Report 10, 1993

THERMAL ENERGY PRODUCTION FROM LOW TEMPERATURE GEOTHERMAL BRINE - TECHNOLOGICAL ASPECTS AND ENERGY EFFICIENCY

Valdas Lukoševičius,
UNU Geothermal Training Programme,
Orkustofnun - National Energy Authority,
Grensasvegur 9,
108 Reykjavik,
ICELAND

Permanent address:
Kaunas University of Technology,
Department of Thermal Power Engineering,
K.Donelaicio 20 - 208,
3042 Kaunas,
LITHUANIA

ABSTRACT

A short description of the West Lithuanian geothermal anomaly is presented in this report. The significant fluctuation of geothermal reservoir characteristics, high salinity and relatively low temperatures cause each case of geothermal utilization in Lithuania to be considered in detail and be well-grounded.

Literature review of geothermal heating systems, exploiting low temperature geothermal fluids was made highlighting the main technological aspects and problems which can arise during utilization of geothermal brines. Experience of geothermal utilization, obtained in other countries, should be used to substantiate technological schemes of geothermal plants in Lithuania.

A computer programme based on a simplified geothermal reservoir model, well construction and geothermal plant scheme has been developed for calculations of geothermal energy production and energy consumption in the main technological equipments. Coefficient of energy performance and gained thermal energy are suggested to estimate thermal energy generation efficiency. The tentative cost of the main equipment has been collected. This data should be the basis for further development with the aim to prepare a method for the consideration of geothermal utilization projects.

Preliminary estimation of efficiency of thermal energy production for existing district heating systems from the West Lithuanian geothermal brines have been made, using computer calculations. The characteristics of geothermal reservoirs and the main technical parameters of a geothermal plant have been examined.

TABLE OF CONTENTS

Page

ABSTRACT 3

1. INTRODUCTION 6

2. WEST-LITHUANIAN GEOTHERMAL ANOMALY 7
    2.1 Location and thermal characteristics 7
    2.2 Well testing data 9
    2.3 Composition of geothermal fluids 10

3. PHYSICAL PROPERTIES OF GEOTHERMAL BRINES 12
    3.1 General 12
    3.2 Density 12
    3.3 Specific heat capacity 14
    3.4 Viscosity 14

4. TECHNOLOGICAL SPECIFICITY OF GEOTHERMAL ENERGY PRODUCTION 17
    4.1 Geothermal heating systems survey 17
    4.2 Characterization of Lithuanian district heating systems 21
    4.3 Preconditions for geothermal utilization in existing district heating systems 21

5. ESTIMATION OF GEOTHERMAL ENERGY PRODUCTION EXPENDITURE . . 23
    5.1 General 23
    5.2 Operational energy consumption and expenditure 23
    5.3 Installation cost 26

6. EFFICIENCY OF THERMAL ENERGY PRODUCTION FROM THE WEST LITHUANIAN GEOTHERMAL BRINES 30
    6.1 General 30
    6.2 Methodological part 30
    6.3 Generation of thermal energy for existing district heating systems 31
    6.4 Discussion and comparison with conventional energy sources 37

7. CONCLUSIONS 39

ACKNOWLEDGEMENTS 40

NOMENCLATURE 41

REFERENCES 43

LIST OF FIGURES

Page

1. The forecasted geothermal resources in the West Lithuanian geothermal anomaly 7
2. Location of the explored geothermal fields 8
3. Location of the investigated boreholes 9
4. Schematic arrangement of the Beauvais district heating scheme 17
5. Schematic lay-out of the Chateauroux district heating scheme 18
6. Ephrata schools schematic arrangement of the heating scheme 18
7. Diagram of the Seltjarnarnes district heating system 20
8. Data of well costs 27
9. Costs of plate heat exchangers 28
10. Heat pump costs 29
11. Geothermal plant for thermal energy production from Cambrian aquifer brines 32
12. Energy efficiency relation to geothermal brine temperature and flow rate 34
13. Net energy from Cambrian aquifer brine 34
14. Lay-out of geothermal plant for Devonian geothermal energy consideration 35
15. Thermal energy production efficiency from Devonian brines 37

LIST OF TABLES

1. Results of the borehole exploration in the WLGA 8
2. The results of hydrodynamic testing of the wells in the WLGA 10
3. General limits of microconcentration in the WLGA 10
4. Average composition of gases in the WLGA waters 10
5. Composition of the WLGA geothermal fluids 11
6. Density of geothermal fluids 13
7. Specific heat capacity 14
8. Viscosity of salt solutions 16
9. Medium temperature geothermal district heating systems 19
10. Well specific cost 27
11. Influence of Cambrian reservoir characteristics to the energy production efficiency .. 33
12. Influence of Devonian reservoir characteristics to the energy production efficiency .. 36
13. Thermal energy production from Devonian aquifer 38

1. INTRODUCTION

More than 90% of Lithuania's primary energy sources are imported, mainly from Russia. Intensive exploration and analysis of possibilities to use local energy sources have been launched after the restoration of state independency in 1990. One of the potential energy sources is geothermal water, obtained in the west part of Lithuania. Such features as high salinity, relatively low temperature, variations in the geothermal reservoir characteristics, need of large investment cost and other reasons mean that every case of geothermal utilization being considered should be carefully examined and well grounded.

There is little experience in the design and exploitation of geothermal systems in Lithuania, and this report is only a limited effort to consider and estimate geothermal energy production efficiency based on other countries' experience. The general assumption that geothermal energy is going to be used in the existing district heating systems is made. Two different geothermal energy production plants from Cambrian and Devonian aquifers are considered.

Analysis of the geothermal energy production efficiency should be one of the first steps in geothermal utilization. Consideration of capital cost, economical and other factors have to be following stages of a feasibility study in case of positive results of the energetic substantiation. The aim of this report is to suggest a methodological and informative basis for the geothermal energy production technological calculations, designing, cost estimation etc. as a decision making tool for geothermal project consideration. The knowledge obtained at the UNU Geothermal Training Programme and other available information sources have been used for this work.

2. WEST-LITHUANIAN GEOTHERMAL ANOMALY

2.1 Location and thermal characteristics

The Baltic thermal anomaly, caused by deep fractures in the crust of the Earth has covered the west part of Latvia, Lithuania and Kaliningrad region of Russia. Three composite geothermal anomalies: Elgava, West-Lithuania and Kaliningrad are specified. West-Lithuanian geothermal anomaly (WLGA) is the most intensive and has the biggest area. The average temperature gradient in the WLGA is ascertained as 40-50°C/km, though in the surrounding regions its mean is usually 20-30°C/km. Distribution of the forecasted resources is described in Figure 1.

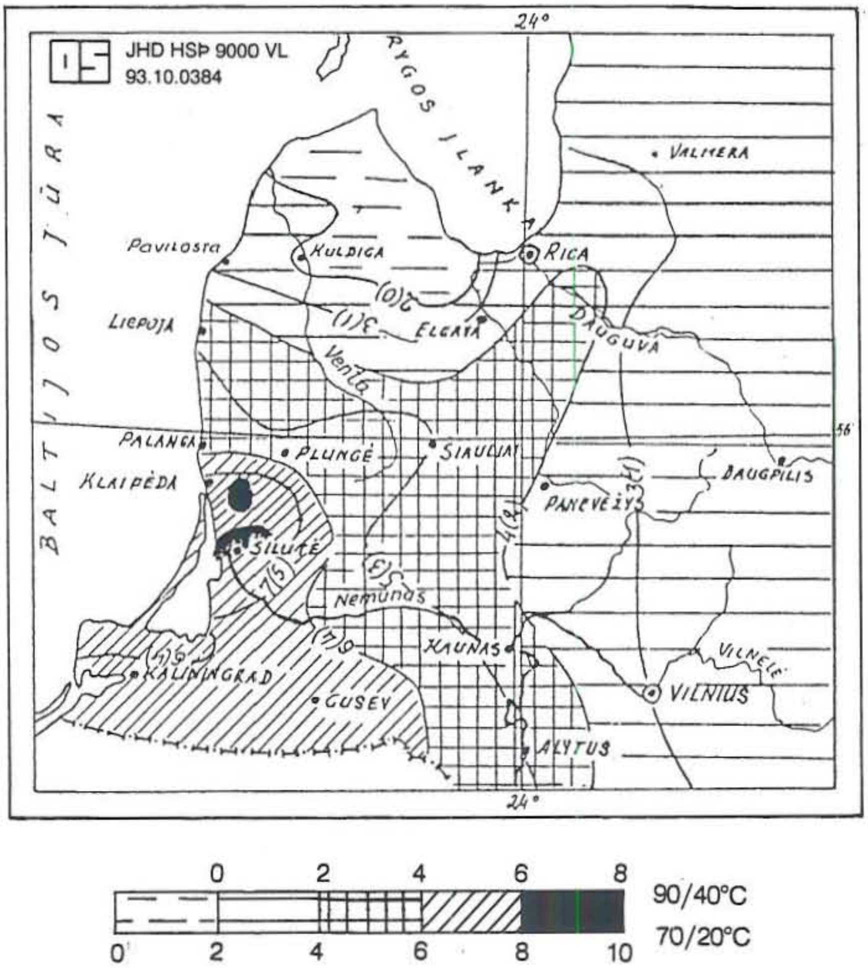

FIGURE 1: The forecasted geothermal resources in the West Lithuanian geothermal anomaly

The units which represent density of thermal energy resources are tons of conventional fuel (calorific value 29.3 GJ/t) per m^2. An upper row of scale represents geothermal resource density for temperature regime 90/40°C and, correspondingly, a lower row for 70/20°C. The fields of the most intensive thermal flow are situated 15-30 km from the seashore, between Klaipeda and Silute cities. The highest density of geothermal resources (>234 GJ/m^2) is characterized in an area of 100 km^2.

Klaipeda, Silute, Palanga, Gargzdai and several smaller cities have been laid out in the region of the WLGA and can be considered as potential users of geothermal energy for district heating and other needs. According to estimation of Lithuanian Geology Institute, resource potential of geothermal energy in the WLGA is considered as 98.6×10^9 tons of conventional fuel for temperature regime 90/40°C (corresponds to 2.9×10^{12} GJ) or 146.4×10^9 tons for regime 70/20°C (4.3×10^{12} GJ).

There are technical possibilities to utilize geothermal energy and replace 1 million tons of imported fossil fuel a year just in this century. Some results of geological and geothermal exploration of the WLGA are presented in Table 1 (Report of the state enterprise Geoterma, Lithuania). Location of the nearest cities and investigated fields is shown in Figure 2.

TABLE 1: Results of the exploration in the West Lithuanian geothermal anomaly

Field of exploration	Characteristics					
	Depth (m)	Density (kg/m³)	Permeability (mD)	Porosity (%)	Temperature (°C)	Salinity (g/l)
Kuliai	1071				31.4	
	1273				35.7	
	2227	2440	173	10	73.2	
Traubai	1018	2250	1000	25	43.7	
	1180	2300	600	23	48.2	
	2156	2500	4	7	85.0	180
Genčiai	890				32.6	
	1020				35.6	
	1886	2400	500	13	72.8	150
Šakučiai	1016				41.5	
	1192	2120	767	20	44.8	105
	2106	2550	107	12	89.0	165
Šilute	991	1990	7000	20	43.7	58
	1171	2250	946	20	48.6	
	2140	2480	90	13	93.0	162
Laukuva	971		700	25	44.0	
	1159		1400	24	47.0	
	1999		273	11	86.0	
Žviliai	921	1800	5000	30	37.0	21
	1112	2330	500	23	45.0	70
	1986	2540	300	11	84.0	168
Vainutas	964	2400	1189	23	35.4	
	1134	2400	313	20	38.2	71
	2029	2550	370	10	70.8	158
Gargždai	1031	1950	3000	29	34.1	35
	1209	2300	120	17	36.0	100
	2160	2520	140	9	75.2	177

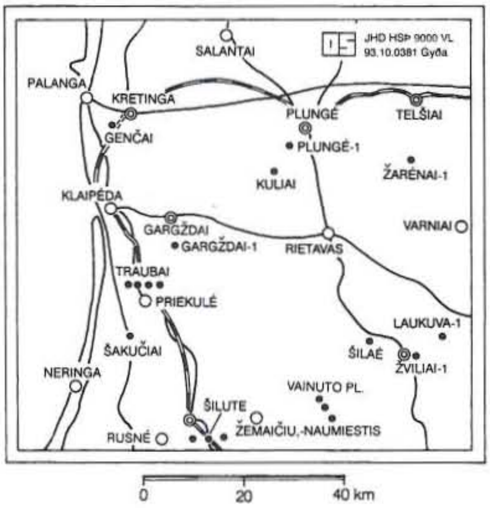

FIGURE 2: Location of the explored geothermal fields

Two of the most perspective aquifer complexes have been discovered during geological and geothermal exploration. Aquifers situated in the middle Cambrian geological system, at the depth of 1700-2100 m, are more attractive for geothermal utilization. The temperature range of 60-95°C has been measured in these aquifers. The highest temperature of 95°C has been found in the borehole Meskine-1 (Figure 3), 92°C in the Vabaliai-1, and 90°C in the Gorainiai-1 and Silute-2. An isotherm of 90°C embraces an area of 300 km^2 around the mentioned wells. An isotherm of 80°C correspondingly embraces 2400 km^2 and the isotherm 60°C about 6000 km^2. The geothermal fluid from these aquifers is called Cambrian water. Another complex, situated at the depth of 700-1100 m, in the middle and

