regarding condition of the generator, routine maintenance/overhaul and long-term condition.

The following benefits of ARGIS application: Less manpower is required to prepare the generator for inspection (2-3 days instead of several weeks), reduction of outage costs (100,000 - 200,000 euros), reduction of lost productivity due to outage time (which can amount to millions of euros). There are fewer risks of damage to the generator stator and rotor parts. A generator inspection is no longer on the critical path of an outage. Inspection has high reproducibility as it is mechanized. All data is stored for future comparison and data trending.

1.2.11 DETERMINATION OF MATERIAL PARAMETERS

1.2.11.1 PMI (HANDHELD XRF)

Material composition, i.e. the concentration of different elements, can be determined using XRF, X-Ray Fluorescence. A material that is bombarded with X-rays excites and emits secondary (or fluorescent) X-rays. More in detail, atoms may be ionized if exposed to radiation with sufficient energy (such as X-rays or gamma rays). Ionization means that electrons from the inner orbitals are removed. Due to the resulting instable electronic structure of the atom, electrons of the outer orbitals fall into the lower orbital to fill the hole left behind, upon which radiation is emitted. The emitted radiation is characteristic for the atoms present.

PMI stands for Positive Material Identification labeled to a handheld XRF spectrometer, see Figure 1.49 for the device. With fast evaluation and low detection limits, the PMI is a very practical device to use in failure analysis (in the laboratory, or on site) or for quality control on site e.g. to determine if the right alloys are used or the right weld filler material.

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Figure 1.49 PMI (Handheld XRF)

1.2.11.2 HARDNESS MEASUREMENTS

Hardness is not a fundamental material property, but rather a 'material response' to a certain test, but nonetheless an important technical material parameter. Hardness is the resistance of a material to penetration. Different methods exist for determination of hardness, of which the Vickers method is one of the must used in the engineering practice of power plants. The method as designed for application in the lab is as follows. A diamond with a top angle of

136° is placed on the material (see Figure 1.50, left) and a load is applied gradually and kept constant for about 15 seconds. The diagonals of the impression are measured using a microscope. As the impression increases (almost) linearly with load, the hardness is independent of the applied load and therefore the hardness can be determined with little damage to the material.

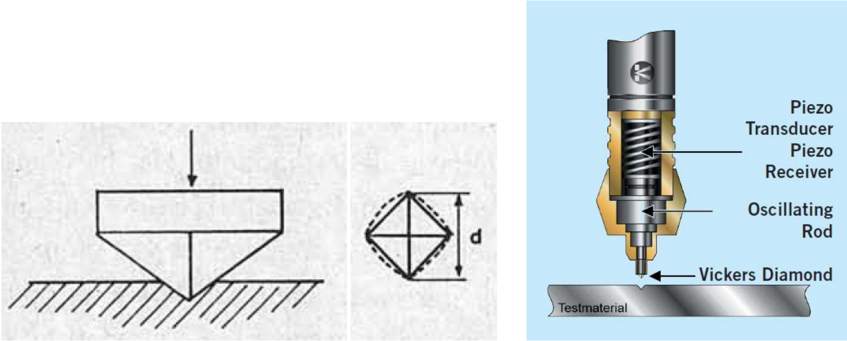


Figure 1.50 Left: Impression body of Vickers hardness testing (laboratory testing). Right: UCI-probe.

A mobile testing device can be used for testing on site. A popular method for mobile Vickers testing is UCI which stands for Ultrasonic Contact Impedance. With this method, a rod with a Vickers-diamond tip oscillates (see Figure X, right) and as the diamond penetrates the material by applying a specific test load, the frequency of resonance changes. The frequency shift is proportional to the size of the test indentation produced by the Vickers diamond (optical evaluation as in the laboratory is therefore not necessary). The resonation of the rod is applied by piezoelectric crystals (typical frequency is 70 kHz) and the rod is spring-loaded with a pre-defined specific load. As frequency shift is also depending on the material's elasticity modulus, the measurement instrument has to be calibrated before testing.

Care must be taken that the surface where the hardness is tested, is representative for the whole microstructure of the material. Hence, with a coarse, heterogeneous microstructure, a larger impression is required than for a homogeneous material. As an oxide skin may be present on the surface (with a different hardness than the base material), surface preparation is normally necessary, i.e. grinding (remove oxide layer) and polishing (remove deformations due to grinding).

A typical application of hardness measurements is as part of a condition assessment. Examples of when such condition assessments occur are temporary overheating of boiler components, major overhaul of a gas turbine, see for both examples Figure 1.51.

Figure 1.51 Areas for hardness measurements. Left: boiler components that have been temporarily overheated. Right: gas turbine disc. As surface preparation is needed for HT and for replication, these tests are normally done at the same position.

1.2.11.3 REPLICATION

In many countries existing boiler components and steam line systems are subjected to an inspection regime due to creep according to a National Pressure Vessel Codes. The replica technique is a repeating tool to classify the degradation of the materials microstructure. Replication can be used for assessing creep damage, but also for other microstructural investigations such as determination of grain size, checking presence of certain phases, establishing whether microstructural changes occur e.g. as a consequence of overheating, heat treatment or deformation.

With replication, the surface that is to be investigated is sanded and polished in different steps to finally etch the microstructure with a suited etchant. Electrolytic polishing and mechanical polishing can be applied. Replication is applied where the prepared surface cannot be brought to a light-optical microscope. However, an offprint (negative image) of the etched microstructure can be made using a softened acetate tape. The tape can be removed from the surface after evaporation of the softening fluid, and be investigated as a 'normal' metal sample using the metal microscope. Figure 1.52 features the making of a replica.

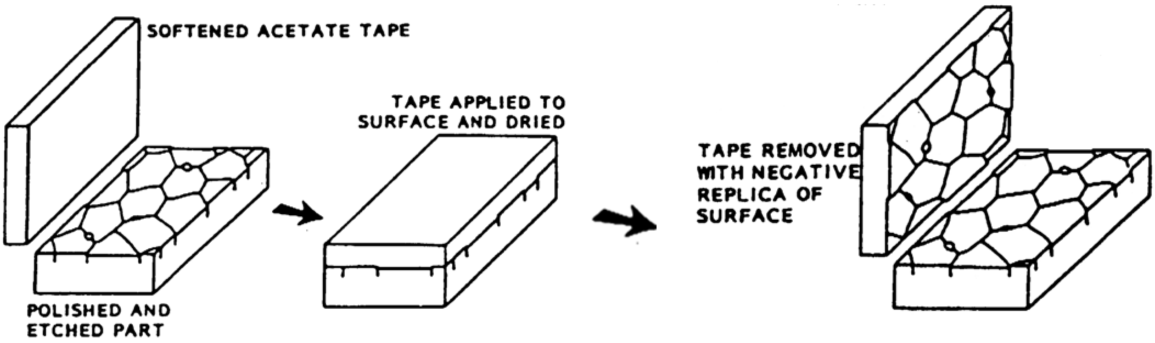


Figure 1.52 Making of a replica

The replica is brought to the optical microscope and it is advisable that gold is sputtered on the surface to increase contrast. A low magnification (20 to 50 times) is started with to investigate the whole replica surface and gradually magnification to a maximum of 500 to 1,000 times depending on the nature of the investigation and the identified characteristics.

A frequently used application of replication is the assessment of creep damage. Different classification systems exist to translate the observed damage to a creep class. The observed damage relates to (orientation and linking of) creep voids, and (micro or macro) cracking where increasing damage relates to a higher creep class number and a higher creep life consumption. By performing replication in consecutive time steps, replication can be used as a (somewhat rough) creep monitoring method. As monitoring technique, the method is not very precise and is dependent on the assessor (as a note, it is added that in many countries there is no official qualification system in place for making and assessing of replicas). Furthermore, creep in ferritic steels appears as void formation on grain boundaries in an early stage, but in martensitic steel this occurs only in a very late stage.

Examples of applications of replication are gas turbine disks, steam lines, boiler tubes and pipes. Photos of surface preparation, etching, removing of tape, surface preparation on blade and a microscopic result are shown in Figure 1.53.

Figure 1.53 surface preparation, etching, removing of tape, surface preparation on blade and a microscopic result

1.2.11.4 BOAT SAMPLING

A boat sample or scoop sample is a sample taken from the surface of the material of the actual component under investigation. Although material is removed, the sample is taken without plastic deformation or thermal degradation and the techniques of boat and scoop sampling are therefore regarded as non-destructive in nature. Boat samples are removed using small angle grinders operated by a skilled person. Special machines are can be used for removing a scoop sample (e.g. for the purpose of small punch testing), an example is shown in Figure 1.54.

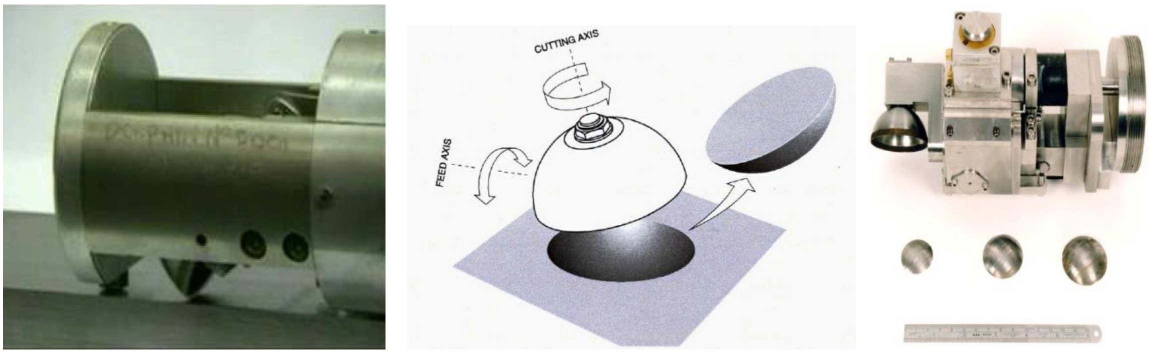


Figure 1.54 Scoop sampling (machine)

Boat sampling can for example be done to investigate the crack growth mechanism at the crack tip. By applying "normal" metallographic techniques, the mechanism can be determined (e.g. mechanical fatigue, stress corrosion, hydrogen embrittlement, overload, et cetera). Analysis at the beginning of the crack are more difficult interpret due to corrosion products and friction corrosion. Another example is assessment of creep damage: a large crack was found in a T-joint after only 16,000 hours of operation. Also, miniature sample can be made that can be used for small punch testing (see section 1.2.10.5) or instrumented indentation testing (IIT, see section 1.2.10.6).

1.2.11.5 SMALL PUNCH TEST

Actual material properties of components in service are essential for residual life time analysis. As components need to stay undamaged, non-destructive testing methods are needed. Small punch testing (SPT) is essentially non-destructive and can provide several material properties.

In the small punch test, a disk like specimen is deformed in a miniaturized deep drawing experiment. The specimen is clamped between a die and a downholder and centrically deformed by the puncher with a spherical head, see Figure 1.55. The temperature is controlled at the required test temperature. Typically, a specimen is 8 mm in diameter and 0.5 mm thick. Displacement and force are recorded. A deformed specimen is shown in Figure 1.55.

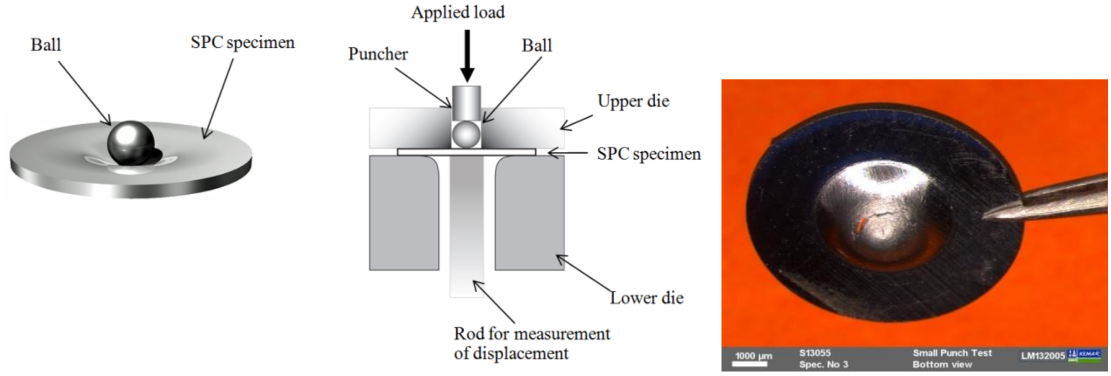


Figure 1.55 Small punch testing. Left: specimen. Middle: testing set-up. Right: deformed specimen after testing.

When the test is also simulated using FEM (Finite Element Modeling), material parameters may be determined. At the beginning, the material parameters are unknown and a set of initial "guessed" values are used. The force against displacement diagram is calculated and results are compared with the actual graph as determined with the small punch test. Based on the error, an optimization route (in Matlab) determines a new set of material parameters until the required minimum of error between FEM simulation and small punch test results are obtained.

