AUBURN LOW-TEMPERATURE GEOTHERMAL WELL

Final Report

Prepared for

NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

Project Manager
Dr. Burton Krakow

and

U.S. DEPARTMENT OF ENERGY

Project Manager
Dr. David Lombard

Prepared by

DONOHUE ANSTEY AND MORRILL
Boston, Massachusetts

Principal Investigator
Mr. Robert S. Lynch

and

ENG, INC.
Boston, Massachusetts

Principal Investigator
Dr. Trevor P. Castor

449-ET-AES-82

NYSERDA Report 84-18

DECEMBER 1983

NOTICE

This report was prepared by Donohue Anstey and Morrill and ENG, INC. in the course of performing work contracted for and sponsored by the New York State Energy Research and Development Authority and the U.S. Department of Energy (hereafter the "Sponsors"). The opinions expressed in this report do not necessarily reflect those of the Sponsors or the State of New York and reference to any specific product, service, process or method does not necessarily constitute an implied or expressed recommendation or endorsement of same. Further, the Sponsors and the State of New York make no warranties or representations, expressed or implied, as to the fitness for particular purpose, merchantability of any product, apparatus or service or the usefulness, completeness or accuracy of any processes, methods or other information contained, described, disclosed or referred to in this report. The Sponsors and the State of New York make no representation that the use of any product, apparatus, process, method or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage resulting from, or occurring in connection with, the use of information contained, described, disclosed, or referred to in this report.

First Printing: December 1984

ABSTRACT

The Auburn well was drilled to explore for low temperature geothermal resources in central New York State. The Auburn site was selected based on: its proximity to the Cayuga County anomaly (30° C/Km), its favorable local geological conditions and the potential to provide hot water and space heating to two educational facilities. The well was drilled to a total depth of 5,250 feet and into the Pre-Cambrian Basement. The well was extensively logged, flow and stress tested, hydraulically stimulated, and pump (pressure transient analysis) tested. The low-temperature geothermal potential was assessed in terms of: geological environment; hydrological conditions; reservoir characteristics; and recoverable hydrothermal reserves. The average geothermal gradient was measured to be as high as 26.7°C/Km with a bottom-hole temperature of 126° ± 1° F. The proved volumetric resources were estimated to be 3.0×10^6 stock tank barrels (STB) with a maximum initial deliverability of ~11,600 STB/D and a continuous deliverability of ~3,400 STB/D. The proved hydrothermal reserves were estimated to be 21.58×10^{10} Btu based on a volumetric component (4.13×10^{10} Btu), and a reinjection component (17.45×10^{10} Btu). The conclusion was made that the Auburn low-temperature reservoir could be utilitzed to provide hot water and space heating to the Auburn School District.

ACKNOWLEDGEMENTS

Donohue Anstey & Morrill acknowledges the support, commitment and cooperation given by the New York State Energy Research and Development Authority (NYSERDA) and its project management team of Dr. Burton Krakow and Mr. Parker Mathusa in the conduct of Contract No. 449-ET-AES-82, the Auburn low-temperature geothermal project in Cayuga County, New York. The work accomplished, as described in this report, is the result of contribution by many individuals and companies. The roster of companies and institutions is as follows:

- Arlington Exploration Company, Boston, MA.
- Cambridge Analytical Services, Watertown, MA.
- Centrilift-Hughes, Inc., Tulsa, OK.
- City of Auburn, Auburn, NY.
- Devonian Drilling Company, Washington, OH.
- Dunn Geoscience, Inc., Latham, NY.
- ENG, INC., Boston, MA.
- Empire State Electric Energy Research Corporation, New York, NY.
- Galson Technical Services, East Syracuse, NY.
- Gas Field Specialists, Inc., Pavilion, NY.
- Halliburton Services, Bradford, PA.
- Lynes, Inc., Houston, TX.
- Microbac Laboratories, Inc., Erie, PA.
- New York State Electric & Gas Corporation (NYSEG), Auburn, NY.
- Schlumberger-Doll Research, Ridgefield, CT.
- United States Geological Survey, Menlo Park, CA.

CONTENTS

ILLUSTRATIONS

TABLES

SUMMARY

The decision to explore central New York State for geothermal energy resources was made by the New York State Energy Research and Development Authority (NYSERDA) and the U.S. Department of Energy (DOE) on the basis of three complementary factors: geophysical evidence; commercialization potential; and geologic conditions. The geophysical evidence was provided by recent work of Dr. Dennis Hodge of the State University of New York at Buffalo in which positive geothermal gradient anomalies were identified to be as high as $15^{\circ}F/1,000$ ft. ($27^{\circ}C/km$) in the East Aurora region, and $16^{\circ}F/1,000$ ft. ($30^{\circ}C/km$) in the Cayuga County area. The Auburn site was picked by NYSERDA and DOE because: of its proximity to the Cayuga County anomaly; the potential existed to impact significantly the hot water and space heating requirements of the Auburn Enlarged School District in the City of Auburn; and its favorable local geologic conditions.

The development operations were conducted in three major phases:

- DRILLING, CORING AND COMPLETION
- LOGGING ACTIVITIES AND LOG ANALYSES
- RESERVOIR AND WELL TESTING

The development of the Auburn geothermal prospect was initiated in January 1982. The well was spudded in February 1982 and drilled to a total depth of 5,250 ft. into the Pre-Cambrian Basement. It was cored and partially completed by early March 1982.

The well was extensively logged throughout all phases of the program in order to characterize the Auburn region in terms of lithology, stratigraphy, hydrology, and geothermal activity. Additionally, the United States Geological Survey (USGS), with support by NYSERDA and the Empire State Electric Energy Research Corporation (ESEERCO), ran borehole televiewer logs to define the distribution and orientation of natural fractures as an aid to finding the most potentially useful zones for geothermal energy. To further support this activity, Schlumberger-Doll Research

ran a suite of computerized logs which included the traditional formation evaluation logs, as well as fracture identification, dipmeter and long-spaced sonic logs.

A preliminary flow test was conducted in April 1982 in order to evaluate the well's potential and the project's viability. The results of the test were encouraging in that: two major water productive zones were identified -- a 30-ft. interval in the Black River limestone starting at 4,150 ft. and a 310 ft. interval spanning the Theresa and Potsdam sandstones starting at 4,650 ft. and ending just above the Pre-Cambrian Basement; the downhole temperatures in the primary producing zone, i.e., the 310 ft. interval, ranged from 123.0^{o}F to 125^{o}F, with the Basement at 126^{o}F; and the instantaneous initial well productivity was estimated to be 300 gpm and 365 gpm at depths of 4,000 ft. and 5,000 ft., respectively. The project appeared at this stage to be worthy of further investigation because of the results of the preliminary flow tests and theoretical estimates that wellhead temperatures could be achieved between 120.0^{o}F - 125.0^{o}F.

The Auburn well was then stress tested, hydraulically stimulated, and pump tested to determine its near wellbore and reservoir characteristics. The stress tests were conducted by the USGS in April 1982 to measure the in situ state of stress in the Auburn region and thus, to predict the orientation and dimensions of an artificially induced fracture. The results of the stress tests were evaluated by Schlumberger researchers who predicted that an induced hydraulic fracture would strike vertically with an N85E strike.

The well was then completed in January 1983 to a depth of 4,700 ft. with a 7-in. production casing string set on a hook-wall packer. This open-hole completion was made to isolate the selected zones of interest, the Theresa and Potsdam formations, for hydraulic stimulation and further reservoir evaluation.

The purpose of the hydraulic stimulation was twofold: to increase the well's productivity; and to extend the well's drainage radius. The well was hydraulically fractured by Haliburton on April 07, 1983, in three stages with a maximum treatment pressure of 2,450 psi. The productivity of the well was most likely increased because the skin factor was subsequently calculated from the pressure transient data to be -5. The induced vertical hydraulic fracture was computed to be less than 10% of the estimated drainage radius of 2,500 ft.

The Auburn reservoir was pump tested over a seven-day period in August 1983. The pump test was designed to meet one of the primary objectives of this project, i.e., the definition of the hydrothermal resources within a commercialization perspective. The pump test design was based on: the results of the preliminary flow tests; values of net capacity estimated from geophysical logs; regional stratigraphy; and estimated values of fluid and reservoir parameters. The results of the pump test, the ensuing pressure transient analysis and supporting data, were used to assess the geothermal potential of the Auburn reservoir.

