ABSTRACT: The abstract, containing not less than 200 words, should be provided in the space below, and on the reverse side of this page.

Since the successful initial flashing on July 2, 1976, HGP-A has undergone five flash discharge tests with the longest duration of 42 days. Production records including wellhead pressure and temperature, production rate and steam quality were kept for drawdown analysis. After two of the discharge tests, Kuster pressure bomb was lowered to the bottomhole repeatedly to record pressure data for buildup analysis.

Initial analysis of the drawdown and buildup tests indicates the Kapoho Geothermal Reservoir where HGP-A is located seems to be tight in formation with possible severe mud damage in the well. The Reservoir also appears to be a liquid dominated system but with two phase flow during the discharge of HGP-A. Evidence of this claim will be presented in this paper.

The pressure drawdown and buildup analysis were performed with the traditional single phase petroleum reservoir engineering techniques as modified when necessary. Attempts will be made in this paper to indicate the validity of this approach to a two-phase production formation.
ABSTRACT

Since the successful initial flashing on July 2, 1976, HGP-A has undergone five flash discharge tests with the longest one lasting 42 days. Production records including wellhead pressure and temperature, production rate and steam quality were kept for drawdown analysis. After two of the discharge tests, Kuster pressure bombs were lowered to the bottom repeatedly to record pressure data for buildup analysis.

Initial analyses of the drawdown and buildup tests indicate that the Kapoho Geothermal Reservoir, where HGP-A is located, seems to be in a tight formation with possible severe mud damage in the well. The reservoir also appears to be a liquid-dominated system but with two-phase flow during the discharge of HGP-A. Evidence of this claim will be presented in this paper.

The pressure drawdown and buildup analyses were performed with the traditional single-phase petroleum reservoir engineering techniques modified when necessary.

INTRODUCTION

The experimental well, HGP-A, drilled under the auspices of the Hawaii Geothermal Project, is located on the island of Hawaii near the eastern rift of Kilauea volcano. Drilling was completed to a depth of 6450 feet (1966 m) in April 1976. The well is cased to 2230 feet (680 m) below the wellhead, which is approximately 600 feet (183 m) above sea level. A slotted liner is placed from the end of the casing to bottomhole. Cuttings and core samples obtained during drilling indicate that the region is composed of volcanic basalt with a profile that contains open fracture zones separated by relatively impermeable layers.1

The well has undergone five flash discharge tests since an initial flashing on July 2, 1976. Figure 1 is a sketch of the equipment and instrumentation for the discharge tests. As shown, the method involves basically the James technique2 for measuring total mass flow with twin cyclone separators for separation of steam and water. A 90° V-notch weir is used to measure the liquid flow rate, permitting steam quality and specific enthalpy to be calculated. A recovery tube is mounted on the wellhead to permit temperature and pressure profiles to be obtained and water samples to be gathered during quiescent and discharge periods.

Since the temperature of the reservoir in general exceeds 300°C (572°F) with a maximum recorded temperature of 358°C (676°F), no electronic equipment can survive the extreme conditions downhole. Therefore, Kuster Amerada RPG-3 Type subsurface recording temperature and pressure gauges were selected to provide all temperature and pressure measurements downhole.

DOWNHOLE FLOW CHARACTERISTICS

During January and March 1977, the flow tests consisted of a series of discharges in which the flow was throttled by placing orifice plates of various sizes in the discharge line. The results are summarized in Table 1. Pressure and temperature profiles taken during the throttled flow tests are shown in Figures 2 and 3. These profiles indicate that the fluid in the wellbore is at saturation conditions with a mixture of liquid and vapor flowing up to the wellhead. Since the steam quality at the wellhead is high and no steam/water interface is found in the wellbore, the conclusion is that flashing occurs in the formation rather than in the wellbore.

Examination of Figure 2 shows that the pressure profiles are essentially three constant slope lines meeting at the junction of the casing and the slotted liner and at approximately 4300 feet (1311 m). These constant pressure gradient

References and illustrations at end of paper.
lines indicate that the major production zones may be near the bottomhole and in the vicinity of 4300 feet (1311 m).

