



UNITED NATIONS  
UNIVERSITY

GEOTHERMAL TRAINING PROGRAMME  
Orkustofnun, Grensásvegur 9,  
IS-108 Reykjavík, Iceland

Reports 2007  
Number 7

## **ROUTE SELECTION AND PIPELINE DESIGN FOR A 50 MWe POWER PLANT IN SABALAN, IRAN**

**Iraj Ghaderi**

MOSHANIR - Power Engineering Consultant

No 37 Shahid Khodami St., Vanak Sq.

P.O. Box 19395-4691

Tehran

IRAN

*Ghaderi\_i@yahoo.com*

### **ABSTRACT**

The Sabalan geothermal field is a high-temperature area under development in Iran. Geothermal exploration was started in 1975 by the Ministry of Energy of Iran. After the 1979 revolution in Iran, it was stopped, and then started again in 1998 by SUNA – the Renewable Energy Organization of Iran. Three deep exploration wells and two shallow reinjection wells were drilled in the period 2002 to 2004 at three sites A, B and C. In addition, preparation was begun for drilling two new sites, D and E. The area is about 16 km southeast of the town of Meshkinshahr. It is expected that there is an overall potential for generation of about 200 MWe over the greater prospect area. SKM (main consultants 1998-2006) assesses that commercial geothermal power generation can be achieved at Sabalan at a levelised cost of electricity of less than 5 USD/kWh. SUNA is planning to drill thirteen new wells, and subsequently build a 50 MWe power plant. As the first part of this project, SUNA will build a pilot power plant in order to confirm that a geothermal power plant can be operated in Iran. Moshanir was the consultant for civil work from 1998-2006. Since 2006, Moshanir was selected as a main consultant for the geothermal field.

In this report, a power plant capacity of 50 MWe at site A is assumed, with steam from production wells on pads D and A, and brine water reinjection at wells on pads B and C. Pipelines will be designed for each line of the two phases, steam and brine water, and the best route based on the minimum cost will be discussed. Finally a layout plan for a power plant and the necessary buildings at site A will be proposed.

### **1. INTRODUCTION**

Iran is situated in the Middle East and has an area of 1,648,195 km<sup>2</sup> with a population of about 70 million. It has big gas and oil reservoirs and is also one of the world's main oil producers. In Iran, there is ample potential for renewable energies such as solar, biomass, wind and geothermal energy. The geothermal activity in Iran was started by the Ministry of Energy of Iran (MOEI) in 1975. A contract between MOEI and Ente Nazionale per L' Energia Elettrica of Italy (ENEL) was signed for geothermal exploration in the northern part of Iran (Azerbaijan and Damavand regions). In 1993

SUNA was established to justify priorities of the above mentioned regions. As a result, Meshkinshahr and Sarein areas in Sabalan region were proposed for electric and direct use, respectively (Figure 1). In 1998 SKM, on behalf of SUNA, completed a resistivity survey consisting of Direct Current (D.C.), Transient electromagnetic (TEM), and Magnetotellurics (MT) measurements in Meshkinshahr.

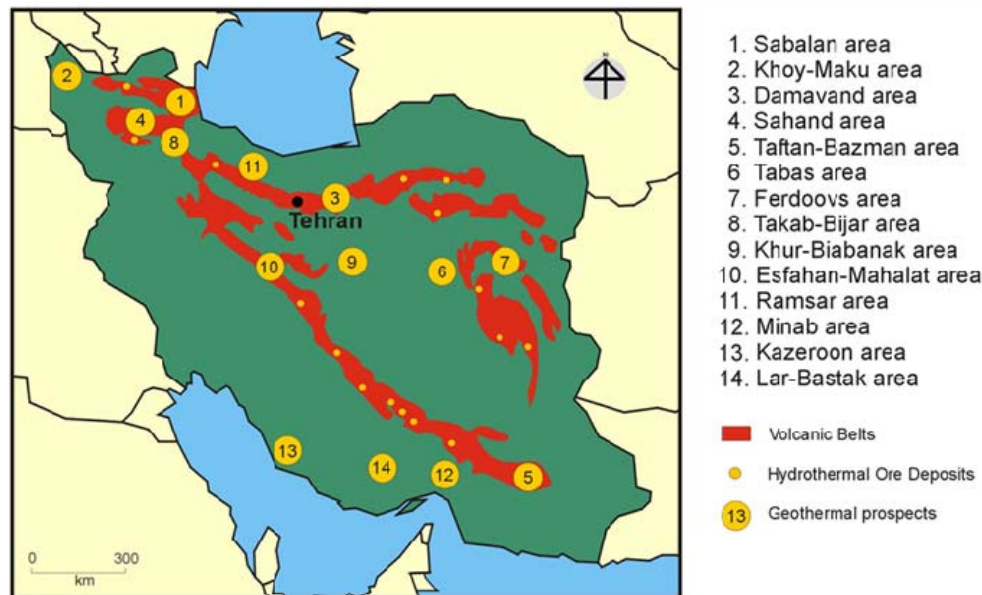


FIGURE 1: Map of Iran with geothermal prospects and volcanic zones (SKM, 2005)

A variety of power generation development options have been formulated and assessed by SKM, with generation capacities ranging from 2 to 100 MWe, utilizing both condensing and non-condensing steam turbines (SKM, 2005).

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 field is located between  $38^{\circ} 11' 55''$  and  $38^{\circ} 22' 00''$  North and  $47^{\circ} 38' 30''$  and  $47^{\circ} 48' 20''$  East (Yousefi, 2004). The resource area has been identified by geo-scientific studies as an approximately quadrangular shaped area that previously covers about  $75 \text{ km}^2$ .

Access to the area is provided by a sealed road from the nearby town of Meshkinshahr to the village of Moil, then to the valley south of the village by an unsealed road. A sealed road connects Meshkinshahr to the provincial capital city of Ardebil, 80 km to the east. Ardebil is serviced by daily flights from Tehran. The project can also be readily accessed through daily flights from Tehran to the large industrial city of Tabriz, 180 km northwest of Meshkinshahr.

The geothermal field is located in an environmentally sensitive area of elevated valley terraces set within the outer caldera rim of the greater Mt. Sabalan complex. Vegetation is limited to light scrub and pasture with some small holdings and associated arable planting. The lower terraces are intensively planted in wheat and lucerne by farmers from the villages of Moil and Illando. The upper terraces are occupied in the summer months only by nomadic people, herding sheep, goats and some cattle (SKM, 2005).

The area is identified as a seismically active location. The National Building Code (Standard 2800) published by the Building and Housing Research Centre for Iran, includes a seismic macrozonation hazard map for Iran. The site location around Mt. Sabalan is identified in the very high risk zone with a typical peak ground acceleration of  $0.35 \times g$ . Of greater significance will be seismically induced slope instability. The steep sided scree slopes of the deeply incised river gullies will experience large-scale translational slides, debris flows and lateral spreading. Any infrastructure or assets located on or

adjacent to this slope will require specific design features to protect or reduce against the effects of earthquake induced slope instability.

Mt. Sabalan is a Quaternary volcanic complex that rises to a height of 4811 m, some 3800 m above the Ahar Chai valley to the north. Volcanism within the Sabalan caldera has formed three major volcanic peaks which rise to elevations of around 4700 m.

TABLE 1: Summary of weather data, NW-Sabalan

Item	Parameter	Moil village station (Year 2000)	Well site B weather station (Year 2001-2002)
Temperature	Annual average	3.8°C	3.6°C
	Annual maximum	30°C	29°C
	Annual minimum	-18°C	-30°C
Humidity	Average annual value	60%	52%
Precipitation	Average annual value	196 mm	306 mm

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). In 2001, a weather station was established at the site by SUNA and has operated intermittently. This has provided a record of dry bulb temperatures, rainfall, wind speed and direction. A summary of the available weather data is given in Table 1. This temperature variation forces the sheep grazers to move during the winter to a warmer area near the Caspian Sea and the Aras River by the Azerbaijan border.

After the geological exploration stage, the project was divided into two phases; the first phase (1998-2006) was aimed at building drill pads at sites A, B, C (Figure 2), including excavation and the construction of concrete pads access roads from Moil village to the sites, a pump station, a water reservoir, and water intake and water pipelines from a pump station to the reservoir and all sites. This phase also included repairing the existing road between Meshkinshahr and Moil village and drilling five exploratory wells. In the

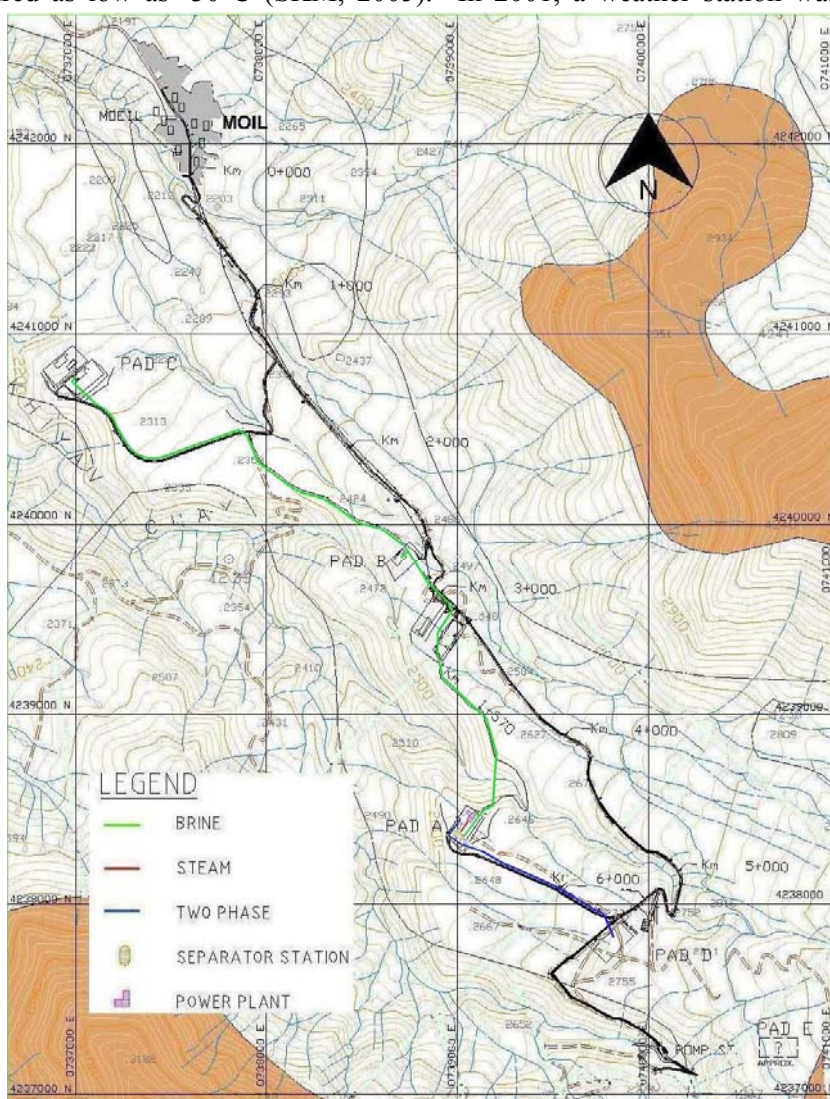


FIGURE 2: Map of the Sabalan area NW-Iran (SKM, 2005)

second phase, SUNA has decided to build a 5 MWe pilot power plant at site B for observing the actual viability of a geothermal power plant in Iran and simultaneously to drill 13 production or reinjection wells, including preparations of well pads A and B, for additional drilling, and well pads D and E, for new drilling. This phase also includes access roads to site E, a water pipeline and a new pump station in order to provide water for drilling at site E. After drilling and well testing, SUNA plans to build a 50 MWe power plant in order to reach 55 MWe total capacity.

In this project, the above 50 MWe 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. Figure 2 shows the planned sites: A, B, C and D.

The main objective of this study is the selection of an optimum route with minimum cost, for each pipeline, and then to determine the diameter and other criteria such as thickness, distance between supports, expansion loops, and expansion units. Also, the layout plan for a power plant will be designed in order to determine the placement of the power plant buildings such as the separator station, powerhouse, office building and others. The design is based on a modelling technique using EES – Engineering Equation Solver (F-Chart Software, 2004) and Excel software. This report will discuss the results of previous exploration studies in this area, the theory and method overview, and finally the pipeline design.

## **2. EXPLORATION OF THE MT. SABALAN GEOTHERMAL AREA**

### **2.1 Geology**

Mt. Sabalan lies on the South Caspian plate, which is underthrust by the Eurasian plate to the north. It is, in turn, underthrust by the Iranian plate, which produces compression in a northwest direction. This is complicated by a dextral rotational movement caused by northward underthrusting of the nearby Arabian plate beneath the Iranian plate. There is no Benioff-Wadati zone to indicate any present day subduction. The current project area is located within the Moil Valley, which on satellite and aerial photographic imagery can be seen to be a major structural zone. Exposed at the surface in the valley are altered Pliocene volcanics, an unaltered Pleistocene trachydacite dome (Ar-Ar dated at 0.9 Ma) and Quaternary terrace deposits (Bogie et al., 2000). These units have been divided into four major stratigraphic units which, in order of increasing age, are (SKM, 2005):

- Quaternary alluvium, fan and terrace deposits;
- Pleistocene post-caldera trachy andesitic flows, domes and lahars;
- Pleistocene syn-caldera trachy dacitic to trachy andesitic domes, flows and lahars;
- Pliocene pre-caldera trachy andesitic lavas, tuffs and pyroclastics.

### **2.2 Geochemistry**

Warm and hot springs are found with Cl-SO<sub>4</sub>, acid Cl-SO<sub>4</sub> and acid SO<sub>4</sub> chemistries within the Moil valley (Bogie et al., 2000). They plot in the immature area of the Na-K-Mg plot (Giggenbach 1991), giving geothermometer temperatures of approximately 50°C (SKM, 2005). One of these, the Gheynarge (Qeynerce) spring has a Cl concentration of 1800 mg/kg. Tritium analyses of this spring water indicate no recent interaction with the atmosphere.



The isotopic composition of the spring waters and their seasonal variation in flow, with little change in temperature or chemistry, suggested that a large regional groundwater aquifer overlies the potential geothermal reservoir (SKM, 2005).

### 2.3 Geophysics

A magneto telluric survey (Bromley et al., 2000) established the existence of a very large zone of low resistivity ( $\approx 70 \text{ km}^2$ ) in the project area. Satellite imagery interpretation identified a large area ( $\approx 10 \text{ km}^2$ ) of surficial hydrothermal alteration in lower elevation parts of the project area, with much of the low-resistivity area in the valley covered by Quaternary terrace deposits. The presence of surficial hydrothermal alteration was confirmed by field work. XRD analyses of this alteration reveals the presence of interlayered illite-smectite clays (which are conductive and will have formed at depth) indicating that at least some of the alteration and the resistivity anomaly is relict. At higher elevations unaltered rocks cover the zone of low resistivity. To define a target area for drilling, an area of very low resistivity ( $< 4 \Omega\text{m}$ ) associated with the thermal features was initially selected.

The early interpretation of the MT work (Bromley et al., 2000) showed low resistivity persisting to depth. However, once the relatively shallow occurrence of the conductive smectitic clays was established from the exploration geothermal wells, the MT data was reinterpreted in terms of the elevation of the base of the conductor. A conductive zone, increasing in elevation to the south, can be partially distinguished from the much larger and deeper resistivity anomaly to the west. This new interpretation is indicative of the current system's upflow occurring south of the drilled wells (Talebi et al., 2005).

