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EVAULATION OF THE MAKUSHIN GEOTHERMAL RESERVOIR, UNALASKA ISLAND

Michael J. Economides(1), Charles W. Morris(2), and Don A. Campbell(3)

1. Unlverslty of Alaska, Fairbanks, AK
Now wlth Douell-Schlumberger, London

2. Republlc Geothermal, Inc., Santa Fe Springs, CA
Now wlth Schlumberger Offshore Servlces, New Orleans, LA

3. Republlc Geothermal, Inc.. Santa Fe Springs, CA

ABSTRACT

Analysis of an extended flow test of well ST-1 on the flanks of Makushln Volcano lndlcates an extenslve. water-domlnated, naturally fractured reservolr. The reservolr appears to be capable of dellverlng extremely large flows when tapped by full-slze productton wells. A productlvlty Index in excess of 30.000 lb/hr/psi lmplles a phenomenal permeablllty-thlckness product, in the range of 500.000 to 1,000.000 md-ft.

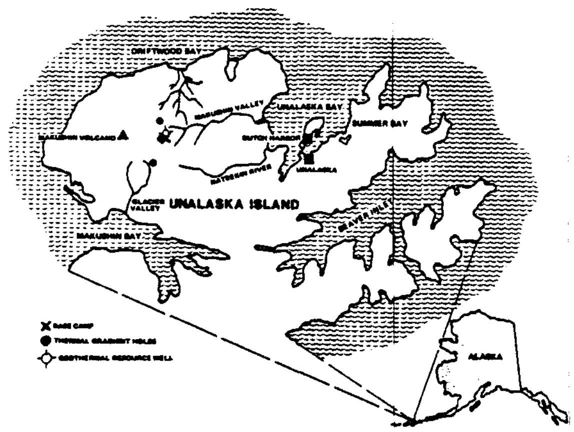
The flowlng bottomhole (1,949-foot) temperature of the fluld is 379°F, whlch is lower than the measured statlc temperature at that depth (395°F). Thls phenomenon, coupled wlth an observed statlc temperature gradlent reversal from the maxlmum 399°F observed at 1,500 feet, lndlcates that the reservolr proper is located some distance from the well. Presumably It is at a temperature sllghtly lower than 379°F and communicates wlth the wellbore via a hlgh conductlvlty fracture system.

A materlal balance calculatlon ylelds an estlmate of reserves that are capable of sustaining all of the present power needs of the Island (13± MW peak) wlth a geothermal power plant for several hundred years. Theoretlcally, a slngle large dlameter well at the slte of ST-1 could sattsfy thls requlrement.

INTRODUCTION

Unalaska Island, located in the central portion of the Aleutlan Chaln has been the slte of a multi-year exploratlon program for'the evaluatlon of its geothermal energy potentlal (Flgure 1). Makushln Volcano, the 6.680-foot hlgh active volcano, situated on the northern end of the Island, has a large number of surface manifesta-tlons, lncludlng several large fumarole flelds.

FIGURE 1
PROJECT LOCATION MAP



Followlng extenslve geological, geo-physical, and geochemical surveys of the Makushln reglon, three ±1,500-foot tempera-ture gradlent holes were sited and drllled in the summer of 1982. The holes and thelr temperature gradlents were descrlbed by Isselhardt, et al (1983a), who also provlded a geothermal resource model of the Makushin geothermal area (Isbelhardt. et al, 1983b).

The heat source of the Makushin geo-thermal system appears to be a burled Igneous Intruston associated wlth the volcano. The temperature and post-glaclal volcanic dlstrlbutlons suggest that the heat source for the system is not directly beneath the summit, but rather is offset to the east. The location of the Makushln productng horlzon. a fracturtd dlorlte, appears to be structurally controlled by a major northeasterly strlklng fracture zone.

In the summer of 1983, a ttratlgraphlc test well (ST-1) was drllled near one of the 1982 temperature gradlent holes (E-1). A steam zone was encountered at 672 feet, followed by a significant fracture at 1,946 feet, where the drillstem dropped free for three feet.

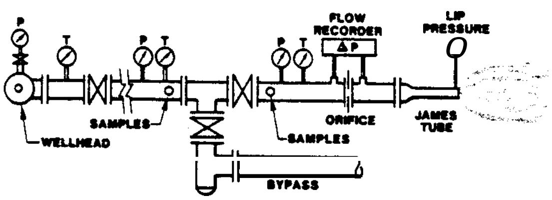
The 1983 well testing described by Campbell and Economides (1983) confirmed a highly prolific reservoir producing 47.000 lb/hr through three-inch pipe with little or no detectable pressure drawdown. Inadequately sensitive Amerada-type pressure instrumentation prevented rigorous analysis. A productivity index of over 3.000 lb/hr/psi and a permeability thickness of over 50.000 md-ft were inferred. A long flow test in the summer of 1984 was intended to provide a better estimate of these reservoir parameters as well as demonstrate sustained flow capability.

