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Analysis of the Heat Losses in the Cerro Prieto Geothermal Field Transportation Network Based on Thermal Insulation Condition of Steam Pipelines: A Quantitative Assessment

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ABSTRACT

In the Cerro Prieto geothermal field (CPGF) the steam from producing wells is transported to the power plants through a large and complex system of pipes which are thermally insulated with a 2” thick mineral wool or fiber glass layer and an external aluminum or iron cover. After a long time of field operation, the insulation has been exposed to weather conditions and has suffered density and thickness changes, and has even been completely lost in some cases, causing an increased heat transfer from the pipes to the environment. In this work, the impact of thermal insulation condition on the heat losses in the CPGF steam pipeline network is analyzed. Then, the heat losses per unit length are calculated by applying an iterative method which determines the surface temperature based on a heat balance considering the three basic mechanisms of heat transfer: conduction, convection and radiation. Finally, based on the results of an inventory of the thermal insulation condition throughout the pipeline network, as well as field operation data, the overall heat losses throughout the pipeline thermal insulation are quantified. The results allowed us to compare the magnitude of these heat losses with the overall energy losses taking place during the steam transport from wells to the power plants and, this way, to evaluate the impact of not having insulations in a good condition.

1. INTRODUCTION

Cerro Prieto is the largest liquid-dominated geothermal field in the world and the oldest Mexican geothermal field in operation. Its first power units were commissioned in 1973. The field comprises of four areas; i.e., Cerro Prieto-1 (CPU), Cerro Prieto-2 (CPD), Cerro Prieto-3 (CPT) and Cerro Prieto-4 (CPC). Up to 2009 there were 13 operating units of condensing type: four 110-MWe double-flash, four 37.5 MWe single-flash, four 25 MWe single-flash and one 30-MWe low-pressure, single-flash, which made up for a total of 720 MWe (Gutiérrez-Negrín et al., 2010).

The power units are fed with the separated steam of about 165 producing wells through a complex system of pipes that includes a high-pressure (AP) and a low-pressure (BP) network (with the exception of CPU that only has high-pressure steam lines), altogether totaling a length of approximately 140 km. Pipe diameters range from 203.2 to 1219.2 mm (8 to 48”).

Originally, all the pipes were thermally insulated with a 50.8 mm (2”) thick mineral wool or fiberglass insulation and an outer protection (cover) of aluminum or galvanized iron. Due to the impact of weather conditions, some parts of the network’s insulation present varying degrees of wear, including geometric distortion, loss of the outer cover, replacement of insulation type, or even no insulation, which has increased the steam pipeline heat losses.

In geothermal fields, the process of steam transport from producing wells to power units through a pipeline network involves a set of dynamic changes in its thermal and transport properties which affect its final conditions. The energy losses associated with this process are mainly due to friction in pipes and fittings, transfer of heat to the environment, and condensation of steam and drainage through condensate pots.

The quantitative assessment of heat losses related to the insulation condition of the CPGF steam pipes constitutes an important consideration for the identification of some areas of improvement for the transportation system, since this makes possible to compare the relative magnitude of these energy losses with other mechanisms of loss. Thus, it is possible to evaluate the feasibility of preserving the insulations in the best condition possible, in terms of cost-benefit, by the impact they have on the efficiency during the steam transportation process to the power stations.

Some studies on heat transfer in the CPGF steam transportation system include the works of Peña (1986) and Peña and Campbell (1988), who derived a model based on the polytrophic expansion of steam as it flows and determined the energy losses in a horizontal large diameter and thermally insulated pipe network. This model calculates the pressure, temperature, enthalpy and steam moisture in a pipe, given the diameter, thickness and insulation type. However, the examples shown include relatively short pipes when compared to the CPGF total network length and number of integrated wells. Other models (Schroeder, 1982; Marconcini and Neri, 1979) presented detailed studies to calculate the temperature at the surface of the thermal insulation and the heat gains or losses through a tube, while varying other flow factors. These models include the transport of heat by conduction, convection and radiation for heat loss calculation in pipes thermally insulated.

A recent work on modeling and numerical simulation of the CPGF steam transportation network (García-Gutiérrez et al., 2006), included an analysis to determine the global heat transfer coefficient used for the simulation of the whole network which took into account the effect of the thermal insulation and assumed average operation and environmental conditions (Ovando-Castelar et al., 2009). It was found that in a steam pipe lacking insulation, the heat transfer increases by more than ten times over the heat transfer in a pipe with insulation, so that insulation condition impacts directly in the fall of temperature in the steam pipelines and therefore determines the steam quality at the inlet of power units as well as the efficiency of the transportation network.

In this paper we describe a study aimed to estimate the magnitude of the heat losses that take place throughout the CPGF pipeline network during the steam transport from the wells to the power units, taking into account the condition of the pipeline thermal insulation. Then, the impact of these heat losses is determined in terms of its comparison with an estimate of the overall energy losses taking place in the CPGF steam transportation system. The paper is based on previous works presented elsewhere (Ovando-Castelar et al., 2010; 2012).

2. METHODOLOGY.

The heat exchange between the steam in the pipe and the environment is controlled by the heat transferred between the steam and the internal wall of the pipe, the heat conducted through the pipe wall, insulating material and metallic lining, and the natural convection and radiation from the external wall of the pipe. Thus, heat losses are given by

$$q = U \; A \left(T_{sat} - T_{\infty}\right) \tag{1}$$

where q is the loss of heat through the pipe, U the overall heat transfer coefficient, A the cross sectional area, T_{sat} the temperature of saturated steam, and T_{∞} the mean ambient temperature. For the calculation of the heat loss along a single pipe or pipe section with a given diameter, Eq. (1) can be rewritten as

$$q = U \; \pi \; D \; L \; (T_{sat} - T_{\infty}) \tag{2}$$

The overall heat transfer coefficient U depends on the physical condition of the insulation since its thickness can be less than the original also impacting the external heat transfer area. Therefore, the quantification of the total heat losses from the CPGF steam pipes to the environ, required the calculation of (a) the length and diameter of each single pipe section in the network, (b) the definition of the current condition of their corresponding insulation, and (c) the overall heat transfer coefficient. The methodology used for the determination of each of these parameters is as follows.

