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A TECHNICAL AND COST ASSESSMENT OF SILICA DEPOSITION IN THE PALINPINON-I GEOTHERMAL FIELD, PHILIPPINES, OVER 16 YEARS OF PRODUCTION AND REINJECTION

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Key Words: Quartz equilibrium, silica saturation index, amorphous silica deposition, chemical inhibition.

ABSTRACT

This paper describes the comprehensive documentation of mineral (mainly amorphous silica) deposition, and the analysis of the factors controlling this phenomenon in the Fluid Collection and Disposal System (FCDS) of the Palinpinon-I Geothermal Production Field, from 1983-1999. The project economics involved in the adoption of remedial measures is also presented. The objectives of this study are: (1) to establish the factors that govern the deposition mechanism, (2) to provide constraints in the operation and design of the FCDS in existing, and future geothermal projects, (3) assess the economics of the present, vs. alternative methods in scale removal, and (4) recommend long-term preventive and remedial solutions.

The latest maintenance inspection indicates an annual deposition rate of 8-19 mm in the cross-country reinjection lines of zero inclination, and is consistently higher than the predicted growth rate of 7-9 mm. Correlation calculations reveal that flow regime, fluid velocity, line gradients, silica saturation index, and residence times of the separated brine are the critical factors which influence the rate of silica deposition. Economic sensitivity analysis demonstrates that although the cost of existing remedial measures is only in the order of 7% of the project's total operating cost, the alternative option of chemical treatment may further improve both the operational and cost effectiveness in dealing with this phenomenon.

1. INTRODUCTION

The Southern Negros Geothermal Production Field (SNGPF) is located in Negros Island, central Philippines, and is subdivided into two geographical areas, Palinpinon-I and II (Figure 1). 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 exploration, development history, and the field hydrological model have been published by several authors, and will not be dealt with here. The production wells produce from a high temperature, liquid dominated reservoir (Maximum measured temperatures of 320^0C in well PN-20D) that is in equilibrium with quartz. The silica saturation indeces of the water phases at different separation conditions vary within a narrow, and consistent range with time of 1.00 to 1.10, and 1.03 to 1.15 (Line 317 and 318, Paln-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).

2. OPERATIONAL CONSTRAINTS

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 1998 (Garcia et al., 1998). 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 primary constraints experienced are the flow reduction in brine lines and injection well capacities, and costly operations had been sunk 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 had to be constructed to maintain line utilization flexibility especially at high plant loads. Other 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. DOCUMENTATION HISTORY

3.1 Silica Deposition In Reinjection lines

Figure 2 shows the schematic diagram of the Paln-I FCDS, and the highlights (representative sampling points) of the documentation conducted in cross-country lines 317, 318 and 319 in 1987, 1995, and 1999. The documentation methods used are photography, thickness measurement, megascopic characterization, and petrochemical analysis of scale samples. 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. The only difference in composition of the scale samples between the 1987 and 1999 inspections were 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 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 second major inspection and documentation was done in 1987, in cross-country lines 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 thins 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. Thickest deposition was noted to occur in the tee and side valve of ML-2RD (Trazona and Camit, 1995). However, in contrast with line 317/318, the distribution of the silica scales in all the pipe cross section is concentric, and the deposition rates are lower.

In May and July 1999, major inspections were conducted in line 319, along the cross-country lines to Ticala and Malaunay, and, in line 317 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. At URP, thickness observed was 180 mm. 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: (1) pipe orientation (2) fluid velocitiy (3) flow regime, and (4) silica saturation index.

3.2 Silica Deposition in Reinjection Wells and Formation

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 initially, even greater than its original values. However, with continued utilization, capacities generally show a consistent decline. Table 1 summarizes the history and cost of well work-overs and acidizing. The rate of well work-overs under the given Palinpinon-I brine chemistry and flow rate history is one well after every two years and eight months.