TEST FACILITIES AND INSTRUMENTATION

The surface equipment utilized during the 1984 testing was basically the same as that used in 1983 and described in the report by Campbell and Economides (1983). Figure 2 shows the surface equipment arrangements utilized during the long-term test of 1984. A relatively simple two-phase orifice meter and James tube were installed at the end of the flow line to measure the flow rate. Upstream and downstream orifice pressures were recorded simultaneously with a differential pressure flow meter. The James tube lip pressure was monitored continuously during the flow test utilizing both a test quality pressure gauge and a Barton pressure recording meter. In addition, the wellhead pressure and temperature were recorded continuously on Barton meters throughout the flow test. The orifice plate described above was utilized to calculate the enthalpy of the fluid using the empirical equation developed by Russel James (1980).

FIGURE 2

MAKUSHIN WELL TEST EQUIPMENT



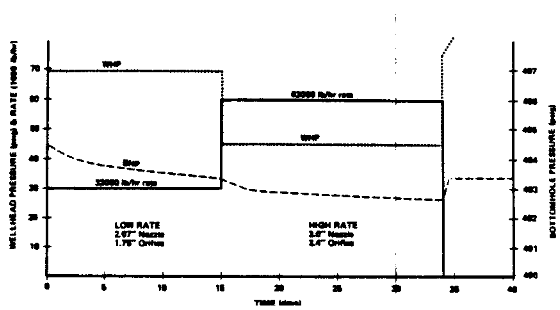
Downhole pressure and temperature measurements were obtained using two separate monitoring systems. The pressure monitoring equipment was a capillary tube system which utilized a gas filled, volumetric chamber downhole connected to a very small diameter capillary tube with a surface recording pressure transducer. This equipment was filled with helium gas as the pressure transmitting medium from the bottomhole to the surface transducer. The equipment utilized in this test has an accuracy of approximately ± 0.3 psi, with a sensitivity of ± 0.1 psi on the transducer. The temperature measurements were obtained using a thermocouple cable system completely separate from the capillary tube. This required that the temperature data and the pressure data be acquired in separate runs in the well. The thermocouple was a chromel-alumel, grounded junction-type with an accuracy of ± 3 degrees F and a sensitivity of $\pm$ 3/4 of a degree F. The thermocouple cable and the capillary tube were contained on two separate spools. As will be seen in the data discussed later, the pressure data and the temperature data were found to be quite reproducible throughout the flow test (unlike the prior years' data with Amerada-type instrumentation).

FLOW TEST MEASUREMENTS

The test of ST-1 consisted of two flow periods of approximately 33.000 lb/hr and 63,000 lb/hr each. The test rate/wellhead pressure/bottomhole pressure history is shown in Figure 3. The first flow period

FIGURE: 3

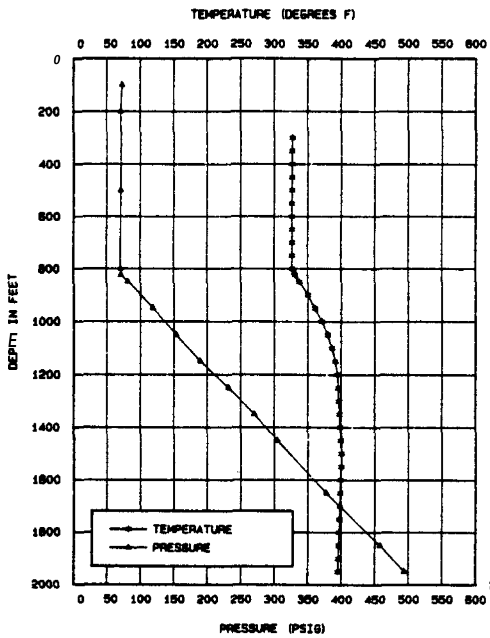
MAKUSHIN ST-1 FLOW TEST
July-August 1984



lasted 15 days, while the second flow period at the higher rate lasted 19 days. During the 34 days of flow from ST-1, there were several minor changes in the flow rate and/or a bypass of the measuring system in order to perform sampling experiments or to modify the flow equipment. However, the test proceeded relatively smoothly, with the two flow rates being maintained at essentially constant conditions throughout their respective test periods.

