FLUID TRANSPORT AND SILICA SCALING POTENTIAL IN CROSS-COUNTRY REINJECTION LINE : THE CASE OF 4RC RI LINE, LEYTE, PHILIPPINES

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ABSTRACT

Optimized transport of waste fluids in the 4RC reinjection main line is determined by evaluating the silica scaling potential at different load utilization. This is in view of the reinjection management strategy for the South Sambaloran and Tongonan sectors of the 700 MWe Leyte Geothermal Production Field. Diversion of wastewater load in 4RC line to the Mahiao in-field reinjection sink is being considered to provide pressure support and arrest the observed fieldwide pressure drawdown.

Results of the study show that at current utilization (200 kg/s), the scaling potential at 4RC reinjection main line is within acceptable levels (SSI<1.13). However, minimum utilization should be 100 kg/s. Flows lower than this may cause severe silica deposition. The reinjection management strategy is feasible up to a maximum diverted flow of 100 kg/s from the 4RC line to the Mahiao reinjection sink. At this utilization, silica scaling potential throughout the pipeline is still within acceptable levels (SSI < 1.16). Validation of simulated values at 150 kg/s show that the actual and calculated SSI values and total brine residence time are comparable.

1.0 INTRODUCTION

The 700 MWe (total rated plant capacities) Leyte Geothermal Production Field (LGPF) is comprised of six sectors namely: the Tongonan-1 main and topping plants (130.5 MWe); the Upper Mahiao main and binary plants (124 MWe); South Sambaloran and Malitbog main and bottoming plants (245 MWe), and the Mahanagdong-A and B main and topping plants (198 MWe). The central sector of South Sambaloran (161 MWe) was initially estimated to handle 400 kg/s of wastewater for disposal. With the experience of reinjection returns being observed with in-field reinjection at Tongonan-1 Mahiao reinjection sink, it was decided to dispose the South Sambaloran wastewater load outfield in the northwestern 4RC reinjection sink. Thus, the 8.6 km 4RC RI line from Separator Station-32 (SS-32) to 4RC pad was constructed, the longest cross-country reinjection line to be operated in any PNOC-EDC steamfield.

With the onset of simultaneous operation of 381.5 MWe of power from the central sector, the massive field exploitation is expected to cause fieldwide reservoir pressure drawdown. In fact, initial signs of reservoir drawdown have been detected with the recent increase in discharge enthalpy and well dryness and changes in chemistry of the discharge fluids. This resulted in a decline of separated wastewater from SS-32 to around 200 kg/s and the under-utilization of the 4RC RI line. Concerns of silica scaling along the pipeline and in the reinjection wells have been raised due to longer brine residence time and bigger temperature drops within the reinjection line.

The objective of this study is to simulate an optimized transport of waste fluids along the 4RC cross-country RI line and to evaluate the degree of silica scaling potential with this utilization. It also has the following specific objectives:

- Evaluate silica scaling problems at projected declined mass flows in 4RC RI line assuming further drawdown occurs.
- Evaluate the feasibility of the planned reinjection management strategy for South Sambaloran and Tongonan at increasing diverted flow.
- Validate the simulation by comparing the results with the data from actual field measurements.

