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SVARTSENGI FIELD PRODUCTION DATA AND DEPLETION ANALYSIS

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INTRODUCTION

There have been two major high-temperature geothermal field developments in Iceland in the last decade; Krafla in the north-east. and Svartsengi in the south-west. These and other geothermal developments have recently been reported by Palmason et al.[1] The Krafla field will not be discussed here, but details about the field are available in Stefansson[2] and the power plant in Eliasson et al.[3] Several reservoir engineering studies of the Krafla field have been published.[4,5,6]

The Svartsengi field is one of several fields on the Reykjanes Peninsula in south-west Iceland. About 15 km west of Svartsengi. on the tip of the Peninsula, the Reykjanes field is now under development, primarily for seawater chemicals production. The recently drilled Eldvorp field is located in line between these two fields. about 5 km west of Svartsengi. There are also several fields to the east of Svartsengi, at 15-20 km distance.

The Svartsengi. Eldvorp, and Reykjanes fields exist in the same tectonic-volcanic environment, and are surrounded by similar geohydrological conditions, as discussed by Georgsson;[7] see also Gudmundsson et al.[8] and Franzson.[9] Optimum development of these and other fields on the Reykjanes Peninsula, requires an understanding of their depletion behavior with time: that is, how the reservoir pressure falls with production. While recognizing that no two geothermal fields are alike, we also realize that an understanding of the depletion behavior of Svartsengi, for example. may prove useful in the development of other similar and nearby fields.

The main purpose of this paper is to report our depletion analysis of the Svartsengi field using lumped-parameter and water influx modeling: we also report the field's production history.

FIELD DEVELOPMENT

The Svartsengi geothermal field is classified as high-temperature and liquid-dominated. The reservoir temperature is in the range 235-240 °C, and the fluids produced are in composition two-thirds seawater and one-third rainwater. The Svartsengi field has been developed by the Sudurnes Regional Heating Company, which provides district heating service for the communities on the lower Reykjanes Peninsula; also called the Sudurnes Region. The two-phase mixtures produced by the wells are piped to the power plant and used in a heat exchange process to produce hot water. This is done by heating and degassing fresh cold water: some electric power is also generated. The capacity of the power plant is 125 MW_t for district heating and 8 MW_e of electric power. The power plant and field developments are discussed by Thorhallsson,[10] and Gudmundsson.[11]

The location of the eleven geothermal wells drilled in the Svartsengi field are shown in Fig 1. Wells 2, 3 and 10 are 239 m, 402 m, and 424 m deep. Wells 4-6 are 1713 m, 1579 m. and 1734 m deep. Wells 7-9, 11 and 12 are 1438 m. 1603 m, 994 m, 1141 m, and 1488 m deep. All wells in the Svattsengi field have been productive. The chemical composition of the brines produced is spatially and temporally uniform, suggesting good fluid mixing within the reservoir. The temperature profile below 400-600 m depth is also uniform, again indicating good fluid mixing (convection) within the system. Limited interference testing has shown that pressure transients travel rapidly (in minutes) across the field. This indicates the high permeability found throughout the wellfield area. These and other data suggest to us that lumped-parameter modeling is appropriate for the Svartsengi reservoir.

Fluid extraction and reservoir draw-down in Svartsengi have been monitored since the start of production on October 18. 1978; these data are shown in Table 1. The rate of production refers to the time period since the previous rate: for example, between 388 and 419 days of production, the rate was 51 kg/s. The cumulative production can be calculated from the rate and time period (interval). In the original data set, the draw-down was not always measured on the days when the rate of production changed. Therefore, for some of the draw-down values in Table 1, we used interpolation to obtain concurrent rate and draw-down. The draw-down is measured as water level in a monitoring well. Well 5 was used the first two years, well 6 for about half a year, and well 4 ever since. The fluid extraction has been estimated from the output characteristics of production wells, and their time on line. The total rate of produation data are shown in Fig. 2 with time. In the last few years the

