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CONTROLLING SILICA DEPOSITION THROUGH RE-ENGINEERING IN THE PALINPINON-I GEOTHERMAL FIELD, PHILIPPINES, OVER 20 YEARS OF COMMERCIAL GENERATION

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ABSTRACT

Solid deposition of minerals from geothermal waters has been identified as a primary constraint in the operation of high temperature geothermal fields for electric power generation. The 20 years operating experience of the Palinpinon-I geothermal production field has shown that mineral deposition, particularly amorphous silica, in well bores and surface pipelines can lead to costly removal operations, lengthy decomissioning periods, and, in certain cases, causing total power plant trips. This paper attempts to provide an interpretation on the physico-chemical mechanism of amorphous silica deposition, through a comprehensive correlation of fluid chemistry, field inspection data, operating parameters, and engineering design of the Fluid Collection and Disposal System (FCDS) of the Palinpinon-I geothermal production field, from 1984-2001, enable a better understanding of this phenomenon, and further minimize the associated operating problems.

The latest inspections indicate a reduced annual deposition rate of 8-19 mm in the cross-country reinjection lines of zero inclination, compared to earlier values. Correlation calculations reveal that fluid chemistry, line separation temperatures, flow regime, fluid velocity, and line gradient of the separated brine are the critical factors which influence the rate of amorphous silica deposition. Mechanical well work-over and acid injection, line scale removal also by mechanical method, installation of deposition spools in long brine lines of zero gradients, relocation of vessel isolation valves, and re-orientation of two-phase line interconnections, have been adopted as remedial solutions only. For future engineering design, drastic increases in diameters of interconnected pipes, zero inclination of cross-country brine lines over long lengths, line fluid velocities of less than 2.0 m/sec, and partially-liquid filled operation of the brine lines, should be avoided.

1.0 FIELD DESCRIPTION, FLUID COLLECTION AND DISPOSAL SYSTEM

Figure 1 shows the location and structural map of the Southern Negros Geothermal Production Field (SNGPF). The SNGPF is located in Negros Island (inset), central Philippines, and is subdivided into two geographical areas, Palinpinon-I and II. Palinpinon-I has an installed capacity of 112.5 MWe (3x37.5 MWe Fuji turbines), and was commissioned in May 1983. Palinpinon-II, which consists of the Balas-balas 1x20 MWe, Nasuji 1x20 MWe, and Sogongon 2x20 MWe modular power plants, also all Fuji, were commissioned in December 1993, June 1994, and January 1995, respectively. A total of 75 wells ranging in measured depths of 603m to 3497m, have been drilled in the SNGPF. The production wells produce from a high temperature, liquid dominated reservoir (Maximum measured temperatures of 320°C in well PN-20D) that is in equilibrium with quartz. The field and hydrological reservoir model has been extensively discussed by several authors, and will not be dealt here.

The Palinpinon-I Fluid Collection and Disposal System (FCDS) is shown in Figure 2. Twenty two productive wells, out of 28 drilled, are distributed over five production well pads and connected via individual 254 mm two-phase lines, which converges into 508 and 762 mm headers, and into a central separator station consisting of twelve separator vessels (SV101-112) of 10 MWe capacity each. The separated steam at a pressure of 0.68 MPaa from each vessel is interconnected to 4 x 914 mm cross-country steam lines, before it is again combined to a single 1524 mm header of the National Power Corporation (NPC). The combined water flow from the 254 mm waste water outlets of

