LIFETIME PREDICTIONS FOR CRITICAL PLANT IN GEOTHERMAL ENERGY SYSTEMS

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SUMMARY - Life extension technology is now a firmly established part of the management of thermal power plant, for providing a framework for assessing whether a plant is safe to operate beyond its design life, for scheduling plant maintenance or replacement and for determining the risk of failure of critical plant. Although the major damaging process in geothermal power stations is corrosion rather than creep, as in thermal power stations, this paper discusses how life extension technology can be applied in geothermal stations. Management procedures required to achieve the desired life extension are outlined.

1.0 INTRODUCTION

The demands on plant used to generate electricity from geothermal steam have much in common with the demands on plant used in conventional thermal power stations and petrochemical plant. These include requirements for:

- a high level of reliability
- a high level of availability.

A more recent demand on conventional thermal plant is the option of extending the life of the plant beyond its design life while still maintaining the same level of reliability and availability. Life extension technology is now a firmly established part of the management of thermal power plant. By 1995, sixty percent of the installed power plant in the USA, Europe and Japan will have reached or exceeded its design life (Tack, 1993). Life extension activities can be undertaken:

- to satisfy regulatory bodies that plant is safe to operate beyond its design life
- to determine the need for maintenance or replacement planning
- to determine the risk of failure of critical plant.

Power stations are normally designed for a minimum life which is typically determined from a mixture of qualitative and quantitative assessments of the rate of component damage accumulation, based on an assumption of the worst-case environment and the worst material properties recognised at the time. Failures can occur before the design life if the known data is not adequate or if the design has not correctly accounted for the conditions. However, the actual life of components is often significantly greater than that of the design, ie when component damage accumulation is below that estimated and/or the worst case environment does not eventuate.

Life extension technology involves the integration of condition assessment with models of damage accumulation. The aims of the technology are to identify critical components and locations on the components where damage accumulation is likely to be at a maximum, to optimise inspection and testing methodologies used to determine actual damage and subsequently to predict the remanent life of the critical components with a view to extending the life beyond the intended design life. Implementation of the technology required to achieve life extension involves a number of phased activities with movement from one phase to the next being determined by a combination of engineering and economic considerations.

The purpose of this paper is to examine the management philosophies and practices involved in life extension technology and to promote their application to geothermal power stations.

2.0 PHASES OF LIFE EXTENSION

The practice of life extension in thermal power stations is often carried out in phases such as are outlined in BSI PD 6510:1983 which deals with high temperature service and BSI PD 6493:1991 which describes levels of assessment for potential failure mechanisms such as fatigue. This same philosophy can be applied in the geothermal power stations.

Phase 1: Life estimation from historical records

This initial phase uses existing records of component history including design data, fabrication details and materials properties through to actual operating conditions and component materials performance to carry out an assessment of the life of a component. This is typically done without any physical examination by comparing the worst case situation used in the design with actual known data from traceable records that are obtained from routine plant monitoring. The data can then be compared with recognised models of damage accumulation to give a statistical lower bound for predicted life.

A Phase 1 assessment can be used to identify critical components and to optimise any inspection programmes. It is important that a Phase 1 assessment is carried out at a relatively early stage in the life of plant so that the information produced can be used to tailor the plant monitoring needed. For many components the estimated lifetime will exceed the design life and/or the desired life and in these instances additional effort may not be required. Where the remaining life is less than desired or the risk of failure is high then the plant engineer has justification in moving to the next phase of assessment or alternatively can initiate plant replacement procedures.

Phase 2: Life estimation from damage assessment using NDE inspection

Phase 2 assessments use NDE (Non Destructive Examination) techniques to determine with greater accuracy the extent of damage and consequently provide a refined estimate of remaining life. Actual damage can be compared with existing damage model predictions and provided the differences are not great the models can be considered valid. Phase 2 activities provide the plant engineer with information necessary to optimise future inspection requirements, their frequency and their cost. A strategy can then be formulated as to whether plant life can be economically extended past the design life and, if and when repairs or replacement are required.