2.1 Inventory of thermal insulation condition and diameters of pipes

As mentioned previously, currently the thermal insulation in the CPGF steam pipeline network shows varying degrees of deterioration, including geometric distortion, loss of the outer cover or replacement of insulation type, or even the absence of its insulation. This increased the steam pipeline heat losses. In order to obtain reliable information on the physical condition of the thermal insulation throughout the pipeline network, a detailed inventory was carried out based on visual inspection. For the study, the insulation conditions were classified in four types or quality levels according to their physical conditions, as shown in Table 1.

Table 1: Classification of the thermal insulation conditions of pipes in the CPGF

Insulation condition	Code
New or complete, with metallic cover	A
Good, without metallic cover	B
Regular, visibly damaged or deformed	C
Absent or totally destroyed	D

Condition A represents a pipeline in good condition (new or complete, without physical damage in the insulation). Condition B characterizes a pipeline that has lost its metal protection, but the insulation thickness is maintained and is in good condition. Condition C is for a pipeline whose insulation has lost its original geometry by crushing, tearing-off or partial removal of some portions. Condition D represents essentially a pipe with no insulation.

The pipeline network insulation condition data were transferred, together with pipe diameter data, into a Geographical Information System (GIS) software package. Use of this tool was very important since it allowed the creation of maps which helped to identify those parts of the pipe network where heat losses are prone to be higher, and facilitated precise quantification of pipeline lengths corresponding to each insulation condition (Martínez-Estrella et al., these proceedings). This procedure was applied to both the high- and low-pressure pipeline networks (Figure 1). Pipe diameter maps were generated as well.

Once insulation condition and pipe diameter maps were completed, spatial overlaying operations were performed in order to obtain output maps corresponding to the topological overlapping (intersection) of each insulation condition category and pipe diameter, as well as their respective lengths. Detailed results of the inventory are shown in later in this paper (tables 6 to 8).

According to the inventory results, the total length of the operating steam pipelines is 139.7 km. From this total, 92.1 km (66%) correspond to the high-pressure steam network and 47.6 km (34%) belong to the low-pressure steam network. For both networks, about 80-82% of its total length has thermal insulations corresponding to A and B qualities which denote good condition, while the remaining 18-20% has insulations with qualities C and D (regular to very bad condition).

2.2 Calculation of the overall heat transfer coefficients

The determination of the overall heat transfer coefficient U constituted an extremely complex task, given the great variety of pipe diameters, different operation conditions, and different types and physical condition of the insulations in the pipe network. Thus, in order to facilitate this complex task, an MS Excel-based application program was developed (Figure 2). With this program the calculation of the overall coefficient was automated according to the operating characteristics of the CPGF pipeline network.

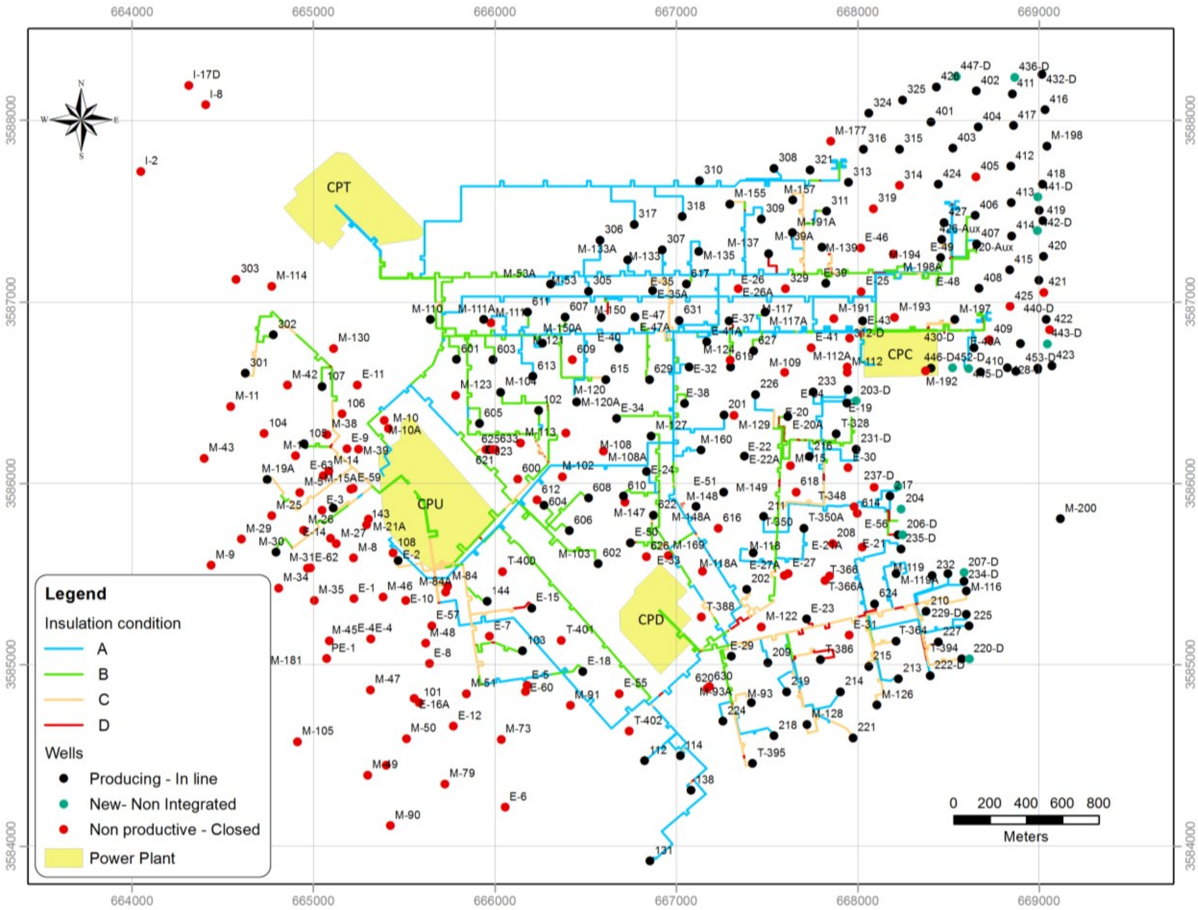

Figure 1: Map showing thermal insulations condition of the CPGF high-pressure pipe network

