

LONG TERM USE OF PRODUCTION WELLS WITH ACIDIC DISCHARGE AT MINDANAO-2 POWER STATION, MINDANAO GEOTHERMAL PRODUCTION FIELD (MGPF), PHILIPPINES

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ABSTRACT

Mindanao-2 power plant is the second geothermal power station in Mindanao Geothermal Production Field operated by PNOC-EDC. Mindanao-2 was commissioned in June 1999 with a base load capacity of 52 MWe. The plant is a dual (high pressure-low pressure) flash type. High-pressure steam is provided by nine production wells piped to two central separator stations, while the low-pressure steam is supplied from second flash of separated water from the adjacent Mindanao-1 power plant. Two production wells used by Mindanao-2 discharge acid $\text{NaCl} + \text{SO}_4^-$ fluids with pH ranging from 3.2 to 5.5 at 25°C. Steam production from these two wells contributes about 35% of total high-pressure steam production. Separated water from the high-pressure steam-liquid separators used by Mindanao-2 is also acidic with pH ranging from 3.8 to 5.8.

After two years of utilization of the acidic wells there were no significant thinning observed in the surface piping and wellhead facilities of Mindanao-2 based on UT (ultrasonic test) measurements and visual inspections. Scales consisting of magnetite and amorphous silica are deposited in the inner surface of the casing from the fluid. These scales are also found in the re-injection piping system and produced by the acidic separated water. Although the silica content of the separated water exceeds saturation level by more than 45% voluminous amorphous silica scales were not observed in the re-injection pipelines. The acidity of brine significantly delayed the onset of silica polymerization effectively preventing scale formation in the injection well and pipelines. However, significant erosion/corrosion was experienced in the piping system when the separated water was discharged to the atmosphere.

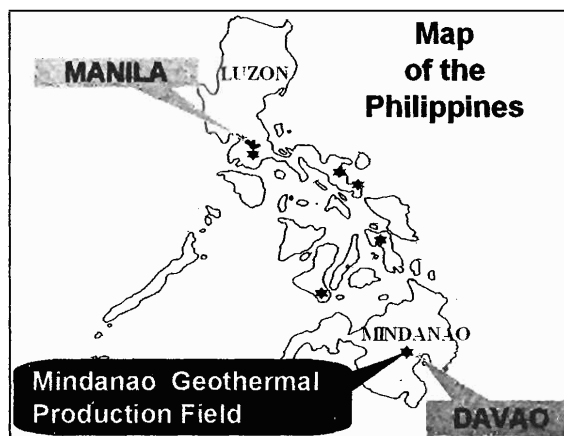


Figure 1. Location map of Mindanao-2 power station.

The experience gained from the use of acid wells in Mindanao-2 is encouraging and may eventually result in the utilization of other acid wells currently not used in the field.

1.0 INTRODUCTION

Mindanao-2 power plant is the second geothermal power station in Mindanao Geothermal Production Field operated by PNOC-EDC in the island of Mindanao in the Philippines (Figure 1). Mindanao-2 was commissioned in June 1999 with a base load capacity of 52 MWe. The plant is a dual (high pressure-low pressure) flash type. High-pressure steam that flows at a rate of 360 TPH is supplied by eight production wells. The turbine inlet pressure of the high-pressure steam is 7.0 bar abs. Low-pressure steam comes from second flash of the separated water from adjacent Mindanao-1 high-pressure separators. Turbine inlet pressure of low-pressure steam is 3.6 bar abs. and flows at a rate of 52 TPH.

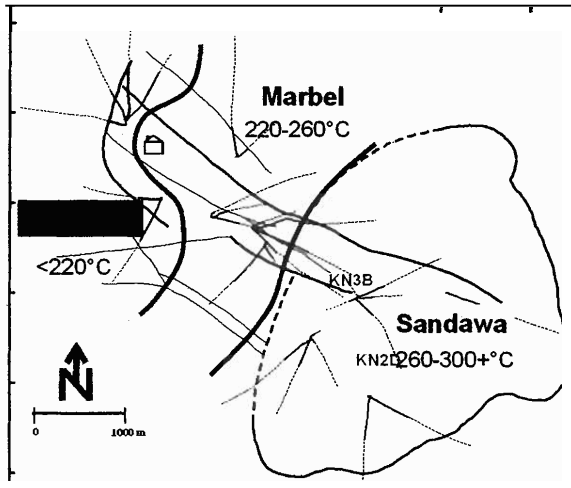


Figure 2. Structural and well location map of Mindanao Geothermal Production Field divided into three sectors: Matigao, Marbel and Sandawa. The subject acid wells are all sited in Sandawa sector.