Phase 3: Life estimation from damage accumulation modelling

Where the data obtained as a result of the Phase 2 assessment is of insufficient accuracy or the results suggest greater damage than predicted by existing damage accumulation models, it may be necessary to carry out additional component surveillance or site examinations of a destructive name. Alternatively additional testing either on-line or in a laboratory simulation may be done to develop refined damage models. This type of work is conducted in the Phase 3 part of the strategy and again cost benefits for doing the work can be based on reasoned arguments having a sound basis in measured data and previously developed damage models.

Although this phase is the last to be formally initiated the life of a critical item can only be extended if the processes causing the damage are well understood long before the end of the design life. Information on which the design was originally based must be correctly archived for critical applications and in those instances where damage accumulation models are poorly defined work on life extension should ideally be started before a plant is commissioned.

3.0 PHASED LIFE EXTENSION ASSESSMENTS IN GEOTHERMAL PLANT

Figure 1 illustrates the three phases of life extension assessment as they might be applied in a geothermal plant. The figure illustrates Phase 1 life estimation assessments including the need for good quality traceable records and a sound understanding of existing damage accumulation models, Phase 2 condition assessments using NDE inspections and on-line monitoring and Phase 3 models of damage accumulation developed and refined through collection of performance and research data. The figure concentrates on problems associated predominantly with geothermal corrosion but engineers will encounter a range of problems common to all energy production plant such as occur with pumps, generators and heat exchangers to name but a few.

3.1 Phase 1 Life Estimation Assessments

There is a need to establish and maintain ***traceable records*** of all plant component parameters which influence long term performance. The component database should include:

- materials selection reports and corrosion and scaling chemistries on which they were based
- materials property information available for the component when it went into service, ie obtained fiom the component manufacturer
- records of component environment exposure, operational stress, temperature, pressure and steam/water chemistry from plant operating records
- inspection results: location and date, type of inspection and results
- monitoring results: location and date, type of monitor and results
- failure investigation reports
- literature and publications describing performance of plant in similar applications.

It is essential to link on going plant failure analysis investigations with plant condition life assessment and to correctly archive plant records. A reliable database management system providing access to these records is a non trivial and vital consideration. An essential but often overlooked requirement for this database is the collection and ordering of technical reports, journal publications, standards and text books.

There is a need to ***identify the critical items*** within a geothermal plant for which life assessment and extension is economically justifiable. Required tasks are outlined in Table 1.

A Phase 1 assessment in a geothermal plant would require a listing of all the components and the environments to which they are exposed, see for example the listing in Table 2. Worst case corrosion chemistries can be estimated or based on regular analysis of the fluid chemistry and an understanding of start-up and shut-down conditions when *air* is present. Known corrosion processes and models describing these processes for the worst case corrosion chemistries can be used to predict damage accumulation expected on critical plant. This information can then be used to identify the conditions under which failure is unlikely, possible or likely - Table 2 for example identifies the expected mode of failure of components fabricated from stainless steel where **mixing** of air with geothermal fluids by design or by accident significantly increases the corrosivity of the fluid.