### 2.4 Exploration drilling programme

On the basis of the results of the MT survey and the presence of hot springs with significant Cl concentrations, a three well exploration programme was undertaken. The topography of the valley limits the location of drill pads to interconnected terraces requiring two of the wells to be directionally drilled to access an extensive anomaly at depth. The drilling and testing programme was carried out between November 2002 and December 2004. The location of the project, with a detailed map of the drilled area, is shown in Figure 3. The three deep exploration wells drilled are coded as NWS-1,

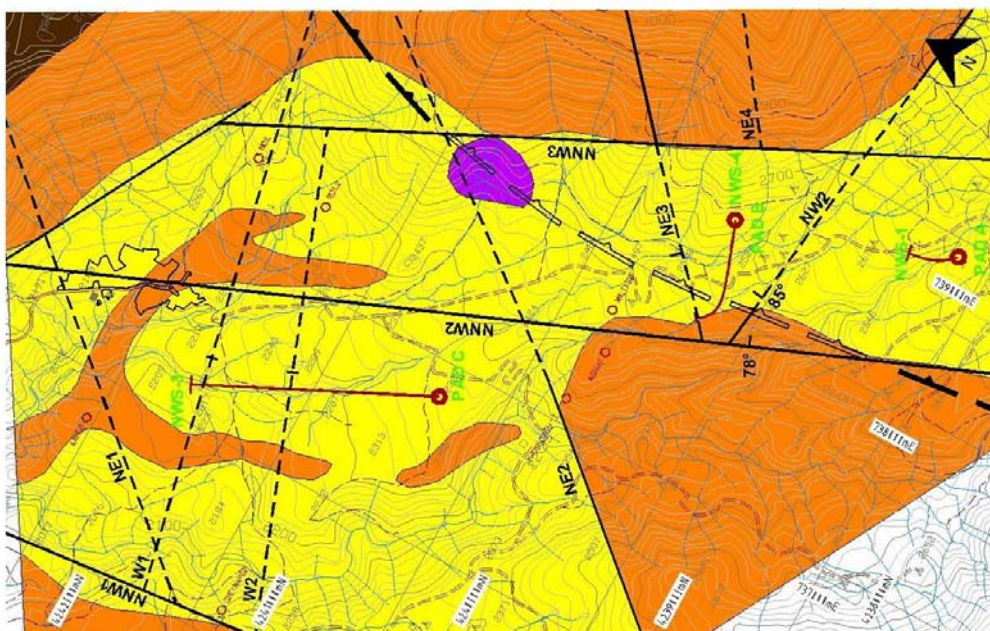


FIGURE 3: Well location and surface geology, NW-Sabalan geothermal project (SKM, 2005)

NWS-3 and NWS-4 on well pads A, C and B, respectively. The wells vary in depth from 2265 to 3197 m MD. Well NWS-1 was drilled vertically while NWS-3 and NWS-4 are deviated wells with throws of 1503 and 818 m, respectively. Additionally, two shallow reinjection wells were drilled to 600 m depth: NWS2R, located on pad A alongside well NWS-1, and NWS-5R on pad B alongside well NWS-4. The basic well completion data are summarised in Table 2.

TABLE 2: Basic completion information of NWS wells (SKM, 2005)

Well	Spud date	Completion date	Depth (mMD / mVD)	Production casing		Production liner	
				Size (in)	Depth (mMD)	Size (in)	Depth (mMD)
NWS-1	22 Nov 02	1 Jun 03	3197	9 $\frac{5}{8}$	1586	7	3197
NWS-3	2 Jul 03	27 Nov 03	3166 / 2603	13 $\frac{3}{8}$	1589	9 $\frac{5}{8}$	3160
NWS-4	17 Dec 03	27 Mar 04	2255 / 1980	9 $\frac{5}{8}$	1166	7	2255
NWS-2R	7 Jun 03	25 Jun 03	638	13 $\frac{3}{8}$	360	9 $\frac{5}{8}$ , 5	638
NWS-5R	7 Apr 04	2 May 04	538	20	139	9 $\frac{5}{8}$	482

## 2.5 Well testing and reservoir results

Well NWS-1 was discharged in May 2004 for a period of 21 days with reinjection of waste brine into shallow well NWS-2R. Well NWS-4 was discharged by airlift stimulation in September 2004 and was flow tested for the next four months with reinjection of waste brine into shallow well NWS-5R. Output curves for well NWS-1 and well NWS-4 are shown in Figure 4. These show variations in total mass and enthalpy with flowing wellhead pressure. Both wells discharged with enthalpies in the range of 950-1000 kJ/kg, which is consistent with production from liquid-only feed zones with temperatures of 230°C (for NWS-1) and 220°C (for NW-4). These are both lower than the maximum temperatures measured in the two wells of 245 and 230°C, respectively.

Due to the relatively low overall permeability, the discharge of well NWS-1 is sensitive to wellhead pressure variation and flow could not be sustained at wellhead pressures above 4.5 bar-g. In contrast, well NWS-4, with a significantly higher permeability, shows a constant enthalpy of 950 kJ/kg at all wellhead pressures, reflecting the dominance of the 1620 m feed zone, and progressive decline in total flow and steam flow up to 10 bar-g wellhead pressure.

The calculated parameters indicate that the potential capacity of the NW-Sabalan resource has a mean value of 209 MWe, with a 90% probability of being greater than 125 MWe and a 50% probability of

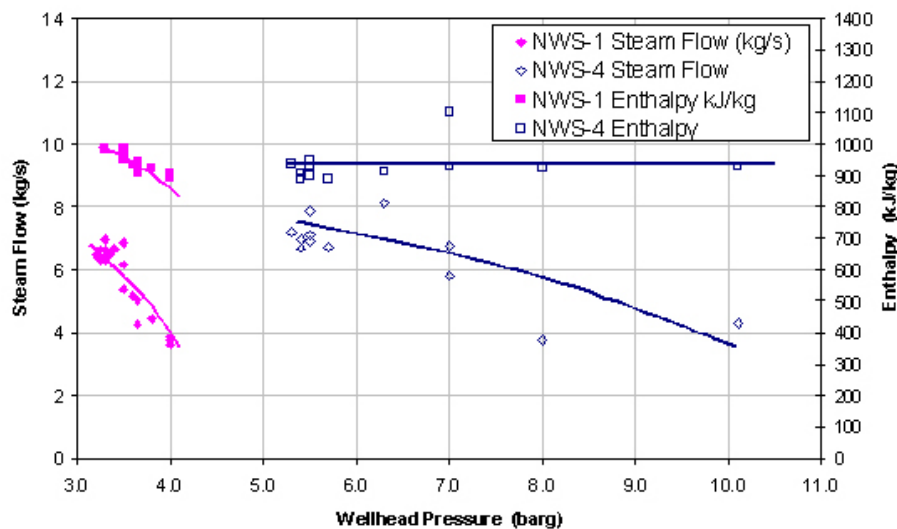


FIGURE 4: Output curves for wells NWS-1 & NWS-4 (SKM, 2004)

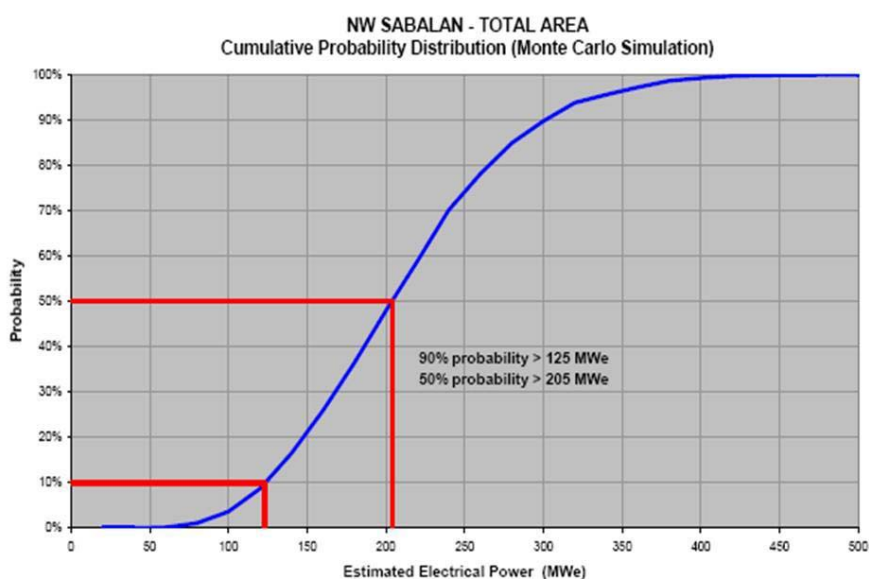


FIGURE 5: Estimated electrical power potential of the NW-Sabalan area, using Monte Carlo simulation (SKM, 2005)

being greater than 205 MWe (Figure 5). The average calculated energy density for the whole area is 11 MW/km<sup>2</sup> (SKM, 2005).

## 2.6 Well geochemistry

Full sets of chemical samples were collected and analysed from NWS-1 and NWS-4 during the discharge test. Chemical analyses of these samples are presented in Table 3. The reservoir fluids

TABLE 3: Summary of geochemistry of the wells NWS-1 and NWS-4 (SKM, 2005)

<b>Sabalan Wells - Brine Analyses:</b>															
Well	Date	Type	C.P.	pH	Li	Na	K	Ca	Mg	Fe	Cl	SO <sub>4</sub>	tHCO <sub>3</sub>	B	SiO <sub>2</sub>
			b.g.												
NWS1	14-Jun-04	SPW	2.4	8.88	8.3	1414	257	15	0.11	0.10	2411	117	105	22	520
NWS1	15-Jun-04	SPW	2.5	8.70	8.1	1402	254	15	0.10	0.05	2375	117	113	22	519
NWS1	16-Jun-04	SPW	3.1	8.56	8.1	1382	255	14	0.09	0.02	2336	118	130	21	506
NWS1	18-Jun-04	SPW	3.0	8.63	8.2	1385	252	14	0.09	0.04	2384	114	115	21	522
NWS4	13-Sep-04	WBX	0.0	8.60				31			2606	123	75	22	418
NWS4	14-Sep-04	ATM	0.0	8.39				31			2482	109	85	21	444
NWS4	15-Sep-04	ATM	0.0	8.42				31			2500	100	85	22	466
NWS4	16-Sep-04	SPW	1.5	8.42				26			2570	116	78	22	484
<i>Analyses for NWS-4 incomplete at time of going to press</i>															
<b>Sabalan Wells - Steam Gas Analyses, Molar Ratios and Brine Geothermometry:</b>															
Well	Date	Type	C.P.	CO <sub>2</sub>	H <sub>2</sub> S	Cl	Cl	Cl	Na	Cl <sub>RES</sub>	T <sub>QTZ</sub>	T <sub>NaK</sub>	CO <sub>2</sub>		
			b.g.	mM/100M		—	—	—	—	mg/kg	°C	°C	—		
NWS1	14-Jun-04	SPW	2.4	917	5.8	185	33	56	9.4	2030	238	266	158		
NWS1	15-Jun-04	SPW	2.5	860	3.8	185	33	55	9.4	1991	238	266	226		
NWS1	16-Jun-04	SPW	3.1	1002	4.9	189	34	54	9.2	2005	237	267	204		
NWS1	18-Jun-04	SPW	3.0			195	35	57	9.3	2050	239	267			
NWS4	13-Sep-04	WBX	0.0			95	37	57		1992	215				
NWS4	14-Sep-04	ATM	0.0	756	6.2	91	35	62		1897	219		122		
NWS4	15-Sep-04	ATM	0.0			91	35	68		1911	223				
NWS4	16-Sep-04	SPW	1.5	742	4.6	112	36	60		2065	230		161		

**Notes:** CP = Collection pressure, SPW = separated water, ATM = at atmospheric pressure, WBX= silencer weirbox, b.g. = pressure in bars gauge

produced by this deep well are slightly alkaline, relatively dilute, sodium chloride brines with chloride concentrations of about 2000 mg/kg and with approximately 0.5% TDS. The concentrations of CO<sub>2</sub> and H<sub>2</sub>S in separated steam average 2%, which is a typical value for developed geothermal fields.

Discharge silica concentrations are in the range 520-540 ppm in the weir box. These equate to quartz geothermometer temperatures of 230-235°C. This is somewhat higher than flowing temperature survey temperatures of only 227°C. Cation temperatures are significantly higher than T<sub>QTZ</sub> temperatures, ranging from 260 (T<sub>NaKCa</sub>) to 280°C (Fournier, 1979). This suggests that higher geothermal reservoir temperatures may exist at Sabalan, outside the immediate area of the NWS1 wellbore, closer to the upflow of the geothermal system.

### 3. THEORY AND METHOD OVERVIEW OF PIPELINE DESIGN

The standard design process for pipelines in a geothermal system is as follows:

- Topology and route selection;
- Demand and flow analysis;
- Pipe diameter optimization with minimum cost due to head loss;
- Thickness and pressure classes;
- Mechanical stress analysis of supports, type and distance between supports;
- Thermal stress analysis of anchors, expansion loops and expansion units;
- Pump size and arrangement.

There are different processes and design criteria, which depend on the fluid that will be transmitted through the pipeline whether it is water, steam or two-phase flow; these processes and criteria are discussed in the following section.

#### 3.1 Route selection

There are many considerations that should be made in selecting the route of a pipeline. These considerations depend on whether the pipe is installed underground or above ground. Since the cost of pipe above ground is less than the underground pipeline, it will be used for pipeline design in this project. Some of the most important considerations for above ground pipeline route selection are (Efotg, 2007):

- The pipeline route should have the shortest distance between two points, and the number of high and low spots should be minimized. High spots require an avoidance of pressure higher than saturation pressure and low spots require drains; the design pressure should also be checked. When designing a two-phase flow pipeline, it is not necessary to take notice of the pressure in the top point.
- Routing the pipeline over moderate slope terrain makes it easier to install the pipe. High slopes can be used, but though not too much.
- There must be access to all portions of the piping equipment along the route.
- Avoid landslide areas and avoid crossing watercourses that are eroding.
- Avoid crossing federal or state land where possible. Permits are required for crossing these lands and the permitting process takes a considerable amount of time, cost and effort to complete.
- The pipeline route should be selected to minimize environmental impacts.
- Full consideration should be given to the possibility of future expansion to the system. If a pipeline extension is anticipated, then pipe size and ratings should be appropriate for the ultimate extension.



- The route with minimum total updated cost should be considered.

### 3.2 Pipe diameter for water or steam pipelines

In order to select a proper diameter of water or steam pipeline, the following two factors should be considered (Jónsson, 2007):

- The maximum allowable velocity; and
- Minimizing the “Total Update Cost” ( $C_t$ ).

Total update cost ( $C_t$ ) is:

$$C_t = C_c + C_e (1 - 1/(1+i)^T)/i \quad (1)$$

where  $C_c$  = Capital cost;  
 $C_e$  = Annual cost;  
 $T$  = Life time;  
 $i$  = Index rate.