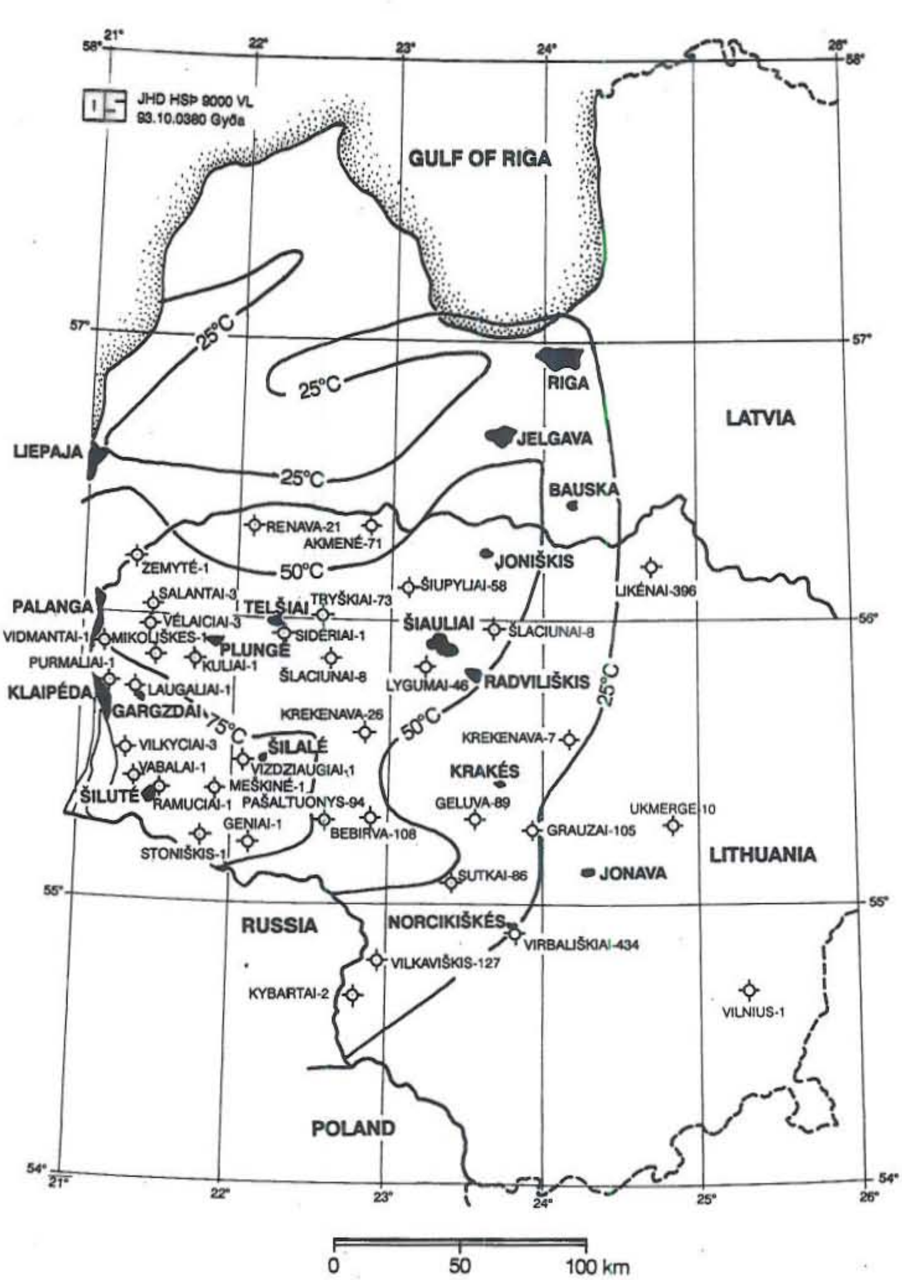

FIGURE 3: Location of the investigated boreholes in Lithuania and isotherms

lower Devonian, is characterized by lower temperatures (30-45°C), but its productivity is much higher (this water is often called Devonian). This geothermal water is less mineralized as well.

2.2 Well testing data

Distribution of the boreholes in the WLGA is shown in Figure 3. The wells are mostly non-artesian. The static water level of Devonian aquifers was measured 4-35 m from the surface and these figures are higher for Cambrian aquifers. It is customary to estimate productivity of the wells in Lithuania by the efficiency coefficient, which means flow rate of geothermal water due to pressure depression of 1 atm (drawdown). Estimation of efficiency coefficient, based on the aquifer thickness and permeability data, shows that productivity of the wells is quite different. A value of the efficiency coefficient varies from the minimum up to the maximum 6-10 m^3/(hatm) in the wells Ablinga-4 and Ablinga-5 (Cambrian aquifers).

Although experimental data of the well testing is limited at present, some of it is presented in Table 2. Air lift up tests have been used during the investigation. The big difference in the well productivity indicates the necessity of detailed investigation of the reservoir characteristics before geothermal utilization is started. There is a general opinion, based on the geological exploration, that the output of Devonian aquifers should be at least two times greater than Cambrian aquifers.

TABLE 2: The results of hydrodynamic testing of the wells
in the Western Lithuanian geothermal anomaly

System	Well	Logging		Flow rate		Water level		Press. drop	Eff. coeff.
		Depth	Temp.			Static	Dynam		
		(m)	(°C)	(m^3/h	(l/s)	(m)	(m)	(atm)	(m^3/hatm)
Devon.	Vilkyciai	1065	43	118	32.7	17.0	50.9	3.50	33.64
	Vilkyciai	1065	43	90.0	25.0	19.0	49.8	3.06	29.44
	Purmaliai			26.1	7.2			21.67	1.20
Cambr.	Vidmantai	1950- -2030	75	26.25	7.29	65	239	19.5	1.35
	Vidmantai		75	28.33	7.87	65	256	21.4	1.32

2.3 Composition of geothermal fluids

Geothermal water in the WLGA is highly mineralized, mainly chloride type. The water is neutral or slightly acid with a pH = 6.8-7.1 in the Devonian aquifers and pH = 5.2-7.4 in the Cambrian. However, more acid water (pH = 3.0-4.5) was obtained in the separate Cambrian aquifers (wells: Vizdžioniai-1, Aukštupiai-1). Table 3 shows the general limits of microconcentration (mg/l) in the waters and Table 4 shows the average composition of gases in % volume. The amount of dissolved gases in the Devonian brines is about 0.1 m^3/m^3 and 0.1-0.2 m^3/m^3 in the Cambrian brine. It should be noted that there is no hydrogen sulphide in either water. High mineralization of the geothermal fluids determines special requirements for the technology of extraction and utilization of geothermal energy. Water analysis data are partly presented in Table 5 (for location of boreholes, see Figure 3).

TABLE 3: General limits of microconcentration (mg/l) in the WLGA waters

	I	Br	H_3BO_3	NH_4	Sr	Li	Zn	C
Devonian	0.1-2.0	100-200	2.0-200	10-70	-	-	-	-
Cambrian	2.0-4.0	700-1200	10-25	20-100	300-400	0-9	3-32	0.05-5

TABLE 4: Average composition of gases in the WLGA waters

	Nitrogen	Carbon dioxide	Hydro-carbons	Helium	Argon
Devonian	90	9	1	-	-
Cambrian	20-50	0.5-5.0	60-70	1-5	0.1-1.0

TABLE 5: Composition of the WLGA geothermal fluids in mg/l

Well	**Test interval (m)**	**Total salinity**	**Anions**				**Cations**		
			HCO_3	**Cl**	**SO_4**	**Br**	**Na+K**	**Ca**	**Mg**
Devonian aquifer water									
Geniai-1	784-799	39263	125	22184	2361		10689	2868	906
Mikoliskes-1	934-939	52398	24	31046	1474	200	15121	3218	1197
Priekule-1	749-764	11290	98	2160	2079	8	1026	835	246
Priekule-1	756-761	12000	110	3220	1755	5	1474	859	211
Siupyliai-68	524-530	5566	72	1637	2078	6	844	753	209
Siupyliai-68	598-606	6227	63	2101	1992	9	1101	823	167
Sutkai-86	410-416	8523	97	3269	2228	16	1785	968	190
Tryskiai-73	638-648	6058	102	1800	2174	8	1040	839	139
Velaiciai-3	760-807	14726	125	6494	2853	40	3762	1160	320
Zemyte-1	911-937	38741	111	21937	2389	139	10235	2946	1013
Cambrian aquifer water									
Bebirva-109	1416-1425	125406	106	77209	898	371	34140	9743	2909
Geniai-1	1780-1792	145304	47	90463	309		31609	18763	3267
Kuliai-1	2031-2040	127084	127	79134	372		27794	15706	3262
Lygumai-46	1368-1407	103661	109	63335	1207	2	29733	6775	2339
Meskine-1	1974-1989	148027	114	92027	500		31426	19925	3262
Priekule-11	1481-1484	120100	13	75200	288	352	30288	11182	3038
Priekule-11	1492-1494	103712	67	70800	520	293	28147	1025	2858
Priekule-11	1527-1537	118100	43	73600	87	412	29816	11810	2396
Siupyliai-68	1232-1243	113599	104	69489	1241	288	32319	7484	2654
Slapgiriai-1	1653-1658	116288	116	72429	229		28057		2842
Stoniskiai-1	2003-2103	165812	227	103830	82	607	33173	24349	3453
Tryskiai-73	1429-1447	113300	6	70514	244	391	28915	10436	2750
Velaiciai-3	1825-1829	159724	24	99901	27	765	34456	2081	3664
Vilkaviskis-127	730-1235	127606	32	77407	1848	276	39013	6367	2654

3. PHYSICAL PROPERTIES OF GEOTHERMAL BRINES

3.1 General

The high mineralization is a significant feature of geothermal water in the West Lithuanian geothermal anomaly (Table 5). Comparison of these data with the composition of geothermal brines from other geothermal fields (Wahl, 1977) shows that higher concentration of dissolved solids has been noted only in the brines of the Salton Sea - more than 200 g/l. On the other hand, domination of Na and K chlorides in the composition of dissolved solids is similar to the majority of geothermal brines exploited in different parts of the world. Such high concentration of dissolved salts, as well as temperature significantly affects physical properties of geothermal water and must be described mathematically. The density, specific heat capacity or enthalpy and viscosity are the main fluid properties used for designing geothermal wells, extraction systems, heat exchangers, transmission lines etc.

3.2 Density

Since geothermal brines are generally 70% or more sodium chloride and the next major constituent, potassium chloride, has similar properties, the density of brines can be estimated by correcting the density of pure water (kg/m^3) by the equation (Wahl, 1977):

$$\rho_b = \rho_w + 7.3S \tag{1}$$

In this equation, 7.3 estimates the "average" influence of dissolved sodium and potassium chlorides, ρ_w represents the density of water and can be calculated (Keenan and Keyes, 1951) by

$$\rho_w = 10^3 \frac{1 + dt^{1/3} + et}{v + at^{1/3} + bt + ct^4} \tag{2}$$

where $v = 3.1975$
$t = 374.11 - T$
$a = -0.315155$
$b = -1.203374 \times 10^{-3}$
$c = 7.48908 \times 10^{-13}$
$d = 0.1342489$
$e = -3.946263 \times 10^{-3}$

These equations are valid for the temperature range (T) 0-200°C and salt concentration (S) 0-30% (weight). Correlation between density and brine salinity at variable temperatures have been derived by the M.W. Kellogg Company. After transformation of that equation to SI units, its form is:

$$\rho_b = a + bT + cS + dST + eT^2 + fS^2 + gS^2T + hST^2 + kS^2T^2 \tag{3}$$

where T is the temperature in °C, (0-200), S is the total salinity in weight fractions (0-0.25). Another polynom has been suggested by the University of California for the temperature range 0-150°C and total salinity S = 0-26% (weight):

$$\rho_b = a + bT + cS + dST + eT^2 + hST^2 \tag{4}$$

The value of the coefficients in Equations 3 is

$a = 1002.287$
$b = -0.183022$
$c = 704.0117$
$d = -0.3295468$
$e = -2.539846 \times 10^{-3}$
$f = 272.0968$
$g = 0.567135$
$h = 1.77677 \times 10^{-4}$
$k = 4.789531 \times 10^{-3}$

and in Equation 4

a = 1001.56 b = -0.2117846 c = 775.1613
d = -0.8220361 e = -2.391614 x 10^{-3} h = 2.048986 x 10^{-4}

Comparison of density calculations by presented formulas with experimental data received in the WLGA is shown in Table 6.

TABLE 6: Density of geothermal fluids

Experimental data			**Inadequacy of calculations**		
Total salinity (mg/l)	**Chlorides (%)**	**Density (g/l)**	**Formula (1) (%)**	**Formula (3) (%)**	**Formula (4) (%)**
		Devonian aquifer water			
39263	83.7	1025	-0.02	-0.03	0.20
52398	88.1	1037	-0.32	-0.33	-0.06
11290	28.2	1004	0.11	0.15	0.242
12000	39.1	1004	0.16	0.20	0.30
5566	44.6	1004	0.55	-0.25	-0.19
6227	61.3	1004	-0.26	-0.20	-0.14
8523	59.3	1004	-0.10	-0.05	0.03
6058	46.9	1002	-0.07	-0.02	0.05
14726	69.6	1000	-0.76	0.79	0.91
38741	83.0	1026	-0.16	-0.16	0.07
		Cambrian aquifer water			
125406	88.8	1087	-0.55	-0.49	-0.10
145304	84.0	1101	-0.71	-0.60	-0.22
127084	84.1	1093	-1.03	-0.97	-0.58
103661	89.8	1078	-1.02	-1.00	-0.62
148027	83.4	1106	-1.04	-0.92	-0.54
120100	87.8	1082	-0.38	-0.34	0.05
118100	87.6	1081	-0.41	-0.36	0.03
113599	89.6	1079	-0.49	-0.46	-0.07
116288	86.4	1086	-1.01	-0.98	-0.60
113300	87.7	1080	-0.61	-0.58	-0.19
159724	84.1	1113	-1.02	-0.87	-0.50
127606	91.2	1109	-2.50	-2.48	-2.10

This is quite important because the formulas approximate results of the investigation of certain brines which could be different from Lithuanian. An inadequacy of calculated values from experimental data has been estimated by the formula:

$$d\rho = \frac{\rho_b - \rho_{be}}{\rho_{be}} 100 \qquad (5)$$

Density of geothermal fluids measured experimentally is noted as ρ_{be}. Experimental data and results of calculations are presented in Table 6. Obviously, the closest figures to measurement values are given by Equation 4. Except for one point which may possibly be mistaken, difference is less than 1%. Therefore, Equation 4 is going to be used in the following calculations.

