

## Application of Risk Based Inspection Methodology to Aging Geothermal Fluid Collection and Disposal System in Tongonan, Philippines

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### ABSTRACT

A methodology has been developed for plant risk assessment of ageing geothermal fluid collection and disposal systems (FCDS) in Tongonan, Philippines, which is already in its 20<sup>th</sup> years of operations. The method applies the principles of risk-based inspection to the plant asset management practices. 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. Assessment starts with quantifying the likelihood of corrosion and metallurgical damage, which has already, or is likely, to occur. Then the consequence of this damage occurring is quantified in terms of commercial, safety and environmental factors. Combination of these likelihood and consequence ratings give an overall risk rating for each component in the plant.

In Tongonan, Phase 1 of the 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. Phase 2 involved actual inspection of identified components within the FCDS. Finally, Phase 3 is the continuous monitoring of the identified high-risk and high-consequence components, as well as potential high-risk areas. 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.

### 1. INTRODUCTION

**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 to safety, environmental and commercial considerations. The application of **Risk Based 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.

PNOC EDC, the operator of Tongonan geothermal field in the Philippines, identified a need to implement a risk based inspection and plant asset management system for

geothermal FCDS in order to improve the plant reliability and life prediction capabilities. A project was conceived between the Materials Performance Technologies (MPT) of New Zealand and PNOC Energy Development Corporation (EDC) with funding support from New Zealand Ministry of Foreign Affairs and Trade (NZMFAT) Asia Development Assistance Facility (ADAF) to assess the risks involved in aging Fluid Collection and Disposal Systems. The emphasis of this program, which started in year 2000, is on the maintenance and life extension of aging geothermal energy plant and equipment.

### 2. GENERAL CONCEPT

Procedures outlined in AS/NZS 3788, AS 4343 and AS 4360 were used to develop the methodology outlined in this paper. MPT and PNOC 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, Philippines in December 2000. It was also part of the program to emplace a computer-based assessment in order to manage volumes of available data.

The assessment methodology uses a three-phase approach to achieve **Risk Based Inspection** (Lichten 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 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** 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.

### 3. PHASE 1 RISK ASSESSMENT

The Phase 1 Plant Risk Assessment is based on the likelihood of corrosion and metallurgical damage and the consequences of failure to safety, environmental and commercial operations. The information on which the