The low-temperature geothermal potential of the Auburn reservoir was assessed in terms of: geological environment; hydrological conditions; reservoir characteristics and recoverable hydrothermal resources. The geological environment was found to be in general conformance with the local and regional geological conditions. The average geothermal gradient in the Auburn well was measured to be as high as 14.7°F/1,000 ft. (26.7°C/km). Hodge (1983) believes that the anomalous gradient at Auburn is partially caused by hydrothermal convection in the fractured Pre-Cambrian Basement and by radiogenic decay, the latter theory is supported by traces of radiogenic material found in the Basement marble. The hydrological conditions were found to be favorable in that a major water-producing zone was found with a net productive sand of 310 ft., and the hydrostatic level in the wellbore was $\sim$350 ft. from the surface or +358 ft. above sea level.

The Auburn low-temperature geothermal reservoir appears to be finite and bounded and to be made up of as many as six different storage and flow regions. These regions consist of a low-porosity dolomitic zone, and a high-porosity sandstone zone both of which are naturally fractured and both of which were hydraulically fractured and propped prior to the test. The two producing zones of contrasting porosity are assumed to be in perfect communication with each other and viewed to be one producing interval with volume averaged properties. This assumption simplified the reservoir analysis by characterizing the Auburn reservoir by three distinct regions, each of which will have dominant flow regimes at different times during reservoir drainage and system shutdown periods.

The three distinct storage regions of the Auburn reservoir are as follows: The vertical hydraulic fracture, Region 1, was identified by the 1/2-slope of log-log plot of ΔP versus Δt, and was computed to have a half-length of $\sim$150 feet and a negative skin factor of 5; Region 2, the natural fractures and fissures or microcracks, was identified from the semilog drawdown and buildup plots and are estimated to be $\sim$26% of the total effective porosity; the porous matrix, Region 3, was computed to have an absolute porosity of 0.0282 (from log analysis), an effective porosity of 0.0027 (from the analysis of pump test data), and an effective permeability of 10 millidarcys. The average reservoir pressure, $\bar{P}$, in these three regions was estimated to be 2,260 psi.

The areal extent, volumetric resources, and reserves of the Auburn low-temperature geothermal reservoir are estimated to be as follows:

Table S-1

ESTIMATED VOLUMETRIC RESOURCES AND RESERVES IN STB

Category	Area (acres)	Resources (STB)	Reserves (STB)
Proved	462.7	3.0×10^6	2.25×10^6
Possible	1,079.5	7.0×10^6	5.25×10^6
Probable	967.3	23.0×10^6	17.25×10^6

The volumetric resources were estimated from reservoir limit tests utilizing pressure drawdown data. The volumetric reserves are based on an estimated recovery efficiency of 75%.

The hydrothermal reserves are made up of two components: a volumetric or in situ component based on the thermal capacity of the formation brine; and a reinjection component in which heat is recovered from the reservoir rock by reinjection of the spent brine. The reserves are defined in terms of the thermal energy recoverable by a wellhead temperature drop from 125°F to an operating temperature of 70°F with an 80% overall heat recovery efficiency. The hydrothermal reserves of the Auburn low-temperature well are estimated as:

Table S-2

ESTIMATED VOLUMETRIC AND REINJECTION HYDROTHERMAL RESERVES IN BTU

Category	Volumetric	Reinjection	Total
Proved	4.13×10^{10}	17.45×10^{10}	21.58×10^{10}
Possible	9.63×10^{10}	44.98×10^{10}	54.61×10^{10}
Probable	31.65×10^{10}	39.10×10^{10}	70.75×10^{10}

Without spent brine reinjection and reservoir recharge, the maximum sustained production rate of the Auburn well is ∿100 gpm over a 3.5-year lifetime of its volumetric reserves. The maximum recoverable thermal energy over six-month periods is thus, $\sim 1.15 \times 10^{10}$ Btu or ∿40% of the schools' Btu demand. Preliminary injectivity tests performed during the pump tests, together with log analysis, indicate that the spent geothermal brine can be reinjected down the annulus into the adjacent Black River Formation.

The production rate for tapping the geothermal potential by reinjecting or recirculating the spent geothermal brine was selected to be 286 gpm. This flow rate was averaged from the maximum drawdown rate for a pump setting at 4,000 ft., and the minimum drawdown rate which can meet the schools' average daily Btu demand. The selected production rate would supply 3.3×10^{10} Btu over a six-month period, or 117% of the schools' Btu demand. The proved lifetime of the reinjection reserves is estimated to be just in excess of 10 years.

Thus, the conclusion can be made that the Auburn low-temperature well can be utilized to provide space heating to the Auburn Middle School and the Cayuga Community College. This conclusion is made primarily on the reservoir's capacity and productivity. The engineering and economics of developing, constructing and operating a geothermal energy surface facility are yet to be evaluated.

Section 1

EXPLORATION RATIONALE

The decision to explore central New York State for geothermal energy resources was made by the New York State Energy Research and Development Authority (NYSERDA) and the U.S. Department of Energy (DOE) on the basis of three complementary factors -- geophysical evidence, commercialization potential, and geologic conditions.

The geophysical evidence was provided by recent work of Dr. Dennis Hodge of the State University of New York at Buffalo. Two positive geothermal gradient anomalies were located in western and central New York State. The anomalous gradients were identified and located by geothermal gradient, geochemical and gravimetric studies. The anomalies, located in East Aurora and Cayuga County, were estimated to be as high as 15°F and 16°F per 1,000 ft.

As a consequence of the geophysical evidence, NYSERDA elected to drill a test well to evaluate the geothermal resource potential of New York State. The athletic field of the Auburn Enlarged City School District was picked as the test site because of its proximity to the Cayuga County anomaly, and the potential that existed for tapping any realized geothermal resources to provide hot water and space heating to the East Middle School and the Cayuga Community College.

The regional and local geologic conditions which favored the exploration for a low-temperature geothermal resource are as follows: regionally, central New York State consists of a sequence of flat-lying carbonates, dolomites and sandstones; and locally, a hypothetical stratigraphic cross-section indicated potential water-bearing horizons in the Cambrian (Theresa and Potsdam) formations and the Pre-Cambrian Basement at depths (~5,000 ft.) capable of producing a low-temperature geothermal resource.

GEOPHYSICAL RATIONALE

The potential existence of geothermal energy resources in New York State is identifiable from the American Association of Petroleum Geologists (AAPG) temperature gradient map of the United States. The map reveals that two of the most prominent geothermal anomalies in the eastern United States are located in western and central New York State. Recent work by Hodge et al. (1981) confirms the existence and defines the location of two positive gradient anomalies:

- East Aurora anomaly with geothermal gradients as high as 15°F/1,000 ft. (27°C/km); and
- Cayuga County anomaly with geothermal gradients as high as 16°F/1,000 ft. (30°C/km).

These two geothermal anomalies were identified and located by Hodge et al. (1981) from revised temperature gradient maps using corrected bottom-hole temperature gradient anomalies with gravity anomalies of the Bouguer map, and estimated values of heat flows by silica geothermometry.

Geothermal Gradient Studies

The revised temperature gradient map, shown in Figure 1-1, was prepared using an automated contouring routine from a data set of 739 wells deeper than 1,650 ft. (500 m). The positive anomaly near East Aurora is delineated to the southeast of Buffalo. In the central portion of the state, the positive anomaly centered near Cayuga Lake has its peak between Rochester and Penn Yan.

Geochemical Studies

The mean regional heat flow in central and western New York State was estimated to be 41.4 mWm^{-2} (∿1.0 HFU) by Hodge et al. (1981) utilizing the silica-heat flow geothermometry method of Swanberg and Morgan (1977, 1978). Heat flows between 50-70 mWm^{-2} were computed along a line trending northeast-southwest through the Cayuga anomaly. Although the East Aurora anomaly was not as distinctly identifiable as the Cayuga anomaly, higher silica heat flow values tended to cluster in several distinct groups throughout an area which includes the East Aurora anomaly.