PRESSURE TRANSIENT TESTS

While data sufficient to assess a producible geothermal field can be obtained only from a number of properly-spaced wells, some limited reservoir information can be obtained from a single geothermal well by utilizing the theory developed for oil and gas fields. These standard petroleum engineering techniques, however, assume single phase flow, while the flow in HGP-A is definitely two-phase, so that caution is required in interpreting the results of these analyses.

PRESSURE DRAWDOWN ANALYSIS

Wellhead pressure vs. time plotted on log-log scales for type-curve matching and on semi-log scales for a pressure drawdown analysis are shown in Figures 4 and 5, respectively. The initial pressure was obtained from Figure 6. These data can be used in a pressure drawdown analysis to obtain information about the geothermal reservoir and the following observations can be made:

1. The analysis is based on a constant production rate during the discharge, and this condition was impossible to achieve. In order to apply the theory, a normalized pressure was obtained by dividing the measured pressure by the concomitant production rate.

2. There was some overpressure at the wellhead prior to the start of the test. Consequently, opening the valve took some effort and about 2 to 3 minutes were needed to open the valve completely. Thus there is an uncertainty of that amount in the determination of zero time.

3. The theory is for bottomhole pressure whereas the data in Figures 4 and 5 are for wellhead pressure. Thus the assumption must be made that wellhead pressure is proportional to downhole pressure and the proportionality factor remains constant throughout the test.

Within these restrictions and assumptions, some information can be obtained. To normalize the pressure with respect to production the pressure relation can be written as:

\[
\frac{P_i - P_{wf}}{q} = \frac{162.6 uB}{kh} \left( \log_{10} t + \frac{k}{\phi u C \cdot r_w^2} \cdot 3.23 + 0.875 \right)
\]  

(1)

The left side of equation (1) is a linear function of \( \log_{10} t \) so that a plot of \( \frac{P_i - P_{wf}}{q} \) vs. \( \log_{10} t \) will yield a straight line with a slope, \( m \), psi/bbl/day/cycle, where

\[
m = \frac{162.6 uB}{kh}
\]  

(2)

and this equation can be used to calculate the permeability-thickness, \( kh \).

Equation (1) can also be used to calculate the skin effect factor, \( s \). Letting \( P_{1hr} \) be the value of \( P_i / \phi u C t r_w^2 \) on the correct semi-log straight line, equation (1) can be rearranged to yield

\[
s = 1.15 \left( \frac{P_i - P_{1hr}}{q} - \log_{10} \frac{k}{\phi u C t r_w^2} + 3.23 \right)
\]  

(3)

By using (3), the pressure drop due to the skin effect can be calculated from

\[
\frac{\Delta P}{q} = 0.87 \left| m \right| \text{s}
\]  

(4)

and the flow efficiency

\[
FE = \frac{P_i - P_{wf} - \Delta P}{P_i - P_{wf}}
\]  

(5)

With the assumptions made previously, a log-log type-curve plot of \( \frac{P_i - P_{wf}}{q} \) vs. \( \log_{10} t \) for the drawdown test is shown in Figure 4. The two unit-slope lines shown verify the existence of wellbore storage effects. From the end of the second straight line, it appears that the semi-log straight line or the radial flow period started at about 10 hours after the test was begun.

Figure 5 is a semi-log graph of \( \frac{P_i - P_{wf}}{q} \) vs. \( \log_{10} t \). An analysis of the plotted data shows that the permeability thickness

\[
kh = 162.6 \text{(psi/bbl)/(0.09 cp)/(1.5 res bbl/std bbl)}
\]

(350 lb/bbl)(1.11 x 10^{-3} psi/lb/hr/cycle)

\[
kh = 1356 \text{ md-ft} \left( 0.408 \text{um}^2 - \text{m} \right)
\]

and if the thickness of the producing layer is assumed to be \( h = 1000 \text{ ft} (305 \text{ m}) \) then the permeability

\[
k = 1.4 \text{ md} \left( 1.38 \times 10^{-3} \text{um}^2 \right)
\]

