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PIPE MATERIAL SELECTION FOR A 50MWE GEOTHERMAL POWER PLANT PIPELINES

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ABSTRACT

Piping materials for geothermal systems have been of numerous types with great variation in cost and durability. The temperature and chemical quality of the geothermal fluids, in addition to cost, usually determine the type of piping network material used. In this paper, four suitable types of piping materials according to chemical quality and temperature of the fluid were taken into consideration for Meshkinshahr 50MWe geothermal power plant pipelines. Pipelines consist of two lines that transport the mixture of brine and steam from wellhead to separators, two steam lines from separator to power house and two brine lines from separator to reinjection wellheads.

The design parameters; number of expansion loops and legs, pressure drop, wall thickness, weight span, pipe weight and length of the pipe are variable with different pipe materials. Each parameter has a specific significance in each line. For example, in steam lines, pressure drop is more important than that in other lines and less pressure drop in steam lines lead to increase the inlet pressure of turbine and more output power. Also, these parameters directly affect the cost of piping, fewer expansion loops and legs lead to use less pipe length and less pressure drop, larger weight spans result in less pipe supporting costs, and different thicknesses make different pipe unit weight and different transportation costs. In this paper we tried to select pipe material for a 50 MWe geothermal power plant pipelines.

INTRODUCTION

The Mt. Sabalan geothermal field is located in the Moil Valley on the northwest flank of Mt. Sabalan, close to the Meshkinshahr town (Khiyav) of Azerbaijan, Iran.

The climate in the area is relatively dry, especially during the summer months. The site is exposed to severe winter weather, including very high wind speeds of up to 180 km/hr. Temperatures over the past 4 years have been measured as low as -30°C (SKM, 2005).

The Renewable Energy Organization of Iran (SUNA) plans to build a 50MWe power plant. In this project, the 50MWe power plant is assumed at site A, with steam from production wells on pads D and A, and with brine reinjection at wells on pads B and C. In order to generate electricity from the power plant, the two-phase flow should be transmitted from production wells to the separator station. The steam should be transmitted from the separator station to a powerhouse, and the brine water should be transmitted from the separator station and powerhouse to reinjection wells. The brine water is the sum of the water that comes from the separator and the powerhouse after condensing in the condenser. [1]

The main purpose of this paper is to reach an optimum pipe material selection for each pipeline. Temperature and Chemical quality of the fluid restrict pipe materials. Geothermal fluids contain dissolved CO_2, H_2S, NH_3 and chloride ions that can cause corrosion of metallic materials. Considering the service temperature and chemical quality of the fluid, four types of materials are preferred; Carbon steel, Stainless steel, Alloy steel and FRP (fiberglass reinforced plastic). It is mentionable that design parameters; number of expansion loops - legs, pressure drop, pipe wall thickness and weight span have been measured for each pipe material in different lines. These parameters will be affecting the cost and eventually the selected material. Fewer numbers of loops, larger weight span, less wall thickness, less pipe length, and less pressure drop are indeed among the features of an ideal material in a pipeline.

PIPE MATERIALS

Some of the materials which can be used in geothermal applications include: asbestos cement (AC), ductile iron (DI), slip-joint steel (STL-S), welded steel (STLW), gasketed polyvinyl chloride (PVC-G), solvent welded PVC (PVC-S), chlorinated polyvinyl chloride (CPVC), polyethylene (PE), cross-linked polyethylene (PEX), mechanical joint fiberglass reinforced plastic (FRP-M), FRP epoxy adhesive joint-military (FRP-EM), FRP epoxy adhesive joint (FRP-E), FRP gasketed joint (FRP-S), and threaded joint FRP (FRP-T).

Figures 1 and 2 introduce the temperature limitations and relative costs of the above mentioned materials. Generally, the various pipe materials with higher temperature rating are more expensive.