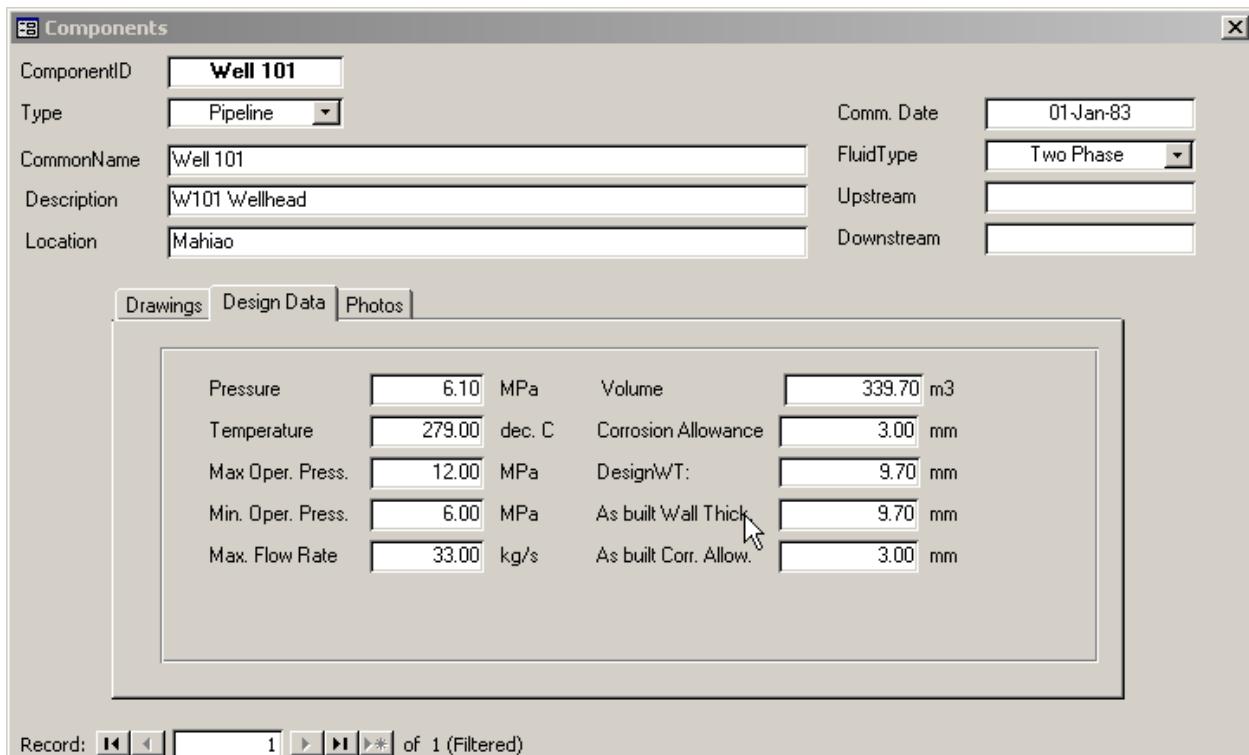


Figure 1: An example of descriptions of FCDS components in Tongonan.

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 injection wells, larger diameter pipelines (that is greater than 100 mm) from wells to the manifolds and from separator stations to the power plant and to injection wells, and two-phase and steam manifolds including those in the separator stations. On the other hand, vessel assessments are focussed on separator vessels. Figure 1 shows an example of the computer interface bearing the properties of one component.

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, for example, Alcober, 1999)
- 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 the Maintenance and Operation History, which include preventive maintenance and reactive maintenance.

Scheduled and unscheduled outages, as well as operational envelope excursions were reviewed.

The Plant Risk Assessment also considers the *Consequences* of failure. The data required to estimate the severity of the Consequences comes from the plant details as outlined above and also from consideration of Stored Energy, Redundancy of Plant, Population Densities, Staff Access to Plant and Eco-System Impact of a Failure.

### 3.1 Likelihood of Corrosion and 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)
- Silica Scale Formation 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. Quantification of the Surface Corrosion models is as follows:

**Please edit desired record**

**Component** Well 101

Date 01-Oct-01 Temp (oC) 195

Corrosion Rate Prediction Scaling Rate Prediction

Calc pH: 6.21 Neutral pH: 5.66 Acidity: Alkaline

Cl (ppm): Corr: Passivating

**Predicted Corrosion Rates**

ML (mm/yr): 0.01

Pit (m/year): 0.01

Erosion (mm/yr): 0.01

Record: 1 of 1

Figure 2: Chemical parameters considered in assessment of corrosion rate prediction of FCDS components.

Table 1: Likelihood ranking for surface corrosion for a 3mm corrosion allowance.

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

Table 2: Five categories used for scaling prediction and the frequency of cleaning required in FCDS

A	= Extreme	Strongly Saturated (SI > 1.2)	More than once/month	= 100
B	= Very High	Weakly Saturated (SI 1 to 1.2)	Once / month	= 10
C	= High	Saturated (SI = 1)	Once / year	= 1
D	= Moderate	Under-saturated (SI < 1)	Once in 10 years	= 0.1
E	= Low	Never Predicted	Never Experienced	= 0.01

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

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  $= (3/25) \times 17 = 2$  mm. A likelihood ranking for surface corrosion for a 3 mm corrosion allowance is shown in Table 1. The use of a logarithmic scale is in accord with the level of corrosion predicted, for example corrosion material loss of 1 mm at the usual time of assessment at 50 % of plant life would be

considered "High". An example of corrosion assessment is shown in Figure 2.

### 3.2 Assessment of Scaling Potentials

Theoretical models for scaling prediction can only be used to give an indication of scaling risk as there are no known relationships between Saturated Index and Scaling Rates. Saturated 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 shown in Table 2, allowing for adjustments for turbulent and high heat loss areas by increasing the ranking by one letter or one decade.