The capital cost is equal to:

$$C_c = L_p k_p + n_b k_b + n_c k_c + n_u k_u + n_v k_v + n_d k_d + L_p k_e \quad (2)$$

where  $L_p$  = Pipe length (m);  
 $k_p$  = Cost of pipe (Euro/m);  
 $n_b$  = Number of bends;  
 $k_b$  = Cost of bends (Euro);  
 $n_c$  = Number of connections;  
 $k_c$  = Cost of connections (Euro);  
 $n_u$  = Number of expansion units;  
 $k_u$  = Cost of expansion units (Euro).  
 $n_v$  = Number of valves;  
 $k_v$  = Cost of valves (Euro);  
 $n_d$  = Number of pumps;  
 $k_d$  = Cost of pumps (Euro);  
 $k_e$  = Cost of insulation (Euro/m).

The annual cost is equal to:

$$C_e = k_e o_h P \quad (3)$$

where  $k_e$  = Cost of electrical energy (Euro/Wh);  
 $o_h$  = Hours in one year =  $365 \times 24 = 8760$  hours;  
 $P$  = Power of the pump (W).

The power of pump was calculated using equation:

$$P = g \rho H_f Q / \eta \quad (4)$$

where  $g$  = Gravity constant ( $\text{m/s}^2$ );  
 $\rho$  = Density of fluid water or steam ( $\text{kg/m}^3$ );

$$\begin{aligned}
 H_f &= \text{Friction head (m);} \\
 Q &= \text{Flow rate of fluid (m}^3\text{/s);} \\
 \eta &= \text{Efficiency of pump.}
 \end{aligned}$$

In order to calculate the friction head ( $H_f$ ), the velocity of fluid ( $V$ ) should be calculated first using equation:

$$V = Q / (\pi D_{in}^2 / 4) \quad (5)$$

$$\begin{aligned}
 \text{where } V &= \text{Velocity of fluid (m/s);} \\
 D_{in} &= \text{Pipe inner diameter (m).}
 \end{aligned}$$

The second equivalent length ( $L_e$ ) can be calculated using equation:

$$L_e = L_p + n_b h_b D_{in} + n_c h_c D_{in} + n_u h_u D_{in} + n_v h_v D_{in} \quad (6)$$

$$\begin{aligned}
 \text{where } L_p &= \text{Pipe length (m);} \\
 D_{in} &= \text{Inner diameter (m);} \\
 h_b &= \text{Equivalent length of bends;} \\
 h_c &= \text{Equivalent length of connections.} \\
 h_u &= \text{Equivalent length of expansion units;} \\
 h_v &= \text{Equivalent length of valves;}
 \end{aligned}$$

The third Reynolds number ( $R_e$ ) should be calculated using equation:

$$R_e = V D_{in} / \nu \quad (7)$$

$$\text{where } \nu = \text{Viscosity of fluid (m}^2\text{/s).}$$

Based on the amount of the Reynolds number, the friction factor ( $f$ ) should be calculated from one of the following equations:

$$R_e \leq 2100 \quad f = 64 / R_e \quad (8)$$

$$R_e > 2100 \quad 1/\sqrt{f} = 1.14 - 2 \log_{10} \left( k/D_{in} + 9.35/(R_e \sqrt{f}) \right) \quad (9)$$

$$\begin{aligned}
 \text{where } R_e &= \text{Reynolds number;} \\
 k &= \text{Absolute roughness (m).}
 \end{aligned}$$

Friction head ( $H_f$ ) can be calculated by using the data from Equations 5-9 as follows:

$$H_f = \frac{f V^2}{2g} \frac{L_e}{D_{in}} \quad (10)$$

$$\begin{aligned}
 \text{where } H_f &= \text{Friction head (m of fluid);} \\
 f &= \text{Friction factor;} \\
 L_e &= \text{Equivalent length (m);}
 \end{aligned}$$

The pressure that we need to pump ( $P_p$ ) can be calculated according to equation:

$$P_p = (\Delta Z + H_f) \rho g \quad (11)$$

where  $P_p$  = Pump pressure (Pa);  
 $\Delta Z$  = Elevation difference between end and start points of line,  $\Delta Z = H_s - H_e$  (m).

When  $P_p$  is negative it is not necessary to pump the fluid, as it is ruled by gravity.

For each diameter, the Total update cost, based on the above Equations, will be calculated. Total update cost is the main parameter for selecting the optimum diameter, as shown in Figure 6. When the diameter increases, the Total capital cost increases but the Updated annual cost decreases. There is an optimum diameter with the minimum Total updated cost. However, in this project the brine water follows gravity, and it is not necessary to pump, hence the annual cost is zero. The diameter will be selected by a proper velocity. In order to avoid corrosion and erosion in the water pipeline, the velocity should be less than 3 m/s; for the steam pipeline, the velocity should be less than 40 m/s.

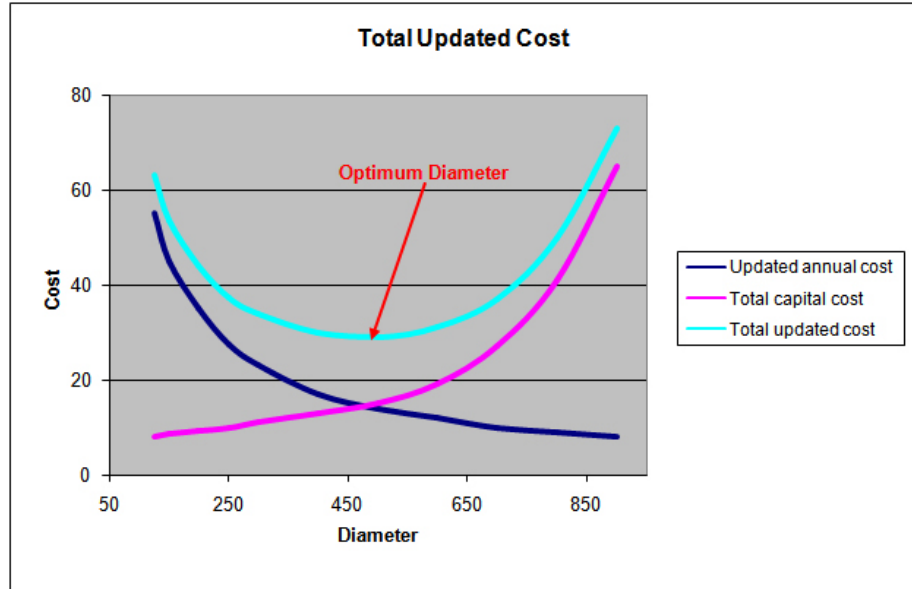


FIGURE 6: Graph showing selection of optimum diameter based on the Total updated cost

### 3.3 Pipe diameter for two-phase flow pipelines

It is important to determine the diameter of a two-phase flow pipeline as efficiently as possible. If there is a high pressure drop in the pipeline, the separator station should be close to the wellhead, and then the steam and the water should be transmitted separately in two pipelines, as the pressure drop in the steam pipeline and the water pipeline are less than in a two-phase flow pipeline. A two-phase mixture can flow through a pipe in a variety of flow regimes as shown in Figure 7. These regimes depend on various conditions:

- Transport properties of fluids;
- Mass and volume fraction in pipes;
- Velocity fraction between phases.

Flow regime maps determine the most likely regime by using the parameters above. There are

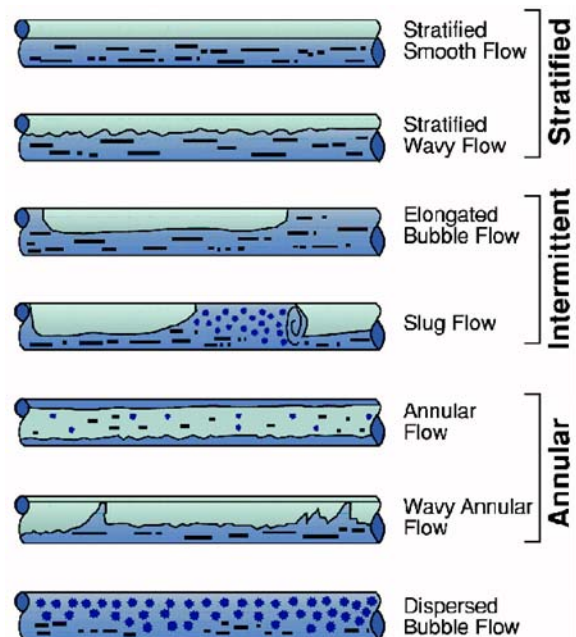


FIGURE 7: Different flow regimes

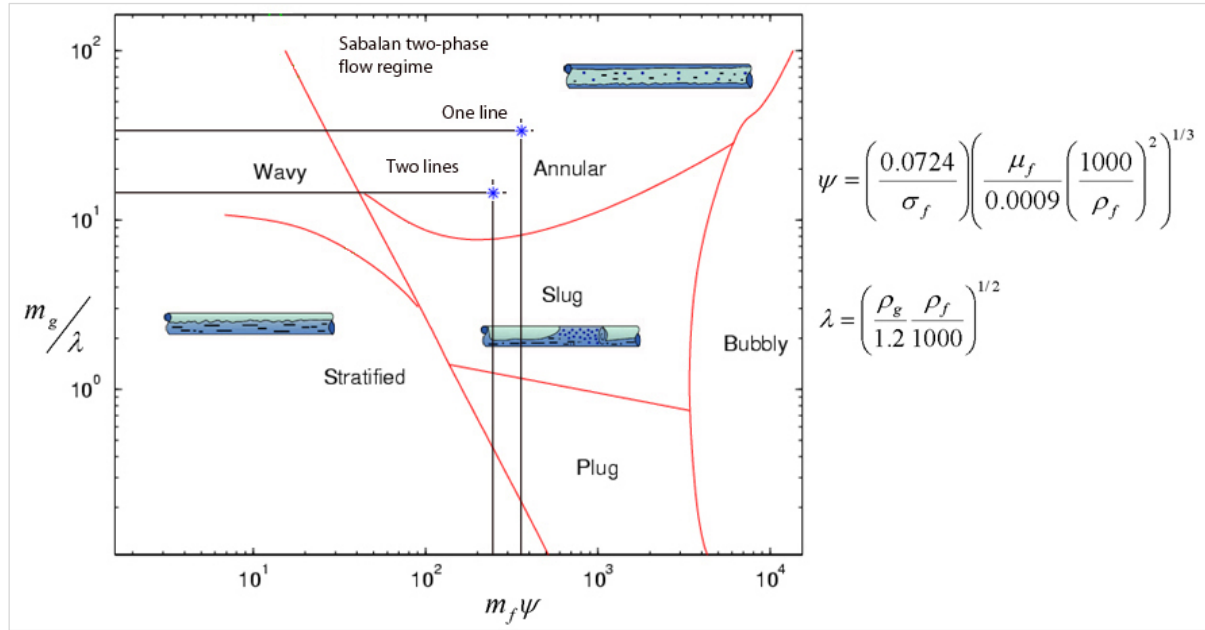


FIGURE 8: The Baker map

three kinds of maps: the Baker map, the Nukherjee and Brill map, and the Spedding and Nguyen map. Based on fluid characteristics of the Sabalan project using the Baker map, the annular regime in this project for flow of five wells is shown in Figure 8.

In a two-phase flow pressure drop prediction of the separated flow model, the void fraction ( $\alpha$ ) is the most important fundamental parameter. It is the ratio of the gas flow cross-section to the total cross-section:

$$\alpha = A_g / A \quad (12)$$

where  $A_g$  = Area of gas or steam;  
 $A$  = Total area.

Zhao et al. (2000) found a new void fraction correlation, that it is derived from the analysis of two-phase flow velocity distribution using the Seventh power law as:

$$\frac{1-\alpha}{\alpha^{7/8}} = \left[ \left( \frac{1}{x} - 1 \right) \left( \frac{\rho_g}{\rho_f} \right) \left( \frac{\mu_f}{\mu_g} \right) \right]^{7/8} \quad (13)$$

To predict the two-phase pressure drop, an equivalent pseudo single-phase flow having the same boundary layer velocity distribution is assumed. The average velocity of the equivalent single-phase flow is used to determine the wall friction factor and hence the two-phase pressure drop. This method gives very good agreement with the experimental data. The average velocity of the equivalent single-phase flow is also a very good correlating parameter for the prediction of geothermal two-phase pressure drops in a horizontal straight pipe.

The void fraction determines other two-phase parameters such as the liquid phase velocity, and the mean density ( $\rho$ ). These, in turn, determine the two-phase pressure drop. The liquid phase velocity ( $\bar{V}_f$ ) can be expressed as:



$$\bar{V}_f = 1.1(1-x) \frac{W(1-x)}{\rho_f(1-\alpha)A} \quad (14)$$

where  $W$  = Total mass flow rate (kg/s);  
 $x$  = Steam quality;  
 $\rho_f$  = Density of water (kg/m<sup>3</sup>);  
 $1.1(1-x)$  = Correction factor mainly for entrainment.

At this stage, a correction factor is introduced to account for the entrainment effect and the simplification made in deriving the void fraction correction. It can be explained as  $1.1(1-x)$  fraction of the liquid phase is left in the liquid phase boundary layer. The other fraction is entrained inside the gaseous phase as water droplets. When the steam quality decreases, the gaseous phase can carry less liquid. This means a higher percentage of the liquid is left in the boundary layer. The choice of factor is mainly to give a good result rather than to provide a rigorous theoretical justification (Zhao et al., 2000). The average velocity of the equivalent single-phase flow ( $\bar{V}$ ) can be calculated using equation:

$$\frac{\bar{V}_f}{\bar{V}} = \frac{(1-\sqrt{\alpha})^{(8/7)} \left(1 + \frac{8}{7} \sqrt{\alpha}\right)}{(1-\alpha)} \quad (15)$$

By using Equations 7 to 9, based on the average velocity of the equivalent single-phase flow ( $\bar{V}$ ) and the density of fluid (water), the Reynolds number ( $R_e$ ) and friction factor ( $f$ ) can be calculated. Then pressure drop, due to the length of the pipe ( $\Delta_{PL}$ ), can be calculated from Equation 16 (Zhao et al., 2000):

$$\Delta_{PL} = \frac{f \rho_f \bar{V}^2}{2D_{in}(1-AC)} \quad (16)$$

where  $\Delta_{PL}$  = Pressure drop due to length (Pa);  
 $\rho_f$  = Density of fluid (water) (kg/m<sup>3</sup>);  
 $AC$  = Acceleration correction,  $AC = m_g / \rho_g (pA^2\alpha)$ ;  
 $m_g$  = Mass of gas (steam) (kg/m<sup>3</sup>);  
 $p$  = Pressure (Pa);  
 $A$  = Inner area (m<sup>2</sup>).

In order to calculate the pressure drop for an installation including bends, connections, expansion units and valves, the first two-phase multipliers ( $\phi_{BLO}^2$ ) for each one should be calculated by (Chisholm, 1983):

$$\phi_{BLO}^2 = 1 + \left( \frac{\rho_f}{\rho_g} - 1 \right) (Bx(1-x) + x^2) \quad (17)$$

where  $x$  = Quality of steam;  
 $B = 1 + 2.2 / K_{BLO}(2+r/D_{in})$ ;  
 $K_{BLO} = 1.6 fh$ ;  
 $h$  = Equal length (m);  
 $r$  = Bend radius (m).

Then the pressure drop can be calculated from the following equation:

$$\Delta_{PI} = \frac{f\rho_m \bar{V}^2}{2} (\varphi_{BLO,b}^2 n_b h_b + \varphi_{BLO,c}^2 n_c h_c + \varphi_{BLO,u}^2 n_u h_u + \varphi_{BLO,v}^2 n_v h_v) \quad (18)$$

where  $\Delta_{PI}$  = Pressure drop for the installation (Pa);  
 $\rho_m$  = Density of mixture of fluid and gas (water and steam) (kg/m<sup>3</sup>);  
 $\varphi_{BLO,b}^2$  = Two-phase multiplier for bends;  
 $\varphi_{BLO,c}^2$  = Two-phase multiplier for connections.  
 $\varphi_{BLO,u}^2$  = Two-phase multiplier for expansion units;  
 $\varphi_{BLO,v}^2$  = Two-phase multiplier for valves.