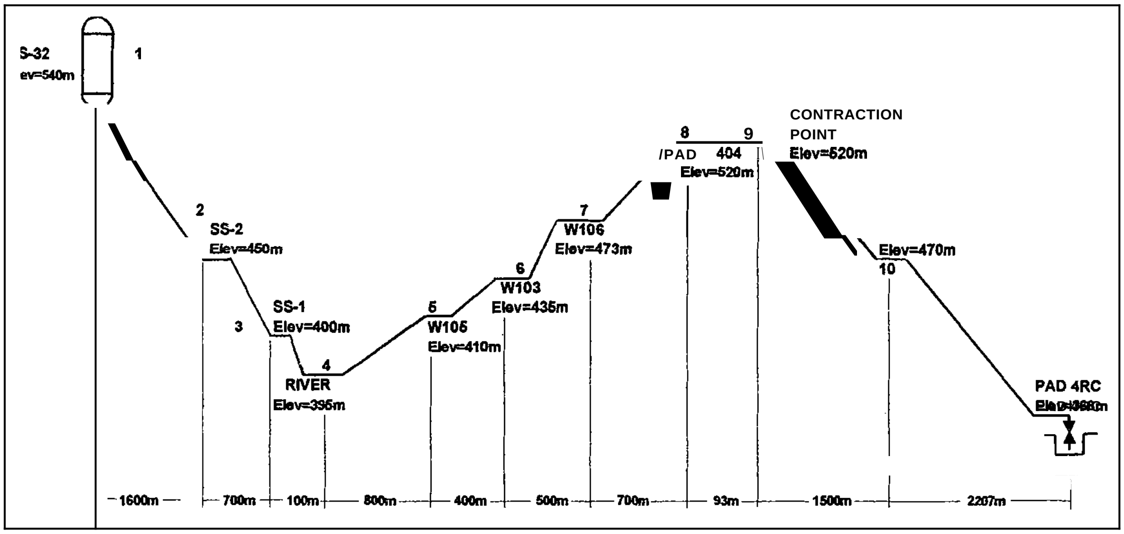


Figure 1. Schematic diagram of 4RC RI Line and sectional points for calculations.

Table 1. Pipe Data for the 4RC Reinjection Pipeline.

Pipe Data	36" section	24" section
Total length (m)	4893	3707
Schedule No.	S40	SXS
Material	CS ANSI 4130	CS ANSI 4130
Outside diameter (m)	0.9144	0.6096
Inside diameter (m)	0.8763	0.5842
Pipe thickness (m)	0.01905	0.0127
Pipe thermal conductivity (W/mK)	43.0	43.0
Insulation	Fibreglass	fibreglass
Insulation thickness (m)	0.0508	0.0508
Insulation thermal conductivity (W/mK)	0.0616	0.0616

2.0 THE SOUTH SAMBALORAN FCDS

The South Sambaloran Fluid Collection and Disposal System (FCDS) is a double-flash system that feeds into the combined Malitbog-South Sambaloran main and bottoming condensing plants. The wastewater that flows through the 4RC RI line comes from **SS-32.** The two-phase fluids are separated in two pressures. The first separation yields high pressure (HP) steam (1.2 MPa) that is supplied to the main plant. The HP water is further flashed at a lower pressure (0.7 MPa) to extract low pressure (LP) steam for the first 7 MWe of the bottoming plant. The separated wastewater comes out of the Flash Vessel (FV) at saturated condition (165°C) and flows through the 4RC cross-country RI line into the 4RC reinjection sink.

The 4RC reinjection line (Fig. 1) spans **8.6 km.** through moderate terrain **from SS-32** to 4RC pad. Its major low point is at the Mahiao river and has a major hump at pad 404. It interconnects with the Tongonan-1 Mahiao reinjection line near Separator Station-1 (SS-1). Designed to handle 400 kg/s of wastewater load, it is currently utilized at about 200 kg/s load due to the decline in separated wastewater **from SS-32.** It is composed of two pipe sizes **(36"** and 24" sections). It is fully insulated with a 2" thick fibreglass composite material. Table 1 lists the important pipe data for the reinjection pipeline.

3.0 THEORY AND METHODS

3.1 Fluid Flow

The calculations were carried out with the assumptions that the fluid flow in the pipeline is characterized by the following (refer to Section 7.0 for Lists of Symbols):

- one-dimensional – the velocity at all points across a section has the same direction and that mean values of velocity, pressure, and elevation are taken along the central streamline
- real fluid flow – frictional (viscous) effects are considered
- compressible fluid flow – though liquids are usually assumed to be incompressible, the fluid considered drops in temperature and slightly changes in density, hence compressible
- steady flow – no accumulation of mass in the pipeline and flow at every point remains constant with respect to time
- pressure flow – flow occurs under pressure and pipe flowing **full**
- spatially variable flow – the fluid density and the local mean velocity change along the flow path especially at the diversion (to Tongonan line) and contraction (36" to 24") points
- turbulent flow – **Reynolds'** number **at** all points > 4000

