UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Federal Center, Denver, Colorado 80225

OIL SHALE-6

HYDRAULIC TESTING AND SAMPLING OF USBM-AEC COLORADO CORE HOLE 3, RIO BLANCO COUNTY, COLORADO

By

E. H. Cordes

December 1969

Open-file Report

Prepared by the Geological Survey for the U.S. Atomic Energy Commission.

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ABSTRACT

On November 21, 1967, the U.S. Geological Survey, in cooperation with the U.S. Bureau of Mines and the U.S. Atomic Energy Commission, completed the hydraulic testing and sampling of USBM-AEC Colorado Core Hole 3 in Rio Blanco County, Colorado. This hole was drilled to explore the site for Project Bronco, a Plowshare experiment to study the feasibility of in situ retorting of oil shale after breaking the rock with a nuclear explosion.

The hydraulic tests indicate the existence of a highly permeable water-bearing zone in the upper and middle parts of the Parachute Creek Member of the Green River Formation of Eocene age. The zone yielded water in excess of 2,700 cubic meters per day (500 gallons per minute). During geologic time and even today, natural ground-water circulation is believed to have dissolved the syngenetic salt deposits from a part of the oil shale formations leaving a highly permeable zone of interconnected vugs and breccia channels. Older rocks underlying the Parachute Creek Member are comparatively impermeable to water flow and yielded less than 16 cubic meters per day (30 gallons per minuted) of highly saline (49,000 parts per million dissolved solids) fluid.

Potential flooding of a rubble chimney is an important consideration for project feasibility and safety. A first approximation of the magnitude of flooding was calculated from the test data.

INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with the U.S. Bureau of Mines (USBM), the U.S. Atomic Energy Commission (AEC), Lawrence Radiation Laboratory and CER Geonuclear Corporation completed a program of hydraulic testing and sampling of USBM-AEC Colorado Core Hole 3 (CCH-3), in Rio Blanco County, Colorado, on November 21, 1968. The work represents a preliminary phase of a site evaluation study for Project Bronco, a proposed experiment to study the feasibility of in-situ retorting of oil shale fractured by an underground nuclear explosion. Project Bronco is part of the AEC's Plowshare Program, which has the task of investigating and developing peaceful uses for nuclear explosives.

The objectives in drilling CCH-3 were:

1) to confirm previous estimates of the thickness of overburden, oil-shale and salt-bearing deposits and to quantitatively determine oil yields;
2) to obtain quantitative hydrologic information relative to project safety and technical feasibility; and
3) to describe the preshot geologic fracture system and rock competence in the experimental area.

The hydrologic test program closely follows the requirements and objectives set forth in the AEC "Bronco Oil Shale Study" of October 13, 1967. They are designed:

1) to determine possible hazard to public safety from circulation of ground water contaminated by radionuclides; and

2) to describe and evaluate the possibility of flooding the rubble chimney. Uncontrolled ground-water inflow into the rubble chimney could adversely affect the technological feasibility of Project Bronco.

A complete understanding of the dynamics of the ground-water flow system both in and around the experimental area would be required, to answer these and other questions.

Hydraulic testing in CCH-3 has provided some of the basic data required to analyze the ground-water flow system. However, these data are limited to an approximation of the transmissivity and hydrostatic potential of multiple aquifer units. Reservations must be placed on quantitative results, particularly if flow characteristics are fracture controlled. A further drawback of the single-well testing program is an inability to calculate a resonable storage coefficient. Extrapolation of these parameters over the regional ground-water basin would require a more detailed hydrologic investigation.

The physical and chemical properties of water samples taken during the tests provide additional information to aid in the interpretation of the flow system.

This report summarizes the methods and procedures used in the hydraulic testing of CCH-3. It is intended to disseminate the basic hydraulic data and to present a brief analysis related to Project Bronco hydrologic objectives.

The author, assisted by Messrs. George Dana and Harold Thomas of the U.S. Bureau of Mines, supervised the testing program.

GEOHYDROLOGY

Previous experience with hydraulic tests in USBM-AEC Colorado Core Holes 1 and 2 (Carroll and others, 1967; Ege and others, 1967), and information from oil and gas wells in the area indicate a copious supply of water in the Parachute Creek Member of the Green River Formation. The surface location of Colorado Core Hole 3, with respect to Colorado Core Holes 1 and 2, is shown in figure 1.

The Green River Formation is a sedimentary sequence of ancient lake-bed deposits of Eocene age (fig. 2). The near shore deposits include much sand, whereas accumulation in the depositional center consists of carbonaceous clay and marlstone. Rocks containing abundant organic matter comprise the oil-shale deposits.

The Parachute Creek Member of the Green River Formation is composed mainly of siltstone and marlstone, and contains a solid hydrocarbon called "kerogen" and various syngenetic salt accumulations in the form of beds and (or) nodules. Throughout much of the Piceance Creek Basin, ground-water circulation is believed to have leached the salt deposits, particularly in the middle and upper part of the Parachute Creek Member, leaving a cavernous and brecciated dissolution zone.

The geologic origin of the Garden Gulch and the Douglas Creek Members (fig. 2) is similar to that of the overlying Parachute Creek Member. However, these older lacustrine sediments do not contain the salt deposits and generally are almost barren of kerogen. Little is known of the hydrologic characteristics of these older rocks, yet they are directly involved in the planning of Project Bronco.

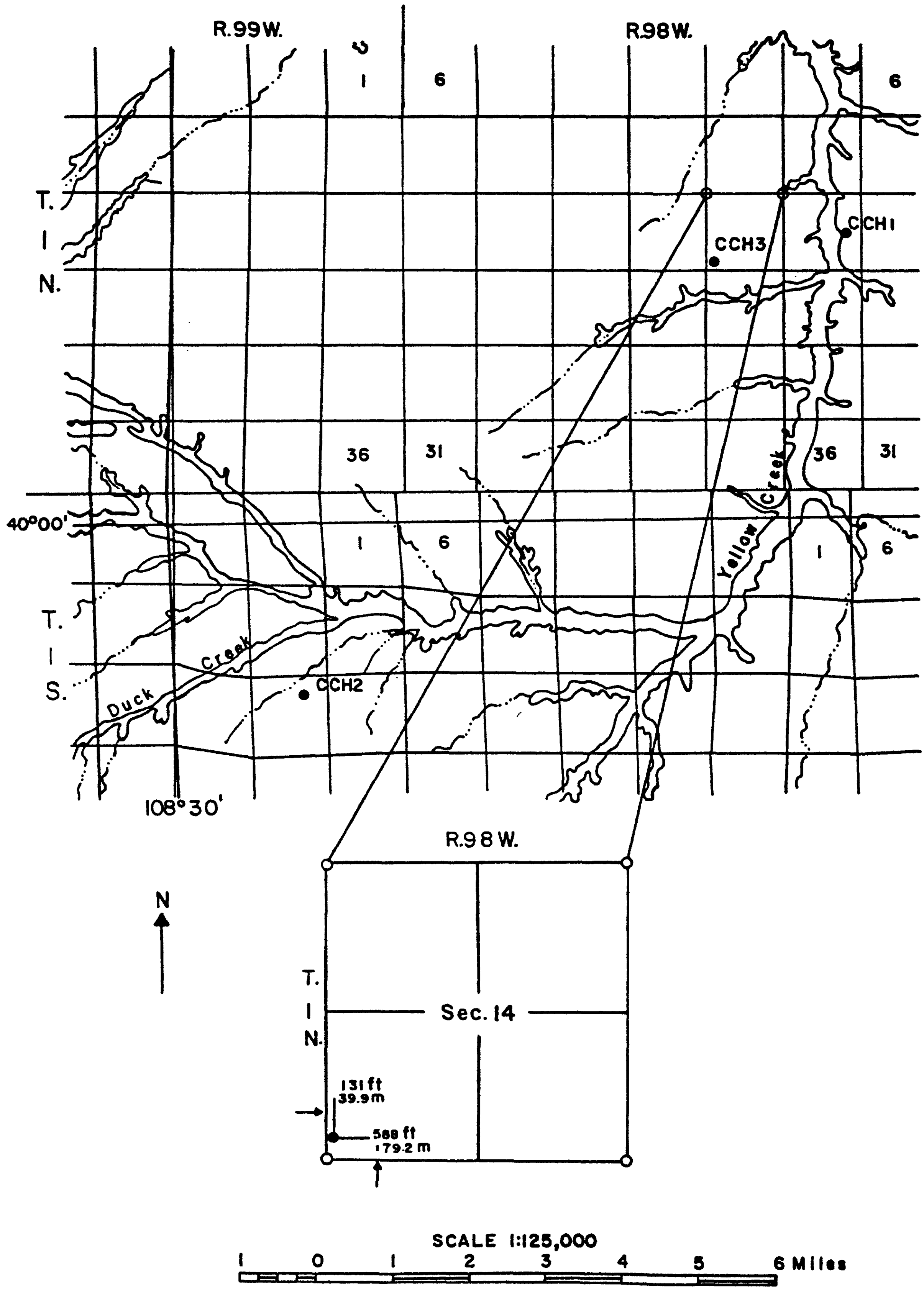

Figure 1.--Locations of USBM-AEC Colorado Core Holes (CCH) 3, 2, and 1.