Mindanao geothermal field is a typical island-arc andesite volcano hosted hydrothermal system. The upflow center of this system is believed to extend from central to the northwest section of a 4.5 x 3-km wide oval shaped depression called Sandawa collapse (Figure 2). Seven out of the nine production wells used in Mindanao-2 were drilled in this sector. Deep temperatures of fluids produced from these wells range from 290-320°C. A shallow two-phase zone formed atop this upflow sector. Three wells: KN5D, TM3D and TM4D tapped this shallow two-phase zone and discharges dry steam at the wellhead. The rest of the production wells tapped the deep liquid reservoir with variable contributions from the two-phase zone. Two wells KN2D and KN3B, which tapped the deep liquid reservoir, discharged highly acidic fluids. The pH of the fluid ranged from 3.2 to 4.5 as measured at ambient condition. Four other wells namely KN1D, PS1D, TO1D and TO2D drilled in Sandawa produce or are expected to produce acid fluids. Well KN1D was converted into a re-injection well. PS1D was cement-plugged while TO1D and TO2D remain unused until now. Steam from wells KN2D and KN3B contributes about 35% of the total high-pressure steam for Mindanao-2.

All Mindanao-2 production wells drilled in Sandawa are piped to a central steam/liquid separator station. The brine from this separator

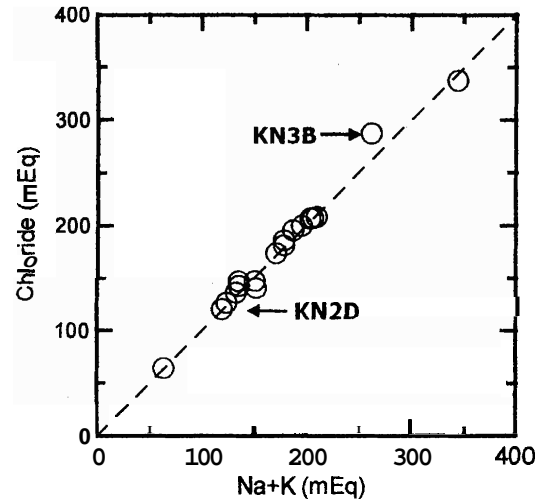


Figure 3. Plot of chloride versus Na+K molar concentration of fluid discharges from MGPF production wells. 'Excess' chloride typical of HCl type acidity is not evident in MGPF acid wells.

is re-injected to well KN1RD at a temperature of 170°C. The injected brine is acidic with pH ranging from 3.2 to 5.5 and silica concentration typically in excess of 1,000 ppm SiO₂. Occasionally, brine from the separator has to be diverted to holding sumps when its flow rate exceeds the capacity of injection well. The brine is allowed to cool to 30-40°C in the sumps before being injected to a cold injection well KURD.

This operational set-up was continued for more than two years with only minor modifications. On April 2001, Mindanao-2 power plant underwent a major plant maintenance shutdown that lasted for almost two weeks. Visual inspections of Mindanao-2 piping system were conducted during this brief lull in operations. This paper presents the consequences of two years continuous utilization of two acidic wells in Mindanao-2 power plant.

2.0 SOURCE OF ACIDITY

Initial assessment of acidity in the well discharges of some wells in MGPF focused on balance of major ions of the fluid. In the case of KN2D and KN3B fluid, Na+K molar concentration is equal to the molar concentration of chloride (Figure 3). This observation eliminates the likelihood of HCl acidity, which is