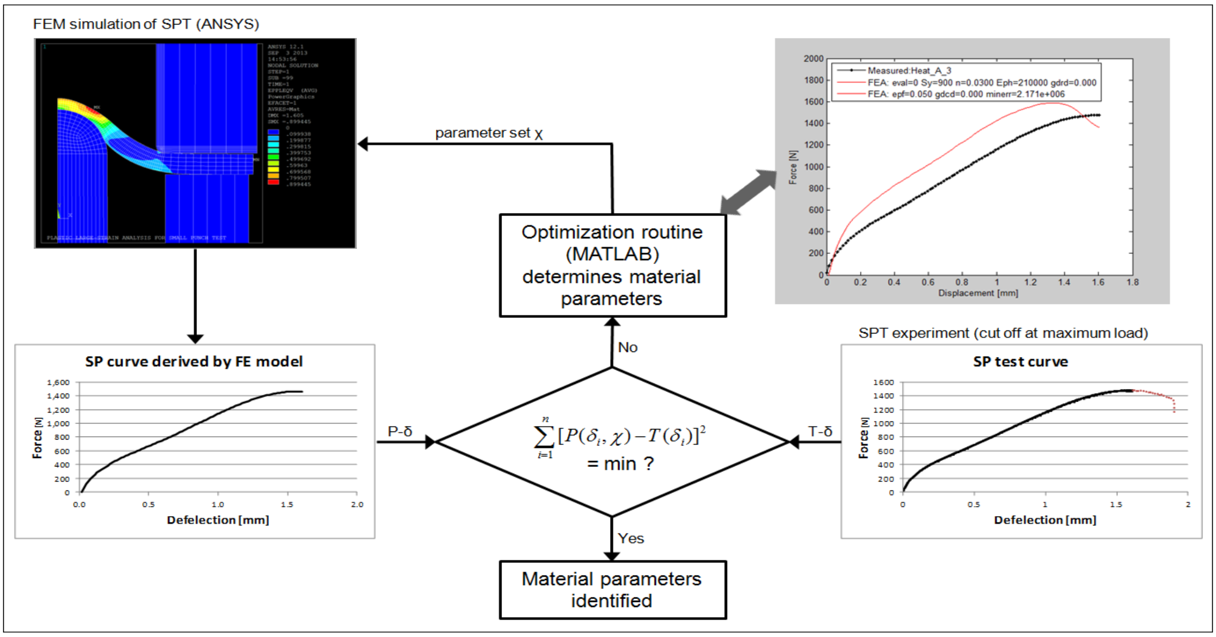


Figure 1.56 Determination of material parameters using small punch testing, simulation of the test using FEM and an optimization routine.

Tensile properties (yield strength and tensile strength) can be predicted within +/- 5% accuracy using the aforementioned approach and for the stress-strain curve there is a reasonable match; fracture strain still needs improvement. Creep properties cannot yet be accurately determined, pilot projects have been carried out and the approach is an ongoing development. For fracture toughness, there is a basic idea of the approach, but there are no validations yet.

1.2.11.6 INSTRUMENTED INDENTATION TEST (IIT)

In determining Fitness For Service (FFS) or in finding the cause of a failure, it is necessary to know material properties. For example, fracture toughness which indicates the resistance to unstable crack growth, is very important in assessing structural integrity. The reality is however, that these parameters cannot be determined without destructive testing. Several attempts have been made to determine actual material properties with non-destructive testing. These methods are, however, deemed to be applied in the laboratory, and therefore unsuited to determine properties of large components such as turbine rotors.

Failure Analysis (FA) and Fitness For Service (FFS) should be based on material property data of the component in its actual state of damage. However, actual parameters are not known, and therefore nominal material properties are used, determined according to norms. The big disadvantage of applying nominal parameters is that calculated residual life fractions may result in conservative estimates. This can mean that a component would be calculated to have a life smaller than a 4 years inspection period (unfit for service), where it would be over 8 years based on actual material properties. Another disadvantage is that specific degradation, such as embrittlement, can be overlooked. Destructive testing in a laboratory of e.g. a turbine rotor is not an option to overcome these disadvantages.

The test is an indentation test in which it is possible to measure both the load and the indentation displacement with high accuracy in the micrometer and nanometer range. Such a method is referred to as Instrumented Indentation Test (IIT). The initial unloading slope and the residual indentation depth after complete unloading are the important parameters. By using these parameters, the elastic and plastic properties of materials can be uniquely determined. For example, a low alloyed steel 10CrMo9.10 was investigated. Both the experimentally observed uni-axial tensile curve and the predicted curve based on the indentation test and the procedure are shown in figure 1.58.

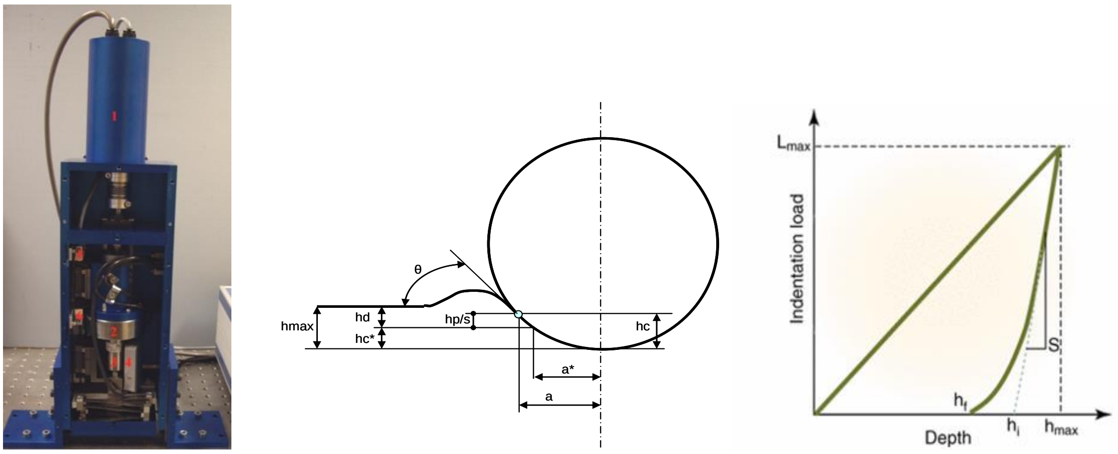


Figure 1.57 Left: indentation test device measuring actual material properties; middle: different indenter shapes possible, often used ball indenter with R = 0.5 mm; right: recording of displacement and force.

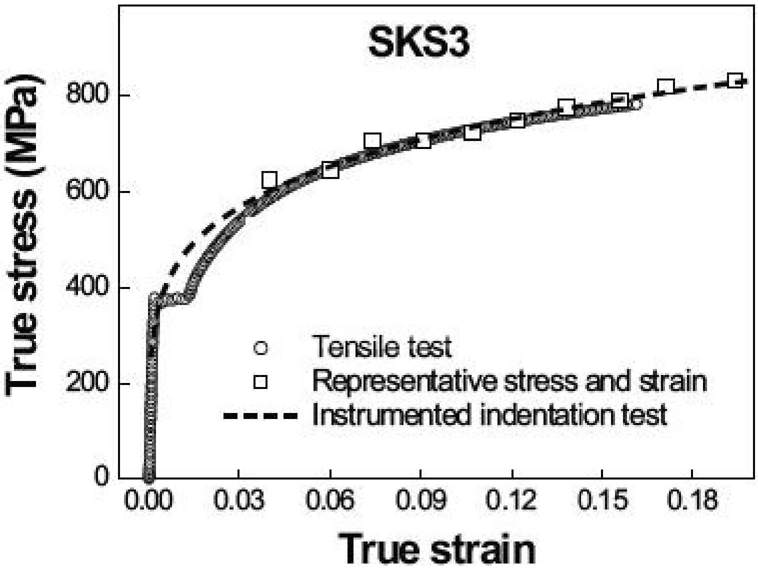


Figure 1.58 Uni-axial tensile curves, experimentally observed (dotted line) and predicted with an indentation test procedure (straight line).

Besides the hardness, other basic mechanical properties, such as Young's modulus, yield strength and tensile strength, can be deduced from the indentation load versus displacement curves for loading and unloading. A multiple cyclic loading-unloading procedure could be used (see figure 1.60) to measure the change of the Young's modulus, from which the fracture toughness can be derived. This is done by a dedicated procedure based on damage mechanics and finite element analysis, simulating the indentation test. The process of performing simulations to obtain a better fit between FEM and the test results can optimized by using neural networks, see Figure 1.59.

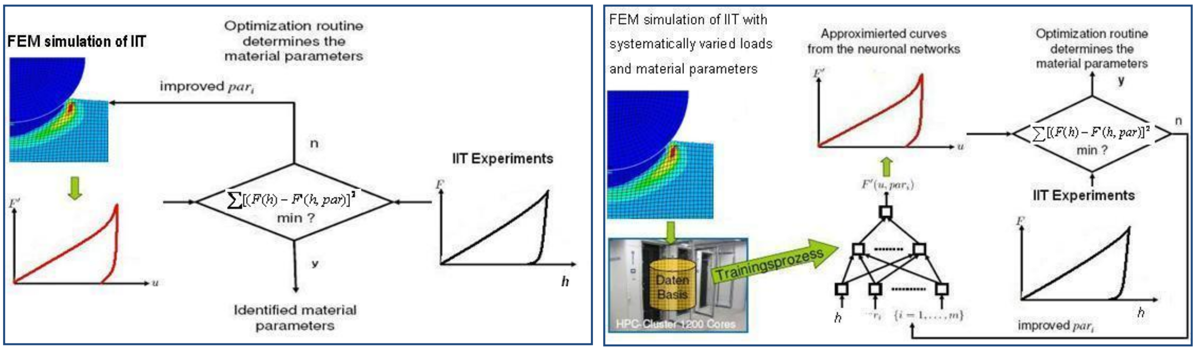


Figure 1.59 Analysis procedure tensile properties with local approach

Investigation is going on how to estimate creep damage on site. An off-line monitoring technique may be possible where the creep increment is determined by comparison of indentation tests results in time. Interpretation methods of the indentation technique are being developed, especially for estimation of fracture toughness and creep damage.

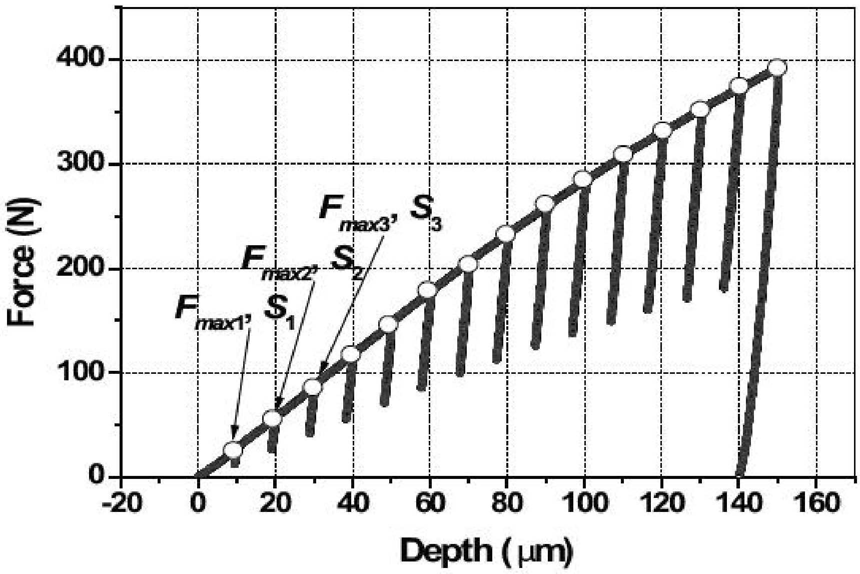


Figure 1.60 Multiple cyclic loading-unload procedure

Many applications in gas and steam turbines are possible. E.g., since parameters can be determined very locally, properties in and around heat affected zones and welds can be determined. Another possible application is the testing of the quality of a thermal barrier coating.

In comparison with other miniature technique, such as small punch, impression, micro-tensile or small ring tests, the IIT technique is fully non-destructive and can be performed on site, no sample machining is needed, and no sample processing is necessary. Other indentation measurement devices exist. However, most of them are for the measurement of nano-sized materials which require a restrict test environment, and are therefore impossible to be carried out on site.

Concluding, an indentation test has been developed to measure actual material properties, that can be used in fitness for service analysis or in failure analysis. Interpretation methods for fracture toughness and creep are under way which has yielded promising results.

1.2.12 MONITORING

1.2.12.1 CREEP MONITORING

Strain gauges

A strain gauge is a device used to measure strain on an object. A strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. For high-temperature applications, the gauge is bonded to the substrate with ceramic cement, a flame sprayed alumina process or, if possible, spot welded. As the object is deformed, the foil is deformed, causing its electrical resistance to change, see Figure 1.61. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor. The strain is obtained by dividing the quotient of resistance change and the resistance of the undeformed gauge by the gauge factor.