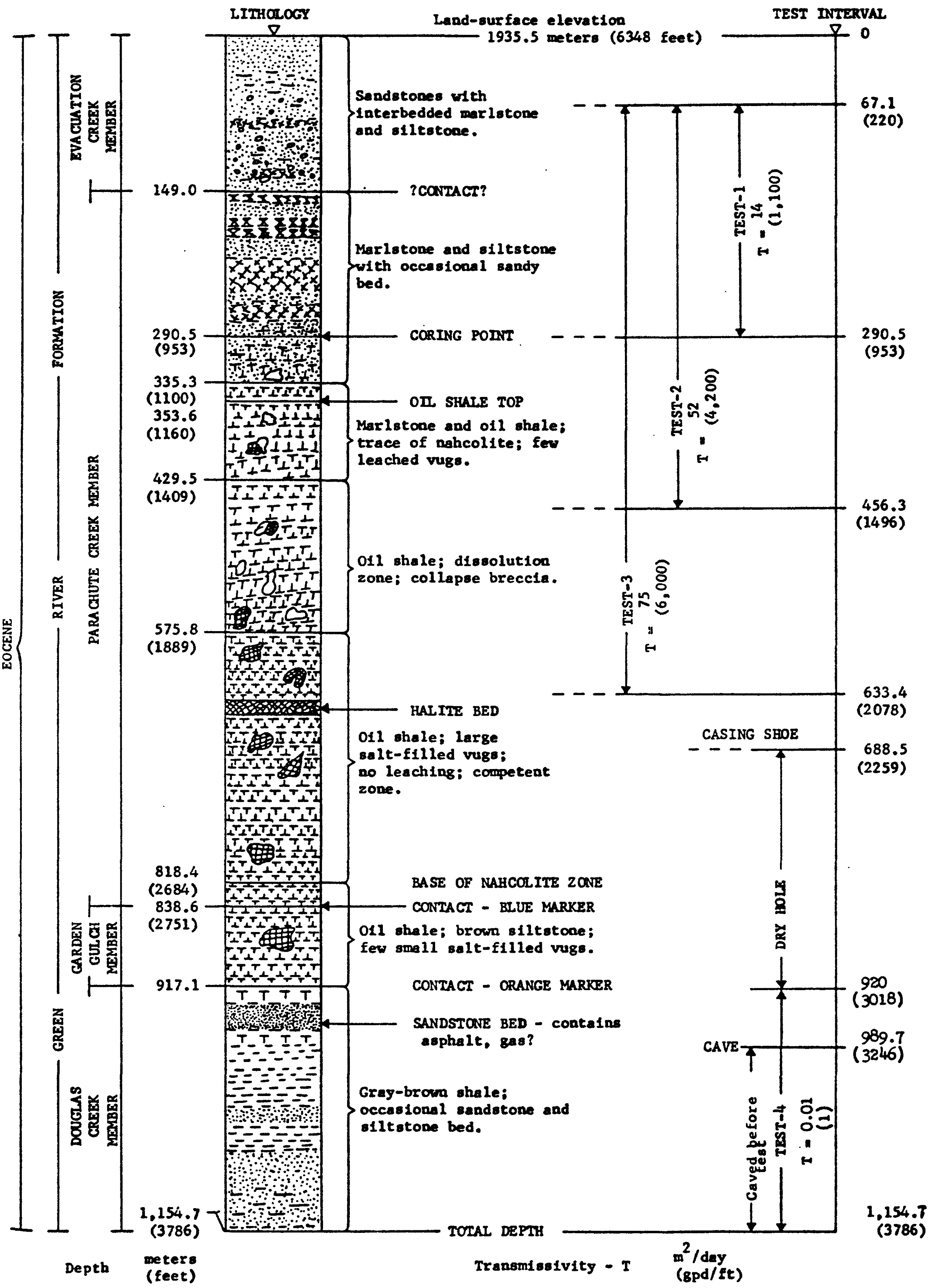

Figure 2.--Lithology and test intervals, USBM-AEC Colorado Core Hole 3.

HYDRAULIC TESTING AND SAMPLING

Drilling of CCH-3 began on October 15, 1967. Approximately 67.1 m (220 ft) of 34.3-cm (13-1/2-in) diameter hole were mud drilled to accommodate 27.4-cm (10-3/4-in) diameter surface casing (fig. 3). After cementing the surface casing, the hole was drilled to a total depth of 1,154.7 m (3,786 ft), using compressed air and foam as circulating media. For hydraulic testing this circulating media is preferable to using drilling fluids which contain compounds that plug the fluid conducting pores.

The well discharge during drilling and testing was continuously recorded with a Stevens type-F water-level recorder behind a 90° V-notch weir. The weir and associated recording equipment was placed about 15.2 m (50 ft) downstream from the discharge sump. Some fluid is lost from this type of open recording system. Infiltration in the discharge sump and in the stream channel accounts for some of the loss but the major loss occurs as water vapor and extraneous surface runoff during initial discharge of the well. An estimate of these losses was used to adjust the discharge data.

Temperature and specific conductance of the discharge fluid were also recorded at the weir. A drilling report (geolograph) was used to correlate these physical parameters and the fluid discharge rate to well depth (figures 4 and 5). Significant changes in these parameters reflect variations in the hydrologic media and an increased efficiency of jetting with greater submergence. Consideration of the observed changes help in the interpretation of the geohydrology.

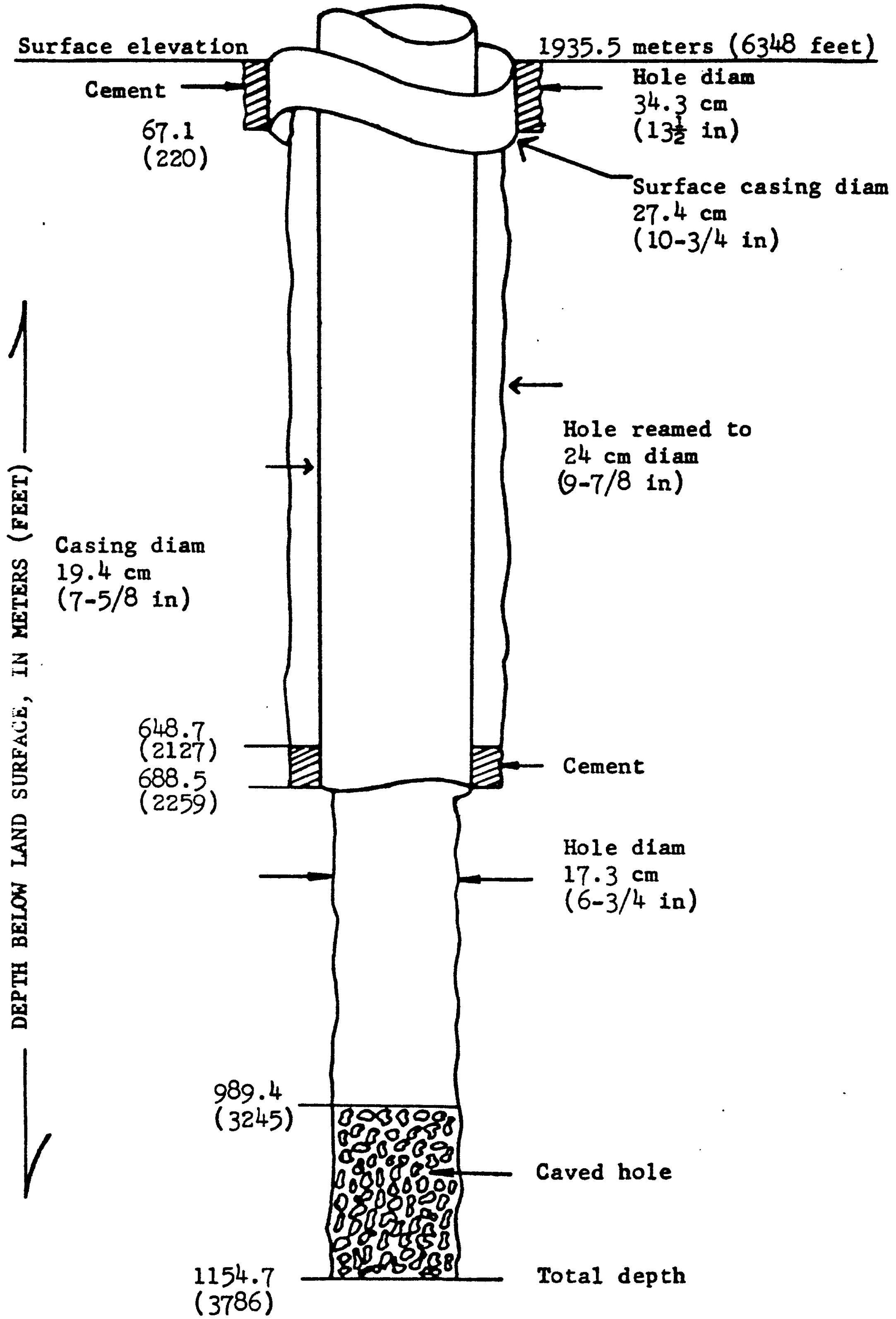

Figure 3.--Well mechanics, USBM-AEC Colorado Core Hole 3, upon completion.

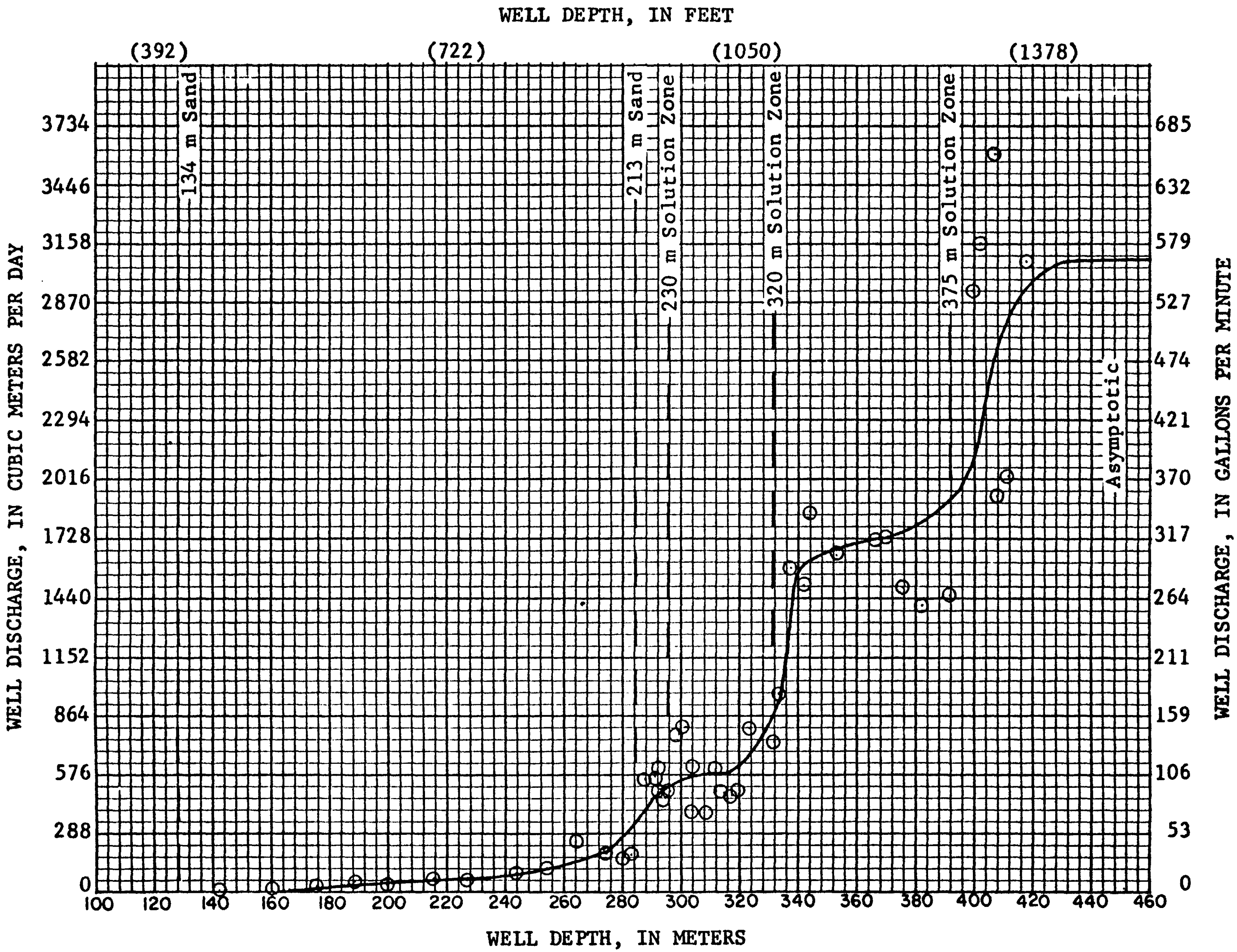

Figure 4.--Fluid discharge trend from USBM-AEC Colorado Core Hole 3 during drilling.