Gravimetric Studies

The Bouguer gravity map of central and western New York (Revetta and Diment, 1971), shown in Figure 1-2, correlates directly with the temperature gradient map in Figure 1-1. The pattern of the Bouguer anomalies can be separated into two distinct zones separated by a north-trending high-gradient area. The western area includes a prominent negative anomaly located near East Aurora. In the eastern part of the map, a low-amplitude negative anomaly is located about 12.5 miles (∿20 km) east of Rochester and extends in a north-south direction to the area

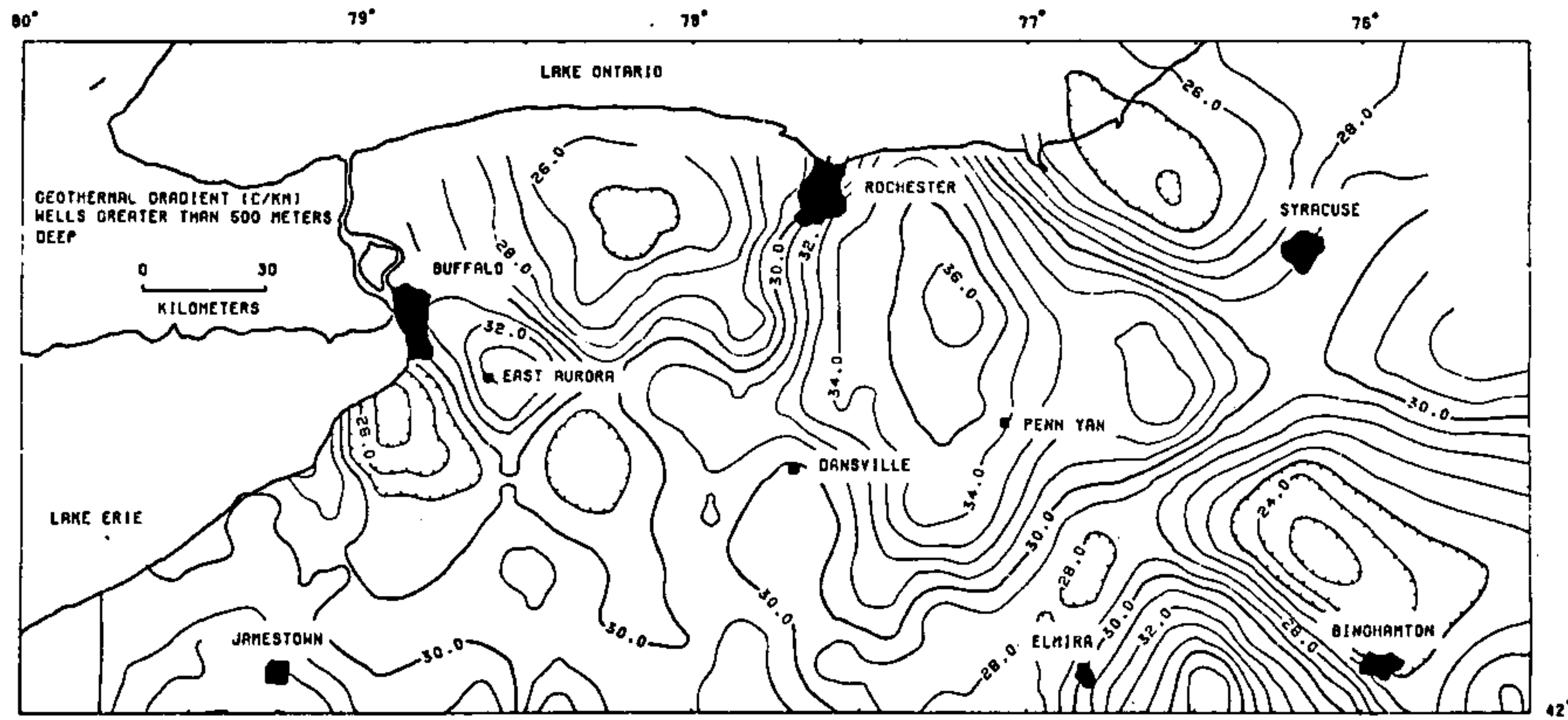


Figure 1-1. Contoured Temperature Gradients for all Wells Greater than 500 meters assuming Drilling Disturbance correction (Hodge, Hilfiker, Morgan and Swanberg, 1981)

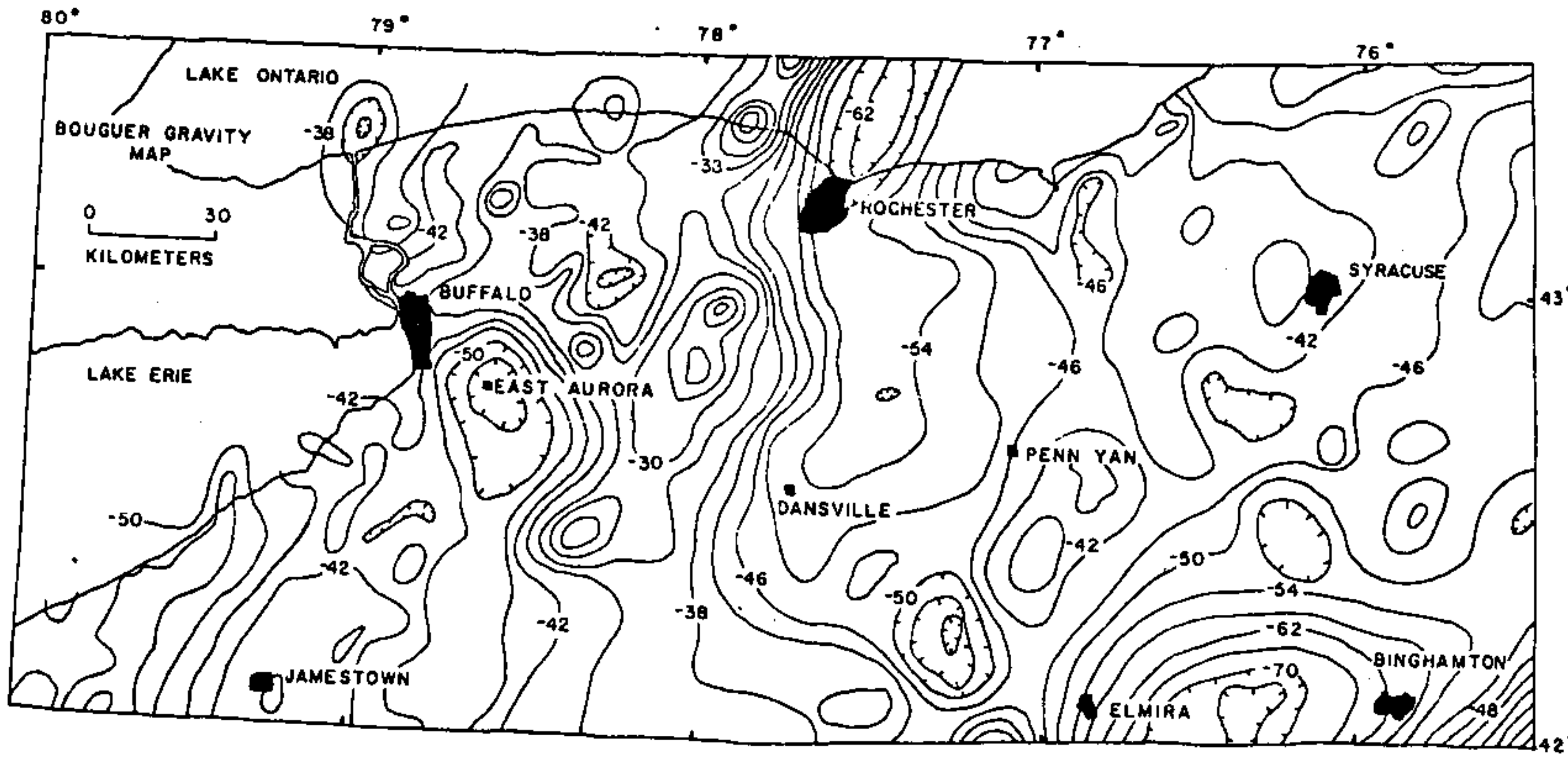


Figure 1-2. Bouguer Gravity Map of Central and Western New York State (Revetta and Diment, 1971)

around Penn Yan. This negative anomaly coincides with the distinct temperature gradient anomaly which defines the Cayuga anomaly. Hodge et al. (1981) attributed the negative gravimetric anomalies at East Aurora and Cayuga to the granitic pluton located near the top of the Pre-Cambrian Basement, and concluded that the radiogenic heat from the granitic rocks in the Pre-Cambrian is the source of the thermal anomalies. More recently, Hodge (1983) contends that the anomalies result in part from hydrothermal convection in the fractured Pre-Cambrian Basement rock.