Prior to the initiation of flow from ST-1, a static temperature profile of the wellbore was obtained on July 3 and a static pressure profile was obtained on July 4, as shown in Figure 4. These surveys clearly indicate that the well has a steam zone, with the vapor-liquid interface located at about 825 feet. This is shown by the constant temperature and pressure conditions existing in the upper part of the wellbore until very near the surface (±200 feet). Below 825 feet there is a liquid zone which increases to a maximum temperature of 399°F at the 1,500-foot depth, then shows a slight decline to a temperature of 395°F at the bottom of the wellbore (1,949 feet).

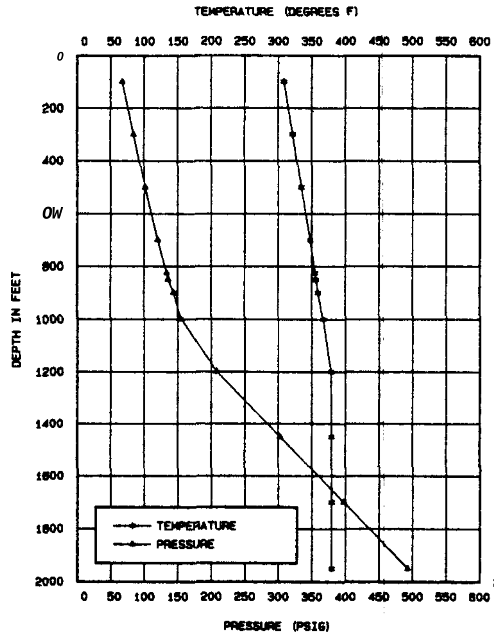
FIGURE 4
STATIC TEMPERATURE (JULY 3, 1984) AND PRESSURE (JULY 4, 1984) IN ST-1



After flow was initiated on July 5. 1984, the well stabilized at a flow rate of about 33,000 lb/hr and this condition was maintained until July 20, 1984. During this flow period the pressure tool was left at the bottom of the well (1,949 feet), continuously recording bottomhole pressure, except for the times when wellbore pressure and temperature profiles were obtained. Flowing pressure and temperature profiles were obtained on July 6. The results are shown in Figure 5. A second set of pressure/ temperature profiles were obtained on July 19. which were exact overlays of the July 6 profiles. About one psi of drawdown was observed over the 15 days at the low rate.

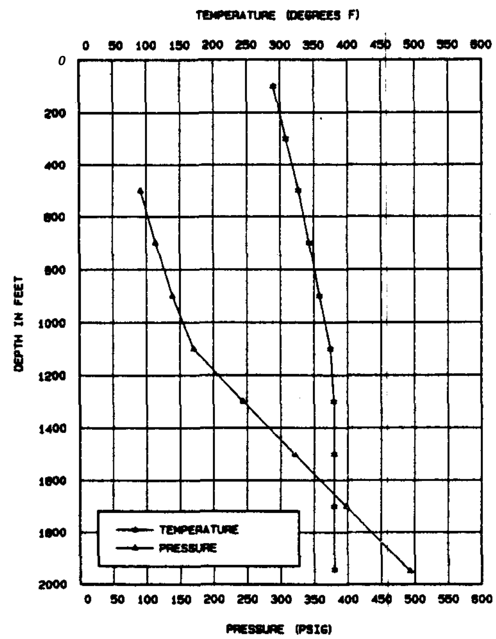
Following the change in the flow to the higher rate of 63.000 lb/hr on July 20-21, another pressure/temperature profile was obtained (Figure 6). On August 7. 1984, a final pressure profile was obtained which was again an exact overlay of the July 21 profile. During the high-rate flow period, the pressure tool was again left at the bottom of the hole continuously recording bottomhole pressure except when profiles were run. An additional one psi of draw-

FIGURE 5
FLOWING TEMPERATURE (JULY 6, 1984) AND PRESSURE (JULY 6, 1984) IN ST-1



down was observed during the 19-day high rate period. The well was shut-in on August 8, 1984, with the pressure tool hanging in the well at bottom, The pressure tool recorded buildup data for the next 17 days, showing less than one psi of increase in bottomhole pressure.