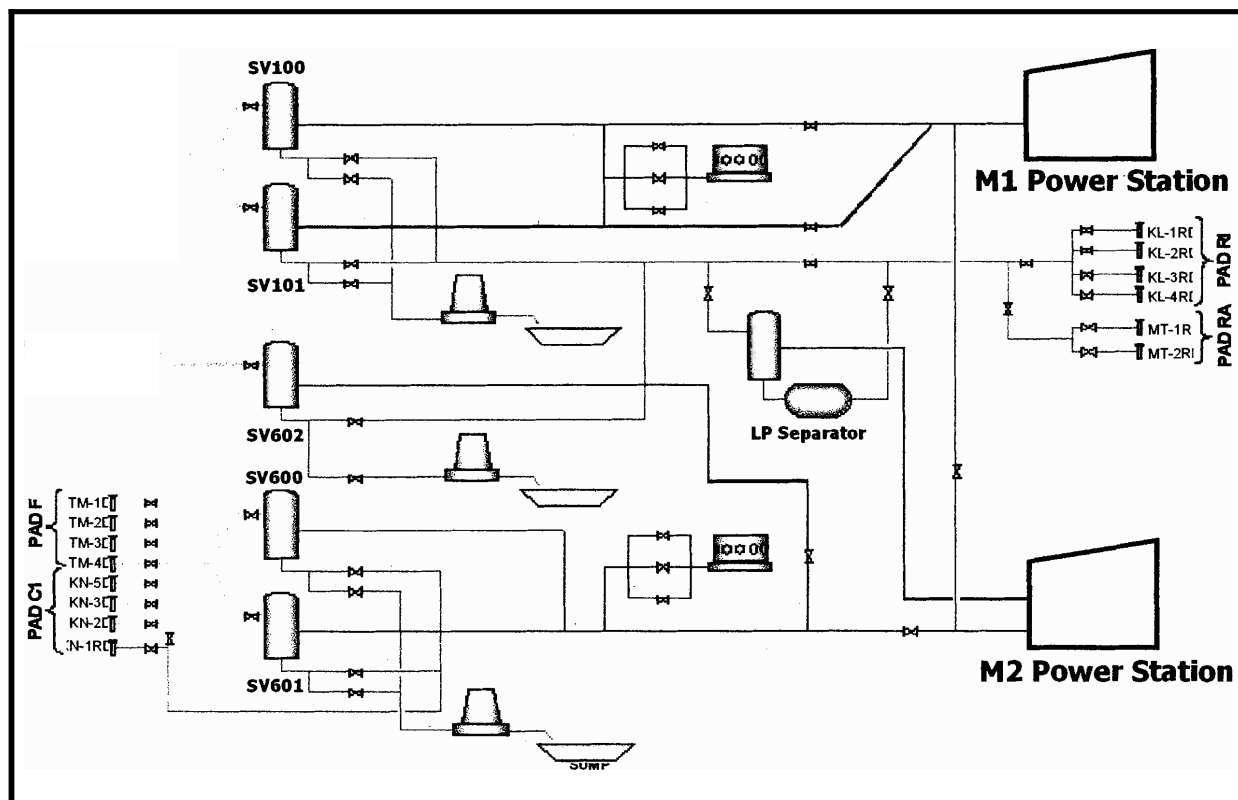


Figure 4. Process flow diagram showing fluid paths to Mindanao-1 and Mindanao-2 power stations. Blue lines represent separated water while red lines show steam pathway.

manifested as chloride 'excess' (Parilla et al., 1997). Further studies on fluid-mineral equilibrium of fluids in MGPF revealed NaCl (+SO₄) fluid type that is found in Sandawa sector (Salonga, 1995). This fluid contains large amounts of SO₄²⁻ and its major dissolved salt is NaCl. At reservoir condition, this fluid exhibits neutral pH and is in equilibrium with K-mica. Acidity of the fluid become evident when this fluid undergoes boiling, such as when ascending through the well bore from the reservoir. This increase in acidity is caused by the complete dissociation of H₂SO₄ to H⁺ and SO₄²⁻. Computer modeling of well bore chemistry by Lichti et al. (1998) clearly demonstrated the relationship of changing sulfur chemistry and pH in this type of fluid. The source of H₂SO₄ at deep reservoir conditions is debatable but is at present attributed mainly to the oxidation of SO₂ into H₂SO₄ and H₂S in the presence of water. Well KN3B has intersected at depth intrusive complexes (Gonzalez et al., 1994), which could be the source of SO₂ produced in the early stages of development of the hydrothermal system.

3.0 OPERATING CONDITIONS

Mindanao-2 power plant utilizes a total of nine production wells. Four of the wells are in Pad F namely TM1D, TM2D, TM3D and TM4D. Three production wells are in Pad C namely KN2D, KN3B and KN5D. The remaining two wells are drilled in Pad B. These are APO2D and MD1D. Wells in pad C and F are connected to two-phase fluid pipe headers and transported to two sets of 20-MW cyclone separators constructed in pad C. The separated brine is re-injected to well KNIRD also in pad C. The steam is transported via 7 kilometers of 42-inch steam pipeline to Mindanao-2 power plant. Production wells in pad B have an independent 10-MW separator (Figure 4). Steam from pad B is transported through 18-inch steam pipeline that merges with the steam line from pad C. In addition to high-pressure steam additional steam is generated from secondary flashing of Mindanao-1

pressure steam that enters the sixth stage blades of the turbine.