COMMERCIALIZATION POTENTIAL

The potential for commercial utilization of the low-temperature geothermal resource was made an integral decision factor by NYSERDA and DOE in their selection of a prospect to evaluate the geothermal potential of New York State. NYSERDA evaluated a number of sites and decided to drill a test well in the Auburn area, approximately 20 miles southwest of Syracuse.

The primary objective of the test well was to penetrate and test warm water aquifers, and thus prove the geothermal potential of central New York State. The secondary objective was to determine if hot water could be produced at a sufficient rate and high enough temperature to provide hot water and space heating to the Cayuga Community College and the East Middle School in Auburn, New York.

The low-temperature geothermal prospect was spotted on the athletic field of the Auburn Enlarged City School District, East Middle School, Auburn, New York. The targets of interest were the Cambrian rocks, specifically the Theresa and Potsdam formations, and the Pre-Cambrian Basement. The prospect was selected because of the geophysical reasons, delineated under Geophysical Rationale, and its geologic condition as discussed under Geological Conditions. The targeted formations were chosen because of their depth, approximately 5,000 ft. subsea, projected temperatures and water production potentials. The commercial goals were production in excess of 100 gpm at a wellhead temperature in excess of 50°C.

GEOLOGIC CONDITIONS

Regionally, central New York State consists of a sequence of flat-lying carbonates, dolomites, shales and sandstones which dip very gently to the south in the Appalachian Plateau. The Auburn well site is located at the outer limit of the Appalachian Fold and Thrust Belt, approximately 15.5 miles north of the northernmost extension of the folds and 18.5 miles southwest of Syracuse. A hypothetical cross-section of the stratigraphy of the Auburn well indicated that the targeted lithological horizons, the Theresa, the Potsdam, and the Pre-Cambrian Basement should occur at 4,610 ft., 4,910 ft., and 5,010 ft., respectively.

Regional Geology

Regionally, the central and western portions of New York State consist of a sequence of flat-lying Paleozoic carbonates, dolomites, shales and sandstones of the Appalachian Plateau.

The Pre-Cambrian basement of New York State is exposed in two areas, the Adirondack Mountains and Hudson Highlands; gravity and magnetic data suggest that the rocks of exposed areas are similar to those beneath the Paleozoic sedimentary rocks. The Pre-Cambrian Basement dips gently to the south, as shown by the contour lines in Figure 1-3. Historically, regional dip has been assigned the value of 52 feet/mile to the south. The thickness of this sedimentary sequence is about 3,000 ft. at the shore of Lake Ontario and increases to the south to over 10,000 ft. Pre-Cambrian crystalline basement rocks underlie these Paleozoic sediments. Although the Paleozoic rock section contains some evaporites, it is composed principally of sandstones. A thin veneer of glacial debris covers most of the area and reaches thicknesses as great as 600 ft. on some valleys (Hodge and Hilfiker, 1981).

Local Geology

The Auburn low-temperature geothermal well site, shown in Figure 1-3, is located within an area of abnormally high geothermal gradients in central New York as delineated by Dr. Dennis Hodge of the State University of New York at Buffalo, and as referenced under Geophysical Rationale. This location is generally thought to be associated with an elongated geomagnetic anomaly which may reflect a deep fault zone which includes the Pre-Cambrian Basement.

The well site is located at the outer limit of the Appalachian Fold and Thrust Belt in the Appalachian Plateau, approximately 18.5 miles southwest of Syracuse. The Appalachian Plateau sediments at Auburn dip very gently to the south (dips $<2^{\circ}$), and form subdued and regularly spaced arcuate folds south of Auburn. These folds trend north of east and the anticlines lie over imbricate high-angle basement faults. The Auburn well site is approximately 15.5 miles (∿25km) north of the northernmost extension of the Appalachian Plateau folds.

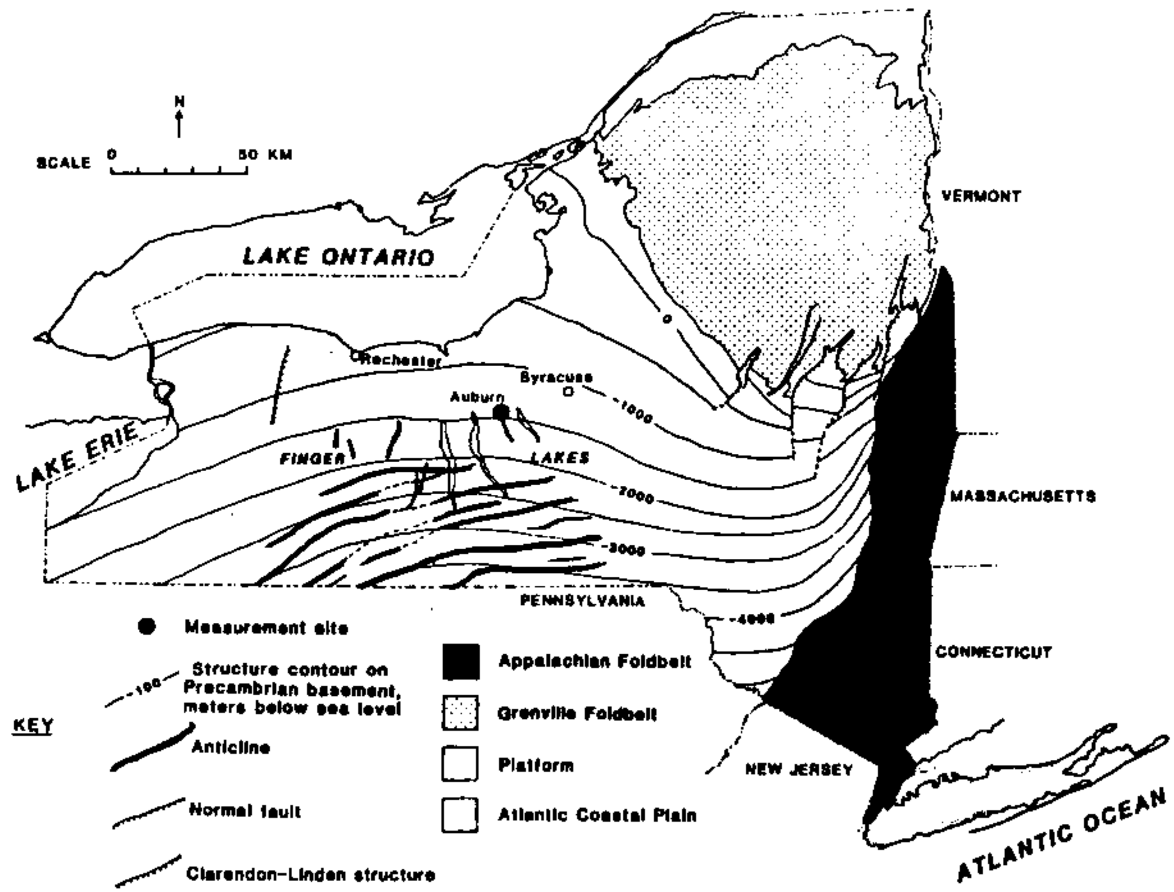


Figure 1-3. Contour and Tectonic Map of New York State Showing Location of Auburn Geothermal Well (Fisher et al., 1971)

Stratigraphy

A hypothetical cross-section was constructed prior to the drilling of the Auburn well for the purpose of anticipating depths of the lithological horizons (Dunn Geoscience, Inc., 1982).

The hypothetical cross-section was constructed from projection of the four nearest deep wells which are the Alnutt #31-011-04715K, the Parker #31-011-0499K, the Johnson #31-011-04365K, and the Old Auburn No. 1. The Alnutt and Parker wells are recent and respectively penetrate the Theresa formation and the Potsdam formation; the Old Auburn No. 1 reaches the Trenton Group, while the Johnson well penetrates the Queenston formation.

The hypothetical cross-section, stratigraphy and formation tops of the Auburn geothermal prospect are detailed in Appendix C. The targeted lithological horizons were hypothesized as shown in Table 1-1.