Table 1. Svartsengi Geothermal Field production data

Time (day)	Rate (kg/s)	Draw-down (m)	Time (day)	Rate (kg/s)	Draw-down (m)	Time (day)	Rate (kg/s)	Draw-down (m)
0.	8.	8.	1250.00	147.00	33.49	1618.00	347.00	63.02
12.80	48.08	0.98	1251.00	134.00	33.51	1660.00	342.80	68.44
14.80	30.00	0.95	1252.00	115.00	33.53	1669.00	336.00	69.24
15.00	5.00	0.97	1258.00	125.00	33.68	1676.80	274.00	69.65
133.80	30.00	3.59	1260.00	60.00	33.73	1681.00	280.00	69.83
146.00	45.00	3.98	1274.00	110.00	34.08	1688.00	218.00	69.52
154.00	30.00	4.26	1288.00	116.00	34.40	1702.00	222.00	70.11
162.00	58.00	4.62	1292.00	131.00	34.58	1761.80	149.80	68.20
241.80	30.00	7.05	1297.00	161.00	34.92	1762.00	152.80	68.25
317.80	31.00	7.94	1302.00	151.80	35.40	1764.80	214.80	68.33
388.88	30.00	8.68	1305.80	168.00	35.82	1768.00	149.00	68.50
419.00	51.00	10.38	1309.00	188.00	36.36	1769.00	152.00	68.55
424.00	30.80	10.67	1319.00	211.00	37.55	1787.00	206.00	69.37
510.00	57.00	13.30	1339.00	116.00	36.71	1789.00	212.80	69.42
520.00	48.00	13.60	1343.80	140.00	37.01	1790.00	272.00	69.44
534.80	45.00	13.84	1345.00	150.00	37.21	1808.00	360.00	73.44
547.00	45.00	13.76	1348.00	171.00	37.58	1839.80	341.00	77.21
576.00	38.00	13.50	1353.80	186.00	38.11	1862.00	322.80	79.48
580.80	30.00	13.80	1358.80	205.00	38154	1864.80	273.00	79.46
600.00	56.00	14.58	1368.00	226.00	38.64	1869.08	269.00	79.61
641.80	52.00	15.19	1415.00	116.80	38.03	1872.00	249.80	79.86
702.00	48.00	15.72	1435.00	120.00	38.57	1901.00	301.80	82.49
764.00	53.00	17.54	1437.80	164.00	38.71	1932.80	299.00	84.73
771.00	71.00	17.95	1438.80	163.80	38.79	1937.00	245.00	84.96
781.00	50.00	18.54	1442.80	175.80	39.29	1940.00	299.00	85.10
792.00	55.80	19.18	1443.88	183.00	39.43	1947.80	275.00	85.25
804.00	85.00	19.61	1451.80	186.80	40.24	1956.00	281.00	85.63
890.00	90.00	23.07	1452.80	192.00	48.22	2025.00	284.00	88.16
927.00	155.00	23.99	1453.80	209.80	48.19	2075.80	224.00	90.30
945.00	95.00	25.33	1472.80	129.00	40.11	2111.08	219.80	91.03
948.00	65.00	25.85	1473.88	164.00	40.14	2122.88	269.08	91.44
1012.00	95.00	27.61	1487.00	172.00	41.04	2129.80	230.00	91.82
1086.80	138.00	29.44	1491.80	202.80	41.28	2133.00	280.08	92.28
1099.00	115.80	29.76	1504.00	129.80	43.15	2143.80	271.88	92.98
1104.00	50.80	29.88	1517.80	129.80	45.51	2146.80	311.00	93.28
1130.00	115.00	30.52	1521.80	135.80	46.23	2150.00	315.00	93.62
1136.08	121.80	30.72	1523.00	339.00	46.60	2157.88	263.00	94.02
1223.00	115.80	32.62	1524.00	279.00	46.78	2171.80	313.08	41.15
1234.00	137.00	33.09	1571.00	326.80	54.95	2265.80	388.80	98.91
1235.00	131.80	33.11	1590.00	344.00	59.07	2319.08	283.08	183.30
1237.80	138.00	33.16	1595.88	294.00	59.76	2331.80	328.80	183.83
1248.00	161.00	33.44						

