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# Long-Term Flow Test #1, Roosevelt Hot Springs, Utah


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## I Introduction

The Roosevelt Hot Springs, Utah geothermal field has been the site of numerous investigations into the behavior of a geothermal system. However, a detailed description of the reservoir is lacking. This paper presents the results of the 237 day Long-Term Flow Test #1, conducted in 1977 and 1978, followed by a 100 day pressure buildup. The responses from one production well and three pressure observation wells, ranging 600 to 12,000 feet from the production well, were used.

This study illustrates the utility of a reevaluation of a geothermal system using old, pre-exploitation data and is part of an ongoing case study of the Roosevelt Hot Springs system. Specific objectives are an improved interpretation of the geothermal reservoir, an estimate of aquifer behavior, and the primary reservoir volume.

## II Geologic Framework

Roosevelt Hot Springs geothermal field is located in southwestern Utah, Figure 1. Production started May 1984, making it the oldest producing geothermal field in the Basin and Range Province. The various geologic, geochemical, geophysical, and engineering aspects of the Roosevelt Hot Springs system have been described by numerous authors with over 230 citations in the literature. Papers by Nielson et al. (1978), Nielson et al. (1986), Bruhn et al. (1982), Bowman and Rohrs (1981), Capuano and Cole (1982), Ward et al. (1978), and Ross et al. (1982) are especially noteworthy but will not be discussed in detail here. However, several features are of relevance to a reservoir description. The geothermal reservoir is bounded on the west by the Opal Mound Fault. This north-south Basin and Range feature separates the Opal Mound horst to the west from a graben to the east in which the reservoir is located. The east-west Hot Springs Fault bisects the reservoir and is normal to the Opal Mound Fault. This pronounced feature is inconsistent with the Basin and Range environment. Nielson (1989) has proposed that the Hot Springs Fault is the driving fault for an east-west graben cutting across the crest of the Mineral Mountains and into the adjacent Beaver Basin to the east. Thus, the geothermal reservoir lies at the intersection of two grabens, the typical north-south feature associated with the Opal Mound Fault and an east-west graben associated with the Hot Springs Fault. The intersection of these two perpendicular grabens has created a volume of intensely fractured rock which contains the commercial geothermal reservoir.

Complementary work by Robinson and Iyer (1981) using P-wave data, and Becker (1993) using gravity filtering and modeling, strongly suggest the presence of a magma chamber 16,000 to 20,000 feet below the reservoir. This feature is most likely the heat source for the hydrothermal system. The most recent rhyolite volcanism in the Mineral Mountains has produced flow, pyroclastic rocks, and domes between 0.8 and 0.5 Ma (Nielson et al., 1986), suggesting the relative age of the heat source.

## III Development History

Active exploration at Roosevelt Hot Springs began in 1974. The discovery well, RHSU 3-1, was drilled in April 1975. The success of this well led to the drilling of four more wells in 1975. Three additional wells were drilled in 1976 and one each in 1977 and 1978. These new wells delineated a productive area associated with the Opal Mound and Hot Springs Faults. Additional production wells were drilled prior to the start of production in May 1984 to supply a 20 $MW_e$ power plant. Two replacement production wells have been drilled since the start of exploitation.

The native-state reservoir temperature and pressure distributions were reconstructed from temperature and pressure surveys collected in 13 wells. The pressure data used cover a time period from 1975 to 1982 (prior to exploitation), while the temperature data includes wells from 1975 to 1987. The initial pressure surveys are plotted versus depth are presented in Figure 2. A liquid-dominated reservoir is present with approximately a 0.37 psi/ft gradient and an areal variation in reservoir pressure at a given elevation. Yearsley (1994) presents a contour of the initial pressure at +4000 MSL, which shows a fairly uniform pressure in the reservoir with an abrupt decrease in pressure west of the Opal Mound Fault. This fault acts as a hydrologic "dam" with water leaking over the top of the impermeable horst into permeable alluvial sediments. The highest pressures are along the intersection of the Opal Mound and Hot Springs Faults.