The fluid from MBL2 represents the separated water from pad C separators. Silica content of the brine normally is in the range of 1000 to 1100 mg/kg. This silica content translates to amorphous silica over saturation of 30% to 50% respectively at fluid temperature of 170°C. In rare cases, changes in production well combinations allow the fluid to attain an 80% over saturation as shown above. Under neutral pH condition, this silica over saturation can cause severe silica scaling in the re-injection pipeline and well bore. However, because of the acidity of the separated water, thick silica scales were not observed in re-injection pipeline of pad C separator. The absence of a decline in the injection capacity of well KN1RD also implies the absence of silica scaling in the well bore. Silica induction experiments conducted in the acidic separated water show polymerization would occur after 90 minutes. Well bore modeling results show maximum residence time of the fluid in the well bore at 60 kg/s of flow is about 30 minutes. It is believed that the injected fluid will be re-heated when it flows out into the formation thereby preventing silica plugging of the fissures.

The injection capacity of KNIRD vanes with time. However, its maximum capacity is barely enough to cover the separated water coming from pad C separators. When mass flow surges occur from the production wells feeding the separator, dumping of wastewater to concrete lined sumps become inevitable. Erosion/corrosion of dump valve, pipeline and silencers has developed when dumping became excessive.

4.0 CORROSION MONITORING

The favorable effect of acidity in controlling silica scale formation in pad C separated water made the utilization of the acidic production wells necessary. However, low pH in addition to high temperature and the presence of H₂S and chloride enhanced the corrosive environment of the fluid. Typical corrosion rate in carbon steel exposed to geothermal fluid is in the order of 20 to 50 mm/y (Lichti et al., 1981). However, studies conducted by Sanada et al. (1998) showed that corrosion rate in carbon and low alloy steels increased from -2 mm/y at pH of 4.5

to more than 100 mm/y at pH 2 at flow velocities between 70 to 110 m/s. These rates are unacceptable for M2 acid wells that use carbon steel pipes. Corrosion rate monitoring using UT (ultrasonic test) meter were conduct@ regularly on surface pipes and facilities of KN2D, KN3B, MBL2 and KNIRD. Measurements were conducted at regular intervals as a means to predict failure of the pipes due to corrosion. The accuracy of the method is about 1 mm.

Monitoring of solution Chemistry has also been adopted. Fluctuations in fluid chemistry such as decreasing pH and increased H₂S in the fluid can be used to predict highly corrosive fluids. The formation and stability of iron oxide-iron sulfide corrosion products from the fluid significantly influence the rates of corrosion of carbon steel (Lichti and Bacon, 1998). Fluid chemistries of KN2D, KN3B and MBL#2 at line condition were modeled using chemical speciation programs (Table 1). The computed chemistries were used to construct Eh-pH diagrams and determine the stability fields of iron-oxide iron sulfide corrosion products. For the well fluid the chemistries were modeled from the reservoir state down to a temperature of 170°C. In KN2D, KN3B and MBL#2 iron oxides and sulfides are stable and are predicted to form from the fluid (Figures 5-7). Free corrosion as shown by the field represented by the Fe²⁺ stability is compressed to a small section representing extremely acidic condition because

Table 3. Typical chemistry of fluids from acidic wells KN2D and KN3B and separated water of Mindanao-2 pad C separators (MBL2).

	KN2D	KN3B	MBL2
DATE	09 August 2001	09 August 2001	15 August 2001
SP, Mpa abs.	0.867	0.857	0.82
Water (mg/kg)			
pH	2.87	4.13	3.32
Na	5320	5920	6720
K	1105	1430	1520
Ca	10.9	155	130
Mg	8	3	
Fe	(4.56)	(1.48)	8.7
Cl	8870	10911	12163
B	219	204	249
SO ₄	169	66.2	385
HCO ₃			
CO ₂			
NH ₃	4.26	0.1	
H ₂ S	1.04	4.53	(5.83)
SiO ₂	965	1294	1374
Gas (mmol/100 mole)			
CO ₂	181	199	
H ₂ S	23.4	17.6	
NH ₃	0.03	0.02	
Silica Saturation Index			1.83