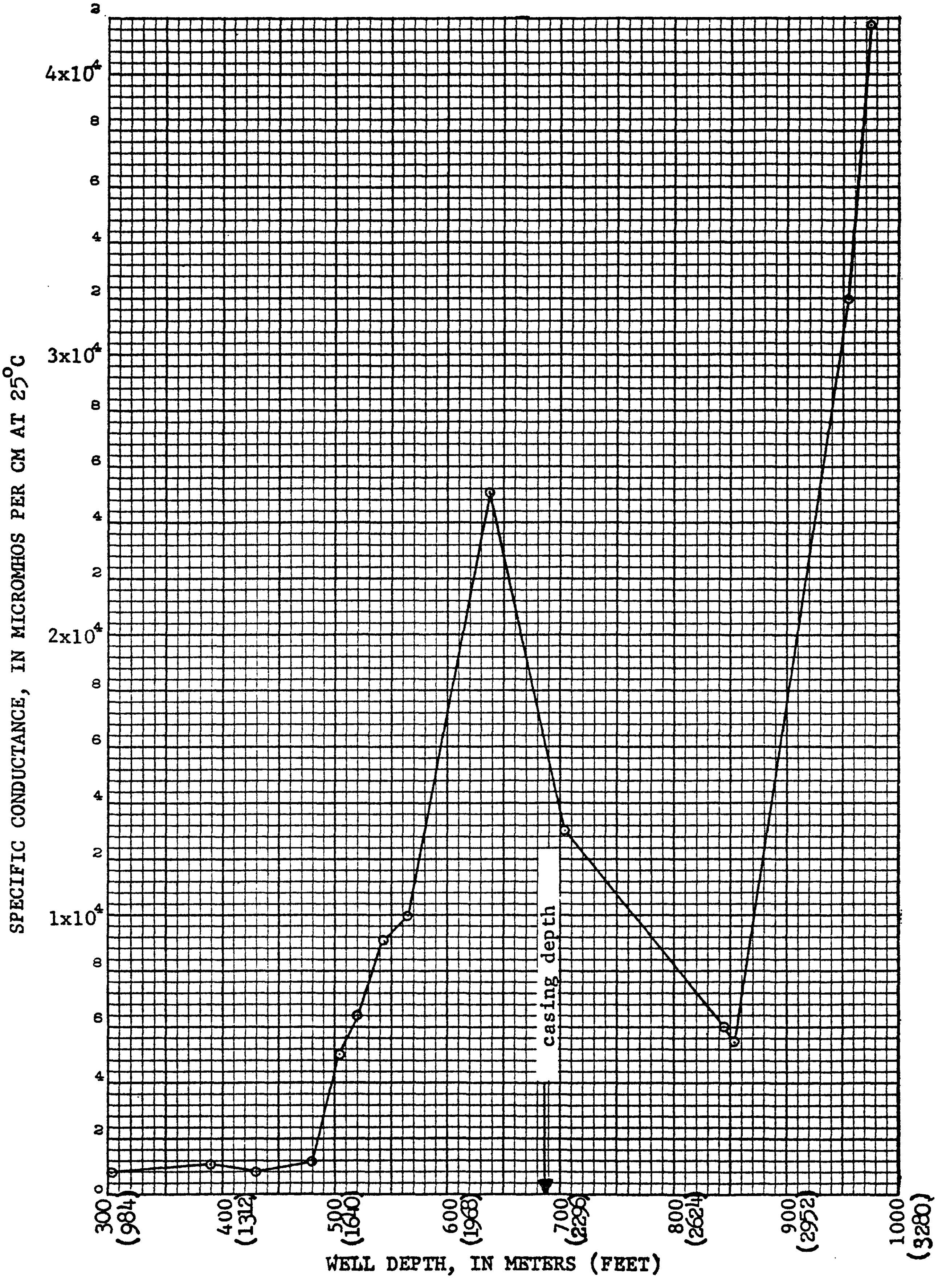

Figure 5.--Specific conductance of discharge fluid during drilling of USBM-AEC Colorado Core Hole 3.

Four aquifer-performance tests were made during the drilling of CCH-3. Suites of water samples were collected for chemical analysis.

The collection and method of analysis of data for each of the four hydraulic tests is as follows. The field procedure is designed to measure parameters in a hydrologic system, that are described by a mathematical model. In the prototype system, cause and effect are related by the characteristics of the porous media. A controlled stress is imposed on the ground-water system by jetting fluid from the hole at a constant rate. After quasi equilibrium is reached, the stress is removed permitting the system to relax. The effect of relaxation (recovery) is carefully monitored.

A mathematical expression, relating cause and effect in a hydrologic system, is given by the modified Theis equation, (Ferris and others, 1962),

$$T = \frac{0.183}{s'}Q \log_{10} \frac{t}{t'} , \qquad (1)$$

where

s' = residual drawdown after time t', in meters

t = time since jetting started

t' = time since jetting stopped

T = transmissivity, in m^2 per day (square meters per day)

Q = fluid discharge rate, in m^3 per day (cubic meters per day).

This equation is ideally the expression for a line passing through the origin. A semi-log plot of s' verses $\log_{10} \frac{t}{t'}$ is a line of constant slope.

A simplified form of equation 1, using the slope of the line through the data points, can be used to approximate the aquifer transmissivity,

$$T = \frac{0.183Q}{m} \tag{2}$$

where

s' = depth to water, in meters

Q = discharge rate during jetting, in m^3 per day

T = transmissivity, in m^2 per day

m = straight-line slope, $\Delta s'$ per log cycle.

The derivation of the mathematical model, and thus its application, hinge on satisfying several important assumptions:

(a) uniform, isotropic, and homogeneous media of infinite areal extent;

(b) two-dimensional flow;

(c) boundary conditions at the well-bore are negligible;

(d) stresses are additive (theory of superposition);

(e) constant coefficient of storage and the instantaneous transfer of mass with a change in head.

Quite often, conditions in the field depart appreciably from these assumptions and cause recovery observations that depart from ideality. The field data will reflect boundary conditions, regional changes in water level, interaquifer leakage, slow drainage, partial penetration, and other more localized effects. All of the above criteria alter the shape and slope of the semi-log curves. Deviation from the ideal solution of equation 2 does not preclude its use as a first approximation of T.

Jacob (1963) showed that hysteresis in the storage coefficient, during recharge (S') and discharge (S) cycles, will account for non-linearity observed in most semi-log plots of the field data, and furthermore, the ratio of the storage coefficients ($\frac{S}{S'}$) has a finite value at the intercept for zero drawdown.

Practical considerations during the testing of CCH-3 precluded the possibility of reaching equilibrium prior to measuring the recovery and required that pretest static water levels be estimated or projected from the recovery curves.

Test 1

The first hydraulic test of Colorado Core Hole 3 was made in the open-hole saturated interval between 111.5 m (360 ft) and the intermediate depth of 290.5 m (953 ft). This test came at a time when well discharge was 600 m^3 per day (110 gpm) and coring was to commence. At a depth of 290.5 m (953 ft), the well had completely penetrated the Evacuation Creek Member of the Green River Formation and had intersected what appeared to be oil-bearing shale in the upper part of the Parachute Creek Member (fig. 2).

The first occurrence of water in the well bore was noted at approximately 111.5 m (360 ft), where an estimated 22 m^3 per day (4 gpm) of soap solution was injected into the compressed air stream. The discharge of formation water increased with depth, as shown in figure 4. Two criteria working simultaneously explain the gradual increase in well discharge:

(1) an increase in the aquifer transmissivity; and

(2) increase in jetting efficiency with increased submergence.

Geologic variations in the porous media, such as solution cavities, fracture frequency, and rock type are roughly correlative to abrupt changes in the slope of the curve in figure 4.

The hydraulic test involved a constant-rate withdrawal of fluid from the well by jetting, and at the end of the jetting period, measurement of water-level recovery in the well. A string of open-end drill rod, 283 m (928 ft), was used to inject compressed air into the well bore. The rising air column in the annulus entrains fluid, lifting it to the surface. A jetting system is highly inefficient and permits recirculation of the fluid within the annulus. Recirculation of the water is likely to affect its initial chemical quality.

Over a 4-hour jetting period that began at 2100 hours on October 19, 1967, the average discharge (Q) recorded at the weir was 600 m^3 per day (110 gpm). Prior to completion of the jetting period, samples of the well discharge were collected for chemical analysis.

The recovery period for test 1 started at 0056 hours on October 20, 1967, and terminated at 0300 hours the same day. Figure 6 is a semi-log plot of depth to water versus the ratio of total time (t) divided by recovery time (t'). The S-shaped curve in figure 6 is typical of tests exhibiting hysteresis in the storage coefficient.