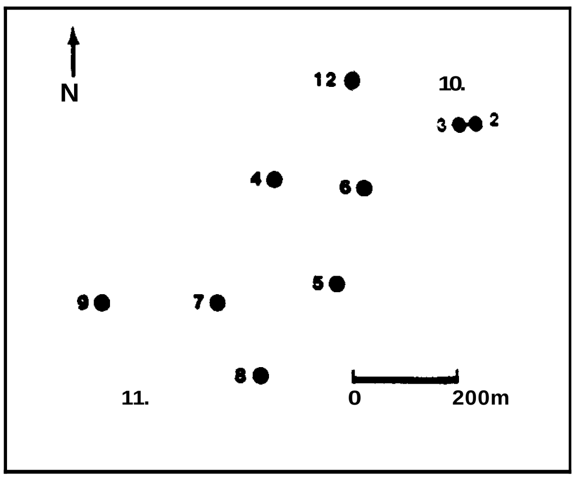

Figure 1. Svartsengi wellfield.

rate of production has been about 300 kg/s of steam-water mixture from the reservoir. The water level draw-down is shown in *Fig.* 3 with time. The last data point is **2331** day after the start **of** production; this was March **7,** 1983. At that **tie** the water level had fallen by about **104** m. which equals ***885*** kPa if the reservoir fluid density **is** taken as 850 kg/m^3.

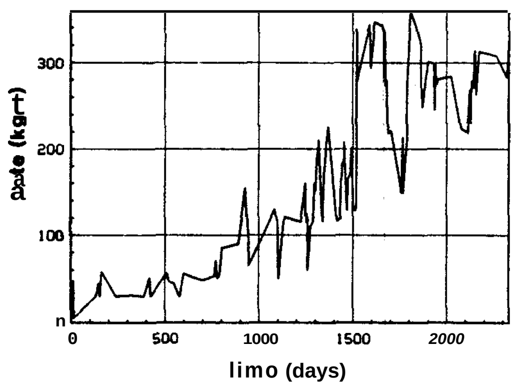

Figure 2. Rate **of** production with time.

From the start ***of*** production, all spent Auids have been disposed of at the surface. The spent geothermal brine is highly supersaturated with silica, which precipitates in a disposal pond by the power plant. The cooled brine percolates into the groundwater system **of** the area.

Because of the rapid draw-down which has occurred in the Svartsengi field, there are plans to inject the spent geothermal brine and steam condensate, in an attempt to support reservoir pressure. Injection tests were carried **out** in **1982**[12] and 1984[13] to study this question by evaluating: (1) the feasibility of long-term pumping and injection of spend fluids with respect to silica deposition and corrosion, (2) fluid connectivity between injection and production wells from a tracer survey, (3) the effect of injection on reservoir draw-down with time, and (4) effect of injected fluid on output of production wells. This work is still in progress.

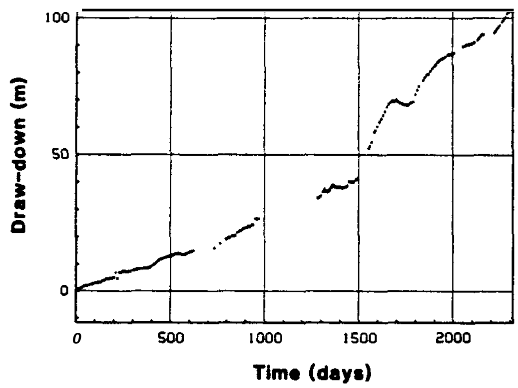

Figure 3. Draw-down with time.

LUMPED-PARAMETER MODELS

An early application of material balance lumped-parameter modeling to geothermal systems is that of Whiting and Ramey,[14] who studied the Wairakei field in Sew Zealand. A later lumped- parameter study is that of Brigham and Neri,[15] who studied a part of the vapor-dominated Larderello system in Italy. A recent discussion of geothermal reservoir modeling is that of Grant[16] The uses of lumped-parameter and water influx models in geothermal reservoir engineering have been reviewed by Olsen,[17] who also derived the expressions in this paper.

In lumped-parameter modeling the reservoir is treated as one element with some average properties. Of primary interest in such modeling is the reservoir production mechanism: is fluid produced due to expansion, or fall in liquid level? Both mechanisms will be considered in this paper.