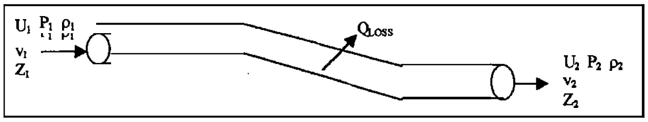
From these flow characteristics, the mean velocity and continuity equations (Daugherty, 1989) are used:

Meanvelocity : $v = M / \rho A$ (1)

Continuity : $\rho_1 A_1 v_1 = \rho_2 A_2 v_2 = M$ (2)

3.2 Steady Flow Energy Equation

For steady flow in a control pipeline volume illustrated in Fig. 2, the Steady Flow Energy Equation (SFEE) for real fluids as derived from the



$$U_1 + P_1V_1 + 1/2v_1^2 + gZ_1 = U_2 + P_2V_2 + 1/2v_2^2 + gZ_2 + Q_{LOSS} \qquad (3)$$

All terms in SFEE *can* readily be found or calculated except U_2 and P_2. We express both unknowns in the relation for enthalpy,

$$H = U + PV \qquad (4)$$

reducing the unknown to just one term (H_2). **Thus,**

$$H_1 + 1/2v_1^2 + gZ_1 = H_2 + 1/2v_2^2 + gZ_2 + Q_{LOSS} \qquad (5)$$

We calculate P_2 in the SFEE from the Bernoulli equation (Eqn. 6). Knowing H_2 and P_2, we can determine the real state and properties (e.g. temperature) of the fluid as it progresses through the pipeline.

3.3 Bernoulli and Darcy-Weisbach Equations

The Bernoulli principle is a corollary of the SFEE. It is a mechanical energy balance and assumes that the change in internal energy of the system is accounted primarily in the heat lost or gained by the *system* (Daugherty, 1989). For real fluids where viscous effects are considered, some energy is dissipated due to fluid friction. Eqn. (3) then simplifies to the Bernoulli equation for real fluids expressed in terms of per unit weight of fluid:

$$\frac{P_1}{\rho_1 g} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\rho_2 g} + \frac{v_2^2}{2g} + z_2 + h_L \qquad (6)$$

In a pipeline configuration, h_L in Eqn. 6 is expressed as

$$h_L = h_{Lpipe} + h_{Lfittings} \qquad (7)$$

For a circular pipe flowing full, the Darcy-Weisbach equation (also known as pipe-fiction equation) gives,

$$h_{Lpipe} = \frac{\lambda L v^2}{D2g} \qquad (8)$$

For bends and fittings in Eqn. 7,

$$h_{L\,fittings} = \Sigma K_{fittings}\frac{(v^2)}{2g} \tag{9}$$

where K values for bends and fittings can be found in handbooks (Perry, 1984). Combining Eqns. (7) to (9) we get,

$$h_L = \Sigma K\frac{(v^2)}{2g} \tag{10}$$

where

$$\Sigma K = \lambda L/D + \Sigma K_{fittings} \tag{11}$$

3.4 Heat Flow in Insulated Pipeline

For an insulated pipeline, two modes of heat transfer are involved: (I) convective heat transfer in the flowing streams (liquid and air); and (II) conductive heat transfer in the pipe and composite insulation. Where a combination of heat transfer modes are involved, the thermal conductance (C) of the pipe system is used, thus:

$$Q_{LOSS} = C\Delta T \tag{12}$$

For a composite pipe system, C is expressed as (Wong, 1972):

$$C = \frac{2\pi L}{\frac{1}{h_i r_1} + \frac{\ln(r_2/r_1)}{k_1} + \frac{\ln(r_3/r_2)}{k_2} + \frac{1}{h_o r_3}} \tag{13}$$