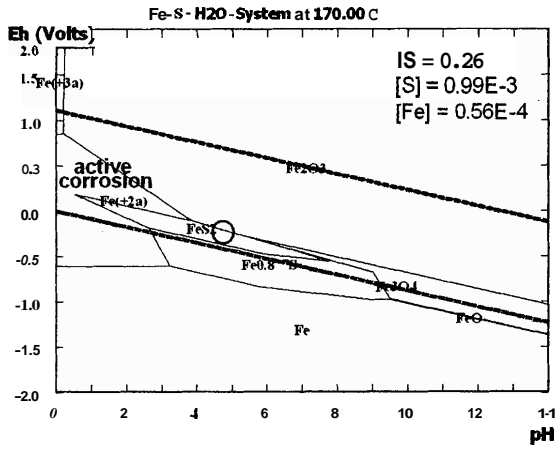


Figure 5. Eh-pH diagram constructed from modeled chemistry of **MBL2** fluid. Calculated pH and potential of fluid predicts the stability and possible formation of iron-sulfides and oxides and absence of active corrosion.

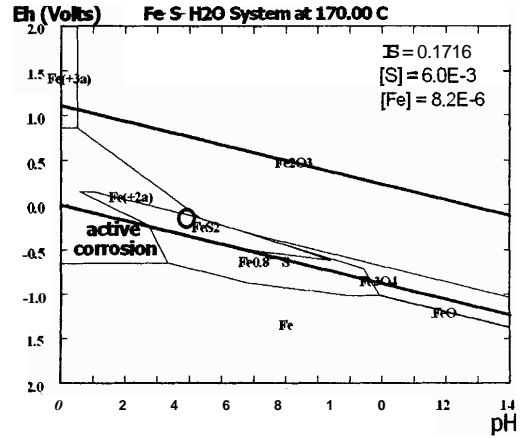


Figure 6 Eh-pH diagram constructed from modeled chemistry of well **KN2D**. The fluid condition is 170°C typical of two-phase line condition near the wellhead and two-phase pipeline.