The initial fluid in place in liquid-dominated reservoirs may be compressed water. In this case, when the reservoir is penetrated by wells and produced, the water expands due to its compressibility. We call this a confined reservoir. For a reservoir of volume V the fluid mass in place is given by

$$W = V\varphi\rho \tag{1}$$

where p is fluid density and φ formation porosity. Differentiating this relationship with respect to time, and using the definition of isothermal compressibility, the following rate equation results

$$(V\varphi\rho c)\frac{dp}{dt} = -w_p \tag{2}$$

where c is liquid compressibility. and w_p represents the rate of fluid production.

The initial fluid in place in liquid-dominated reservoirs may be unconfined water. In geothermal fields which have surface manifestations such as hot springs and fumaroles, good pressure communication between the reservoir and surface formations seems likely. In this case we visualize the fluid production resulting in falling liquid level in the reservoir; like draining a tank.

The volume of a geothermal reservoir with vertical outer boundaries can be expressed as

$$V = Ah \tag{3}$$

where A is the lateral area, and h the vertical height. This volume can be used in an expression giving the liquid mass in place

$$W = Ah\varphi\rho \tag{4}$$

In our lumped-parameter model we assume that the rock porosity φ and fluid density ρ remain constant throughout the production petiod. We further assume that the pressure in the reservoir is hydrostatic and can be expressed by

$$p = \rho g h \tag{5}$$

We use p and h interchangeably for reservoir pressure and water level. Differentiating Eq. 4 with respect to time, and using Eq. 5 and rearranging. we arrive at the following rate equation for unconfined geothermal reservoirs

$$\left(\frac{A\varphi}{g}\right)\frac{dp}{dt} = -w_p \tag{6}$$

The host rocks of geothermal reservoirs are usually volcanic or metamorphic, and have lower primary porosity than most sedimentary rocks. Nevertheless, the permeability of geothermal reservoirs is high in Comparison to most hydrocarbon reservoirs. A likely reason for this is that geothermal reservoirs are characterized by extensive fracturing. Fractures and faults tend to be vertical, so unconfined geothermal reservoirs are likely to drain easily. This means that a steam zone is likely to form when an unconfined liquid-dominated field is produced. Wells completed deep in the reservoir may be liquid-fed while shallow wells, completed in the two-phase steam cap Lone, may receive steam or steam-water mixtures.

PREVIOUS STUDIES

Several exploration and fleld development studies have been carried out in the Svartsengi area, only a few of which will be mentioned here. Franzson[9] described the subsurface geology and hydrothermal alteration in the field. The rocks *are* of basaltic composition, but have formed in two different environments. There are lava flows that erupted during interglacial periods, and there are hyaloclastite formations which erupted during glacial periods. Intrusive rocks are not found above 700 m depth, but below 800 m depth the proportion of intrusions increases to 20-40 % quite sharply. The formation of cap rock is evident between **300-500** m depth, and is attributed to the filling of pore space by alteration minerals and the absence of intrusives. The high permeability within the reservoir is thought to result from near vertical intrusives and fractures. Hydrothermal surface manifestations are evident in an area of about 4 km^2.

Resistivity surveys are commonly used to delineate liquid-dominated geothermal areas, fields. and reservoirs. Georgsson,[7] and more recently Georgsson and Tulinius,[18] reported results of resistivity surveys from the Reykjanes Peninsula, including the Svartsengi field. Rocks penetrated by geothermal brine were found to show 2-5 Ωm resistivity, and the cold brine outside the field showed 6-15 Ωm. Using 5 Ωm as the resistivity delineating the field. Georgsson and Tulinius[18] found the near surface area to be about 10 km^2. Converting the measured resistivity values into approximate subsurface temperatures, taking 200 °C at 600 m depth as the field boundary, they estimated the central part of the reservoir to cover a *6-7* km^2 lateral area. The surveys showed the Svartsengi resistivity anomaly to be linear in an east-west direction. extending toward the Eldvorp field to the west. The width of this linear trend was found to increase with depth. A cross-section of the linear resistivity anomaly is shown in Fig. 4, based on Georgsson.[7]

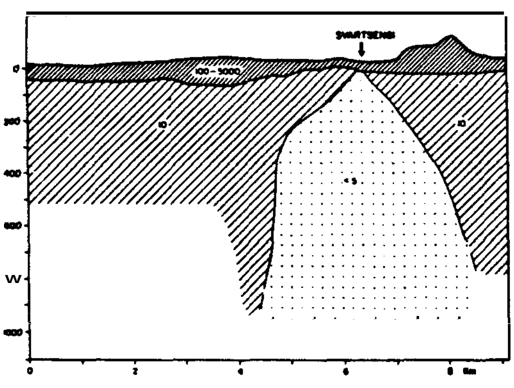

Figure 4. Resistivity cross-section.