Please edit desired record

Component	Well 101		
Date	01-Oct-01	Temp (oC)	195
Corrosion Rate Prediction		Scaling Rate Prediction	
Scaling Index:	Never Predicted		
Flowing:	Low		
Turbulent:	Low		
Heat Loss:	Low		
PredictedScaling:			

Record: **1** of 1

Figure 3: Chemical parameters used in assessing silica scaling potentials in FCDS.

An example of silica scaling potentials is shown in Figure 3.

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 (see column 4 of Table 2).

### 3.3 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 (Lichten 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, such as in circumferential welds is less likely to result in rupture but may readily leak. Table 3 shows how historical record was developed for the initial cracking likelihood rating.

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.

### 3.4 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 as shown in Table 4):

- 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

**Table 3: Likelihood of cracking based on historical records.**

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

**Table 4: The final resultant probability values of likelihood. Where the resultant combined likelihood has a value between two ratings, the higher rating is used.**

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

**Table 5: Conversion of Letter Ranking of consequences to logarithmic values.**

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

$$\text{Surface Corrosion (Predicted or Actual)...} \\ = \frac{\text{+ Scaling (Predicted or Actual) + Cracking}}{300}$$

The use of logarithmic scale allows the values to be summed and normalized rather than multiplied. Table 4 shows the resultant likelihood ratings

### 3.5 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),  $pV$  can be calculated where:  $p$  is the pressure in MPa and  $V$  is the volume in Litres.
- For Pipelines (data initially from design drawings and specifications),  $pD$  can be calculated where  $p$  is the pressure in MPa and  $D$  is the diameter in mm.
- Adjustments to the above calculations are outlined in AS 4343 for process fluid properties, population and staff access, and specific plant details
- The rating is numerical but can be graphically related to a letter ranking as outlined in AS4343 - 1999

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.

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, and then converted to logarithmic scale (Table 5).

### 3.6 Commercial Consequences

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% is assigned an “A” Consequences Rating (Table 6). 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.

### 3.7 Combination of Consequences

The combination of Consequences – Hazard Rating and Commercial Rating – is done in a similar manner to Likelihood 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)

**Table 6: The resultant letter and logarithmic ranking of commercial consequences.**

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

**Table 7: Severity Rating for Combined Consequences.**

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

**Table 8: The final resultant values for the probability rating considering likelihood and consequences.**

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

$$\text{Consequences Hazard...} \\ = \frac{\text{+ Consequences Commercial}}{200}$$

Table 7 shows the resultant Consequences rating.

### 3.8 Overall Plant Risk Assessment

The combination of Likelihood and Consequences (shown in Table 8) 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) . . .

$$= \frac{\text{Likelihood + Consequences}}{200}$$

The overall Risk Ranking is expected to be high during Phase 1 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. An example of component risk profile is shown in Figure 4, while an example of overall Plant Risk Assessment for a number of component is shown in Figure 5.

### 4. PHASE 2: CONDITION INSPECTION

The Phase 1 Plant Risk Assessment identifies the At-Risk plant components requiring attention for the Phase 2 Risk Based Condition Inspection. The components that had high risk, both in likelihood and consequences were given priority. New measurements and inspections were made. In addition review of the previous inspections conducted were also compiled as shown by the example in Figure 6.

Inspection standards applied at construction were 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. An example of this Condition Inspection is the wall thickness measurements and collection of scale samples in a separator vessel shown in Figure 7. In general, the adapted inspection procedure for Tongonan FCDS is as follows:

- Visual Inspection and Mechanical Measurements
- NDT Inspections
- Life Prediction Methods
- Determination of Next Inspection Period

For the last two steps, several models are developed to predict the remaining life of the components. As of this writing, there is still no general model that can be used, but it is expected that a more precise model will evolve with continuing monitoring as discussed in the next section.