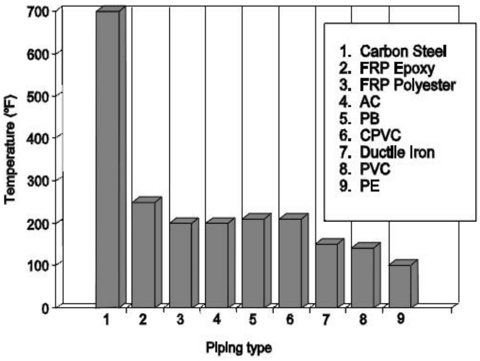


Figure 1 Maximum service temperature for pipe materials

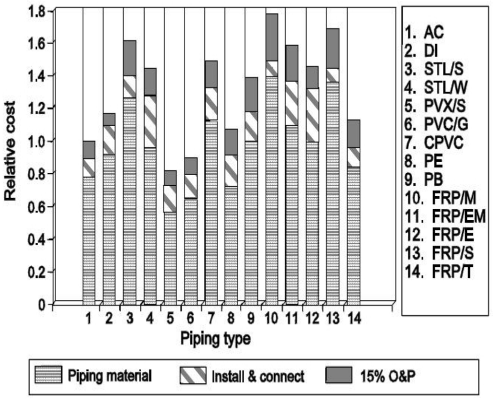


Figure 2 relative cost of piping by type

Both metallic and nonmetallic piping can be considered for geothermal applications. [2] Presently, most piping (56%) in geothermal systems is of asbestos cement construction. Some fiberglass (19%) and steel (19%) is also in use. asbestos cement (AC) was very successful in terms of installed cost and chemical compatibility with the fluids. Unfortunately, concern regarding the health related aspects of asbestos cement products has rendered this product unusable from a practical standpoint.[3]

Carbon steel is the most widely used metallic pipe and has an acceptable service life if properly applied. Ductile iron has seen limited application.

The attractiveness of metallic piping is primarily related to its ability to handle high temperature fluids. In addition, its properties and installation requirements are familiar to most installation crews. The advantage of nonmetallic materials is that they are virtually impervious to most chemicals found in geothermal fluids. However, the installation procedures, particularly for fiberglass and polyethylene are, in many cases, outside the experience of typical laborers and local code officials. This is particularly true in rural areas. [2]

Maximum service temperature in this project has been measured for two-phase lines 155.5 ˚C and for steam flow lines 120.2˚C and for brine lines 80 ˚C. Maximum operating temperature for class 2400 FRP pipes is 121 ˚C [4].

CARBON STEEL

Available in almost all areas, steel pipe is manufactured in sizes ranging from 1/4 to over 72 in. Steel is the material most familiar to pipe fitters and installation crews.

Commonly used steel pipe ratings are Schedule 40 (standard) and Schedule 80 (extra strong). Corrosion is a major concern with steel piping, particularly in geothermal applications. In many geothermal fluids, there are various concentrations of dissolved chemicals or gases that can result primarily in pitting or crevice corrosion. If the potential exists for this type of attack, or if the fluid has been exposed to the air before entering the system, carbon steel should be the material of last resort. [2]

The low cost, availability, and ease of fabrication of carbon steels (mild steels) make them attractive construction materials for geothermal power plants. However, the reliability of these steels depends upon their applications in the power plants.

By taking appropriate precautions, mild steels can be used for thick-walled applications in contact with most geothermal fluids. Thin walled applications will be limited by the susceptibility of these materials to localized attack such as pitting and crevice corrosion. High salinity geothermal fluids will cause high uniform and localized corrosion rates and will severely limit the use of low carbon steels. The applications of mild steels to geothermal environments require that precautions be taken for aeration, flow rate, scaling, galvanic coupling, exterior surfaces, and steel specifications.