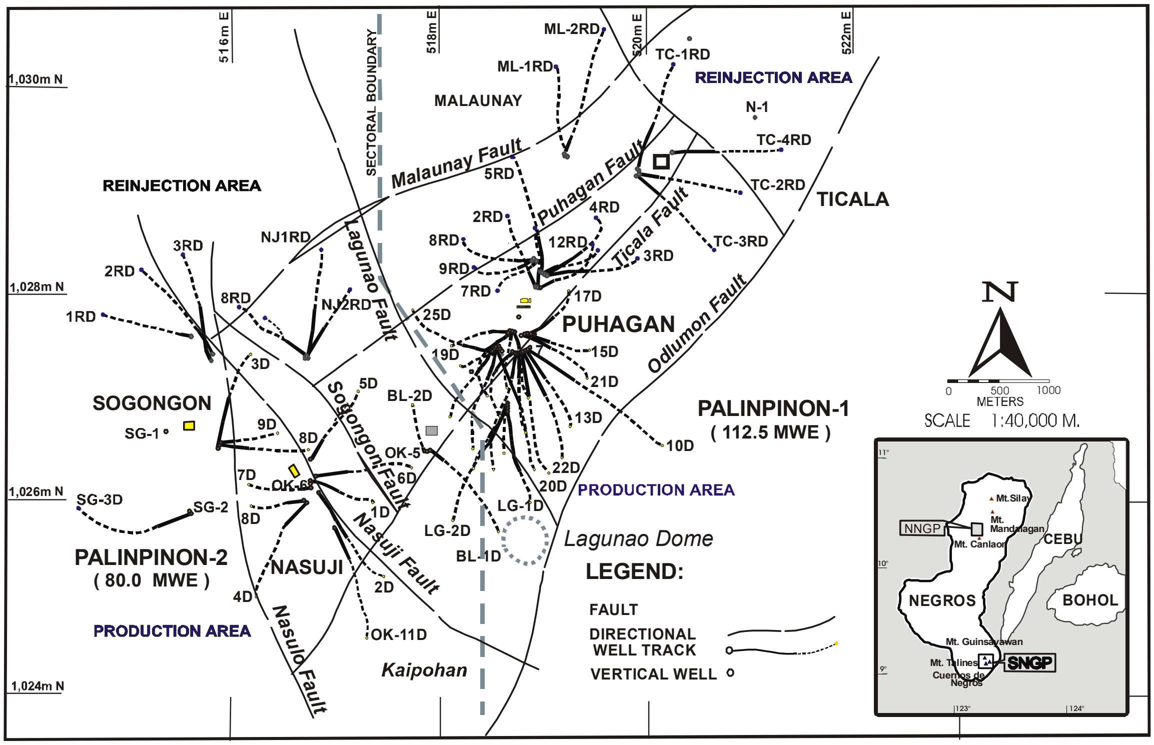

Figure 1. Location and structural map of Southern Negros Geothermal Production Field (SNGPF).