Table 1-1

TARGETED LITHOLOGICAL HORIZONS

Formation	Description	Depth (feet)
Theresa	May be predominantly sandstone in some areas while containing limey dolomites.	4,610
Potsdam	Coarse orthoquartizite which may be an altered chloritic quartz sandstone.	4,910
Basement	Metamorphosized sedimentary rock or marble.	5,010

Section 2

DEVELOPMENT OPERATIONS

The development of the Auburn geothermal prospect was initiated in January 1982 with the preparation of the drill site on the baseball diamond of the athletic field of the Auburn East Middle School in Cayuga County, New York State. The well was spudded in February 1982, drilled to a total depth of 5,250 ft. into the Pre-Cambrian Basement, cored and partially completed with surface casing and an intermediate casing string to 1,287 ft.

The well was extensively logged throughout all phases of the program, from lithological or mud logging during drilling to a complete suite of formation and production logs during the reservoir evaluation and testing phases. Additionally, borehole televiewer logs were run by the United States Geological Survey.

The Auburn low-temperature geothermal well was flow tested, stress tested, hydraulically stimulated, and then pump tested to determine its near wellbore and reservoir characteristics. The borehole televiewer logs were run before and after the stress tests. The well was open-hole completed with 7-in. casing prior to the conduct of the pump test in August 1983.

The development operations, their designs, actual work performed, and relevant results are further detailed in this section on:

- DRILLING, CORING, AND COMPLETION
- LOGGING ACTIVITIES AND LOG ANALYSES
- RESERVOIR AND WELL TESTING

DRILLING, CORING, AND COMPLETION

Drilling, coring, and completion operations were initiated in January 1982 with the preparation of the drill site which is located in the athletic field of the East Middle School of the Auburn Enlarged City School District in Auburn, New York.

The well, named the City of Auburn Lot 39 #1 well, was spudded in early February 1982, and drilled to a total depth (TD) of 5,250 ft. into the Pre-Cambrian Basement by early March 1982. Two casing strings were set and cemented - a surface string to 495 ft., and an intermediate string to 1,287 ft. Prior to reaching TD, two cores were retrieved, one each from the Theresa formation and the Pre-Cambrian Basement.

Subsequent to logging and preliminary well testing but prior to reservoir (pressure transient analysis) testing, the Auburn geothermal well was open-hole completed with 7-in. casing to $\sim$4,700 ft. The drilling, coring, and completion operations are detailed below in terms of: site preparation; drilling and analyses of drill cuttings; coring and core analyses; and well completion.

Site Preparation

Figure 2-1 is a drawing of the site location. Following a survey of the East Middle School property, a well location was selected in the athletic field behind the school. A bulldozer was used to remove the sod and loam from an area approximately 200 ft. by 150 ft.; the ground was leveled; three mud pits were excavated and lined with polyethylene; and an access road was built.

Drilling and Analyses of Drill Cuttings

Drilling operations were managed by Robert S. Lynch, now of Lynch Consulting Company, and conducted by Devonian Drilling Company under contract with Donohue Anstey and Morrill (DA&M), the prime contractor.

Devonian Drilling Company moved its Rig No. 1, a Kremco K-600 equipped to drill on air or mud, onto the drill site on February 1, 1982. The surface hole was drilled to 492 ft. with a 17½-in. bit. The 13 3/8 in. casing was run in the hole but would not go beyond 320 ft. After running back in several times alternating between the bit and casing, the hole was reamed from 304 to 492 ft. Surface casing (466 ft.) was then run and set at 478 ft., and cemented with 135 sacks of cement on February 2, 1982.

A 12¼ in. bit was used to drill out underneath the surface casing to 1,287 ft. An intermediate casing string (1,273 ft. of 9 5/8 in.) was run into the hole and set at 1,287 ft. The intermediate casing was cemented with 125 sacks of cement on February 16, 1982.

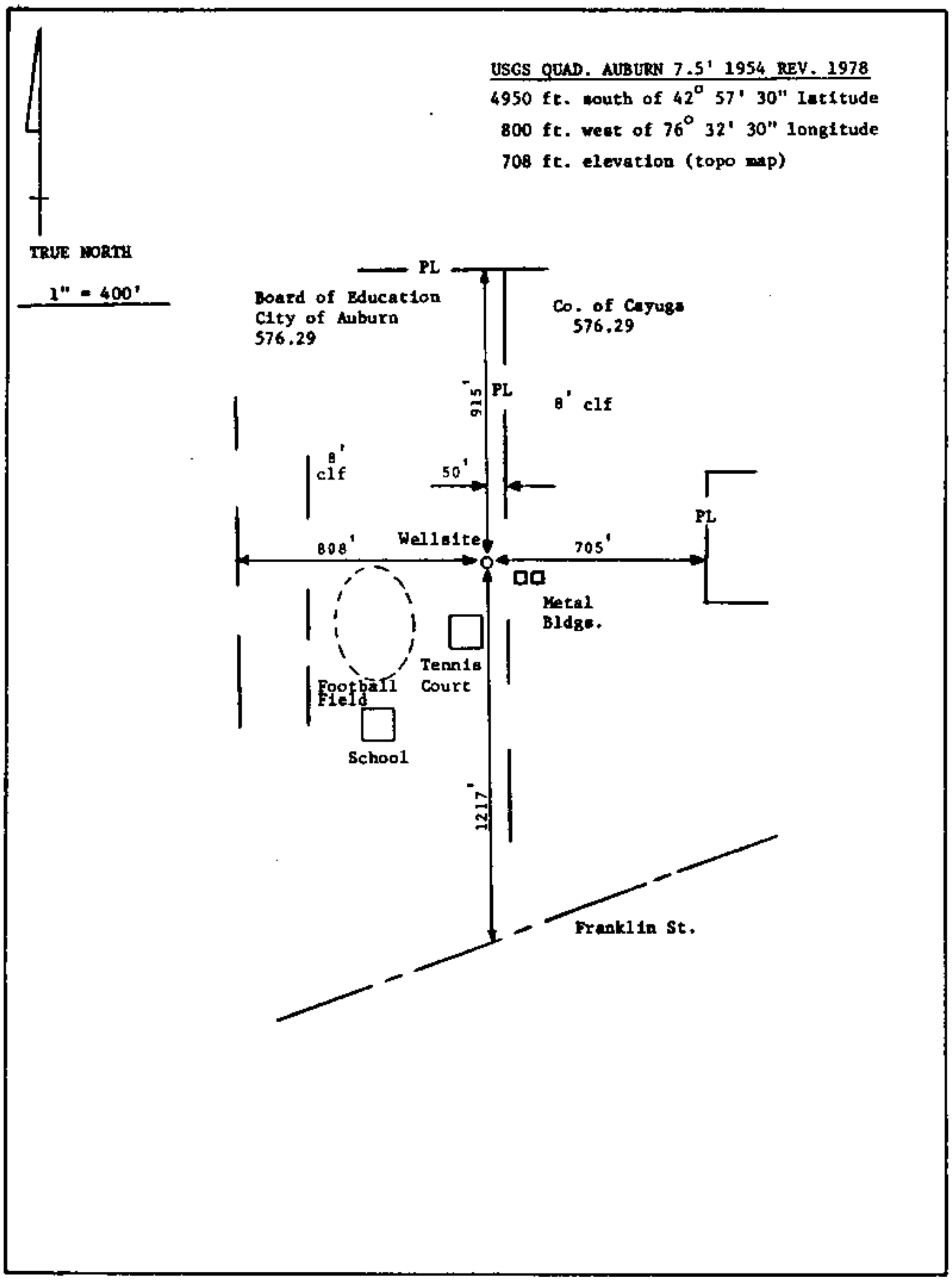


Figure 2-1. Wellsite Location for the City of Auburn, Lot 39, #1 Well

Three 8 3/4 in. bits were used to air drill out underneath the intermediate casing string to 4,160 ft. at which depth the rig switched to drilling with formation water. Fluid drilling was used down to TD. The first core point was reached at 4,700 ft. The well was cored over two intervals, the Theresa and the Pre-Cambrian Basement, and then drilled to a total depth (TD) of 5,250 ft. on March 2, 1982.

The drill cuttings were examined onsite by NYSERDA's consulting geologist, Brayton Foster, in conjunction with DA&M and Baroid personnel. Detailed descriptions of the lithology of selected drill cuttings, which were made by Dunn Geoscience Corp., Latham, New York, are listed in Table 2-1. Dunn's major surprise with the lithologies occurred with the Theresa formation which, contrary to the expected limey dolomite with quartz grains, was predominantly a fine sandstone with a dark carbonaceous coating on the quartz grains in some horizons.