STAINLESS STEEL

The uniform corrosion rate of most stainless steels is low (less than 0.5 mpy) in geothermal fluids , but many are subject to the more serious forms of corrosion: pitting , crevice corrosion, stress corrosion cracking (SCC), sulfide stress cracking (SSC), intergranular corrosion, and corrosion-fatigue.[6]

Stainless steel material decreases the probability of uniform corrosion formation in geothermal fluid environment. However, more serious corrosion problems may occur. These are; pit corrosion, cracking corrosion, breaking with stressed corrosion, breaking with sulphur stressed corrosion, corrosion between the particles and wearing corrosion. Cracking corrosion can be a serious problem for stainless steel when used with sophisticated equipment in geothermal fields. An increase in the Cl ion concentration in the environment results in an increase in the effect of local corrosion. Rising temperature increases the pit potential. The resistance of stainless steel against pit and cracking corrosion depends on its chrome and Mo content. These two elements increase the resistance of stainless steel in an environment without oxygen. Austenitic stainless steels are vulnerable to breaking with stressed corrosion in the presence of Cl ion at high temperatures. Ferric stainless steels are generally stronger. Breaking with stressed corrosion depends on Cl ions, oxygen concentration, pH value, temperature, and tension and alloy components.

Alloys with nickel can be affected by stressed corrosion. Addition of Mo and silica increases the resistance to stressed corrosion. Corrosion between the particles can be seen in austenite and ferric stainless steels. Especially during the welding operation this may be observed. Ferric stainless steels can be influenced by sulphur stressed breaking but austenite stainless steels cannot. Low strength steels are more vulnerable to sulphur stressed breaking.

AISI 400 series stainless steels contain 12-18 % chrome. In order to prevent the pit corrosion and breaking problems in wellhead valves, geothermal fluids containing high amounts of Cl ions, sulphur and oxygen in solution, it is more suitable to use AISI 430 (Ferrite) AISI 300 series stainless steels show well performance in geothermal condensates at low temperatures and geothermal fluids not containing oxygen. [5]

NICKEL ALLOYS

High nickel alloys are frequently used to combat severe corrosion problems. The higher ranked Ni-Cr-Mo alloys, such as Inconel 625 and Hastelloy C-276, have given excellent resistance to corrosion in geothermal systems.

The Ni-Cr-Mo alloys appear to be the most resistant to high temperature geothermal fluids. Inconel 625 and Hasteloy C-276 in particular can also normally tolerate very high flow rates and occasional aeration.

Similar alloys containing iron in place of molybdenum face competition from the most resistant stainless steels, but may find application where their mechanical properties are desirable. Cupronickels and Monels will have limited usefulness in geothermal streams containing even trace quantities of hydrogen sulfide. [6]

FIRBER GLASS REINFORCED PLASTIC (FRP)

The usage of Fiberglass Reinforced Plastic (FRP) increases because of high resistance of corrosion and low cost. Especially, it is used safely in corrosive geothermal water transport lines. Fiberglass Reinforced Plastic (FRP) pipelines are supplied at low cost by means of smooth surface in central geothermal heating systems and water and hot water transport lines. Moreover, Fiberglass Reinforced pipelines decrease the usage of scaling inhibitor and supplies low cost by means of smooth surfaces because of low contact of CaCO3 to the pipeline surface in high CaCO3 settlement. The mechanical properties of Fiberglass Reinforced Plastic (FRP) pipes, its durability in high pressure (>200 bar) and its durability in high temperature (>250 ˚F) improved with the last studies.

In addition, when they are used with mistakes, it creates some problems, such as brittleness and break off. Because of that, material producers should consider the project at which the material will be used, the design and the management conditions. The most important criterion about the life-time of Fiberglass Reinforced Plastic (FRP) pipeline is the assembly situation. In the case of wrong assembling, the break off and brittleness are inevitable. [5]

As shown in Table 3 the axial expansion of FRP is approximately twice that of steel. However, because of the relatively low axial modulus, forces developed as a result of this expansion are only 3 to 5% that of steel under the same conditions (Smith-Inland, 1982). As a result, for buried installations with at least 3 ft of cover, sufficient restraint is provided by the overlying soil and no special precautions need be made for expansion other than adequate thrust blocking. For aboveground installations (on hangers), changes in direction are the most economical method of allowing for expansion [2]