FIGURE 6
FLOWING TEMPERATURE (JULY 20, 1984) AND PRESSURE (JULY 21. 1984) IN ST-1



DISCUSSION AND INTERPRETATION OF RESULTS

Although the resolutlon of the pressure equlpment durlng thls test was far superlor to that used durlng the 1983 test program, lt was agaln found that the drawdown pressure response ln ST-1 was extremely small, perhaps beyond the true sensttlvlty of the lnstrumentatlon. It appears that the pressure drawdown durlng the low-rate flow perlod was on the order of one psl, whlle the pressure drawdown ln ST-1 durlng the hlgh-flow rate was on the order of two psl. Thus, the productlvlty lndex derlved from the two flow perlods equals 31,000-33,000 lb/hr/psl. These values are very large (an order of magnltude more than the ones postulated ln 1983), and lndlcate that the productlvlty of the Makushln reservolr ls extremely hlgh. Preclse calculatlon of the permeablllty-thlckness product ls not posslble wlth these data, although lt ls easy to lnfer that the value ls phenomenally large (l.e., 500,000 to 1,000,000 md-ft).

Produced fluld enters the wellbore at the bottom of the well, 1,946-1,949 feet, at a temperature of 379°F, whlch ls less than the statlc temperature ln the wellbore at that level (395°F). Thls lndlcates that colder water ls enterlng the well from some other area of the reservolr, probably shallower, along an unknown Fracture path. After shut-ln, the wellbore re-equlllbrates to lts statlc condltlon. Thus, the fluld denslty wlthln much of the uellbore column llghtens over a perlod of tlme as lt returns to a hlgher statlc temperature. Because there ls essentlally only one Inflow polnt, however. and pressure bulldup was measured opposlte thls polnt, the re-equlllbratlon of the wellbore fluld denslty should have no effect on the accuracy of the measured reservolr pressure. Therefore, the lack of full pressure recovery (only one psl rather than two) ls not explalned by thermal equlllbratlon, but rather may be attributable to a real decrease ln average reservolr pressure.

Well Potentlal

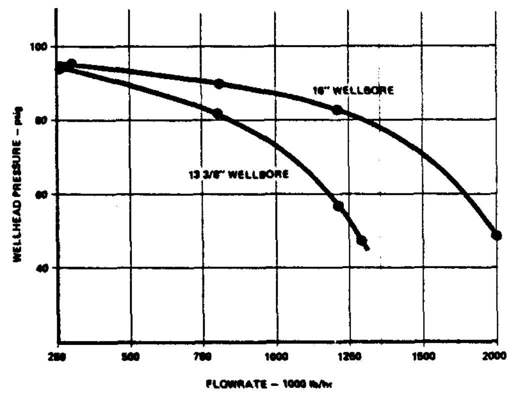
The estlmatlon of lndlvldual well power potentlal for comnerclal operattons requlres the fundamental assumptlon that an extenslve reservolr can be represented by the fluld propertles. Inltlal pressure, temperature, and productlvlty lndex derlved from sllm hole data such as that from ST-1. Glven thls as a basls, a wellbore flow model yleldlng wellhead pressure vs rate must flrst be valldated agalnst the measured sllm hole condltlons. Once a match ls achleved. then wellhead pressure vs rate curves for varlous commerclal-slze wellbore conflguratlons may be generated and related to approprlate power cycles wlth some degree of confldence.

The flow stmulator used for thls study was developed by Intercomp (1982) and has been used extenslvely by the Industry for geothermal and geopressured vellbore flow calculatlons for several years. It ls a vertlcal, multlphase flow slmulator whlch Incorporates treatment for varlable well diameter wlth depth, heat losses, and noncondensable gases. The "nomlnal" comnerclal well condltlons arrlved at were as follows:

Inltlal Pressure	= 494 pstg at 1,949 feet
Inflow Temperature	= 379°F at 1,949 feet
Sallnlty	= 4,000 ppm TDS
CO_2 Content	= 200 ppm
Productlvlty Index	= 31.500 lb/hr/psl
13-3/8 or 16 Inch Wellbore	

Uslng these condltlons, slmulator-generated curves for wellhead pressure vs flow rate were constructed for the two dlfferent "commerclal" wellbore slzes (Flgure 7). At a reasonably optlmum wellhead pressure of 60 psla (for power generatlon from thls resource), a flow rate of 1,250,000 to 2,000.000 lb/hr ls predlcted, dependlng on wellbore slze.

