

# APPLICATION OF RISK BASED INSPECTION METHODOLOGY TO PNO-C-EDC GEOTHERMAL FLUID COLLECTION AND DISPOSAL SYSTEMS: A PROGRESS REPORT

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## ABSTRACT

*A methodology has been developed for completing a plant risk assessment for geothermal fluid collection and disposal systems (FCDS) with a view to applying the principles of risk based inspection to the plant asset management practices. The joint Australian Standard/New Zealand Standard, AS/NZS 3788 Pressure Equipment - In-Service Inspection, is the base resource document for the work. The plant risk assessment assigns each individual component within the plant a risk rating, which allows plant inspection and maintenance to be targeted and prioritised, both during operation and at scheduled shut downs. The plant risk assessment is developed by quantifying the likelihood of corrosion and metallurgical damage, which has already, or is likely, to occur. Secondly the consequence of this damage occurring is quantified in terms of commercial, safety and environmental factors. A methodology has been developed for combining these likelihood and consequence ratings to give an overall risk rating for each component in the plant. This Phase 1 assessment of a three phase Risk Based Inspection programme provides a rigorous analysis on which to base an initial prediction of the remaining life of the individual components being assessed. The immediate advantages are an ability to predict which items require detailed condition inspection, which are likely to require maintenance or replacement in a given timescale and which are suitable for immediate life extension beyond their design life. This has obvious cost benefit implications for the optimised and prolonged operation of the plant.*

order to improve the plant reliability and life prediction capabilities. An application by Materials Performance Technologies (MPT) and PNO-C Energy Development Corporation (EDC) for funding support for this programme from New Zealand Ministry of Foreign Affairs and Trade (NZMFAT) Asia Development Assistance Facility (ADAF) was formally approved in July 2000. ADAF is a part of New Zealand's Official Development Assistance (NZODA) programme which is run by the New Zealand Ministry of Foreign Affairs and Trade. The ADAF support provides for MPT technology transfer to PNO-C-EDC with the overall objective being to enhance the development of rural Philippine communities through sustainable cost-effective production of indigenous geothermal energy. The emphasis of this programme is on the maintenance and life extension of aging geothermal energy plant and equipment.

Plant Risk Assessment procedures include a risk assessment from a combination of Likelihood of corrosion and metallurgical damage and the severity of Consequences of failure for example from safety, environmental and commercial considerations. The application of Risk Based Condition Inspection follows for specific combined high-risk plant components for the most likely corrosion and metallurgical damage mechanisms. The objective is to reduce the number of plant components having a combined high-risk rating to low levels by more accurate prediction of the Likelihood or by reducing the Consequences through changes in operational practices. Ultimately a limited number of plant items will be identified for on-going monitoring planned replacement or rehabilitation to reduce the combined risk.

## 1.0 INTRODUCTION

PNO-C-EDC identified a need to implement a **risk** based inspection and plant asset management system for geothermal FCDS in

Procedures outlined in AS/NZS **3788**, AS **4343** and AS **4360** were used to develop the methodology outlined in this paper. MPT and PNO-C-EDC jointly developed the specific procedures used in two Workshops, the first

held in Wellington, New Zealand in October 2000 and the second held in Cebu, The Philippines in December 2000.

Participants in the workshops and others **who** contributed significantly to the preparation of the procedures as outlined in this paper are named in the Acknowledgements for this paper.

The assessment methodology uses a three-phase approach to achieve **Risk Based Inspection (Lichti et al, 1993)**:

- Phase 1 Plant **Risk** Assessment is a paper-based study with limited access to the plant and is based on design data and operation history. The outcome of this phase is to identify the at risk components, the likely damage mechanisms and their locations and to specify the inspection test procedures required to confirm or deny the damage process and the extent of damage. A **risk** profile and life prediction matrix can be prepared from this initial phase.
- Phase 2 involves a focused Condition Inspection effort of the 'at risk' plant and the results of this inspection allow a **refinement** of the risk profile and a more accurate life prediction matrix.
- **Phase 3** effort is designed to provide Monitoring Activities for critical plant with **less than** Ideal life by tracking the damage **accumulation** and factors that cause the **damage**. The aim of these activities is to **extend** the life of the plant even though the damage may exceed original design criteria. Procedures for assessing the risk of failure **from** accumulated localised damage are provided by **AS/NZS 3788** and similar BS and **API** standards.