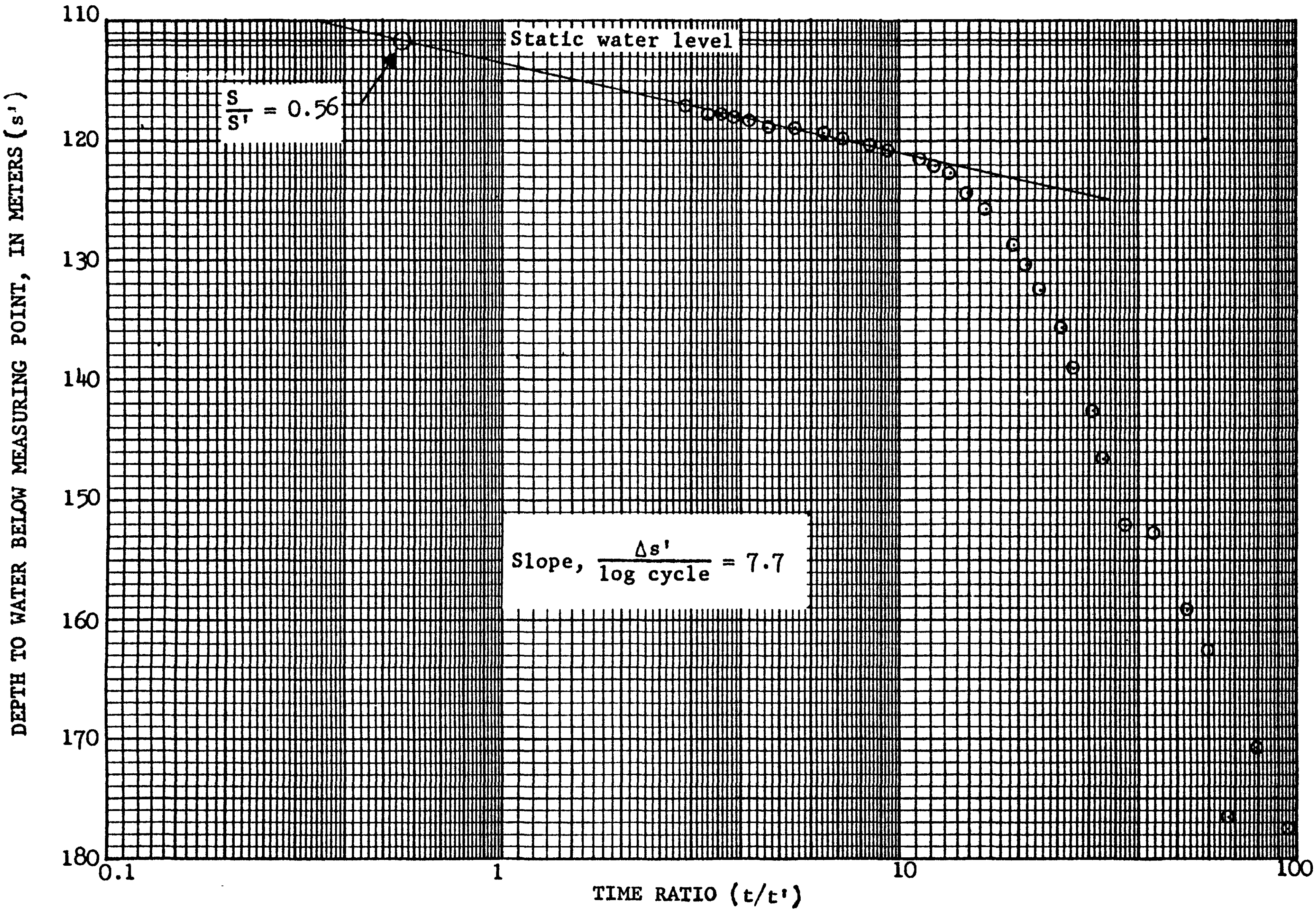

Figure 6.--Test 1, USBM-AEC Colorado Core Hole 3.

The static water level in the well is assumed to be 112 m (367 ft) below land surface, the depth at which water was first encountered during drilling. The water level, measured one hour before the start of the test, was 118 m (387 ft). Sufficient time could not be allowed for the system to completely recover from the fluid withdrawals during drilling. Two hours after recovery began, when $\frac{t}{t'}$ in figure 6 is equal to 2.92, the water level in the well had nearly recovered to the static level.

Using the line slope from figure 6 and a Q of 600 m^3 per day (110 gpm), the calculation of T from equation 2 is equal to 14 m^3 per day (1,100 gpd per ft). Water density changes during the test are neglected. The magnitude of $\frac{S}{S'}$ equal to 0.56 was also evaluated from figure 6 at the line intercept with the static water level. Had $\frac{S}{S'}$ been unity, it would imply an artesian response to the applied stress with essentially two-dimensional flow and no dewatering of the sediments. Actually, the prototype conditions for this test and the others only begin to satisfy the basic assumptions, and the quantitative results are, at best, a first approximation.

Test 2

The second hydraulic test was made when the core hole was 456.3 m (1,496 ft) deep. The test interval extended from 111.5 m (360 ft) to the bottom of the hole, 456.3 m (1,496 ft).

Two criteria, during drilling, prompted this hydraulic test. First, well discharge had leveled off to air compressor limitation (fig. 4) and secondly, the core from this interval was highly fractured and brecciated. All coring below the first test interval (fig. 2) was in highly fractured and leached oil shale of the upper Parachute Creek Member of the Green River Formation. Ground-water circulation dissolved most of the salt-filled vugs, leaving a labyrinth of voids in the shale. Stress release in the formation has resulted in collapse brecciation.

Coring in this interval was slow, with frequent short runs, due to blocking of the core barrel. Similar lithology and drilling conditions were encountered in Colorado Core Holes 1 and 2. In previous reports (Carrol, Coffin, Ege, and Welder, 1967; and Ege, Carroll, and Welder, 1967), this part of the oil shale sequence is referred to as the incompetent zone or the zone of poor core recovery.

The procedure for this test was similar to test 1. Air injection through 444 m (1,456 ft) of open-end drill stem jetted the fluid to the surface. The jetting period began at 1300 hours on October 26, 1967. Discharge was continuously recorded at the weir. At 1830 hours on October 26, water samples were collected for chemical analysis. Equipment failure during the recovery part of this test forced its abandonment. A second 6-hour jetting period was started immediately. It began at 2200 hours on October 26, 1967, and continued until 0355 hours on October 27. Water was jetted from the well at an average rate of 2,000 m^3 per day (360 gpm).

Recovery data was measured for 6 hours from 0355 to 0955 hours on October 27, 1967. For the first 60 minutes of the recovery period, for $\frac{t}{t'}$ greater than 9.6 in figure 7, the response was very erratic. The premature rise of the water level shown in figure 7 may be explained by density variations. Aerated water in the well bore and drill stem is displaced by denser water from the formation. The aerated water columns retain anomalous levels until the fluid densities equilibrate. Additional error and scatter of the data is introduced by the electrical measuring device. Frothing and foaming at the water surface made the electrical water-level indicator difficult to read accurately.

The recovery data in figure 7 began to approximate a straight line after $\frac{t}{t'}$ reached 9.6. The slope of the line (7.1) and the jetting rate of Q of 2,000 m^3 per day (360 gpm) was used in equation 2 to calculate T equal to 52 m^2 per day (4,200 gpd per ft).

Test 3

A third hydraulic test was made at a depth of 633.4 m (2,078 ft). The test interval extended from 111.5 m (360 ft) to total depth. Coring from 456.3 m (1,496 ft) to 633.4 m (2,078 ft) penetrated leached and fractured shale that progressively changed with depth to dense unleached shale (fig. 2). The bottom of the leached zone is believed to be the base-level of ground-water circulation. The areal expanse of the leached zone is geologically restricted to the massive deposition of salt deposits near the stratigraphic center of the Piceance Creek Basin.

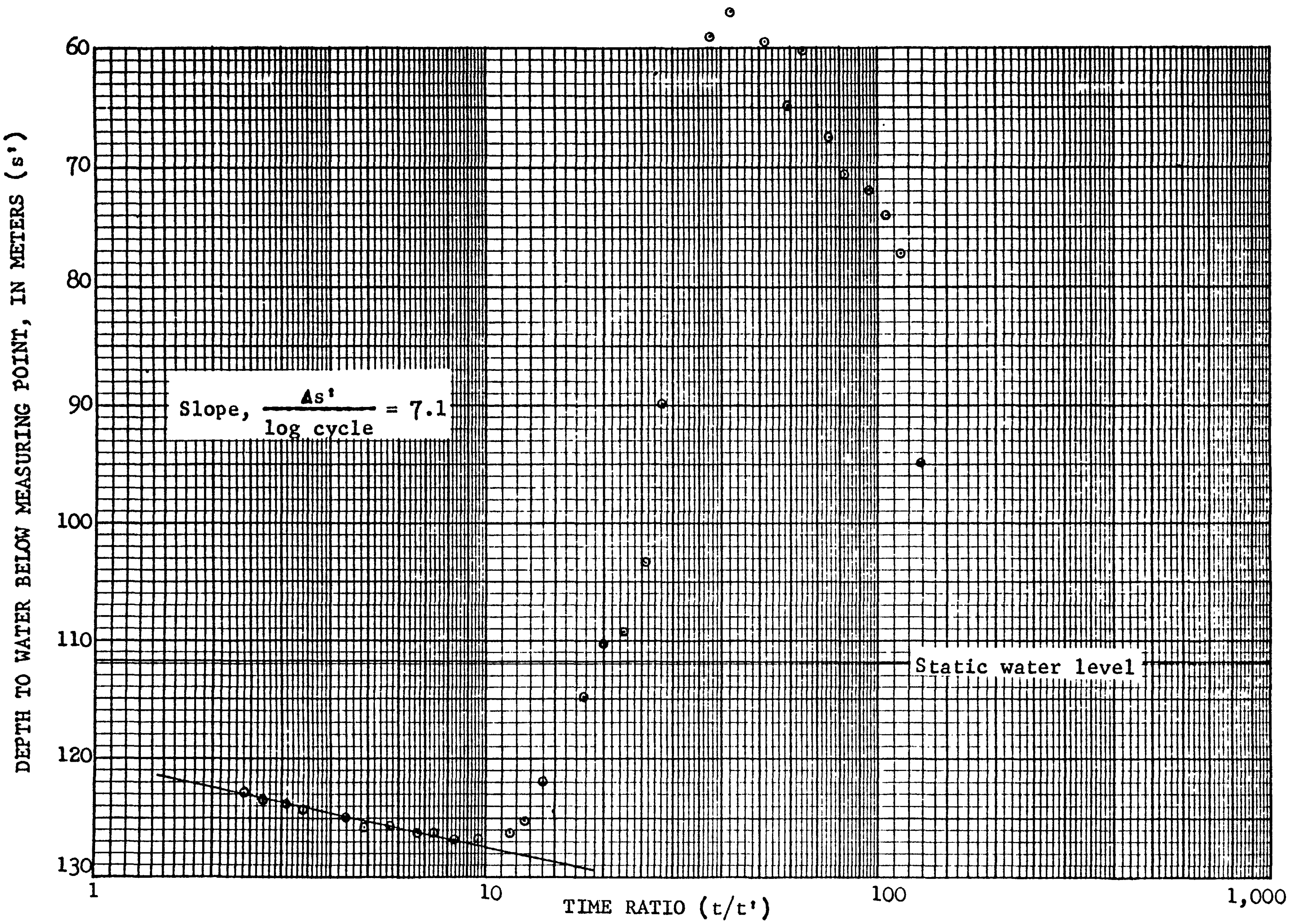

Figure 7.--Test 2, USBM-AEC Colorado Core Hole 3.