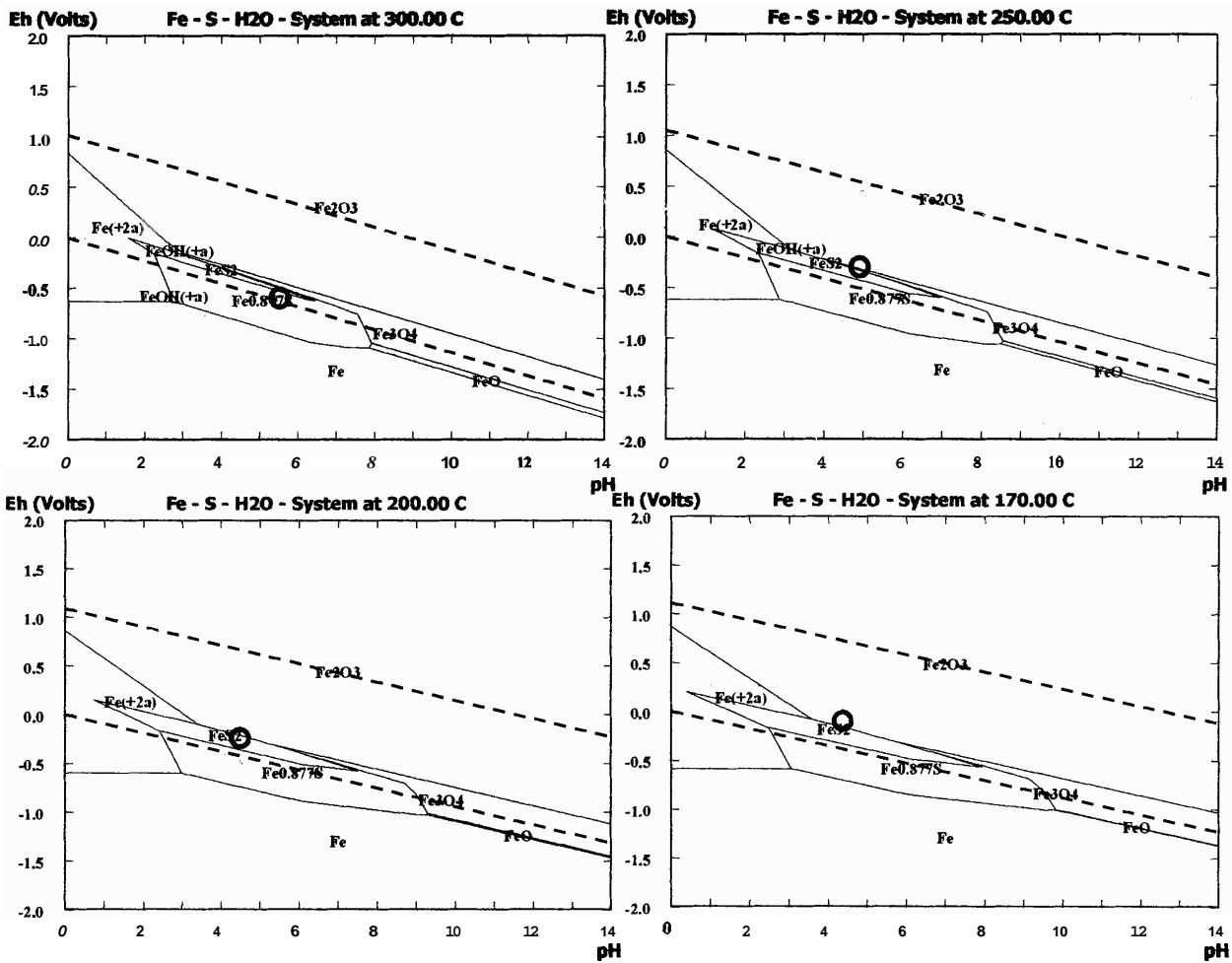


Figure 7. Eh-pH diagrams constructed from modeled fluid chemistry of **KN3B** fluid. The chemical process associated with boiling of the fluid from aquifer towards the two-phase pipeline is simulated. Active corrosion bounded by the region where Fe^{2+} ion is stable is not anticipated in any stage during upflow