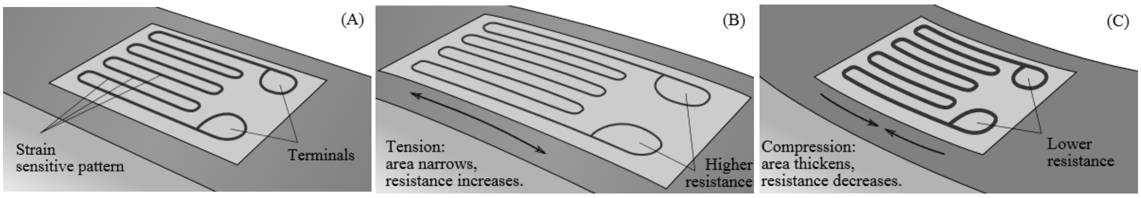


Figure 1.61 Concept of strain gauge on a beam under bending

Strain gauges are especially useful for measuring transients, i.e. changes within a short period of time (e.g. ~30 minutes). For longer time intervals, SPICA (see following) is superior but sufficient place to mount a SPICA sensor or to maneuver the camera is not always present, which may be a reason for applying strain gauges. Strain gauges have cables, and in practice these can break or deteriorate. An example of a measurement result of location where the expert has applied strain gauges is shown in Figure 1.62.

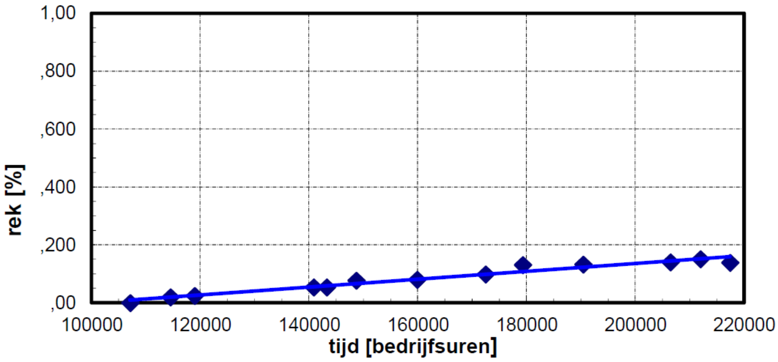


Figure 1.62 Results of strain measurement using capacitive strain gauges. Operational hours ("bedrijfsuren") versus strain ("rek")

SPICA

Typically, operators or maintenance managers of power plants and refineries are responsible for pressure equipment. Pressurized material is subjected to creep when operating at temperatures above approximately 400-450°C. The consumption of creep life can be evaluated by in-service evaluation standards. Due to the conservative nature of such an evaluation, the resulting life time consumption is in many cases much higher than the actual consumption. On the other hand, local creep exhaustion due to stress concentration is usually not addressed by this approach which causes a risk of overlooking regions with severe creep damage. A more accurate approach of determining life time consumption and remaining life is determining the actual creep damage by measurement of the creep strain. SPICA is a method to perform such strain measurements accurately and during operation. Furthermore SPICA has the ability to monitor local creep life exhaustion, for example in the heat affected zone of a weld.

An oxidation resistant foil is role-welded to the surface of investigation. Photographing the foil with time intervals allows for determination of displacements and therewith (creep) strain. A stub is placed on the foil, to close of the surface (for protection) and the stub contains holes for accurate re-placement of the camera, see Figure 1.63. The camera makes use of special heat resistant lenses that allow for some error in re-placement to provide a sharp image. Digital image correlation is used for determination of strain.

Figure 1.63 Left: mounted SPICA sensor; middle: photographing the

A more accurate determination of remaining life can save money. If, for example, it can be shown by strain measurement that creep life consumption is still low inspection intervals can be longer compared to the situation of higher consumed creep life. Also, the actual condition can be assessed during service, enabling planning of repair or replacement before upcoming inspections. Components that are 'suspected' (e.g. having repair welds, or have long service life) can be monitored. For example, a plant being near the end of design life had SPICA installed sensors to monitor creep strain. This allowed the plant management to safely increase the steam temperature with a few degrees, yielding substantial extra income.

SPICA measurements are carried out during operation, so, unlike replication, they are done independent of an outage. Also the results are, again unlike replication, independent of the assessor. Interpretation of creep damage of martensitic steels is uncertain using replication and will give warning only in a late stage. Conversely, SPICA strain measurement is material-independent and, in addition, allows for local strain measurements in the heat affected zone which act as early warming as problems normally arise there first. Strain gauges are not able to detect this local strain in the HAZ because the gauge strain is measured- and averaged over a larger length across the parent material, HAZ and weld material. SPICA does not involve cables and is very robust: sensors cannot be easily destroyed like strain gauges.

Steps in a SPICA-project

SPICA sensors are installed at selected critical locations (experts can provide an advice on which locations are critical). A 'Hot Measurement' consists of photographing the sensor surface using a SPICA camera. The measurement is referred to as 'Hot' since it is performed during operation. After subsequent 'Hot Measurements', image correlations can be made from which strain and strain rate are determined. Based on a strain criterion, creep life consumption can be determined. If first measurements are not taken from the start of service, creep life consumption until the first measurement can be estimated by in-service evaluation standards. In summary, the following steps are taken:

- Selection of critical locations;
- Mounting of sensors;
- Hot measurements;
- Digital correlation analysis;
- Evaluation of strain and strain rate;
- Determine creep life consumption.

Typical applications

SPICA is an in-house development as a method for in-service strain measurements in industrial plants. SPICA sensors have applied in plants throughout Europe, the Middle East, South-Africa, Japan and China. Plants where SPICA is applied are power plants, refineries and chemical plants. Typically, 5 – 20 sensors are applied per plant at components like Y-pieces, T-pieces, girth welds, headers, bends, HP steam valves, and hydro cracking reactors.

1.2.12.2 CORROSION MONITORING

High corrosion rates can apply and uncertainty can exist with changes of operation (air distribution, temperatures) and especially with change of the fuel diet. Corrosion monitoring can therefore be a very helpful tool that can assist operators or asset managers. Most experts applies two types of monitoring, including monitoring corrosion of membrane walls using KEMCOPs and monitoring of superheaters using electrochemical measurements.

KEMCOP

KEMCOPs are in-house developed corrosion probes installed in the strips of the membrane wall. A hole is drilled in the strip where a thread has been cut allowing the KEMCOPs to be screwed in. The KEMCOPs can be screwed in so that the probe tip is flush with the evaporator wall. In this case, the conditions at the boiler wall and probe tip are equal. The KEMCOP can also be screwed in further, as indicated in Figure 1.64. Hereby the probe tip is exposed at a higher temperature than the strip metal surface which is done if one is interested in corrosion depending on a certain temperature. The temperature is measured first using a 'measurement-KEMCOP' in which a hole is drilled in the axial direction ending just before the tip surface, allowing for measurement of the tip temperature with a thermocouple.

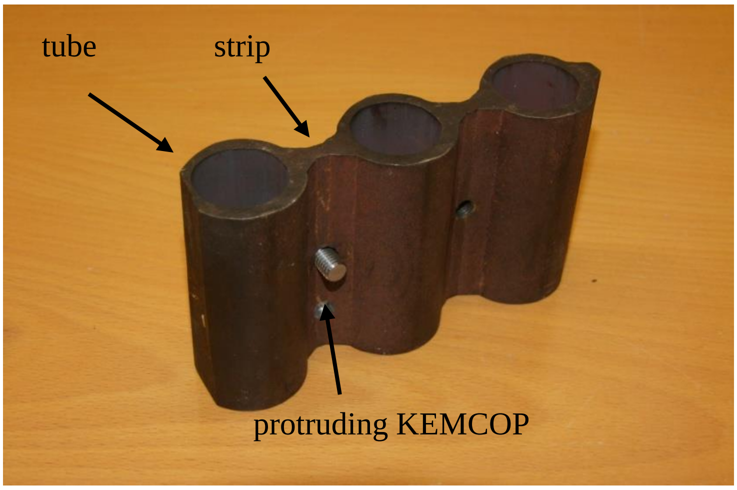


Figure 1.64 Example of KEMCOP protruding through strip

After exposure, probe length reduction and therewith corrosion rates are determined. These rates can be compared with acceptable levels off wall thickness reduction.

If problematic corrosion occurs in a boiler, the corrosion probes are normally placed with the probe tip flush with inside of the boiler wall. A typical example is of the 1990's when coal-fired boilers were retrofitted with low-NOx burners. This caused reducing conditions in the combustion zone due to which more corrosive compounds are formed, sometimes leading to catastrophic corrosion rates. Measures such as optimal air distribution and curtain air were introduced and KEMCOPs were used to monitor corrosion and evaluate these measures.

If problems are anticipated on, and not yet quantified, KEMCOPs are normally inserted where the temperature of the probe tip is set. An example is the change of the fuel diet, e.g. the introduction of co-firing biomass or the increase of biomass shares. Another example is the introduction of newer type of high-efficient boilers with higher steam temperatures and different (more heat-resistant) materials.

Electrochemical Noise Measurements

On-line corrosion measurement is applied by most experts using Electrochemical Noise measurements. A theoretical background on this type of measurement, the probe design, an example of results and reference projects over the last years are described in this memo.

Theoretical background

Corrosion is an electrochemical process where anodic metal dissolution and cathodic reduction of ions occurs simultaneously on the metal surface. Metal is lost from the corroding surface and goes into solution in the electrolyte, releasing electrons while so doing:

$$\mathrm{Me} \rightarrow \mathrm{Me}^{2+} + 2e^{-}$$

The electrons are consumed at cathodic sites by a corresponding reaction. The two components then may combine to form a corrosion product – in the case of iron corrosion, for example, the corrosion products are typically iron oxides. The reaction essentially proceeds with direct reduction of oxygen, as in:

$$O_2 + 4e^{-} \rightarrow 2O^{2-}$$

and the corrosion product is direct formation of the metal oxide (or sulphate, chloride, etc).

Having established that high temperature corrosion is electrochemical in nature and therefore involves a charge-transfer process in precisely the same manner as aqueous corrosion, conventional polarisation theory can be applied to obtain the corrosion rate. The corrosion current is obtained using the Stern-Geary approach:

$$I_{corrosion} = \frac{B'}{R_p}$$

where B′ is a constant derived from the Tafel coefficients of the electrochemical reaction and R_p is the polarisation resistance.

Oxides, ash deposits and corrosion products become semi-conductive at elevated temperature, thereby providing the ionic and charge-conducting capabilities of an in-situ solid-state electrolyte. This explains why corrosion rates on clean metal surfaces exhibit an ‘incubation period’ (during which the charge transfer between anodic and cathodic sites is restricted by the ‘solution resistance’ of a very thin electrolyte layer) and why the corrosion rate subsequently increases as the deposit/corrosion product layer increases in thickness, thereby increasing its capacity to conduct charge and transport ions.

According to Ohm’s law, it holds for electrochemical noise measurements:

$$R_n = \frac{V_n}{I_n}$$

where V_n (the potential noise value) is the fluctuation on the potential signal, I_n (the current noise value) is the fluctuation on the current signal between nominally ‘identical’ electrodes, and R_n is the notional resistance value associated with them in the electrochemical circuit. It should be noted that the magnitude of the potential and current signals is not important, the ratio between the two values is however vital and controls the value of the resistance component. Once the R_n value has been calculated it can be substituted directly for R_p in the Stern-Geary relationship to obtain $I_{corrosion}$ from which an accurate indication of the instantaneous and cumulative corrosion rate can be computed using Faraday’s Law, again in accordance with traditional dc polarisation theory.

Work undertaken by Davis *et al.* (2000) confirmed by comparison of physical metal loss with predicted cumulative rate estimates obtained in laboratory conditions and field applications using EN-based high temperature corrosion monitoring instrumentation that the corrosion rate indications obtained from the instrumentation were in very close agreement.

Probe design

The superheater probe consists of a heat-resistant steel tube that contains the corrosion sensors at the tip of the probe. The sensor rings are cooled to a pre-set temperature, in line with the surface temperature of the superheater tubes (normally steam temperature plus 50K). The rings are made of material similar to the superheater tubes. The diameter of the sensor block may vary according to the external diameter of the available tube, but typically would be 38mm OD with a 4mm wall thickness. The cooling air is normally pressurized air available at the plant. A very limited amount of air is used and does not compromise the plant air system. Excess cooling air is blown off in the boiler. The electrodes feed into the ECN unit where the data is processed and logged to a computer. A schematic of the system is shown in Figure 1.65.