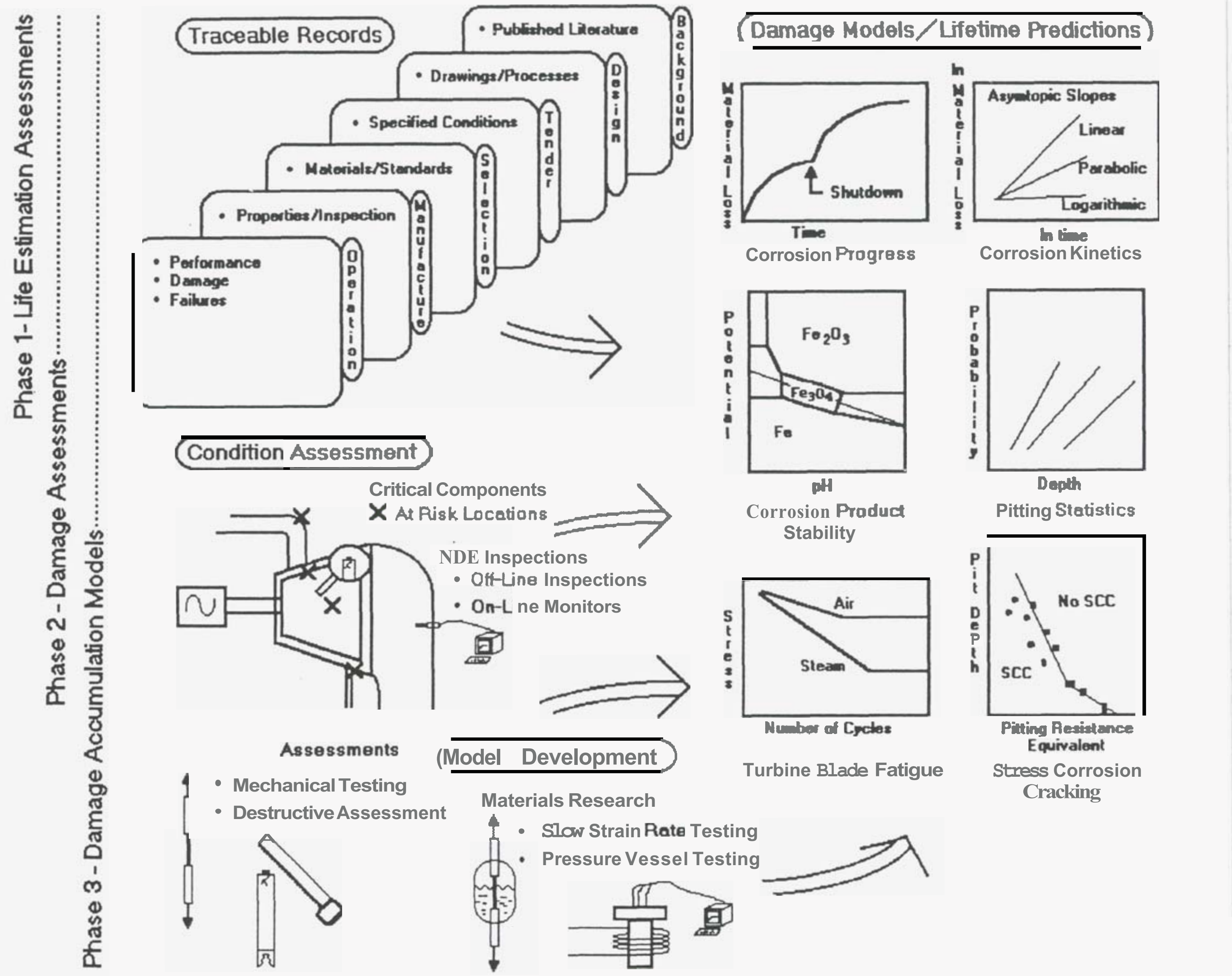

Figure 1 - Illustration of Phases of Life Extension Technology Applied to Geothermal Power Stations.

Non-metallics including concrete and polymeric materials can also be subjected to this same analysis methodology and indeed for some environments very little is known of the performance of these materials.

Damage accumulation models for conventional thermal power stations are related to the major damaging processes; creep, high temperature oxidation, fatigue and corrosion. Creep is the most significant of these as large portions of the plant are exposed to temperatures in excess of 400°C where creep is the predominant mode of failure (Cane and williams, 1987).

In geothermal power stations corrosion and corrosion related damage processes are the most important to consider; creep of steels is not considered to be a problem as the maximum temperature is about 180°C. Damage can be in the form of corrosion, erosion-corrosion, stress corrosion cracking, wear, fatigue and scaling to name but a few. Mechanistic models for corrosion processes for a range of geothermal chemistries encountered in New Zealand and overseas are now available (Lichti and Wilson, 1983, Lichti *et al.,* 1984, Astrawinata, 1989, Wilson and McIlhone, 1992). These models generally allow a qualitative or semi quantitative estimate of the rate of damage accumulation. Scaling models are also available (Henley, 1981) and in recent times scaling inhibitors have been successfully applied to geothermal fluids (Robson and Stevens, 1989).

Models for other damage and failure mechanisms are readily available in the materials literature, for example damage as a result of fatigue cracking from defects *can* be assessed using BSI PD 6493:1991. Although this procedure refers to welded structures, it can be used on other structures where defects are a problem. One qualification to the use of BSI PD 6493:1991 is the need to have fatigue data relevant to the specific environment and this is often not available for geothermal environments.