Figure 3 shows an illustration of injective capacity decline with time using well OK-3R data. This well was commisioned in 1989, and was worked-over and acidized after six years of utilization due to a significant decline in its capacity from about 120 to less than 20 kg/s. Silica scale deposits, pervasive in the well bore, 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. 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. LOAD GENERATION HISTORY AND FLUID VELOCITIES

The Palinpinon-I Geothermal Power Plant has been operated at variable loads (load following). Initial generation was low (10-15 MWe), mainly due to the shutdown of a mining operation connected to the grid. Corresponding brine flows were also low (~100-200 kg/s). This scenario changed only when the neighboring islands of Panay and Cebu was interconnected to the grid by submarine cables in 1989 and 1994 respectively. The load variations created gross differences in line fluid velocities and 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 is one factor believed to have influenced the rate of silica scale growth over the past sixteen years, particularly the common characteristic of distinct phases of banding and interlayering.
Since August 1999, the power plant plant had been on 3 units (full load operation), with peak loads of 97-105 Mwe.

5. SILICA GROWTH RATE VS. BRINE VELOCITY AND PIPELINE SLOPE

The first attempt to quantitatively correlate the silica scale growth rate, fluid velocity, pipeline orientation, and silica saturation index, was done by Borromeo (1993). The methodology of this statistical approach used data from actual line inspection and correlated with brine velocities and silica saturation indices. Fluid flows were classified as type I, II and III, representing flows in horizontal, inclined pipes, and in pipe bends / constrictions, respectively. Velocity and pipeline section configuration were observed to be the dominant factors affecting silica scale growth rates. Using more documentation data obtained from the May and July 1999 line inspections, and actual line velocity measurements using sodium fluorescein chemical tracer (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 Figure 4. It is noted that although the estimated velocities in the branchlines and tees of ML-1RD/2RD and OK-3R are low, deposition rates are comparatively lower than in 317 and 318. This is interpreted to be due to the operation of the line at liquid filled conditions, which eliminated turbulence and effectively reduced the deposition rates. Using Figure 4, 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 is 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 sodium fluorescein tracers. The former could have underestimated fluid velocities (assumed a clean pipe), resulting in lower predicted deposition rates.

Figure 5 shows the plot of the calculated deposition rate vs. the inclination of the pipelines at the point of sample collection. Minimal deposition rates are consistently observed in line slopes of at least 1.7^0 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 9.7^0 . 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.

6. EFFECT OF PARTIAL VS. COMPLETELY LIQUID FILLED INJECTION LINES

Monthly injection line pressure profile measurements have been conducted in Palinpinon-I since commissioning, a typical profile (Sept. 1999 test) of which is shown in Figure 6. Based on the pressure readings from 27 test points, the section operated at liquid filled conditions is estimated to commence above the upper reinjection pad at an elevation of 660 m AMSL, and downstream towards the Malaunay and Ticala reinjection wells. Starting at said point, line pressures significantly increase above separation, to 0.74 MPabs. Upstream of this point, the lines are only partially filled. The reason for this condition is that the level control valves in the 250 mm waste water outlets of the separator vessels are partially throttled to maintain a required, normal water level; consequently, this creates flashing and additional turbulence due to the increase in pipe diameter from 250 to 600 mm in the cross-country line. Partial filling of the lines provide space to create more brine turbulence as it migrates with the steam phase along the pipe network, being further enhanced by abrupt changes in flow directions and pipe diameters, i.e. across orifice plates, tees, etc. Turbulence increases the incidence of collision between silica molecules, and the degree of adhesion of the silica particles with the pipewalls. On the other hand, turbulence is minimized in lines operated at liquid filled conditions, hence this collision incidence is also reduced. This explains the low deposition rates observed in the Malaunay brine line 321, and the individual branchlines of well OK-3, ML-1RD, and ML-2RD.

The deposition rates in line 317 and 318 showed an overall decline in 1999, compared to 1987, and this is attributed to: (1) higher brine loads and velocities in 1999, (2) less well debris in the scale samples, (3) less degree of level control valve throttling at higher plant load and consequent reduced extent of line turbulence, and, (4) decrease in silica saturation indeces, as a result of reservoir processes that reduced temperatures in some wells, as shown in Figure 7.