In a report by Carroll, Coffin, Ege, and Welder (1967), reference is made to the unleached oil shale as the competent zone, the zone of good core recovery, and they show it correlative to high resistivity on geophysical logs. The core barrel for the first time was completely filled while coring the last 15 m (50 ft) of the coring interval.

The unleached oil shale contains salt deposits as nodules and beds. Many of the fractures in the shale are filled with salt. The shale appears dense and impermeable. A solid bed of nahcolite and halite, 2.5 m (8 ft) thick, was encountered immediately below the test-3 interval (fig. 2).

Test 3 is important in the evaluation of the Project Bronco test site, for both safety and feasibility considerations. To make the most of this test an additional three-stage Magcobar compressor was added to the three compressors on location, nearly doubling the capacity for jetting. The additional air made it possible to jet the well at 3,000 m^3 per day (550 gpm). The increase in discharge, over test 2, was due to greater total submergence and to an increase in thickness of the saturated media.

Below the leached zone, at a depth of 580 m (1,900 ft), the formation is believed to be nearly impermeable to water movement and not part of the effective aquifer system. Only by packing off the leached zone, and jetting from below the packer, can the transmissivity of the competent oil shale be tested. As it was, the entire interval from 111.5 m (360 ft) to 633.4 m (2,078 ft) was open to production.

Two suites of chemical samples were taken from the well. Sample 68-635 was collected after 2¼ hours of jetting at an average rate of 2,700 m^3 per day (490 gpm) through 630 m (2,066 ft) of open drill rod. The second sample, 68-636, was collected during the jetting period for test 3.

Jetting with both compressor units through 427 m (1,400 ft) of open drill rod began at 1230 hours on November 3, 1967, and continued until 1200 hours on November 4, 1967. The average discharge during the test was 3,000 m^3 per day (550 gpm). The tremendous force of both compressor units running wide open blew some of the discharge beyond the sump. Most of the blowby was measured with a 3-inch flume and added to the weir measurements.

The recovery period for this test began at 1700 hours on November 4, 1967, and continued for 12 hours. Figure 8 is a semi-log plot of the recovery data. The slope of the line in figure 8 and a Q of 3,000 m^3 per day (550 gpm) were used in equation 2 to calculate T equal to 75 m^2 per day (6,000 gpd per ft). This transmissivity (T) is considered reasonable despite density effects in the early recovery data and fracture control of the flow system.

Test 4

Test 4 is perhaps the most important of the four tests for site evaluation as it relates to Project Bronco feasibility. Rocks in the vicinity of the proposed shot point at 1,021 m (3,350 ft) below land surface must contain the nuclear detonation and isolate the rubble chimney from flooding and the possible spread of radioactive contamination.

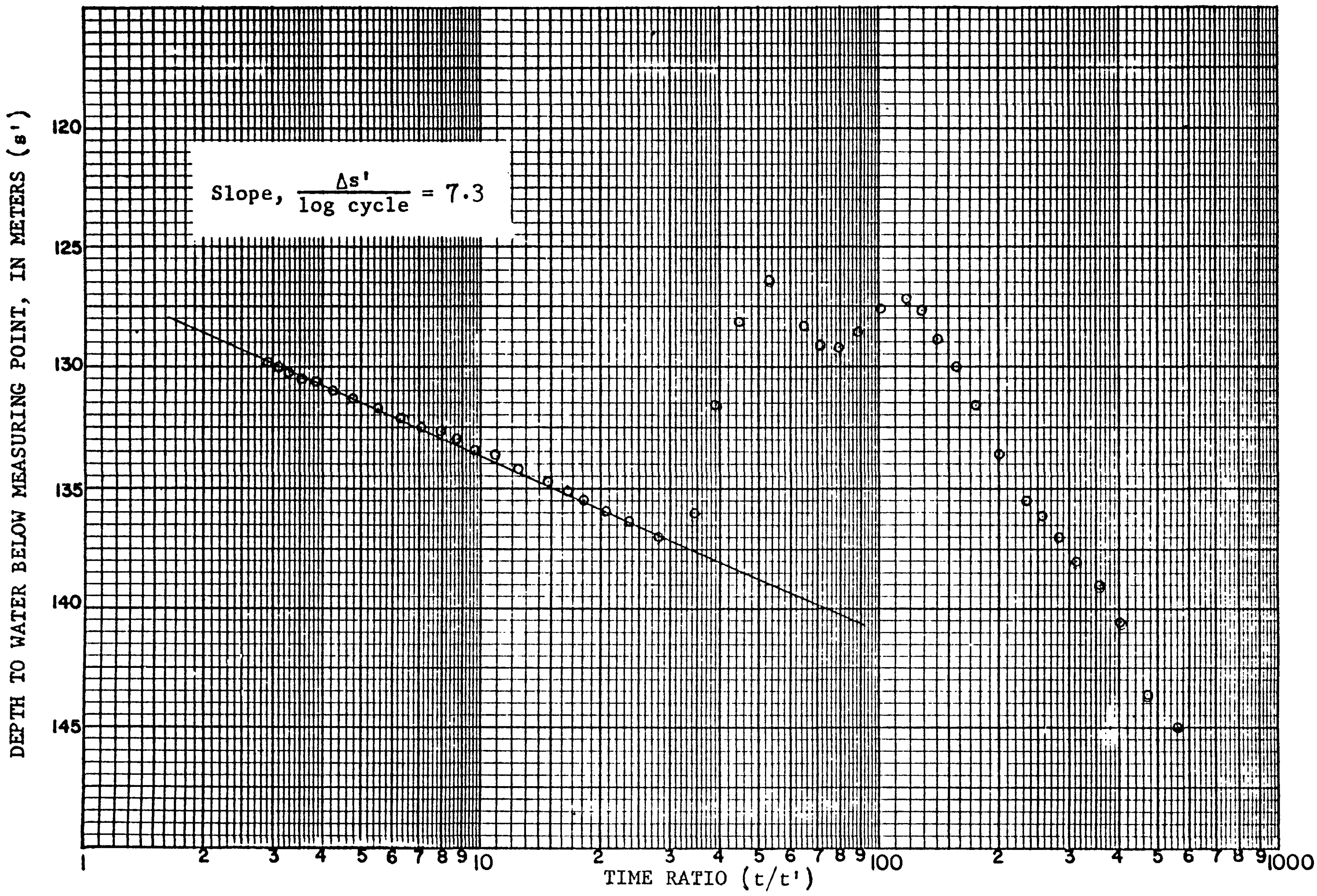

Figure 8.--Test 3, USBM-AEC Colorado Core Hole 3.

The well was core drilled from 633.4 m (2,078 ft) to 1,011 m (3,314 ft). The remainder of well was drilled with a rock bit to total depth of 1,154.7 m (3,786 ft). Caving of the Douglas Creek Member of the Green River Formation (fig. 2) forced termination of drilling short of the objective depth of 1,190 m (3,900 ft).

According to the drilling contractor, past drilling experience in the Piceance Creek Basin indicated that downhole explosions during drilling occur when the bottom-hole pressure exceeds about 34.5 bars, equivalent to 500 psi (pounds per square inch). Pockets of raw gas are known to occur in the lower part of the Parachute Creek Member and in the sandy facies of the Douglas Creek Member of the Green River Formation. It is highly probable that hydrostatic pressure above 34.5 bars (500 psi) relates to depth and the possible occurrence of gas pockets, but it is doubtful that pressure alone is the catalyst of downhole explosions.

In the interest of caution, the drilling contractor set 19.4-cm (7-5/8-in) casing at a depth of 688.5 m (2,258 ft) (fig. 3), mainly to relieve the working pressure on the compressors. Below the casing, core drilling continued with dry air as a circulating medium. At a depth of 951 m (3,120 ft) a sandstone facies of the Douglas Creek Member called the Piceance Creek Sand by Ritzma (1956) yielded the first occurrence of water below the casing. Detergent solution was immediately added to the circulating system to prevent balling of the cuttings and reduce rod friction. Other sandy layers interbedded in siltstones and shale, encountered below 951 m (3,120 ft), also produce water. For test 4 the entire geologic section below 920 m (3,013 ft) to total depth is assumed to be an effective aquifer unit (fig. 2).

Before test 4 was started, the well had caved-in below 989.4 m (3,245 ft) (fig. 2). As a safety precaution, the jetting rod for the test was set at 975 m (3,200 ft), putting it above the caving hazard. Jetting from the well began at 1615 hours on November 19, 1967. The recorded discharge rate declined very gradually during the entire 12-hour jetting period. Since equilibrium was not attained, it is likely that the well could eventually be blown dry. The average recorded discharge during the jetting period was 60 m^3 per day (11 gpm) with more than 600 m (1,970 ft) of drawdown. The specific capacity, defined as the ratio of discharge to drawdown, in consistent units, is less than 0.1. Chemical sample 68-638 was collected at 0400 hours on November 20, 1967, just before termination of the jetting period.

Recovery data were measured for about $1\frac{1}{4}$ days beginning at 0430 hours on November 20, 1967. Figure 9 is a semi-log plot of the recovery data. The slope of line in figure 9 and a Q of 60 m^3 per day (11 gpm) were used in equation 2 to calculate T equal to 0.01 m^2 per day (1 gpd per ft). If the well bore had been clean during this test, the transmissivity (T) might have been one order of magnitude larger, 0.1 m^2 per day (10 gpd per ft).

A water level of 305.5 m (1,002 ft) below land surface was measured on November 19, 1967, at 1600 hours. No fluid had been jetted from the well since 0230 hours on November 18; thus, a partial return to equilibrium resulted prior to the start of test 4. The water level after jetting was 267.7 m (878 ft) by 1226 hours on November 21, 1967. Curvilinear projection of the final recovery measurements would place the static water level around 200 m (656 ft) below land surface. The projected static level was used in figure 9 to evaluate $\frac{s}{s'}$ equal to 1.3.