Finally, total pressure drop ( $\Delta_{PT}$ ) can be calculated from the following equation:

$$\Delta_{PT} = \rho_m g \Delta_Z - (\Delta_{PL} + \Delta_{PI}) \quad (19)$$

### 3.4 Pipe thickness

The thickness of a pipe should be determined based on the pressure inside the pipe, called design pressure. That is the maximum pressure along the pipe under all conditions, for example, in this project for brine water pipelines, static pressure plus the pressure after the separator station, when the system dose not work, and when no reinjection occurs. In order to calculate the thickness for a brine water pipeline, it will be assumed that the friction head ( $H_f$ ) equals zero and design pressure ( $P_D$ ) equals ( $-P_P$ ). From Equation 11, if there is pressure after the separator, this pressure should be added to the calculated pressure. For a two-phase flow pipeline, design pressure ( $P_D$ ) is equal to the wellhead pressure and for a steam pipeline the design pressure is equal to the separator pressure. According to ANSI B31.3 the nominal pipe thickness ( $t_n$ ) is larger or equal to the requisite pipe thickness ( $t_m$ ), shown in the following equation:

$$t_n \geq t_m = P_D D_o / (2(S_h E + P y)) + A \quad (20)$$

where  $P_D$  = Design pressure (Pa);  
 $D_o$  = Outer diameter of pipe (m);  
 $S_h$  = Allowable stresses (Pa);  
 $E$  = Welding factor for butt-weld joint, = 0.85;  
 $y$  = Temperature dependent coefficient for steel for  $T < 480^\circ\text{C}$ , = 0.4;  
 $A$  = Additional thickness for milling and corrosion (m) = 0.0015 m.



FIGURE 9: Pipeline supports

### 3.5 Distance between supports

When the pipe is installed above the ground, it is supported by supports as shown in Figure 9. There are two kinds of supports. The first allows the pipe to move vertically and horizontally as shown in Figure 10; the second allows the pipe to only move horizontally as shown in Figure 11. The second one uses the part of a pipeline that is called the arm of an expansion loop. Here, horizontal means along the



FIGURE 10: Pipeline support with horizontal and vertical movement



FIGURE 11: Pipeline support with only horizontal movement

pipeline; and vertical means perpendicular to the pipeline.

### 3.5.1 Allowable stresses

In order to calculate the distance between supports, we should know the basic allowable stresses of a pipe ( $S$ ). Based on the yield limit ( $R_{p/t}$ ) and designating the ultimate strength at the calculated temperature ( $R_{m/T}$ ), allowable stresses can be calculated from equations (Jónsson, 2007):

$$S = \min(R_{m/T}/3, R_{m/h}/3, 2R_{p/c}/3, 2R_{p/h}/3) \quad (21)$$

$$S_h = \min(R_{m/h}/3, 2R_{p/h}/3) \quad (22)$$

$$S_c = \min(R_{m/c}/3, 2R_{p/c}/3) \quad (23)$$

where the following values (MPa) are given for different steel types:

Steel	$S_{235}$	$S_{275}$	$S_{335}$
$R_{m/T} = R_{m/c\&h}$	340	410	490
$R_{p/50}$	235	275	355
$R_{p/200}$	185	115	245
$R_{p/300}$	140	165	195

In this project, the steel class required is ( $S_{235}$ ). For water with a temperature  $T = 80^\circ\text{C}$ , then  $R_{m/T} = 340$ ,  $R_{p/c} = 235$ ,  $R_{p/h} = 225$ , and  $S = \min(113.3, 113.3, 156.7, 150.0) = 113.3$  MPa. For the two-phase flow  $T = 155.5^\circ\text{C}$ , then  $R_{p/h} = 200$  and  $S = 113.3$  MPa. For steam from the first separator  $T = 152.8^\circ\text{C}$ , then  $R_{p/h} = 200.7$  and  $S = 113.3$  MPa. Finally, for steam from the second separator  $T = 120.2^\circ\text{C}$ , then  $R_{p/h} = 211.6$  and  $S = 113.3$  MPa. For all cases, allowable stress equals 113.3 MPa.

### 3.5.2 Distance between horizontal and vertical supports ( $L_s$ )

In order to calculate the distance between supports with only horizontal movement ( $L_s$ ), the pipe is assumed as a simple beam between two supports. The stress of sustained load and dynamic load plus the stress resulting from the pipe pressure are calculated, and should be less than the allowable stress, as shown in Equation 24 (Jónsson, 2007):

$$P_D D_o / (4t_n) + (0.75i)(M_A / Z) + (0.75i)(M_B / Z) \leq kS_h \quad (24)$$

$$Z = \pi / \left( 32 (D_o^4 - D_{in}^4) \right) / D_o \quad (25)$$

where  $t_n$  = Thickness (m);  
 $i$  = Stress intensity factor (where  $0.75i \geq 1.0$ );  
 $M_A$  = Sustained bending moment (Nm);  
 $M_B$  = Dynamic bending moment (Nm);  
 $Z$  = Section modulus (m<sup>3</sup>);  
 $k$  = 1.15 if load is sustained less than 10% of operational time;  
= 1.20 if load is sustained less than 1% of operational time;  
= 1.00 for other cases.

In order to calculate the bending moments ( $M_A$ ) and ( $M_B$ ), first all vertical and horizontal loads should be calculated. Vertical sustained load ( $q_{sv}$ ) contains pipe weight and insulation weight that can be calculated from Equations 26-28.

$$q_{sv} = q_p + q_e \quad (26)$$

$$q_p = \pi g \rho_s (D_o^2 - D_{in}^2) / 4 \quad (27)$$

$$q_e = \pi g \rho_e (D_e^2 - D_o^2) / 4 \quad (28)$$

where  $q_p$  = Pipe weight (N/m);  
 $q_e$  = Insulation weight (N/m);  
 $\rho_s$  = Steel density (kg/m<sup>3</sup>) here  $\rho_s = 7,850$  kg/m<sup>3</sup>;  
 $\rho_e$  = Insulation density (kg/m<sup>3</sup>) here  $\rho_e = 730$  kg/m<sup>3</sup>;  
 $D_e$  = Insulation diameter (m).

The weight of insulation includes both the rock wool and the aluminium plate cover. The vertical dynamic load ( $q_{dv}$ ) contains medium (steam, water or two-phase) weight, snow weight and seismic load, and can be calculated from Equations 29-33:

$$q_{dv} = q_v + q_s + q_{jv} \quad (29)$$

$$q_v = \pi g \rho_v D_{in}^2 / 4 \quad (30)$$

$$q_s = 0.2SD_e \quad (31)$$

$$q_{jv} = 0.5eq_0 \quad (32)$$

$$q_0 = q_p + q_e + q_v \quad (33)$$

where  $q_v$  = Medium weight (N/m);  
 $\rho_v$  = Medium density (kg/m<sup>3</sup>); for brine water  $\rho_v = 971.8$  kg/m<sup>3</sup>;  
for steam  $\rho_v = 2.9$  kg/m<sup>3</sup>;  
for two-phase flow  $\rho_v = 20.4$  kg/m<sup>3</sup>;  
 $q_s$  = Snow weight (N/m);  
 $q_{jv}$  = Seismic vertical load (N/m);  
 $e$  = Seismic coefficient; here  $e = 0.24$ .

Horizontal dynamic load ( $q_{dh}$ ) equals the maximum of wind load and horizontal seismic load that can be calculated from Equations 25-27.

$$q_{dh} = \max(q_w, q_{jh}) \quad (34)$$



$$q_w = C p D_e \quad (35)$$

$$q_{jh} = e q_0 \quad (36)$$

where  $q_w$  = Wind load (N/m);  
 $C$  = Form factor for pipe,  $C=0.6$ ;  
 $p$  = Wind pressure,  $p = V_w^2/1.6$  where  $V_w = 50$  is maximum wind speed (m/s);  
 $q_{jh}$  = Seismic horizontal load (N/m).

As mentioned before, the pipe is assumed as a simple beam, thus, the bending moment for sustained load and dynamic load is calculated from Equations 37 and 38.

$$M_A = q_{sv} L_s^2 / 8 \quad (37)$$

$$M_B = (q_{dv}^2 + q_{dh}^2)^{1/2} L_s^2 / 8 \quad (38)$$

Based on the moments, that were calculated from Equations 37 and 38, and also using Equation 24, the distance between supports ( $L_s$ ) should be less than or equal to the resulting value from Equation 39.

$$L_s \leq \left[ \left[ kS_h - PD_o / (4t_n) \right] / \left[ ((0.75i)/8Z) \left( q_{sv} + (q_{dv}^2 + q_{dh}^2)^{1/2} \right) \right] \right]^{1/2} \quad (39)$$

### 3.5.3 Distance between vertical supports ( $L_s$ )

In order to calculate the distance between supports with horizontal and vertical movement ( $L_{sv}$ ), the pipe is assumed as a simple beam between two supports. The stress of sustained load and dynamic load plus the stress resulting from the pipe pressure is calculated, and should be less than the allowable stress. In this case the span of the pipe in a horizontal direction and a vertical direction are not the same. The vertical span equals the distance between supports ( $L_{sv}$ ), while the horizontal span equals the arm of loop along the pipeline ( $L_{sh}$ ) as shown in Figure 12. Bending moment for sustained load and dynamic load can be calculated from Equations 40 and 41, similar to Equations 37 and 38 (Jónsson, 2007):

$$M_A = q_{sv} L_{sv}^2 / 8 \quad (40)$$

$$M_B = \left( (q_{dv} L_{sv}^2)^2 + (q_{dh} L_{sh}^2)^2 \right)^{1/2} / 8 \quad (41)$$

Based on the moments that were calculated from Equations 40 and 41 and also using Equation 24, gives Equation 42. The distances between the supports ( $L_{sv}$ ) and the arm of loop ( $L_{sh}$ ) are assumed, resulting in:

$$q_{sv} L_{sv}^2 + \left( (q_{dv} L_{sv}^2)^2 + (q_{dh} L_s^2)^2 \right)^{1/2} \leq (kS_h - PD_o / (4t_n)) / ((0.75i)/8Z) \quad (42)$$

The deflection ( $\delta$ ) of the pipe between two supports should be checked, often determined by allowable deflection from the following equation:

$$\delta = 2.07 q_0 L_s^3 / (384 EI) \quad (43)$$

where  $E$  = Young modulus (N/m<sup>2</sup>);  
 $I$  =  $\pi/64 (D_o^4 - d^4)$ .

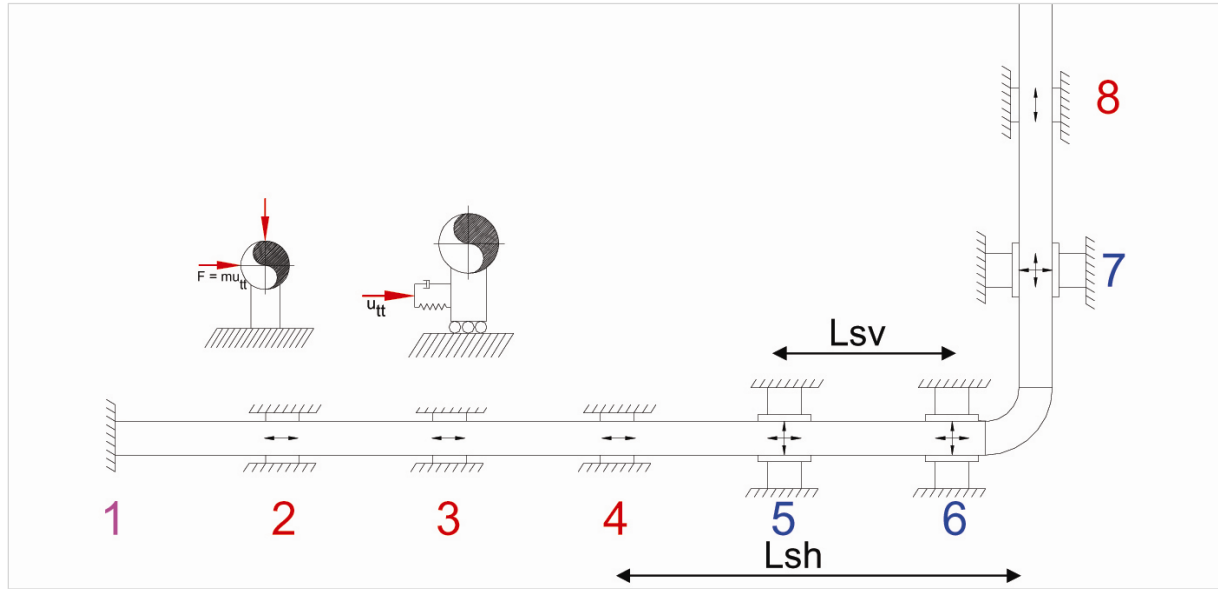


FIGURE 12: Pipeline supports

### 3.6 Thermal expansion

All pipes will be installed at ambient temperature. Pipes carrying hot fluids such as water or steam operate at higher temperatures. It follows that they expand, especially in length, with an increase from ambient to working temperatures. This will create stress upon certain areas within the distribution system, such as pipe joints, which, in the extreme, could fracture. The amount of expansion ( $\Delta L$ ) in a pipe with the length ( $L$ ) is readily calculated using Equation 35:

$$\Delta L = \alpha L \Delta T \quad (44)$$

where  $\alpha$  = Coefficient of thermal expansion ( $1/^\circ\text{C}$ );  
 $\Delta L$  = Temperature difference ( $^\circ\text{C}$ ).

Then thermal strain ( $\varepsilon_x$ ) is equal to:

$$\varepsilon_x = \Delta L / L = \alpha / \Delta T \quad (45)$$

If the pipe is fixed between two ends, the thermal stresses ( $\sigma_x$ ) and the force ( $F$ ) are calculated from Equations 46 and 47:

$$\sigma_x = E \Delta L / L = E \alpha \Delta T \quad (46)$$

$$F = A \sigma_x = A E \alpha \Delta T \quad (47)$$

where  $E$  = Young modulus ( $\text{N/m}^2$ ).

#### 3.6.1 Expansion loop

The expansion loop is a common way to absorb the temperature expansion in steel pipes. Expansion loops can be fabricated from standard pipes and elbows, as shown in Figure 13 (Harvel, 2007). Piping supports should restrict lateral movement and should direct axial movement into the expansion loop. Configurations featuring “change in direction” should not be restrained by butting up against joists, studs, walls or other structures (Figure 13).