7. PREVENTIVE AND REMEDIAL SOLUTIONS

In the early design phase of Palinpinon-I, the preventive measures adopted were: (1) Separation pressures were limited to 0.68 MPabs., to maintain the silica saturation index close to 1.00, or lower, (2) Installation of solid traps and Y-strainers immediately upstream of reinjection well heads, (3) Provision for line spooling in horizontally oriented lines and drain valves (4) Other design parameters such as 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 Ticala/Malaunay reinjection line 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 adpoted. 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. The only remedial measures adopted were: (1) de-commissioning, and de-scaling of the affected line 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 length 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). The most recent line (313 and 317) inspection and documentation was conducted in July 1999, during the three days shutdown of the Paln-I plant. A total of 39 m of the 600 mm line 313 to 317 was de-scaled for 12 days.

To address this operational constraint with more efficient methods, alternative options have been tested. In 1987, the first concept tested in SNGPF was to use heated, de-aerated river water to dilute the separated brine to silica saturation indices of less than 1.0. The pre-heating and de-aeration process was achievable using excess steam, but the cold water flow requirement, and the added injection load created more constraints that further tests were discontinued. 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. The use of on-line chemical inhibitors was first considered in 1992, and pilot experiments using the inhibitor (recently commercialized as GEOGARD SX) was conducted in the Malitbog sector of the Leyte Geothermal Production Field (Garcia et al., 1998). 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. Application in other fields, where silica concentration are lower, remains to be demonstrated. The remedial solution adopted to deal with reinjection well capacity declines was done initially by mechanical work-over with the use of a drilling rig. Newer technology such as the injection of acids, was adopted lately.

8. COST ANALYSIS - CHEMICAL TREATMENT AND LINE/WELL MECHANICAL DE-SCALING

A cost comparison of these remedial measures with respect to the actual operating cost of the project indicates that it comprises only about 7%, and has been considered operationally tolerable (i.e. between 1983-1999, the total cost of well work-overs / acidizing, line de-scaling, and redundant line construction was US$3,691,080, vs. an average annual total project operating cost of US$3,373,040. This cost was the actual cash flow, and excluded depreciation, amortization, insurance, 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.

A company wide economic analysis have been conducted by Dolor (1995) on the option of using an on-line chemical treatment vs. that of mechanical de-scaling, construction of redundant lines, and well work-overs and acid injection. For the Palinpinon scenario, calculations show that at optimized inhibitor line concentrations of 3.8 ppm, chemical treatment is more economical in regulating silica deposition than the present well maintenance program at then the cost of the chemical inhibitor of US$12.64/Kg. 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 elimination of environmental and cost constraints arising from solid scale disposal requirements.