Temperature surveys are presented in Figure 3. The temperature surveys can be placed in three categories: high temperature wells with long isothermal sections, intermediate temperature

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wells with long conductive intervals interrupted by temperature increases and reversals, and one cooler well with a long conductive interval. These data were contoured by Yearsley (1994) using a datum of +1800 MSL, showing the highest temperatures are along the intersection of the Opal Mound and Hot Springs Faults. The coincidence of the highest reservoir pressures and temperatures is interpreted to be the location of the upwelling of thermal fluids. This area of high temperature extends south to RHSU 72-16 along the Opal Mound Fault. There is a cooling trend southeast of RHSU 72-16, which may represent local influx of shallow, cooler meteoric water. The 400°F contour at this datum generally defines the productive region of the reservoir. Both the pressure and temperature contours clearly indicate the Opal Mound Fault as a western boundary of the commercial reservoir. The southern boundary of the reservoir is located between wells RHSU 25-15 and RHSU 52-21, corresponding to a mapped fault in this region. The northern boundary of the reservoir is ill-defined and is located somewhere north of RHSU 12-35. The eastern boundary is also poorly constrained due to the lack of well control, but lies to the east of RHSU 14-2 and RHSU 25-15. RHSU 82-33 is located outside the reservoir and has a shallow temperature reversal. This temperature reversal is due to a tongue of hot water discharging from the reservoir into the shallow alluvial sediments and flowing to the northwest down hydrologic gradient.

## IV Conceptual Model

Several elements define a conceptual model of a hydrothermal system: fluid recharge, fluid circulation paths, a heat source, a reservoir, and fluid discharge. A conceptual model of the Roosevelt Hot Springs hydrothermal system has been proposed by Faulder (1991) and is briefly reviewed below. Fluid recharge is presumed to occur in the Mineral Mountains to the east of the reservoir, though some interbasin flow from the Beaver Basin to the Milford Basin cannot be ruled out. The extensive joint and fracture system associated with the Hot Springs Fault graben allows meteoric water to circulate to a depth in proximity to the heat source. The meteoric water is heated, rises along the Hot Springs Fault, and spreads laterally into the reservoir along the Opal Mound Fault. The intersection of the Hot Springs and Opal Mound grabens hosts a complex fractured reservoir. Discharge from the reservoir occurs by leakage toward the Milford Basin near the intersection of the Opal Mound and Hot Springs Faults. Parry et al. (1980) estimated a convective mass flux of $1.3(10^{-6})$ kg/m$^2$s to explain the observed temperature gradient. An area of 3 x 7 km (approximating the commercial reservoir), would suggest a native state mass flux on the order of 27.3 kg/s, or about 220 K lbm/hr.

## V Long-Term Flow Test #1

Well testing during 1975 and 1976 consisted of a number of short-term deliverability tests with very limited pressure interference measurements. Although the short-term tests were encouraging, as the development of the reservoir progressed, doubts existed as to the long term sustainability of a fractured granitic reservoir under exploitation. Three Long-Term Flow Tests (LTFT) were conducted prior to exploitation to address this issue. It should be noted these data received only minimal analysis at that time, as the primary focus was to demonstrate sustained reservoir deliverability.

LTFT #1 was conducted from October 7, 1977 to May 31, 1978, using a single production well, RHSU 54-3. Observation downhole pressures were monitored in wells RHSU 3-1, RHSU 13-10, and RHSU 25-15 from October 7, 1977 to September 7, 1978 using capillary tubing and Heise gauges. The downhole pressure chamber setting depths for the three observation wells were not recorded. This test resulted in 236 days of sustained production and 336 days of continuous pressure monitoring. The flowrate and observation well pressure histories are presented in Figures 4 and 5. Two-phase production from RHSU 54-3 was discharged through a test separator and the brine was reinjected into RHSU 82-33, located outside of the reservoir.