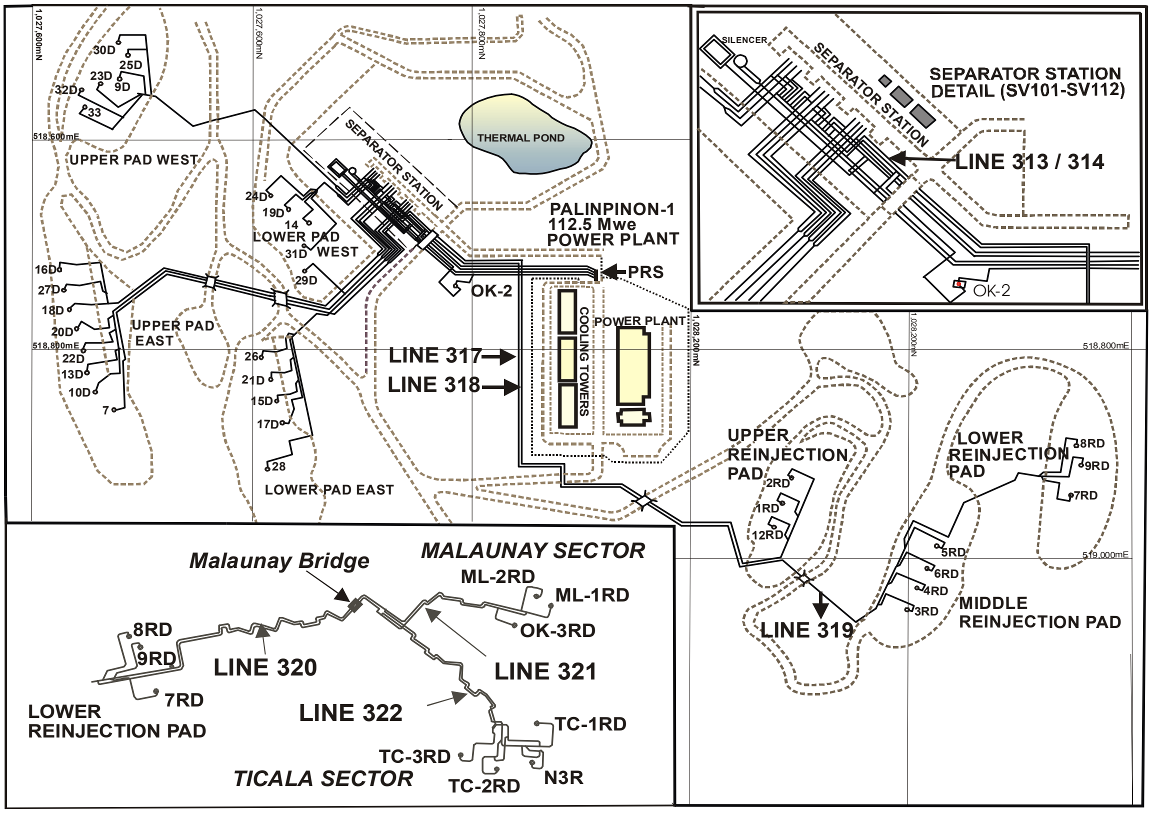

Figure 2. The Palinpinon-I geothermal field Fluid Collection and Disposal System (FCDS).

each vessel are chanelled into 2 x 610 mm main brine lines 313 and 314. Further downstream (line 317 and 318), the two lines are currently connected by the 350 mm line 322 to reinjection wells in the Ticala pad (TC-1RD, TC-2RD, TC-3RD and TC-4RD) by line 321 and in the Malaunay pad (wells OK-3, ML-1RD and ML-2RD). Prior to 1989, reinjection was concentrated in the eastern, western, and northern Puhagan reinjection wells, but, except for well PN-5RD, all the wells showed very rapid reinjection fluid returns to the production wells, hence, the bulk injection was shifted towards the current sector. The silica saturation indeces during the commissioning phase of the separated water vary within a narrow range of 1.00 to 1.10, and 1.03 to 1.15 (Line 317 and 318, Palinpinon-I), 1.08 to 1.15 (Nasuji brine line), 1.05 to 1.10 (Sogongon-I brine line), and 1.10 to 1.20 (Sogongon-II brine line). With time, Palinpinon-I silica concentrations gradually decreased to slightly below amorphous silica saturation levels (Figure 3), and this is attributed to the cooling of reservoir fluids due to the combined effectof reinjection fluid returns, pressure drawdown, and entry of shallow, less mineralized, cooler fluids.

2.0 LOAD GENERATION HISTORY AND OPERATIONAL CONSTRAINTS

The Palinpinon-I Geothermal Power Plant has been operated at variable loads (load following). Initial generation was low (10-15 MWe between 1983-1984), mainly due to the shutdown of a mining operation connected to the grid. Corresponding brine flows were also low (~100-200 kg/s). The generation increased only when the neighboring islands of Panay and Cebu were interconnected to the grid by submarine cables in 1989 and 1994, respectively. The load variations created gross differences in line fluid velocities and injection mass flow rates with time. The calculated velocities at the region of the lowest loads ranged only from about 0.20-1.20 m/s. This variable load is believed to have influenced the nature of silica scale growth over the past twenty years, particularly the common characteristic of distinct phases of banding and interlayering. Since August 1999 to end of 2002, the power plant had been on 3 units (full load operation), with peak loads of 95-97 MWe, though there were also periods of reduced loading during both scheduled and unscheduled shutdowns of the individual turbine units as dictated by the maintenance programme and other operating exigencies of the National Power Corporation (NPC).

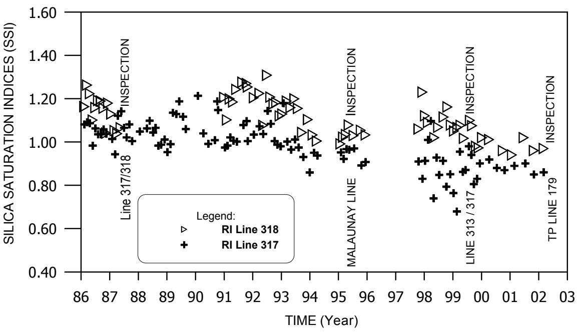

Figure 3. Palinpinon-I reinjection line 317 and 318 SSI's vs. time.