9. SUMMARY AND CONCLUSIONS

The principal factors governing the rate and magnitude of silica deposition in the injection pipelines are flow regime, fluid velocity, line gradients, and silica saturation index. The actual rate of deposition in the cross-country reinjection lines is 8-19 mm/year using the 1999 inspection data. Comparison of the predicted and actual deposition rates revealed higher rates in the latter, and this is attributed to the method of estimating fluid velocity that is used to calibrate the curve. 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 only remedial measures adopted so far are limited to 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 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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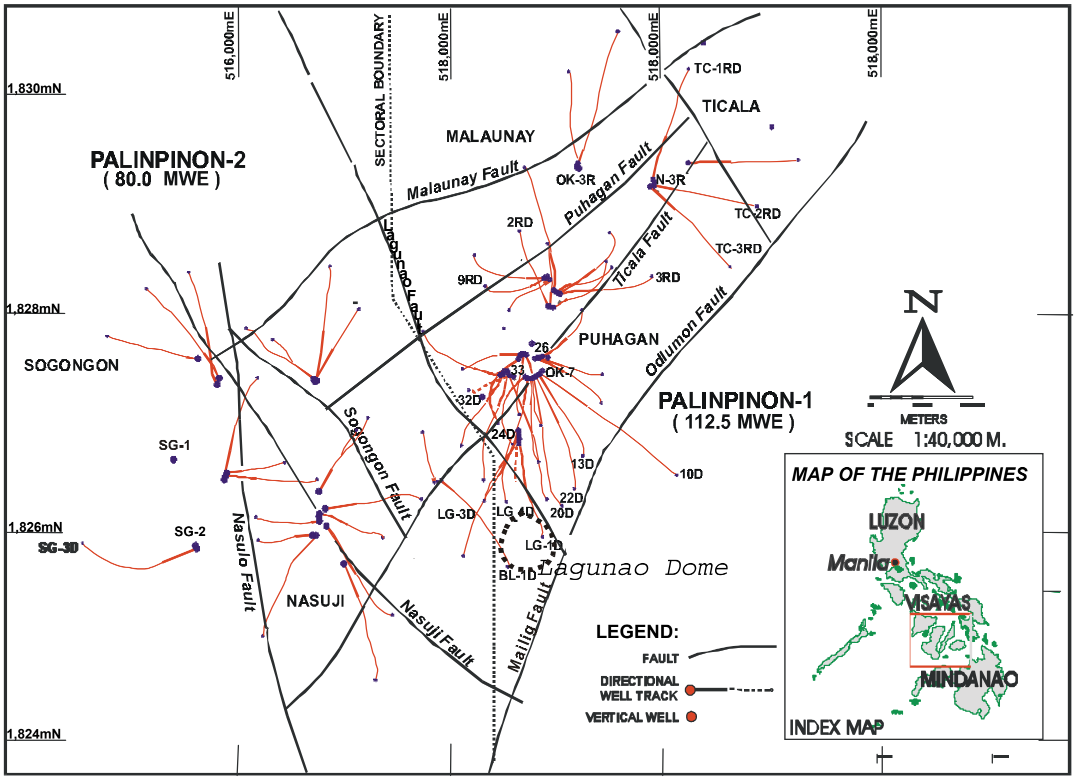

Figure 1. Location map, Southern Negros Geothermal Field, showing the Palinpinon-I and II geothermal production fields.