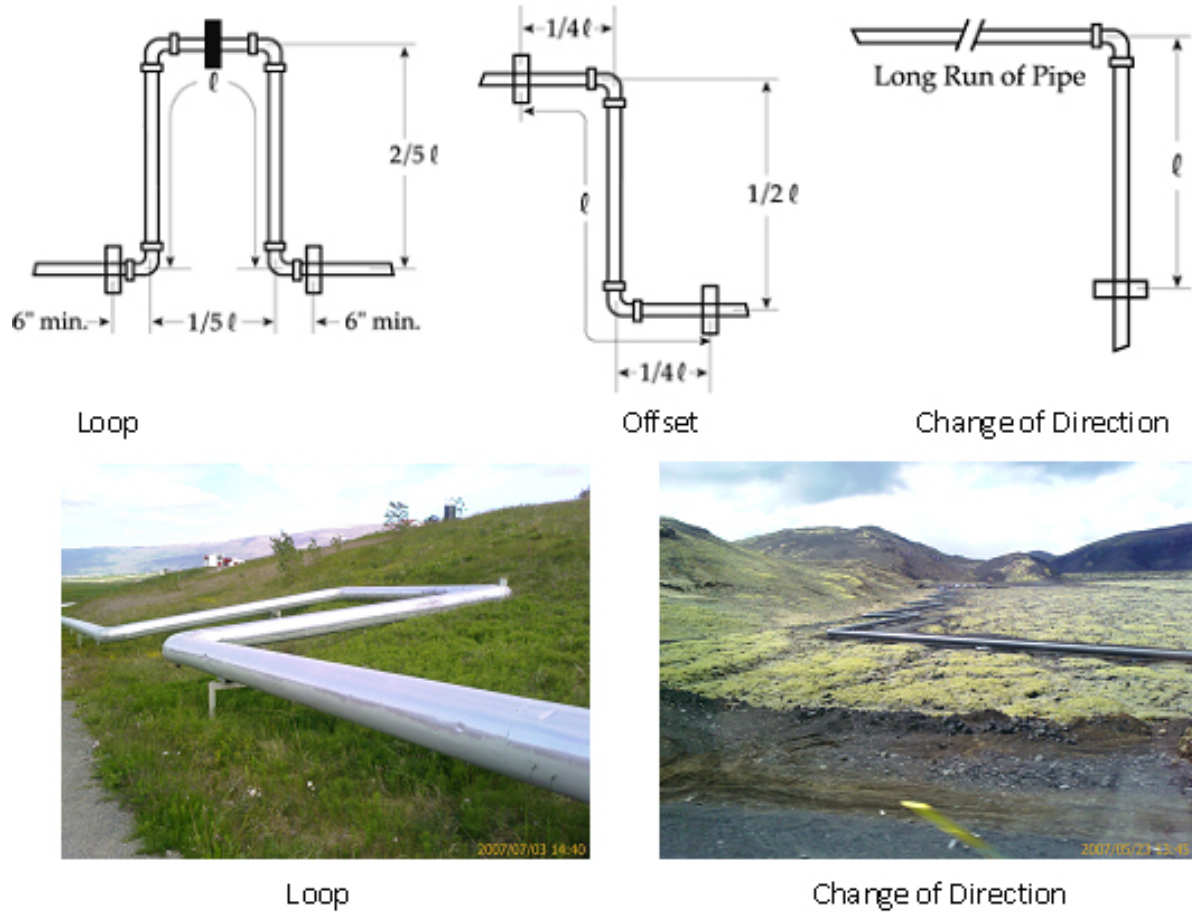


FIGURE 13: Examples of expansion loops

In this project the change of direction method will be used for the piping system with only two anchors and no intermediate restraints. This expansion loop meets the following requirements with respect to thermal expansion (Figure 14) (Jónsson, 2007):

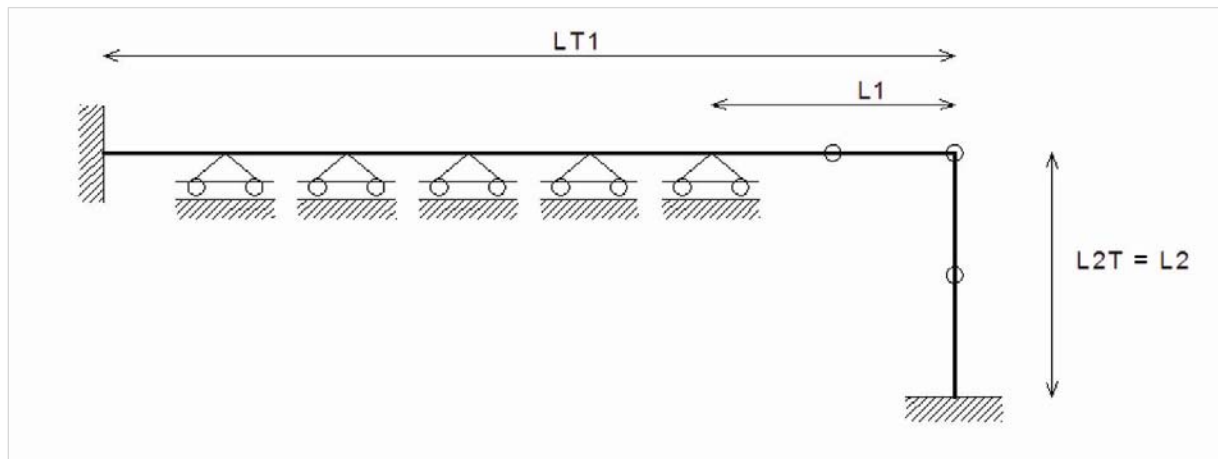


FIGURE 14: Expansion loop with only two anchors, used in the project

$$D_o Y / (L - L_A)^2 \leq 208.3 \quad (48)$$

$$Y = \alpha \Delta T (L_{T1}^2 + L_{T2}^2)^{1/2} \quad (49)$$

$$L = L_1 + L_2 \quad (50)$$

$$L_A = (L_1^2 + L_2^2)^{1/2} \quad (51)$$

where  $Y$  = Resultant movement to be absorbed by the pipe loop (mm);  
 $L$  = Developed length of line axis (m);  
 $L_1$  &  $L_2$  = Length of arm (m);  
 $L_{T1}$  &  $L_{T2}$  = Total length in each direction (m);  
 $L_A$  = Straight distance between two anchors (m);  
 $\alpha$  = Coefficient of thermal expansion ( $1/^\circ\text{C}$ );  
 $\Delta T$  = Temperature difference ( $^\circ\text{C}$ ).

Assuming  $L_a = L_1 = L_2$  and using Equations 48-51, the length of arm will be calculated by:

$$L_a \geq (D_o \alpha \Delta T L_A / 71.477)^{1/2} \quad (52)$$

### 3.6.2 Expansion units

There are three kinds of expansion units, axial, angular and lateral, shown in Figure 15 (Jónsson, 2007).

- Axial units can be used in a straight pipeline, such as an installation between two pipes, and can also be used in an expansion loop or direction change between two long pipelines that are perpendicular to each other.
- Angular units can be used in direction changes between two long pipelines with an angle less than  $90^\circ$ .
- Lateral units can be used in an offset between two pipelines that are parallel to each other.

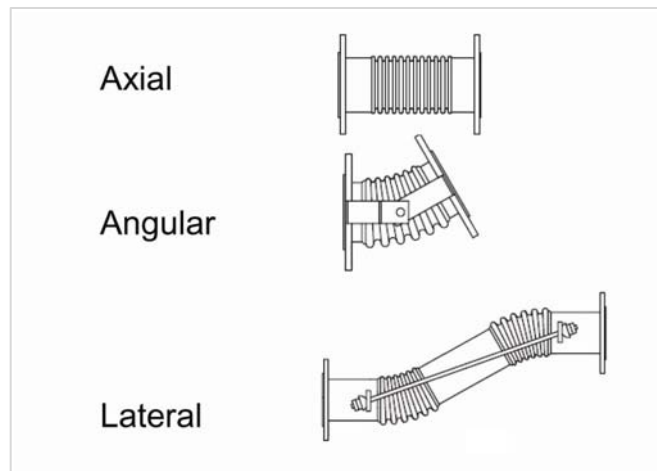


FIGURE 15: Expansion units for pipelines

## 4. PIPELINE DESIGN IN THE SABALAN PROJECT

Site A was selected for the placement of a 50 MWe power plant, with steam from production wells on pads D and A, and with brine reinjection at wells on pads B and C. The project involves the design of two-phase flow, steam and brine water pipelines as follows:

- Two-phase flow pipeline from wellheads in site D to a separator station in site A;
- Two-phase flow pipeline from wellheads in site A to a separator station in site A;
- Brine water pipeline from a separator station in site A to the wellheads in site B
- Brine water pipeline from the wellheads in site B to the wellheads in site C;
- Steam pipeline from the first separator in the separator station in site A to the powerhouse, also in site A;
- Steam pipeline from the second separator in the separator station in site A to the powerhouse.

During the first part of the Sabalan project, 5 wells were drilled. Two of them were tested. The output curve for well NWS-4 (SKM, 2004) is shown in Figure 4. For new wells, the results from well NWS-4, regarding the pressure, flow rate and temprature are assumed to apply for the proposed 50 MWe power plant as follows:

- Number of production wells is ten, thereof five production wells in site D and other five production wells in site A;



- Mass flow for each well is assumed to be 56 kg/s;
- Enthalpy of the mass flow is assumed to be 950 kJ/kg;
- The maximum reinjection rate (IR) is 75 kg/s; and
- Number of reinjection wells = 6, thereof 4 reinjection wells in site B, and other 2 reinjection wells in site C.

The elevation above sea level of each site is given in Table 4, while the general assumptions are summarised in Table 5.

TABLE 4: Elevation of the sites at Sabalan

Situation	Elevation	Unit
Site D	2742.55	m
Site A	2624.65	m
Camping site	2540.58	m
Central Site	2520.00	m
Site B	2474.70	m
Site C	2264.02	m

TABLE 5: General assumptions for the designed pipeline

Item	Amount	Unit
Two-phase flow rate from wellheads on pad D to separator station	280	kg/s
Two-phase flow rate from wellheads on pad A to separator station	280	kg/s
Steam flow rate from first separator in the sep. station to powerhouse	82	kg/s
Steam flow rate from second separator in the sep. station to powerhouse	30	kg/s
Brine flow rate from separator station to wellheads on pad B	560	kg/s
Brine flow rate from wellheads on pad B to wellheads on pad C	187	kg/s
Wellhead pressure	5.5	bar-g
Enthalpy two-phase fluid	950	kJ/kg
Temperature two-phase fluid	155.5	°C
Brine temperature	80	°C
Steel grade	S <sub>235</sub>	
Thickness of insulation of brine water pipeline	50	mm
Thickness of insulation of steam and two-phase flow pipeline	100	mm
Roughness	0.046	mm

#### 4.1 Layout plan for the separator station and the powerhouse in site A

SKM, 2005 suggested the area requirements for each building of a power plant with various capacities. In addition, a study was performed in Google Earth on other existing power plants such as Svartsengi – 46 MWe in Iceland, Berlin – 95 MWe and Ahuachapán – 95 MWe in El Salvador, and Ikaria – 45 MWe in Kenya. Then the area for each building in these power plants was calculated and a sketch drawn of the power plant, site A (Figure 16). The area that is used for each building is given in Table 6.

TABLE 6: Area requirements for buildings at the power plant site

Building	Area	Unit
Powerhouse and electrical annex	1200	m <sup>2</sup>
Switchyard and power take-off	1200	m <sup>2</sup>
Offices and workshop	800	m <sup>2</sup>
Non-condensable gas extraction	400	m <sup>2</sup>
Cooling towers	2400	m <sup>2</sup>
Separator station	1000	m <sup>2</sup>
Pipeline and header	250	m <sup>2</sup>
Access and parking	1000	m <sup>2</sup>

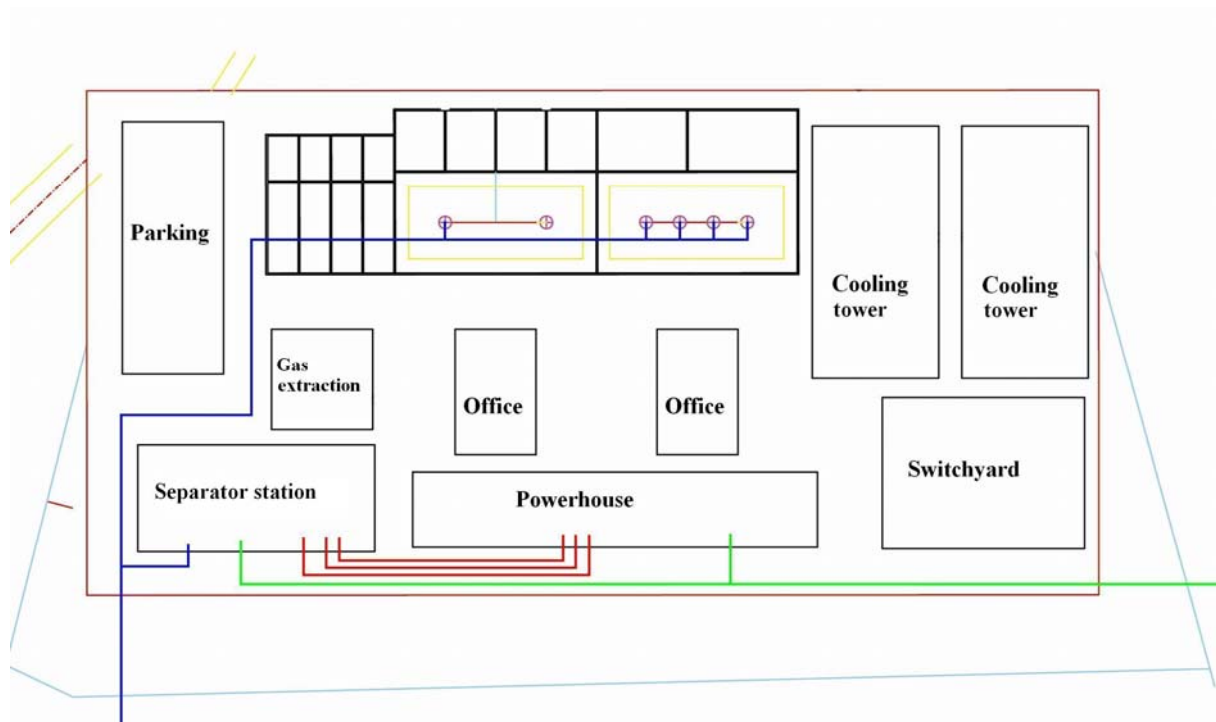


FIGURE 16: Layout plan for the proposed power plant

A diagram of pipelines and a double flash power plant were drawn and calculated in EES (Figure 17). The diagram shows that with these pipelines and the existing pressure drop in a two-phase pipeline, 50 MWe can be generated by this power plant.