3.3 Specific heat capacity

Experimental data on heat capacity of sodium and potassium chloride solutions show that they have similar effects (Likke and Bromley, 1973). Therefore, the influence of these salts on heat capacity is in many studies related to salinity (total mineralization). The formula to calculate heat capacity of sodium chloride brines in kJ/(kg°C) has been derived for the temperature range 60-200°C (Wahl, 1977):

$$c_b = c_w\left(1-\frac{S}{100}\right)+0.002S-\left[0.0062+0.0016\left(\frac{T-50}{100}\right)^3\right]\times S\left(1-0.21S^{0.4}\right) \tag{6}$$

where S is total salinity in % and T temperature in °C.

The study performed by M.W. Kellogg Company formed an equation to calculate heat capacity (kJ/kg°C) in the temperature range 20-200°C, for the salt concentrations 0-0.25 (mass fractions). The equation is a polynom of the same form as Equation 3 where the coefficients after transformation to SI units are

$a = 4.196168$ $\quad b = -6.869244 \times 10^{-4}$ $\quad c = -5.939293$
$d = 2.517106 \times 10^{-2}$ $\quad e = 8.830384 \times 10^{-6}$ $\quad f = 9.108311$
$g = 6.672605 \times 10^{-2}$ $\quad h = 1.206574 \times 10^{-4}$ $\quad k = 4.881956 \times 10^{-4}$

The results of heat capacity calculations performed by both methods are given in Table 7. The experimental data, at 57°C, is from International Critical Tables and at 70°C from references (Likke and Bromley, 1973). The least difference (<1%) and most stable results are given by Equation 3, and therefore it is used in the following calculations.

TABLE 7: Specific heat capacity

Solution		Exp. data	Calculated data (6)		Calculated data (3)	
T (°C)	S (%)	c_b (J/kg K)	c_b (J/kg K)	error (%)	c_b (J/kg K)	error (%)
57	7.0	3852	3751	-2.62	3877	0.64
	13.5	3643	3423	-6.04	3650	0.20
	17.5	3517	3243	-7.79	3540	0.64
70	2.0	4087	4045	-1.03	4090	0.08
	3.0	4025	3978	-1.14	4045	0.51
	5.0	3941	3853	-2.22	3958	0.44
	8.0	3815	3681	-3.52	3838	0.61
	11.0	3710	3522	-5.07	3731	0.55

3.4 Viscosity

The measurements of sea water viscosity have been fulfilled in the temperature range 20-180°C for salinities up to 150 g/kg (Isdale et al., 1972). The experimental measurements were smoothed by fitting to the equation:

$$\log_{10}\left(\frac{\mu_{b20}}{\mu_f}\right) = \left(\frac{T-20}{T+109}\right)\times\left[A(1+a_1S+a_2S^2)+B(1+b_1S+b_2S^2)(T-20)\right] \tag{7}$$

and

$$\mu_{b20} = 1.002+c_1S+c_2S^2$$

where μ_{b20} - viscosity of solution at 20°C (mNs/m^2)
μ_b - viscosity of solution at T°C, (mNs/m^2)
S - salinity in g/kg

The smoothing equation constants are given as:

a_1 = -0.00105 b_1 = 0.006102 c_1 = 0.001550
a_2 = 0.000005 b_2 = -0.000040 c_2 = 0.0000093
A = 1.37220 B = 0.000813

M.W. Kellogg Company has derived a formula to calculate viscosity in the temperature range of 0-200°C, for the salt concentration range of 0-0.25 (mass fraction):

$$\mu_b = a+bS+ct+dtS+eS^2+ft^2+gt^2S+htS^2+kt^2S^2 \tag{8}$$

where $t = \log_{10}(1.8\ T + 32)$, and T the temperature in °C. The values of the coefficients in Equation 8 for calculation of viscosity in SI units (Ns/m^2) are the following:

$a = 9.184221 \times 10^{-3}$ $b = -5.854171 \times 10^{-3}$ $c = -6.804807 \times 10^{-3}$
$d = 6.792396 \times 10^{-3}$ $e = 0.1177557$ $f = 1.279456 \times 10^{-3}$
$g = -1.738456 \times 10^{-3}$ $h = -9.070116 \times 10^{-2}$ $k = 1.748175 \times 10^{-2}$

The influence of salts on the viscosity of geothermal water has been estimated for Na, K, Ca chlorides (Wahl, 1977). A formula to correct the viscosity of "average" geothermal brines from those for pure water viscosities at the same temperatures has been derived:

$$\frac{\mu_b}{\mu_w} = 1+0.021S+0.00027S^2 \tag{9}$$

where μ_w is the viscosity of pure water and S salt concentration in weight %.

A relation between pure water viscosity and temperature can be described mathematically as:

$$\log_{\mu_w} = -2.03+\frac{560}{T+273} \tag{10}$$

where the temperature, T, is in °C. The results of viscosity calculations by all three methods are represented in Table 8. The difference between calculated and measured values (Isdale et al., 1972) is expressed in %.

TABLE 8: Viscosity of salt solutions

Experimental data			Difference between calculated and measured values		
Salinity (g/kg)	**Temperature (°C)**	**Viscosity (mNs/m^2)**	**Formula (7) (%)**	**Formula (8) (%)**	**Formula (9) (%)**
32.33	20.00	1.0663	0.38	-1.90	6.61
	50.00	0.5904	0.45	-0.85	-0.55
	75.00	0.4110	0.43	-1.71	-1.22
	83.78	0.3624	-1.34	-0.58	0.17
63.16	20.00	1.1395	0.17	-3.51	0.54
	75.00	0.4447	0.11	-2.95	-2.51
	82.22	0.4063	-0.05	-3.29	-2.83
107.15	20.00	1.2700	-0.45	-4.77	-0.90
	50.00	0.7153	-0.05	-3.59	-3.70
	82.71	0.4527	-1.00	-4.25	-4.74
148.38	20.00	1.4405	0.17	-6.38	-4.63
	50.00	0.8034	0.05	-4.26	-6.41
	75.00	0.5650	0.32	-5.70	-7.99
	97.44	0.4344	-0.47	-7.87	-8.56

Searched mathematical expressions with minimal error values have been used in the computer programme, presented in this report, as its constituent part and could be corrected if further experimental data from the WLGA are available.

4. TECHNOLOGICAL SPECIFICITY OF GEOTHERMAL ENERGY PRODUCTION

4.1 Geothermal heating systems survey

As geothermal utilization in Lithuania is only in its first stages, it is useful to study other countries' experience. Advanced experience of geothermal fluid utilization at the temperature range of 25-100°C for heating has been gained in France, Iceland, Japan, USA and other countries. The use of medium and low temperature geothermal brines from deep aquifers for district heating is a well established technology in France. Utilization of the Dogger aquifer has been especially successful. There have not been significant failures in this region.

The Dogger aquifer is the most productive aquifer in the Paris basin. The total reservoir thickness is high, in the region of 100 m, but productive thickness may be only 20% of the total, because of variation in rock porosity. Permeabilities in the productive zones are high and consequently, so are the transmissivities; between 10 and 100 Dm. Many wells produce flows of 150 m^3/hr under artesian pressure, but in most cases production pumps are used and flows range from 100 to 300 m^3/hr (Lemale and Pivin, 1986).

It is common to classify geothermal schemes into high temperature, when geothermal fluid has temperatures over 100°C (sometimes 150°C) and low temperature when temperature does not exceed 100°C (or 150°C, correspondingly). As there are two aquifer complexes in Lithuania with different temperature ranges, it is reasonable to classify the geothermal systems as low temperature (when temperature does not exceed 50°C) and medium temperature for temperature range 51-100°C when literature survey is being done. The first group would correspond to Devonian and the second to Cambrian brines of West Lithuanian geothermal anomaly. Literature review of geothermal schemes shows that there is significant technological difference between schemes operating at these temperature intervals as well.

Low temperature geothermal schemes
As an example of utilization of low temperature geothermal heat (analogical to Devonian water in the WLGA) the Beauvais heating scheme, which went into service in 1982, could be mentioned. This system exploits geothermal water at 47°C from the Dogger aquifer. Schematic arrangement of the Beauvais heating scheme is shown in Figure 4. In this scheme the heat pumps, which are driven by gas engines (EG), dominate the heat transfer to one group of low temperature users (LT). A second group of high temperature users (HT) is supplied directly from the heat exchangers and is additionally supplied by the recuperators (R) which recover heat from the gas engines (EG). Three gas engine driven heat pumps are connected in series giving a total thermal power of 5.6 MW (1.2 MW compressor power). The heating network has been modified to make it compatible with the low supply temperature characteristics of the heat pump. This has been done by increasing the network flow above its original design level so that the peak supply temperature can be reduced to 78.5°C. When high external temperature (12.5-18°C) causes low heat demand, the heat pumps are operating at reduced power levels, LT are supplied by the heat pumps entirely and the radiators are supplied by the recuperator. The users are supplied partly by heat pumps,

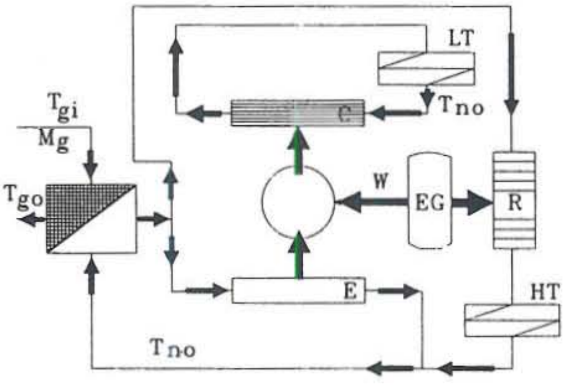

FIGURE 4: Schematic arrangement of the Beauvais district heating scheme

partly by back-up boiler when external temperatures are between 1.6 and 12.5°C. When the highest demand is, the heat pumps are operating at full power as well as a recuperator and a back-up boiler which covers the peak heat demands.

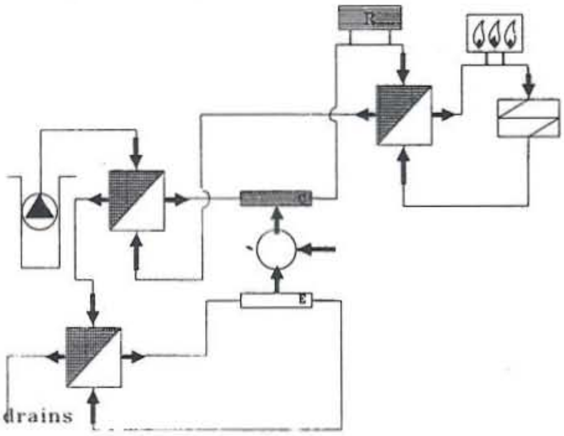

FIGURE 5: Schematic lay-out of the Chateauroux district heating scheme

Chateauroux district heating system, lies in the southern margins of Paris and exploits a single geothermal well which produces 100 m^3 water with temperature of 32°C. Schematic arrangement of Chateauroux district heating scheme is shown in Figure 5. Low temperature heaters are used in the rooms with peak supply and return temperatures of 50 and 40°C respectively. The fluids are not re-injected but are disposed of in surface drains. A gas engine was chosen to drive the 0.5 MW compressor. Both these district heating systems are characterized by high capital costs and this caused the discounted payback time of more than 20 years.

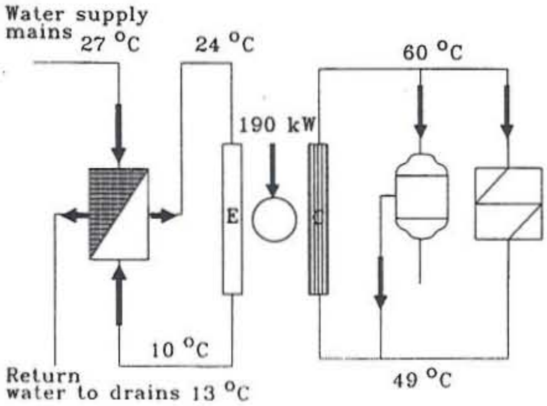

FIGURE 6: Ephrata schools schematic arrangement of the heating scheme

The city of Ephrata (Washington) draws its water supply from a basalt formation at a depth of 550 m with temperature of 27°C. A heat pump is applied to boost the temperature to 60°C. Configuration of heat pump corresponds to "heat pump only" (HPO) and its arrangement is shown in Figure 6. In this case, the payback period is about 15 years, as there were no subsurface costs.

Bruyeres-le-Chatel geothermal district heating system lies to the south of Paris and uses low salinity water at a temperature of 34°C from the Neocomien aquifer at a depth of about 700 m. An 80 kW downhole pump is used to produce 150 m^3/hr of water. Three parallel heat pumps are installed according to HPO configuration. The compressors are driven by a complex arrangement of gas engines, alternators and electric motors. Use of gas engine through the alternator or the electric motor can be chosen depending on seasonal price level. Heat is recuperated at a high temperature from the gas engines. Payback time of this scheme is 12-13 years, which is significantly shorter than for systems with electric engine driven heat pumps.

The following rough conclusions are based on reviews of district heating systems utilizing geothermal water with temperature of 25-50°C:

1. Despite constructional variations in district heating systems, a primary heat exchanger, heat pump, and back-up boiler plant are obligatory parts in most cases.
2. Most of the heat pumps are connected to the district heating systems by HPO configuration. This means, that all usable thermal energy is transformed to higher temperature level before it is supplied to users.
3. As a heat pump uses a great amount of mechanical energy in these systems, the selection

of gas or internal combustion engines with waste heat recovery has an advantage.