This paper describes progress achieved in the development of Phase 1 Plant **Risk** Assessment procedures for FCDS.

## 20 PHASE 1 PLANT **RISK** ASSESSMENT

The geothermal FCDS, Phase 1 Plant Risk Assessment is based on:

- The Likelihood of Corrosion and Metallurgical Damage

- The Consequences of Failure – Safety, Environmental and Commercial

The information on which the assessment is based is specific for the lowest level of plant component being assessed. The level used for FCDS in the first instance is Lines (Including Wells, Pipelines and Manifolds) and Vessels.

Lines assessments are focussed on:

- production and reinjection wells
- larger diameter pipelines (ie greater than **100 mm**) from wells to the manifolds and from separator stations to the power plant and to reinjection wells
- two-phase and steam manifolds including those in the separator stations.

Vessel assessments are focussed on:

- separation vessels.

The Likelihood of Corrosion and Metallurgical Damage is determined for collections of common plant items. It is desired to predict the likelihood of surface corrosion and pinhole formation, the likelihood of erosion leading to perforation or rupture, the likelihood of cracking leading to perforation or rupture, and the likelihood of scaling requiring maintenance or compromising production. These assessments are based on:

- Surface Corrosion Damage Models (Uniform, Pitting and Erosion) (Braithwaite and Lichti, **1980**, Lichti et al, **1981**, Lichti and Wilson, **1983**, Lichti et al, **1993**, Lichti, **1995**, Lichti et al, **1997**, Soylemezoglu et al, **1980**)
- Likelihood of Scaling Models (PNOC-EDC Developed Models)
- Stress Corrosion Cracking, Corrosion Fatigue Cracking and Thermal Fatigue Cracking (Lichti and Wilson, **1983**, Lichti et al, **1995**).

Equally important in this assessment is the previous history and experience of the plant and similar plant:

- Maintenance and Operation History
  - 4 Preventive Maintenance
    - ◆ Reactive Maintenance
- Previous Outages
  - ◆ Scheduled (for inspections and maintenance)

- ◆ Unscheduled, (due to failures or downstream factors)
- Operational Envelope Excursions

The Consequences of failure are also considered by the Plant Risk Assessment. The data required to estimate the severity of the Consequences comes from the plant details as outlined above and also from consideration of:

- The Stored Energy
- The Redundancy of Plant
- Population Densities
- Staff Access to Plant
- Eco-System Impact of a Failure.

## 2.1 Likelihood of Corrosion and Damage

### 2.1.1 Surface Corrosion Damage

Available design, chemical, maintenance, operational and environmental data is used as input parameters to established the following models of surface corrosion damage accumulation in geothermal FCDS:

- Surface Corrosion On-Line (based on Chemistry and Known Models)
- Scale Formation (ie Silica) On-Line (based on Chemistry and Experience)
- Surface Corrosion Off-Line (based on Experiments and Experience)
- Pitting Corrosion On-Line (based on Chemistry and Known Models)
- Pitting Corrosion Off-Line (based on Experiments and Experience)
- Erosion Corrosion On-Line (based on Chemistry and Flow Rates As Well As Experiments and Experience)
- External Corrosion (based on Observations)
- Soil Corrosion in Cold and Hot (Geothermal Contaminated) Soils (based on Experiments and Experience)

These models are applied in a theoretical manner to identify the plant items and specific locations of localised high likelihood of damage being greater than or equal to that allowed by the design. The assessment identifies the at-risk plant and by corollary the low-risk plant. Where insufficient knowledge is available to make a realistic assessment the result is classified as normal to high risk so that additional data is collected (in Phase 2) to enable a more accurate prediction. The damage

prediction models are quantitative and hence can predict expected life and remaining life.