	A	B	C	D	E	F	G	H	I	J	K	L
1	Calculation of Overall Heat Transfer Coefficients											
2												
3	***CPD,CPT,CPC***		**WELLS**									
4				*Low Pressure*								
5		**$p_{máx}$ [barg]:**		5.50		**$m_{máx}$ [tons/h]:**		24.70				
6		**p_{min} [barg]:**		2.80		**m_{min} [tons/h]:**		1.20				
7		**p_m [barg]:**		**4.15**		**Δm [tons/h]:**		**5.88**				
8												
9	**Fully insulated pipe**										**ε**	
10					ITERA		Commercial aluminum sheet:			polished -	0.05	
11										rusty -	0.11	
12							Galvanized metal sheet:			new -	0.13	
13	**V [m/s]**	2.63		**σ[W/m^2-K^4]**		**ε**				oxidized -	0.28	
14	**T_∞ [°C]**	23.81		5.669E-08		0.22						
15												
16												
17	**Low Pressure Pipelines**						Carbon Steel Pipe ASTM A-53 Gr. B ó A-285 Gr. C					
18	**Dnom[in], Sched.**	8, 20	10, 20	12, 20	14,10	16, 10	18, 10	20, 10	22, 10	24, 10	26, st	28, st
19	**Di [in]**	*8.125*	*10.250*	*12.250*	*13.500*	*15.500*	*17.500*	*19.500*	*21.500*	*23.500*	*25.500*	*27.500*
20	**De [in]**	*8.625*	*10.750*	*12.750*	*14.000*	*16.000*	*18.000*	*20.000*	*22.000*	*24.000*	*26.000*	*28.000*
21	**Da [in]**	*11.625*	*13.750*	*16.750*	*18.000*	*20.000*	*22.000*	*24.000*	*26.000*	*28.000*	*30.000*	*32.000*
22	**P_{sat} [barg]**	3.792	3.935	3.620	3.562	4.314	4.150	4.494	4.150	4.150	4.150	4.150
23	**T_{sat} [°C]**	150.35	151.44	148.99	148.52	154.24	153.05	155.51	153.05	153.05	153.05	153.05
24	**T_i [°C]**	*150.339*	*151.436*	*148.976*	*148.514*	*154.232*	*153.012*	*155.509*	*153.010*	*153.014*	*153.013*	*153.012*
25	**T_e [°C]**	*149.406*	*150.192*	*147.516*	*146.843*	*153.032*	*143.739*	*153.978*	*140.154*	*136.626*	*134.515*	*132.376*
26	**T_W [°C]**	*33.496*	*34.340*	*32.006*	*32.204*	*33.146*	*32.609*	*33.907*	*32.802*	*33.848*	*33.846*	*33.816*
27	**T_f [°C]**	*28.652*	*29.074*	*27.907*	*28.006*	*28.477*	*28.208*	*28.857*	*28.305*	*28.828*	*28.827*	*28.812*
28	**k_{mt}**	*49.228*	*49.205*	*49.268*	*49.282*	*49.136*	*49.265*	*49.109*	*49.309*	*49.353*	*49.379*	*49.406*
29	**k_{ma}**	*0.049*	*0.050*	*0.049*	*0.049*	*0.050*	*0.049*	*0.050*	*0.048*	*0.055*	*0.055*	*0.054*
30	***h internal***											

Figure 2: Application program for the calculation of overall heat transfer coefficients in MS-Excel worksheet.

The program includes four worksheets, one for each insulation condition classification (refer to Table 1), in which the overall heat transfer coefficient, the temperature on the inner and outer pipe surface, the temperature in the pipe-insulation interface and the heat loss per unit length from the pipe towards the ambient are calculated.

Heat loss calculations throughout the CPGF pipeline network are based on a heat balance which involves the three basic mechanisms of heat transfer: conduction, convection and thermal radiation. The correlations and basic equations used to determine both internal and external heat transfer coefficients by convection, heat conduction through the pipe wall and insulation, the thermal radiation heat flow, and the calculation of the overall heat transfer coefficient can be found in Ovando-Castelar et al. (2009).

The thermal conductivities of the insulation and pipes are average values obtained at the operational temperature range of each steam pipeline in the network. They are based on thermal conductivity and temperature data provided by a world-wide industry-leader manufacturer. The fitted equations to these data are shown in Table 2.

Given the wide range of pipe diameters operating in both the high- and low-pressure pipeline networks, the overall heat transfer coefficient for each pipeline were preliminary evaluated according to its diameter. In addition, since the inside and outside film coefficients, air and water steam thermo-physical properties, and the thermal conductivities of the pipes and insulation are affected by the network operating conditions (pressure and steam mass flow rate), different estimates of the coefficients were performed based on data from the CPGF for a specific date. Regarding ambient air temperature and wind velocity, the measured annual averages of the preceding year were considered.

Preliminary calculations of the overall heat transfer coefficient were conducted by grouping the CPGF in two separate sectors, Cerro Prieto-1 (CPU) and Cerro Prieto-2, 3 and 4 areas (CPDTC). The CPU sector has only high-pressure steam lines, however they operate at lower pressures and flow rates compared with CPDTC. For the CPDTC grouping, the calculations were carried out separately for the high- and low-pressure steam lines.