Despite this relatively low degree of brine supersaturation, silica deposition has been identified as one of the operating constraints in sustaining the steam supply for the Palinpinon-I 112.5 MWe Power Plant from 1983 to 1999 (Jordan et al., 2000). Deposition varies in rate and magnitude, and has been documented to occur in separator vessels, waste water lines, cross-country reinjection lines, reinjection well branchlines, in the reinjection well bores, and also immediately downstream of valves, solid traps, and Y-strainers. The operational problems experienced are the restricted flow in brine lines, reduced injection well capacities, and, consequently, costly removal operations for remedial measures. For example, six reinjection wells in Palinpinon-I (PN-2RD, PN-8RD, TC-1RD, TC-2RD, OK-3R and PN-5RD) have been worked over and acidized to recover original capacities, and a redundant reinjection line to the Ticala and Malaunay injection pads had to be constructed to maintain line utilization flexibility especially at high plant loads. Other specific problems experienced were clogging of standpipe and level switch isolation valves, clogging of drains, hard operation of control valves, and uncertainty in water flow measurements using the orifice plate method.

3.0 DOCUMENTATION HISTORY

3.1 Silica Deposition in Reinjection Lines

Major cross-country reinjection line inspections and scale removal operations have been conducted in 1987, 1995, 1999, 2000, and 2001.

Table 1. Summary of cross-country line inspections and documentation, 1987-2002

Year	Injection Line/ Size, (mm)	Scale Thickness Range, mm	Ave. Deposition Rate (mm / year)	Petrochemical Analysis
1987	RL 313 / 317 (600)	0-305	38	65% opal, 35% opaques, 0-10% well debris
	RL 318 / (600)	38-254	63	No data available
1995	RL 321 / (350)	14 (Ave.)	2.4	Amorphous silica, with iron oxides
1999-2001	RL 313 / 317 (600)	0-203	9	70-80% amorphous silica, 20% amorphous clay, <1% cuttings
2002	Two-phase line179 /(500)	50-75	Not Applicable	50% multi-layered amorphous silica, 25% cement, 10% corrosion prod.

A summary of the pertinent field data during these inspections is shown in Table 1. The common composition of the mineral deposits is hydrated, banded and interlayered light gray to black, amorphous silica comprising at least 80% of the recovered samples. Impurities vary in composition, but consist mainly of 3-5% corrosion products (hematite, magnetite, goethite) and rock cuttings imbedded in the silica deposit. In some recent samples from separator vessel 111, impurities comprising about 12%, were identified as fragments of plagioclase, epidote and opaques, smectite-vermiculite scales and cryptocrystalline materials (Dulce and Delfin, 1999). The only difference in composition of the scale samples between the 1987, and later 1999-2001 inspections, was the presence of more impurities (well debris of 1-12%) in the former, compared to <1% in the latter period. The first documentation to be conducted since commissioning was in vessels 107 and 108 (Mongcupa, 1984). Heavy deposition, identified as banded and interlayered amorphous silica, was observed to occur within the vessel, and along the 250 mm waste water lines upstream of the level control valves, where thickness ranged from 4-22 mm. Downstream of this section, deposition was considered minimal over the length of time these vessels were in service (about three months). This trend is consistent with the low fluid velocity sections of water lines.

The first major inspection and documentation of the cross-country brine lines was done in 1987, in cross-country lines 313, 317 and 318 (Virata, 1987). Two observations are notable: (1) heaviest deposition occurred along the pipe sections with valves and fittings that create additional turbulence, i.e. downstream of branchline isolation valves, in the vicinity of pipeline junctions, cross-over lines, and orifice plates. For example, in the line at upper reinjection pad (URP) downstream of the block valve, deposition was thickest at 305 mm, covering nearly 50% of pipe cross-sectional area. In the 600 mm cross-country reinjection lines, along the horizontally oriented sections, i.e the entire length in 317 and 318 (back of the cooling tower of the power plant) and the trench at middle reinjection pad (MRP), deposition was also heavy, at 150-305 mm thick. Scale deposits are generally thickest in the lower half of the pipe cross-section, and thin out towards the upper half, indicative of only a partially liquid filled line. (2) in all the inclined sections of the pipelines, very minimal deposition was observed.

In 1995, six years after the commissioning of the Malaunay reinjection line, the 250 mm branchlines of well OK-3R, ML-1RD and ML-2RD were inspected, and the results showed cumulative deposition, ranging from 8-40 mm, or a calculated rate of 1.6-6 mm/year. However, in contrast with line 317/318, the distribution of the silica scales in the entire pipe cross section is concentric, and the deposition rates are substantially lower. Figure 4 shows a representative photograph of this type of deposition noted in the horizontal section of the Malaunay branch line within the reinjection well pad.