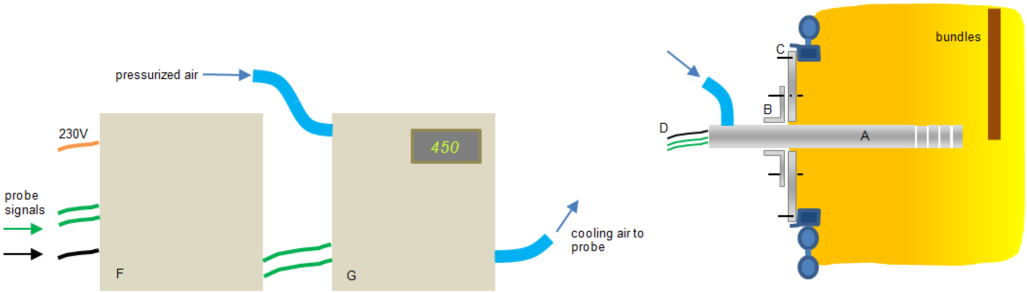


Figure 1.65 Schematic of furnace wall probe. A) Probe (sensors are located at the tip, exposed in the boiler). B) Flange for mounting the probe. C) Insert plate, mounted on an inspection hatch to which the flange is bolted. D) thermocouples and electrodes. E) Compressed air supply. F) ECN unit, data processing and logging. G) temperature controller

The probe lance is introduced through the sidewall, for example through an unused access door, and normally just before or just after the first bank of the superheater tubes. The lance typically would project one to two metres in from the sidewall in order to ensure that the exposure environment was typical of that part of the superheater

The element block should be positioned in the hot gas stream close to a location where it is known from previous experience that maximum corrosion is likely to occur. Within limits, the sensitivity of the sensor can be adjusted by slightly increasing the control temperature, compared to the likely tube wall temperature at the target location. Alternatively, the actual metal temperature of a target superheater tube can be monitored and the temperature of the corrosion sensor controlled in real time to track that of the target tube, or increased by a fixed margin to reflect likely future flue gas temperatures.

The membrane wall probe works in the same way as the superheater probe. A schematic is shown in Figure 1.66 (left), the control system and data processing is not shown. Where the corrosion sensors for the superheater probe are rings, normally directly cut from tube material, the membrane wall probe has a miniature sensor design. The miniature sensor set is shown in Figure 1.66 (right).

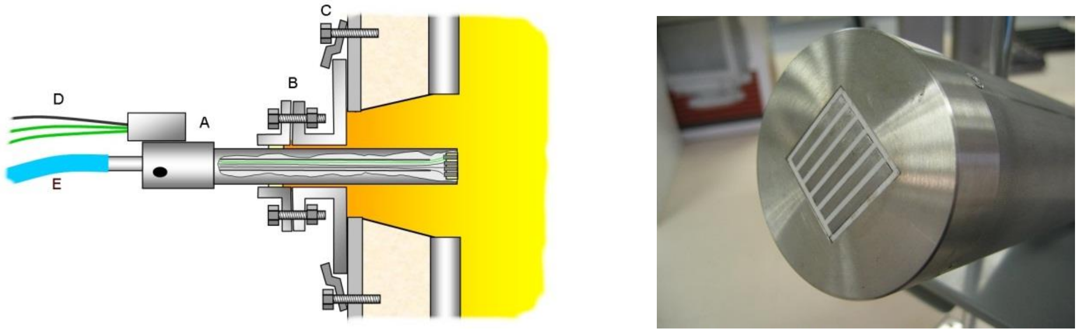


Figure 1.66 Left: schematic of furnace wall probe; indications of A – E as in Figure 1.x. Right: probe front with miniature sensor set.

Example results

Paper sludge ash consists of paper filler material which is mainly kaolinite and calcium carbonate. A paper sludge ash combustor was located next to a waste incinerator and it was claimed that corrosion and fouling could be reduced by adding the paper sludge ash (left over from the paper sludge combustion) to the waste incinerator boiler. This claim was verified by exposing corrosion probes near the superheaters in a period before and during continuous dosing of the additive. The tip of the probes after exposure is shown in Figure 1.x.

Figure 1.67 Tip of exposed corrosion probes

Measurement results are shown in Figure 1.x. Thermocouples are mounted in the rings on two different distances from the surface, allowing for calculating the metal surface temperature. This temperature is used for controlling the cooling air and is plotted in blue. The temperature is controlled in a very narrow window of +/- 5K around the set value. The corrosion rate is plotted in red.

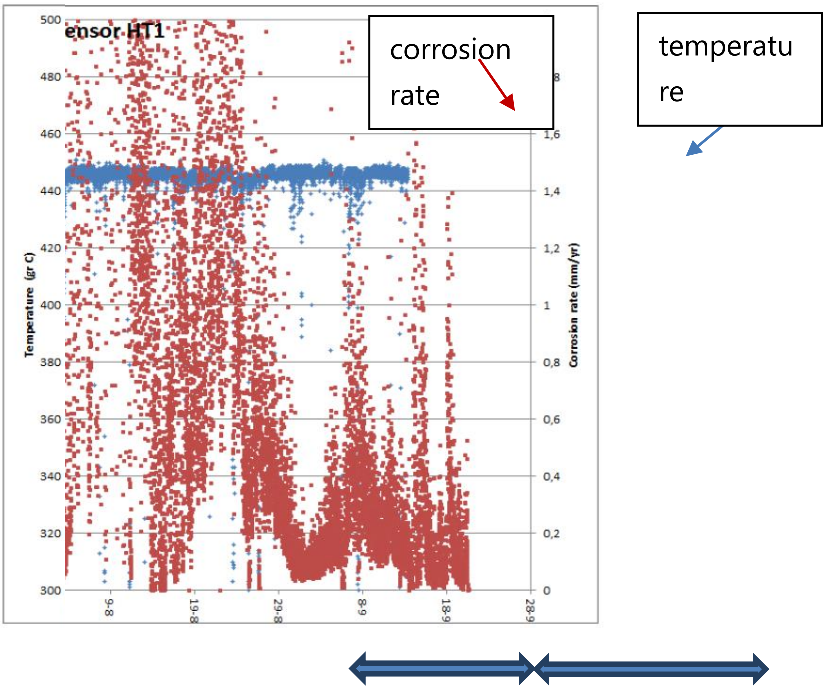


Figure 1.68 Measurement results: in blue the temperature of the surface of the material is plotted and in red the wall thickness reduction (‘corrosion rate’).

A post-exposure analysis of the deposits obtained before and during paper sludge addition was performed using SEM. This showed the differences in chemical composition and that the deposit was more porous, especially in regards to the deposit layer directly on the probe material (see Figure 1.x)

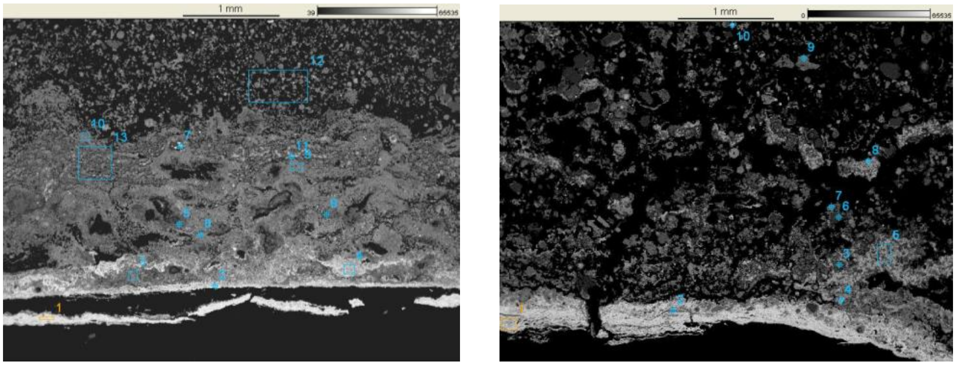


Figure 1.69 Deposit layer without dosing additive (left) and with dosing additive (right)

1.3 DESCRIPTION OF PERSONNEL

Typical qualifications for personnel working in the field of the topics discussed in the previous section are given in Table 1.

Table 1 Typical personnel qualification for institute for geothermics

	Education (school / university)	Education (job specific)
QA QC	Mechanical engineering, BSc	Inspector
RAMS	Mechanical engineering and statistics, MSc	
In-service inspections	Material and Mechanical engineering, BSc	Inspector
Condition and remaining life	Material and Mechanical engineering, BSc and MSc	Inspector
Fitness for Service	Material and Mechanical engineering, BSc and MSc / PhD	
Failure and root cause analysis	Material, mechanical and chemical engineering, BSc and MSc / PhD	Welding engineer
Corrosion	Mechanical or chemical engineering,	Corrosion engineer

analysis	BSc and MSc / PhD	
Monitoring sensor design	Physics, mechanical engineering MSc / PhD	
Mechanized NDT design	BSc mechanical engineering – construction and design	Levels 1/2
NDT, up to level 2	Lower / middle technical education	Levels 1/2
NDT, ET and UT level 3	Physics, mechanical engineering BSc and MSc	Level 3

1.4 RECOMMENDATIONS FOR SETTING UP INSTITUTE FOR GEOTHERMAL PLANTS IN INDONESIA

For providing (the right) services to a geothermal plant, it is vital to understand the position of the operator of such a plant and how this relates to the services independent experts can provide. This is shown in Figure 1.70. An operator has a maintenance concept / plan, including an inspection plan according to which inspections are performed. Such a plan is made upon commissioning the plant. The operator is influenced by the outside world: a notified body will have to approve the inspection plans (legal, safety) while in some countries the insurance has a similar influence. Also, the management of the plant (on its turn influenced by the market) will set certain goals, for example, it requires maximum output, or an output delivered when required, influencing how components are operated and to what extent they will degrade (e.g. by fatigue). The operation of a plant can also be influenced by the steam input (varying amount or composition of steam and contaminants). This will influence e.g. corrosion of parts.

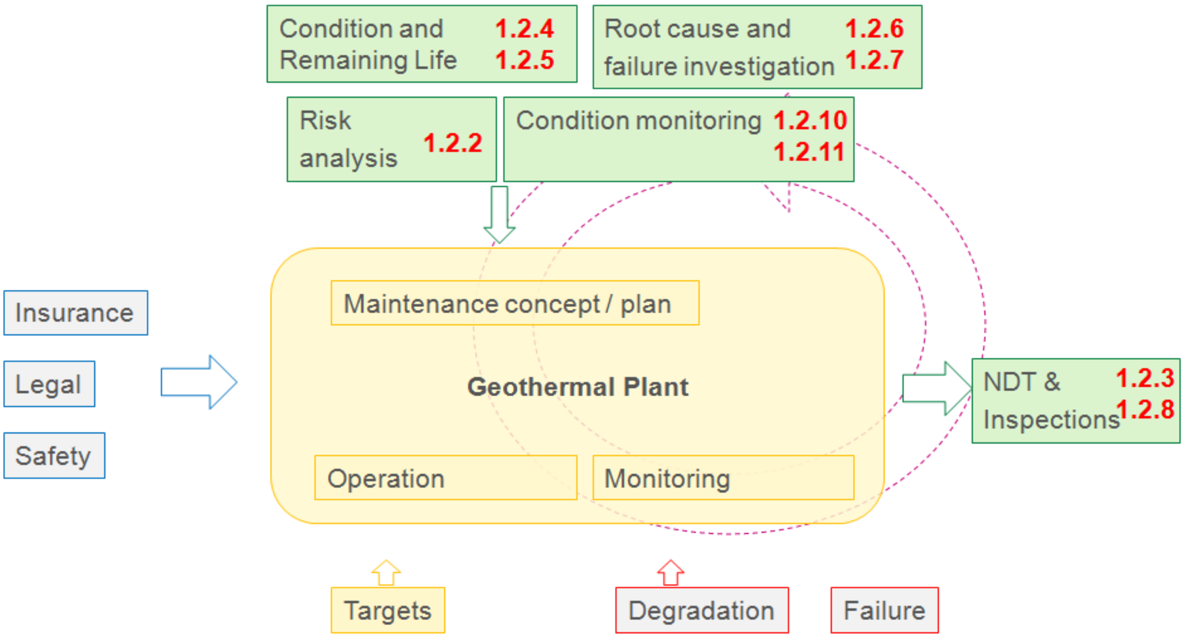


Figure 1.70 Situation of operator of a geothermal plant

As the plant is operated, components degrade due to various failure mechanisms (fatigue, corrosion, etc.). If not repaired or replaced in time, ultimately components will fail. For above reasons, in-service inspections (see section 1.2.3) and NDT (see section 1.2.8) will be performed to investigate the condition (see section 1.2.8). Additionally, monitoring can be performed (see section 1.29). NDT will result in either no indications or indications. This information is fed back to the operator that will have to decide what to do with it. Is the indication a crack, and if so, does the crack grow, on basis of what mechanism, and what are dimensions at which instable crack growth starts, et cetera. Determination of fitness for service has to be done, see section 1.2.4, possibly based on actual material properties (see section 1.2.10). A component can fail which either shows directly or during an in-service inspection (see section 1.2.3). If a failure is unexpected, or unexplained, especially if the failure provides a situation compromising safety or availability, there is a need to investigate the failure to determine the failure mechanism, and possibly to find the root cause of the failure (see sections 1.2.6 and 1.2.7). Some degradation mechanisms (corrosion, creep) are known to occur in certain components, it is however not known at what rate the degradation process takes place. Under certain conditions, degradation will progress slowly, but under other conditions, degradation can progress very fast. Hence, it is necessary to monitor the condition of certain components of which it is known that they are subjected to degradation mechanisms with a rather unpredictable character (see 1.2.10 and 1.2.11).