The skin effect factor

\[
s = 1.15 \left[ \frac{5.23 \times 10^{-3}}{1.11 \times 10^{-3}} - \frac{1.4}{(0.03)(0.09)(8 \times 10^{-6})(8.755)^2} + 3.23 \right]
\]

\[
= -0.86
\]

The small negative skin effect factor suggests that skin damage is not present. Therefore, the flow efficiency of the well is approximately 1, or the well is discharging as much as it is able to produce.
Figure 7 shows the total mass flow rate vs. time in the drawdown test. Note that the flow rate did not change significantly after the initial five or six hours of flow. However, if we neglect the fact that the flow is not constant and plot the wellhead pressure vs. time as in Figure 8 we would have obtained a slope

$$|m| = 11 \text{ psi/cycle (76 kPa/cycle)}$$

Assuming $$q = 86.00 \text{ Klb/hr (10.8 kg/s)}$$, one would have obtained:

$$kh = \frac{162.6(86,000 \text{ lb/hr})(24 \text{ hr/day})}{(350 \text{ lb/bbl})(0.09 \text{ cp}) (1.5 \text{ res bbl/std bbl})} \left( \frac{11 \text{ psi/cycle}}{11,200 \text{ md-ft (3.37 \mu m}^2 - \text{ m})} \right)$$

which is one order of magnitude greater than the normalized value.

PRESSURE BUILDUP ANALYSIS

Following the December discharge, a pressure buildup test was conducted, with bottomhole pressure being measured using two Kuster KPG pressure elements and recorders in tandem to ensure that pressure data were acquired in spite of equipment malfunction because of the high temperature. Figure 9 is a log-log type curve of the difference between bottomhole pressures during static (no flow) and flow conditions. It shows two distinct wellbore storage effects; the top of the second wellbore storage interval is indicated by the arrow A. Arrow B indicates the onset of the radial flow period, roughly 70 hours after the well is shut in. From these curves, the product of permeability and production zone thickness ($kh$) is calculated to be approximately 880 millidarcy-feet ($0.25 \mu m^2 - m$), with the pressure drop across the mud-damaged skin of the well being 560 psi (3861 kPa).

Bottomhole pressure measurements made after HGP-A was shut in following the January test produced data and plots similar to those for the December test. However, close examination of the data shows that two consecutive straight-line approximations may be made to the Horner plot (Figure 10). Interpretation of this occurrence is that there are at least two different production layers in the wellbore with different $kh$ values. The same effect is also present in the December data, but until it was reproduced in the January test, little credence was given to it. The results of these analyses are summarized in Table 2.

DISCUSSION

From the above analyses, it appears that the Kapoho Geothermal Reservoir, where HGP-A is located, has a fairly tight formation with a permeability thickness of approximately 1000 millidarcy-feet ($0.301 \mu m^2 - m$). During production, the HGP-A wellbore contains steam and water at saturation and flashing appears to occur in the formation. There are possibly two production layers, one at bottomhole and another at approximately 4300 ft (1311 m) from the wellhead. The buildup analyses show that HGP-A may have severe skin damage.

As stated before, one cannot obtain the characteristics of the Kapoho Geothermal Reservoir with only one producing well. Thus the above conclusions are preliminary and present the best estimates at this time. It is also evident that pressure buildup analyses are more reliable than the pressure drawdown analyses.

ACKNOWLEDGMENTS

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Special thanks are due to Dr. Henry J. Ramey, Jr., who has encouraged us in conducting the tests and analyses.