During the first 47 days of LTFT#1, the production from RHSU 54-3 was about 100 K lbm/hr. On day 48, the rate was increased to about 200 K lbm/hr. On day 145 the rate was increased to over 600 K lbm/hr and then allowed to decline, probably due to wellbore scaling. From 175 to 200 days the average rate was about 471K lbm/hr. The flow test was terminated on day 237 and observation well pressures were monitored for an additional 100 days. The buildup portion of this comprehensive dataset was analyzed using a line source solution for interwell conductivity and storativity. These results are presented in Table 1.

**Table 1. Interference results for LTFT #1**

| Observation Wells | | Interference Results | |
|---|---|---|---|
| Well | Distance, ft. | kh, mD-ft | $\phi c_t h$, ft/psi |
| RHSU 3-1 | 575 | 29,400 | $1.11(10^{-1})$ |
| RHSU 13-10 | 7,400 | 68,500 | $6.89(10^{-4})$ |
| RHSU 25-15 | 12,400 | 46,900 | $2.85(10^{-4})$ |

One objective of this study was to refine the estimated reservoir volume. A reservoir model of the field has been developed and calibrated by the operator (Yearsley, 1994). This model provides an accurate match of exploitation pressures, but underpredicts the observed 100 psi pressure recovery in response observed in RHSU 25-15 to an extended (three month) shutdown of the field in 1993. As this well is over a mile away from the nearest production well, the pressure in this well is representative of average reservoir pressure. Several items were examined to resolve this: 1) location of one or several reservoir boundaries, 2) estimates of reservoir volume, and 3) aquifer characterization.

An attempt was made to analyze the interference response using the ellipse of interference technique of Vela (1977) to locate the undetermined boundaries in the reservoir. This was unsuccessful, as the observation wells were located too close to a boundary (the Opal Mound Fault) to use this technique.

Inspection of Figure 5 shows that for days 50 to 150, the pressure responses in the three observation wells were parallel, indicating that the boundaries of the reservoir had been encountered by the pressure transient. This reservoir-limits test is an ideal means of estimating the reservoir fluid volume in pressure communication with the production well. A Cartesian plot of the observation pressures versus time becomes a straight line, with the pressure in all wells declining at the same rate once a pressure transient has encountered the reservoir limit and the reservoir is in pseudo steady-state. The volume of fluid contacted by a flow test can be calculated using a relationship presented by Earlougher (1977; p. 29).

$$\phi hA = \frac{-0.23395 qB}{c_t m^*} \qquad (1)$$

This calculation is the basis for the reservoir volume of 19 billion barrels reported by Kerna and Allen (1984).

After initial drawdown, the flat pressure response for the first 144 days suggests the reservoir response may be influenced by aquifer influx. A plot of pressure drawdown in the observation wells vs. cumulative mass production should result in a straight line if no aquifer influx in present. An inspection of Figure 6 shows that this is not the case, demonstrating that influx is occurring during LTFT #1. Aquifer influx calculations were made using a Fetkovich finite linear aquifer (Dake, 1978; p. 303-341) to estimate aquifer parameters and influx rate and to determine the net production stress on the reservoir (mass produced minus aquifer influx). The pressure response in RHSU 25-15, the most distant observation well, was selected to most closely represent the average reservoir pressure. The aquifer parameters that resulted in an influx that closely matches the production during this time period are an aquifer thickness of 5,000 feet, a dimensionless aquifer radius of 10 and a permeability of 20 mD. The calculated cumulative aquifer influx using these parameters and cumulative mass production is presented in Figure 7. The estimated influx roughly balances the production from RHSU 54-3 during the first 144 days, resulting in the very flat observation pressure response. During days 175 to 200, when the production rate was fairly constant (average of 471 K lbm/hr), the estimated aquifer influx rate was about 320 K lbm/hr, or about 70% of the total production rate from RHSU 54-3. The volume of fluid contacted by the flow test, assuming the estimated influx (net production stress) and with no influx for these two distinct time periods is presented in Table 2. The pressure versus time slope of the three wells is essentially parallel, given the test conditions and data quality for the late 1970's, verifying pseudo steady-state flow. As can be seen from Table 2, the estimated reservoir volume is dependent on the assumption of the occurrence of aquifer influx. Based on the conceptual model, the observed pressure and temperature distributions, and temperature gradient considerations, some level of aquifer recharge must be present in the native state. If the reservoir is disturbed by a flow test, an increase in the aquifer influx should occur. The estimated reservoir volume reported by Kerna and Allen (1984) is similar to the values calculated for the reservoir volume without recharge between days 125 through 144 and for days 175 through 200. However, this presents a paradox, as the larger the reservoir volume, the greater the influx required to create a given pressure increase.