In May and July 1999, inspections were conducted in line 313, 317, and in line 319 (along the cross-country lines to Ticala) during the 3 days total plant shutdown of Palinpinon-I. In the 600 mm line 313, heaviest deposition, ranging in thickness from 100-200 mm, was observed. Further downstream at the back of the cooling tower, the deposition thickness was still significant at 100-120 mm. Figure 5 shows a representative section of line 313 and 317 at the longest horizontal section of the pipeline. Except in a limited section in line 313, there is an observed reduction in the deposition rate in line 317 from 1987 to 1999, and a consistent correlation between the rate of deposition and pipe orientation, fluid velocity, flow regime, and silica saturation index. Full scale removal in line 317 was only pursued the following year (March 2000) when the National Power Corporation implemented a one month, one unit preventive maintenance shutdown, while that in line 319 was conducted only in April to July of 2001. Compared to line 317, 319 had shorter lengths necessary for scale removal, with the deposits thinner, well distributed throughout the pipe circumference, but harder. This is type of deposition is postulated to be the result of operating the line at full liquid conditions, where turbulence is absent, as will be elaborated in succeeding sections.

3.2 Silica Deposition in Two-phase Lines

In June 2002, the 508 mm two-phase line 179 supplying vessels 101 and 102 was also subjected to internal inspection as an off-shoot of the necessity to further investigate the unusual presence of debris the amount of which practically sealed off the entire 250 mm waste water line of separator vessel 102. This phenomenon even contributed to the total power plant trip on May 6 2002. In the case of line 179, the production line of one of the wells (OK-2), is uniquely introduced into the system through a stub-in perpendicular to the flow and proximate to the bifurcator, very much different from the others wherein the wells on line converge to the header several hundred meters away from the bifurcator ensuring a more laminar flow to the separator vessels. The internal inspection of line 179 bared the location of significant deposition, which originated from the point where OK-2 "stub-in" is located and farther downstream to the bifurcator where deposition is thickest on both sections of the 500 mm lines. A representative photograph of the inspection results is shown in Figure 6. It is unlikely however, that the deposition extends farther to the vessel, since inspection at the vessel entry yielded negative results. A re-engineering program on line 179 is awaiting implementation to undertake spooling from the bifurcator to the

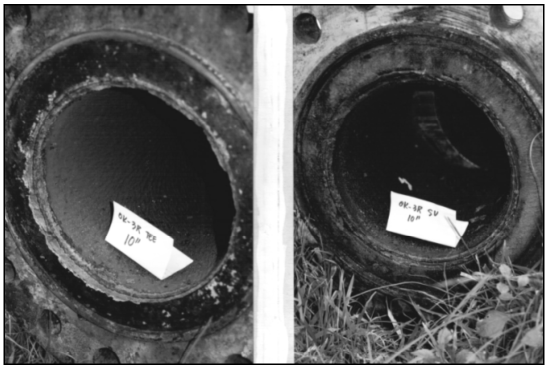

Figure 4. Section of 250 mm Malaunay branch line 321.

Figure 5. Section of 810 mm line 317, horizontal most section (back of cooling tower).

Figure 6. Section of 508 mm two-phase line 179, 2m downstream of ell OK-2 tapping

separator vessels. Spooling shall be such that the bifurcator and its downstream and upstream sections can be periodically inspected and cleaned of scale deposits. So far, no other two-phase line has manifested problems like line 179.

3.3 Silica Deposition in Reinjection Wells and Formation

Six reinjection wells (PN-8RD, PN-2RD, TC-1RD, TC-2RD, OK-3R and PN-5RD) have shown injective capacity declines attributed to amorphous silica deposition inside the wellbores, and even in the formation. Consequently, these wells were worked over and acidized. Their injection capacities have been restored, even greater than its original values. However, with continued utilization, capacities generally show a consistent decline. Table 2 summarizes the history and cost of well work-over and acidizing. The rate of well work-over under the given Palinpinon-I brine chemistry and flow rate history is one well after every two years and eight months. Well OK-3, (this well was commisioned in 1989) for example, showed a significant decline in its capacity from about 120, to 20 kg/s. This well was worked-over and acidized after six years of utilization due to a silica scale deposits, pervasive in the well bore which were found during the clearing process. The acidizing operation initially recovered about 90 % of its capacity, but with only about 3-4 months of re-utilization, its capacity decreased and stabilized at about 20-30 kg/s, and to date is nearly zero. Repeated downhole surveys, however did not show any obstruction up to the bottomhole. The latter trend has been interpreted to be a combination of formation damage by silica deposition in the cooler country of the outflow zone, and interference from nearby injection wells ML-1RD and ML-2RD.