Quantification of the Surface Corrosion models is as follows:

$$\text{Material Loss (ML) Compared to } \frac{\text{Corrosion Allowance} \times \text{Years of Service}}{\text{Design Life}}$$

A 3 mm Corrosion Allowance for a 25 year Design Life would allow a Material Loss of 3/25 or 0.12 mm/year. For 17 years of service the Allowed Material Wastage (Material Loss) would therefore be = (3/25)\*17 = 2 mm.

The collection of wall thickness measurements for areas of plant that have experienced corrosion or been the subject of a Condition Monitoring exercise will not be great. However where "Actual" measurements are available then "Actual" rather than "Predicted" damage should be used for the Plant Risk Assessment.

A Likelihood Ranking for Surface Corrosion for a 3 mm Corrosion Allowance would be as follows:

A	= Extreme	ML >> Allowed (ie > 3 mm)	= 100
B	= Very High	ML > Allowed (ie 2 to 3 mm)	= 10
C	= High	ML = Allowed (ie 1 to 2 mm)	= 1
D	= Moderate	ML < Allowed (ie 0.1 to 1 mm)	= 0.1
E	= Low	ML << Allowed (ie < 0.1 mm)	= 0.01

The use of a logarithmic scale is in accord with the level of corrosion predicted, ie corrosion material loss of 1 mm at the usual time of assessment at 50 % of plant life would be considered "High" as for conservative life extension the wastage should be lower.

### 2.1.2 Scaling Requiring Cleaning

Theoretical models for scaling prediction can only be used to give an indication of scaling risk as there are no known relationships between Saturation Index and Scaling Rates. Saturation Index calculations provide a qualitative measure of risk for differing physical conditions where the scaling risk might be High, Moderate or Low. The basic model proposed for Scaling Risk ranking is as follows, allowing for adjustments for turbulent and high heat loss areas by increasing the ranking by one letter or one decade:

Five categories used for Scaling Prediction are:

A	= Extreme	Strongly Saturated (Saturation Index > 1.2)	= 100
B	= Very High	Weakly Saturated (Saturation Index 1 to 1.2)	= 10
C	= High	Saturated (Saturation Index = 1)	= 1
D	= Moderate	Under-saturated (Saturation Index < 1)	= 0.1
E	= Low	Never Predicted	= 0.01

The theoretical predictions of scaling index are supplemented by a knowledge of plant history and in particular scale removal activities. These Actual Scale Removal activities dominate in the Risk Assessment for existing plant with a history of scaling.

The likelihood ranking for Actual Scaling Risk is based on scale removal or cleaning frequency as follows:

A	= Extreme	More than once/month	= 100
B	= Very High	Once / month	= 10
C	= High	Once / year	= 1
D	= Moderate	Once in 10 years	= 0.1
E	= Low	Never Experienced	= 0.01

2.1.3 Likelihood of Cracking

The risk of cracking leading to leaks and rupture can be evaluated from consideration of the fluid being contained, the material used and the predicted and observed failure mechanisms and rate of damage propagation. Prediction of crack initiation is difficult, however, there is growing history of cracking in FCDS and initial quantification of this damage mechanism was based on the available history.

The risk of crack initiation will depend on (see Lichti et al., 1995):

- Materials used for geothermal steam containment systems that are compliant with the NACE Standard MR0175 Standard Material Requirements for Sulfide Stress Cracking Resistant Materials for Oilfield Equipment have a low risk of Sulfide Stress Corrosion Cracking (Sulfide SCC).
- The risk of Sulfide SCC of stainless steels in aerated geothermal environments encountered at shutdown has been modelled as a function of pH, temperature, wetness and material susceptibility.