Coring and Core Analyses

Two segments of core were retrieved during drilling, one each from the Theresa formation and the Pre-Cambrian Basement. The first core point was reached at 4,700 ft. on February 23, 1982. The drill bit was tripped out and Christensen Diamond Products, USA, rigged-up a 7 27/32 in. core barrel. One and one-half feet of core were cut; 3 inches were recovered. The diamonds on the core bit had been worn or knocked off and therefore, caused the shorter-than-planned cored interval.

The hole was reamed from 4,700 to 4,701.5 ft. with a 8 3/4-in., J-99 bit (Hughes Tool Company's hardest formation button bit). The hole was then drilled, with the same bit, to the second core point at 5,117 ft. Christensen rigged up a full hole core bit. Nine and one-half feet of core were cut; 3 feet were recovered. Again, the diamonds on the core bit were well worn or missing.

Using a second 8 3/4-in., J-99 bit, the hole was reamed through the cored interval (5,117.0 ft. - 5,126.5 ft.), and drilling continued to a total depth of 5,250 ft. The hole was circulated for one hour and fifteen minutes after which Schlumberger was rigged up to log the hole on March 2, 1982.

The physical and mineralogical aspects of the core taken from the Pre-Cambrian Basement are described in Appendix C. The core sample from the Theresa formation was approximately 2.9-in. long and 2.6-in. in diameter. The core had one apparent fracture along one edge, oriented 13 degrees from the core axis; bedding was represented by numerous thin laminae (1-3 mm thick) composed of light and dark

Table 2-1. LITHOLOGIC DESCRIPTION OF DRILL CUTTINGS

INTERVAL DEPTH (feet)	FORMATION	DESCRIPTION
1690 - 1700	MEDINA	Gray, fine-grained non-calcareous shale.
1700 - 1710		Red and gray to greenish-gray siltstone, sandstone and shale.
2350 - 2360	QUEENSTON	Predominantly red fine-grained sandstone.
2360 - 2370		Red and green fine-grained sandstone.
2830 - 2840	LORRAINE	White to gray to greenish and reddish-gray fine to medium-grained sandstone.
2840 - 2850		White to gray, fine to medium grained sandstone with traces of pyrite.
2860 - 2870		Light to medium gray, non-calcareous silstone and fine-grained sandstone.
2990 - 3000		Silty sandstone to fine-grained sandstone and some medium-grained sandstone.
3420 - 3430	TRENTON	Dark gray shaly and silty limestone.
3460 - 3470		Dark gray micritic to coarsely crystalline limestone.
4180 - 4190		Dark gray micritic to medium crystalline limestone.
4150 - 4160	BLACK RIVER	Dark gray, argillaceous, platy limestone and medium crystalline limestone.
4170 - 4180		Clear to dark gray micro-crystalline limestone with some calcitic fragments.
4200 - 4210		Medium to dark gray, finely crystalline limestone.
4520 - 4530	LITTLE FALLS	Light to dark gray, finely crystalline calcareous limestone with traces of pyrite.
4530 - 4540		Light to dary gray dolomitic limestone with carbonaceous grain coatings, traces of pyrite and limonite staining.
4550 - 4560		Light to medium-dark gray calcareous dolomite.
4580 - 4590		Light to medium gray dolomite containing some subangular quartz grains, and traces of pyrite and limonite.
4620 - 4630	THERESA	White to medium gray calcareous dolomite with angular to slightly rounded, rarely frosted quartz and traces of limonite.
4630 - 4640		Predominantly white calcareous dolomite containing subangular to rounded, occasionally frosted quartz grains with traces of pyrite.
4640 - 4650		Clear to gray sandstone with angular to subangular quartz, occasionally rounded frosted grains with traces of dark gray dolomite, pyrite, and anhydrite.
4660 - 4670		Clear to medium gray sandstone with dark gray carbonaceous coatings with traces of pyrite, anhydrite and frosted quartz grains.
4700 - 4710		Clear to gray sandstone containing angular to rounded frosted quartz grains with light to medium gray dolomite and traces of pyrite, anhydrite and limonite.
4950 - 4960	THERESA	White to light gray sandstone containing subangular to rounded, frosted quartz grains with rare biotite and chlorite grains.
4960 - 4970		White to light gray sandstone containing rounded to angular quartz grains, commonly frosted with traces of pyrite.
4970 - 4980		White to light gray sandstone containing angular to subangular occasionally frosted quartz grains.
5050 - 5060	PRE-CAMBRIAN	Clear to white coarsely crystalline marble with abundant angular to subangular quartz grains, with rare phlogopite, and frosted quartz grains.
5110 - 5120		White to yellow-stained medium to coarsely crystalline marble containing angular to subangular quartz grains and hornblende.
5200 - 5210		Clean, white to pinkish marble with some sulfide staining.

stained grains; dip in the bedding planes was approximately 2 degrees. The core was medium dark gray with medium to very find grained sandstone. Grains were subangular to subrounded clear-to-dark quartz with minor plagioclase feldspar. The matrix consisted of very fine-to extremely fine-grained quartz with some larger rounded grains and iron sulfides. There was some evidence of local grain overgrowth.

The composition of the Theresa core taken at 4700 ft. was determined to be 77.3 $\pm$ 4.5% quartz; 9.0 $\pm$ 3.3% secondary quartz; 11.6 $\pm$ 3.5 % opaque (Mn oxide or tar with pyrite); and 2.0 $\pm$ 2.0% voids. Petrographically, this Theresa core can be classified as a quartz arenite rock type.

The Pre-Cambrian Basement can be classified as a medium-grained, dolomitic marble. The composition of the Pre-Cambrian Basement rock is estimated to be as follows: 3.2 $\pm$ 2.0% quartz; 88.8 $\pm$ 4.0% dolomite; 7.7 $\pm$ 3% chlorite; trace quantities of apatite, montmorillonite/biotite, pyrite, magnetite, geothite/hematite, and rutile; and $\sim$0.3 + % voids. In addition to the petrographic description, a bulk chemical analysis of the Basement rock was made by inductively coupled plasma (ICP) spectroscopy analysis. Results are given in Table 2-2 in oxide weight percent, where applicable, or in parts per million (ppm). The total is 53.108% because only oxides are reported; the remainder of the analysis is assumed to be carbonate. It should be noted that strontium (93 ppm) was the most abundant of the trace minerals detected.

Samples of the Theresa and Basement cores were sent to Terra Tek Laboratories in Salt Lake City, Utah, for porosity and permeability determinations. Terra Tek elected not to perform standard porosity and permeability tests due to the extremely tight nature of the samples. Instead, the samples were impregnated with a colored epoxy and made into thin sections so that a visual determination of the porosity could be made by point count. Evaluation of the epoxy-impregnated thin sections of the Theresa sandstone indicated a primary porosity of approximately 2 percent. Analysis of thin sections of the Pre-Cambrian Basement indicated that the dolomitic marble has a primary porosity of zero; secondary porosity, attributable to fractures, was estimated to be approximately 0.3 volume percent.

The thermal conductivity of the Pre-Cambrian Basement core was estimated to be 11.17 mcal/cm-sec-$^{\circ}$C from three measurements made at Virginia Polytechnic Institute and State University.

Table 2-2

BULK CHEMICAL ANALYSIS (ICP) OF THE PRE-CAMBRIAN BASEMENT ROCK

ELEMENT	CONCENTRATION[a/]	UNIT
Na	0.052	%ox.
K	0.096	%ox.
Ca	27.46	%ox.
Mg	21.83	%ox.
Fe	1.07	%ox.
Al	0.698	%ox.
Si	<1.60	%ox.
Ti	0.039	%ox.
P	0.046	%ox.
Sr	93	ppm
Ba	0.043	%ox.
V	<250	ppm
Cr	8	ppm
Mn	0.168	%ox.
Co	12	ppm
Ni	<5.00	ppm
Cu	6	ppm
Mo	<50	ppm
Pb	<10	ppm
Zn	<5	ppm
Cd	<5	ppm
Ag	<2	ppm
Au	<10	ppm
As	<25	ppm
Sb	<30	ppm
Bi	<100	ppm
U	<2500	ppm
Te	<50	ppm
Sn	<5	ppm
W	<1200	ppm
Li	10	ppm
Be	0.5	ppm
B	<400	ppm
Zr	5	ppm
La	10	ppm
Ce	22	ppm
Th	<150	ppm
TOTAL	53.108	

[a/] Elemental abundances reported as less than a specific concentration indicate that the element was not present at the detection limit of the instrument.