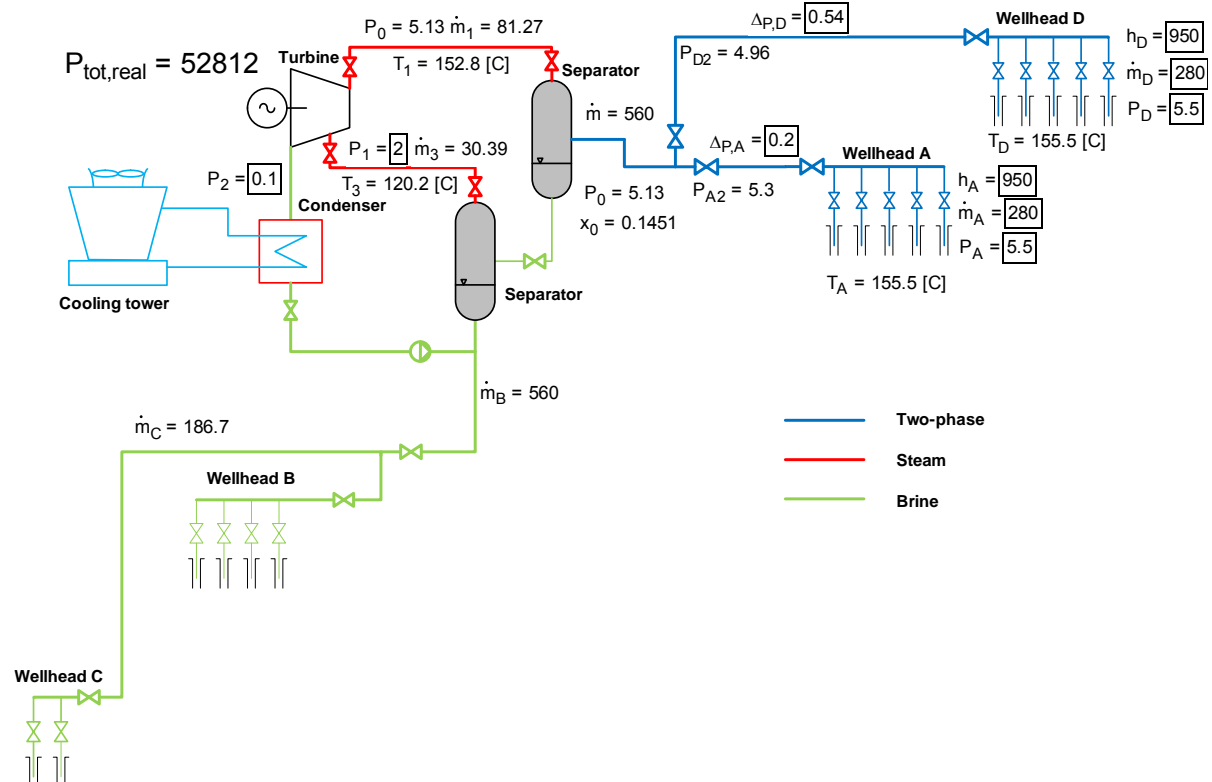


FIGURE 17: Diagram of pipelines and power plant for Sabalan

#### 4.2 Two-phase pipeline from wellheads on pad D to separator station in site A

This pipeline is designed to transmit two-phase flow from wellheads on pad D to the separator station in site A. A topographical plan is shown in Figure 18 and data for the pipeline is given in Table 7.

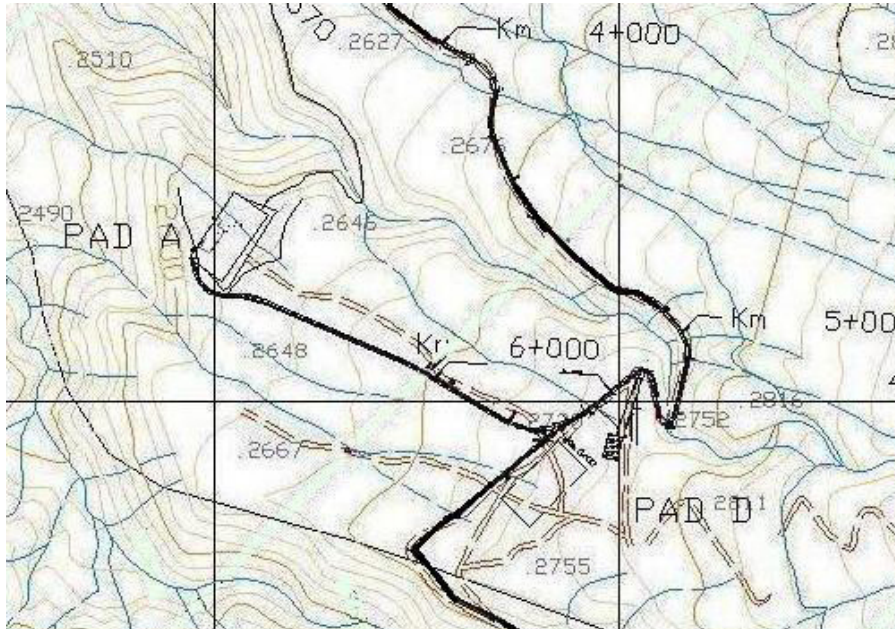


FIGURE 18: Topographical plan between sites D and A

TABLE 7: Data for the pipeline from wellheads on pad D to the separator station

Item	Amount	Unit
Height differences, $\Delta H$	117.9	m
Number of bends	15	
Number of expansion units	0	
Number of connections	0	
Number of valves	2	

There is a main access road between these two sites. The best route that can be selected between them is next to this main road because this route does not need any new excavation nor buying of land, and it is a straight run between the two sites. The longitude profile and plan are shown in Figure 19. There are two assumptions for this pipeline: using one pipeline and two pipelines. For each option, the pressure drop due to the pipes, bends, expansion units, connections and valves were calculated using Equation 19. The total cost of each diameter was also calculated. In each option the best diameter based on pressure drop and cost of pipeline was selected; the results are shown in Table 8.

TABLE 8: Options for pipelines between sites D and A

Option	Length (m)	Diameter (mm)	Pressure drop (bar-g)	Cost of pipeline (1000 Euro)	Cost of construction (1000 Euro)	Total cost (1000 Euro)
1.1	1143	700	1.08	207	0	207
1.2	1143	800	0.54	248	0	248
2.1	1143	2*500	1.99	301	0	301
2.2	1143	2*600	0.66	362	0	362

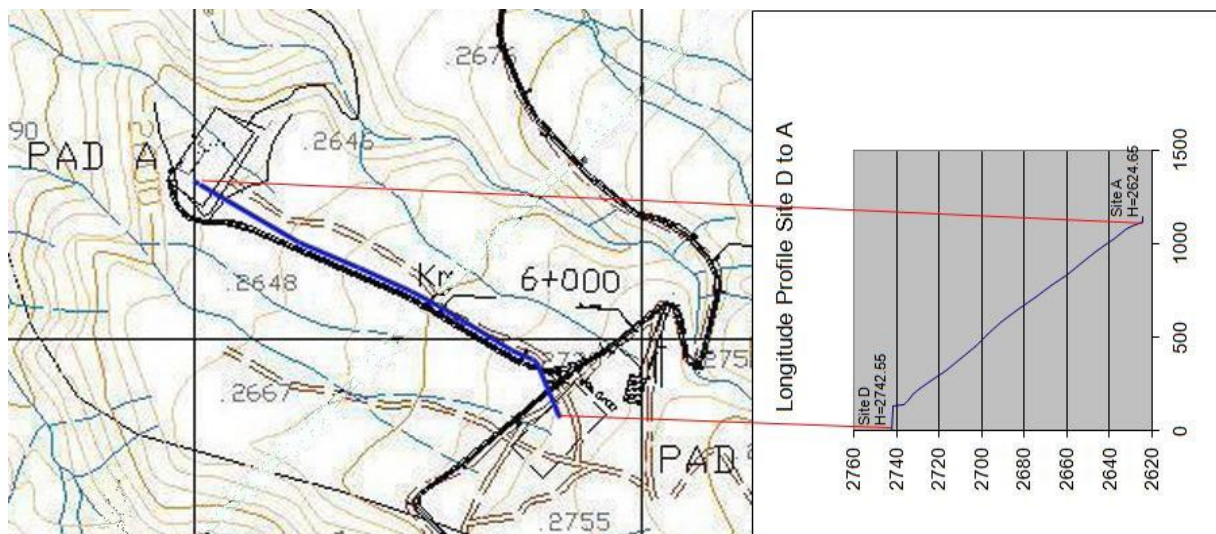


FIGURE 19: Longitude and plan between sites D and A

The best option is no. 1.2 because of the 40,000 Euro difference in costs between it option and option 1.1, together with the fact that the pressure drop is cut by half. The total cost equals 248,000 Euro. Further calculations will be based on option 1.2. The pipe diameter is therefore 800 mm. The results shown in Table 9 are based on calculations and the equations presented in Section 3.

TABLE 9: Pipeline requirements between sites D and A

Item	Amount	Unit
Nominal thickness ( $t_n$ )	6.3	mm
Distance between supports ( $L_s$ )	18	m
Distance between two anchors ( $L_A$ )	65	m
Length of arm ( $L_{sh}$ )	37	m
Distance between vertical supports ( $L_{sv}$ )	9	m

#### 4.3 Two-phase pipeline from wellheads on pad A to the separator station in site A

This pipeline is designed to transmit the two-phase flow from the wellheads at pad A to the separator station in site A. The length is found to be close to 120 m. Data for this pipeline is shown in Table 10. Based on these data, the pressure drop was calculated and finally a diameter of 800 mm selected. The calculated results are the same as those shown in Table 9. The pressure drop equals 0.20 bar-g and the total cost is 26,000 Euro.

TABLE 10: Data for the pipeline from wellheads on pad A to the separator station

Item	Amount	Unit
Height differences, $\Delta H$	0	m
Number of bends	5	
Number of expansion units	0	
Number of connections	0	
Number of valves	2	

#### 4.4 Brine water pipeline from separator station in site A to wellheads on pad B

This pipeline is designed to transmit the brine water from the separator station and powerhouse in site A to the wellheads in site B. The data for this pipeline are given in Table 11. A topographical plan is shown in Figure 20.



TABLE 11: Data for the pipeline from wellheads on pad A to the separator station

Item	Amount	Unit
Height differences, $\Delta H$	149.95	m
Number of bends	12	
Number of expansion units	16	
Number of connections	3	
Number of valves	6	

There is a big cliff in the northwest section of site A as shown in Figure 21; thus the pipeline cannot run straight between the two sites. Also, there is a secondary road between these two sites (shown in Figure 20) that was used at the beginning of construction and excavation in site A in the winter. Based on these two facts, the best route that could be selected between these two sites is the secondary road. By using this road for the pipeline route, no new excavation would be needed.

Four options were explored, each one using some part of the secondary road for the pipeline's route. For each option, two kinds of pipeline were assumed: one line in the first and two lines in the second. And finally, for each option the cost of the pipeline plus the cost for construction and excavation of a road or buying land were calculated. The plan and profile for each option are shown in Figures 22 to 25. In each option the pressure in the top point was compared with the saturation pressure. The best diameter based on maximum velocity was selected and the results of all options are shown in Table 12.

According to the calculations, options 1 and 2, using two pipelines, cost more than options 3 and 4 where only one pipeline is assumed. Option 3.1 is the best option; the total cost equals 234,000 Euro. This option will be used in further calculations. The diameter of pipe chosen is 500 mm. The results shown in Table 13 are based on calculations and the equations presented in Section 3. The design pressure equals static pressure plus the pressure after the separator station.

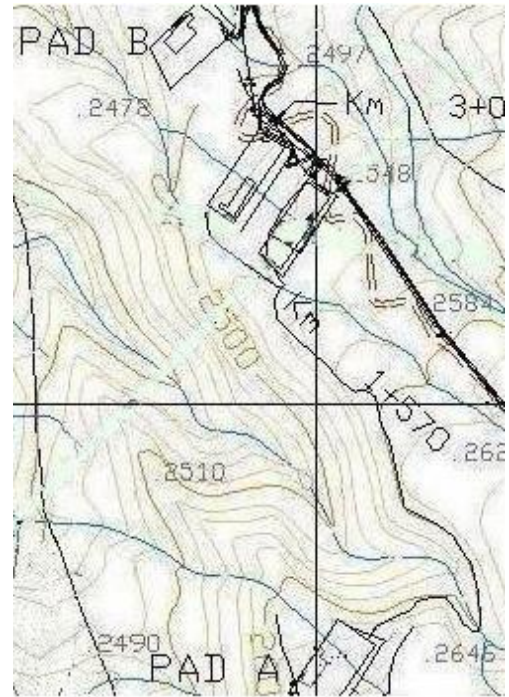


FIGURE 20: Topography plan between sites A and B



FIGURE 21: View of a cliff close to site A

TABLE 12: Options for pipelines for the pipeline between sites A and B

Option	Length (m)	Diameter (mm)	Velocity (m/s)	Cost of pipeline (1000 Euro)	Cost of construction (1000 Euro)	Total cost (1000 Euro)
1.1	2151	500	2.99	275	0	275
1.2	2151	2*400	2.37	423	0	423
2.1	1762	500	2.99	229	60	289
2.2	1762	2*400	2.37	355	60	415
3.1	1823	500	2.99	234	0	234
4.1	1730	500	2.37	222	13	235

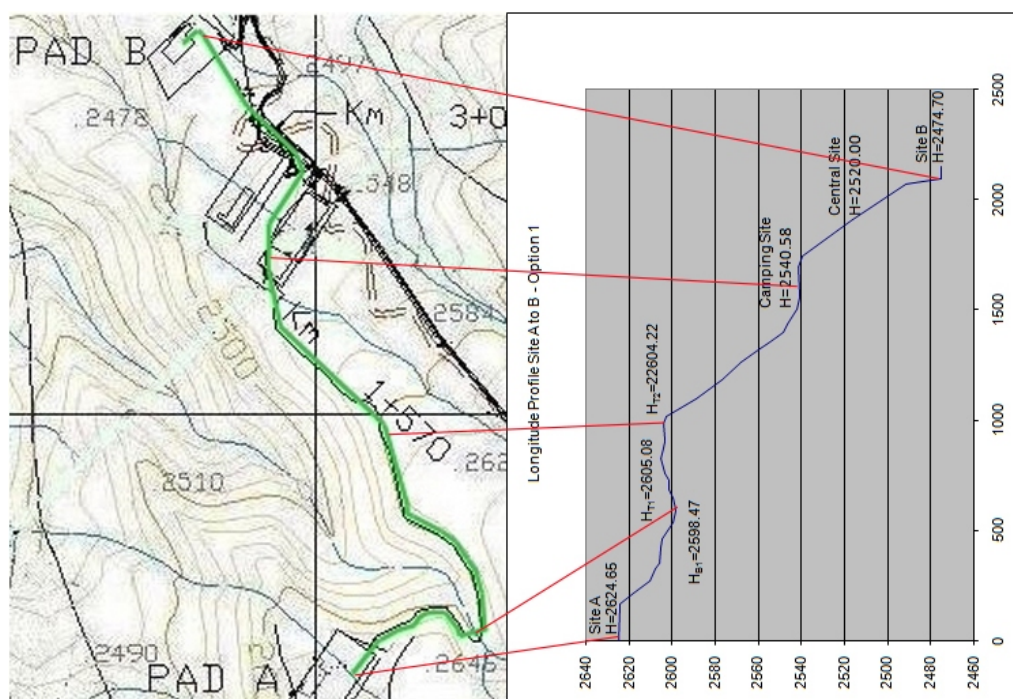


FIGURE 22: Longitude and plan between sites A and B, option 1

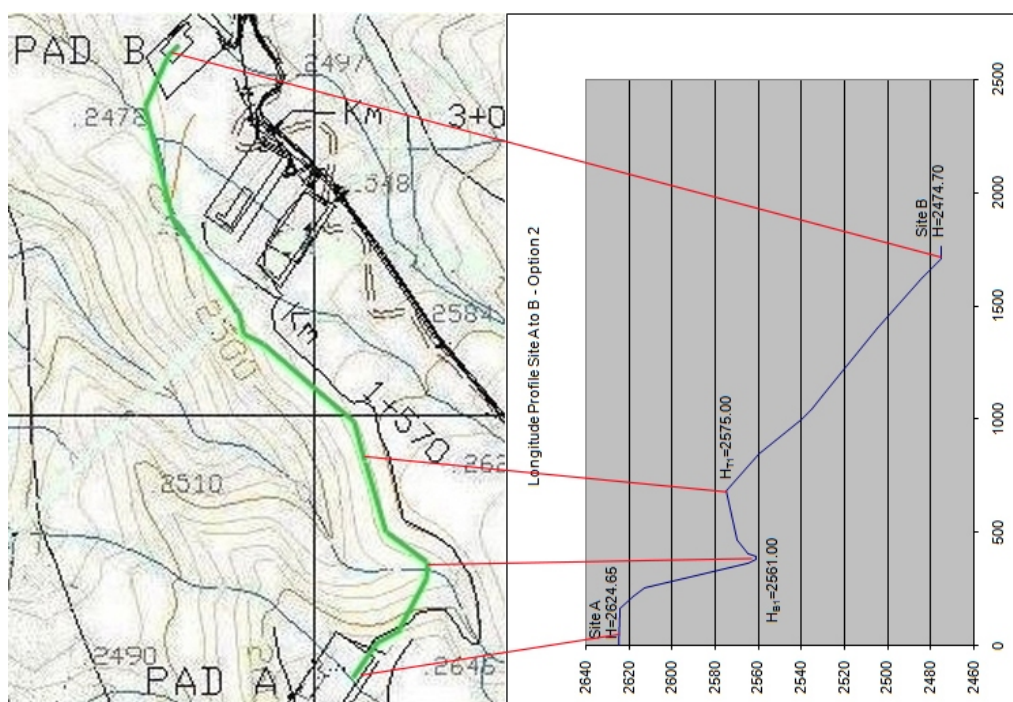


FIGURE 23: Longitude and plan between sites A and B, option 2

TABLE 13: Pipeline requirements between sites A and B

Item	Amount	Unit
Nominal thickness ( $t_n$ )	5.6	mm
Distance between supports ( $L_s$ )	15	m
Distance between two anchors ( $L_A$ )	80	m
Length of arm ( $L_{sh}$ )	24	m
Distance between vertical supports ( $L_{sv}$ )	13	m