Table 2: Equations for the calculation of the average thermal conductivity of pipes and thermal insulation of the CGCP steam pipeline network

Material	Thermal conductivity [W/(m-K)]; T [°C]
Pipe (carbon steel ASTM A-53 Gr B)	$k_{mt} = -\frac{106118}{T_2 - T_1}\left(e^{-0.0005T_2} - e^{-0.0005T_1}\right)$
Mineral glass fiber insulation, half-pipe preformed (ASTM C-547)	$k_{map} = \frac{7.6774}{T_2 - T_1}\left(e^{-0.0043T_2} - e^{-0.0043T_1}\right)$
Mineral rock fiber insulation, metal mesh blanket type (ASTM C-795)	$k_{mac} = \frac{12.4848}{T_2 - T_1}\left(e^{-0.0033T_2} - e^{-0.0033T_1}\right)$

The overall coefficients of the various pipeline diameters existing in the network were determined by varying mass flow rate and pressure. These calculations were performed first for three of the four insulation qualities considered: A, B and D. For condition C (regular or deteriorated), the calculations of the heat loss were treated separately.

The behavior of the overall heat transfer coefficient as a function of the diameter, pressure, mass flow rate and insulation condition was analyzed. It is mostly affected by the pipe diameter and the insulation condition. The estimated overall heat transfer coefficients were compared with results from commercially-available software which perform similar calculations, and with field measured temperatures of a number of network pipelines. The results of this comparison were quite satisfactory.

2.3 Calculation of the overall heat transfer coefficient for insulation condition C

The calculation of the overall coefficient for insulation condition C was even more complicated due to the evident loss of the cylindrical geometry due to irregular and reduced thickness and loss of portions of insulation caused by the absence of mechanical protection. In addition, the increase of the insulation thermal conductivity due to porosity reduction by the presence of dust and humidity, are factors that can hardly be theoretically evaluated.

To assess the impact of these two factors, sensitivity studies were carried out varying the pipeline insulation thickness, and by gradually increasing insulation thermal conductivity. It was found that the overall coefficient increased proportionally with an increase in thermal conductivity and a reduction in insulation thickness. Both effects are observed in practice for insulation condition C. This led us to carry out a more specific analysis in order to assess their real impact in estimating the appropriate overall coefficient. In this way, surface temperature was defined as a benchmark for the heat loss. Thus, pipelines with different diameters and operating conditions throughout the network (particularly in CPD and CPU areas) were selected. The surface temperature was obtained from averaging field measured temperatures using two infrared thermo-graphic cameras and a laser infrared thermometer.

Afterwards, through simulations performed with the MS Excel-based application program, the insulation thickness of each pipeline was reduced until the theoretical surface temperature reached the average field-measured temperature. Thus, the percentage reduction of the original insulation thickness related to the current physical condition was estimated. Table 3 shows a summary of results of the measured insulation thickness reduction of various steam pipelines.

Table 3: Field-measured insulation thickness reduction for different steam pipelines

High-pressure wells – CPU (AP)	M-30 int. R3	M-30	M-20	M-20 int. R3	E-15
Dnom, in	30	16	16	34	16
Tavg(field), °C	50.925	48.725	46.075	51.400	42.350
Insul. thick., in	0.9945	1.0046	1.2568	1.04755	1.24745
Orig. thick., in	2	2	2	2	2
% reduction	50.275	49.77	37.16	47.6225	37.6275
Tw(calc.), °C	*50.925*	48.725	46.075	51.400	42.350
Um, W/m^2-°C	1.95213	2.01288	1.69015	1.96036	1.67919
Insulation /cover mat. & cond.	Blanket without metal mesh, very crushed	Metal mesh blanket, crushed	Black mastic asphalt	Metal mesh blanket, plastered over, very damaged	Half-pipe preformed insulation, deformed ("fluffy")

High-pressure wells – CPDTC (AP)	M-127	M-116	624	Int. SC 30-20	R1-CPD bef. M-122	R1-CPD aft. M-122
Dnom, in	16	16	28	36	42	44
Tavg(field), °C	54.000	54.650	57.200	57.800	51.075	52.25
Insul. thick., in	0.9468	0.9425	1.09795	1.1376	1.87645	1.8023
Orig. thick., in	2	2	2	2	2	2
% reduction	52.66	52.875	45.1025	43.12	6.1775	9.885
Tw(calc.), °C	*54.000*	54.650	57.200	57.800	51.075	52.250
Um, W/m^2-°C	2.21412	2.31720	2.11340	2.01854	1.27554	1.31948
Insulation/cover mat. & cond.	White mastic asphalt, with metal mesh	Painted canvas, deformed	Blanket without metal mesh, deformed ("fluffy")	Metal mesh blanket, partially plastered over	Metal mesh blanket, good condition	Plastered over, good condition

Low-pressure wells – CPDTC (BP)	M-116	624	Int. SC 30-20	R1-CPD bef. M-122	Int. R1-R2 CPD	138
Dnom, in	8	18	20	24	28	10
Tavg(field), °C	48.425	55.375	60.650	66.050	49.725	45.54
Insul. thick., in	0.8534	0.7066	0.54555	0.49376	1.17995	0.6686
Orig. thick., in	1.5	2	2	2	2	2
% reduction	43.10667	64.67	72.7225	75.312	41.0025	66.57
Tw(calc.), °C	*48.425*	55.375	60.650	66.050	49.725	45.540
Um, W/m^2-°C	2.46064	2.65640	3.25218	3.72997	1.80666	2.76883
Insulation/cover mat. & cond.	Painted canvas, deformed	Blanket without metal mesh, deformed ("fluffy")	Metal mesh blanket, dirty and dusty	Blanket without metal mesh, very damaged, "fluffy" or crushed	Plastered over, good condition	Complete with metallic cover, very crushed

In order to obtain a representative result of the heat loss through type-C insulation, the percentages of thickness reduction of the steam pipeline analyzed were averaged. Based on physical inspection of their current condition, different degrees of damage were distinguished, ranging from the least critical that denotes less physical damage to the most critical that represents a badly damaged insulation (wear out and very compacted).