NOMENCLATURE

$$P_i = \text{initial pressure, psi (kPa)}$$
$$P_{wf} = \text{flowing pressure, psi (kPa)}$$
$$P_{wh} = \text{wellhead pressure, psi (kPa)}$$
$$P_{ws} = \text{shut in pressure, psi (kPa)}$$
$$q = \text{production rate, std bbl/day (m}^3/\text{day)}$$
$$\mu = \text{viscosity, cp (Pa-s)}$$
$$B = \text{formation volume factor, res vol/std vol}$$
$$k = \text{permeability, md (\mu m}^2)$$
$$h = \text{formation thickness, ft (m)}$$
$$t = \text{time, hr (hr)}$$
$$\phi = \text{fractional porosity}$$
$$C_t = \text{total system effective isothermal compressibility, psi}^{-1} (\text{kPa}^{-1})$$
$$r_w = \text{well radius, ft (m)}$$
$$s = \text{skin effect factor}$$

REFERENCES

### TABLE 1
**PRELIMINARY THROTTLED FLOW DATA**

<table>
<thead>
<tr>
<th>Orifice Size (Inches)</th>
<th>Total Mass Flow Rate (Klb/hr) (kg/s)</th>
<th>Flow Rate (Klb/hr) (kg/s)</th>
<th>Steam Quality (l)</th>
<th>Pressure (psig) (kPa)</th>
<th>Temp. (°F) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 (203)</td>
<td>101 (12.7)</td>
<td>64 (8.1)</td>
<td>64</td>
<td>51 (352)</td>
<td>295 (164)</td>
</tr>
<tr>
<td>6 (152)</td>
<td>99 (12.5)</td>
<td>65 (8.2)</td>
<td>66</td>
<td>54 (372)</td>
<td>300 (167)</td>
</tr>
<tr>
<td>4 (102)</td>
<td>93 (11.7)</td>
<td>57 (7.2)</td>
<td>64</td>
<td>100 (689)</td>
<td>338 (188)</td>
</tr>
<tr>
<td>3 (76)</td>
<td>89 (11.2)</td>
<td>54 (6.8)</td>
<td>60</td>
<td>165 (1138)</td>
<td>372 (207)</td>
</tr>
<tr>
<td>2-1/2 (64)</td>
<td>84 (10.6)</td>
<td>48 (6.1)</td>
<td>57</td>
<td>237 (1634)</td>
<td>401 (223)</td>
</tr>
<tr>
<td>2 (51)</td>
<td>81 (10.2)</td>
<td>43 (5.4)</td>
<td>53</td>
<td>293 (2020)</td>
<td>419 (233)</td>
</tr>
<tr>
<td>1-3/4 (45)</td>
<td>76 (9.6)</td>
<td>39 (4.9)</td>
<td>52</td>
<td>375 (2585)</td>
<td>439 (244)</td>
</tr>
</tbody>
</table>

### TABLE 2
**COMPARISON OF PRESSURE DRAWDOWN AND BUILDUP TESTS**

<table>
<thead>
<tr>
<th>Permeability thickness, kh, md-ft (m² - m)</th>
<th>Constant Production Drawdown</th>
<th>December Buildup One Layer</th>
<th>December Buildup Two Layer</th>
<th>January Buildup Two Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1356 (0.408)</td>
<td>880 (0.265)</td>
<td>1553 (0.467)</td>
<td>1089 (0.328)</td>
</tr>
<tr>
<td>Apparent skin factor, s</td>
<td>-0.86</td>
<td>4.3</td>
<td>14.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Pressure drop across skin, psi (kPa)</td>
<td>---</td>
<td>561 (3868)</td>
<td>1098 (7570)</td>
<td>575 (3964)</td>
</tr>
<tr>
<td>Flow efficiency</td>
<td>1</td>
<td>0.65</td>
<td>0.38</td>
<td>0.60</td>
</tr>
</tbody>
</table>

![Fig. 1 - Flow test equipment and instrumentation.](image-url)
Fig. 2 - Pressure profiles for HGP-A.

Fig. 3 - Temperature profiles for HGP-A.
Fig. 4 - Log-log plot of November 1976 discharge test data.

Fig. 5 - Semi-log plot of November 1976 discharge test data.
Fig. 6 - Linear plot of initial data for November 1976 discharge test.

Fig. 7 - Total mass flow as a function of time.
Fig. 8 - Wellhead pressure as a function of time.

Fig. 9 - Log-log plot of December 1976 buildup test data.

Fig. 10 - Semi-log plot of January/February 1977 buildup test data.