### 5. PHASE 3: MONITORING OF OPERATING ENVELOPE

In year 2002, the computer-based system incorporating the results of Phases 1 and 2 was completed. It is expected that

**PRA Calc : Form**

Component:	Well 101				
Assessment Date:	31-May-04				
PRA Value:	1 PRA Rate: C				
Likelihood					
Likelihood:	0.01				
Corrosion					
Actual ML:	0.000	A Rating:	0.01		
Predicted ML:	0.21	P Rating:	0.10		
Allowable ML:	2.57	Eff Rating:	0.10		
Cracking					
Cracking Rate:	0.01				
Scaling					
Predicted:	0.01	Actual:	0.01	Effective:	0.01
Consequences					
Consequences:	10.00				
Hazard					
EF:	1.00	pV or pD:	2072.17		
SF:	0.50	Corrected pV or pD:	1036.09		
Final Rating:	100.00				
Commercial					
Rating:	0.01				

Record: **1** of 1 (Filtered)

Figure 4: An example of computation of risks of likelihood and consequences of FCDS components.

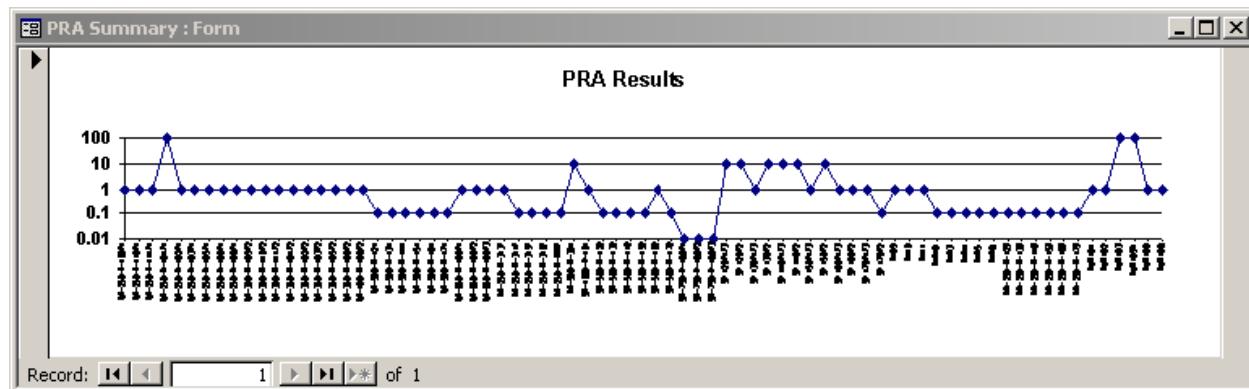


Figure 5: Overall Plant Risk Assessment (PRA) of Tongonan FCDS. Take note that there are components with very high risk, or ratings of 100.

the data would continue to build-up with regular monitoring.

In Tongonan, critical components are inspected regularly, most often coinciding with the scheduled Annual Power Plant Preventive Maintenance. Inspections are focussed in the items that have high-risk rating. During inspections, data on the physical conditions of each component is

collected. An example is shown in Figure 8, which shows inspection results for a separator vessel.

Collection and analysis of chemical data is an important monitoring tool in Tongonan FCDS. It is being collected in a monthly to quarterly basis. By examining the changes in salinity, acidity, gas components, and the amount of transported solids, it is possible to predict the potential

Component	Date	Event Type	Duration	Incident Cost
Well 101	01-Oct-01	Maintenance, Uncheduled	4.00	500000
<b>Description</b> Master Valve Replacement (Geopak), Frequency: 0.2 (once in 5 years)				
Well 101	01-Oct-01	Maintenance, Uncheduled	4.00	35000
<b>Description</b> casing repair, Frequency: 0.2 (once in 5 years)				
Well 101	01-Oct-01	Maintenance, Scheduled	4.00	5000
<b>Description</b> Retouch/Painting, Frequency: Four				
Well 101	01-Oct-01	Maintenance, Scheduled	1.00	500
<b>Description</b> Servicing, Frequency: 12				
Well 101	01-Oct-01	Maintenance, Scheduled	4.00	35000
<b>Description</b> Anchor casing repair, Frequency: 0.2 (once in 5 years)				

Record: 1 of 5

Figure 6: An example of historical inspection done in a component of Tongonan FCDS. This data helps assess the lifetime of the components.