Pipe property	Units	Value
Thermal conductivity	W(m•k)	.33
Thermal expansivity (lineair)	10^{-6} mm/mm/°C	18.0
Flow coefficient	Hazen-Williams	150
Absolute roughness	10^{-6} m	5.3
Density	g/cm^3	1.8
Shielding capability*	volts	100^1
Grounding resistance @1500 volts*	10^6 ohms	1.0^1

Table 1 physical properties of fiberglass pipe and fittings **[4]**

EXPANSION LOOPS AND LEGS

For aboveground installations, changes in direction are the most economical method of allowing for expansion [2] Expansion loops and legs can be used simultaneously in geothermal pipelines. In this project we only use expansion loops, and we determine number and dimension of expansion loops for damping the expansion.

Number of expansion loops and legs increases pipe length and pressure drop in each line.

Number of expansion loops in each line equals the length of linear thermal expansion divided by expansion loop capacity in each line. The expansion loop capacity depends on the pipe and equipment nozzles allowable stresses, overlap, and pipe material. 300 mm is an acceptable loop expansion capacity for steel pipes in process piping. In FRP pipes the loop expansion capacity considered 125 mm [4].

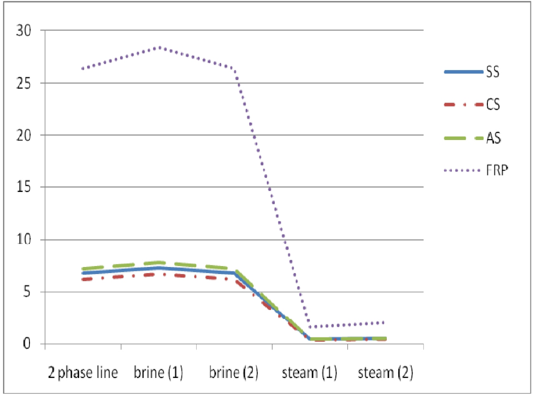


Figure 3 number of expansion loops for different materials in different lines

PRESSURE DROP

One of the main concerns in the design of the gathering system is the pressure loss in the steam lines from the wellhead to the powerhouse. The steam pressure drop is a function of the diameter, length and configuration of the steam piping, as well as the density and mass flow rate of the steam.

$$\Delta P_f = 0.8\frac{L\dot{m}^{1.85}}{\rho D^{4.97}}$$

Where:

L	length of the pipe (ft)
$\dot{m}$	Mass flow rate (lbm/h)
ρ	Density (lbm/ft^3)
D	Inside diameter of the pipe (inch)

Length of the pipe varies with different pipe materials as a result of different expansion legs in steam lines. Since the density of steam is relatively low, the change in pressure due to changes in pipe elevation is much smaller than the friction term given by eq.

The pressure drop in the liquid lines is less of a concern since the liquid is going to be disposed of by injection, but unnecessarily high pressure losses might require pumps to maintain sufficient reinjection pressure. The frictional pressure drop in the liquid pipes depends on the same variables as in steam pipes plus the friction factor which in turn is a function of the pipe diameter, internal roughness, and the viscosity of the liquid. . [7] According to the Darcy Weisbach equation equivalent length method, the pressure drop is determined in liquid lines.

$$h_l = f\frac{l_e}{d_i}\frac{v^2}{2g}$$

Where:

h_l	head loss (m)
f	friction factor
l_e	equivalent length of pipe for minor losses (m)
d_i	inside pipe diameter (m)
v	fluid velocity (m/s)
g	gravitational acceleration (m/s2)

Length of pipe, equivalent length of valves and fittings and equivalent length of elbows that are used in expansion loops and legs are considered in total equivalent length in each line.

Friction factor varies with different pipe materials, according to the moody diagram and pipe roughness, the friction factor is determined in each line. [8]

Absolute roughness for FRP pipes considered 0.0002 inches (ameron catalogues) and for steel pipes 0.0018 inches.

If there is a change in the elevation of the pipe, the gravity head contribution must be included:

$$\Delta P_g = \rho g \Delta H$$

Where g is the local gravitational acceleration and ΔH is the change in elevation (ft). The gravity-head term is positive for down comers and negative for risers.