4.0 FLUID VELOCITY, PIPELINE SLOPE, AND TURBULENCE VS. SILICA GROWTH RATE

Velocity, pipeline section configuration and orientation, and turbulence, were observed to be the dominant factors affecting silica scale growth rates in the Palinpinon-I brine lines (Borromeo, 1983; Jordan et al., 2000). Using more recent line inspection data (1999, 2000, and 2001) and actual line velocity measurements using chemical tracers (instead of relying on flow rates and pipe diameters), this correlation, and scale growth predictive method were validated and calibrated further with the added data points, and this is shown in Figures 7 and 8.

Table 2. Summary of reinjection wells worked-over and acidized, in Palinpinon-I from 1984-2000.

Reinj. Well	Commiss'ng. Date	Date of Work-Over / Acidz'g.	Total Cost (K $)
PN-8RD	April, 1984	March 1987	113.53
PN-2RD	May, 1983	April 1993	328.82
OK-3R	October, 1989	August 1995	271.58
TC-1RD	August, 1990	March 1994	369.9
TC-2RD	February1991	April 1994	321.25
PN-5RD	May, 1983	Sept., 1999	127.5
		Grand Total (K$)	**1,532.58**

It is noted that although the estimated velocities in the branchlines and tees of ML-1RD, ML-2RD and OK-3R are low, deposition rates are comparatively lower than in 317 and 318. Based on the monthly reinjection line pressure profiling conducted since commissioning to date, the sections operated at liquid filled conditions starts at the upper reinjection pad, where line pressures significantly increase above separator pressures, i.e. to 0.84 MPaa, downwards to the Ticala and Malaunay reinjection wells. Thus, due to the operation of the line at liquid filled conditions starting from this point, turbulent flow is eliminated and effectively reduced the deposition rates. This explains the more concentric distribution of silica scales to the walls of the pipelines, and the low deposition rates observed in Malaunay line 321, and in the individual branchlines of OK-3, ML-1RD, and ML-2RD, despite the lower line fluid velocities.

Using Figure 7, the predicted deposition rate in line 317 would be 7-9 mm/year, while using the actual scale thickness measurements, the scaling rate would be 8-19 mm/year. The lower rates using the predictive method are attributed to the methodology of fluid velocity estimates utilized in calibrating the curves (using mass flows and pipe sizes), vs. the current projections, which utilized actual line fluid velocity measurements using chemical tracers. The former could have underestimated fluid velocities (assumed a clean pipe), resulting in lower predicted deposition rates.

Figure 8 shows the plot of the calculated deposition rate vs. the inclination of the pipelines

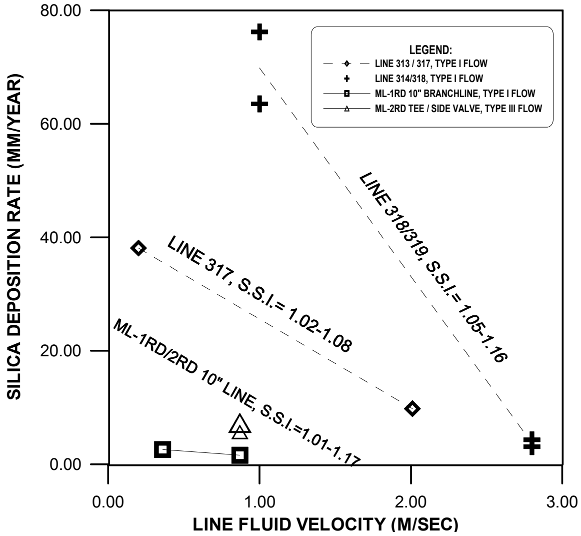

Figure 7. Silica deposition rate vs. fluid velocity, type I and III flows (Jordan et al., 2000).