FIGURE: 7
MAKUSHIN
COMMERCIAL SIZE WELL
PREDICTED FLOW RATE vs. WELLHEAD PRESSURE



Reserve Estlmatlon Uslng a Materlal Balance Calculatton

Materlal balance calculatlons for largely Incompresstble systems, such as the one at the Makushln geothermal reservolr. have been developed and used by a number of Investlgators ln the petroleum llterature. The lnltlatlng step ls an expresslon provldlng the lsothermal compresslblllty.

$$c = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T \quad (1)$$

Assumlng that the total compresslbtllty of the system 1s constant, Equatlon 1 may be Integrated:

$$\frac{V_2}{V_1} = e^{c\Delta p} \qquad (2)$$

and because the recovery 1n terns of reservolr volumes 1s deflned as:

$$r = \frac{V_2-V_1}{V_1} \qquad (3)$$

then a comblnatlon of Equatlons 2 and 3 results 1n:

$$\frac{V_2-V_1}{V_1} = e^{c\Delta p} -1$$

The cumulative productlon 1n terms of reservolr volumes 1s, of course, V_2-V_1 and, because the fluld 1s consldered Incompresslble, the ratlo

$$\frac{V_2-V_1}{V_1} \qquad (4)$$

may be taken as:

$$\frac{W_p}{W}$$

whlch 1s the ratlo of the cumulative mass produced to the Inltlal mass-ln-place. Hence, Equatlon 4 becomes:

$$\frac{W_p}{W} = e^{(c\Delta p)} - 1 \qquad (5)$$

Of the varlables 1n Equatlon 5, W_p 1s the one known wlth certainty. In thls case W_p 1s equal to:

W_p = 33.000 x 15 x 24 t 63,000 x 19 x 24 = 4.06 x 10^7 lbs

reflecting the two flow perlods.

The varlables contalned 1n the exponentlal expresslon conslst of the total compresslbllity of the system and the average reservotr pressure drop observed durlng the flow perlod. In thls system, the total compresslbllity 1s the sum of the Indlvldual rock and fluld compresslbllltles.

$$c_t = c_y + c_f \qquad (6)$$

Yater compresslbllity 1s normally taken as 3 x 10^{-6} psi^{-1}, whlle the compressibllty of the rock could reasonably range between 2 x 10-6 psi^{-1} and 6 x 10^{-6} psi^{-1}, dependlng on the llthology and the elasticity of the geologic features. For most reservolrs the value of the compresslbllity 1s taken as equal to 6 x 10-6 psi-1. Thls value will be used here wlth the knowledge that 1t could be somewhat hlgher or lower.

The total observed bottomhole pressure drop at ST-1 durlng the 34 days of the flow test was less than two psl. The subsequent pressure bulldup test resulted 1n less than one psl pressure galn. Both tests Indlcate an extremely large permeability-thickness product whlch 1s consistent ulth the small pressure dtfferences observed, The total average reservolr pressure drap 1s assumed to be roughly one psl.

Uslng Equatlon 5, the Inltlal-fluld-ln-place may then be calculated:

$$\frac{4.06 \times 10^7}{Y} = e^{(6 \times 10^{-6} \times 1)} - 1$$

yleldlng W = 6.8 x 10^{12} lbs. Glven the uncertalntles Inherent 1n thls calculatlon. the value of "W" can be consldered order of maghltude only. Nonetheless. assuming a slngle full-slze productlon well drilled on the site of ST-1 yleldlng 1,500,000 lb/hr (dependlng on the power cycle used 1t could generate 7-12 MWe), the longevlty of thls reservolr Is extremely large relatlve to the needs of Unalaska Island (currently only about 13 MW peak). The calculated initial-mass-in-place could dellver thls flow rate for over 500 years.

CONCLUSIONS

Results from the sllm hohe ST-1 flow test 1n 1984 confirmed the basic Hakushln model of a shallow steam zone overlylng a llquld-domlnated reservolr In fractured dlorlte. A flowlng temperature at 1,949 feet was found to be 379°F. Thls fluld appears to be enterlng the wellbore along a fracture whlch brings 1n colder water than would be expected by the 395°F statlc temperature of the fracture zone. The flow testlng of the well 1n 1984 proved that the reservolr 1s potentlally hlghly productlve, even wlth only three feet of fracture Interval open to the wellbore. Sustalned flow through a three-inch diameter wellbore of 63,000 lb/hr was achleved wlth less than two psl of pressure drawdown from the Inltlal pressure of 494 psi. Thls suggests a very large permeabllity-thickness value for the reservoir. The well productlvlty Index obtalned durlng thls test was approxlmately 30,000 lb/hr/psi. Wellbore flow modellng Indlcates that commerical-size wells should be capable of one to two million lb/hr rates. A materlal balance calculatlon Indlcates a theoretical electrlclty reserve sufflclent for the needs of the Island for several hundred years at current consumptlon rates. In general, the data obtalned durlng the 1984 flow test la conslstent ulth the results obtained durlng the short-term flow test of 1983. and confirms the existence of a substantlal resource.

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