Well Completion

The Auburn low-temperature geothermal well was open-hole completed from ~4,700 ft. to TD. Surface casing (13 3/8-in., 48 #, N-40) was set at 478 ft. and cemented back to the surface. An intermediate casing string (9 5/8 in., 36 #, J-55) was set just into the Lockport formation, and cemented back to approximately 850 ft. The production string (~4,707 ft. of 7-in., 26 #, N-80 casing) was set on a hookwall packer at 4,722.4 ft. KB and cemented back approximately 500 ft., just under the top of the Black River. The completed well, and wellhead, with a 2 7/8 in. tubing string and header, are shown in Figure 2-2.

LOGGING ACTIVITIES AND LOG ANALYSIS

The Auburn low-temperature geothermal well was extensively logged throughout all phases of the program, from during and immediately after the completion of drilling operations to just before pump testing and reservoir evaluation. The sequence, dates, phase and types of the different logging activities are as follows.

Table 2-3

LOGGING ACTIVITIES

Date	Phase	Type of Logging	Company
02/08/82-03/02/82	Drilling	Lithologic or Mud	N. L. Baroid
03/02/82-03/03/82	Evaluation	Formation (Open Hole)	Schlumberger
04/05/82-04/08/82	Flow Test	Production	Schlumberger
04/17/82	Stress Test	Borehole Televiewer	USGS
04/17/82	Evaluation	Formation (Open Hole)	Schlumberger
01/06/83	Casing	Location (Open Hole)	Schlumberger
03/30/83	Stimulation	Location (Cased Hole)	Birdwell

The logging activities and the log analyses are detailed below.

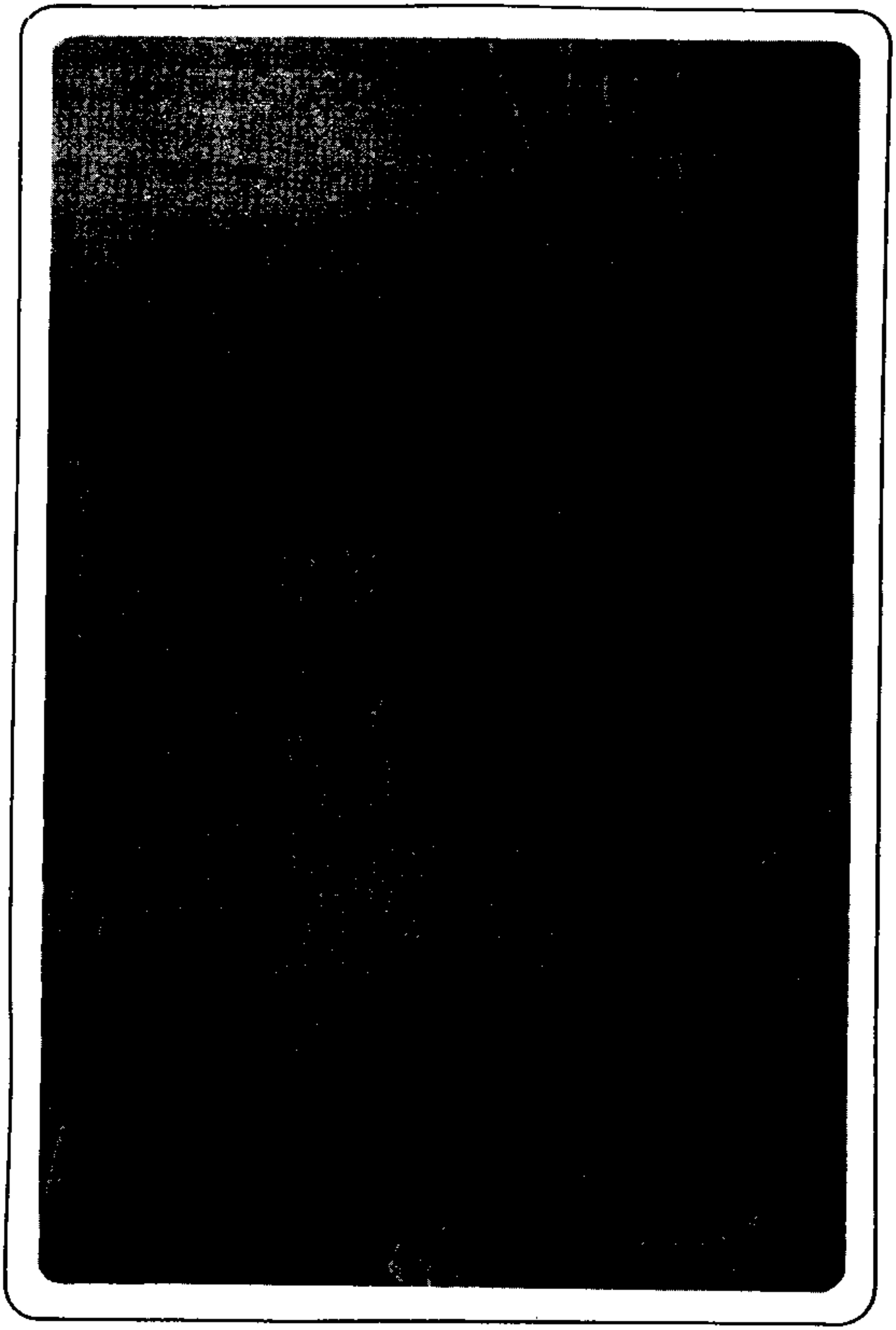


Figure 2-2. Casing and Wellhead Completion

Lithologic Log

The Litho Log, or "mud log", prepared by N. L. Baroid, during the course of the drilling, presents a lithologic description of the chip samples; a graphic log of the lithology, the drilling rate, gas readings and water shows; and notations concerning drill bit replacement, rig down time and similar information. The lithologic log of the Theresa and Potsdam formations is presented in Figure 2-3. The lithologic log was confirmed by the detailed description of selected drill cuttings presented in Table 2-1.

Formation Logging

Schlumberger commenced logging operations on March 2, 1982 with analog tape recording (TTR) equipment sent from the Bradford, Pennsylvania district. The open-hole logging suite, which was run from the drillers T.D. of 5,250 ft. to the bottom of the intermediate casing string at 1,287 ft., included:

- Formation Density Compensated/Compensated Neutron/Gamma Ray/ Caliper (FDC - CNL - GR - CAL) logs. 1/
- Dual laterolog (Resistivity)/Gamma Ray (DLL - GR) logs. 1/
- Borehole Compensated Sonic/Gamma Ray (BNC - TT - CAL - GR) logs. 1/
- Temperature and Differential Temperature logs.
- Dipmeter/Fracture Identification (FIL) logs. 1/

This suite of logs is partially presented in condensed form in Figure 2-4.