4. Low temperature heat users are desirable in these district heating systems.
5. High investment costs and exploitation expenditures cause a payback period of 12-20 years.

Medium temperature geothermal schemes

There are many geothermal district heating systems, operating on geothermal brine in the temperature range 60-80°C, (analogical to Cambrian water in the WLGA). Some examples of this kind of systems have been listed in Table 9. Hungary, Japan, Romania and other countries have much experience in exploitation of geothermal district heating systems as well. All these systems, as a rule, have a primary heat exchanger to transfer thermal energy from geothermal brines to the secondary fluid (intermediate fluid or DHS water). If a heat pump is used, usually it has the configuration "heat pump assisted", meaning only part of the thermal energy is transferred to higher temperature (on the supplying or returning line). Multistage heat users, at different temperature levels, are included to reduce the temperature of returning water. A peak boiler plant is incorporated into a system if heat production from a geothermal reservoir does not cover the heat demand.

TABLE 9: Medium temperature geothermal district heating systems

Geothermal heating system		Well depth	Temperature	Flow rate
Country	Location	(m)	(°C)	(m^3/hr)
England	Southampton	1796	76	72
France	Fontainebleu	1725	72	180
	Orly Gaziers	1750	67	200
	Meaux-Beauval	1900	77	600
Iceland	Seltjarnarnes	856-2200	70-116	180-300
USA	Monroe	457	76	136
	Boise City	600	76	900

Seltjarnarnes district heating system (Iceland) utilizes saline geothermal water at a temperature range of 70-116°C. Concentration of dissolved solids, mainly chlorides, is about 1/3 of sea water level and has tendency to increase. Unlike the other systems, heat exchangers in this district heating system have been installed in houses (Figure 7). The geothermal water, withdrawn from the wells, is pumped into a degasser tank (volume 4 m^3). The hot water after degassing is mixed with part of the return water to keep a stable 80°C temperature in the distribution network. About 60% of the hot water is supplied by a single pipeline and after heat utilization is released into the sewer. The double pipe system extends to about 40% of the users.

Geothermal water of similar characteristics to Cambrian water (WLGA) is utilized in the Southampton district heating system, England (ECDP). The aquifer is situated at the depth of 1729-1796 m, water temperature at the bottom of the hole is 76°C, salinity 125 g/l (75.9 g/l chlorides), pH is 6, and the gas (ammonia) content 36 mg/l. A single production well is used. The output is 72 m^3/hr and a corresponding drawdown is 300 m. After use, the cooled geothermal water is discharged into a nearby estuary through a main storm water sewer. A turbopump has been used for pumping the brine from the well. Hydraulic power is supplied from a multi-stage charge pump located at the well head. The pump turbine unit is installed at a depth of 652 m. The downhole pump is designed to produce 12 l/s against a head of 500 m (drawdown

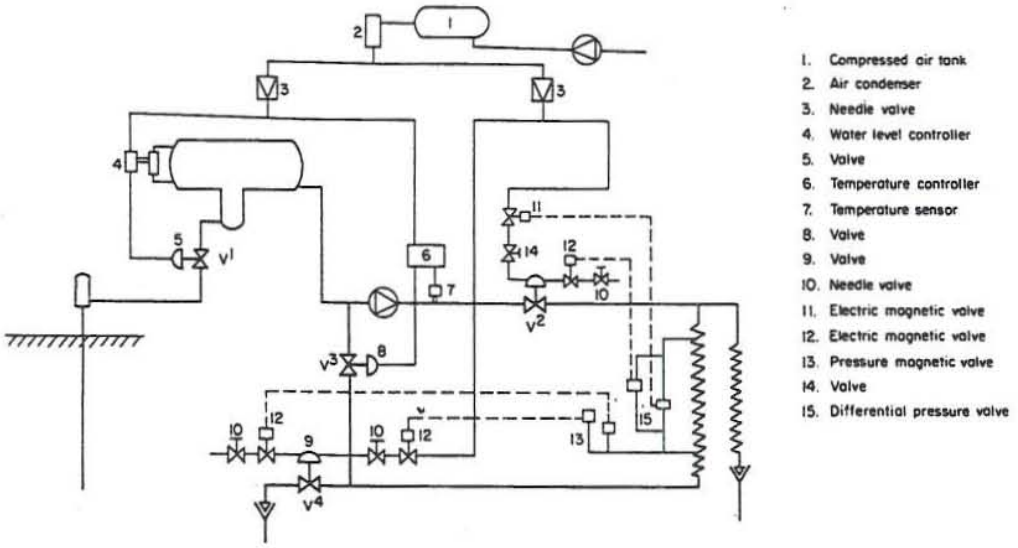

FIGURE 7: Diagram of the Seltjarnarnes district heating system

and static lift). The 250 kW charge pump motor is speed controlled by a variable frequency inverter. The heat station is situated 200 m from the well head. It contains:

- a 2000 kW geothermal heat exchanger;
- a 250 kVA diesel generator with engine and exhaust gas heat recovery (400 kW (H));
- a 2000 kW gas/gasoil fired high efficiency (92%) water tube boiler;
- a water treatment plant for the district heating system;
- generator control and switchgear panels;
- a central control and monitoring system for the heat station.

The heat station is designed to enable future plant extension with installation of a heat pump. In this case, heat capacity will increase from 1400 kW to 2700 kW. Thermal energy produced in the Southampton geothermal power station is about 7% cheaper than the cost of conventional energy (ECDP). Annual savings are 2.7 times more than maintenance costs. A pay back period of 7-8 years is considered if investment costs related to geothermal installations only are included. This period can be improved by using heat pumps.

Analysis of district heating systems, exploiting geothermal brines at 60-80°C, shows the following main features:

1. The sedimentary aquifers are at relatively deep levels, 1000-2500 m in many cases.
2. Because of a low static water level and a large drawdown electrically-driven submersible or hydraulically-driven turbine pumps are usually used.
3. High salinity makes it necessary to use heat exchangers, which are located in the heating station close to a well-head (central) or can be installed at the users buildings (individual) if they are situated near to geothermal wells. Titanium or stainless steel plate heat exchangers or fluidized bed heat exchangers are exploited in most geothermal systems.
4. If brine temperature is too low for user's heating equipment, heat pump assisted systems are installed, which improves the economical characteristics of the district heating system as well.
5. If well output is not enough to cover heat demands, a back-up boiler plant is used during the coldest periods.
6. Heat users at the different temperature level (preferably low) are desirable.
7. Pay-back period of 6-10 years has been estimated in many of these district heating systems.

4.2 Characterization of Lithuanian district heating systems

District heating covers about 55% of the buildings in the country and more than 70% in larger towns of Lithuania. They are supplied both from co-generation power plants and from boiler plants, burning mostly natural gas or heavy oil. However, the consumption of primary energy is around 450 kWh/m^2, which is about twice the consumption in Denmark, for example, the main reason being the poor thermal insulation of buildings. Heat losses in the networks are high also, and users have no possibility to regulate the heating individually in most cases. Heat consumption in residential sector came to 25.5% of total direct consumption in 1985. Transition to the world prices of primary energy sources has caused a difficult energy situation in Lithuania. Energy saving programmes, improvement of district heating systems, utilization of local energy sources are among the means, which should help to solve this problem.

There are 4 main types of sources for heat and hot water supply in Lithuania:

1. Cogeneration power plants.
2. Steam boilers.
3. Water heating boilers.
4. Electrical heaters.

The district heating systems fed from cogeneration power plants and central boiler plants have been designed for supplying water to a distribution network at a temperature of 70-120°C (to 150°C for peak heating in some cases) and return temperature of 30-70°C. Supplied water temperature regime is usually regulated from the central heat source. Return water is partly mixed to supply water before entering space heaters, as the temperature of radiators in resident buildings must not exceed 80-90°C, according to design standards.

Most district heating systems have double pipe distribution network and the same water is used to prepare domestic hot water in the heat exchangers, which are located in separate houses or in central heat stations. To guarantee cold water heating to 55-65°C for domestic use, the supply water temperature has to be 70°C or higher. There are some attempts to introduce three pipe systems and supply hot water for heating separately from the water which is used for preparing domestic hot water. In this case, lower minimal temperature of hot water could be used in the system's network.

4.3 Preconditions for geothermal energy utilization in existing district heating systems

Geothermal district heating system analysis shows that geothermal energy cost is mainly caused by the capital investment cost. Because of recent economical and financial difficulties in Lithuania, it should be more rational to adapt existing systems (or after minimal reconstruction) for utilization of geothermal energy. Of course, a detailed investigation and feasibility study for every specific case should be carried out. The purpose of this report is to touch some aspects of this problem and mention some general considerations.

Information about well productivity in the WLGA is too limited and complex for geothermal and boiler plants to be considered as an energy source for district heating systems, at least, in the first stage of geothermal utilization. The most simple and the least investment demanding way is to heat returning water from the district heating system in the geothermal plant to the possible high temperature and to cover minimal heat demand by geothermal energy. A geothermal plant is here considered a complex equipment (a well, a downhole pump, heat exchangers, heat pumps etc.) aimed to extract geothermal energy and supply it to a network of the district heating systems. A boiler plant could work as an additional and regulating energy source with this complex. To operate this complex with existing district heating systems, water in a geothermal plant has to be heated to at least 70°C, as this temperature level is sufficient for minimal heating and preparing of domestic water. Additional means to keep returning water temperature in the range 30-50°C or less are desirable. They could be: low temperature heat users, heating of feed water in a boiler plant, use of heat pumps, introduction of control systems etc.

Both kinds of geothermal water in the West Lithuanian geothermal anomaly contain high amount of chloride ion, which is a strong promoter of localized corrosion of carbon and stainless steel. It influences threshold temperature of pitting. High concentration of chloride (above 100 g/l) at the temperature about 100°C destroys steel passivation. Investigation of geothermal brine corrosion activity shows that concentration of chloride just above 100 ppm is able to produce localized corrosion of 304 and 316 stainless steel at any temperature range (Efird and Moller, 1978). Pitting is localized corrosion forming cavities in the metal surface. The rate of pit penetration is highly unpredictable. Pitting is particularly serious in heat exchangers because of the thin walls and large area, and because a single pinhole perforation may constitute a failure. These are the reasons to use heat exchangers based on titanium plates in any low temperature geothermal fluid, regardless of dissolved oxygen content.

High mineralization of geothermal fluids in the WLGA is a possible source of scaling in the brine pipelines and equipments, during cooling. A specialized computer programme, WATCH, has been used for calculation of geothermal solution saturation features at different temperatures. As a typical example of Cambrian water, data about composition, taken from the well Aukštupiai-1, has been included into calculations. The following concentrations (mg/kg) were used for the calculation:

CO_2 = 50
NH_3 = 20
Na = 28,828
K = 649
Mg = 3153
Ca = 18,108
Cl = 86,126
SO_4 = 117
Fe = 596
Total dissolved solids = 138,739

Parameter pH = 4.5 at the temperature of 20°C was included and cooling from 90 to 20°C was simulated during the calculations. The main parameter, characterizing possibility of scaling, is a relative logarithmic solubility of minerals in geothermal water. The results, obtained using available data, show that this geothermal solution does not reach saturation state in the examined temperature interval (logarithmic solubility means are negative). The closest state to saturation had been noted for anhydrite and calcite. However, the calculations based on the more comprehensive data about water composition and other characteristics should be used to support this preliminary conclusion.

Generation of thermal energy production, suitable for existing district heating systems, is described in the following chapters. Two different geothermal energy sources, Devonian and Cambrian water have been assumed. Different schemes of geothermal plant for each of these sources are considered. The assumption is made that supply water temperature must be in the range 70-80°C and return water 30-50°C.

5. ESTIMATION OF GEOTHERMAL ENERGY PRODUCTION EXPENDITURE

5.1 General

The analysis of geothermal district heating systems, based on low enthalpy and highly mineralized water, shows that the main operational expenses are caused by consumption of electricity in the following equipment:

- Deep well pumps, to extract geothermal water from non artesian wells
- Heat pumps, to raise the temperature to be fit for direct utilization in the system

Assessment methods of physical and cost calculations for geothermal energy production can be found in the literature (Harrison et al., 1990, and others). These methods and other available references have been used to estimate the main expenses for geothermal energy generation efficiency in the Lithuanian case. Technology of geothermal energy transformation from aquifer water to energy carrier suitable for existing district heating systems is only considered. Attention has mainly been paid to operational energy consumption, as this is the main base to substantiate technological schemes of geothermal plants. The reference prices of the main components of the geothermal system (well, deep well pump, heat exchanger, heat pump) have been included in this report and can be used for rough estimation of installation cost. The purpose is to prepare methodology for calculations of geothermal energy cost, consideration of the technological systems, analysis of technical parameters and geothermal reservoir characteristics, the comparison with thermal energy produced in convenient ways and so on. Reinjection systems are not considered here, because there is not enough data and technical solution about reinjection efficiency, as well as possible methods of cooled geothermal water disposal in the WLGA. Assessment methods for reinjection expenditure are however available.