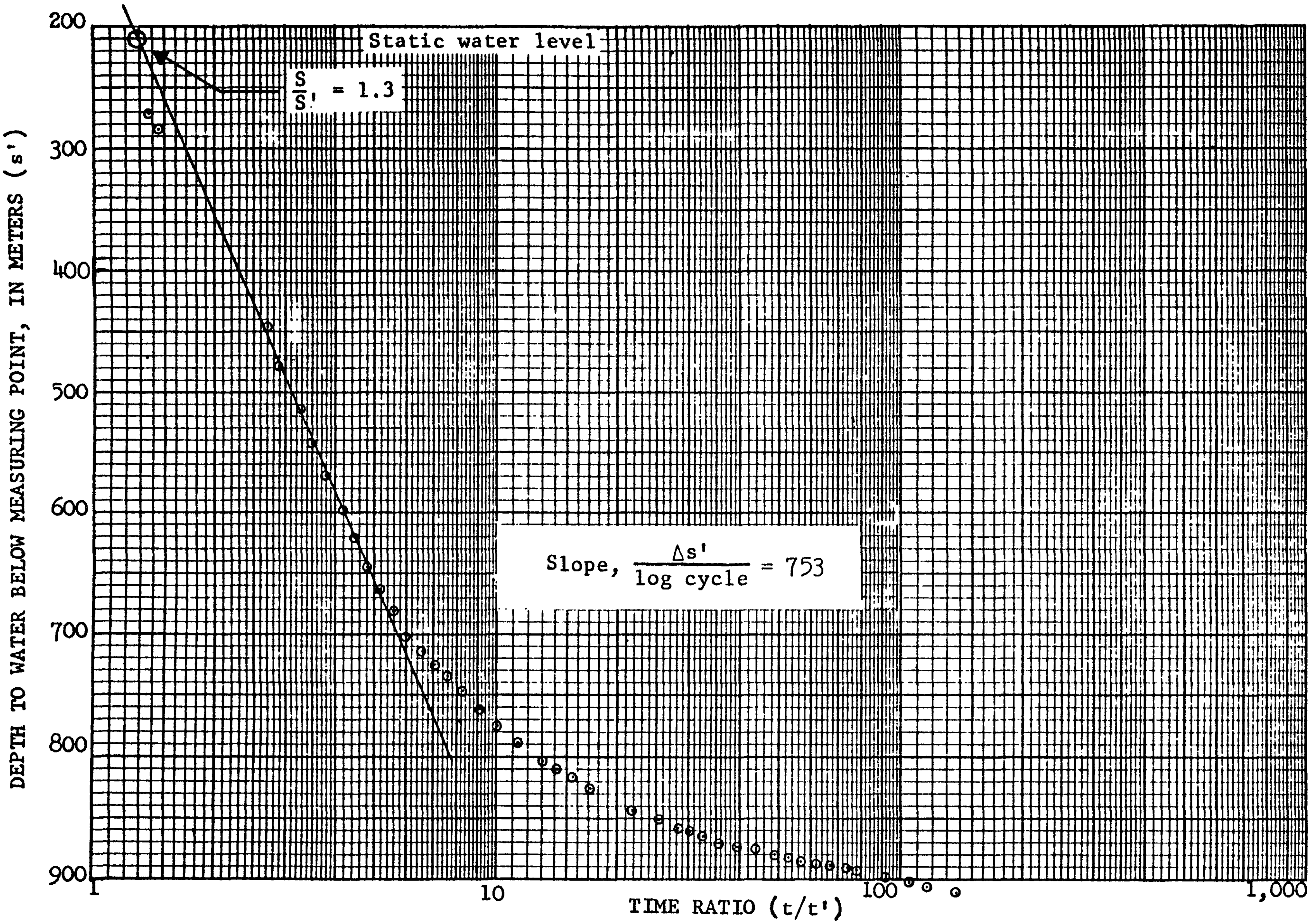

Figure 9.--Test 4, USBM-AEC Colorado Core Hole 3.

A summary of the hydraulic test data is shown in table 1. Results of chemical analyses are presented in the next section.

CHEMICAL ANALYSES OF CCH-3 WATER SAMPLES

Water samples were collected from various depths during the drilling and testing of CCH-3. Table 2 describes the pertinent information relating these samples to the hydrologic system and to each other.

The results of the general chemical analyses, table 3, show a significant increase in dissolved-solids content with depth. The general trend is recognized even if the magnitude of change is somewhat affected by recirculation within the well bore during sampling.

Analyses of samples 68-637 and 68-638 are distinctly different and certainly originate from separate aquifers and lithologies. Water from the deepest zone, sample 68-638, showed a reversal in the anion concentration of carbonate and bicarbonate. Both of these constituents had been steadily increasing with depth (table 3). The chloride ion concentration of sample 68-638 increased five times in relation to the previous sample (68-637). A sharp change in ionic ratios suggests the presence of a geologic contact, somewhere between the two sampled intervals. The bottom-hole water may be fluid derived from the original evaporite environment.

The Denver Hydrogeochemical Laboratory, U.S. Geological Survey, analyzed samples 68-630 and 68-635 for tritium content and reported both samples below 400 tritium units. These analyses provide background data to be used in assessing the effects of Project Bronco.

Table 1.--Summary of hydraulic-test data for USBM-AEC Colorado Core Hole 3

	Test 1	Test 2	Test 3	Test 4
Interval tested, meters (feet) below lsd[1]	111.5-290.5 (360-953)	111.5 -456.3 (360-1,496)	111.5 -633.4 (360-2,078)	920-1,154.7 (3,018-3,786)
Static water level, meters (feet) below lsd[2]	112 (367)	118 (387)	124 (407)	200 (656)
Jetting depth, meters (feet) below lsd	283 (928)	444 (1,456)	427 (1,400)	975 (3,198)
Jetting pressure, bars (psi)	12.8 (186)	20.4 (295)	20.1 (292)	10.3 (150)
Jetting time, min.	236	515	1,353	732
Air volume,[3] m^3 per day (cfm)	49 x 10^3 (1,200)	49 x 10^3 (1,200)	100 x 10^3 (2,500)	49 x 10^3 (1,200)
Average well discharge,[4] m^3 per day (gpm)	600 (110)	2,000 (360)	3,000 (550)	60 (11)
Water level recovery period, min.	123	360	732	1,909
Transmissivity (T) m^2 per day (gpd per ft)	14 (1,100)	52 (4,200)	75 (6,000)	0.01 (1)
Estimated specific capacity m^3 per day per mdd[5] (gpm per ft dd)	[6]7.6 (0.42)	--	--	[7]0.1
$\frac{S}{S'}$[8]	0.56	--	--	1.3

[1] Land surface datum.
[2] Projected from recovery curves.
[3] Derated estimate.
[4] Recorded by weir, corrected for losses.
[5] Mdd, meter of drawdown; ft dd, foot of drawdown.
[6] After 4 hours.
[7] After 12 hours.
[8] S, storage coefficient during pumping; S', coefficient during recharge.

Table 2.--Water samples from USBM-AEC Colorado Core Hole 3

U.S.G.S. lab. no.	Sampled zone		Type[1] of analysis	Date collected	Time	Jetting time (hours)	Jetting rate		Specific[2] conductance (micromhos per cm at 25°C)	Temperature	
	meters below lsd	feet below lsd					m^3pd	gpm		°C	°F
68-630	111.5 - 290.5	360 - 953	G, M, T	10-20-67	2400	3	600	110	e470	15.5	60
68-631	111.5 - 370.6	360 - 1,216	G, M	10-22-67	1345	0.75	e1,100	e200	e600	15.5	60
68-632	111.5 - 431.6	360 - 1,416	G, M	10-25-67	1125	1	1,600	300	700	15.5	60
68-633	111.5 - 456.3	360 - 1,496	G, M	10-26-67	1830	6	2,000	370	800	17.8	64
68-634	111.5 - 542.5	360 - 1,780	G, M	10-31-67	1400	1.5	2,500	460	9,000	18.3	65
68-635	111.5 - 633.4	360 - 2,078	G, M, T	11-3-67	0945	2.25	2,700	490	25,000	21.1	70
68-636	111.5 - 480	360 - 1,575	G, M	11-4-67	0715	23.5	3,000	550	14,000	22.2	72
68-637	688.5 - 960.7	2,259 - 3,152	G, M	11-16-67	1545	1	e60	e11	32,100	15.5	60
68-638	688.5 - 975.4	2,259 - 3,199	G, M	11-20-67	0400	11.5	60	11	e45,000	16.7	62

[1] G, general; M, minor elements; T, tritium. [2] Field determination.
e Estimated value.

Table 3.--Chemical analyses of water from USBM-AEC Colorado Core Hole 3

(Results in milligrams per liter except as indicated)

Lab. no.	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Lithium (Li)	Carbonate (CO_3)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (Fl)	Nitrate (NO_3)	Boron (B)	Orthophosphate (PO_4)	Strontium (Sr)	Dissolved solids (residue at 180°C)	Hardness as $CaCO_3$: Calcium magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (µmhos at 25°C)	pH	Percent sodium	Sodium absorption ratio
68-630	21	0.02	12	0.01	196	0.3	0.06	16	386	137	6.4	0.4	0.1	0.18	<0.01	3.7	602	75	0	1,040	8.5	85	9.9
68-631	21	.05	10	.02	225	.4	.07	14	515	130	6.4	1.2	.0	.25	<.01	3.7	717	112	0	1,070	8.5	81	9.3
68-632	16	.03	5.6	<.01	250	.2	.08	16	621	54	6.3	9.4	.1	.38	<.01	1.6	718	66	0	1,090	8.5	89	13.0
68-633	15	.03	5.2	<.01	280	.4	.08	16	655	40	5.9	11.0	.1	.62	<.01	1.4	704	55	0	1,120	8.5	92	16.0
68-634	17	.13	4.1	.01	3,880	9.2	.64	422	8,640	28	294	24	.0	2.1	2.2	.88	8,900	40	0	11,400	8.4	99	269.0
68-636	18	.07	4.1	<.01	7,200	28	.83	118	18,600	25	780	28	.0	3.4	4.7	.86	17,500	42	0	20,200	8.5	99	486.0
68-635	18	.21	3.4	<.01	10,700	48	1.5	884	26,800	24	1,180	34	.0	4.6	7.3	.60	26,500	32	0	27,500	8.3	100	823.0
68-637	21	10	8.8	.12	16,000	30	2.5	5,100	31,500	45	3,700	3.4	.0	3.4	7.0	.08	37,800	63	0	39,700	8.9	100	877.0
68-638	17	4.6	11	.17	18,400	71	3.3	3,210	14,100	205	18,800	2.8	.0	3.1	.16	4.4	48,700	267	0	50,300	8.8	99	490.0

CHIMNEY FLOODING

The in-situ method of retorting oil shale, proposed in the Project Bronco experiment, assumes a dry rubble chimney. Figure 10 illustrates the anticipated geometry of the proposed chimney (U.S. Atomic Energy Comm., 1967), and related hydrologic regime. Hydraulic testing of CCH-3 indicates inflow into the chimney can be expected from below the leached zone and from the leached zone itself if hydraulic continuity is established. Each probable source of inflow is analyzed separately using available mathematical models. In view of the complexity of the hydrologic regime, the limited amount of available data and the fact that the basic assumptions of the analytical models vary significantly from actual conditions, the predictions of chimney flooding should be regarded only as first approximation. Use of other analytical models and their application to data from the Piceance Creek Basin is under consideration by the USGS. As additional knowledge and computation techniques become available, the approximations can be revised.