To evaluate the inside and outside heat transfer coefficients (hi, h_o), we use the Nusselt and Dittus-Boelter correlations,

$$Nu_{i,o} = cRe_{i,o}^{\ m}Pr_{i,o}^{\ n} \tag{14}$$

where for turbulent flow through cylindrical tube

$c = 0.023$, $m = 0.8$
$n = 0.4$ for heating
$= 0.3$ for cooling

and

$$Nu_{i,o} = h_{i,o}D/k \tag{15}$$

$$Re_{i,o} = Dv\rho/\mu \tag{16}$$

$$Pr_{i,o} = Cp\mu/k \tag{17}$$

where i = evaluated using water properties
o = evaluated using air properties

3.5 Concepts on Silica *Scaling* Potential

Silica is the most common dissolved chemical compound responsible for scaling in geothermal development (Louwrier, 1983). Amorphous silica is the form of silica usually deposited at surface and reinjection pipelines. Silica scaling is controlled by the thermodynamics and kinetics of its deposition. Some of the more important factors that affect silica deposition are (Brown, 1998): (1) Degree of supersaturation; (2) Temperature; (3) Other ions in solution (e.g. salinity); (4) pH, and (5) Flow rates.

The degree of supersaturation is indicated by the saturation ratio or silica saturation index (SSI). Field experience in Tongonan demonstrated that the tolerable level of silica saturation is 1.2. Other factors in silica scaling are extensively discussed by Fournier and Rowe, 1977; Chen and Marshall, 1982; Fournier and Potter, 1982; and Dunstall and Brown, 1998.

3.6 Calculation Methods

The 4RC RI line was divided into ten sections as shown schematically in Figure 1. The sectional points were pre-selected as major points of interest like the diversion, low, high, and contraction points. Calculations were carried out from point to point as the pipeline progresses, determining the steady state of the fluid and its properties at each point. From the calculated enthalpy and pressure at each point, actual fluid properties like temperature, density, viscosity, specific heat and thermal conductivity were determined from the ASMETAB program of ASME. Fluid transport and silica scaling potential were evaluated at different mass flows (200, 150, 100, 50 kg/s), diverted flows (50, 100, 150 kg/s), ambient temperature (25°C), wind velocity (10 m/s) and reinjection fluid chemistry (SiO_{2total} = 749 mg/kg, Cl_{RI} = 11721 mg/kg).

4.0 RESULTS AND DISCUSSIONS

4.1 Projected Silica Scaling Problems

Table 2 presents the summary of calculated parameters evaluated at declining mass flows to 4RC RI line. Figure 3 shows the profile along 4RC RI line. Results show that the current utilization at about 200 kg/s should not cause grave concern as the silica scaling potential is still within acceptable level (1.13) even at a temperature drop of 4°C. Utilization at 150 kg/s would still be acceptable at a slightly higher temperature drop of 6°C. However, at current reinjection fluid chemistry, the minimum utilization of 4RC RI line should be around 100 kg/s, where total temperature drop would only be 8°C and scaling potential would still be at acceptable level (1.18). At a lower flow of 50 kg/s, the degree of silica scaling may not be acceptable at the 4700m distance and beyond (Figure 3).

4.2 Planned Reinjection Management Strategy

The planned reinjection management strategy is to divert part of the load in 4RC RI line to the Tongonan-1 Mahiao in-field reinjection sink (Fig. 4). The calculations were carried out starting at the current utilization of around 200 kg/s and diverted near Tongonan SS-1 at 50 kg/s increment (50, 100, 150 kg/s diverted flow). Table 3 summarizes the calculated parameters while Figure 5 shows the profile along 4RC RI line.

Table 2. Summary of Calculated Parameters at Declining Mass Flows.

Mass flow (kg/s)	**200**	**150**	**100**	**50**
Reinjection pressure (MPa)	2.20	2.22	2.23	2.26
Total fluid residence time (hrs)	4.96	6.61	9.93	19.92
Total temperature drop (°C)	4	6	8	16
SiO_{2am} solubility (mg/kg)	660	652	636	591
Reinjection SSI at 4RC pad	1.13	1.15	1.18	1.27

Table 3. Summary of Calculated Parameters at Different Diverted Flows to Mahiao RI Sink.