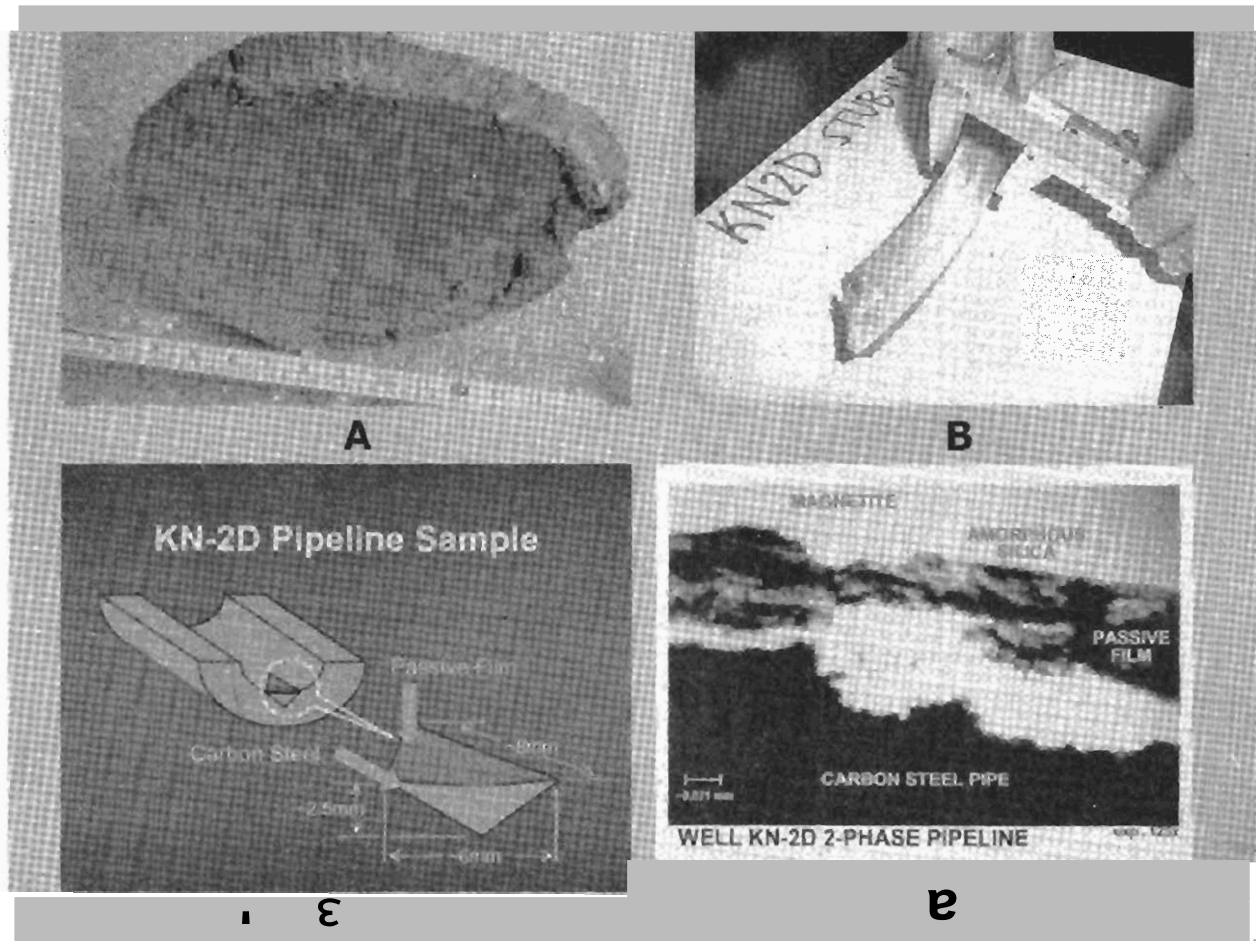


Figure 8. A piece of pipe (A) cut from KN2D two-phase line during M2 shutdown. The thickness of the pipe was measured (B) to determine possible thinning after exposure to acidic fluid for two years. A small sample was cut from the pipe strips for petrographic evaluation (C) Photomicrograph of thin section of pipe sample under cross-polarized light at 125x magnification (D). Passive film consists of layers of amorphous silica and magnetite.

of the high concentration of sulfur bearing species. In all cases free corrosion is not predicted from the well chemistry and thermal conditions.

5.0 MINDANAO-2 MAINTENANCE SHUTDOWN VISUAL INSPECTIONS

After two years of continuous uninterrupted operation Mindanao-2 power station underwent maintenance shutdown in April 2001. The shutdown was an opportunity to inspect the surface piping facilities of Mindanao-2. Visual inspection of MBL#2 pipeline revealed the presence of highly adherent black scale coating the inner surface of the pipe. Samples of this black scales was sent to PNOC-EDC Petrology

laboratory for scale analyses. Large quantities of amorphous silica scales were absent. This observation is evidence of the effectiveness of fluid acidity in preventing silica scaling. Pipe thickness measurements using UT meter indicated that significant uniform corrosion is absent in MBL#2 pipeline and wellhead of KN1RD. Large crevices and pits were also not observed in the inner surface of the pipes.

A ten-inch bypass line was installed in well KN2D during the shutdown. A small section of the pipe was cut to accommodate the pipeline to be welded (Figure 8). The small section of pipe was cut into thin strips and measured for thickness and sent to PNOC-EDC Petrology laboratory for scale analysis. The baseline thickness of the cut pipe was 23.83-mm.