A simple material balance calculation can be made to illustrate this paradox. The volume of fluid required to change the pressure of a single phase tank can be estimated by:

$$N_p = N c_t \Delta P \qquad (2)$$

Net influx is divided by the time period to provide a rough estimate of the average influx rate. Using a representative value for total system compressibility of $6.7(10^{-6})$ psi$^{-1}$, and assuming a 100 psi change in average reservoir pressure in 90 days, (from the 1993 extended field shutdown), a reservoir volume of 19 billion barrels requires an influx rate on the order of 2,100 K lbm/hr, which is approximately four times greater than the reservoir voidage rate (production minus injection) during 10 years of exploitation. A reservoir volume of 6.7 billion barrels requires an influx rate of 700 K lbm/hr.

Another way to view the issue is to use the primary reservoir area in Section IV (3 x 7 km) and a thickness of 10,000 feet. The porosity required to contain 19 billion barrels is 4.8%, while for 6.7 billion barrels, 1.7%. As the reservoir is a fractured granite, a fracture porosity of 4.8% is implausible for the large bulk volume considered in this calculation. The no recharge values in Table 2 infer unreasonably large values of porosity. The production well had a fairly constant flowrate

Table 2. Reservoir volume estimates from LTFT #1

| Well | Days 125-144: Slope, $m^*$, psi/hr | Days 125-144: Reservoir Volume, (bbl) w/o influx[a] | Days 125-144: Reservoir Volume, (bbl) w/ influx | Days 175-200: Slope, $m^*$ psi/hr | Days 175-200: Reservoir Volume, (bbl) w/o influx | Days 175-200: Reservoir Volume, (bbl) w/ influx |
|---|---|---|---|---|---|---|
| RHSU 3-1 | -0.003831 | $20.6(10^9)$ | $1.94(10^9)$ | -0.008861 | $25.7(10^9)$ | $8.02(10^9)$ |
| RHSU 13-10 | -0.004430 | $17.0(10^9)$ | $1.67(10^9)$ | -0.009722 | $23.3(10^9)$ | $7.31(10^9)$ |
| RHSU 25-15 | -0.003402 | $22.1(10^9)$ | $2.21(10^9)$ | -0.010665 | $21.4(10^9)$ | $6.66(10^9)$ |

a. The volume of fluid that was calculated by Kerna and Allen (1984).

during the time period 175 through 200 days. The calculated reservoir volume, assuming a Fetkovich finite linear aquifer is between 6 to 8 billion barrels.

## VI Conclusions

The primary reservoir fluid volume at Roosevelt Hot Springs geothermal system, ignoring the role of aquifer influx, had previously been estimated at 19 billion barrels from a reservoir-limits test. This volume, when used in a numerical model study, under-predicted the pressure recovery due to an extended shutdown of the field in 1993. A review of LTFT #1, including the role of aquifer influx, was made to estimate the fluid volume in pressure communication with the single production well. The presence of aquifer influx is supported by initial pressure and temperature data and by thermal gradients. The analysis of LTFT #1 reduced the estimate of reservoir fluid volume to approximately 6 to 8 billion barrels supported by aquifer influx. Yearsley (1994) estimated the reservoir volume at 3.3 billion barrels from a history match of a numerical reservoir model. The reservoir volume calculated is sensitive to the assumed aquifer response and other aquifer models need to be investigated. Material balance and fracture porosity considerations, however, support this lower estimate. While additional work is required to better resolve the aquifer behavior at Roosevelt Hot Springs, ignoring the role of aquifers in geothermal systems may result in over optimistic estimates of reservoir fluid volumes from reservoir limits testing.