Diverted flow (kg/s)	**50**	**100**	**150**
Remaining flow (kg/s)	150	100	50
Pressure at diversion point (MPa)	1.94	1.94	1.94
Reinjection pressure (MPa)	2.21	2.23	2.25
Total fluid residence time (hrs)	6.00	8.10	14.42
Total temperature drop (°C)	5	7	12
SiO_{2am} solubility (mg/kg)	655	644	612
Reinjection SSI at 4RC pad	1.14	1.16	1.22

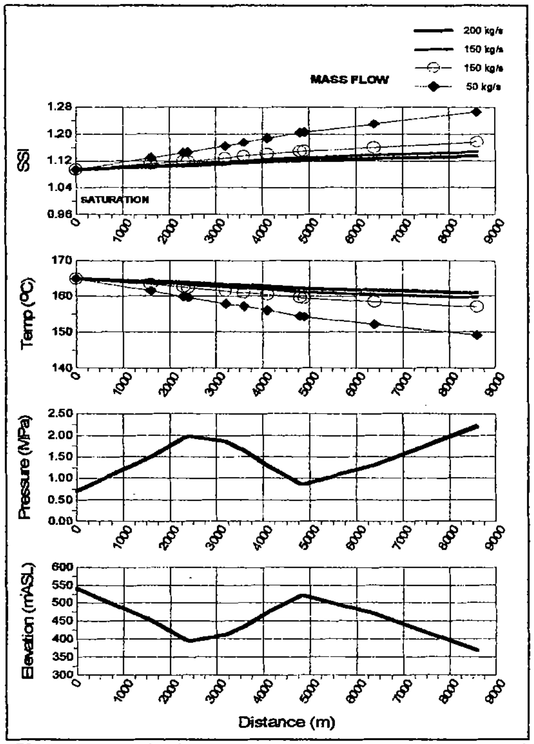


Figure 3. Calculated pressure, temperature and silica saturation index (SSI) at current and simulated mass flows in 4RC RI line.

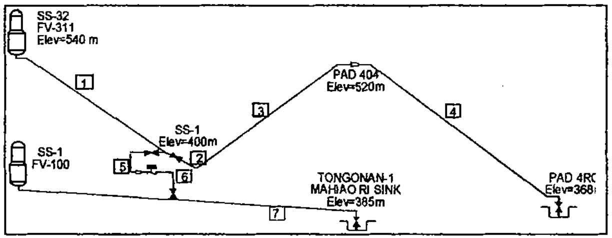
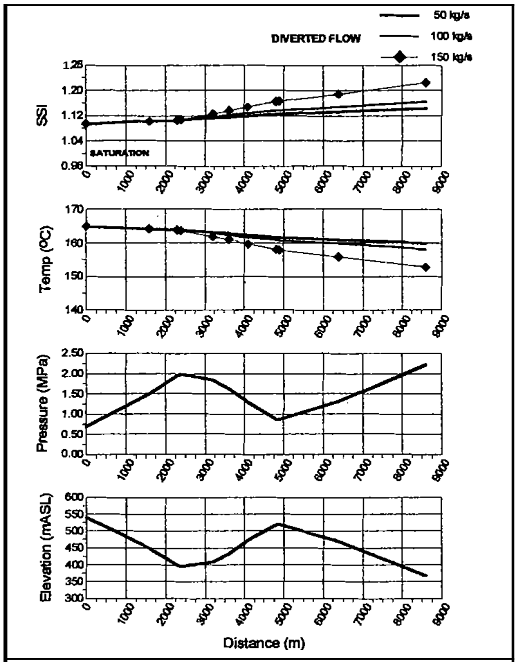


Figure 4. Schematic diagram of 4RC RI line interconnection to Tongonan-1 Mahiao reinjection sink.