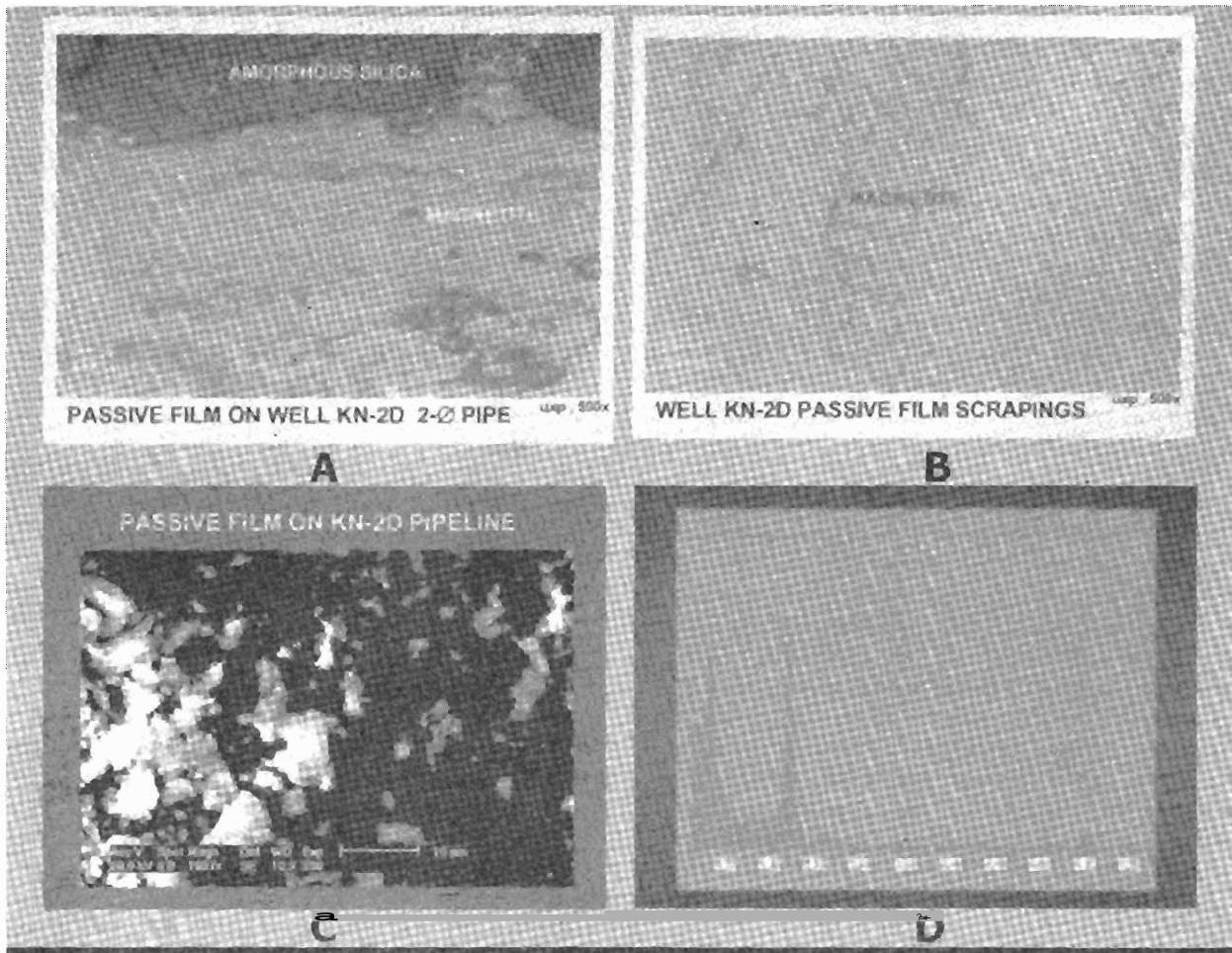


Figure 9. Top left image is a photomicrograph of polished section under polarized light at 500x magnification showing the boundary of amorphous silica-magnetite layer. Thin section of passive film scrapings show magnetite crystals cemented by amorphous silica. Scanning electron microscope (SEM) image of magnetite crystals (C) and energy dispersive x-ray (EDAX) analysis of passive film (D).

Average thickness of the cut strips were measured at **23.95** mm. This fact confirms the absence of significant uniform corrosion on the two-phase pipeline of **KN1RD** from the UT measurements. There was no opportunity to inspect the **KN3B** two-phase pipelines during the shutdown but UT results also indicated the absence of significant thinning of the pipe walls.

6.0 PETROLOGY OF PIPELINE SCALES

The scale samples from **MBL#2** were mounted on thin and polished sections and photomicrographed. The photomicrographs were analyzed visually for mineral composition. The samples were composed of amorphous silica (**35%**), amorphous clay (**37%**), and

corrosion products (**-25%**). Corrosion products consist mainly of iron oxide (magnetite) and iron sulfides (pyrrhotite and pyrite) and traces of chalcopyrite (CuFeS_2) and bornite (Cu_3FeS_4).

Casing strips obtained from **KN2D** two-phase line was also mounted on thin and polished sections and analyzed. Samples were also subjected to energy dispersive x-ray analyses (EDAX) and scanning electrode micro-probe (SEM) (Figure 9). Results of analyses show the adherent scale is composed mainly of interlayered amorphous silica, crystalline magnetite, minor pyrrhotite and traces of chalcopyrite. The scale has a maximum thickness of **-0.37** mm.

7.0 CONCLUSION

Two production wells which discharges acid NaCl + SO₄ fluids with ambient pH in the range of 3.2 to 5.8 have been used for more than two years in Mindanao-2 power station. Separated water from high-pressure separators fed by the two acid wells also produce fluid with pH in the range of 3.8 to 5.8 as measured in the laboratory and calculated to be 4.0 to 6.0 at 170°C line temperature condition. Although the separated water has amorphous silica over saturation normally in excess of 40% large amorphous silica scales were not observed in the pipes because of low pH.

Inspection of KN2D two-phase pipeline and MBL#2 pipeline during a routine maintenance shutdown showed the inner surface of the casing have been covered with a thin adherent black deposit consisting of amorphous silica and iron oxide-sulfides corrosion products. Pipe thickness measurements showed absence of significant thinning as a result of uniform corrosion in both pipelines. Results of visual inspection confirmed the results of regular UT measurements conducted on the pipelines. The formation of amorphous silica-iron oxide film on the inner wall of the pipes is believed to have prevented rapid free corrosion of carbon steel pipelines in KN2D, KN3B and MBL#2.

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