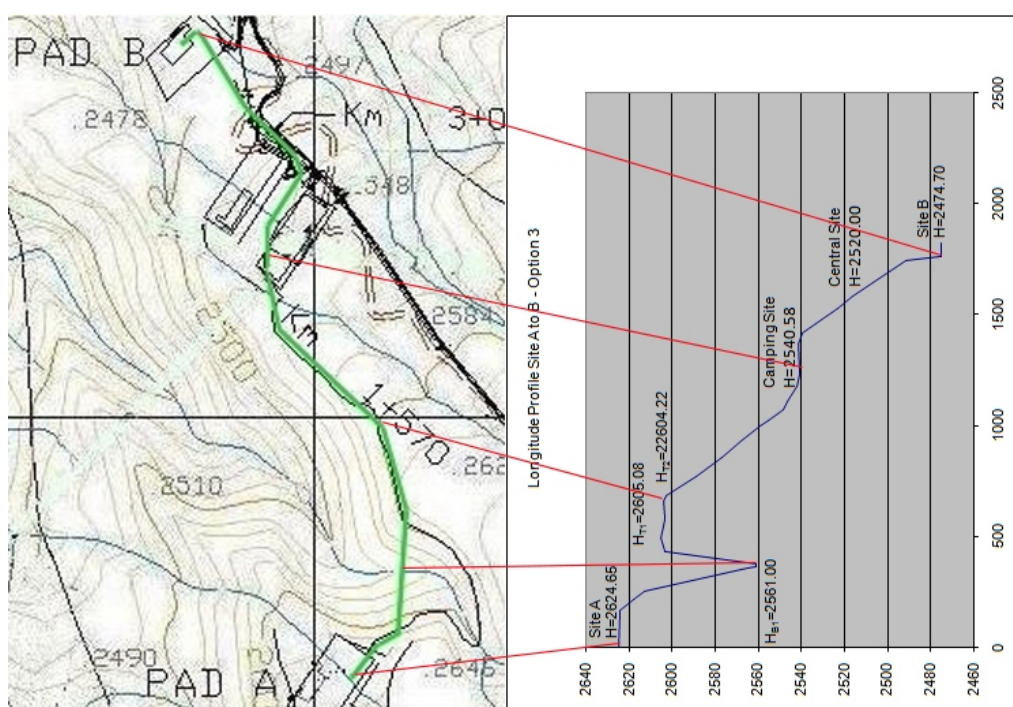


FIGURE 24: Longitude and plan between sites A and B, option 3

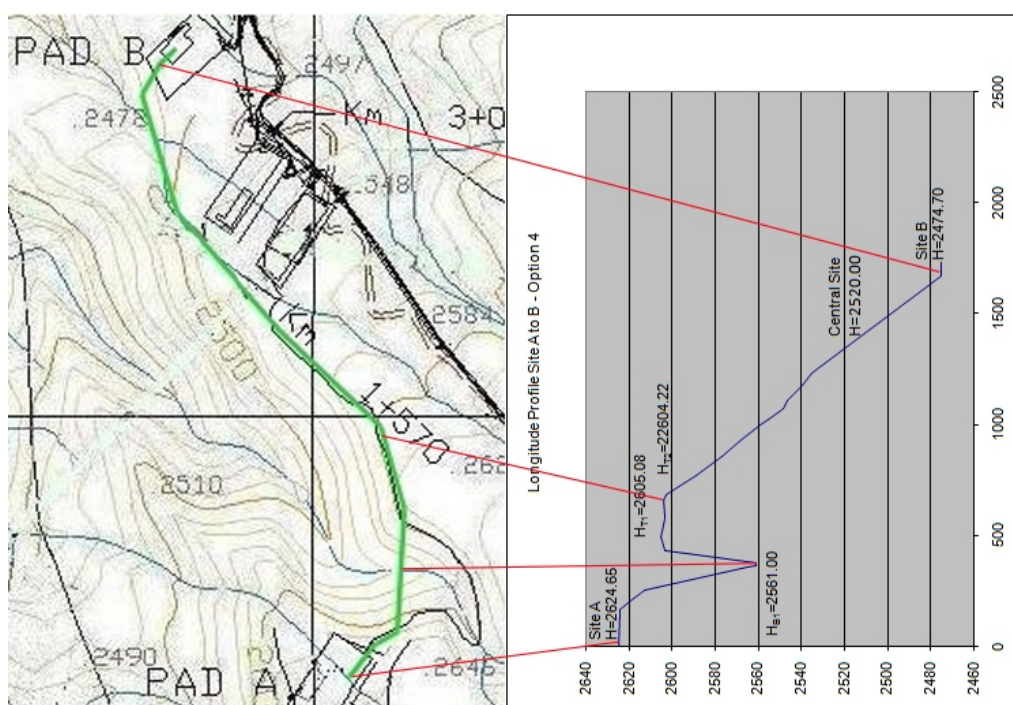


FIGURE 25: Longitude and plan between sites A and B, option 4

#### 4.5 Brine water pipeline from wellheads on pad B to wellheads on pad C

This pipeline is designed to transmit brine water from the wellheads in site B to the wellheads in site C, the data are given in Table 14. A topographical plan is shown in Figure 26.

TABLE 14: Data for the pipeline from wellheads on pad B to wellheads on pad C

Item	Amount	Unit
Height differences, $\Delta H$	210.68	m
Number of bends	30	
Number of expansion units	0	
Number of connections	0	
Number of valves	4	

Here, there exists a water pipeline and also a main access road. Thus, in option 1 the route was selected next to the pipeline and main access road, while option 2 is the same as option 1, except that in some parts of the route a straight line was chosen, which would require some buying of land. Finally, for both options the cost of the pipeline and the cost for buying land were calculated. The plan and profile for both options are shown in Figures 27 and 28. For both options, the best diameter based on maximum velocity was selected and the results are given in Table 15.

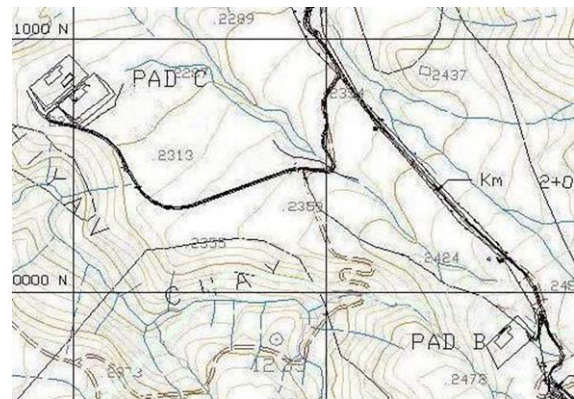


FIGURE 26: Topography plan between sites B

TABLE 15: The results of all options

Option	Length (m)	Diameter (mm)	Velocity (m/s)	Cost of pipeline (1000 Euro)	Cost of construction (1000 Euro)	Total cost (1000 Euro)
1	2315	300	2.5	171	0	171
2	2167	300	2.5	160	300	460

The best option is no. 1, and this option will be used in further calculations. Here the diameter of the pipe is 300 mm; and the total cost is 171,000 Euro. The results shown in Table 16 are based on calculations and the equations presented in Section 3. The design pressure equals the static pressure.

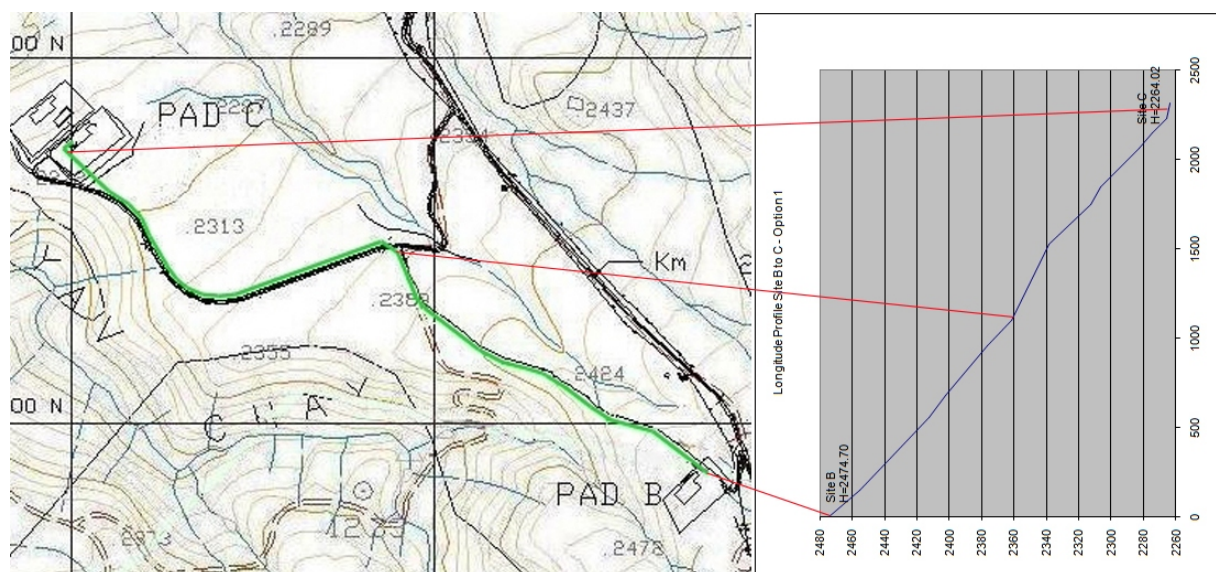


FIGURE 27: Longitude and plan between sites B and C, option 1



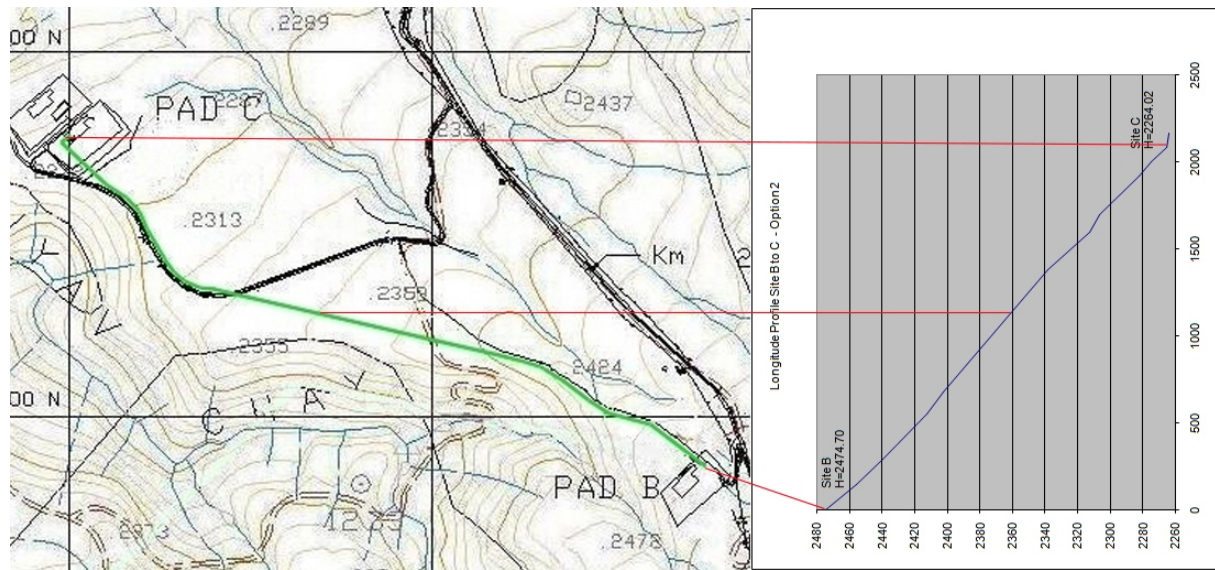


FIGURE 28: Longitude and plan between sites B and C, option 2

TABLE 16: Pipeline requirements between sites B and C

Item	Amount	Unit
Nominal thickness ( $t_n$ )	5	mm
Distance between supports ( $L_s$ )	12	m
Distance between two anchors ( $L_A$ )	80	m
Length of arm ( $L_{sh}$ )	19	m
Distance between vertical supports ( $L_{sv}$ )	10	m

#### 4.6 Steam pipeline from the first separator to the powerhouse in site A

This pipeline is designed to transmit steam from the first separator in the separator station in site A to the powerhouse, also in site A. The length of this pipeline is close to 90 m and data for this pipeline are shown in Table 17. Three options were assumed. For each option, based on the data in Table 17, the velocity of steam was calculated, and the diameter assuming a velocity less than 40 m/s was selected. The steam's pressure drop and the total cost for each option were calculated and are shown in Table 18.

TABLE 17: Data for the pipeline from the separator station to the powerhouse

Item	Amount	Unit
Height differences, $\Delta H$	0	m
Number of bends	5	
Number of expansion units	0	
Number of connections	0	
Number of valves	2	

TABLE 18: The results of all options

Option	Length (m)	Diameter (mm)	Velocity (m/s)	Pressure drop (bar-g)	Total cost (1000 Euro)
1	90	1000	35.6	0.04	34
2	90	2*700	36.7	0.06	43
3	90	3*600	33.5	0.05	56

With two lines for the two-phase flow from site A and D, here option 2 was selected, that assumes two pipelines with a diameter of 700 mm and a pressure drop of 0.06 bar-g. The total cost equals 43,000 Euro. The results shown in Table 19 are based on the selected diameter, calculations and the equations presented in Section 3. The design pressure is the pressure after the separator, 5.13 bar-g.