Reservoir engineering studies in Svartsengi are discussed by Kjaran et al.[19] Several models have been developed for the Svartsengi geothermal field, some of which are available in reports.[20,21] The main features of these models have recently been discussed by Olsen.[17] Kjaran et al.[20] developed a hydrological model where the reservoir geometry was assumed rectangular, with three closed boundaries and one open boundary at infinite distance. The wellfield was assumed near *the* closed end of the rectangle. They used the boundary value equation for flow in porous medium, and solved it for a well located in a rectangle. Kjaran et al.[20] achieved a good history match when taking 1800-2500 m as the rectangle width. The permeability of the modeled rectangle was in the range 100-150 mD, depending on the thickness assumed. Another model developed by Kjaran and co-workers has been reported by Regalado.[21] This model is based on the unit response function of Barelli and Palama.[22] The empirical unit response function was determined by curve fitting the production data. The two models (hydrological and unit response function) match the production history of the Svartsengi field equally well.

DEPLETION ANALYSIS

In depletion analysis we consider the reservoir draw-down with cumulative mass production, as shown in Fig. *5.* This figure was constructed by integrating the production rate given in Fig. 3, and plotting it with the draw-down in Fig. 4.

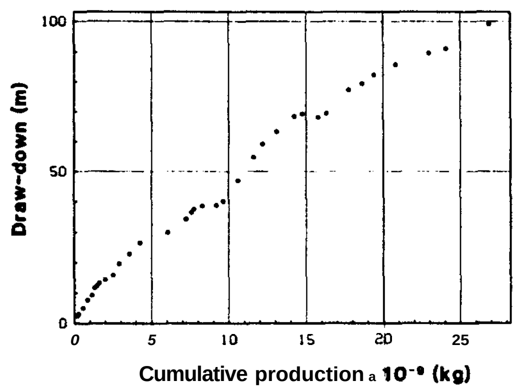

Figure 5. Draw-down with cumulative production.

The simplest possible depletion model is an empirical curve fit to the cumulative production data. We plotted on log-log scales the draw-down Δh (m) in Svartsengi fleld with the cumulative production W_p (kg). as shown in Fig. 6. The best curve through the data is given by the expression

$$\Delta h = 2.23 \cdot 10^{-6} \, W_p^{0.732} \tag{7}$$

The match of this empirical equation to the production data is plotted in Fig. *7,* using linear scales. An examination of this figure shows that the match is poor when the rate of production changes significantly. as evident by comparing it to Figs. 2 and 3. There is clearly a correlation between the production rate and reservoir draw-down. For example, when the rate was decreased from above 300 kg/s to below 200 kg/s between 1600 and 1700 days, the draw-down was not only halted, but reverted for some time. This behavior

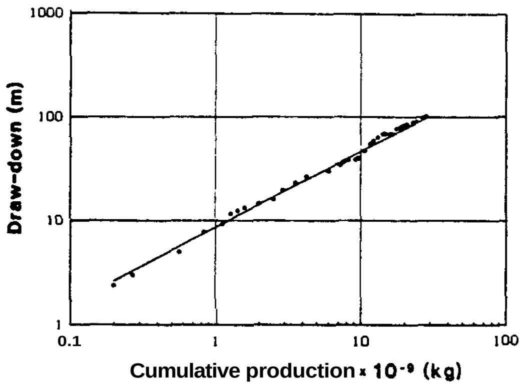

Figure **6.** Empirical log-log curve fit to production data.