Understanding of these damage models can aid in conducting reliable condition assessment of critical components, adding to accumulated knowledge of component history and material properties. The models

Table 1 - Tasks Required in the Identification of Critical Items for Phase 1 Assessments.

Tasks	Comment
1) Listing of items critical to the long term performance within geothermal plant	Collected data should include: • alloys used • operational parameters • operating environment • inspection time interval
2) Identify industry practise	Collected information should include: • Modes of failure • Expected life • Possibility of extension of life
3) Establish priorities and estimate the current cost of inspection or monitoring	Quantifies the scope and cost of inspections required for life extension
4) Independent consultation	Provides second opinion

Table 2 - Worst Case Assessment of Performance of Stainless Steel Components Exposed to Geothermal Steam

Component	Extent of Exposure, to Aeration	Significant Parameters'	Likely Mode of Corrosion
Turbine Blades	intermittent: at start-up and shut-down	time of wetness	pitting corrosion followed by corrosion fatigue during operation
Valve Stems	continuous	wear of valve stem seals	pitting corrosion; corrosion fatigue cracking
Condensing and Cooling Plant	continuous	stagnant areas; biofilms	pitting corrosion; stress corrosion cracking
Gas Extraction System	continuous	stagnant areas; sulphur deposition	pitting corrosion; stress corrosion cracking
Auxiliary Cooling System	continuous	biofilm formation; standby conditions	pitting corrosion
Steam Pipework Expansion Joints	intermittent	time of wetness at shutdown	pitting corrosion followed by corrosion fatigue during operation
Gland Steam Condensers	continuous		pitting corrosion; stress corrosion cracking

[a] For all components, the chemical composition and temperature of the fluids are significant parameters.

help to identify critical locations expected to experience maximum damage accumulation and thereby allow geothermal plant operators to select optimum condition diagnosis and monitoring techniques.

3.2 Phase 2 Damage Assessments

Phase *2 condition assessments* are generally based on plant off-line inspection and statistical diagnostic techniques. For geothermal plant this would typically require chemistry monitoring of the environment to which plant components are exposed together with NDE techniques for assessing the condition of the plant. Monitors for corrosion and scaling in geothermal plant are readily available (Lichti and Wilson, 1983, Inman *et al.*, 1992, Brown and McDowell, 1983), however the use of on-line monitors as a means of identifying problem areas is not commonplace. For most geothermal plant., corrosion and scaling chemistries are identified prior to process design and materials selection and simple chemistry monitoring is conducted once the plant is in operation to ensure conditions do not become excessively damaging.

NDE techniques used in conventional thermal power stations for defect assessments, such as ultrasonics and eddy current techniques are readily available and the effects of defects can be assessed using for example BSI PD 6493:1991. This recommended practice can also be used to determine the defect sizes and defect locations which have to be located to define the NDE technique to be used.

Phase 2 damage assessments, see Table 2, could involve measurement of the depth of pitting corrosion or extent of cracking using non destructive evaluation such as optical, eddy current or ultrasonic techniques which provide an assessment of the current condition of the plant, These results will give a measure of the actual corrosivity of the environment which can be compared with the worst case environment assumed during design. As a result, a better estimate of corrosion rates and consequently, the life before failure can be obtained.

There is a need to improve NDE methodologies in geothermal power stations. Typical improvements which can be made are in selected use of on-line corrosion monitors as well as video imaging/recording, noise analysis, stress analysis, chemistry sampling and determination of on-site microstructural information.

If the plant is experiencing trouble free operation, Phase 1 and Phase 2 type assessments are generally sufficient for geothermal plant. In the absence of such assessments early in life, the cost of plant failures may be higher. Traceable records may be inadequate to determine the cause of damage or to make accurate predictions. It may be possible to generate additional data when a failure is imminent using on-line monitoring but often the risk of unscheduled down-time, once an unexpected problem is identified, necessitates immediate component replacement.

3 3 Phase 3 Damage Accumulation Models

Phase 3 assessment requires the ***development of robust models*** of damage accumulation involving research under controlled conditions coupled with detailed condition assessment of critical components. A life extension programme designed to provide alloy performance information under controlled conditions and generating mechanistic models is an efficient method of providing high quality information especially if it is linked with on-going in-situ investigations of alloy performance. The expertise required for a life extension programme includes corrosion and metallurgical expertise relevant to geothermal plant and knowledge of plant operation characteristics. The latter information can only be provided by geothermal plant operators and hence a partnership or team approach is required to achieve optimum results.