TABLE 19: Pipeline requirements between site A and the separator station

Item	Amount	Unit
Nominal thickness ( $t_n$ )	6.3	mm
Distance between support ( $L_s$ )	26	m
Distance between two anchor ( $L_A$ )	50	m
Length of arm ( $L_{sh}$ )	33	m
Distance between vertical support ( $L_{sv}$ )	23	m

#### 4.7 Steam pipeline from the second separator to the powerhouse in site A

This pipeline is designed to transmit steam from the second separator in the separator station (in site A) to the powerhouse, also in site A. The length of the pipeline is close to 90 m and is shown in Table 20. Here, only one option was assumed and velocity of steam calculated. Then a diameter of 900 mm was selected, assuming velocity less than 40 m/s, with a pressure drop of 0.02 bar-g. The total cost is 29,000 Euro. The results shown in Table 21 are based on calculations and the equations presented in Section 3. The design pressure equals the pressure after the separator, 2.0 bar-g.

TABLE 20: Data for the pipeline from the separator station to the powerhouse

Item	Amount	Unit
Height differences, $\Delta H$	0	m
Number of bends	5	
Number of expansion units	0	
Number of connections	0	
Number of valves	2	

TABLE 21: Pipeline requirements between the separator station in site A and the powerhouse

Item	Amount	Unit
Nominal thickness ( $t_n$ )	6.3	mm
Distance between supports ( $L_s$ )	28	m
Distance between two anchors ( $L_A$ )	50	m
Length of arm ( $L_{sh}$ )	31	m
Distance between vertical supports ( $L_{sv}$ )	25	m

## 5. CONCLUSIONS

In this project a model-based design was used for designing pipelines for a 50 MWe power plant in the Sabalan area in Iran. With 10 production wells, similar to NWS-4, and 6 reinjection wells, and the pipelines designed in this project with the calculated pressure drops, a 50 MWe electricity can be generated in a power plant built in site A. A layout plan is suggested for the power plant, showing the placement of the power plant buildings at the selected site. A summary of the calculations gives the following requirements:

- Two-phase flow pipeline from the wellhead in site D to the separator station in site A, using for it ND 800×6.3 mm;
- Two-phase flow pipeline from the wellhead in site A to the separator station in site A, using for it ND 800×6.3 mm;



- Brine water pipeline from the separator station in site A to the wellheads in site B, using for it ND 500×5.6 mm;
- Brine water pipeline from the wellheads in site B to the wellheads in site C, using for it ND 300×5.0 mm;
- Steam pipeline from the first separator in site A to the powerhouse in site A, using for it 2×ND 700×6.3 mm;
- Steam pipeline from the second separator in site A to the powerhouse in site A, using for it ND 800×6.3 mm; and
- The total cost of the pipeline equals 751,000 Euro.

The report can be used as a manual for designing a pipeline intended to transmit water, steam and/or two-phase flow.

### ACKNOWLEDGEMENTS

I would like to express my gratitude to the UNU staff: Dr. Ingvar B. Fridleifsson, Mr. Lúdvík S. Georgsson, and the Moshanir staff: Mohammad Ali Moallemi, Mohammad Bagher Kiaei, Fatolah Paykani, for giving me the opportunity to participate in this special course as well as for their assistance. My kindest thanks go to Mrs. Dorthe H. Holm and Ms. Thórhildur Ísberg for their care and generous help. I am sincerely thankful to my supervisor, Mr. Magnus Th. Jónsson for his help and advice throughout this project. Thanks to all UNU-GTP lecturers and staff members of ISOR and Orkustofnun. I would also like to thank my best friend Saied Jalili Nasrabadi for his help during my stay in Iceland and Mr. Masoud Zarifbani for his help on the topographical drawings.

My deepest gratitude goes to my dear wife and her family and my family for their moral and emotional support during these six months. This project is dedicated to my wife Elham Hassibi for her support, and encouragement throughout these six months in Iceland.

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## APPENDIX I: An example of Excel file calculations

Brine from Site A to B - OPTION 3 - ONE LINE		
Brine from Site A to B $q_b =$	560	kg/s
$T_p =$	80	°C
delta H=	-149.95	m
max delta (start and top 1) H=	-19.57	m
max delta (start and top 2) H=	-20.43	m
Q=	576.25	(l/s)
Roughness=	0.046	mm
Pressure saturation= $P_s =$	4.737	m
Density=	971.8	kg/m <sup>3</sup>
Length=	1823.29	m
dynamic Viscosity= $\mu =$	0.0003545	kg/m-s
H=	-149.95	
Length that need expansion loop=	950	$950/80+1 = 12.9$
Length that need expansion joint=	870	$1200/80 = 10.875$
Number of bend= $n_b =$	13	$h_b = 20$
Number of expansion unit= $n_e =$	11	$h_e = 18$
Number of con.= $n_c =$	3	$h_c = 20$
Number of valve= $n_v =$	6	$h_v = 10$
1 valve added for reducer valve for price of this vavle added 1.5 valve		

D (mm)	125	150	200	250	300	400	500	600
D <sub>o</sub> (mm)	139.7	168.3	219.1	273	323.9	406.4	508	609.6
t (mm)	3.6	4	4.5	5	5.6	6.3	6.3	6.3
D <sub>in</sub> (mm)	132.5	160.3	210.1	263	312.7	393.8	495.4	597
Roughness k(mm)	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046
Flow	0.5763	0.5763	0.5763	0.5763	0.5763	0.5763	0.5763	0.5763
Velocity (m/s)=Q/( $\pi \cdot d^2/4$ )	41.81	28.57	16.63	10.61	7.51	4.73	2.99	2.06
Density (kg/m <sup>3</sup> )	971.8	971.8	971.8	971.8	971.8	971.8	971.8	971.8
Length=L <sub>p</sub>	1823.29	1823.29	1823.29	1823.29	1823.29	1823.29	1823.29	1823.29
Kinematic								
Re=V*d/ $\nu$ that $\nu=\mu/\text{Density}$	15187499	12553609	9578027	7651496	6435381	5110065	4062058	3370760
Friction factor (solved by EES)	0.01544	0.01485	0.01408	0.01351	0.01311	0.01265	0.01227	0.01202
$1/\sqrt{f}=1.14-2\log_{10}(k/d+9.35/(Re\sqrt{f}))$								
$L_e=L_p \cdot \sum h_n/D_i$	1899.88	1915.94	1944.73	1975.30	2004.03	2050.91	2109.63	2168.36
$H_f = (f \cdot V^2/2g) \cdot (L_e/D_{in})$	19727.72	7382.87	1837.03	582.50	241.35	75.24	23.83	9.44
D (mm)	125	150	200	250	300	400	500	600
Pipe Euro/m	25	32	42	45	57	72	95	115
Bend Euro	26	42	39	55	59	69	86	107
Expansion unit Euro	290	351	468	556	673	717	859	957
Valve Euro	579	702	936	1,112	1,346	1,434	1,717	1,913
Connection Euro	39	44	53	70	114	132	155	217
Insulation Euro 5 cm	6	7	9	11	13	17	21	24
Cc=Cost of equipment	63,925	80,210	104,886	116,373	144,891	180,774	233,689	278,435
Cost of road	-	-	-	-	-	-	-	-
Total Cost	63,925	80,210	104,886	116,373	144,891	180,774	233,689	278,435

Calculating pressure in site B

L(between site A and B)= 1823.29 m

D (mm)	125	150	200	250	300	400	500	600
D <sub>o</sub> (mm)	139.7	168.3	219.1	273	323.9	406.4	508	609.6
t (mm)	3.6	4	4.5	5	5.6	6.3	6.3	6.3
D <sub>in</sub> (mm)	132.5	160.3	210.1	263	312.7	393.8	495.4	597
Le (Total path)	1899.875	1915.9434	1944.7278	1975.304	2004.0306	2050.9064	2109.6312	2168.356
Velocity (m/s)	41.81	28.57	16.63	10.61	7.51	4.73	2.99	2.06
Friction factor	0.01544	0.01485	0.01408	0.01351	0.01311	0.01265	0.01227	0.01202
H <sub>f</sub> for in this part	19727.72	7382.87	1837.03	582.50	241.35	75.24	23.83	9.44
Hh-total	-149.95	-149.95	-149.95	-149.95	-149.95	-149.95	-149.95	-149.95
Pipe pressure (site B) P <sub>a</sub> (site B)=	-19577.77	-7232.92	-1687.08	-432.55	-91.40	74.71	126.12	140.51

Control pressure in the Top point for saturation

L(between sit A and top point 1) 495.23 m Hh-top1=2605.08-2624.65= -19.57  
Length that need expansion loop= 0

Number of bend=n<sub>b</sub>= 0 h<sub>b</sub>= 20  
 Number of expansion unit=n<sub>e</sub>= 7 h<sub>e</sub>= 18  
 Number of con.=n<sub>c</sub>= 2 h<sub>c</sub>= 20  
 Number of valve=n<sub>v</sub>= 3 h<sub>v</sub>= 10

D (mm)	125	150	200	250	300	400	500	600
D <sub>o</sub> (mm)	139.7	168.3	219.1	273	323.9	406.4	508	609.6
t (mm)	3.6	4	4.5	5	5.6	6.3	6.3	6.3
D <sub>in</sub> (mm)	132.5	160.3	210.1	263	312.7	393.8	495.4	597
Le	521.20	526.65	536.41	546.78	556.52	572.41	592.33	612.24
Velocity (m/s)	41.81	28.57	16.63	10.61	7.51	4.73	2.99	2.06
Friction factor	0.01544	0.01485	0.01408	0.01351	0.01311	0.01265	0.01227	0.01202
H <sub>f</sub> for in this part	5411.98	2029.38	506.70	161.24	67.02	21.00	6.69	2.67
pressure saturation	4.737	4.737	4.737	4.737	4.737	4.737	4.737	4.737
Hh-top	-19.57	-19.57	-19.57	-19.57	-19.57	-19.57	-19.57	-19.57
Pipe pressure (Top point 1) P <sub>a</sub> (top1)=	-5392.41	-2009.81	-487.13	-141.67	-47.45	-1.43	12.88	16.90

Control pressure in the Top point for saturation

L(between sit A and top point 2) 658.89 m Hh-top2=2604.22-2624.65= -20.43  
Length that need expansion loop= 0

Number of bend=n<sub>b</sub>= 0 h<sub>b</sub>= 20  
 Number of expansion unit=n<sub>e</sub>= 9 h<sub>e</sub>= 18  
 Number of con.=n<sub>c</sub>= 3 h<sub>c</sub>= 20  
 Number of valve=n<sub>v</sub>= 4 h<sub>v</sub>= 10

D (mm)	125	150	200	250	300	400	500	600
D <sub>o</sub> (mm)	139.7	168.3	219.1	273	323.9	406.4	508	609.6
t (mm)	3.6	4	4.5	5	5.6	6.3	6.3	6.3
D <sub>in</sub> (mm)	132.5	160.3	210.1	263	312.7	393.8	495.4	597
Le	693.61	700.89	713.94	727.80	740.82	762.07	788.68	815.30
Velocity (m/s)	41.81	28.57	16.63	10.61	7.51	4.73	2.99	2.06
Friction factor	0.01544	0.01485	0.01408	0.01351	0.01311	0.01265	0.01227	0.01202
H <sub>f</sub> for in this part	7202.18	2700.80	674.40	214.62	89.22	27.96	8.91	3.55
pressure saturation	4.737	4.737	4.737	4.737	4.737	4.737	4.737	4.737
Hh-top	-20.43	-20.43	-20.43	-20.43	-20.43	-20.43	-20.43	-20.43
Pipe pressure (Top point 2) P <sub>a</sub> (top2)=	-7181.75	-2680.37	-653.97	-194.19	-68.79	-7.53	11.52	16.88

Pump pressure (top) $P_p$	(m)	126.12
Static pressure	(m)	149.95
Design pressure	(m)	149.95

$D$	(mm)	500
$D_o$	(mm)	508
$t$	(mm)	6.3
$D_{in}$	(mm)	495.4

$$T_{in} > t_{in} = P D / (2 (S E + P y) + A$$

Pressure in separator 2 bar

$P$  (Pa) is the design pressure

$D$  (m) is the outer diameter

$S$  (Pa) is the allowable stresses =  $\min((Rm/c)/3, (Rm/h)/3, 2(Rp/c)/3, 2(Rp/h)/3) =$

$S$  (Pa) is the allowable stresses 113.3 Mpa

$$(Rm/c)/3 = 340/3 = 113.3$$

$$(Rm/h)/3 = 340/4 = 113.3$$

$$2(Rp/c)/3 = 2 \cdot 235/3 = 156.7$$

$$2(Rp/h)/3 = 2 \cdot 225/3 = 150.0$$

$E$  is the Welding factor = 0.85

$y$  is the temperature dependent coefficient = 0.4

$A$  (m) is additional thickness milling and corrosion = 0.0015

$D_o$	(mm)	508
$L_A$	(m)	80
$\alpha$		1.20E-05
$\Delta T$		80
$Y = \alpha \cdot \Delta T \cdot L_A$		7.68E-02
$L_{min} = (D_o \cdot Y / 71.477)^{0.5}$		23.3629951
$L_{in} > L_{min}$ assumption		24
$L_{sv}$		13
$q_{sv} \cdot L_{sv}^2 + [(q_{sv} \cdot L_{sv})^2 + (q_{in} \cdot L_{in})^2]^{0.5}$		834011
$(k \cdot S_{in} \cdot P \cdot d / (4 \cdot t_{in})) \cdot 8 \cdot z / (0.75 \cdot i) = \text{part1} / \text{part2}$		864704
Ratio		0.96

$P$ (Pa)		1629527
$D_o$ (m)		0.508
$S$ (Pa)		113333333
$E$ is the Welding factor		0.85
$y$ is the temperature coefficient		0.4
$A$ (m) is additional thickness		0.0015
$L_m$ (m) =		0.00576766

$L_m$ (mm) =		5.8
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Nominal thickness $t_n$ (mm)		6.3
Outer diameter $D_o$ (mm)		508.0
Inner diameter $D_{in}$ (mm)		495.4
Section modulus $Z$ (m3)		0.00122955
Insulation thickness $T_e$ (mm)		50
Insulation diameter $D_o$ (mm)		608.0
Steel density (kg/m3)		7850
Insulation density (kg/m3)		730
Media density (kg/m3)		971.8
Wind speed (m/s)		50
Seismic factor (N/m2)		0.24
Snow factor (N/m2)		1200
Load Pipe weight $q_p$ (N/m)		764
Load Insulation weight $q_i$ (N/m)		627
Load Media weight $q_m$ (N/m)		1835
Load Snow weight $q_s$ (N/m)		146
Load Seismic $q_l$ (N/m)		774
Load Wind $q_w$ (N/m)		570
Vertical sustained load $q_{sv} = q_p + q_i$ (N/M)		1390
Vertical occasional load $q_{ov} = q_m + q_s + 5q_l$		2368
Horizontal occasional load $q_{oh} = \max(q_w, q_l)$		774
Load factor $k$		1
Allowable stress at operation temp $S_n$		113333333
Stress intensification facot $i$		1
0.75 $i$ (if 0.75 $i < 1$ than =1)		1
Part 1 $k \cdot S_n - P \cdot D_o / (4 \cdot t_n)$		87908380
Part 2 $0.75 \cdot i / (8 \cdot Z)$		102
Part 3 $(q_{sv}^2 + (q_{ov}^2 + q_{oh}^2)^{0.5})$		3881
$L_s^2 = < \text{part1} / (\text{part2} \cdot \text{part3})$		222.79
$L_s$		14.93
$L_s$		15