After a plant has run for several years, the plant will be in a certain condition that may be near to the end of life according to design. The plant management can take decisions to extend the plant life, as the design life is normally conservatively estimated. To take such a decision, including decisions on necessary investments is based on knowing the actual condition and remaining life (see sections 1.2.4 and 1.2.5).

Figure 1.71 shows the above whereby indicated the stage of the plant life. Emphasis is put on the function of failure databases (i.e. a database recording failure reports and a database recording failures).

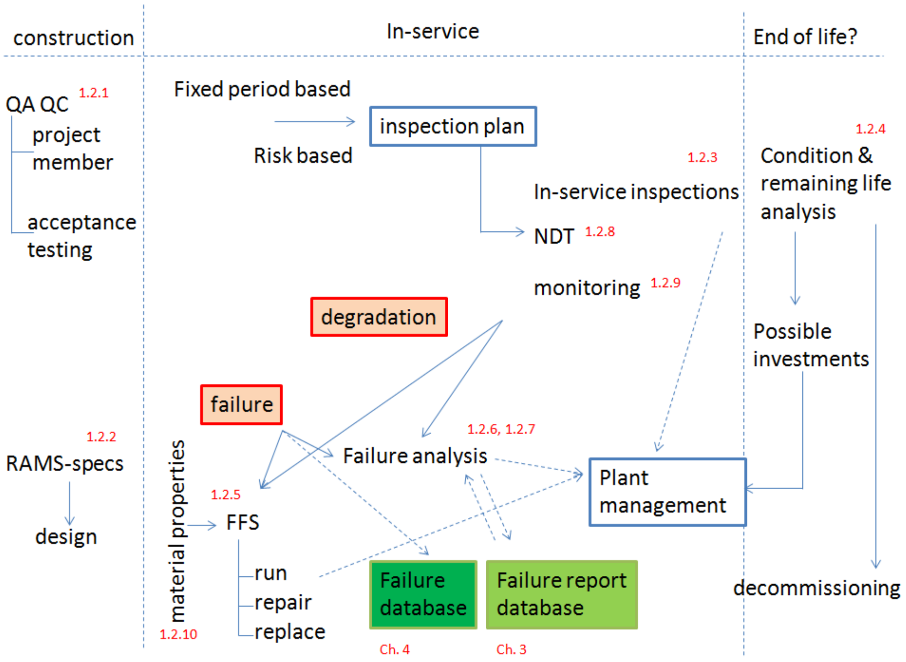


Figure 1.71 Overview of services and databases related to plant life

2 TECHNICAL SERVICE AGREEMENT

Introduction

In the present energy market power plant operators attach great value to short-term solutions and applications. Finding these solutions will require efforts to develop new technologies, methods and practices. In the Netherlands many years of experience are gained with a R&D program, where multiple power generation companies joined forces to share costs and benefits. The projects are generally carried out by a knowledge centre (i.e. KEMA), with experts in many disciplines to work in relevant projects. This program was designed not only to optimize efforts and reduce costs for R&D, but also to improve daily operation and maintenance by sharing mutual experience. Basis for the cooperation is that only project subjects will be awarded of the information is are not sensitive to mutual competition between participants; the benefit of sharing information and efforts is the key for a successful agreement.

This so called Technical Service Agreement (TSA) aims to provide short-term solutions and applications, embedded in a portfolio of several future options. The participant's individual positions and strategies must be fully recognized: enabled by individual project selection with optional partnership and optional fund-pooling and risk-spreading. The Technical Service Agreement is based on the trends and challenges in the liberalized market, on the new and forthcoming government energy policy and on technical developments. The targets and objectives of the agreement are defined and adjusted on a yearly basis, thus enabling a flexible project program to accommodate participant's requirements and changes in the market.

Program outline

The TSA is a contract on an individual basis. It has the leverage advantages of a consortium agreement, fully developed know-how and product transfer, and an open and professional control and (know-how) management structure.

The TSA setup as successfully applied in the Netherlands consists of two main constituents:

1. base fee part, part providing access to:
    - the Help Desk Consultancy
    - power plant expert working group meetings, for mutual exchange of experience
    - strategic scouting & support issues
    - access to all former (collective) R&D products;

2. non-base fee part: each individual participant is offered - without any further obligations - subscriptions to a large choice of projects in three main areas:
   - new technology/new construction
   - operational support
   - preservation/maintenance of units.

Other issues / areas of interest can be defined to suit the needs of the participants.

Co-funder benefits

The benefits for the participants of the Technical Service Agreement Power Generation are:

- access to specialist know-how on all aspects of modern power generation
- multiple project participants, with an increasing leverage perspective
- access to the Help Desk Consultancy, with senior consultants that have a broad operational know-how standing by
- access - via an exclusive R&D Products website - to all former (collective) R&D products,
- software/hardware tools and reports produced.

The main characteristics of the Technical Service Agreement Geothermal Power Generation are:

- separate contracts with each participant / co-funder
- base fee tariff according to the co-funder's installed capacity
- non-base fee part: subscription without obligations and with a leverage option, depending on the number of participants
- project scope defined and adjusted on a yearly base, to accommodate the participants' needs and changes in the market
- backup by and easy access to knowledge centre experts.

Transfer of know-how

Know-how and products are being transferred in a digital format. Manuals, databases, guidelines, et cetera, are published on CD-ROMs, some of which are interactive. Products, services, databases, reports and software can be accessed via a R&D products website. Face-to-face transfers take place through the Help Desk Consultancy, product demonstration and introduction, and directly through the co-funders of the individual projects.

The reports from the non-base fee projects are only accessible to the respective co-funders.

A general summary of these projects will be published on the R&D Products website in order to raise interest at potential new co-funders and to prevent duplications.

Structure, management and quality

The TSA program is supervised by a Steering Committee, which comprehends a management representative of each participants. The base fee package is directly monitored and guided by the Steering Committee. The non-base fee projects are monitored by the Steering Committee at arm's length and these program parts are supervised by separate Cluster Program Committees. The Cluster Program Committees are populated with experts from the participants and the program manager from the knowledge centre. The Cluster Program Committees are the forum where individual projects are reviewed, discussed and tailored to the needs of participants. Each project has a Project Manager, who is responsible, and the subscribing participants appoint a member for project control.

The Steering Committee also supervises the groups of power plant experts. Proposed are four working groups:

- Plant Chemistry
- Inspection & Welding
- Process Control and Electro Technical
- Legislation and Governmental subjects.

The main task for the working groups is exchange of information and experiences between participating power generating companies. Experts in various fields will exchange their daily experiences, to learn from each other and to identify common problems. These working groups are a good platform to define proposals for joint R&D projects.

Project organization and quality

The project manager coordinates the development activities and is responsible for the delivery of products as contracted within the project. Technical progress is monitored by and discussed with the co-funders. The overall Agreement progress is reported to all participants in the digital E-status, which is updated on a monthly basis. The E-status provides information on the status of ongoing projects: products, budgets, planned and realized delivery dates, names of the project managers and of the members of the Project, Program and Steering Committees. The progress report is part of the exclusive R&D Products website and is accessible to all Technical Service Agreement participants. Every three months an E-status report is produced, containing condensed overall management information on the progress of the total Agreement

3 KNOWLEDGE DATABASE AND FAILURE DATABASE

3.1 INTRODUCTION

Interruption in the electrical power production can be detrimental in a modern society. It can lead to power shortages or black outs and questions might be raised in the press or even in parliament. Due to the constant incentive to lower electricity prices there is the risk to cut too much on maintenance costs which can increase the risk on breakdown of crucial components in the power station. And if a crucial component breaks down and power production is interrupted there is much pressure to minimise the unexpected outage period. Suddenly many questions are raised that need to be answered, even although their relevance for the root cause might not always be confirmed afterwards. Questions such as:

- did the failed component already see similar failures in the past?
- do other Power Stations use a component of a similar type
    - if yes, did that component suffer from a similar failure in the past?
    - if not, what kind of component do they use instead?
- what material is the component made off?
    - what type of material is that?
    - has there been a change of material since design?
    - are the components used in other Power stations made of the same material?
- the manufacturer states that e.g. stress corrosion cracking is the cause
    - but what is stress corrosion cracking?
    - what does a stress corrosion crack look like?
    - is the construction material susceptible for stress corrosion cracking?
- etc. etc.

Many of the requested answers might be somewhere in the available databases or at the internet but how to find them quickly? Even quick confirmation that the answer cannot be found in the available information might be relevant so that the focus momentarily can be shifted to another question which can be answered.

Purpose of the Knowledge Bank

DEKRA (previously KEMA) was asked by the Dutch power station operators to develop an easy to use information system which would support both the layman and the expert in supplying available knowledge on request. The knowledge bank should not only consist of general available information retrieved from handbooks and the internet made understandable for a layman, but also confidential information available only to the Dutch power station operators collaborating in this project such as inspection reports and welding procedures accepted by the National Pressure Safety Directive.

Description of the Knowledge Bank

The knowledge bank had a modular design. It started with a searchable database of failure summaries covering all the failure investigations carried out by KEMA failure investigation department for the collaborating Dutch power station operators for more than 20 years. This was not necessarily a complete list of all failures experienced by any power station but certainly a list of interesting failure investigations which would be of use in the future. The complete text and figures of the reports of the failure investigations could also be retrieved when available.

Another database contained a list of most of the materials and alloys used in the power industry, such as many stainless steels, high creep steels and tool steels. This database contained the general chemical composition, mechanical properties and physical properties as reported in handbooks, the names of specific grades of roughly the same composition as provided by different steel suppliers. The datasheets of the supplier were included for each commercial grade. This database was used together with a hypertext system which provided the relation between the different grades of stainless steel for instance. Examples are the relative differences between AISI 304, AISI 304L, AISI 347, AISI 316, AISI 309, et cetera, not only in composition (see figure below) but also in use and their benefits.

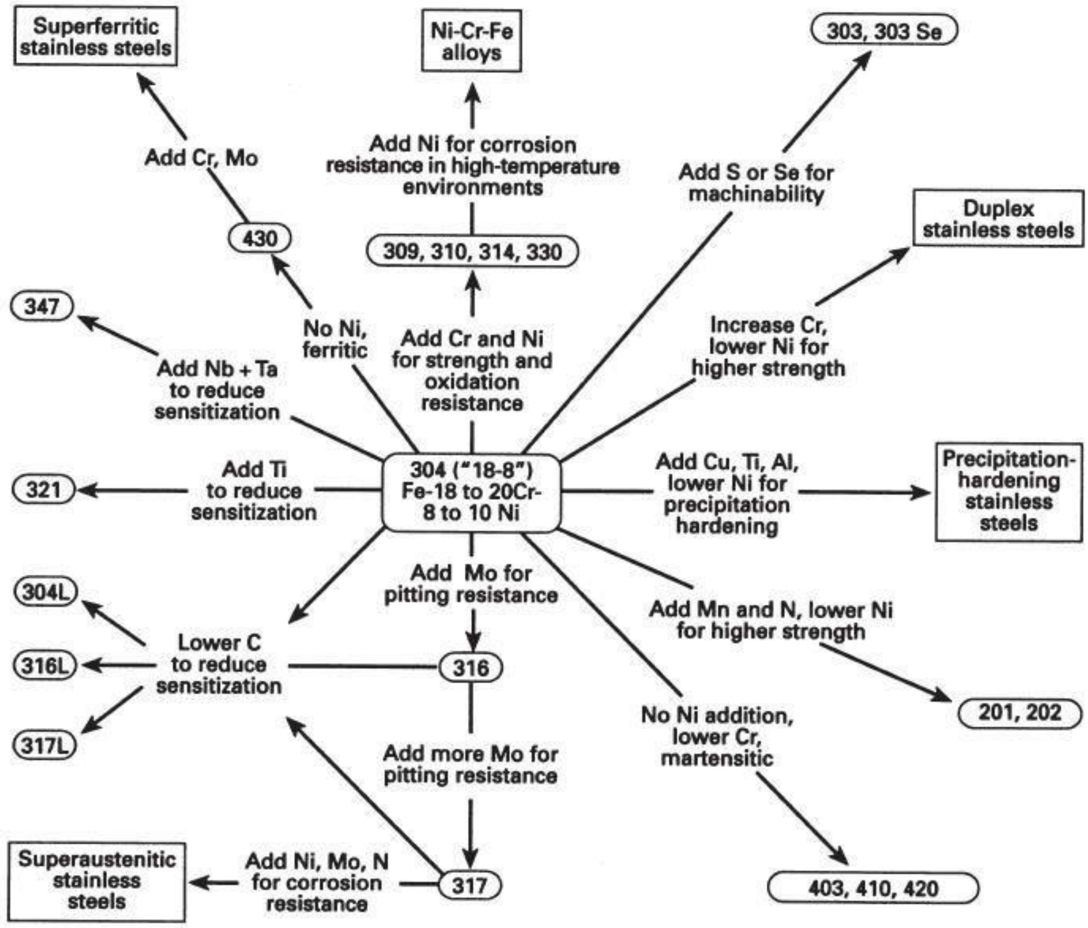


Figure 3.1 Relative differences between austenitics stainless steels based on their composition

This figure shows that the main difference between AISI 304 and AISI 316 is the increased pitting resistance of AIS 316 by adding molybdenum to the alloy. By clicking on the button with 316 one would open a text file which provided a short description of AISI 316, which included the typical use of this alloy and the commercial grade names by different steel suppliers as hyperlinks. By activating these links one would arrive at the data sheet of that grade as provided by the steel works. This information might be biased for commercial reasons but as long as the origin of this information was clear, this should not be a problem.