Materials testing and research activities required for reliable life prediction include:

- metallographic preparation and examination with optical or electron microscopy of corrosion products, scales and base material removed from damaged plant
- mechanical testing of material removed from damaged plant to a range of BS, ASTM, ASME, DIN or JIS standards
- statistical characterisation of corrosion damage and integration of these results into theoretical models
- development and revision of theoretical models of damage processes based on results obtained under controlled conditions using for example:
  - the slow strain rate testing technique for stress corrosion cracking
  - corrosion testing in pressure vessels, ie to 250°C to accurately simulate actual operating conditions
  - fracture mechanics tests for determining critical defect size, ie fracture mechanics tests such as CTOD and K_{IC}
  - fatigue crack propagation data, ie da/dn vs ΔK.

An example would be to remove a turbine blade (*see* Figure 1 and Table 2) for metallurgical examination to determine the type of corrosion product being formed, to characterise any pitting corrosion and possible corrosion fatigue cracks initiating fiom corrosion pits. This could then be extended further to carry out laboratory corrosion tests if the mode and rate of damage accumulation did not follow existing models.

3.4 Research needs for Life Extension

The technology associated with the extension of life of geothermal plant life is of interest to plant operators around the world. Geothermal research activity related to damage models is undoubtedly being pursued in a number of countries and occasionally this is being published (Astrawinata, 1989, McIlhone and Wilson, 1992, Kurata *et al.*, **1992).** However, the major thrust in research on life extension strategy is in thermal power plants (Cane, 1991). Extension of this research to geothermal plant is expected to accelerate as large numbers of geothermal plant commissioned in the 1980's move closer to their design lifetimes (*see* for example Stacy and Thain, 1983). The value of such a programme includes:

- generation of life extension technology which is needed for the operational practices and conditions peculiar to geothermal plants
- provision of an independent check on manufacturers information and test methods
- generation of specific information on materials used in geothermal plant.

Currently, serious corrosion problems receive an immediate response in geothermal power plant, but there is seldom a systematic review of likely damage mechanisms before such problems are discovered. The methodology for conducting such reviews to avoid the surprise onset of serious corrosion problems is addressed by activities outlined above. Carrying out these activities will provide plant operators with the potential for substantially extending life of existing plant.

Efficient communication between geothermal plant operators, research institutes and other consultants is essential to ensure a continuing exchange of experience and knowledge. This can be achieved by a regular series of publications and seminars:

- publication of research reports from consulting agencies
  - new inspection techniques
  - new damage accumulation models
  - reviews of component performance
- geothermal plant condition assessment reports
- summaries of failure investigations
- utilisation of annual workshops to review activities.

4.0 CONCLUSIONS

Activities required for the application of life extension technology to geothermal power generation plant can be divided into three phases:

- Phase 1 Life Estimation Assessments
  - determining and providing traceable records of operational parameters and component material properties
  - reliable condition assessment of critical components using damage models to identify critical locations suffering maximum damage accumulation, optimum condition diagnosis techniques and knowledge of exposure history and material properties
  - prediction of remanent life of critical components through integration of damage models, optimum condition diagnosis corrosion/scaling chemistry history and material properties
- Phase 2 Damage Assessments
  - development and selection of both on-line and off-line damage monitoring, NDE plant inspection and statistical diagnostic techniques
  - revised prediction of remanent life of critical components through actual condition assessment, confirmation of damage accumulation models, corrosion/scaling chemistry history and material properties
- Phase 3 Damage Accumulation Models
  - destructive assessment of selected plant component parts
  - research using on-line monitors and laboratory simulation tests for the study of corrosion problems
  - development and revision of mechanistic models for damage processes and damage accumulation.

The application of life extension technology can have immediate benefits in meeting safety requirements, optimising plant maintenance and equipment replacement programmes and utilisation of plant to its ultimate lifetime. Long term confidence in the reliability of plant is reinforced as damage accumulation models are revised and proven.

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