5.2 Operational energy consumption and expenditure

Geothermal water extraction

As the wells in the WLGA are non artesian and drawdown is significant (see Chapter 2) deep well pumps must be used to lift geothermal brines to the surface. Consumption of electricity in the pump engine depends on hydraulic power needed to establish a given flow rate over a calculated total pressure difference. A general relationship is

$$w_{wp} = 2.78\ 10^{-7} \Delta P f \tag{11}$$

where
w_{wp} - hydraulic power required in a production well (kW)
ΔP - total pressure change in a production well (Pa)
f - production well flow rate (m^3/hr)

The total pressure change in a production well is the result of separate pressure changes which can be described by the following expression:

$$\Delta P = \Delta P_o - P_o + \Delta P_f + \Delta P_d + \Delta P_i + \Delta P_s \tag{12}$$

where
ΔP_o - surface over pressure (Pa)
P_o - static formation pressure at the production well head (Pa)
ΔP_f - frictional pressure term (Pa)
ΔP_d - dynamic pressure term (Pa)
ΔP_i - production well interference pressure term (Pa)
ΔP_s - skin effect pressure term (Pa)

Generally, in the beginning of geothermal utilization, separate wells can be considered and well interference pressure term eliminated. Skin effect pressure term is neglected as well. The skin effect, which affects the flow at the interface between the well and reservoir, is sometimes considered separately from well losses. However, the last two pressure terms should be determined from pump tests. The surface over pressure included in Equation 12, is an additional pressure drop encountered in a production well due to the flow of fluid through surface pipework and equipment. For the preliminary estimation it can be taken as approximately 1 bar.

Static formation pressure at the well head is measured as the additional pressure required to raise a column of fluid to the surface from its natural level within the well and can be calculated by the formula:

$$P_o = -\rho_b g h_o \tag{13}$$

where h_o is the static water level from the surface (m). It must be based on the experimental investigation and for the consideration of the WLGA can be taken from Table 2. Frictional pressure term is calculated by empirical equation:

$$\Delta P_f = 1.89\ 10^{-5} D_t \left[1 + \left(\frac{D_d}{D_t}\right)^2\right]^{0.5} \frac{\mu_b^{0.21} f^{1.79}}{d_w^{4.79}} \tag{14}$$

where D_t - total vertical depth of the well (m)
D_d - displacement of the well from vertical at total depth (m)
f - geothermal fluid flow rate in the production well (m^3/hr)
d_w - inside diameter of the final section of the well casing (m)

The minimal diameter of casing according to recommendation (Lienau and Lunis, 1991) corresponds to standard diameter of casing pipes and has to guarantee geothermal fluid velocity less than 1.5 m/s at the maximal flow rate.

A dynamic pressure term is caused by the resistance to the flow of fluid through the reservoir. The resulting change in pressure due to this cause can be estimated using a simplified reservoir model. For the pre-feasibility study dynamic pressure term, which is sometimes known as the dynamic pressure change, in the single well can be calculated by the equation:

$$\Delta P_d = 5.03\ 10^{-5} \frac{f_b \mu_b}{K\ h_e} \log_{10}\left(\frac{2.9 \cdot 10^8 K t}{\Theta \mu_b \sigma d^2{}_w}\right) \tag{15}$$

where K - permeability of the reservoir (m^2)
h_e - effective thickness of the reservoir (m)
t - time, associated with the operating life of the well pump (years)
Θ - fractional porosity of the reservoir (m)
σ - compressibility of the reservoir fluid (Pa^{-1})

Some data about permeability of the geothermal reservoirs in the WLGA are given in Table 1. This parameter varies quite significantly but average means can be used for general calculations. An average value of permeability 664 mD (6.55×10^{-13} m^2) of the Devonian aquifer and 244 mD (2.4×10^{-13} m^2) of Cambrian aquifer have been assumed for calculations. Information about effective thickness of the reservoirs is limited. Data of borehole investigations show that in the

Cambrian aquifers it fluctuates from 3.2 to 46.8 m. However, it is normally prudent to assume the lowest values in order to avoid under estimating of the geothermal reservoirs. So, h_e = 4.0 m is estimated for the consideration of Cambrian and h_e = 15.0 m for the Devonian aquifers. It has been assumed in a number of pre-feasibility studies for geothermal projects that the average operating life of downhole production well pumps is between 4 and 5 years, however average values as low as 1 year have been observed in practice. This is the reason to assume t = 1 year. Fractional porosity Θ has been assumed 0.15. Compressibility of the fluid 5×10^{-10} Pa^{-1} is recommended to use as a suitable approximated value for the geothermal water.

Heat pump performance and energy consumption

A vapour compression heat pump is the most common type of heat pump used in geothermal district heating systems. The main parameter characterizing efficiency of a heat pump operated in a geothermal heating system is considered a coefficient of cooling performance. It is defined as the ratio of the heat extracted from the geothermal fluid in the evaporator (q_c) to the work input (w_{hp}):

$$C_c = \frac{q_c}{w_{hp}} \tag{16}$$

It is easy to show that its relation to coefficient of heating performance (C_h) can be expressed as:

$$C_c = C_h - 1 \tag{17}$$

Analysis of real heat pumps, exploited in France (Harrison et al., 1990), shows that the C_c is a strong inverse function of the temperature difference but a relatively weak function of the actual temperature levels of the condenser and evaporator outlets. The experimental data is well represented by

$$C_c = 9.376 - 0.24\Delta + 1.87 \cdot 10^{-3}\Delta^2 \tag{18}$$

where $\Delta = T_{ho} - T_{co}$ is the difference between the outlet temperatures in a hot reservoir (condenser) and cold reservoir (evaporator) in °C. It has been shown that these temperatures are more characterizing than temperature of evaporation and condensation. The heat supplied to the fluid at a higher temperature in a condenser (q_h) can be calculated by an easily derived formula:

$$q_h = q_c\left(1 + \frac{1}{C_c}\right) \tag{19}$$

In this formula, q_c is the heat approximately equal to extracted geothermal energy, when the "heat pump only" system is used. In the case of "heat pump assisted" system, q_c would be equal to part of geothermal energy, obtained in the evaporator. In both cases q_c depends on geothermal reservoir and district heating system configurations and parameters. The mechanical work used in a heat pump compressor is:

$$w_{hp} = q_h - q_c \tag{20}$$

This work can be covered by different means, by an electrical motor, internal combustion engine, gas engine etc. Primary energy transformation efficiency in an engine strongly affects the overall performance of a geothermal plant. Waste heat from a compressor or exhaust gas sometimes is recovered to improve energetic characteristics of geothermal systems exploiting low temperature fluids.

Energy consumption and cost estimation
If a well pump or heat pump are driven by electric engine (the usual way), the cost of consumed electricity can be estimated quite simply in the following manner:

$$U_e = \frac{wtu_e}{\eta_p} \tag{21}$$

where w - energy used during pumping process (kW)
t - period of estimation (hr)
u_e - unit price of electricity (currency/kWh)
η_p - mechanical efficiency of equipment

Mechanical efficiency can be assumed to be between 0.7 and 0.8 for most estimating purposes. The unit price of electricity depends on local market and is changeable due to various circumstances. So, it is more rational to use the thermal energy equivalent (q_e), which corresponds to electricity production, for the energy generation principal analysis. It makes it easier to compare different energy sources and eliminates prices as well. Thermal energy equivalent, depends on the method used for electricity generation and its characteristics. Typical total efficiency (η_e) of a fuel burned power plant is approximately equal to 0.37. Then the thermal energy equivalent can be calculated in the following way:

$$q_e = \frac{w}{\eta_p \eta_e} \tag{22}$$

If an internal combustion engine is used for heat pump operation, its fractional efficiency can be assumed $\eta_p = 0.32$ roughly. There is a possibility of the heat recovering and increasing efficiency in the last case.

Thermal energy equivalent can be converted into currency using the following equation:

$$U_t = \frac{q_e u_f t}{1000Q} \tag{23}$$

where u_f - price of fuel unit (currency/t)
Q - fuel calorific value (kJ/kg)

The cost of equipment maintenance depends on many factors and is difficult to estimate. These expenditures are insignificant in the normal exploitation of geothermal plants. However, operating life of downhole production well pumps as low as 9 months has been observed in practice (Harrison et al., 1990). A replacement of well pumps results in high operation costs. The studies on French geothermal schemes show that the cost of maintaining well pumps is about 21% of the capital cost in a year. Maintenance expense of other equipment can be estimated in a similar way.

5.3 Installation cost

Well prices
The well price and its characteristics strongly affects the economical feasibility of the system. Some data about well prices is presented in Figure 8. Relatively high prices of French low-enthalpy geothermal wells are caused by complicated well profiles, casing programmes, mud

composition, drilling time etc. Comparison of well costs indicates that it is very difficult to provide a definitive variation relating well costs to a single parameter such as depth. However, preliminary estimates of well costs are required for pre-feasibility study assessment. It has been suggested (Piatti et al., 1992), to use approximated specific well cost given in Table 10, which is an increasing function of well depth. The assumption that a reinjection well has the same specific cost (ECU/m) as the production well is often used when a geothermal brine is highly saline and requires a reinjection well. In a rough evaluation the cost of the two wells may be calculated as double the cost of the production well.

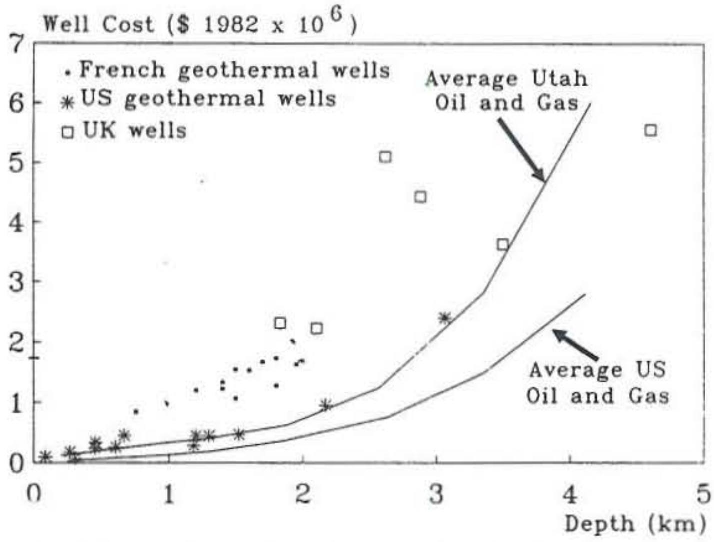

FIGURE 8: Data of well costs (Mortimer, 1984)

There are several computer programmes aimed for well cost estimating. For instance, GEOWELL programme developed by the Los Alamos Scientific Laboratory, the WELCST programme produced by the Mitre Laboratory etc. Estimating procedure created by the Bureau de Recherches Geologiques et Minieres in France should be suitable for Lithuania, as it is based on experience obtained in sedimentary basins and using double directionally drilled wells. However, well price in Lithuania could be lower due to difference in the economical situation, price level, labour wages, possibility to use oil exploration boreholes etc.

TABLE 10: Well specific cost

Depth (km)	0	0.5	1	1.5	2	2.5	3
Specific well cost (ECU/m)	400	475	550	600	650	690	720

Well pumps

There are three types of production pumps, used in geothermal wells:

1. Shaft-driven vertical turbine pumps.
2. Electrically-driven submersible pump.
3. Hydraulically-driven turbine pumps.

Submersible pumps are more advantageous at setting depths greater than 250 m and for lower temperatures than about 85°C. Technical development of these pumps has been done in recent years and their temperature tolerance level increased to about 120°C (Eliasson et al., 1990). This type of downhole pumps is widespread in deep sedimentary geothermal reservoirs. Well pumps, produced by Byron Jackson (life 3 years), Centrilift (4 yrs), Guinard turbo-pump (7 yrs) have been exploited in French geothermal district heating systems (Lenoir, 1992). According to Icelandic experience, geothermal pump has a life of 4-7 years of continuous use.

Both the capital and operating costs of a well pump can be determined from the hydraulic power

The capital cost of a production well pump is also influenced by the pump setting depth, which can be estimated by means of the following expression

$$D_s = \frac{\Delta P}{9.81\,\rho_b + \left(\dfrac{\Delta P_f}{D_t}\right)} \tag{24}$$

where
D_s - production pump setting depth (m)
ρ_g - density of geothermal brine (kg/m^3)
ΔP_f - frictional pressure term (Pa)
D_t - total vertical depth (m)

Using information provided by submersible well pump manufacturers, the following expression for the total purchasing and installation cost, in 1988 US$, was derived by Harrison et al. (1990):

$$U_{wp} = (495 \pm 9)\,w_{wp} + (110 \pm 30)\,D_s + (17600 \pm 2000) \tag{25}$$

Where w_{wp} is the hydraulic power required in the production well (kW). This expression could be used for rough estimation of geothermal plant cost after transferring currency rate to the desirable units.

Heat exchanger types and cost

The gasketed plate heat exchanger is the most widely used configuration in geothermal systems. Its cost depends upon the plate material, the method of construction and also the size. Capital costs for titanium and stainless steel for preliminary estimation could be taken from Figure 9. The necessary heat exchanger area for a concrete case can be easily found, assuming the overall heat transfer coefficient of a titanium plates between 3 and 4 kW/(°Cm^2) and the geothermal fluid flow has the lower thermal capacity of the two streams with a value of 200 kW/°C. Heat exchangers produced by Alpha Laval, Vicarb and Barriquand have been used in French geothermal systems. Average life is as long as 15-20 years (Lenoir, 1992).