- The risk of Chloride SCC of stainless steels has been modelled as a function of chloride concentration, oxygen concentration, temperature, wetness, stress levels and material susceptibility.
- The risk of low cycle thermally induced fatigue and high cycle fatigue can be predicted from knowledge of the stress levels and the direction of application of the stress and the likelihood of stress concentration factors, as well as experience of previous failures and a consideration of highest cyclic stress and highest strain locations as being potential sites for crack initiation.

The risk of rupture as a consequence of cracking is related to the location and orientation of the crack, to the pressures encountered and to the material properties around the location of the crack area. The greatest risk is predicted to be for longitudinal areas of cracking and cracking around nozzles (refer AS/NZS 3788). Damage in this orientation is more likely to result in rupture. Damage transverse to the pipe direction, ie in circumferential welds is less likely to result in rupture but may readily leak.

The following historical record based rating was developed for this initial cracking likelihood rating:

A	= Extreme	Cracking Previously Observed, Rupture	= 100
B	= Very High	Cracks Previously Observed, No Rupture	= 10
C	= High	Cracks Observed, No Leak	= 1
D	= Moderate	No Cracks Observed but Cyclic Stress Areas	= 0.1
D	= Moderate	No Cracks Observed but High Strain Areas	= 0.1
E	= Low	No Cracks Observed, No Strain	= 0.01

The observed incidence of cracking was taken from the plant operation and maintenance records but the prediction of cyclic stress and high strain required a review of the design drawings and line and vessel external inspections.

2.1.4 Combination of Corrosion, Scaling and Cracking Damage Likelihood

The combination of Corrosion and Damage factors to give a single Likelihood Ranking to

provide a quantified assessment is as follows (the use of a logarithmic scale allows the values to be summed rather than multiplied):

- Surface Corrosion = 100, 10, 1, 0.1 or 0.01
- Scaling Requiring Cleaning = 100, 10, 1, 0.1 or 0.01
- Cracking = 100, 10, 1, 0.1 or 0.01

Plant Risk Assessment (expressed as a probability from 0.0001 to 1)

$$= \frac{\text{Surface Corrosion (Predicted or Actual)} + \text{Scalina (Predicted or Actual)} + \text{Crackina}}{300}$$

The final resultant probability values of Likelihood are as follows:

Frequent	= A	= 0.3 to 1	Predicted and Observed to Occur
Occasional	= B	= 0.1 to 0.3	Handled by Predictive Maintenance
Infrequent	= C	= 0.01 to 0.1	Predicted to Occur But Not Yet Observed
Rare	= D	= 0.001 to 0.01	May Occur Near the End Of Extended Life
Very rare	= E	= 0.0001 to 0.001	Predicted to Not Occur

Where the resultant combined likelihood has a value between two ratings, the higher rating is used. For example, a value of 0.3 is considered as an A (Frequent) rating.

## 2.2 Severity of Consequences

### 2.2.1 Consequences (Hazard - Safety and Environmental)

The Consequences of Failure (Hazard - Safety and Environmental) can be assessed from considerations of Hazard Rating (from AS/NZS 3788 and AS 4343 - 1999)

- For Vessels (data initially from design drawings)
  - ♦  $pV$  where:  $p$  = pressure in MPa  
 $V$  = volume in Liters
- For Pipelines (data initially from design drawings and specifications)
  - ♦  $pD$  where:  $p$  = pressure in MPa  
♦  $D$  = diameter in mm

- Adjustments to the above calculations are outlined in AS 4343 for:
  - ♦ Process Fluid Properties
  - ♦ Population and Staff Access
  - ♦ Specific Plant Details
- The rating is numerical but can be graphically related to a letter ranking as outlined in AS4343 - 1999:
  - ♦ A = High
  - ♦ B = Average
  - ♦ C = Low
  - ♦ D = Extra Low
  - ♦ E = Negligible

A variation of the hazard calculation in AS4343 was developed whereby the environment was considered as being at risk in the same way as a person. The hazard ratings are kept at the calculated level (based on p, V and D) for two-phase and brine processes but are reduced for plant containing steam and condensate.