The pressure loss in a two-phase, steam-liquid pipeline is far more complex and less reliably predicted analytically. Correlations may be used to estimate the pressure drop but often field tests are conducted to determine the losses experimentally. [7]

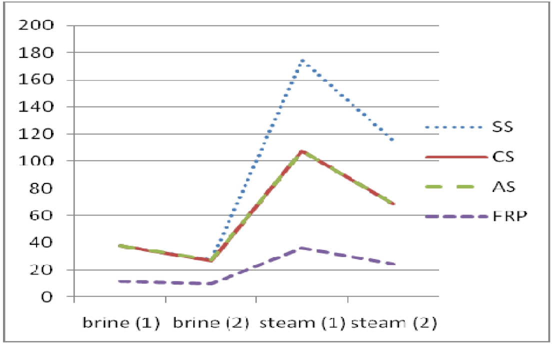


Figure 4 pressure drop (m) for different pipe materials in different lines

PIPE WALL THICKNESS

One of the design parameters that affect material selection is pipe wall thickness. Different pipe materials with different yielding strength, joint factor and corrosion allowance have different wall thicknesses. Pipe weight is one of the features that affect the cost of pipe especially for metallic materials. Also, pipe weight has an important role in cost of transportation.

ASME B31.1 gives the equation for calculating the internal pressure wall thickness of power plant piping as follows:

$$t = \frac{PD}{2(SE + PY)}$$

Where:

t = Internal pressure design thickness, in.
P = Internal design pressure, psig.
D = Outside diameter of pipe, in.
E = Longitudinal-joint quality factor.
S = Allowable hoop stress, psi.
Y = Wall thickness correction factor.

For FRP pipes AMERON catalogue tables uses to determine the wall thickness. In these tables the minimum pipe wall thickness is calculated with the formula according to ASME B31.3 Paragraph A304.1.2. [4]

Corrosion, Erosion, and Thread Allowances:

Allowances for corrosion, erosion, or threads must be accounted for in determining the required pipe wall thickness. Thread allowances apply only to smaller diameter pipes which may be threaded. The appropriate allowance is added to the thickness that was calculated for internal pressure to arrive at a total required pipe wall thickness. [9]

Geothermal fluids commonly contain seven key chemical species that produce a significant corrosive effect. The key species are:

- Oxygen (generally from aeration)
- Hydrogen ion (pH)
- Chloride ion
- Sulfide species
- Carbon dioxide species
- Ammonia species
- Sulfate ion

A number of different corrosive phenomena have been observed in geothermal systems.

In low- and very-low-temperature geothermal systems, the following are most likely to be significant: Uniform corrosion, Pitting, Crevice corrosion, Stress corrosion cracking, Erosion-corrosion, Inter-granular corrosion, Dealloying.

While developing the Materials Selection Guidelines for Geothermal Energy Utilization Systems, Radian invented a Geothermal Corrosivity Classification System that divided the currently developed geothermal resources into six classes based on key corrosive species, wellhead temperature, and similarities of corrosion behavior. [10]

Parameters of class IV with following properties have the most similarity with our geothermal power plant among 6 classes;

<u>Defining parameters:</u>

Resource type	liquid dominated
Total key species (TKS)(1)	500 to 10,000 ppm
Chloride fraction in TKS	45 to 95 Percent
pH (unflashed fluid)	Greater than or equal to 5
pH (flashed fluid)	greater than 7
Vol. gas in steam less than 2.5	
Plant inlet temperature	250 to 390° F

<u>Sites Reviewed - in class IV*:*</u>

El Salvador - Ahuachapan
Iceland - HTA (four sites)
Japan - Hatchobaru
Japan - Otake
New Zealand - Broadlands
New Zealand-Wairakei
USA - Baca, **NM**
USA - Brady, H.S.,***NV***
USA - Heber, CA
USA - Raft River, ID

<u>Observed Corrosion of Carbon steels:</u>

-In nonaerated fluid at 250 to 390°F,uniform corrosion rates are typically less than 5 mpy with minor pitting.