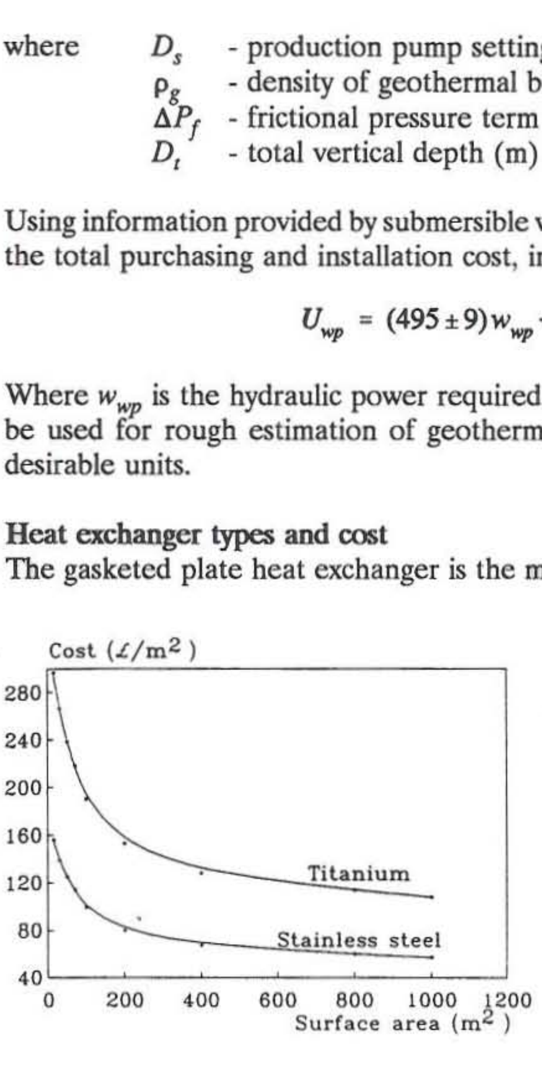

FIGURE 9: Costs of plate heat exchangers (Saunders, 1989)

Two fluidized bed heat exchangers are installed to transfer heat from separated geothermal brine to the cold ground water at the Nesjavellir geothermal power plant (Iceland). Experience of their exploitation allows them to be considered as perspectives for thermal energy transfer from geothermal brines to secondary fluids, where there is possibility of scaling.

Heat pumps

The most common heat pumps in geothermal application are of the vapour compression type. In recent years the possibility of adapting absorption refrigeration cycles have been considered. The lithium bromide/water cycle is mainly used. An absorption heat pump supplying 7 MW in a district heating system in Sweden and in a geothermal heating scheme at Thisted (Denmark) have been installed. However, operational experience in the geothermal systems is limited yet.

Large tonnage lithium bromide chiller installation costs vary linearly between 180-500 thousand US$ when its capacity changes from 200 to 800 tons.

Reference costs for traditional vapour compression heat pumps can be selected from Figure 10.

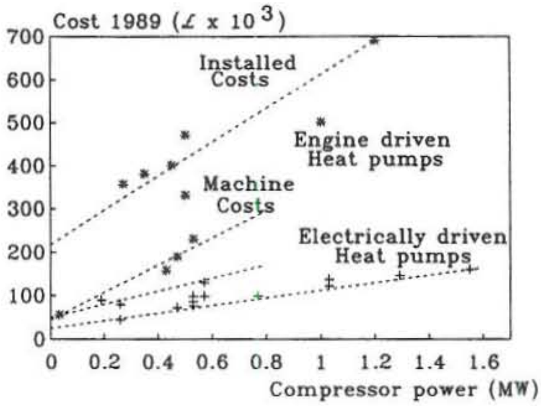

FIGURE 10: Heat pump costs (Harrison, 1990)

Though, heat pumps are being intensively developed, at present, mainly because of ecological problems related with limitation of refrigerant use, and seeking for efficiency improvement. For instance, working fluid ammonia is used in the heat pumps, produced by Sabroe (Denmark) and their coefficient of performance has been significantly increased. Development of efficient heat pumps should increase competitiveness of geothermal district heating systems, operating at low temperature sources.

Many other devices such as an automatic valve at a well-head, safety valves, settlers and filters removing solid particles, a degasser tank and so on, are used, but their installation costs are relatively low and could be estimated as an additional cost to the main equipment.

6. EFFICIENCY OF THERMAL ENERGY PRODUCTION FROM THE WEST LITHUANIAN GEOTHERMAL BRINES

6.1 General

A specific feature of the West Lithuanian geothermal anomaly is the two main distinctly expressed aquifer complexes with different characteristics. For instance, Cambrian aquifers contain geothermal brines with higher temperature (70-95°C), but they are deep and their productivity is usually lower than Devonian aquifers. Devonian aquifers are characterized by a lower temperature range (35-45°C), but they are situated at a relatively shallow depth and the productivity is much higher (see Chapter 2). The purpose of this chapter is to estimate preliminary energy production efficiency for existing district heating systems. A computer programme GENERGEO, which has been prepared as a part of this study, has been used for this purpose. Comparison with ordinary thermal power generation methods is made as well.

Estimation of energetical efficiency of geothermal energy production should be one of the first steps of feasibility studies. The investment cost, economical factors and the others are then considered in the case where positive energy efficiency is confirmed.

6.2 Methodological part

From the general energetical point of view, energy efficiency of geothermal energy generation can be expressed as the ratio of the thermal energy supplied to the district heating system (useful energy), and energy consumed during a production process (fluid withdrawing, raising its temperature to be fit for district heating systems, electrical installation etc.). It is reasonable, in such a case, to use characteristics as an overall coefficient of energy performance of a geothermal plant (C_g). A complex consisting of a geothermal well, pumps, heat exchangers, heat pumps and other equipment ordered to produce hot water as a fit carrier of thermal energy, is considered a geothermal plant. The coefficient of energy performance of geothermal plant determines the ratio between produced (q_{hg}) and lost energy (q_e). A parameter q_e is the thermal energy equivalent corresponding to all kinds of energy consumed during geothermal energy production. Then, in the mathematical form, C_g can be expressed as:

$$C_g = \frac{q_{hg}}{q_e} \tag{26}$$

The energy consumption (q_e) can be estimated for the main users (well pump, heat pump), only at the preliminary stage of investigation. If the main equipment uses electrical energy, it should be estimated as thermal energy equivalent to what was shown in Chapter 5. A q_e value depends on equipment type, its characteristics etc. The method of q_{hg} calculation is connected to a particular scheme of a geothermal heating system.

A conventional thermal power source in the west part of Lithuania is a boiler plant burning heavy oil or natural gas. Energy conversion efficiency of a boiler plant from fuel to hot water, utilized in the district heating system, can be estimated as produced and consumed energy, and written in the following manner:

$$C_b = \frac{q_{hb}}{q_f + q_e} \tag{27}$$

where q_{hb} - thermal energy output from boiler plant to the district heating system
q_f - fuel thermal energy used to produce q_{hb}

q_e - thermal energy equivalent, corresponding to electricity consumption

Actually, C_b is about the same as the net efficiency coefficient of the boiler plant. The coefficient of energy performance for any other energy source, can be estimated in a similar way as well. An advantage of this coefficient is that it allows estimation of energy production efficiency by universal fuel thermal energy equivalent. It eliminates fuel prices and enables comparison of energy generation efficiency in different systems assuming that all electric energy is produced in a fossil fuel power plant. This is important in the situation, when fuel prices are changeable. An absolute value of summarized (gained) thermal energy is important for economical consideration and can be calculated as a difference between produced geothermal energy (q_{hg}) and consumed thermal energy equivalent (q_e):

$$\Delta q = q_{hg} - q_e \tag{28}$$

A notion of conventional fuel is common in Lithuania to estimate thermal energy amount as well. It means fictive fuel with Gross calorific value 29.3 MJ/kg (7000 kcal/kg). It is easy to transform gained thermal energy or any other energy kind to the equivalent amount of conventional or natural fuel, dividing them by calorific fuel value.

The computer programme GENERGEO has been developed as a part of this work and used for preliminary calculations of energy production efficiency in the case of the WLGA. The main programme parts are:

Input data. Input parameters, characterising the geothermal reservoir, geothermal brine, well construction, downhole pump, heat exchangers and heat pumps. Selection of fixed or variable values (depends on calculation goals) is available.
Geothermal brine physical properties. In this part, geothermal fluid density, specific heat capacity and other characteristics, partly described in Chapter 3, are calculated.
Pressure drop in a well. Pressure terms, occurring during pumping of geothermal fluid, are calculated according to methods presented in Chapter 5.
Energy consumption in production well pump.
Heat pump performance. Heat pump characteristics, energy consumption and transformation are calculated (see Chapter 5).
Energy production efficiency. Calculation of C_g values (Equations 26-28).
Print. Printing input data, calculated values, formation data bank etc.

The programme can be extended and corrected by adding new parts, more reliable data, mathematical relations etc. It has applications as a partial tool for the feasibility analysis of geothermal energy utilization projects, if they are developed further.

6.3 Generation of thermal energy for existing district heating systems

Cambrian aquifer thermal energy

Analysis of district heating systems (Chapter 4) shows, that Cambrian water temperature is fit for utilization in district heating systems using primary heat exchangers only. A simplified sketch of the system is represented in Figure 11.

A well pump is used for pumping of geothermal brine to a primary heat exchanger where a secondary fluid - DHS water is heated. The geothermal plant supplies hot water at minimal temperature and the boiler plant is for additional water heating if necessary. The users are connected to the district heating system network between supply and return pipelines. Heat losses at the geothermal plant of approximately 2% have been assumed in the following

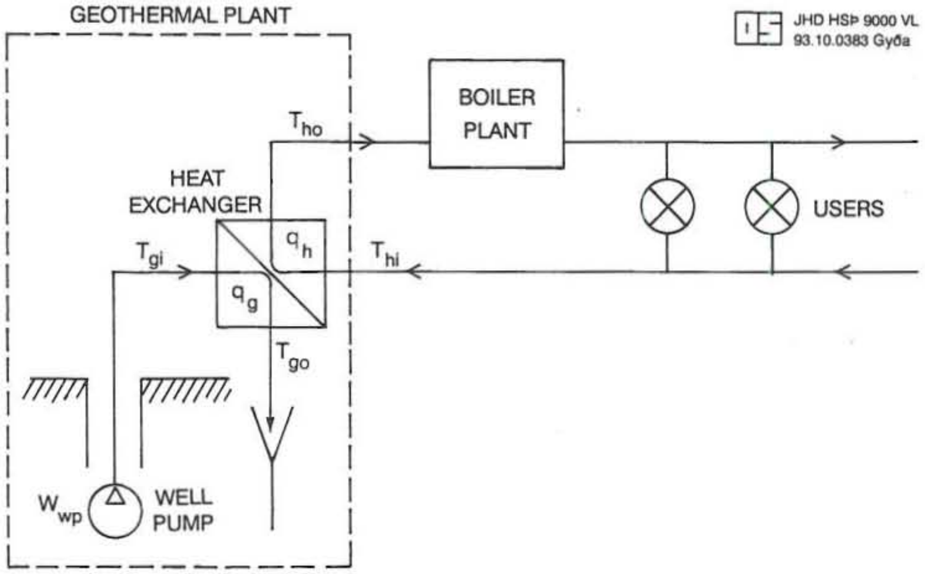

FIGURE 11: Geothermal plant for thermal energy production from Cambrian aquifer brines

calculations. Approach temperature difference in a heat exchanger has been assumed 4°C, according to recommendations (Saunders, 1989). Therefore, in this case, $T_{ho} = T_{gi}$ - 4°C and $T_{go} = Thi$ + 4°C. No limitations for fluid flow through the heat exchanger has been assumed.

Consideration of thermal energy generation at geothermal plant has been divided into three parts:

1. Variation of geothermal reservoir characteristics at fixed "average" geothermal plant technical parameters.
2. Energy production efficiency depending on geothermal fluid flow rate and temperature.
3. Influence of technical parameters at fixed "average" reservoir characteristics.

In all cases, pressure drop in a well (ΔP), produced thermal energy (q_{hg}), consumed thermal energy equivalent (q_e), coefficient of energy performance (C_g) and other parameters have been withdrawn, as the characteristics of the geothermal plant's energy production efficiency.

In the first case, the following fixed parameters were assumed:

- inside diameter of the final casing section d_w = 0.206 m, (8" pipe)
- DHS water return temperature T_{hi} = 40°C
- well pump coefficient of mechanical efficiency $\eta_{wp} = 0.75$
- electricity generation fractional efficiency $\eta_e = .37$
- geothermal brine temperature T_{gi} = 78°C
- flow rate f = 50 m^3/hr

A part of the results are presented in Table 11. The calculated results were obtained keeping all parameters constant, except one, which is verified between the possible natural limits, prognosed in the WLGA. The data shows that reservoir characteristics such as permeability (K) and effective reservoir thickness (h_e) have the most significant influence on the geothermal energy production efficiency. It should be noted that flow rate of 50 m^3/hr is too high for some determined complexes of geothermal characteristics (Table 11) and this is a reason for unnormally big pressure drop in a production well. The "average" fixed reservoir characteristics are being assumed during variation of technical and fluid parameters:

static water level, h_o = 60 m
reservoir's permeability, $K = 2.4 \times 10^{-13}$ m^2
reservoir's effective thickness, h_e = 4 m
fractional porosity of the reservoir, Θ = 0.15
weight fraction of salinity S = 15%
total well depth, D_t = 2000 m

TABLE 11: Influence of Cambrian reservoir characteristics on the energy production efficiency

Reservoir characteristics						**Calculated values**				
D_t (m)	h_o (m)	Kx10^{13} (m^2)	h_e (m)	Θ	S (%)	ΔP (bar)	q_{hg} (kW)	w_{wp} (kW)	q_{hg}-q_e (kW)	C_g
1800	65	2.4	4	0.15	15	151.1	1636	210.1	887.0	2.184
2000						151.2			886.9	
2200						151.2			886.9	
2000	0	2.4	4	0.15	15	144.3	1636	200.5	921.1	2.288
	30					147.5		205.0	904.3	2.239
	90					153.8		213.8	863.8	2.146
2000	65	0.5	4	0.15	15	650.9	1636	904.8	-1590	0.507
		5.4				73.8		102.5	1270	4.476
		9.0				48.3		67.1	1397	6.839
2000	65	2.4	2	0.15	15	294.3	1636	409.0	177.8	1.122
			8			79.6		110.7	1242	4.147
			20			36.7		51.0	1454	9.002
2000	65	2.4	4	0.05	15	157.6	1636	219.0	855.1	2.095
				0.10		153.5		213.4	875.2	2.150
				0.25		148.2		206.0	901.7	2.228
2000	65	2.4	4	0.15	10	134.5	1717	186.9	1051	2.577
					12	140.8	1683	195.7	985	2.412
					20	170.9	1573	237.5	728	1.858

The data presented in Figure 12 shows that geothermal brine temperature is directly connected to C_g, but relative efficiency of geothermal plant decreases when flow rate is growing, because of higher energy consumption in the well pump. The parameter f in Figure 12 means flow rate in m^3/hr. Gained thermal energy (difference between extracted and consumed energy) is affected strongly by geothermal fluid characteristics (Figure 13). It should be noted that almost each curve has maximum value which corresponds to optimal energetical regime. Energy consumption increases rapidly when flow rate is too high for concrete geothermal reservoir characteristics. The gained thermal energy declines and becomes negative when energy consumption overtakes extracted energy amount.