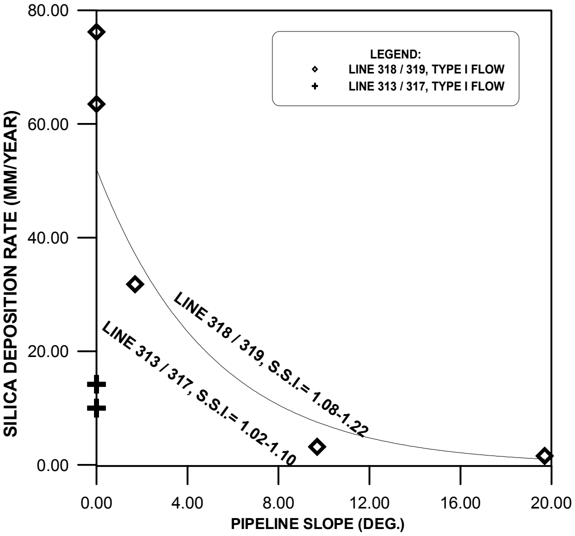

Figure 8. Silica deposition rate vs. pipeline slope (after Jordan et al., 2000)..

at the point of sample collection. Minimal deposition rates are consistently observed in line slopes of at least 1.7° at a saturation index of 1.05 to 1.10 (line 317). At higher saturation indeces of 1.08 to 1.15 in line 318, this limit increases to 9.7°. This is interpreted to be due to the reduced influence of gravitational segregation that induces silica polymers to drop out from solution as a solid particle. Reinjection pipelines should be provided with such minimum inclination to minimize silica deposition rates.

5.0 PREVENTIVE AND REMEDIAL SOLUTIONS

In the early design phase and commissioning of Palinpinon-I, the only preventive measure adopted was to maintain the calculated silica saturation index close to 1.00, i.e. separation pressures of not lower than 0.68 MPaa. Initial design of the FCDS provided for the installation of solid traps and Y-strainers immediately upstream of reinjection well heads, line spooling in horizontally oriented lines and drain valves. Later, adequate line gradient, better insulation to minimize heat loss, and establishment of a lower limit in the fluid velocities were considered during the design and construction of the extended reinjection line to the Ticala and Malaunay wells in 1989, and the redundant line in 1995.

In the first few years of Palinpinon-I operation, the practice of hot-slugging (raising separation pressures and temperatures to lower the existing brine saturation indeces to less than 1.00, before a reinjection well is de-commissioned) was adopted. This practice was however, discontinued since its benefit was transient, i.e. saturation indices in the well bore were dictated by the final equilibrium temperature between the injected fluid and wellbore temperature. Thus, the only remedial measures adopted were: (1) de-commissioning, and de-scaling of the affected line, or vessel by mechanical means, using a long year 24 rig, (2) construction of a redundant reinjection line from the upper reinjection pad in Palinpinon-I to the Malaunay sector.

In 1987, the first major de-scaling of lines 317 and 318 had to be implemented. A total pipeline length of 1540 m was de-scaled for a period of seven months with a cost of US$25,800. This activity resulted in a load shedding of the Palinpinon-I Power Plant. Consequent to this experience, the lengths of pipelines oriented horizontally were spooled to allow future de-scaling operations. The second cross-country line inspection and de-scaling was conducted in 1995, in line 321 towards the branchlines of well OK-3R, ML-1RD, and ML-2RD. The total length de-scaled was 145 m using an X-ray drill, and which took 48 days to accomplish, at a total cost of US$1,000 (Abellon, 1995). A second major inspection and documentation was conducted in line 313 and 317 in July 1999, during the three days shutdown of the Palinpinon-I plant. A total of 39 m of the 600 mm line 313 to 317 was de-scaled for 12 days. In the year 2000, scale removal in line 317 was resumed, covering a total 442 meters of cleared pipelines. The balance of 143 meters represents the inclined sections of the lines and were found out to be free of deposits, and is consistent with previous correlations established using line 318 data that at slopes of greater than 2°, no deposition takes place. The most recent scale removal was conducted in line 319 in 2001, which did not require a power plant downloading since a redundant line was available. The effort lasted for 65 days and succeeded in clearing 188 meters of 600 mm pipeline. Comparatively, scale removal in line 319 took longer at a higher cost in spite of a shorter length than 317, due to its well adhered scale deposits, and, a long section of the pipeline is located inside trenches which requires a longer period to set up and pull-out the mechanical equipment. The total cost of these cleaning operations was $15,633 in 2000, and $7,799 in 2001.