Similarly the knowledge system included a hyperlinked information system on power production components such as an evaporating steam boiler, steam turbine, condensing boilers and generator. This part consisted out of several modules containing general information components on these such as the relevant differences between the different types of steam turbines such as back pressure and extraction steam turbine, the design difference between turbine blades of an impulse and a reaction turbine, an explanation of the common problems with steam turbines as known worldwide but also a detailed list of the type and serial numbers of the steam turbine in use by the collaborating power stations and the failures experienced with steam turbines by the collaborating power stations.

Figure 3.2 Different types of steam turbine blades

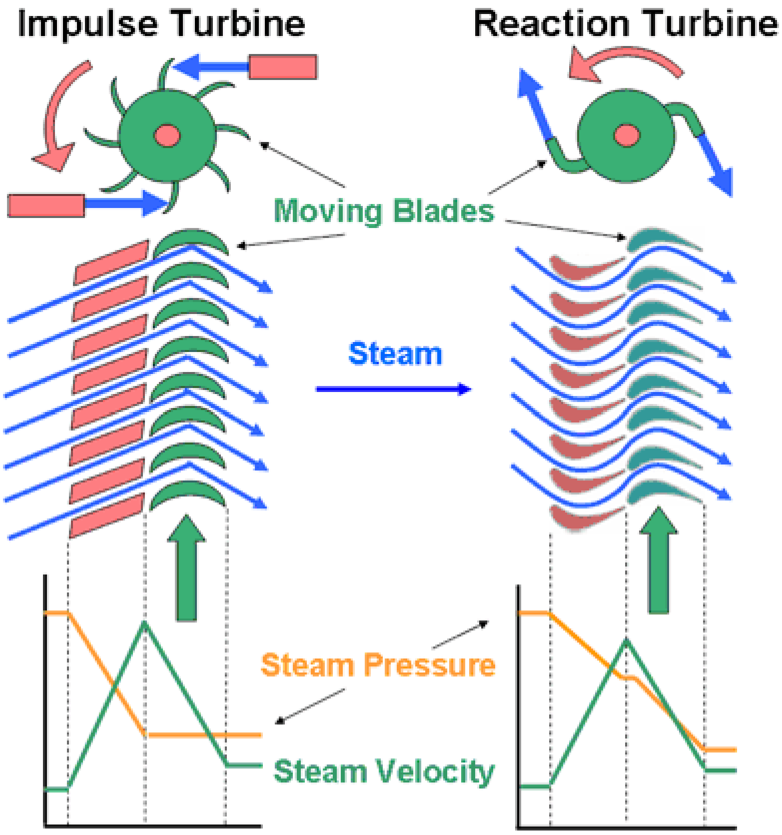


Figure 3.3

For the evaporating steam boilers the system showed cross sections of the boiler with clear indications of the flow of steam and water through the different overheaters, reheaters, economisers, preheaters and evaporator. A list of the modern tube materials investigated in Collaborative European Reseach Programs with the main results. Common practices of determining remaining tube wall thicknesses, cladding and welding techniques for evaporation tubes, cleaning techniques for corroded finned tubes, etc.

Another module of the knowledge system dealt with non destructive inspection techniques such as radiographic, ultrasound, eddy current, magnetic particle, replication and dye penetrant and an explanation of sophisticated techniques like surface waves, ToFD and Phased Array ultrasonic testing. This part provided a general explanation of these techniques together with a list of which technique to use where in the power station, the minimal size of detectable defects for these techniques and common procedures. All the parts were interlinked by hyperlinks, so whenever the term 'eddy current' was used in any report or text, this phrase was automatically made into a hyperlink which, when activated, brought the reader to the general information on this NDT technique. And from this general information links were available to NDT or replication reports of specific overhauls or outages of the boilers of the collaborating power stations.

Similarly, a module was available on destructive testing such as mechanical testing; tensile testing, creep testing, fatigue testing, hardness tests, the different standards used in ASME and European NEN, the influence of elongation speed, sample taking and sample preparation but also on analysis, metallographic and microscopic techniques available to failure investigation. This module was meant to provide some background information when reading or evaluating the failure investigation reports provided by the manufacturer of the failed component or by a third party hired to investigate the experienced failure.

Other modules contained information on welding techniques, including commercial available welding wire and electrodes and a list of repair welding procedures for components subjected to creep which had already been accepted by the National Pressure Safety Directive. A module on degradation mechanisms such as creep, fatigue, wear, overload, the many different types of corrosion with typical examples of such failures worldwide and specifically for the collaborating power stations and what countermeasures were taken.

One can imagine that the information was not all inclusive. The metal database did only include materials used for the most relevant components in the power station and of which information was publically available. For instance confidential information on turbine blade alloys used was not included. Creep data was only available for a subset of materials, and one metal supplier listed recommended weld wires and electrodes for each alloy whereas other suppliers did not.

The information system was not written from start to end as one system but organic growth was applied. First the information already available from collaborating failure and research investigations was collected and hyperlinked with the material database, and later other modules were added one by one on request of the users.

The first set-up of the knowledge system was a dedicated standalone PC provided to the technicians of the collaborative power stations. Later on this was changed to an internet based information system based on Wiki technology and was available to all employees of the collaborative power stations. It proved most useful in areas with rapid technical developments such as gas turbines, condensing boilers and rubber coated flue gas desulphurisation systems which were new technology to power stations technicians.

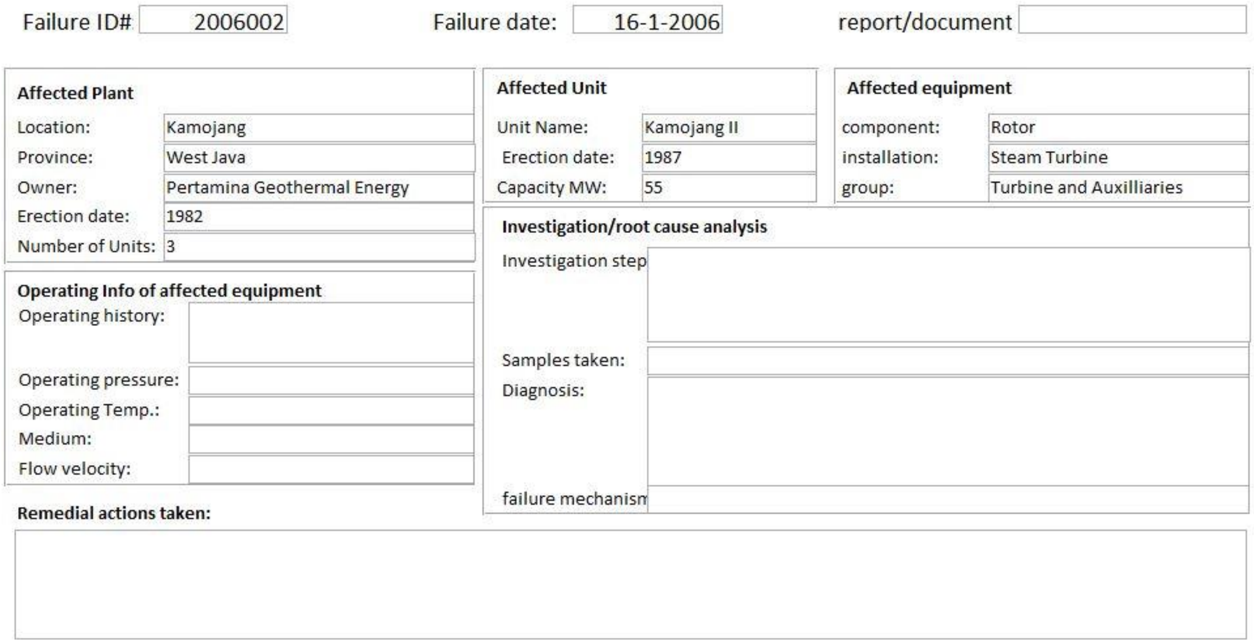
As part of the knowledge system it was tried to develop reason based expert tools even using fuzzy logic and neural networks but the development costs of these systems proved too high for their benefit as these could only be designed for areas with mature technology in which power station technicians already felt secure.

3.2 RECOMMENDATION FOR A SIMILAR KNOWLEDGE BASE ON GEOTHERMAL POWER IN INDONESIA

For the situation of geothermal power stations in Indonesia one could image that a list of available power stations is drawn up with general information such as electrical output, heat exchange principle, type of steam turbine, type of generator and transformers, commissioning date. A list of failures encountered as well as a list of investigated failures with the final reports. A list of outages with internal and external inspection reports of these outages. A list of maintenance companies used by the power stations and the inspection and repair techniques available via these companies and the track record of these companies as service provider for the geothermal plants. The repair technique could be explained and when different are available the advantages and disadvantages will be provided. A list of local companies providing RCA services can also be included with examples of their reports and a list of contact persons and the testing and inspection techniques can be included.

Figure 3.4 Map of geothermal development in Indonesia

For the listing of the relevant failures a data sheet was drafted which included the relevant information to be stored per failure:



Failure ID# 2006002 Failure date: 16-1-2006 report/document

Affected Plant

Location: Kamojang
Province: West Java
Owner: Pertamina Geothermal Energy
Erection date: 1982
Number of Units: 3

Affected Unit

Unit Name: Kamojang II
Erection date: 1987
Capacity MW: 55

Affected equipment

component: Rotor
installation: Steam Turbine
group: Turbine and Auxilliaries

Operating Info of affected equipment

Operating history:
Operating pressure:
Operating Temp.:
Medium:
Flow velocity:

Investigation/root cause analysis

Investigation step
Samples taken:
Diagnosis:
failure mechanism

Remedial actions taken:

Figure 3.5

4 CONTENT AND USE OF FAILURE DATABASES

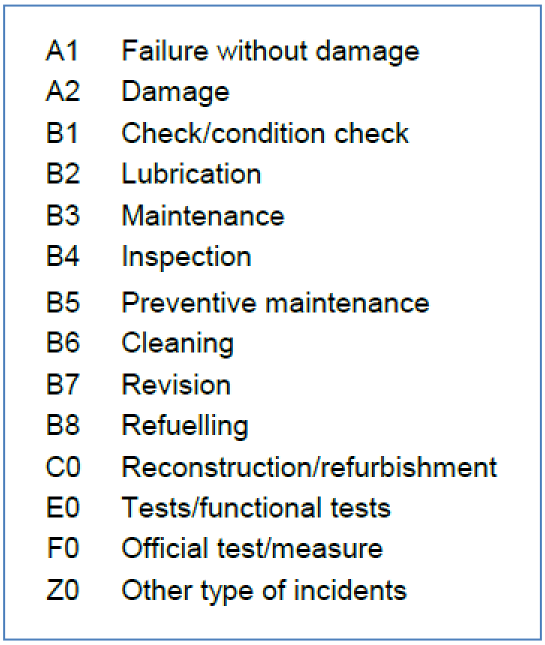
4.1 BACKGROUND

It is understood that a failure database for GeoCap to record failures of geothermal plant(s) is hampered by uncertainty on what events to record in the database, the effort to enter events and the benefit of such a database. This is quite common and can be remedied by explanation of the purpose and benefits, as has been carried out for conventional power plants before. For nuclear power plants, such data have to be entered as requested by the regulator however the amount of detail for nuclear is much larger than for conventional plant(s) therefore while learning from nuclear is paramount, the setup for a nuclear database should not be copied for other types of plants.

4.2 DIFFERENCE BETWEEN A DATABASE TO RECORD FAILURES AND TO RECORD DAMAGE INVESTIGATIONS

Plant failures are all events where a plant delivers less power than being able to, based on an agreed power level which usually is less than nameplate power. As defined by VGB Powertech, as part of its EMS-coding (EMS = Ereignis Merkmal Schlussel, translated as Event Type Code), for each component given by its KKS-code (KKS = Kraftwerk Merkmal Schlussel) once it causes a power loss, the event should be recorded. From figure 1 it will be

clear that failure without damage (such as a trip because of an operator error) or a damage (such as a superheater failure) are different. The recording of events allows to pinpoint the majority of components causing forced unavailability and the EMS codes hint at the measures for improvement. Not all events warrant detailed investigations. To this purpose, VGB makes a yearly report of total unavailability per plant type and of components in plants causing forced unavailability. Definitions are given in the so called VGB Booklet 3. The definitions make sure that the forced unavailability results for 1 plant can be compared with other plants inside and outside the company. A database such as the VGB database allows analyzing more failures than those having occurred at only 1 plant as some components have only a moderate probability to fail in 1 plant such as a stepup transformer. However it may pay to take precautions to prevent such failures at the plant under consideration.