### 2.2.2 Final Consequences (Hazard - Safety and Environmental)

The final Consequences (Safety and Environmental) Hazard Rating is a value quantitative calculation from 0.1 to greater than 300,000,000 for Vessels and from 10 to greater than 10,000 for Piping. The calculated values are converted to Letter Ranking in AS 4343.

Conversion of this Letter Ranking to logarithmic values is as follows:

A	= High	= 100
B	= Average	= 10
C	= Low	= 1
D	= Extra Low	= 0.1
E	= Negligible	= 0.01

### 2.2.3 Consequences (Commercial)

The Consequences of Failure (Commercial) is addressed by consideration of loss of production. A decrease in ability to supply production capacity by 20 to 25 of is assigned an " A Consequences Rating.

The resultant Letter and Logarithmic ranking are therefore:

A	= High	% Ability to Supply Decreased by 20 to 25%	= 100
B	= Average	% Ability to Supply Decreased by 15 to 20%	= 10
C	= Low	% Ability to Supply Decreased by 10 to 15%	= 1
D	= Extra Low	% Ability to Supply Decreased by 5 to 10%	= 0.1
E	= Negligible	% Ability to Supply Decreased by 0 to 5%	= 0.01

The Ability to Supply is based firstly on the Energy Capacity or Percentage Flow Rate of the Sector being considered and secondly on the ability to substitute this supply if the sector is lost.

**2.2.4 Combination of Consequences - Hazard Rating (Safety and Environmental) and Commercial Rating**

The combination of Consequences - Hazard Rating and Commercial Rating is done in a simple manner by letter combinations, automated using logarithmic combinations:

- The Hazard Rating is Provided as a Letter Ranking and an equivalent logarithmic quantification
- The Commercial Rating is Provided as a Letter Ranking and an equivalent logarithmic quantification

The mathematical combination based on logarithmic values gives a measure for severity from the following:

Combined Consequences Severity (expressed as probability from 0.0001 to 1)  
 =  $\frac{\text{Consequences Hazard} + \text{Consequences Commercial}}{200}$

Where Severity Rating for Combined Consequences is:

High	= A	= 0.55 to 1.0	= 100
Average	= B	= 0.055 to 0.55	= 10
Low	= C	= 0.0055 to 0.055	= 1
Extra Low	= D	= 0.00055 to 0.0055	= 0.1
Negligible	= E	= 0.0001 to 0.00055	= 0.01

**2.3 Overall Plant Risk Assessment**

The combination of Likelihood and Consequences is as follows to provide a quantified assessment:

- Likelihood = 100, 10, 1, 0.1 or 0.01

- Consequences (S&E and C) = 100, 10, 1, 0.1 or 0.01

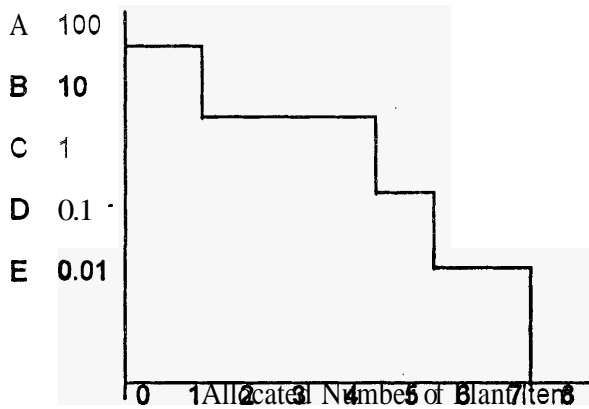
Plant Risk Assessment (expressed as a probability from 0.0001 to 1)  
 =  $\frac{\text{Likelihood} + \text{Consequences}}{200}$

The final resultant values for the probability rating is as follows:

Extreme	= A	= 0.55 to 1	Immediate Action Required
High	= B	= 0.055 to 0.55	On-Line Inspection and Monitoring
Normal	= C	= 0.0055 to 0.055	Annual or Extended Off-line Inspection
Low	= D	= 0.00055 to 0.0055	Manage by Routine Maintenance
Very Low	= E	= 0.0001 to 0.00055	External Inspection Only

Normal to Very Low ratings do not necessarily mean these components can be ignored, rather some situations will require monitoring of the operating envelope to ensure compliance with the requirements of AS/NZS 3788.