Efficiency of thermal energy generation at a geothermal plant depends on the DHS return water temperature (T_{hi}) very significantly. For instance, at T_{gi} = 78°C, reduction of T_{hi} from 60°C to 30°C causes an increasing in C_g of more than 3 times.

The programme GENERGEO allows complex considerations of the geothermal system to be made. For example, calculations have been performed for fixed "average" Cambrian reservoir characteristics and for two border temperature cases. At the constant flow rate of 50 m^3/hr, in the "optimistic" case (T_{gi} = 95°C, T_{hi} = 30°C), 2322 kW of thermal energy could be gained from one well. In the "pessimistic" case (T_{gi} = 70°C, T_{hi} = 50°C), produced thermal energy would be

57 kW less than energy amount used for water extraction.

Calculations performed using the programme GENERGEO, show that thermal energy extracted from Cambrian aquifers and fit for existing district heating systems is in most cases energetically well-founded. More detailed and exact calculations should be performed for each concrete case. Installation cost, economical feasibility and other considerations should be the next stage of the geothermal development.

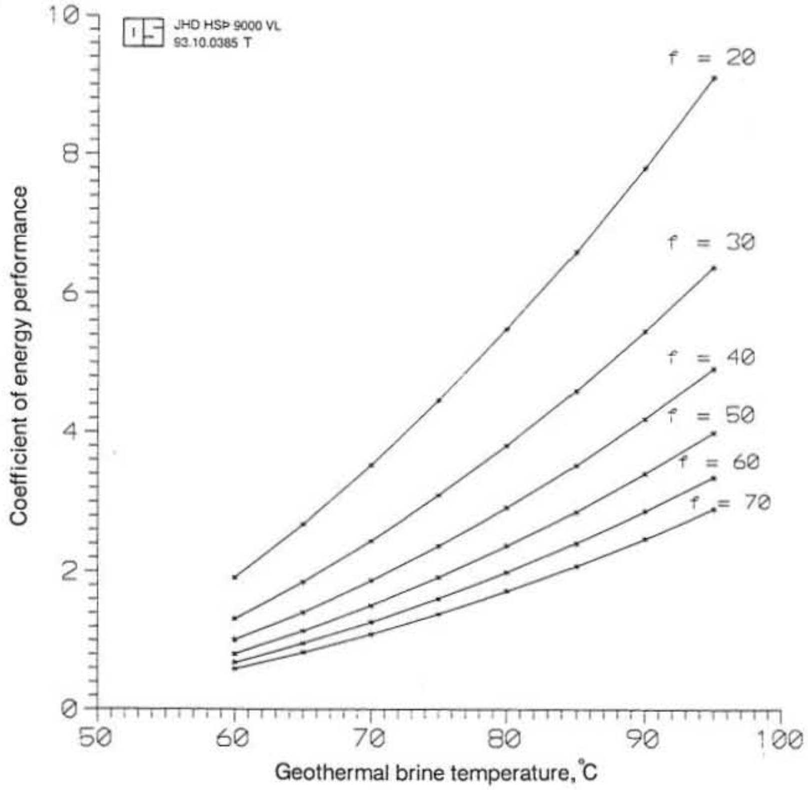

FIGURE 12: Energy production efficiency from Cambrian aquifer

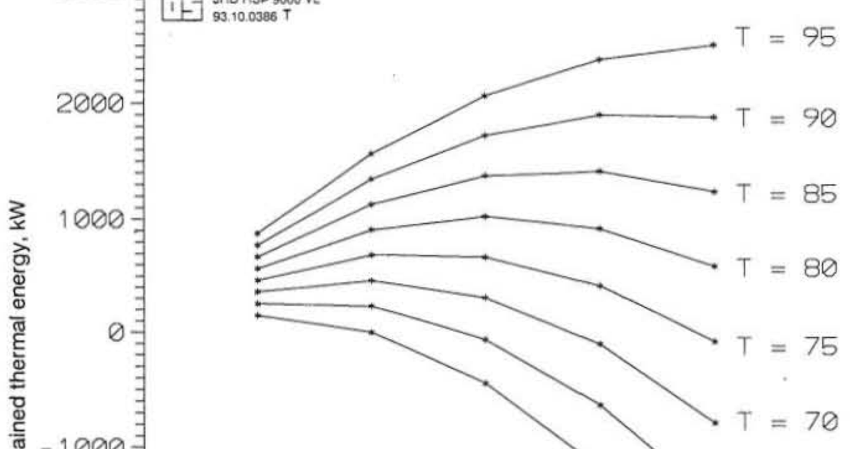

FIGURE 13: Net energy from Cambrian aquifer brine

Devonian aquifer thermal energy

Water temperature in the Devonian aquifers fluctuates from about 30 to 45°C, and the productivity of the wells is about 20-120 m^3/hr, according to well testing data (Table 2). As the return water temperature from the district heating system is about 30-50°C, geothermal water can be utilized for district heating only by using heat pumps. In the case, when return water temperature is lower or about the same as the geothermal water temperature, "heat pump only" system (HPO) is recommended (Piatti et al., 1992). The lay-out of the plant, based on heat pump only, is shown in Figure 14.

The following fixed parameters are assumed in the calculations:

- inside diameter of the final section of casing 0.206 m,
- temperature of the geothermal fluid 38°C,
- flow rate of geothermal fluid 70 m^3/hr,
- well pump mechanical efficiency coefficient, $\eta_{wp} = 0.75$,
- heat pump compressor efficiency coefficient, $\eta_{hp} = 0.8$.

The results are presented in Table 12:

TABLE 12: Influence of Devonian reservoir characteristics on the energy production efficiency

Reservoir characteristics						Calculated parameters					
D_t (m)	h_o (m)	Kx10^{13} (m^2)	h_e (m)	Θ	S (%)	ΔP (bar)	q_{hg} (kW)	q_{ewp} (kW)	q_{ehp} (kW)	Δq (kW)	C_g
800	17	6.5	10	0.17	2	44.5	3567	311.8	4432	-1177	0.752
1000								312.0		-1177	0.752
1200								312.2		-1177	0.752
1000	0	6.5	10	0.17	2	42.8	3567	300.3	4432	-1165	0.754
	10							307.2		-1172	0.753
	30							321.0		-1186	0.750
1000	17	2.6	10	0.17	2	131	3567	924.5	4432	-1789	0.666
		4.0				69.2		485.4		-1350	0.725
		9.0				33.3		233.6		-1098	0.765
1000	17	6.5	2	0.17	2	211	3567	1480	4432	-2345	0.603
			5					604.1		-1469	0.708
			20					165.9		-1031	0.776
1000	17	6.5	10	0.05	2	46.5	3567	326.3	4432	-1191	0.750
				0.10		45.4		318.2		-1183	0.751
				0.30		43.5		305.4		-1170	0.753
1000	17	6.5	10	0.17	0.5	43.7	3643	306.3	4527	-1190	0.754
					4.0	45.8	3471	321.3	4313	-1163	0.749
					6.0	47.4	3382	332.6	4202	-1153	0.746

These data show that reservoir permeability and aquifer effective thickness have the most significant influence on the energy production efficiency. However, thermal energy extraction efficiency from Devonian aquifers are generally much lower than in the Cambrian case. In spite of greater amount of extracted energy, coefficient of energy performance is relatively low, as much energy is consumed in the heat pump (q_{ehp}) to increase fluid temperature to be suitable for district heating systems. Gained thermal energy amount (Δq) is negative and C_g is less than 1 in all considered cases. As the energy consumption in the heat pump is about 10 times higher than in the well pump (q_{ewp}), the technical characteristics of surface equipment should be the main way to improve energy production efficiency from Devonian brines.

The average characteristics of the Devonian reservoirs, recurred in Table 12, were used for calculations with variable geothermal fluid temperature and flow rate. The results of these calculations are presented in Figure 15.

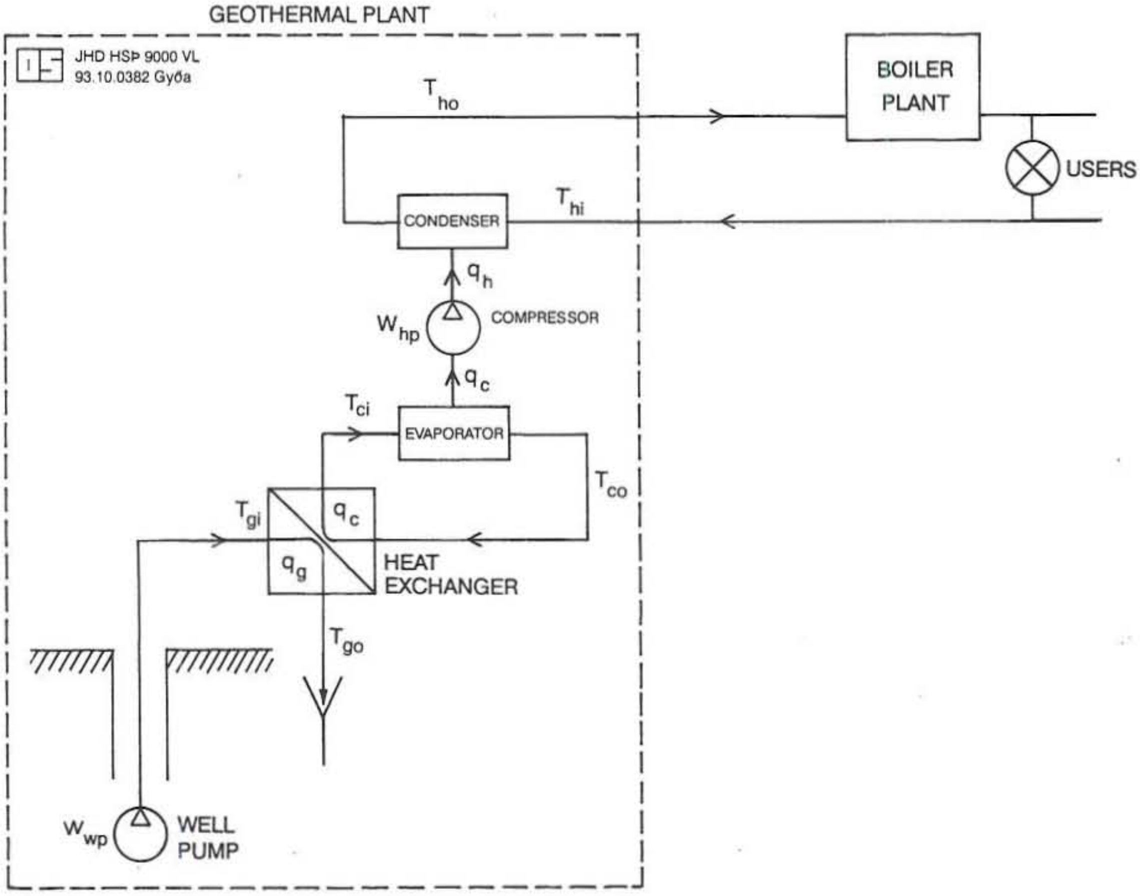

FIGURE 14: Lay-out of geothermal plant for Devonian geothermal energy consideration

In addition to the previous system a heat pump between heat exchanger and the district heating system network is installed. Two main energy consumers (well pump and heat pump electric engines) have to be considered in heat pump only systems. Estimation of electrical energy by the thermal energy equivalent was described in Chapter 5.

Vapour compression heat pumps are usually used in geothermal schemes. In the real heat pump cycles there are physical limits beyond which heat pumps will not operate effectively. These constraints arise because of the thermal properties of the working fluid. For instance, normal condensation temperature is about 70°C for refrigerant R12, but it may vary by 25°C around this level. The high temperature limit at high pressure can be taken to be 85°C. The minimum temperature difference between working fluids and the water outlets must be in the region of 4°C to enable heat transfers to take place. The average condensation temperature 78°C and condenser water outlet 74°C have been assumed in the following calculations. It enables comparison of thermal energy generation from the Cambrian and Devonian aquifers. The minimum evaporator water outlet temperature is set at a level of about 5°C in geothermal applications in order to avoid freezing in the evaporator. In this case T_{go} = 9°C can be assumed. The approach temperature difference in a primary heat exchanger of 4°C has been assumed.

The influence of Devonian geothermal reservoir characteristics on the thermal energy production efficiency has been estimated using the computer programme GENERGEO. These characteristics have been determined between the limits observed in the WLGA or in the analogical geothermal reservoirs.

Obviously, the coefficient of energy performance is less than 1 for a wide range of flow rates, at the temperatures expected to be in the Devonian aquifers. Effects of possible variations in temperature regimes and equipment efficiency have been estimated keeping constant the average values for the geothermal reservoir characteristics.