Table 4 shows the average percentage thickness reduction of insulation type-C with greater physical (red and orange color in Table 3). From these results, it was determined that, in a practical manner, a reduction of 50% in insulation thickness is a representative value of type-C insulated pipelines.

Table 4: Average thickness reduction of type-C insulation with greater physical damage (red + orange color in Table 3).

CPGF Sector	Average thickness reduction, %	Average thickness reduction (critical), %
CPU-AP	44.49	44.49
CPDTC-AP	34.97	48.44
CPDTC-BP	60.56	64.48
	46.67	52.47

From field measurements, it was observed that heat loss is greater in pipelines with insulations that are not covered with metallic sheet nor with a metallic mesh and that have lost their geometry. On the other hand, pipelines with complete insulation (including metallic protection) but being crushed, also exhibit increased heat losses. Thus, heat losses for type-C insulation were finally determined to be modeled in the MS Excel application program as pipelines lacking metal protection and whose thermal insulation has been reduced by 50% of its original thickness.

3. RESULTS

Heat loss calculations with more homogeneous operating conditions were performed separately for CPU and for the CPDTC high- and low-pressure steam pipelines. Additionally, according to the connectivity scheme of the CPGF steam pipeline network, the operating steam pipelines follow a hierarchical classification: single-well pipeline, sub-collector and main collector or branch. Therefore, different considerations were used for each case.

For the single-well pipelines, the operation conditions used for the calculations correspond to the average steam production data (mass flow and pressure) for each pipe diameter reported for the study reference date.

In the case of the main collectors or branches, which typically present great length and a telescopic configuration, the pressure follows a linear distribution depending on pipe diameter, and varies from the average separation pressure of the wells connected at the beginning of the collector, to the average pressure of the steam delivery points at the power plants inlets.

For the CPU sector, where there is virtually no difference between the average well separation pressure and the average pressure at the arrival to the power plants, a constant pressure was used for all pipe diameters. This pressure is an average value derived from the average pressure of the wells connected to a given branch, and the average pressure at the inlet of the power plant being fed for that branch. For the mass flow, an average value obtained from the production data per branch, was considered for all branches.

Regarding the sub-collectors, well separation pressure was averaged using the main collector pressures for each operating pipe diameter. For the mass flow, a linear distribution as function of pipeline diameter was used, starting from the average flow per well until reaching the average flow per branch (main collector). Table 5 shows the operating conditions used in the heat loss calculations for the CPU pipelines for the three categories in which they were classified according to their hierarchy and operating conditions.

Table 5. Operating conditions used for CPU steam pipelines based on production data

CPU Wells	Dint [in]	Dnom [in]	$P_{LINE-PS}$ [psig]	Steam FlowRate [tons/h]
M-30	15.25	16,STD	100.00	6.537
E-15	15.25	16,STD	100.00	11.209
M-20	15.38	16,20	100.00	7.541
105	17.25	18,STD	100.00	8.024
107	17.25	18,STD	100.00	10.321
301	17.25	18,STD	97.50	17.219
302	17.25	18,STD	105.00	10.813
102	17.25	18,STD	100.00	23.412
103	17.25	18,STD	100.00	16.425
M-19A	17.38	18,20	100.00	18.668
E-2	17.38	18,20	97.50	6.155
M-104	17.38	18,20	104.00	16.344
605	19.25	20,STD	100.00	16.404
144	19.25	20,STD	95.00	11.817
E-18	19.25	20,STD	95.00	6.205
Average/Wells (general)			99.60	12.47

Average/Branch (general)	$P_{LINE-PS}$ [barg]	$P_m(PP_{INLET})$ [psig]	$P_{LINE-PS}$ [psig]	Steam FlowRate [tons/h]	$P_{LINE-PS}$ [barg]
	99.60	*100*	99.80	31.18	6.881

Averages (based on diameter)		Dnom [in]	$P_{LINE-PS}$ [psig]	Steam FlowRate [tons/h]	$P_{LINE-PS}$ [barg]
	Well	16	100.00	8.43	6.895
		18	100.44	14.15	6.925
		20	96.67	11.48	6.665
	Subcolector	16	99.70	21.83	6.874
		18	99.60	12.47	6.867
		20	99.70	21.83	6.874
		24	99.80	31.18	6.881
	Branch	18	99.80	31.18	6.881
		22	99.80	31.18	6.881
		26	99.80	31.18	6.881
		30	99.80	31.18	6.881
		32	99.80	31.18	6.881
		34	99.80	31.18	6.881

Since the results obtained with the MS Excel calculation program are given as heat loss per unit length, the total heat transfer was determined by multiplying the heat loss per unit length calculated for each insulation condition and for each diameter, by the corresponding length obtained from the thermal insulation condition inventory.

Table 6 shows the total heat losses of the CPU high-pressure network while tables 7 and 8 show the total heat losses of the CPDTC high- and low-pressure networks, respectively. Results are given as function of their insulation condition and diameter. The lengths corresponding to each case are also included.

The heat losses caused by deterioration of the pipeline network insulation eventually results in the condensation of steam inside the pipelines with a consequent reduction of steam delivery to the power plants and a decrease in generated power. The steam condensation rate in the transportation pipes is calculated from equation (3)

$$\dot{m}_{cond} = \frac{3.6 \quad q}{h_{fg}} \tag{3}$$

where m_{cond} is the steam condensation rate (tons/h), q is the heat loss to environment (kWt) and h_{fg} is the latent heat of condensation (kJ/kg).