Inflow to chimney from below the leached zone

Inflow to the chimney from below the leached zone is imperative. The most favorable economic criteria for chimney flooding is to assume complete confinement of both the rubble chimney and its fracture zone, below 623.6 m (2,045 ft). Chimney development would remain within the quasi-impermeable oil shales of the competent zone. Under such conditions, inflow to the chimney would originate from a few porous sandstone lenses in the Garden Gulch and Douglas Creek Members of the Green River Formation (fig. 2). A transmissivity for this zone of 0.1 m^2 per day (1 gpd per ft) was calculated from test 4.

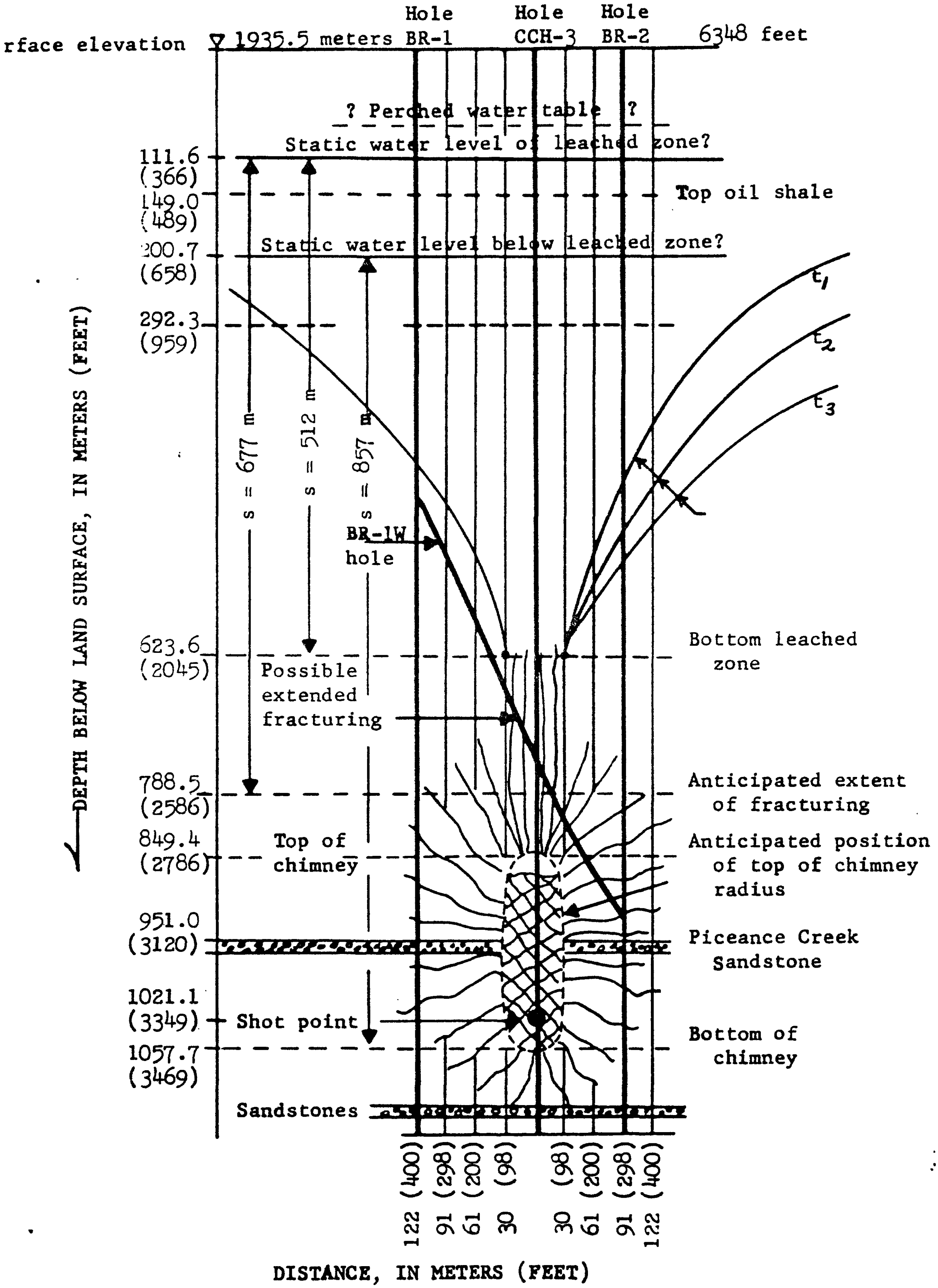

Figure 10.--Diagrammatic sketch of Project Bronco rubble chimney.

The pumping rate required to dewater the proposed rubble chimney depends on the inflow from the surrounding aquifers. A first approximation of the inflow rate (Q) can be calculated from the constant head, variable discharge equation, of Jacob and Lohman (1952),

$$Q = 2\pi T s_w G(\alpha) \tag{3}$$

where $G(\alpha)$ and α are defined as:

$$G(\alpha) = \frac{4\alpha}{\pi} \int_0^\infty x e^{-(\alpha x^2)} \left[\frac{\pi}{2} + \tan^{-1} \frac{Yo(x)}{Jo(x)} \right] dx$$

$$\alpha = \frac{Tt}{r_w^2 S}$$

and

Q = discharge of well, in m^3 per day

T = transmissivity, in m^2 per day

S = storage coefficient

t = time, in days

r_w = effective radius of discharge well, in meters

s_w = drawdown in discharge well, in meters.

The terms $Jo(x)$ and $Yo(x)$ are Bessel functions of zero order, the first and second kinds respectively. The integration is made by numerical methods, and values of $G(\alpha)$ for α are tabulated by Jacob and Lohman (1952, p. 561).

Equation 3 assumes total drawdown at initial time (t_o). Immediately after detonation and for an undetermined period, extreme temperature and pressure will create a cavity void of fluid, which is comparable to an instantaneous drawdown of 857 m (2,811 ft) in a hypothetical well completed to the base of the chimney. As the chimney pressures dissipate, inflow to the chimney will begin. Figure 11 is a composite plot of the pumping regime calculated to balance the inflow from formations below the leached zone and maintain a dewatered chimney. If the chimney had been partially filled prior to pumping, the pumping rates would be slightly higher to account for the drainage of the rubble chimney. No attempt is made to adjust the curves in figure 11 for changes in T due to dewatering the aquifer.

Inflow to the chimney from the leached zone

Flow into the rubble chimney from the overlying leached zone may occur if a hydraulic connection is established. Extensive vertical fracturing associated with formation of the rubble chimney may intersect the leached zone to complete such a permeable avenues of flow. Sealing of any connecting fractures would eliminate the necessity of dewatering the entire leached zone to keep the chimney dry and isolate radioactive contaminants. Dewatering the leached zone should be considered only after freezing, chemical grout, or other methods of fracture sealing fail.

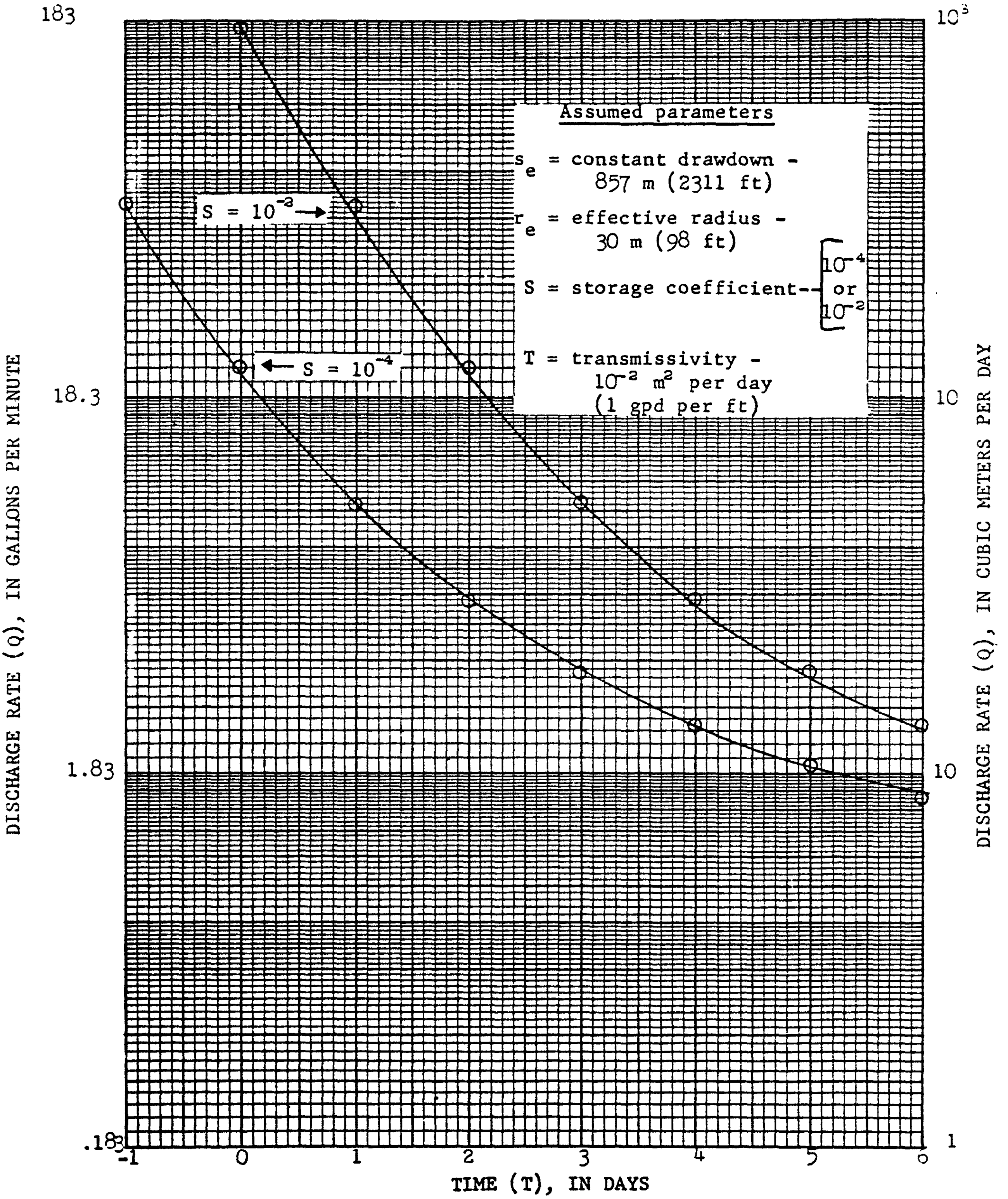

Figure 11.--Variable pumping regime to balance inflow from below the leached zone.