In 1995, it was decided to implement the construction of a redundant reinjection line tapped from the Middle Reinjection Pad, to the Ticala and Malaunay reinjection wells. The total cost of this line was US $2,131,700. In the year 2002, FCDS maintenance scheduled and implemented the repair of pipeline insulation such as 200 meters and 165 meters of 16 inch and 30 inch lines, respectively. This is to prevent heat loss along the production two-phase lines of the system. In the immediate future and as soon as opportunity comes, the isolation valve entry of vessel 101 and 102 shall be relocated immediately downstream of the bifurcator and appropriate spooling undertaken, the former to eliminate “wet leg” during isolation of vessels. Besides, a backheating line and drains are to be provided to keep the line heated even when isolated. One of the main problems encountered during scale removal has been the unusually long sections of pipeline. Past experience suggests that pipelines should be reduced to a maximum of 20 meters spool to facilitate scale removal.

The use of chemical inhibitors was first tested in Palinpinon-I brine from 2000-2001 using the recently commercialized GEOGARD SX (Mejorada et al. 2001). The pilot tests results showed that at line concentrations of 0.50 to 1ppm, this inhibitor was effective, to a certain degree, of controlling silica deposition for this type of low saturation index fluids. The application of chemical inhibitors to date, however, have been limited only to the Botong sector of the Bacon-Manito geothermal Production Field, where silica concentrations are unusually high and field specific, i.e. silica saturation index of ~1.60. The remedial solution adopted, in the case of reinjection well capacity declines, is still by mechanical work-over with the use of a drilling rig, and later, the injection of acids.

6.0 COST COMPARISON - LINE / WELL MECHANICAL DE-SCALING VS. CHEMICAL TREATMENT

A cost comparison of these remedial measures with respect to the actual operating cost of the project indicates that it comprises only approximately 4.5%, and has been tolerably treated (i.e. between 1984-2002, the total cost of well work-overs / acidizing, line de-scaling, and redundant line construction was US$3,716,539, vs. an average annual (2002) total actual project operating cost of US$4,326,904. This cost was the actual cash flow, and excluded depreciation, and amortization, and uninflated to the current year). Despite this, alternative options have been reviewed with the purpose of improving the present operational and cost efficiency of dealing with this phenomenon.

Dolor (1995) reported that for the Palinpinon-I scenario, at an optimized inhibitor line concentration of 3.8 ppm, chemical treatment is more economical in regulating silica deposition than the present well maintenance program, then at the cost of the chemical inhibitor of US$12.64/Kg. However, the current market price of the same inhibitor increased to $25.00-30.00/Kg. The application of chemical inhibitors to specific wells with historical injective capacity declines (e.g. using well OK-3 as a model) due to silica deposition, would still be economical and worth pursuing (Mejorada et al. 2001). Other benefits associated with chemical dosing is the flexibility of decreasing separation pressures for more efficient geothermal fluid utilization, such as increased steam recovery by secondary flash, reduction of reinjection loads and number of make-up and replacement reinjection wells, reduction in non condensable gases, and reduction of environmental constraints arising from solid scale disposal requirements.

7.0 SUMMARY AND CONCLUSIONS

The primary factors governing the rate and magnitude of silica deposition in the injection pipelines are fluid chemistry, flow regime, fluid velocity, and line gradient. The current rate of deposition in the cross-country reinjection lines is 8-19 mm/year using the latest (1999-2001) inspection data. Amorphous silica deposition has been tolerated by PNOC-EDC both from the economic and operational points of view. However, options are available to improve the cost and operational efficiency of dealing with this problem. Raising the separation pressures to limit the brine saturation state to less than 1.00 is a strategy that has not changed for the past two decades. The opportunity to increase utilization efficiency, e.g. additional steam generation, say, by secondary flash and binary plants utilizing the heat of the waste brine is thus restricted mainly due to the risk of silica deposition from the supersaturated waste liquid. Application of chemical inhibitors might address this constraint. The measures adopted so far to control silica deposition are remedial, rather than pre-emptive, such as mechanical de-scaling of brine lines, construction of redundant reinjection lines, and work-over and acid injection using a drilling rig, in the case of reinjection wells. Future strategy of controlling silica depostion shoud be more pre-emptive, e.g. engineering design of reinjection lines should be constrained by line size optimization to maximize fluid velocity and line gradient. Operation at low plant loads should be constrained by a lower limit of brine flows for a given pipe diameter.

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