A1	Failure without damage
A2	Damage
B1	Check/condition check
B2	Lubrication
B3	Maintenance
B4	Inspection
B5	Preventive maintenance
B6	Cleaning
B7	Revision
B8	Refuelling
C0	Reconstruction/refurbishment
E0	Tests/functional tests
F0	Official test/measure
Z0	Other type of incidents

Figure 4.1 VGB's EMS codes for type of events

In a database for damage investigations, clearly only a subset of failures related to plant unavailability is recorded namely those failures with damage and usually only those failures investigated in some detail. The DEKRA AIM = Asset Integrity Management department and its predecessors at DNV GL and KEMA have operated such a database on behalf of the Dutch electricity power producers for decades. It can still be accessed and contains failure investigations by the department and failure investigations by the producers that they found important enough to be documented. The purpose of a damage investigation usually is to find the direct cause of the damage and the purpose of a damage investigation database is to see if similar damages have occurred that may help to explain the cause under investigation and, given a significant number of such damages, set up projects to remove the cause. A direct cause (for instance a tube failure due to wall thinning related to insufficient boiler water quality) should be differentiated from a root cause (in the example insufficient attention for boiler water quality despite many recommendations for improvement earlier in time). A root cause is the cause that could have prevented the failure AND other failures, only in a limited number of failure investigations for power plants in practice root causes are investigated.

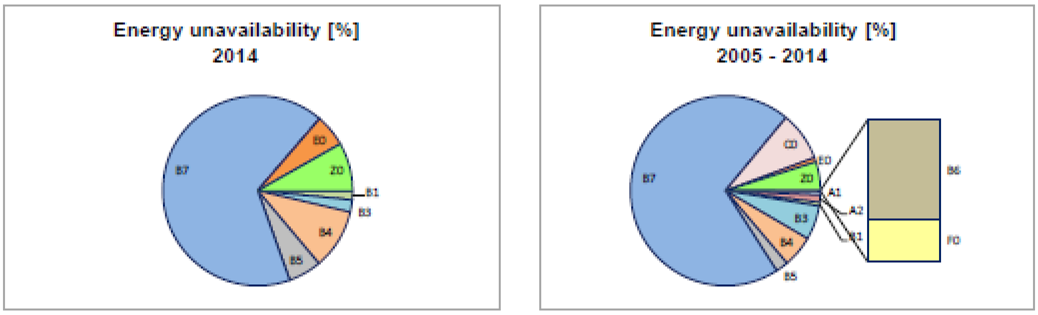
4.3 EXAMPLE OF A FORCED UNAVAILABILITY DATABASE

The prime example is VGB’s KISSY database and an example of its recording is shown in figure 2. Please note the KKS-coding for components and the EMS-coding (limited to codes EMS41 and 42 only) to record circumstances and causes.

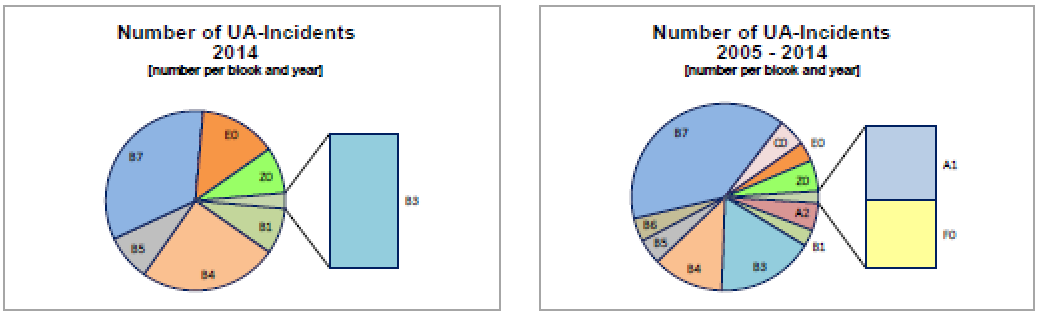
Unit Name	Begin[Date]	Begin[Time]	End[Date]	End[Time]	Capacity Power plant	Unavailable Capacity [%]	Unavailable Energy [MWh]	KKS	EMS1 code	EMS41 code	EMS42 code	Comment	Type of power plant
27	29-8-2008	21:23	16-9-2008	7:33	5: 600 - 999 MW	96.15	365895.834	999	B7 - Revision	K - Jahresstillstandsprogramm	4 - Stillstand	Revision	Fossiler Block Mono
27	17-1-2003	19:09	18-1-2003	2:16	5: 600 - 999 MW	95.05	6155.916	BAB	A2 - Schaden	A - Automatischer Lastabwurf/Schnellschluss	4 - Stillstand	Ausfall wegen eines defekten Spannungswandlers im Generatorschutz	Fossiler Block Mono
27	17-4-2011	2:17	17-4-2011	3:41	5: 600 - 999 MW	96.15	1225.001	BAT	B5 - vorbeugende Instandsetzung	C - Geordnete Abfahrt innerhalb von 12 Stunden	2 - Leistungseinschränkung	OM Entnahme Ölprobe Maschinentrafo	Fossiler Block Mono
27	28-6-2002	2:45	28-6-2002	8:29	5: 600 - 999 MW	73.08	3812.666	BBB	A1 - Störung ohne Schaden	A - Automatischer Lastabwurf/Schnellschluss	2 - Leistungseinschränkung	Erdschlussauslösung Saugzug 2	Fossiler Block Mono
27	13-7-2010	18:07	14-7-2010	2:04	5: 600 - 999 MW	96.15	6956.251	BFB	A1 - Störung ohne Schaden	A - Automatischer Lastabwurf/Schnellschluss	4 - Stillstand	Ausfall Schaltanlage	Fossiler Block Mono
27	13-11-2011	14:28	13-11-2011	16:11	5: 600 - 999 MW	96.15	1502.084	BFB	A1 - Störung ohne Schaden	B - Manueller Lastabwurf/Schnellschluss	4 - Stillstand	Störung Einspeiseschalter BFB	Fossiler Block Mono
27	6-5-2003	5:42	6-5-2003	7:13	5: 600 - 999 MW	95.05	1311.916	CJA	A1 - Störung ohne Schaden	A - Automatischer Lastabwurf/Schnellschluss	4 - Stillstand	Störung Dampfkreislauf (Enthalpieregler)	Fossiler Block Mono
27	6-7-2005	17:23	6-7-2005	17:41	5: 600 - 999 MW	72.53	198.001	CJA	A1 - Störung ohne Schaden	A - Automatischer Lastabwurf/Schnellschluss	4 - Stillstand	Ausfall nach Störung in zweiter Mühle	Fossiler Block Mono

Figure 4.2 Raw KISSY data input

Plants are made anonymous. A free text column (Comment) is used to record some technical details of the failure. By contacting VGB, a subset of data will be made available at limited costs (no profit) once a member contributes to the database. For non-members or non-contributors, costs are to be agreed with VGB. In the yearly report made available to the general public, standard tables per type of plant are presented such as figure 3 and figure 4 (report 2016 is pending).



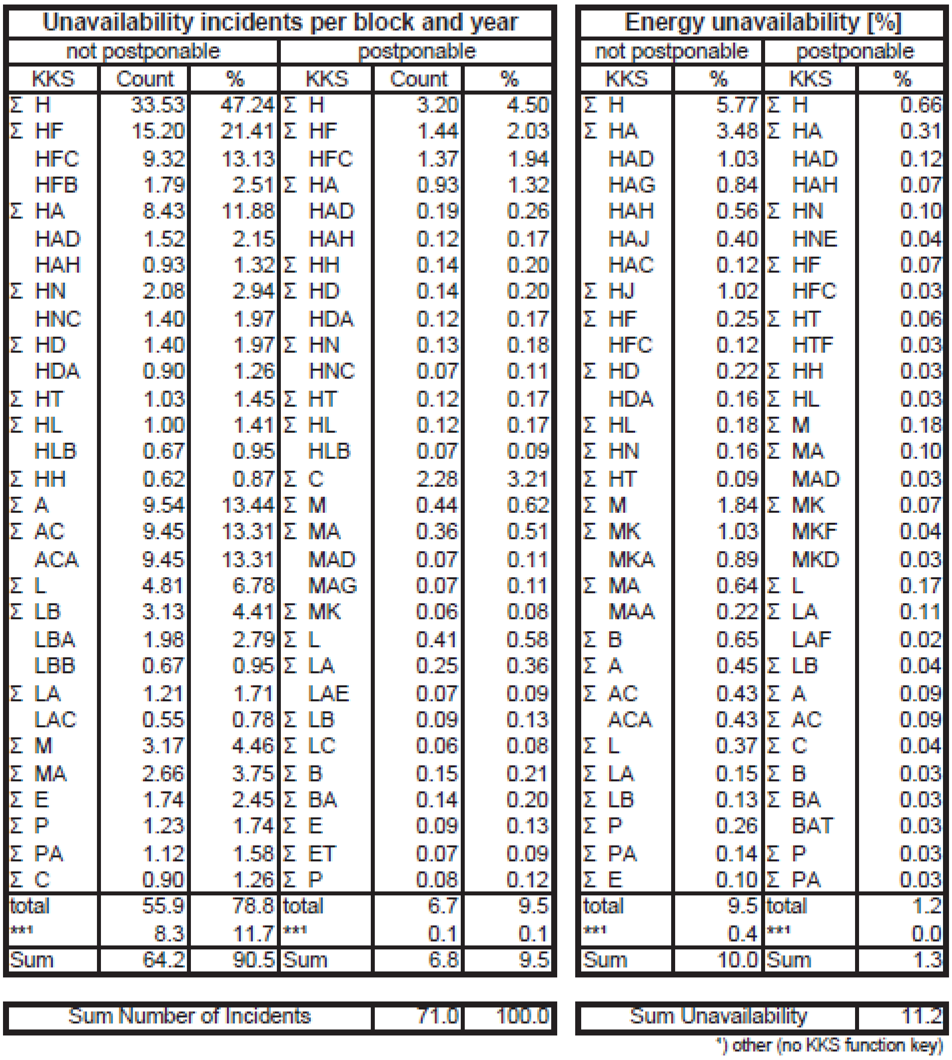
	EMS 1	Units	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	C0	E0	F0	Z0
Energy unavailability [%]	2014	21	0.00	0.00	0.09	0.00	0.11	0.56	0.31	0.00	3.66	0.00	0.00	0.30	0.00	0.45
	2005 - 2014	54	0.06	0.11	0.06	0.00	0.52	0.48	0.19	0.01	6.26	0.00	0.74	0.07	0.00	0.43
Unavailability incidents per block and year	2014	21	0.00	0.00	0.14	0.00	0.05	0.43	0.00	0.00	0.57	0.00	0.00	0.24	0.00	0.14
	2005 - 2014	54	0.03	0.15	0.09	0.00	0.52	0.38	0.13	0.12	1.20	0.00	0.15	0.10	0.03	0.16



Types of incidents of planned unavailability (EMS 1)

A1	Failure without damage
A2	Damage
B1	Check/condition check
B2	Lubrication
B3	Maintenance
B4	Inspection
B5	Preventive maintenance
B6	Cleaning
B7	Revision
B8	Refuelling
C0	Reconstruction/refurbishment
E0	Tests/functional tests
F0	Official test/measure
Z0	Other type of incidents

Figure 4.3 EMS-codes in yearly VGB report



Unavailability incidents per block and year					
not postponable			postponable		
KKS	Count	%	KKS	Count	%
Σ H	33.53	47.24	Σ H	3.20	4.50
Σ HF	15.20	21.41	Σ HF	1.44	2.03
HFC	9.32	13.13	HFC	1.37	1.94
HFB	1.79	2.51	Σ HA	0.93	1.32
Σ HA	8.43	11.88	HAD	0.19	0.26
HAD	1.52	2.15	HAH	0.12	0.17
HAH	0.93	1.32	Σ HH	0.14	0.20
Σ HN	2.08	2.94	Σ HD	0.14	0.20
HNC	1.40	1.97	HDA	0.12	0.17
Σ HD	1.40	1.97	Σ HN	0.13	0.18
HDA	0.90	1.26	HNC	0.07	0.11
Σ HT	1.03	1.45	Σ HT	0.12	0.17
Σ HL	1.00	1.41	Σ HL	0.12	0.17
HLB	0.67	0.95	HLB	0.07	0.09
Σ HH	0.62	0.87	Σ C	2.28	3.21
Σ A	9.54	13.44	Σ M	0.44	0.62
Σ AC	9.45	13.31	Σ MA	0.36	0.51
ACA	9.45	13.31	MAD	0.07	0.11
Σ L	4.81	6.78	MAG	0.07	0.11
Σ LB	3.13	4.41	Σ MK	0.06	0.08
LBA	1.98	2.79	Σ L	0.41	0.58
LBB	0.67	0.95	Σ LA	0.25	0.36
Σ LA	1.21	1.71	LAE	0.07	0.09
LAC	0.55	0.78	Σ LB	0.09	0.13
Σ M	3.17	4.46	Σ LC	0.06	0.08
Σ MA	2.66	3.75	Σ B	0.15	0.21
Σ E	1.74	2.45	Σ BA	0.14	0.20
Σ P	1.23	1.74	Σ E	0.09	0.13
Σ PA	1.12	1.58	Σ ET	0.07	0.09
Σ C	0.90	1.26	Σ P	0.08	0.12
total	55.9	78.8	total	6.7	9.5
*)	8.3	11.7	*)	0.1	0.1
Sum	64.2	90.5	Sum	6.8	9.5
Sum Number of Incidents				71.0	100.0