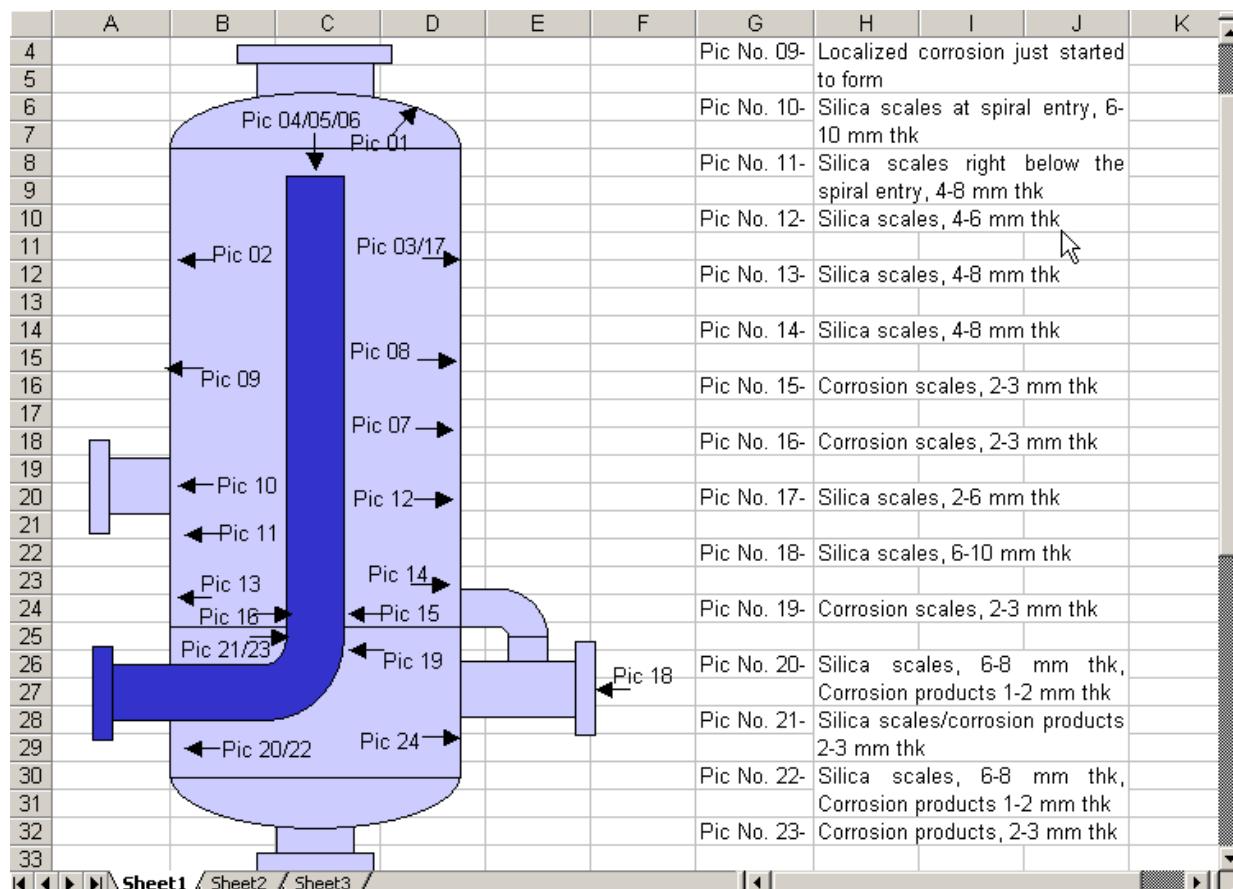


Figure 7: An example of Condition Inspection done in a separator vessel in Tongonan FCDS.