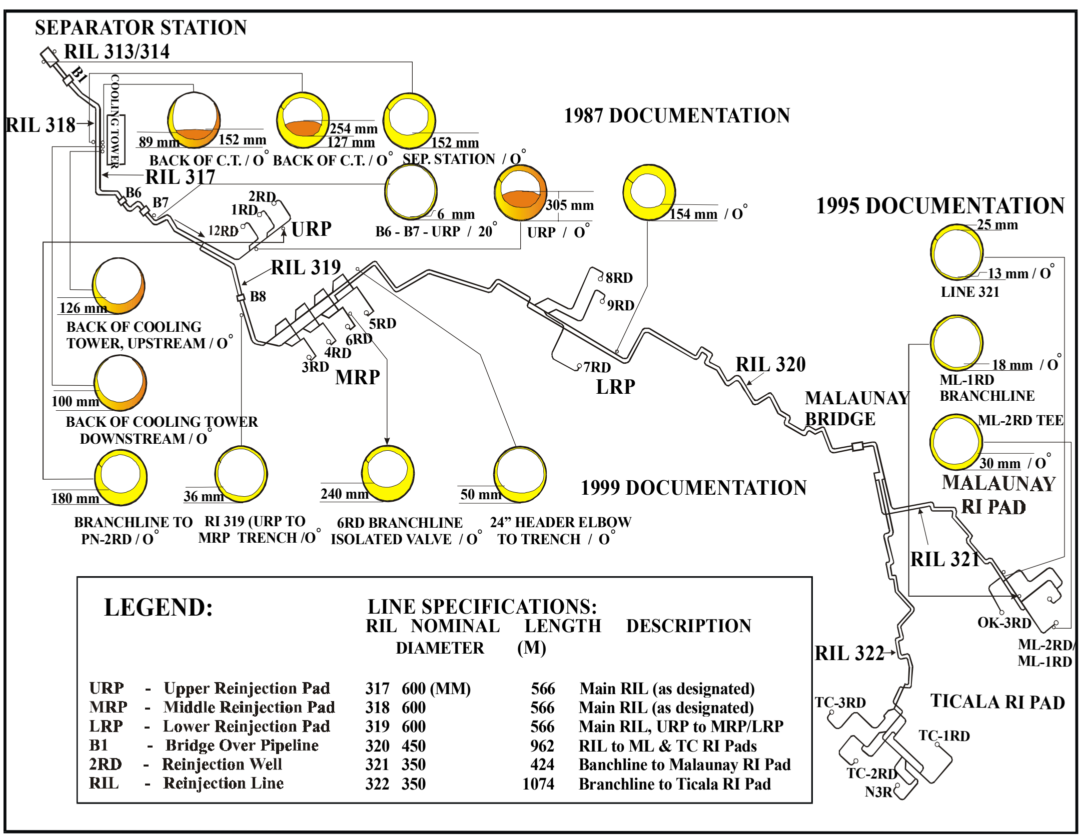

Figure 2. Palinpinon-I reinjection line schematic diagram and representative documentation results, 1987, 1995, and 1999.

Table 1.
Summary of injection wells worked-over and acidized, and total cost involved in Palinpinon-I, from 1984 -1999.

Reinj. Well	Commiss'ng. Date	Date of Work Over / Acidz'g.	Total Cost(K$)
PN-8RD	April, 1984	March, 1987	113.53
PN-2RD	May, 1983	April, 1993	328.82
OK-3R	October, 1989	August, 1995	271.58
TC-1RD	August, 1990	March, 1994	369.90
TC-2RD	February, 1991	April, 1994	321.25
PN-5RD	May, 1983	Sept., 1999	127.50
		GRAND TOTAL (K$)	1,532.58

Notes: (1) Costs in US$ and excludes rig mobilization.
(2) Only wells PN-8RD/PN-5RD were not acidized.

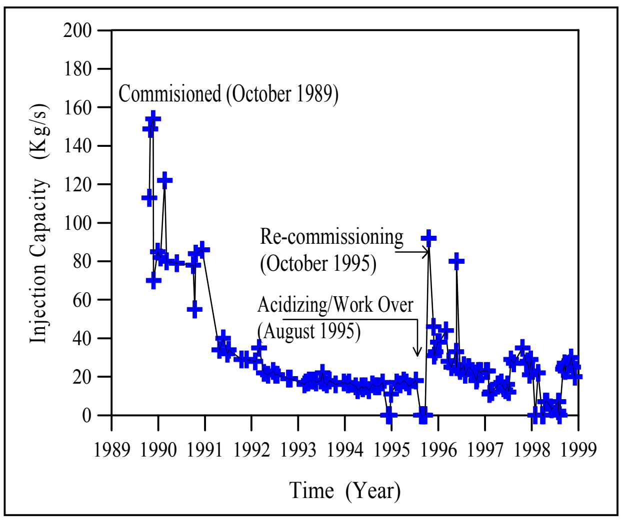

Figure 3. Well OK-3R Injection capacity vs. time

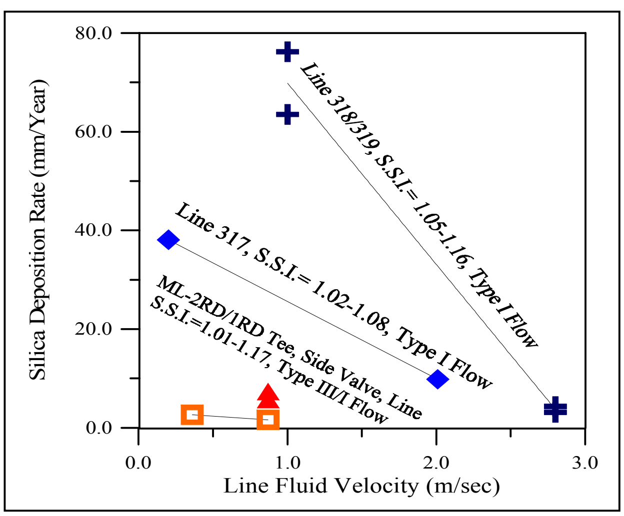

Figure 4. Silica deposition rate vs. line fluid velocity (Revised and updated after Borromeo, 1993).