Figure 5 show that at current reinjection fluid chemistry, the planned reinjection management strategy is feasible up to a maximum diverted flow of **100** kg/s. At **this** utilization, the silica scaling potential is still acceptable throughout the **4RC** pipeline **(SSI<1.16).** At a higher diverted flow of **150** kg/s, the degree of silica scaling in the **4RC** line may not be acceptable at the 7000m distance and beyond. At 200 kg/s initial flow, the calculated pressure at the diversion point is **1.94** MPa. Since the receiving line (Mahiao RI line) is only at 0.7 MPa, a pressure control valve would be necessary at the interconnection point (Figure **4)** to prevent backflow in the Mahiao RI line.

4.3 Comparison of Simulated vs. Actual Values

Actual field measurements in the **4RC RI** line was conducted last June **1998** (Salazar, **1998).** Profiling of **SSI,** temperature, pressure and brine residence time at a measured load utilization of **140** kg/s was conducted. Results are presented in Table **4** and compared with the simulated values at **150** kg/s mass flow.



igure 5. **Calculated pressure, temperature an silica saturation index (SSI) in 4RC RI line at different diverted flows** to **Tongonan-1** Mahiao **RI sink.**

Results show that the actual and calculated SSI values and total brine residence time are comparable. However, for temperature and pressure values, there are significant differences due to the slightly lower Starting temperature and pressure **at SS-32** (i.e. **158°C,** 0.58 MPa) during the field **measurement.** The **difference** in temperature drop (± **4°C),** however, would not significantly change the calculated SSI. The pressure measurements are erratic and do not follow the pressure profile due to elevation head.

Location	Elev. (mASL)	SSI			Temperature ("C)			Pressure (MPa)		
		Actual	Calc.	Diff.	Actual	Calc.	Diff.	Actual	Calc.	Diff.
SP-1	540	1.17	1.09	0.08	158	165	7	0.58	0.70	0.12
SP-2	400	1.19	1.11	0.08	154	163	9	1.65	1.94	0.29
SP-3	520	1.19	1.13	0.06	152	161	9	0.54	0.87	0.33
SP-4	470	1.19	1.14	0.05	152	160	8	0.66	1.31	0.65
SP-5	363	1.19	1.15	0.04	151	159	8	0.54	1.32	0.78
SP-6	368	1.23	1.15	0.08	148	159	11	0.53	2.20	1.67

Total Brine Residence Time:
Actual = 6 hrs. **50** min.
Calc. = **6 hrs. 37 min**

Total Temperature Drop:
Actual = **10°C**
Calc. = **6°C**

5.0 CONCLUSIONS

- At the present flow of 200 kg/s, silica scaling potential throughout the pipeline is still within acceptable levels (SSI < **1.13).**
- **The minimum** utilization of **4RC** RI line **should** be **100** kg/s **to** prevent silica scaling in the pipeline.

- The planned reinjection management strategy for the South Sambaloran and Tongonan sectors of diverting load from 4RC RI line to the Tongonan-1 Mahiao reinjection **sink** is feasible up to a maximum diverted flow of 100 **kg/s.** At this utilization, the silica scaling potential throughout the 4RC pipeline is still within acceptable levels (SSI < 1.18).
- The actual and calculated SSI values and total brine residence time are comparable, while the temperature and pressure values have significant differences due to the different testing condition.

6.0 LIST OF SYMBOLS

A - pipe cross sectional area, m^2
C - pipe system thermal conductance, W/K
C_p - specific heat, kJ/kgK
D - pipe diameter, m
g - gravitational constant, **m/s^2**
H - specific enthalpy, kJkg
$h_{i,o}$ - heat transfer coefficient, W/m^{2}K
h_L - head loss, m
K - friction coefficient
k - thermal conductivity, kW/mK
L - pipe length, **m**
M - total mass flow, kg/s
Nu - Nusselt number
P - pressure, MPa
Pr - Prandtl number

Q - heat loss, kJ/kg
r - pipe radius, **m**
Re - Reynolds number
T - temperature, K
u - internal energy, kJkg
V - specific volume, m^3/kg
v - fluid mean velocity, m/s
Z - elevation, m
p - fluid density, **kg/m^3**
A - change in
Σ - summation
λ - fiction factor
π - Pi number
μ - viscosity, kg/ms

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