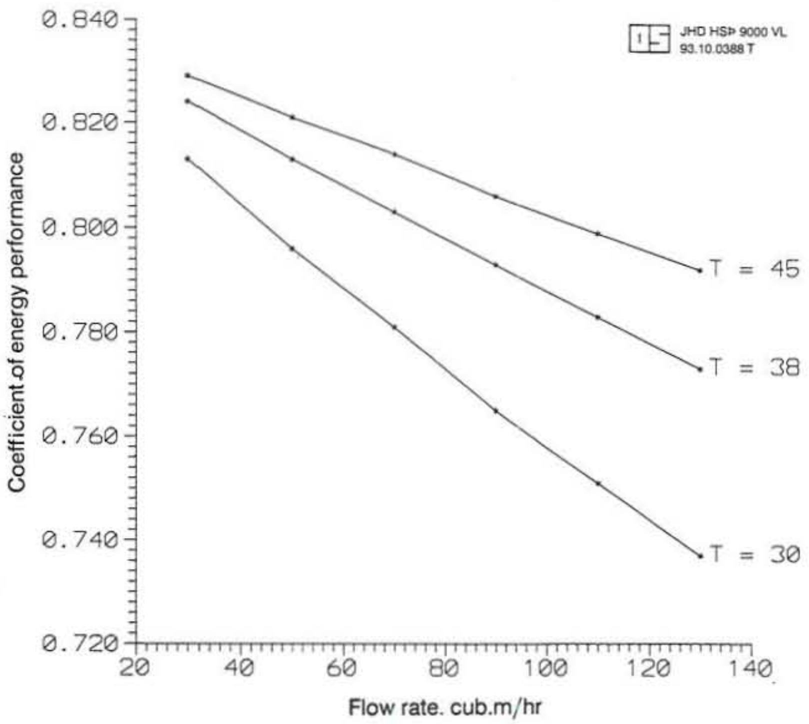

FIGURE 15: Thermal energy production efficiency from Devonian brines

The data given in Table 13 shows that the main consumer of electricity is the heat pump. The last two rows in Table 13 represent the "worst" and "best" cases. The flow rate of 70 m^3/hr has been assumed in these calculations. The results indicate that possibilities of thermal energy production for existing high-temperature district heating systems in Lithuania from the Devonian aquifers at the considered assumptions from the energetic point of view are quite limited. However, use of an internal combustion engine or gas turbine as a heat pump motor, flue gas heat recovery or more advanced geothermal plant configurations could increase energy production efficiency and should be objects of further consideration.

6.4 Discussion and comparison with conventional energy sources

The energy performance coefficient at a conventional boiler plant (C_b), operating on natural gas or heavy oil, is usually found to be between 0.7 and 0.8. Comparison of this parameter to C_g of geothermal plant shows that from an energetic point of view Cambrian water is more desirable for district heating applications in existing district heating systems. The main restriction in this case, is the productivity of the geothermal reservoir. Probably, more extensive subsurface exploration and correct estimation of aquifer discharge possibilities will enable Cambrian waters to be utilized on a significant scale. Technological aspects of salt water behaviour are quite well known and there is many-years experience of saltproof equipment exploitation. This experience has been obtained in some geothermal fields, water desalination plants, geothermal salt producing factories and so on.

The results of preliminary calculations indicate that possibilities for Devonian water utilization in existing district heating systems are quite limited. Coefficient of energy performance is less than 1 in most cases. In spite of its higher output, energy consumption in the heat pump is relatively large. This is the main reason for low energetic efficiency of thermal energy generation from Devonian aquifers.

TABLE 13: Thermal energy production from Devonian aquifers

Parameters					Calculated parameters				
T_{gi} (°C)	T_{co} (°C)	T_{ho} (°C)	η_{wp}	η_{hp}	q_{hg} (kW)	q_{ewp} (kW)	q_{ehp} (kW)	Δq (kW)	C_g
30	10	74	0.75	0.80	1987	359.3	2509	-881.3	0.693
38					2980	312.0	3763	-1095	0.731
45					3848	278.7	4860	-1290	0.749
38	5	74	0.75	0.80	3567	312.0	4432	-1177	0.752
	15				2334		2893	-871.0	0.728
	20				1671		1968	-608.7	0.733
38	10	60	0.75	0.80	2776	312.0	3074	-609.9	0.820
		65			2885		3440	-867.6	0.769
		80			2939		3627	-998.2	0.749
38	10	74	0.70	0.80	2980	334.3	3763	-1117	0.727
			0.78			300.0		-1083	0.733
			0.80			292.5		-1075	0.735
38	10	74	0.75	0.70	2980	312.0	4301	-1632	0.646
				0.75			4014	-1346	0.689
				0.90			3345	-676.8	0.815
30	20	80	0.7	0.7	739.7	384.9	1055	-699.9	0.514
45	5	60	0.8	0.9	4327	261.3	4587	-521.3	0.892

Coefficient of heat performance, used in these calculations, was in the range of 2-4, according to the experience obtained in French geothermal systems. However, more efficient absorption of heat pumps or new construction vapour compressor heat pumps could reach COP between 5-7. Asthe efficiency of heat pump only systems is limitted mainly by heat pump characteristics, other heat pump arrangements and other kinds of engines should be considered. Apart from high energy consumption, geothermal systems with heat pumps are characterized by high capital investment cost. These are the main reasons for long pay-back periods (see Chapter 4). It seems, that more careful investigations and feasibility studies should be made before Devonian water utilization is started.

It should be noted that these considerations are very approximate, based on preliminary geothermal reservoir data only. The scope of this report does not allow estimation of many other factors, like electricity prices, economical and ecological circumstances etc., affecting geothermal energy cost. This is an attempt to jointly consider the factors affecting the future utilization of geothermal water in Lithuania, only.

7. CONCLUSIONS

1. Investigations of the West Lithuanian geothermal anomaly have revealed the existence of two aquifer complexes with different characteristics. The high salinity and a relatively low temperature is a technological challenge for geothermal water utilization.

2. Mathematical equations to approximate salt water physical properties have been selected after analysis of several information sources and its comparison with experimental data. The accuracy of the approximation has been assessed.

3. Literature review of geothermal district heating systems, utilizing low temperature geothermal water was made to draw the main technological schemes, operational experience and other features of thermal energy production for district heating. High investment costs and long payback periods are the main problems at the mentioned systems. Only high energy performance of geothermal plants can cover their installation cost.

4. Scaling problems should not be significant for cooling of typical Cambrian geothermal brines as the main expected minerals do not reach saturation state, according to results of calculations, performed using computer programme WATCH. Corrosion activity of brine indicates that titanium plate heat exchangers should be used for thermal energy transfer from the brine to a secondary fluid.

5. Methods of geothermal reservoir modelling, geothermal brine extraction, and energy parameter transformation have been described. Characteristics of several Lithuanian geothermal fields have been considered and their average values selected. These data were used for the calculations of efficiency of geothermal energy utilization in existing district heating systems of Lithuania.

6. A computer programme, GENERGEO, was made as a part of this study for calculations of geothermal brine physical properties, heat balance, energy consumption in the well and heat pumps during thermal energy production and so on.

7. "Heat exchanger only" system was selected to estimate Cambrian water utilization efficiency. Results of calculations for a range of reservoir characteristics and technical parameters of surface equipment showed, that, on an energetical point of view, utilization of Cambrian water in the existing district heating systems is well-founded in most cases. The main limitation is the well discharge rate, which depends on the geothermal reservoir characteristics.

8. "Heat pump only" system was used for analysis of Devonian water utilization as an analog common in other geothermal heating systems, operating on 30-50°C brines. Calculations, performed using the programme GENERGEO, show that the possibilities of using Devonian water in the traditional district heating systems are quite limited, due to high energy consumption in the heat pumps. Utilization efficiency depends mainly on the technical characteristics of the surface equipments. More efficient heat pumps, mechanical engines with heat recovery, low temperature users etc. could, however, make these systems competitive with conventional thermal energy sources.

ACKNOWLEDGEMENTS

The author wishes to express his thanks and gratitude to the United Nations University, Government of Iceland and Dr. Ingvar Birgir Fridleifsson, director of the Geothermal Training Programme for the opportunity to participate in the geothermal training course.

The author would like to acknowledge efforts of the Orkustofnun staff and other persons in their guidance and useful assistance, thus making successful completion of the Geothermal Training Programme.

Special thanks to Arni Ragnarsson, Einar T. Eliasson and Sverrir Thorhallsson for their advice and useful discussions.

Ludvik S. Georgsson and Margret Westlund are thanked for their kind and useful care during geothermal training in Iceland.

NOMENCLATURE

C_b - Coefficient of energy performance of a boiler plant
C_c - Coefficient of cooling performance
C_g - Coefficient of energy performance of a geothermal plant
C_h - Coefficient of heating performance
c_b - Specific heat capacity of brine [kJ/kg°C]
c_w - Specific heat capacity of pure water [kJ/kg°C]
D_d - Displacement of the well from vertical at total depth [m]
D_s - Well pump setting depth [m]
D_t - Total vertical depth of a well [m]
d_w - Inside diameter of the final section of casing [m]
$d\rho$ - Error of brine density approximation [%]
f - Well flow rate [m^3/hr]
h_o - Static water level from the surface [m]
h_e - Effective thickness of the reservoir [m]
g - Acceleration of gravity [m/s^2]
K - Permeability of the reservoir [m^2]
P_o - Static formation pressure at the production well [Pa]
Q - Fuel calorific value [kJ/kg]
q_c - Thermal energy transferred at the evaporator of a heat pump [kW]
q_e - Thermal energy equivalent, corresponding amount of electric energy [kW]
q_f - Fuel thermal energy consumed in a boiler plant [kW]
q_g - Thermal energy extracted from geothermal brine [kW]
q_h - Thermal energy transferred at the condenser of a heat pump [kW]
q_{hb} - Thermal energy supplied for district heating from a boiler plant [kW]
q_{hg} - Thermal energy supplied for district heating from a geothermal plant [kW]
S - Salinity of geothermal brine [g/l or %]
T - Temperature [°C]
T_{gi} - Geothermal brine inlet temperature to the heat exchanger [°C]
T_{go} - Geothermal brine outlet temperature from the heat exchanger [°C]
T_{ci} - Condenser inlet temperature [°C]
T_{co} - Condenser outlet temperature [°C]
T_{hi} - Temperature of the water returning from district heating system [°C]
T_{ho} - Temperature of the water supplied to district heating system [°C]
t - Time [hr]
U_e - Total cost of electricity [currency]
u_e - Unit price for electricity [currency/kWh]
u_f - Price of fuel unit [currency/t]
w_{wp} - Energy used in a production well pump [kW]
w_{hp} - Energy used in a heat pump [kW]

Greek letters:

Δ - Outlet temperature difference at the condenser and evaporator [°C]
ΔP - Total pressure drop in a production well [Pa]
ΔP_o - Surface over-pressure [Pa]
ΔP_f - Frictional pressure term [Pa]
ΔP_d - Dynamic pressure term [Pa]

ΔP_i - Production well interference pressure term [Pa]

ΔP_s - Skin effect pressure term [Pa]

Δq - Gained thermal energy at a geothermal plant [kW]

η_e - Fractional energy generation efficiency

η_{hp} - Heat pump engine fractional efficiency

η_{wp} - Well pump fractional efficiency

Θ - Fractional porosity of the geothermal reservoir

μ_b - Viscosity of geothermal brine [Ns/m^2]

μ_w - Viscosity of pure water [Ns/m^2]

ρ_b - Geothermal brine density [kg/m^3]

ρ_w - Pure water density [kg/m^3]

σ - Compressibility of the geothermal brine [Pa^{-1}]

REFERENCES

ECDP: Geothermal energy for district heating in Southampton. European Community Demonstration projects for energy saving and alternative energy sources. Projects No. GE/69/81-UK and GE/607/83-UK.

Efird, K.D., and Moller, G.D., 1978: Electrochemical characteristics of 304 & 316 stainless steels in fresh water as functions of chloride concentration and temperature. Corrosion/78, Houston, Transactions, Paper 87.

Eliasson, E.T., Armannsson, H., Fridleifsson, I.B., Gunnarsdottir, O.B., Thorhallsson, S., and Karlsson, T., 1990: Space and district heating. Small Geothermal Resources. A guide to development and utilization. UNITAR/UNDP, Centre on Small Energy Resources, Rome, 101-128.

Harrison, R., Mortimer, N.D., and Smarason O.B., 1990: Geothermal Heating. A handbook of engineering economics. Pergamon Press, Oxford, 558 pp.

Isdale, J.D., Spence, C.M., and Tudhope, J.S., 1972: Physical properties of sea water solutions: Viscosity. Desalination, 10, 319-328.

Keenan, J.H., and Keyes, F.G., 1951: Thermodynamic Properties of Steam. John Wiley & Sons, New York.

Lemale, J., and Pivin, M., 1986: La Filiere Geothermique Premiere Bilan - Evaluation Technico-Economique de la Geothermie Basse, Energie en France. Agence Francaise pour la Maistrise de l'Énergie, Paris.

Lenoir, D., 1992: Geothermal exploitation of the Dogger in the Paris basin. Maintenance, renewal and reliability of the geothermal loop. International Conference on Industrial Uses of Geothermal Energy, Reykjavik, 5 pp.

Lienau, P.J., and Lunis, B.C., (editors), 1991: Geothermal Direct Use Engineering and Design Guidebook. Geo-Heat Centre, Oregon Institute of Technology, Oregon, 445 pp.

Likke, S., and Bromley, L.A., 1973: Heat capacities of aqueous NaCl, KCl, $MgCl_2$, $MgSO_4$, and Na_2SO_4 solutions between 80°C and 200°C. Journal Chem. Eng., 18, 189-195.

Mortimer, N.D., 1984: International comparison of low enthalpy geothermal well costs. Working Paper No. 6.10, Energy Workshop, Sunderland Polytechnic, U.K.

Piatti, A., Piemonte, C., and Szego, E., 1992: Planing of geothermal district heating systems. Kluwer Academic Publishers, Dordrecht, 308 pp.

Saunders, E.A.D., 1989: Heat exchangers, selection, design and construction. Longman Scientific & Technical, U.K.

Wahl, E.F., 1977: Geothermal Energy Utilization. John Wiley & Sons, New York, 302 pp.