Table 6: Insulation condition map of the LP-steam pipeline network

Pipeline type	Nominal diameter [in]	Pipe Length [m]	Length A [m]	Length B [m]	Length C [m]	Length D [m]	Condition A [kWt]	Condition B [kWt]	Condition C [kWt]	Condition D [kWt]	Heat loss [kWt]
Single-well	16.00	256.42	0.00	141.12	115.29	0.00	0.00	27.93	40.93	0.00	**68.86**
	18.00	3055.43	48.00	1791.37	1051.49	164.57	10.44	395.53	419.23	579.59	**1404.79**
	20.00	860.52	454.43	406.09	0.00	0.00	106.55	96.78	0.00	0.00	**203.32**
	SubTotal	**4172.37**	**502.43**	**2338.58**	**1166.78**	**164.57**	**116.98**	**520.24**	**460.16**	**579.59**	**1676.97**
Sub-collector	18.00	548.77	0.00	411.92	127.84	9.01	0.00	81.77	45.69	29.28	**121.59**
	20.00	94.57	0.00	94.57	0.00	0.00	0.00	20.79	0.00	0.00	**22.94**
	24.00	688.19	0.00	399.76	272.44	15.99	0.00	96.99	119.94	63.12	**200.77**
	SubTotal	**1331.54**	**0.00**	**906.26**	**400.28**	**25.00**	**0.00**	**199.56**	**165.62**	**92.40**	**345.31**
Main collector or branch	18.00	4.00	0.00	0.00	0.00	4.00	0.00	0.00	0.00	15.40	**15.40**
	22.00	241.48	0.00	56.67	154.12	30.70	0.00	15.01	74.36	133.81	**223.19**
	26.00	815.71	0.00	214.78	573.93	27.00	0.00	73.60	355.52	129.18	**558.30**
	30.00	1372.56	0.00	603.22	749.33	20.00	0.00	235.00	527.52	102.71	**865.23**
	32.00	2021.97	0.00	1419.94	595.03	7.00	0.00	586.03	443.48	36.94	**1066.45**
	34.00	2518.28	58.51	793.82	1664.95	1.00	24.87	345.92	1309.18	5.42	**1685.38**
	SubTotal	**6973.99**	**58.51**	**3088.43**	**3737.36**	**89.70**	**24.87**	**1255.56**	**2710.06**	**423.46**	**4413.95**
	TOTAL	**12477.90**	**560.94**	**6333.27**	**5304.42**	**279.27**	**141.85**	**1975.36**	**3335.84**	**1095.45**	**6436.23**

Table 7. Total heat losses in the CPDTC high-pressure (HP) steam transportation network as function of the pipe insulation condition and diameter

Pipeline type	Nominal diameter [in]	Pipe Length [m]	Length A [m]	Length B [m]	Length C [m]	Length D [m]	Condition A [kWt]	Condition B [kWt]	Condition C [kWt]	Condition D [kWt]	Heat loss [kWt]
Single-well	14.00	1549.34	370.82	0.00	905.49	273.03	79.37	0.00	353.41	1052.70	**1485.47**
	16.00	5689.23	1333.12	1824.25	2079.90	451.97	326.55	453.62	935.32	1998.84	**3714.32**
	18.00	3459.79	990.57	1745.41	675.31	48.50	264.92	474.28	332.41	222.21	**1293.82**
	20.00	18851.48	12547.73	3856.78	1697.74	749.23	3711.44	1160.07	927.91	3757.97	**9557.39**
	22.00	306.67	0.00	0.00	306.67	0.00	0.00	0.00	175.11	0.00	**175.11**
	24.00	322.92	320.92	0.00	0.00	2.00	122.11	0.00	0.00	11.26	**133.36**
	SubTotal	**30179.43**	**15563.16**	**7426.44**	**5665.10**	**1524.73**	**4504.39**	**2087.97**	**2724.16**	**7042.97**	**16359.48**
Sub-collector	14.00	244.54	0.00	244.54	0.00	0.00	0.00	53.49	0.00	0.00	**53.49**
	18.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
	20.00	1972.23	908.30	562.66	501.27	0.00	269.69	169.90	276.27	0.00	**715.87**
	22.00	531.76	0.00	518.85	0.91	12.00	0.00	169.60	0.55	70.85	**240.99**
	24.00	1388.18	442.49	378.84	549.85	17.01	169.18	148.08	390.94	108.80	**817.00**
	28.00	877.08	225.94	462.70	188.43	0.00	98.97	207.54	154.23	0.00	**460.74**
	30.00	2111.73	2098.92	12.81	0.00	0.00	977.43	6.11	0.00	0.00	**983.54**
	32.00	214.93	116.80	97.54	0.59	0.00	57.61	49.33	0.54	0.00	**107.48**
	36.00	785.65	0.00	785.65	0.00	0.00	0.00	441.69	0.00	0.00	**441.69**
	SubTotal	**8126.09**	**3792.46**	**3063.58**	**1241.05**	**29.01**	**1572.88**	**1245.74**	**822.53**	**179.64**	**3820.80**
Main collector or branch	18.00	604.24	53.51	542.72	0.00	8.00	14.52	149.65	0.00	41.20	**205.36**
	22.00	329.13	0.00	284.41	0.00	44.72	0.00	93.58	0.00	269.79	**363.37**
	24.00	941.87	159.68	512.35	188.40	81.44	60.89	199.73	133.66	525.40	**919.68**
	26.00	173.40	0.00	164.94	0.00	8.46	0.00	68.91	0.00	58.06	**126.97**
	28.00	2914.24	23.79	2323.34	476.79	90.32	10.35	1035.16	387.84	655.56	**2088.92**
	30.00	24.67	24.67	0.00	0.00	0.00	11.39	0.00	0.00	0.00	**11.39**
	32.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
	34.00	252.22	0.00	157.89	93.75	0.59	0.00	83.20	90.46	4.93	**178.60**
	36.00	14093.62	7669.79	5364.81	876.19	182.83	4135.02	2969.82	888.75	1596.63	**9590.21**
	38.00	1092.18	0.00	247.67	526.35	318.16	0.00	143.62	559.59	2888.49	**3591.69**
	40.00	4302.01	4110.24	164.24	17.97	9.57	2422.56	99.51	19.97	90.07	**2632.11**
	42.00	7588.06	7342.49	47.06	198.50	0.00	4508.94	29.72	230.07	0.00	**4768.74**
	44.00	1035.32	713.75	72.62	248.94	0.00	455.72	47.72	300.24	0.00	**803.68**
	46.00	7381.70	3648.47	3577.89	120.56	34.77	2417.40	2440.75	151.00	360.22	**5369.38**
	48.00	562.83	534.81	0.00	0.00	28.02	367.08	0.00	0.00	298.54	**665.62**
	SubTotal	**41295.49**	**24281.21**	**13459.95**	**2747.45**	**806.89**	**14403.87**	**7361.38**	**2761.59**	**6788.88**	**31315.71**
	TOTAL	**79601.01**	**43636.82**	**23949.96**	**9653.60**	**2360.62**	**20481.14**	**10695.09**	**6308.27**	**14011.50**	**51496.00**