-In nonaerated steam, corrosion rates are typically less than 5 mpy

-High strength low alloy steels are susceptible to sulfide stress cracking.

Aerated steam condensate is very corrosive.

<u>General performance of other steels:</u>

-Type 316 stainless steel is susceptible to stress corrosion cracking in aerated fluid.

-Corrosion-fatigue of 12 Cr turbine blades by geothermal steam is twice as severe as corrosion-fatigue by boiler quality steam. [6]

(1) Total chloride + sulfate + carbon dioxide species + sulfide species + ammonia

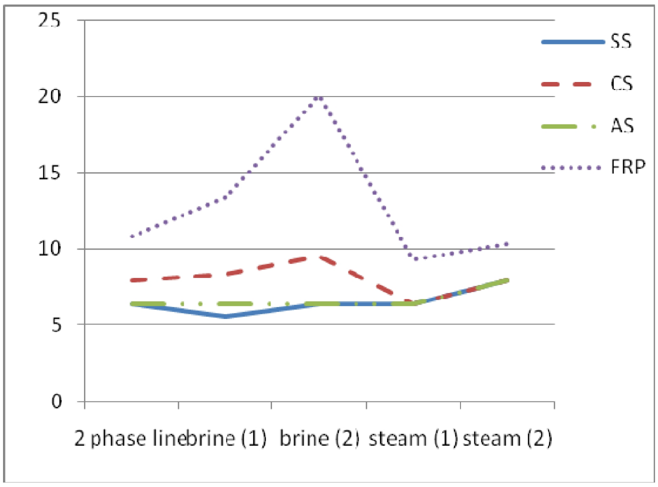


Figure 5 pipe wall thickness (mm) for different pipe materials in different line

WEIGHT SPAN

For steel pipes the following equation calculates the maximum acceptable weight span [11]:

$$L = \sqrt[4]{\frac{EID}{17.1W}}$$

Where:

D: permissible mid-span deflection (in)

I: pipe moment of inertia, (in^4)

E: bending modulus of elasticity, (psi)

W: weight of pipe and fluid, (lb/ft)

Permissible mid-span deflection for process piping is considered lower than 5 cm, and about the utility piping lower than 12 cm. in this project 4 cm is considered as midpoint deflection.

Fiberglass pipe support spacing is determined using beam deflection equations. Deflection is normally limited to ½ in (1.27cm). The resulting pipe bending stress is normally well below the allowable bending stress. Maximum pipe span based on deflection can be calculated using the following equation: [12]

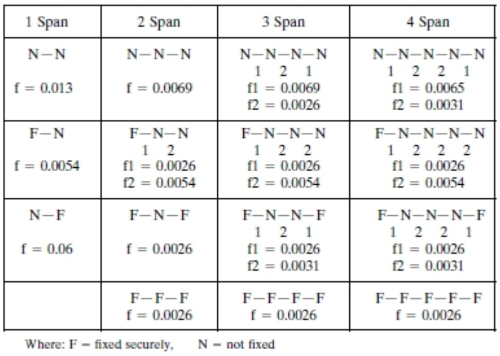
$$L = \left(\frac{DEI}{FW}\right)^{0.25}$$

Where

L: unsupported span length, (cm)

D: allowable midpoint deflection, (cm)

E: bending modulus of elasticity, (kg/cm2)
I: pipe moment of inertia, (cm4)
F: deflection coefficient. Figure6
W: weight of pipe and fluid, lbs/in (kg/cm)



1 Span	2 Span	3 Span	4 Span
N—N f = 0.013	N—N—N f = 0.0069	N—N—N—N 1 2 1 f1 = 0.0069 f2 = 0.0026	N—N—N—N—N 1 2 2 1 f1 = 0.0065 f2 = 0.0031
F—N f = 0.0054	F—N—N 1 2 f1 = 0.0026 f2 = 0.0054	F—N—N—N 1 2 2 f1 = 0.0026 f2 = 0.0054	F—N—N—N—N 1 2 2 2 f1 = 0.0026 f2 = 0.0054
N—F f = 0.06	F—N—F f = 0.0026	F—N—N—F 1 2 1 f1 = 0.0026 f2 = 0.0031	F—N—N—N—F 1 2 2 1 f1 = 0.0026 f2 = 0.0031
	F—F—F f = 0.0026	F—F—F—F f = 0.0026	F—F—F—F—F f = 0.0026