## VII Acknowledgments

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# IX Nomenclature

| | | |
|---|---|---|
| A | = | reservoir area, $ft^2$ |
| B | = | formation volume factor, reservoir bbl/stock tank bbl |
| $c_t$ | = | total system compressibility, $psi^{-1}$ |
| h | = | reservoir thickness, ft |
| k | = | permeability, mD |
| $m^*$ | = | slope of well pressure versus time, psi/hr |
| N | = | reservoir volume, bbl |
| $N_p$ | = | net influx, bbl |
| q | = | production rate, bbl/day |
| $\Delta P$ | = | pressure difference |
| $W_e$ | = | aquifer influx rate, bbl/day |
| $W_{ei}$ | = | maximum influx of aquifer, bbl |
| $\phi$ | = | porosity, fraction |
| $\mu$ | = | viscosity, cp |

**FIGURE 1. - Location of Roosevelt Hot Springs and Well Field Map**

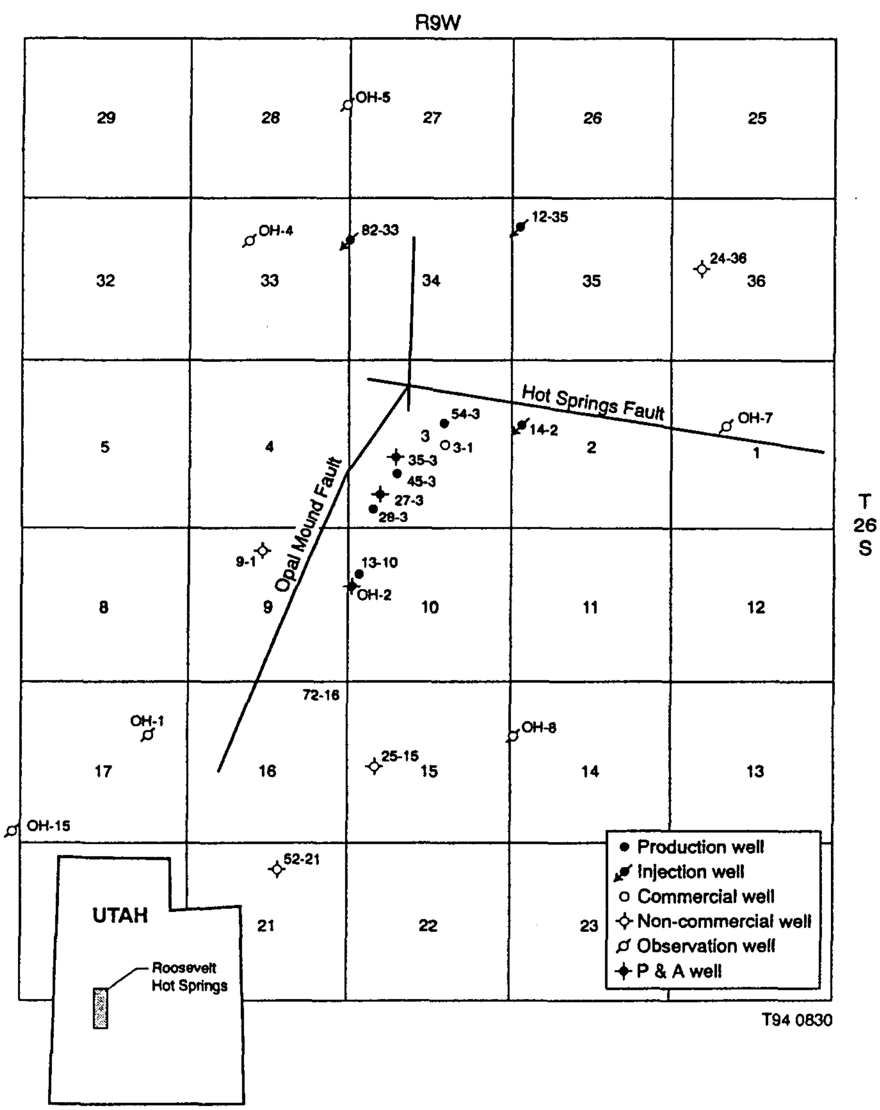

**FIGURE 2. Initial Pressure Surveys**

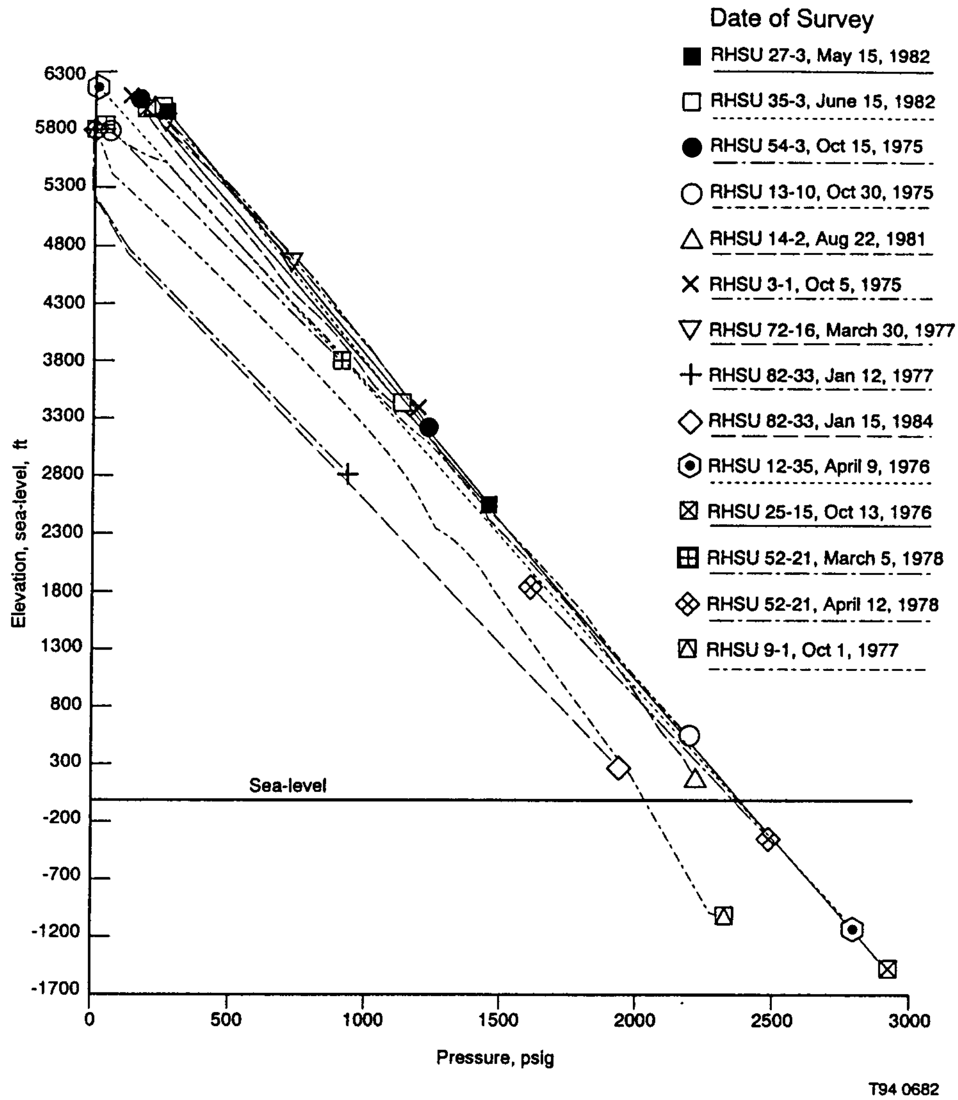

**FIGURE 3. Initial Temperature Surveys**

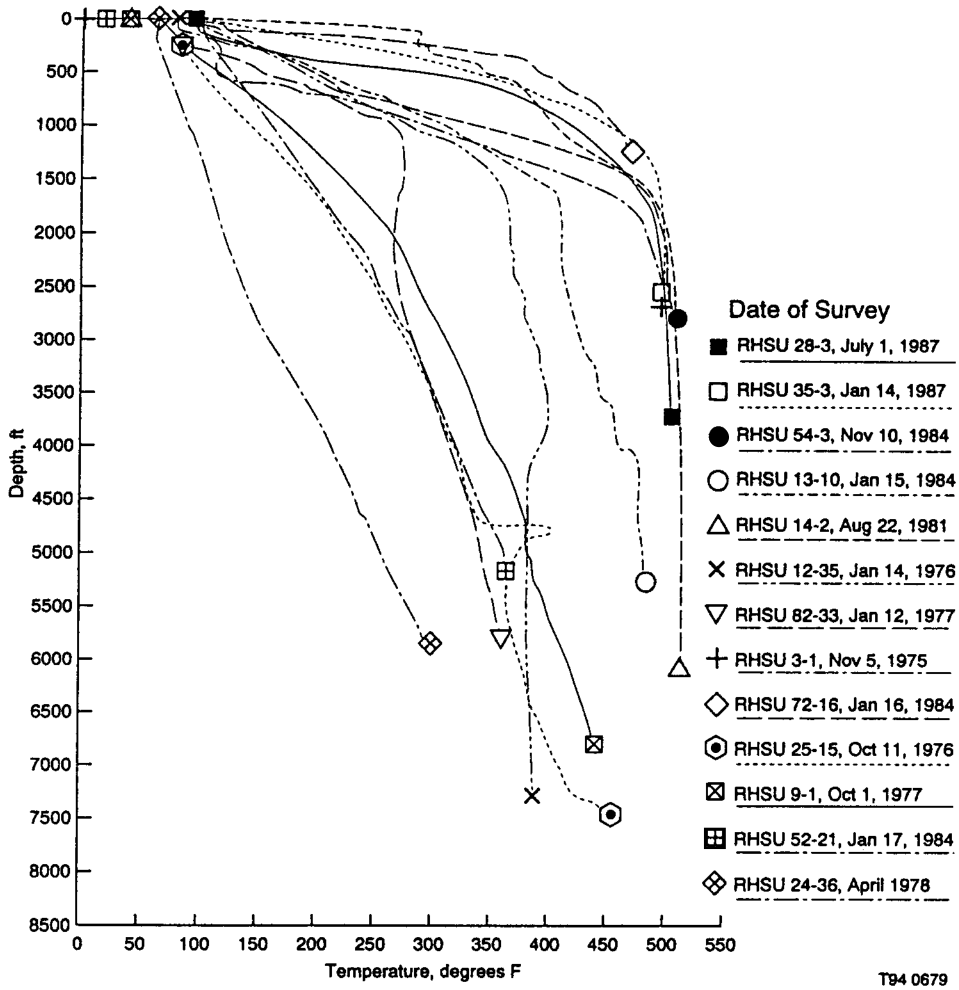