Based on the results reported in tables 6 to 8, the steam condensation rate related to these heat losses was estimated according to the network operating conditions. Finally, taking into account the specific steam consumption of each CPGF power plant, the equivalent loss of electrical power due to the heat loss caused by the current condition of the steam pipeline network insulation was obtained. The results are summarized in Table 9.

Finally, a comparison of these results with an estimate of the overall energy losses taking place in the CPGF steam transportation system (García Gutiérrez et al. 2009), which add up 180 MWt (126.6 MWt and 53.4 MWt, for the high-pressure and low-pressure networks, respectively), indicates that the heat losses to the environment influenced by the physical condition of the insulations, represent approximately 46% of the total energy losses in the high-pressure network, while in the low-pressure network they account for about 28%. The rest of the energy losses are attributed to heat loss in network pipeline fittings (most of them with no insulation; not considered in this study), friction losses and energy lost in the hot water formed by condensation of steam.

From the insulation condition field inventory, it was determined that only 18-20% of the total pipeline network length has insulations from regular to very bad condition (qualities C and D, respectively). However, these pipelines account for nearly half of the heat losses, 48% and 43%, for the high- and low-pressure pipeline networks, respectively. This represents undoubtedly an area of improvement for the steam transportation system efficiency.

Table 8: Total heat losses in the CPDTC low-pressure (LP) steam transportation network as function of the pipe insulation condition and diameter

Pipeline type	Nominal diameter [in]	Pipe Length [m]	Length A [m]	Length B [m]	Length C [m]	Length D [m]	Condition A [kWt]	Condition B [kWt]	Condition C [kWt]	Condition D [kWt]	Heat loss [kWt]
Single-well	8.00	548.04	0.00	0.00	548.04	0.00	0.00	0.00	117.97	0.00	**117.97**
	10.00	11917.17	9017.09	1924.11	828.07	147.89	1322.65	286.67	218.65	293.09	**2121.06**
	12.00	2037.42	348.18	587.24	868.61	233.39	45.44	77.63	203.98	479.18	**806.23**
	14.00	1461.77	752.24	0.00	709.53	0.00	105.66	0.00	1798.47	0.00	**1904.13**
	16.00	724.88	53.37	457.50	176.49	37.52	8.97	78.05	54.12	101.94	**243.08**
	20.00	674.93	134.38	342.46	181.09	17.00	27.80	72.01	68.76	53.67	**222.23**
	SubTotal	**17364.21**	**10305.26**	**3311.31**	**3311.84**	**435.80**	**1510.52**	**514.35**	**2461.94**	**927.88**	**5414.70**
Sub-collector	10.00	1052.26	552.18	0.00	500.08	0.00	81.47	0.00	133.09	0.00	**214.56**
	14.00	1162.03	927.41	171.03	18.96	44.62	134.38	25.12	5.01	117.33	**281.85**
	16.00	1247.59	282.76	556.58	408.24	0.00	46.98	93.83	124.51	0.00	**265.31**
	18.00	355.68	0.00	0.00	329.68	26.00	0.00	0.00	111.89	86.97	**198.85**
	20.00	2341.35	2147.45	129.69	64.21	0.00	429.61	26.37	23.81	0.00	**479.80**
	SubTotal	**6158.91**	**3909.79**	**857.30**	**1321.18**	**70.62**	**692.44**	**145.33**	**398.30**	**204.30**	**1440.37**
Main collector or branch	14.00	309.07	84.94	0.00	224.13	0.00	12.57	0.00	60.61	0.00	**73.17**
	16.00	823.31	0.00	312.17	423.03	88.11	0.00	51.61	126.69	269.47	**447.77**
	18.00	1464.10	60.07	971.88	359.20	72.95	10.63	174.66	117.38	238.02	**540.68**
	20.00	379.49	0.00	165.22	179.51	34.77	0.00	31.91	63.22	119.63	**214.76**
	22.00	4353.87	787.96	3163.05	338.94	63.92	159.26	650.31	127.33	229.59	**1166.49**
	24.00	8535.23	5190.14	2223.74	976.41	144.94	1248.29	546.39	435.09	538.63	**2768.39**
	26.00	228.19	0.00	19.37	114.93	93.89	0.00	4.99	53.74	358.09	**416.82**
	28.00	8006.32	2703.30	5067.46	135.70	99.88	708.39	1358.57	66.09	388.27	**2521.32**
	SubTotal	**24099.59**	**8826.41**	**11922.90**	**2751.83**	**598.45**	**2139.13**	**2818.45**	**1050.13**	**2141.69**	**8149.40**
	TOTAL	**47622.71**	**23041.47**	**16091.51**	**7384.86**	**1104.87**	**4342.09**	**3478.13**	**3910.38**	**3273.87**	**15004.47**

Table 9: Estimated total heat losses, steam condensation rate and power loss in the CPGF steam pipeline transportation network

	Length [m]	%	q [MW_t]	m [tons/h]	q [MW_e]
TOTAL CPU	12477.9	8.9	6.4	11.5	1.2
TOTAL CPDTC-AP	79601.0	57.0	51.5	99.4	13.1
TOTAL CPDTC-BP	47622.7	34.1	15.0	25.4	3.3
TOTAL CP	139701.6	100.00	72.9	136.3	17.6

4. CONCLUSIONS

The effect of thermal insulation conditions on the heat losses taking place in the CPGF steam pipeline network was studied. This was done by quantifying the magnitude of such losses and their comparison with the overall energy losses taking place during the steam transport from the wells to the power units.