Two calculations were made to determine the pumping regime and time required to dewater the entire leached zone over a 30-m (98-ft) radius. One calculation used equation 3; the second calculation employed the Theis equation (Ferris and others, 1962),

$$s_w = \frac{Q}{4\pi T} \int_o^\infty \frac{e^{-u}}{u} \, du \qquad (4)$$

where

$$u = \frac{r_w^2 S}{4Tt} .$$

The other parameters were previously defined. For values of u >0.02, the integral in equation 4 is approximated by an expanded series for which tables are available.

The transmissivity of the leached zone was measured during test 3. For fracture controlled media, S. W. Lohman (oral commun., 1968) suggests a storage coefficient of 1.830×10^{-6} per meter of saturated material. Other assumed parameters are indicated on the curves.

The curves in figure 12 are unique solutions to equations 3 and 4, uncompensated in regard to the extent to which certain of the basic model assumptions disagree with field conditions. For example, dewatering of the aquifer decreases the transmissivity and increases the storage coefficient by several orders of magnitude. Since the ratio $\frac{S}{T}$ (diffusivity) is increased by dewatering, the actual field data should fall between the respective extremes in figure 12. The error involved in this analysis is greater during the early pumping period.

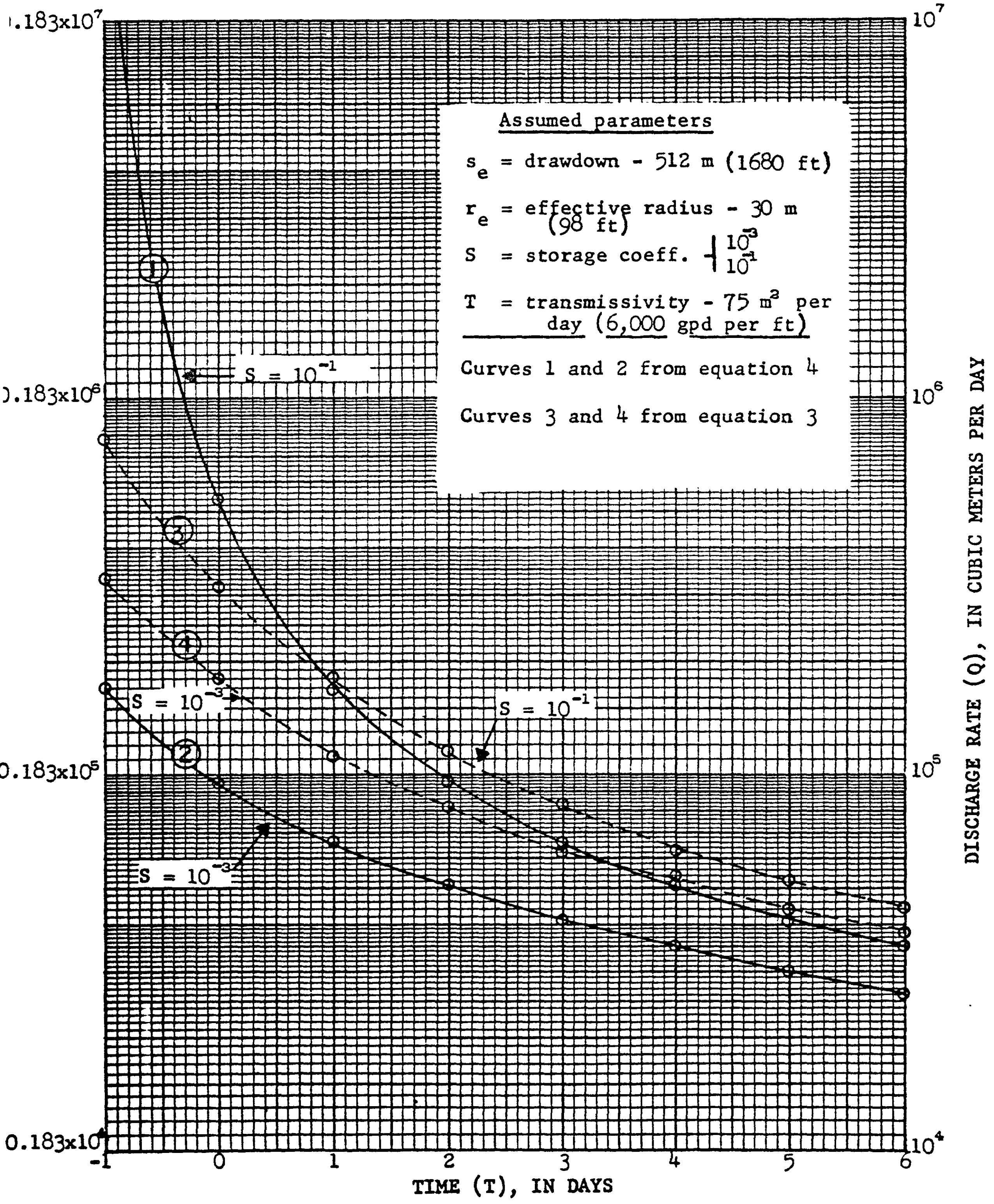

Figure 12.--Variable pumping regime to dewater the leached zone over one chimney radius.

CONCLUSIONS

During drilling and testing of CCH-3 the local geohydrologic characteristics of the Piceance Creek Basin were evaluated at the proposed Project Bronco test site. The data complement existing regional hydrologic concepts outlined in previous reports. A thorough knowledge of the regional hydrology of the Piceance Creek Basin must be understood if the safety and feasibility of Project Bronco are to be insured.

The major water-bearing aquifer intersected by CCH-3 is the leached zone of the Parachute Creek Member. During geologic time, the natural circulation of ground water through the upper and middle parts of the oil shale formation dissolved much of the syngenetic salt deposits and formed a highly porous zone of interconnected vugs and channels. This process is undoubtedly in operation today. Results of hydraulic tests indicate that a copious quantity of saline water, about 3,000 m^3 per day (550 gpm), can be pumped from wells in the leached zone. The transmissivity of the dissolution zone, about 50 to 70 m^2 per day (4,025 to 5,640 gpd per ft), is obviously related to the extent of leaching and fracturing.

A gradual increase in the specific conductance of the discharge fluid was recorded during the drilling of CCH-3. Formation water, at depth, in equilibrium with partially leached salt, would be expected to contain higher concentrations of dissolved solids. Also, water that is brought into contact with salt deposits in the well bore will dissolve additional salt during jetting. Therefore, the observed increase in specific conductance with depth may be attributed to a combination of both natural and man-made phenomena.

From interpretation of the IES (induction-electrical survey) log of CCH-3, the bottom of the leached zone is 623.6 m (2,045 ft) below land surface. The base of the leached zone is the lower boundary of a hydrologic unit.

Immediately below the leached zone, to a depth of 940 m (3,083 ft) are nearly 320 m (1,050 ft) of quasi-impermeable oil shale. Nearly 262 m (859 ft) of dry formation were drilled from below the casing shoe at 688.5 m (2,259 ft) to the first water-bearing sands at 950 m (3,120 ft). These same water-bearing sands yield gas and a liquid form of hydrocarbon. They are probably correlative to the Piceance Creek sandstones that produce gas in the Piceance Creek gas field (Ritzma, 1965).

Below the leached zone, the water-bearing sands yielded a small quantity, 60 m^3 per day (11 gpm), of highly saline brine during a pumping test. Laboratory measurements of dissolved-solids content in water from below the Parachute Creek Member revealed concentrations in excess of 4×10^4 mg/l. This fluid is probably the original lacustrine brine entrapped in the sandy units of the Douglas Creek Member of the Green River Formation during deposition. The hydrostatic water level in this lower zone is estimated to be about 200 m (656 ft) below land surface. This is about 91 m (300 ft) below the hydrostatic water level in the upper leached zone. No hydraulic connection between the leached zone and the deeper water-bearing sands is evident in CCH-3. It is possible that both water-bearing zones have a common source of recharge at the basin rim and that the differential head in CCH-3 represents a difference in transmissivity of the two aquifer zones. If the hydrostatic differential is a temporary condition brought on by drilling and testing, it will eventually equilibrate. Given sufficient time, any residual variations in hydrostatic potential can be measured and integrated into the basin concept. Additional testing should be scheduled to determine if natural circulation patterns exist within the leached zone.

The apparent ease of fluid movement through the leached zone may cause concern for both the feasibility and safety of Project Bronco. Hydraulic communication between the rubble chimney and the water-bearing formations will result in chimney flooding and the possible dispersion of radioactive nuclides. An understanding of the nature and extent of contaminant transport would require a thorough knowledge of the regional hydrologic regime.

A prerequisite to the feasibility of Project Bronco is a dry rubble chimney for in-situ retorting of the oil shale. Flow into the rubble chimney will occur from the sandy layers of the Douglas Creek Member of the Green River Formation. A first approximation of the pumping regime that would be needed to maintain a dry chimney was calculated from the test data; the pumping rate would be less than 10 m^3 per day (less than 2 gpm) within six days after inflow begins.

Vertical inflow to the chimney from the overlying leached zone will occur if hydraulic communication is established. The greater hydrostatic head in the leached zone will cause downward circulation through the chimney and into the lower water-bearing zone. The only way that circulation could take place from the chimney into the leached zone is by a reversal of the head relationship that has been observed in CCH-3. The area of discharge for the lower water-bearing zone is not known and, to insure the safety of Project Bronco, this information should be obtained.

Dewatering the leached zone beyond one chimney radius would provide a partial solution to the problem of chimney flooding. This may not be practical, however, in view of the large pumping requirements. Calculations of the pumping history to dewater the leached zone were made from two mathematical models. The curves in figure 12 indicate pumping rates in excess of 2 x 10^4 m^3 per day (3,660 gpm) after 6 days. The change in the pumping regime with time is decreasing slowly after 6 to 10 days, thus the above pumping rates will not decrease appreciably even after 1 year of continuous pumping.

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