**FIGURE 4. Flowrate History of RHSU 54-3**

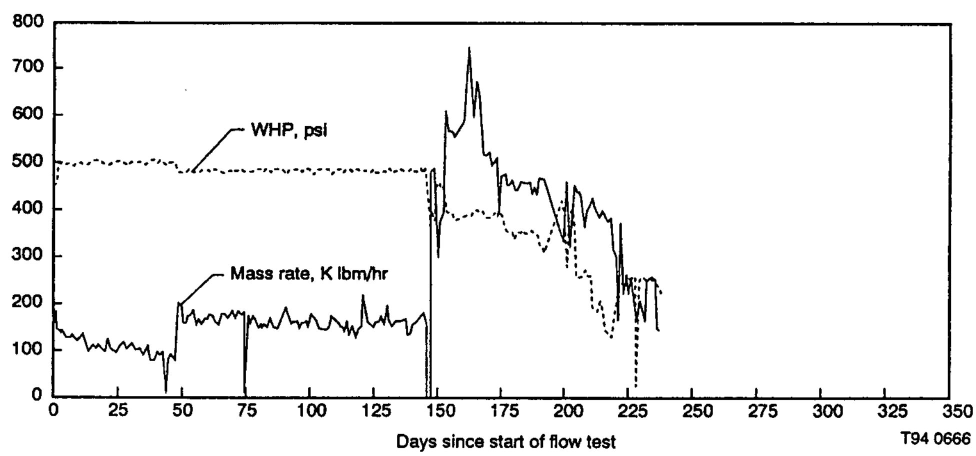

**FIGURE 5. Observation Pressure Response**

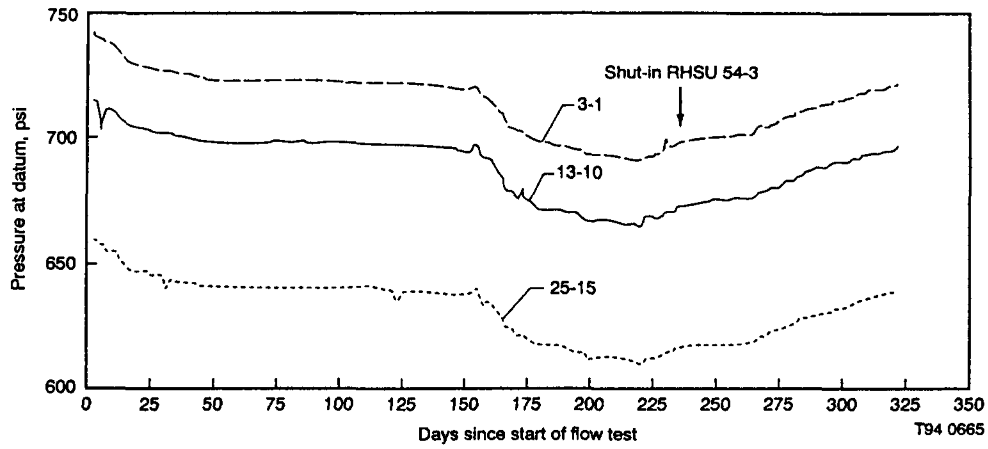


**FIGURE 6. Cumulative Mass Produced versus Drawdown in Observation Wells**

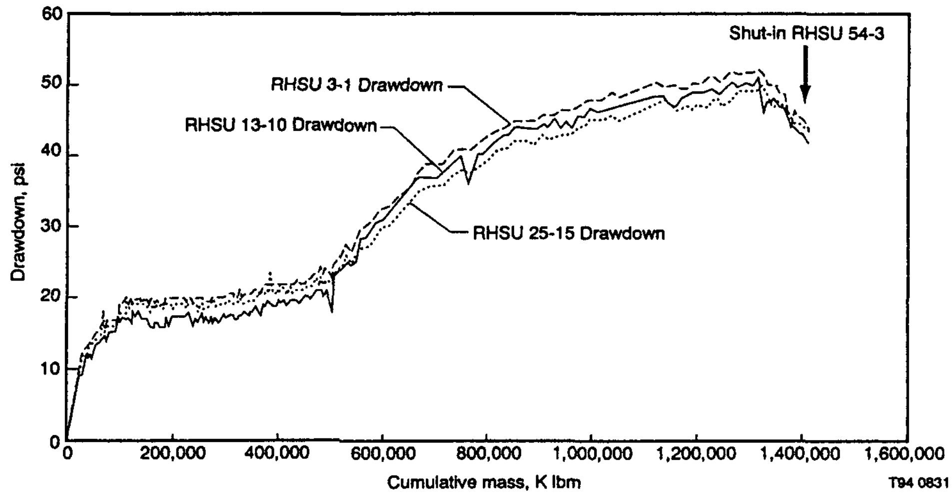


**FIGURE 7. Cumulative Mass Production and Estimated Cumulative Aquifer Influx**