The study was based on the results of a field inventory of the conditions of pipelines thermal insulation and the use of a MS Excel-based application program to compute the heat transfer considering the operating conditions of the overall network at a specific date.

Results indicate that the estimated heat losses for all the pipes in the CPGF steam pipeline network amounted to 72.9 MWt. Of these, 57.9 MWt correspond to the high-pressure network, and 15.0 MWt to the low-pressure network. These losses resulted in 136.3 tons/h of condensate, 110.9 tons/h of which are in the high-pressure network, and 25.4 tons/h in the low-pressure network.

The total equivalent electrical power lost due to the heat transferred to the environment, and related to the current conditions of the steam pipeline insulation, was estimated as 17.57 MWe. This represents about 2.44% of the total installed capacity in the CPGF (720 MWe).

The comparison of these results with the total energy loss estimates occurring in the CPGF network at that time indicates that the heat losses through the insulations in the high- and low-pressure networks represent 46% and 28% of the total, respectively. The remainder corresponds to heat losses in network fittings, friction losses and steam condensation.

According to the insulation condition inventory, only 18-20% of the total length of the pipeline network has insulations with qualities C and D (from regular to very bad condition). However, they are responsible for nearly half of the heat losses (48% and 43% for high-pressure and low-pressure networks, respectively). The optimization of the efficiency of the CPGF steam transportation system (i.e., the reduction of heat losses by improving thermal insulations) is an area that needs attention.

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REFERENCES

García, A., J.I. Martínez, A.F. Hernández, M. Ceceñas, R. Ovando, E. Salaices, I. Canchola, O. Mora, S. Gutiérrez, C. Miranda, M. Hernández and S. López: Numerical simulation of the Cerro Prieto steam pipeline network. *Geothermal Resources Council Transactions*, Vol. 30 (2006), 19-23.

García-Gutiérrez, A., J.I. Martínez-Estrella and R. Ovando-Castelar: Evaluación y optimización de la eficiencia del ciclo geotérmico del Campo Geotérmico de Cerro Prieto: Parte 1-Sistema de producción y transporte de fluidos geotérmicos, Final Report IIE/11/13743/I02/F/DC, (2009), Instituto de Investigaciones Eléctricas, Cuernavaca, Mexico.

Gutiérrez-Negrín, Luis C.A., R. Maya-González and J.L. Quijano-León: Current Status of Geothermics in Mexico, *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 25-29 April, 2010, Paper 101.

Marconcini, R. and Neri, G.: Numerical simulation of a steam pipeline network, *Geothermics*, Vol. 7, (1979), 17-27.

Martínez-Estrella, J.I., Ovando-Castelar, R., García-Gutiérrez, A., Gutiérrez-Lara, C., Canchola-Félix, I., Jacobo-Galván, P.: Using GIS for Practical Geothermal Applications: an Inventory of the Thermal Insulation Condition of the Cerro Prieto Geothermal Field Pipeline Transportation Network. *Proceedings World Geothermal Congress 2015*, Melbourne, Australia, 19-25 April (2015).

Ovando-Castelar, R., A. García-Gutiérrez, M. Ceceñas-Falcón, J.I. Martínez-Estrella, A.F. Hernández-Ochoa, I. Canchola-Félix, O. Mora-Pérez and C. Miranda-Herrera: Efecto del Estado del Aislamiento sobre el Coeficiente Global de Transferencia de Calor en Componentes de la Red de Vaporductos del Campo Geotérmico de Cerro Prieto, *VII Congreso Internacional en Innovación y Desarrollo Tecnológico* (2009), Cuernavaca, Morelos, México, Paper 569.

Ovando-Castelar, R., A. García-Gutiérrez, J.I. Martínez-Estrella, I. Canchola-Félix, P. Jacobo Galván, C. Miranda-Herrera, and O. Mora-Pérez: Determinación de pérdidas de calor en la red de transporte de vapor del campo geotérmico de Cerro Prieto, BC, con base en el estado físico del aislamiento térmico de vaporductos, *Proc. XVIII Annual Congress, Mexican Geothermal Association*, Morelia, Michoacán, México, (2010) Paper 5.

Ovando-Castelar, R., Martínez-Estrella, J. I., García-Gutiérrez, A., Canchola-Félix, I., Miranda-Herrera, C.A., Jacobo-Galván, V.P.: Estimation of steam pipeline network heat losses at the Cerro Prieto Geothermal Field based on pipeline thermal insulation conditions. *Geothermal Resources Council Transactions*, v. 36 (2012), 1111-1118.

Peña, J.M.: Energy losses in horizontal steam lines. *Geothermal Resources Council Transactions*, Vol. 10 (1986), 347-352.

Peña, J M. and Campbell H.: Evaluación de las pérdidas de calor en líneas de vapor geotérmico, In: *Proceedings Third Latinamerican Congress on Heat and Mass Transfer*, Guanajuato, México (1988), pp. 53-64.

Schroder, F. S.: Calculating heat loss or gain by an insulated pipe, *Chemical Engineering*, January 25 (1982), 111- 114.