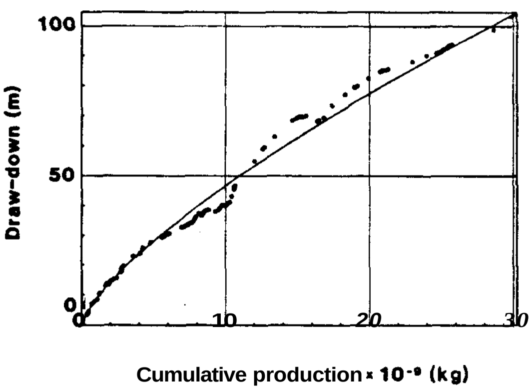

Figure **7.** Empirical match to production data.

demonstrates the effect of water influx on the Svartsengi reservoir.

The depletion behavior of the Svartsengi reservoir will now be analyzed using the confined model given by Eq. 2, without recharge or water influx. Integrating Eq. 2 and using Eq. 5, the draw-down can be expressed as

$$\Delta h = \left(\frac{1}{V\varphi\rho^2 gc}\right) W_p \qquad (8)$$

where all values refer to reservoir conditions. For approximate calculations we observe from Fig. 5, that when 30×10^9 kg of fluid had been produced, the draw-down Δh was about 100 m. Using porosity $\varphi = 0.1$, brine density $\rho = 850\ kg/m^3$, and compressibility $c = 2.35\times10^{-9}\ Pa^{-1}$, we calculate the reservoir volume $V = 180\times10^9\ m^3$. Assuming the lateral area to be about 7 km^2, the reservoir thickness becomes h = **26** km. This value is impossibly large and we conclude that: (1) either the production mechanism is unlikely to be liquid water expansion, or (2) the reservoir and surrounding aquifers act as one volume element. Assuming the reservoir thickness to be 1.5-2.5 km, the surface area becomes 72 to 120 km^2; again, these values seem impossibly large.

For an unconfined reservoir without recharge or water influx, Integrating as before, except now using Eqs. 5 and 8, the draw-down can be expressed by

$$\Delta h = \left(\frac{1}{A\varphi\rho}\right) W_p \qquad (9)$$

using the same data as above, we aalculated the lateral area $A = 3.5\times10^6\ m^2$. This area is of the same order as that indicated by resistivity measurements. If we use a lower porosity value of $\varphi = 0.05$, which is probably more realistic, the calculated lateral area becomes exactly 7 km^2. We conclude that liquid drainage is a likely production mechanism. Graphing Δh vs. W_p should give a straight line if there is no water influx. We see from Fig. 5, that the rate of draw- down decreases with cumulative production: this indicates recharge, so water influx modeling appears appropriale for the Svartsengi reservoir.

WATER INFLUX MODELING

The Svartsengi geothermal reservoir may be thought of as a large volume of hot water-filled rock which is surrounded by warm and cold aquifers. With fluid production and draw-down the aquifers will encroach into the reservoir and cool down the rock. How this happens and at what rate, is likely to depend on the relative sizes of the reservoir and aquifers, their geometry, and the flow resistance across the reservoir-aquifer boundary. Traditional water influx methods used in the petroleum industry may apply to this geothermal situation.

Several options are available in modeling aquifers surrounding geothermal reservoirs. The reservoir-aquifer geometry can be radial, linear, or even spherical; and the outside boundary of the aquifer can be closed, at constant pressure, or at infinite distance. Miller et al.[26] discussed the use of water influx techniques in geothetmal reservoir evaluation. Craft and Hawkins[27] and Dake[28] provide additional details.

We used the Schilthuis,[23] the Fetkovitch,[24] and the Hurst[25] simplified water influx methods to model the Svartsengi reservoir; these methods can be described as steady, pseudo-steady, and unsteady state, respectively.'' We found that the Hurst[25] simpliied method gave the best match. The reservoir-aquifer system was assumed to be linear, and the outer boundary of the aquifer was taken at infinite distance.