The following plot of an example Plant Risk Assessment rankings as a function of number of plant items is considered typical of a Phase 1 Plant Risk Assessment for FCDS:



The overall Risk Ranking is expected to be high because of a lack of data for components which might normally be considered of low likelihood of corrosion damage but which have a high cost consequence from loss of production capacity if they fail. The overall risk is expected

to decrease substantially once the absence of corrosion and cracking is confirmed by the visual and NDT examinations to be conducted in the Phase 2 Condition Inspection activities.

### 3.0 PHASES 2 and 3 of RISK BASED INSPECTION

The Phase 4 Plant Risk Assessment identifies the At-Risk plant components requiring attention for the Phase 2 Risk Based Condition Inspection. The data collection and assessment procedure identifies the most likely damage mechanisms and their locations. Completion of the Phase 1 Plant Risk Assessment includes specification of the at-risk components, the most likely damage risk areas and the inspection test procedures for the Condition Inspection. Inspection standards applied at construction can be used for RBI with some additions, namely assessment methods that quantify the extent of corrosion damage. AS/NZS 3788 provides extensive discussion on inspection methods.

The Plant Risk Assessment procedures currently under development are for:

- Phase 2 Condition Inspection
  - ◆ Visual Inspection and Mechanical Measurements
  - ◆ NDT Inspections
  - ◆ Life Prediction Methods
  - ◆ Determination of Next Inspection Period
- Phase 3 Monitoring of Operating Envelope
  - ◆ Physical Conditions
  - ◆ Chemical Conditions
- Annual or Bi-Annual External Inspection

### 4.0 APPLICATION OF THE TECHNOLOGY

The methodology developed for Plant Risk Assessment of FCDS is being trailed at two geothermal fields in the Philippines. Detailed procedures and guidelines have been prepared and the trials are intended to identify deficiencies in the guidelines and to suggest enhancements that will improve the accuracy and value of the predictions.

The results of the Phase 1 Plant Risk Assessments are expected to show that 50 to 80 % of the plant has a low overall risk and hence will have extended plant life (beyond design life). The remaining 20 to 50% of plant items having a

higher than desired risk ranking will be targeted for detailed Condition Inspection.

Plant having a high risk ranking because of predicted corrosion and damage can have their rating decreased by confirmation of damage being at a low and acceptable rate. Hence the Phase 2 Condition Inspection would be expected to see a further reduction in the percentage of at risk components to perhaps 10 to 20%.

Reduction of the risk ranking by reduction of the consequences of failure by for example installation of alternative supply lines or policy decisions such as the Zero Discharge Policy of PNOC-EDC can further reduce the percentage of components that pose a failure risk. It is expected that less than 5 to 10 % of plant will remain as presenting a critical risk requiring on-going risk management.

The on-going risk management of these remaining at-risk components is expected to take one of several forms:

- on-line monitoring of the process conditions
- on-line monitoring of the damage accumulation
- metallurgical and process chemistry investigations to further define the damage processes and the damage kinetics
- additional maintenance and repair activities
- planned replacement.

The remaining life of those components having acceptable damage accumulation can be calculated and in many instances the greater understanding of the damage processes and condition assessment data will allow the time between detail inspections to be increased from annual to 2 and 4 years. AS/NZS3788 allows repeat inspection periods of 8 to 12 years provided satisfactory results are obtained from repeated shorter term Condition Inspections.

The cost savings from the application of RBI are in avoidance of lost production, and increased benefit from planned maintenance and planned replacement.

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