Energy unavailability [%]			
not postponable		postponable	
KKS	%	KKS	%
Σ H	5.77	Σ H	0.66
Σ HA	3.48	Σ HA	0.31
HAD	1.03	HAD	0.12
HAG	0.84	HAH	0.07
HAH	0.56	Σ HN	0.10
HAJ	0.40	HNE	0.04
HAC	0.12	Σ HF	0.07
Σ HJ	1.02	HFC	0.03
Σ HF	0.25	Σ HT	0.06
HFC	0.12	HTF	0.03
Σ HD	0.22	Σ HH	0.03
HDA	0.16	Σ HL	0.03
Σ HL	0.18	Σ M	0.18
Σ HN	0.16	Σ MA	0.10
Σ HT	0.09	MAD	0.03
Σ M	1.84	Σ MK	0.07
Σ MK	1.03	MKF	0.04
MKA	0.89	MKD	0.03
Σ MA	0.64	Σ L	0.17
MAA	0.22	Σ LA	0.11
Σ B	0.65	LAF	0.02
Σ A	0.45	Σ LB	0.04
Σ AC	0.43	Σ A	0.09
ACA	0.43	Σ AC	0.09
Σ L	0.37	Σ C	0.04
Σ LA	0.15	Σ B	0.03
Σ LB	0.13	Σ BA	0.03
Σ P	0.26	BAT	0.03
Σ PA	0.14	Σ P	0.03
Σ E	0.10	Σ PA	0.03
total	9.5	total	1.2
*)	0.4	*)	0.0
Sum	10.0	Sum	1.3
Sum Unavailability			11.2

*) other (no KKS function key)

Figure 4.4 KKS-codes in yearly VGB report

Please note that a project has been defined to arrive at on-line calculation of reliability data from KISSY such as failure rate per KKS-code, average and standard deviation of repair time, statistical differences between individual plants, statistical uncertainty in failure rate, amount of repeat within 1 week, ageing = increase in failure rate as a function of time, etc. Results for several plant types were already reported in VGB Research project 361, see also the 2015 paper in Kraftwerk Technik.

Databases like KISSY are also present in the US for instance by NERC, however raw data allowing to investigate more details are generally not present in these databases nor in the books resulting from databases (OREDA 2015 for offshore plant, T-Book for nuclear, etc.).

The KISSY database and a similar database used for the Dutch utilities has seen many occasions for fossil power plant betterment as shown in the accompanying reference list.

4.4 SET UP OF A SYSTEMATIC DAMAGE DATABASE

On behalf of the Dutch utilities, a setup was made to systematically classify all existing damage investigation failures by DEKRA AIM and its predecessors and add new failures investigated. In the next, this set up will be explained. However, due to restructurisation in the E-production sector , new failures have not been added yet. The basic idea for setup is shown in figure 5, with implementation in Excel and Acces.

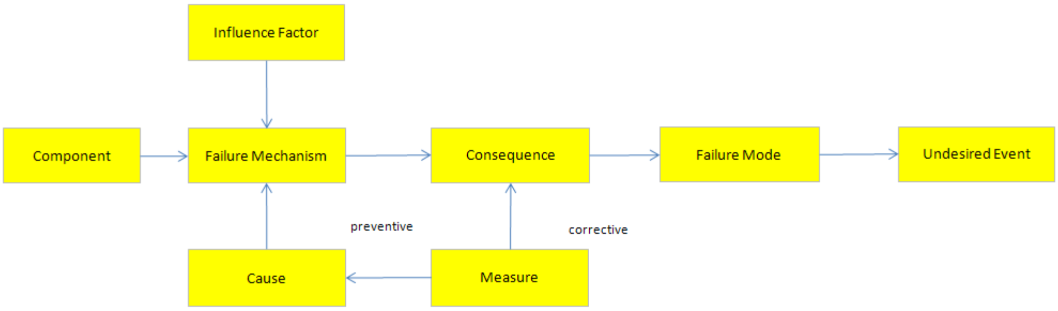


Figure 4.5 Basic idea for setup

For each of the building blocks, a description is given below:

- <u>Component:</u> 3 digit KKS-code for component on which damage occurred
- <u>Failure Mechanism</u> is the process “fabricating” the damage: thermal fatigue, corrosion, creep, etc.
- <u>Influence Factor</u> makes that a failure mechanism acts more strongly due to the circumstances: “thermal fatigue” occurs during cycling, not during base load
- <u>Cause</u> = direct cause explains WHY the failure mechanism occurs, f.i. due to a design error OR clogging by materials left
- <u>Consequence</u> = direct consequence, f.i. steam leakage or blocking of valve
- <u>Failure Mode</u> = way of failure, f.i. valve cannot move OR moves spuriously OR heat exchanger leaks internally, as based on OREDA coding
- <u>Measure</u> can be preventive (cause is less probable, f.i. boiler water conditioning) or corrective (consequence is less severe, f.i. spare part)

- Undesired event is a short & clear description (f.i. boiler tube rupture plus 3 tubes damaged by steam from rupture OR first row blades severely damaged and 2-nd and 3-rd row “stripped”)

For the failure under investigation, using appropriate coding, it is possible to compare with other damages and analyze whether the damage is an incident only or is comparable with other damages given the failure mechanism, etc. This is shown in figure 6, regrettably in Dutch. In green is the HP turbine (KKS = MAA) failure under consideration with reference S75085, with failure mechanism “vermoeiing” = fatigue. Out of 33 MAA events in the database (containing 515 events in total), 11 are related to fatigue. Similarly, 5 damages, including that under investigation, have as consequence “scheur/gat” = crack / hole. The cause “Ontwerp” = Design is present at four events. This shows the damage under investigation is no incident in general and may occur sufficiently to warrant further actions such as a publication on the subject or recording in a so-called Black Book to prevent damages in future.

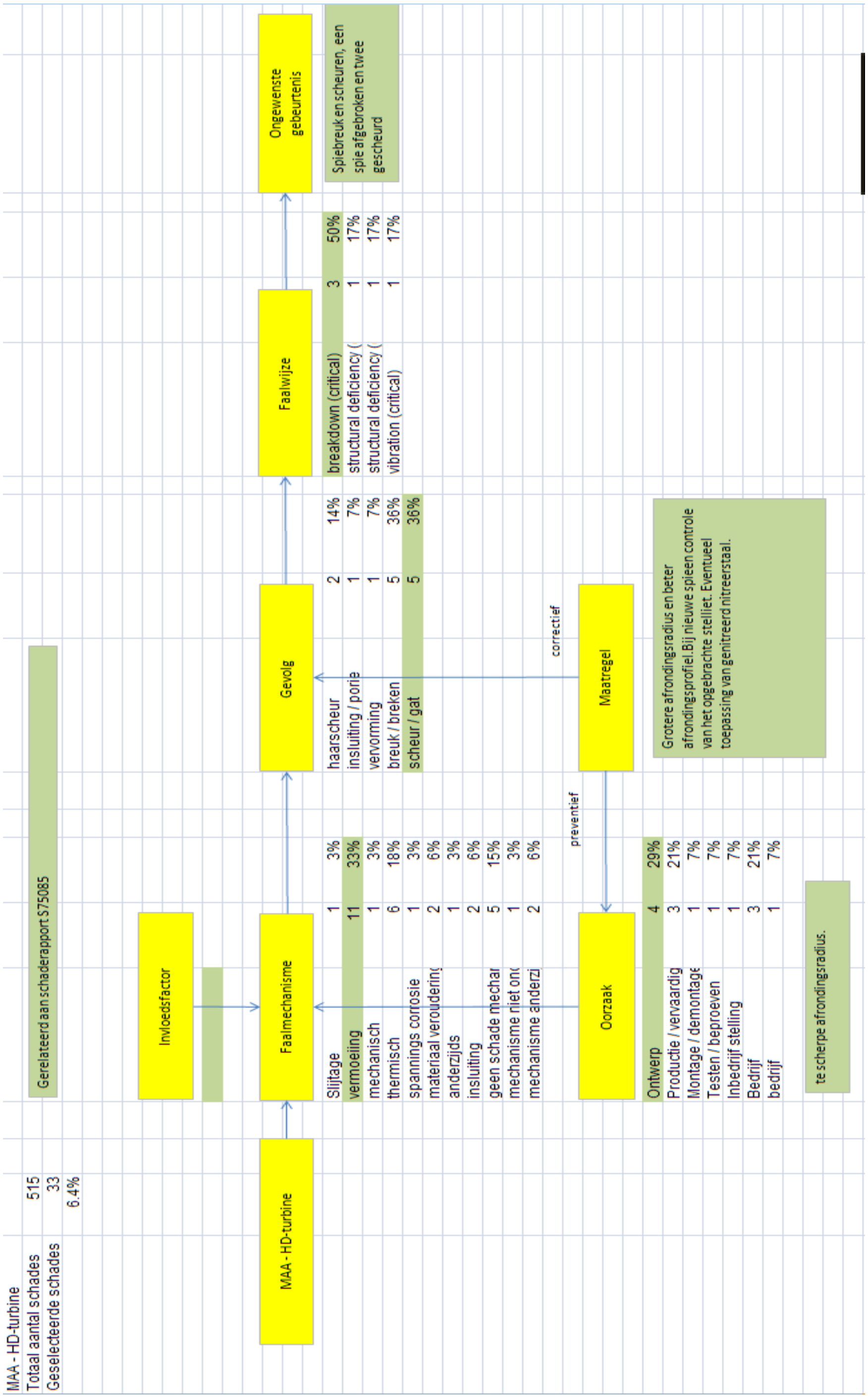


Figure 4.6 Setup in practice

By plotting the time of occurrence of the damage, it can be shown for instance that HP turbine fatigue problems are not limited to teething problems only but may occur even after 100.000 hrs operating time.

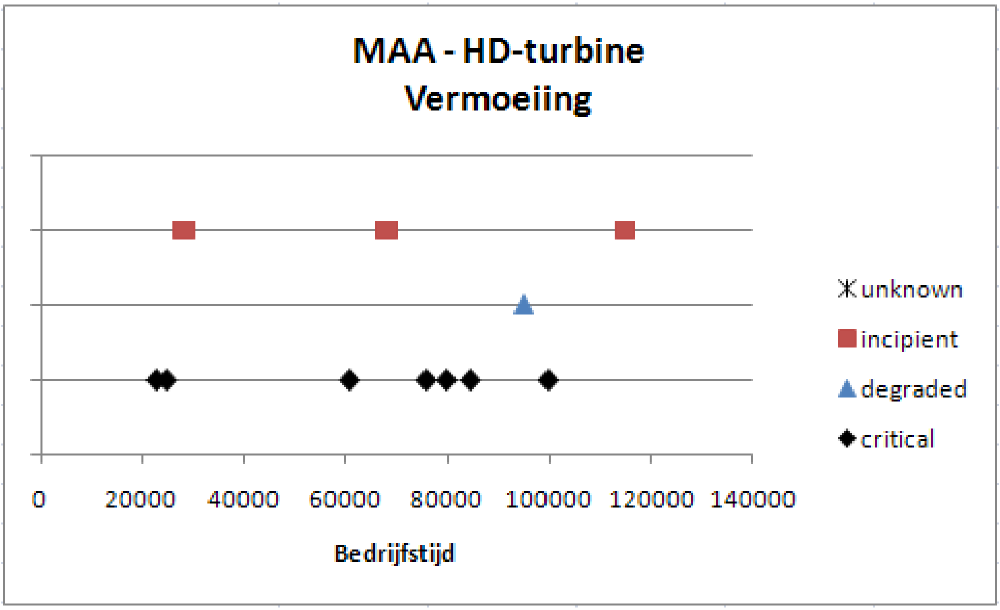


Figure 4.7 Time of occurrence

References:

1) Paper Kraftwerk Technik showing the VGB KISSY database as well as derivation of failure rates and repair time, analysis of ageing, an example of reliability modeling, etc.

2) Paper for ESREDA showing the benefits of RAM data for life extension of power plants in practice

3) Reference list showing applications in the areas of:

- Forecasting plant reliability and forced unavailability
- Whether or not too apply redundancy in a system
- Maintenance optimization
- Spare parts optimization
- RAM = Reliability Availability Maintainability -specification for a new plant
- Life extension optimization