The production data reported in this work covers a period of more than six years; from mid-October 1976 to early-March 1983. Using the Hurst[25] simplied model match, we calculated the expected draw-down for an equally long period: until about mid-1989. This prediction is shown in Fig. *8,* taking 100 kg/s, 200 kg/s, and 300 kg/s as the rate of production. For a future production rate of

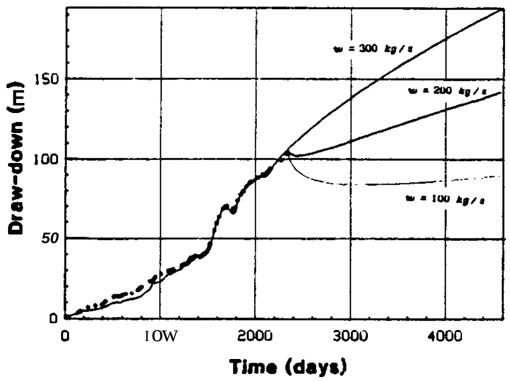

Figure *8*. Hurst simplified water influx method match and prediction.

100 kg/s, the draw-down reverts a little and stays nearly constant for the prediction period. The effect of water influx for a future production rate of 200 kg/s is also evident. We can think of the predictions in Fig. *8* as representing the net mass production from the reservoir. The net production concept may prove useful when evaluating the maximum benefit of injecting spent fluids into the reservoir. Partial or full-scale injection of the spent brine in Svartsengi is now being considered to reduce the **draw-down.**[12,13]

CONCLUSIONS

1. Lumped-parameter models provide the first steps in the evaluation of production data from liquid-dominated geothermal reservoirs. They are simple to use and can indicate whether the main production mechanism is decompression or drainage; confined or unconfined production. Volume drainage seems to be the most likely mechanism in the Svartsengi fleld.

2. Empirical models provide a simple At to depletion data (draw-down with cumulative production) and can be used to predict future field behavior when the rate of production schedule does not vary much with time. They should only be used for short term predictions.

3. Water influx modeling seems to model the depletion behavior or the Svartsengi field accurately. The best match was obtained when using the Hurst simplified method, assuming the reservoir-aquifer system as linear and infinite. Information about reservoir size can be obtained from this model if the physical properties of the reservoir are known.

4. We consider it significant that the depletion analysis does not contradict the geophysical (resistivity) data for the Svartsengi field and surrounding area, nor does it contradict previous modeling work of the reservoir. The areal extent of the hot reservoir seems to be in the range **5** to 10 km^2, the reservoir-aquifer systems appears linear, and the outer boundary of the aquifer must be at great distance.

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REFERENCES

(1) Palmason, G., Stefansson, V., Thorhallsson, S. and Thorsteinsson, Th.: "Geothermal Field Development in Iceland." Proc.. Ninth Workshop Geoth. Reservoir Engineering, Report SGP-TR-74, Stanford University. Stanford, CA (1983).

(2) Stefansson. V.: "The Krafla Geothermal Field, Northeast Iceland," Geothermal,Systems: Principles and Case Histories, L. Rybach and L.J.P. Muffler (eds.), John Wiley & Sons Ltd., Chichester. England (1981), 273-294.

(3) Eliasson, E.T., Gunnarsson, G.I., Sigfusson, S., Maach, R and Matthiasson. M.: "The Krafla Project: Technical Features and Operating Experience," Trans., Geoth. Resources Council (1981) **15-22.**

(4) Stefansson. V. and Steingrimsson, B.: "Production Characterisics of Wells Tapping **Two** Phase Reservoirs at Krafla and Namafjiall." Proc., Sixth Workshop Geoth. Reservoir Engineering, Report SGP-TR-50. 49-59.

(5) Bodvarsson G.S., Benson, S., Sigurdsson, O., I-Ialldorsson. G.K. and Stefansson, V.: "Analysis of Well Data From the Krafla Geothermal Field in Iceland," Proc., Seventh Workshop Geoth. Reservoir Engineering, Report SGP-TR-55, 71-76.

(6) Bodvarsson. G.S.. Pruess, K.. Stefansson, V. and Eliasson, E.T.: "Modeling Studies of the Natural State of the Krafla Geothermal Field, Iceland," Proc., Eighth Workshop Geoth. Reservoir Engineering, Report SGP-TR-60, 211-217.

(7) Georgsson, L.S.: **"A** Resistivity Survey on the Plate Boundaries in the Western Reykjanes Peninsula, Iceland," Trans., Geoth. Resources council, (1981) 75-8.

(8) Gudmundsson, J.S.. Hauksson, T. and Tomasson. J,: 'The Reykjanes Geothermal Field in Iceland: Subsurface Exploration and Well Discharge Characteristics." Proc.. Seventh Workshop Geoth. Reservoir Engineering, Re**port** SGP-TR-55, 61-9.