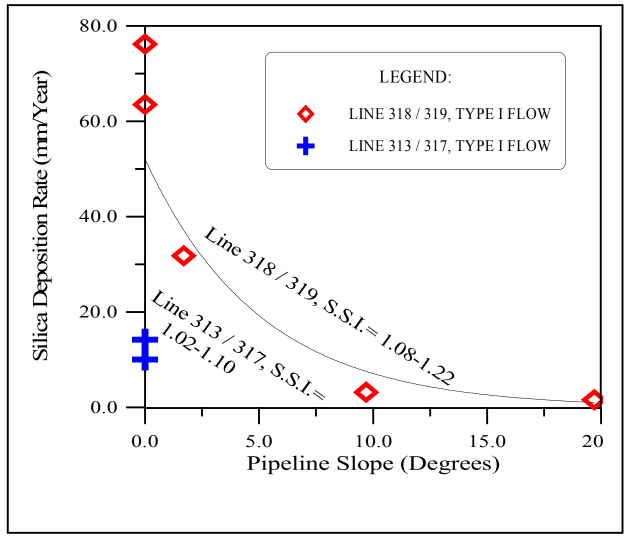

Figure 5. Silica deposition rate vs. pipeline slope (revised after Borromeo, 1993).

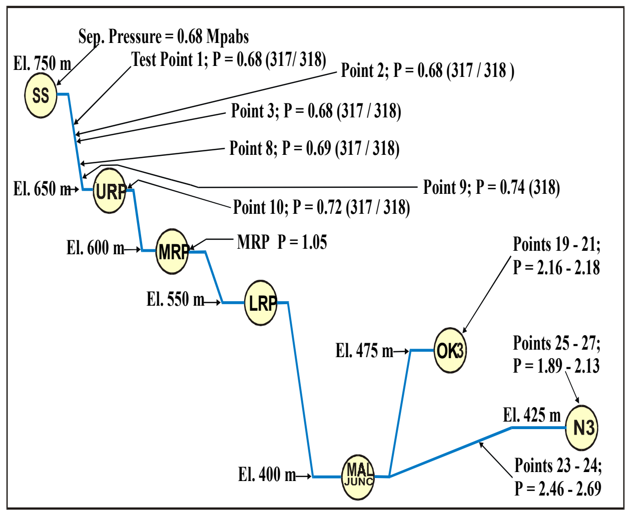

Figure 6. Palinpinon-I typical line pressure profiling (September 1999 measurements).

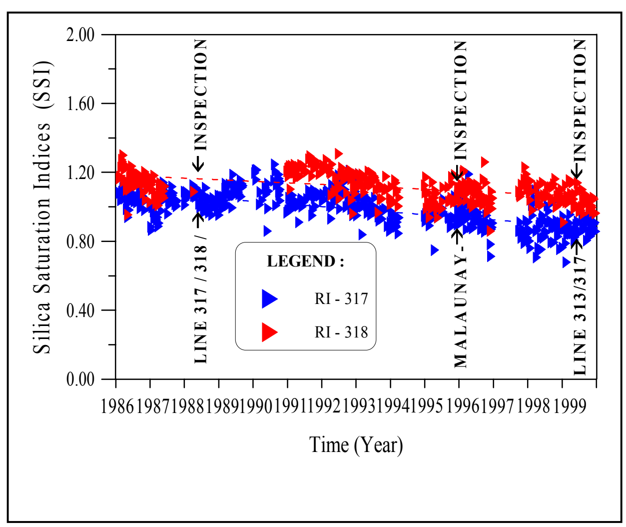

Figure 7. Palinpinon-I line silica saturation indeces vs. time