**GEO23105INSPECTOR - Inspection Data Entry Form**

**INSPECTION DATA**

Project Code	MGPF	Component Code	SL800	Sector Name	KN
Location of Sampling	BASE OF SILENCER	Sample Code		Part Inspected	INNER.CONFINE
Inspection Number	1	Inspection Date	2002-11-06	Inspector Name	JB.Nogara
Operating Condition	SHUT DOWN	Physical Environment		Physical Infrastructures	
<input type="checkbox"/> Scale present?	<input type="checkbox"/> Corrosion present?	<input type="checkbox"/> Scale sample collected?	<input type="checkbox"/> Corrosion sample collected?		
Physical Deformation		Sample Abundance	HI	Sample Color	GREY TO BLACK
Sample Thickness (mm)	16	Sample Structure		Sample Texture	RIPPLED, IRREGUL
Sample Composition	FORMATION CUTT	Sample Hardness	VARIABLE	Sample Density	LOOSE
Sample Homogeneity	VARIABLE	Inspection Remarks		<input checked="" type="checkbox"/> Petro Analysis Requested?	

**Upload Photo!** **Petro Analysis**

**Figure 8: An example of monitoring data conducted in a separator vessel**

damages to the FCDS, and thereby assess the risk involved in these changes.

## 6. CONCLUSIONS

A methodology was developed for Plant Risk Assessment of FCDS in Tongonan geothermal fields in the Philippines. Detailed procedures and guidelines have been prepared and practical application of these is 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 showed that 50 to 80 % of the plant had 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 were further assessed in Phase 2 Condition Inspection.

In Phase 3, Continuous Monitoring will be implemented at high-risk areas. The on-going risk management of the remaining at-risk components involves the following:

- 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.

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## REFERENCES

Alcober, EH, (1999) Fluid Transport and Silica Scaling Potential in Cross Country Injection Lines: The Case of 4RC Line, Leyte, Philippines. Proc. 20<sup>th</sup> PNOC-EDC Annual Geothermal Conference, pp. 107-113.

AS/NZS 3788:1996, Australian/New Zealand Standard, Pressure equipment--In-Service inspection.

AS4343-1999, Australian Standard, Pressure equipment—Hazard levels.

AS/NZS4360:1999, Australian/New Zealand Standard, Risk management.

NACE MR0175-00 NACE Standard Material Requirements, Sulfide Stress Cracking Resistant Metallic materials for Oilfield Equipment. (re-issued annually)

Braithwaite, W R and Lichti, K A (1980) Surface Corrosion of Metals in Geothermal Fluids at Broadlands, New Zealand, in Geothermal Scaling and Corrosion, ASTM STP 717, L A Casper and T R Pinchback, Eds, pp 81-112.

Lichti, K A, Soylemezoglu, S and Cunliffe, K D (1981) Geothermal Corrosion and Corrosion Products, in Proc New Zealand Geothermal Workshop.

Lichti, K A and Wilson, P T (1983) Materials Testing in Geothermal Steam, in Proc Int Symposium on Solving Corrosion and Scaling Problems in Geothermal Systems, San Francisco, NACE, pp 269-284.

Lichti K A, Firth D M and Wilson P T (1993) Lifetime Predictions for Critical Plant in Geothermal Energy Systems. Proc. 15th NZ Geothermal Workshop, p.81-86.

Lichti, K A, Johnson, C A, McIlhone, P G H and Wilson, P T (1995) Corrosion of Iron-Nickel Base and Titanium Alloys in Aerated Geothermal Fluids, in Proc World Geothermal Congress, Florence, Italy, pp 2375-2380.

Lichti, K A (1995) Selection and Use of Materials for Geothermal Energy Applications Using Computer Based Technology, in Proc World Geothermal Congress, Florence, Italy, pp 2981-2986.

Lichti, K A, Wilson, P T and Inman, M E (1997) Corrosivity of Kawerau Geothermal Steam, in Geothermal resources Council transactions, Vol 21, pp 25-32.

Soylemezoglu, S, Lichti, K A and Bijnen, H (1980) Geothermal Corrosion Case Studies at the Wairakei and Broadlands Fields Using the "Corrosometer" Method, in Proc NZ Geothermal Workshop, Auckland.