(9) Franzson. H.: "The Svartsengi High-Temperature Field: Subsurface Geology and Alteration," Trans., Geoth. Resources Council **(1983) 141-5.**

(10) Thorhallsson. S.: "Combined Generation of Heat and Electricity From Geothermal Brine at Svartsengi in S.W. Iceland," Trans., Geoth. Resources Council **(1979) 733-6.**

(11) Gudmundsson. J.S.: "Geothermal Electric Power in Iceland: Development in Perspective," Energy **(1983) 491-513.**

(12) Gudmundsson. J.S.: "Injection Testing in **1982** at the Svartsengi High-Temperature Field in Iceland," Trans., Geoth. Resources Council **(1983) 423-8.**

(13) Gudmundsson. J.S.. Hauksson. T.. Thorhallsson, S., Albertsson, A. and Thorolfsson, G.: "Injection and Tracer Testing in Svartsengi Geothermal Field, Iceland," Proc., **6th** New Zealand Geoth. Workshop, Auckland. New Zealand **(1984) 175-80.**

(14) Whiting, R.L. and Ramey, H.J. Jr.: "Application of Material and Energy Balances to Geothermal Steam Production," J. Pet. Tech. (July, **1989) 893-900.**

(15) Brigham. W.E. and Neri. G.: "A Depletion Model for the Gabbro Zone (Northern Part of Larderello Field)," Proc.. Second DOE-ENEL Workshop Cooperative Research Geothermal Energy, Berkeley, **CA,** Oct. 20-22, 1980, Report **LDL-11555, 434-63.**

(16) Grant, M.A.: "Geothermal Reservoir Modeling." Geothermics **(1983) 251-63.**

(17) Olsen, G.: Depletion Modeling of Liquid-Dominated Geothermal Reservoirs, **MS** Report, Pet. **Eng.** Dept., Stanford U.. Stanford, CA **(1984).**

(18) Georgsson. **L.S.** and Tulinius, H.: "Resistivity Measurements on Outer Reykjanes Penisula **1981** and **1982,** "Report OS-83049/JHD-09, Geothermal Division, National Energy Authority, Reykjavik. Iceland (1983), (in Icelandic).

(19) Kjaran. S.P.. Halldorsson, G.K., Thorhallsson, S. and Eliasson, J.: "Reservoir Engineering Aspects of Svartsengi Geothermal Area." Trans., Geoth. Resources Council **(1979) 337-9.**

(20) Kjaran, S.P., Eliasson, J. and Halldorsson, **G.K.:** "Svartsengi: Reservoir Engineering Study," Report OS80021/ROD10/JHD17, National Energy Authority, Reykjavik, Iceland **(1980).** (in Icelandic).

(21) Regalado, J.R.: "A Study of the Responce to **Ex**ploitation of the Svartsengi Geothermal Field, SW-Iceland," Report 1981-7, UNU Geothermal Training Programme, Reykjavik. Iceland **(1981).**

(22) Barelli, A. and Palama, A.: "On **Some** Computationa Methods **of** Unit Responce Functions From Varying-Rate Data," Geothermics (1980) **261-9.**

(23) Schilthuis, R.J.: "Active Oil and Reservoir Energy," Trans. AIME **118 (1936) 33-52.**

(24) Fetkovitch, M.J.: **"A** Simplified Approach to Water Influx Calculations-Finite Aquifer **Systems,"** J. Pet. Tech. (July **1971) 814-28.**

(25) Hurst. W.: "The Simplification of the Material Balance Formulas by the Laplace Transformation," Trans. AIME **213 (1958) 292-303.**

(26) Miller, F.G.: "Theory of Unsteady-State Influx **of** Water in Linear Reservoirs," **J.** Inst. Pet. **48** (Nov. **1962) 365-79.**

(27) Craft. B.C. and Hawkins, **M.F.:** Applied Petroleum Reservoir Engineering, Prentice Hall. Englewood Cliffs, NJ **(1959).**

(28) **Dake,** L.P.: Fundamentals **of** Reservoir Engineering, Elsevier. Amsterdam **(1978).**