Where: F – fixed securely, N – not fixed

Figure 6 Deflection Coefficients, f, for Various Span Configurations

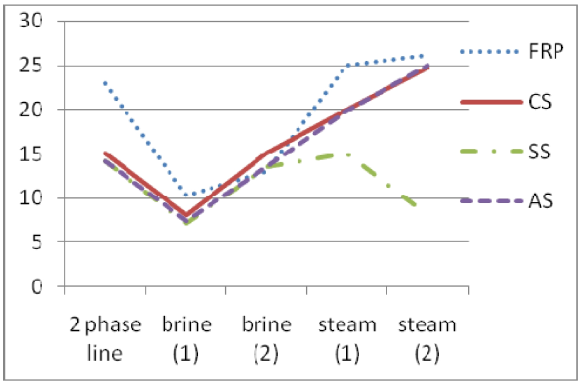


Figure 7 weight span (m) for different pipe materials in different lines

RESULTS:

In this project suitable materials were determined according to temperature and chemical properties of a geothermal fluid. And then the effect of each design parameter such as expansion loops, weight span, wall thickness, and pressure drop were studied on material selection process separately.

In brine lines FRP has the lowest pressure drop and largest weight span and because of its high resistance of corrosion, it is determined as a suitable pipe material. Although FRP has the lowest pressure drop in steam lines, it cannot be used in steam and two phase lines because of its temperature limitation.

Carbon steel and alloy steel almost have equal pressure drop and number of expansion loops in steam lines. Carbon steel with identical wall thickness is cheaper than alloy steel, so carbon steel is preferred in steam lines.

Pressure drop and number of expansion loops are nearly equal for carbon steel and alloy steel in two phase lines. Alloy steel pipe wall thickness is less than carbon steel material so alloy steel selected for two phase lines.

REFRENCES:

[1] Iraj Ghaderi, Route selection and pipeline design for a 50 MWe power plant in Sabalan Iran, united nations university geothermal training program Orkustofnun, Grensásvegur 9, IS-108 Reykjavík, Iceland REPORTS 2007 PP 111-114.

[2] Kevin D. Rafferty, P.E. Geo-Heat Center Klamath Falls, Oregon 97601, chapter 10 piping P 241- 247.

[3] Kevin D. Rafferty, Geothermal district piping – a primer November, 1989 P 1-3.

[4] Series 2400 Fiberglass Pipe and Fittings using Key-Lock mechanical joint or Taper/ Taper adhesive joint, Ameron 2005. FP 158 A 08/05. Page 1 of 6.

[5] Tevfik KAYA & Pelin HOŞHAN, Corrosion and Material Selection for Geothermal Systems, Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005 P 2-4

[6] Peter F. Ellis, II Marshall F. Conover , materials selection guidelines for geothermal energy utilization systems, appendix A P A2 & P 61& P A-54

[7] Ronald Dippipo, Geothermal Power Plants Principles Applications Case Studies and Environmental Impact second edition, May 2007, p 84-87

[8] Liquid Process Piping, US Army Corps of Engineers, 5 May 1999, p 3-8

[9] Pipe wall Thickness Calculation, Engineering Encyclopedia, Saudi Aramco DeskTop Standards, p 20

[10] Peter F. Ellis II Companion study guide to short course on geothermal corrosion and mitigation in low temprature geothermal heating systems, 24 April 1985, p 1-5

[11] Glyn E.woods PE Roy B baguly p.ENG, practical guide to ASME B31.3 process piping, P 101

[12] Mohinder L. Nayyar, MC GRAW-HILL piping handbook seventh edition chapter D2, P D128