On April 1, 1982, Schlumberger ran an additional suite of logs from a computerized logging truck (CSU) sent from the Indiana-Pennsylvania district. This second suite included the following:

- Dipmeter/Fracture Identification (FIL) logs. 1/
- Long-Spaced Sonic (SLS - SC) logs. 1/

The formation logs were utilized by the consulting geologist, Mr. Foster, and DA&M's wellsite manager, Mr. Lynch, to pick the formation tops. These logs were subsequently analyzed to determine net capacities and absolute porosities of the

1/ Marks of Schlumberger

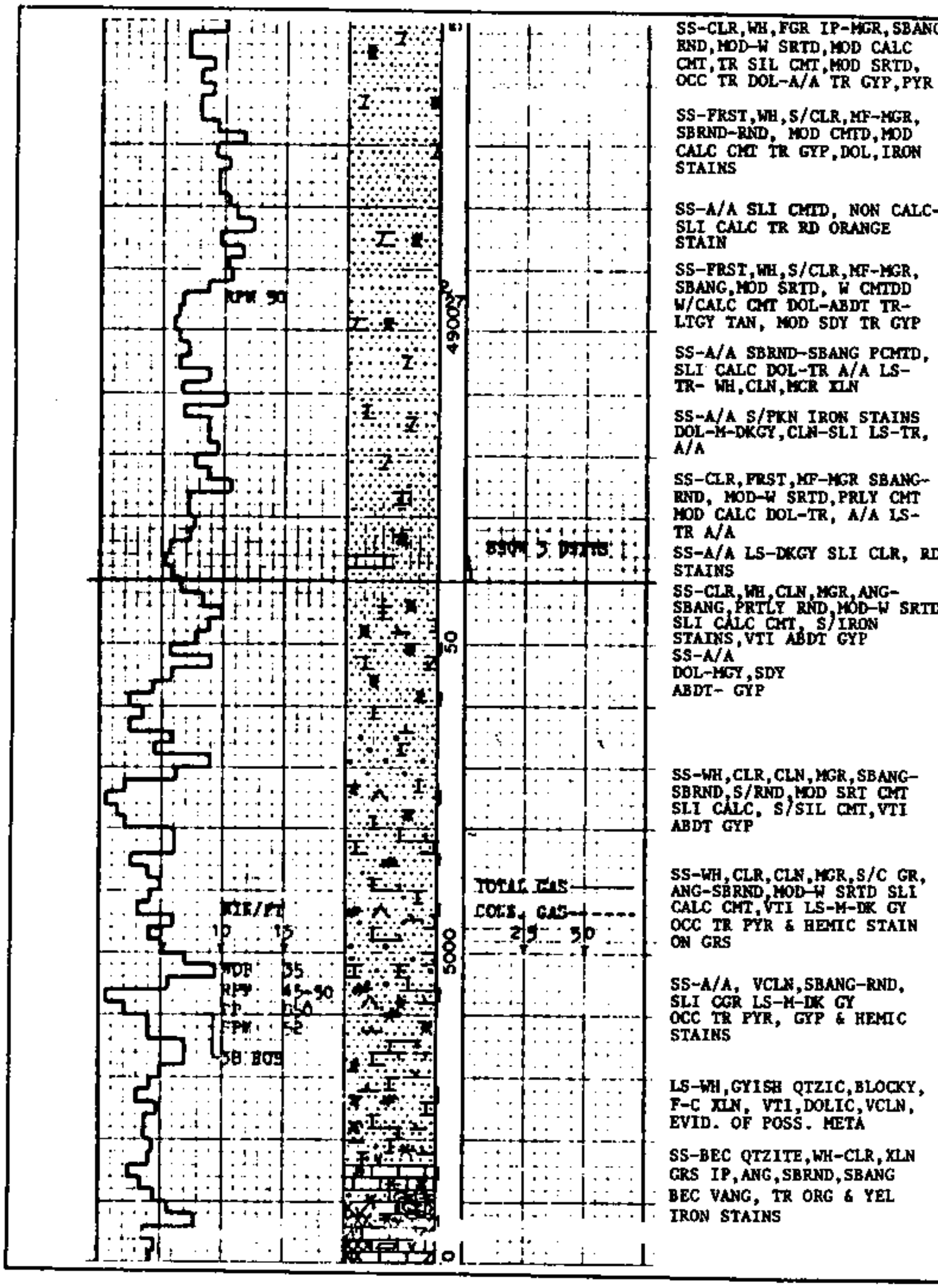


Figure 2-3. Lithologic Log of Theresa and Potsdam Formations

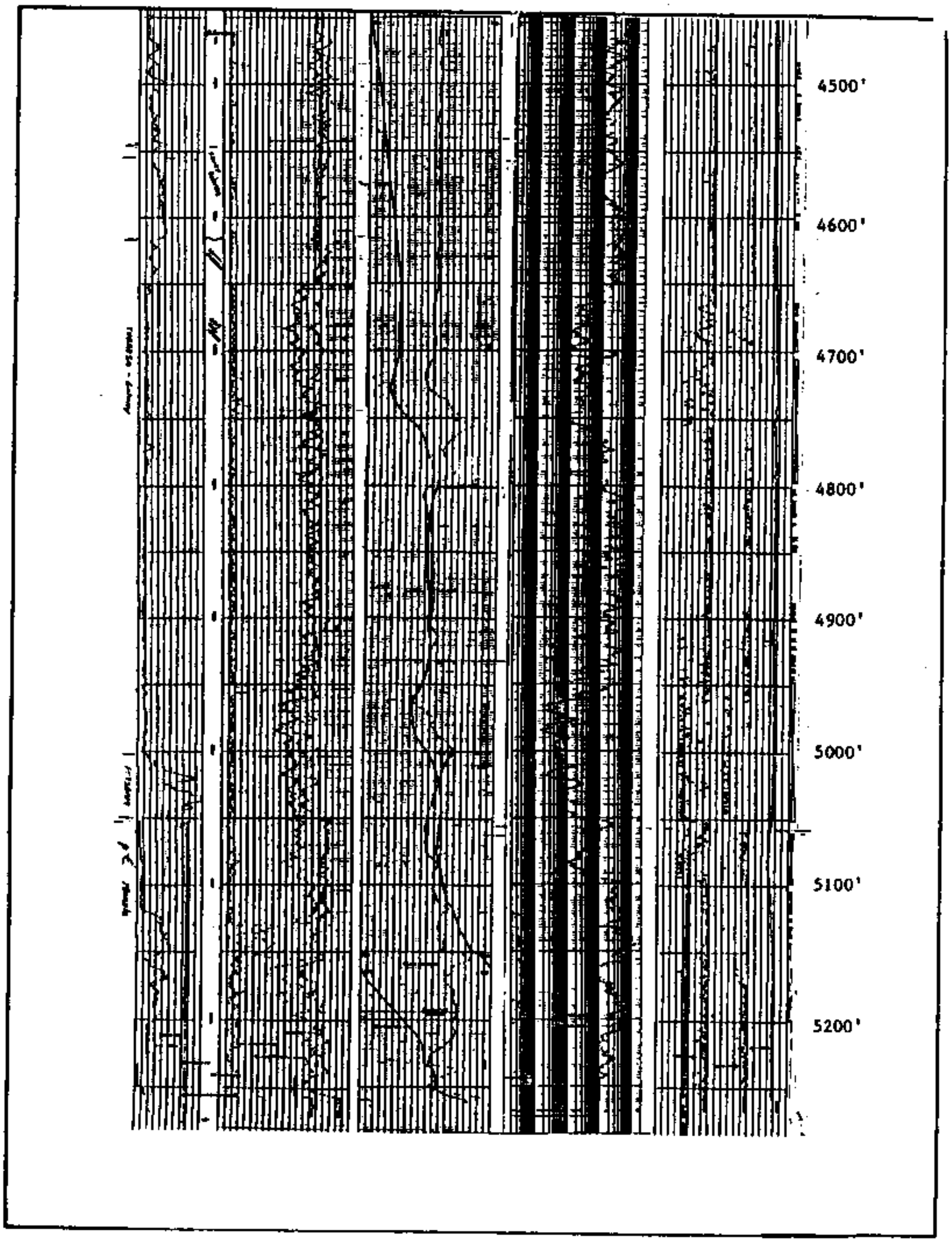


Figure 2-4. Auburn Geothermal Well - Gamma Ray & Caliper, Compensated Neutron and Bulk Densities, Temperature & Gradient, Deep & Shallow Laterlogs and Fracture Identification Logs (Schlumberger, 1982)

producing zones (ENG, INC., 1982). The estimated values of porosity and feet-porosity are listed below:

Table 2-4

FORMATION LOGS

Formation Composition	Interval (feet)	h (ft)	Porosity, ϕ	Gross $h\phi$ (ft)
Theresa				
33%ss/67%dol	4616-4650	34	0.000	0.000
80%ss/20%dol	4650-4736	86	0.018	1.519
74%ss/26%dol	4736-4900	164	0.002	0.328
63%ss/37%dol	4900-4950	50	0.010	0.483
100% ss	4950-5008	58	0.098	5.703
	4616-5008	392	0.020	8.033
Potsdam				
100%ss	5008-5050	42	0.062	2.618
Total Net	4740-5050	310	0.029	9.124
Zone 1	4740-4950	210	0.004	0.803
Zone 2	4950-5050	100	0.083	8.32

The estimated values of absolute porosities were averaged from the compensated formation density log, the borehole compensated sonic log, and cross-plotted values. The average deviations from the mean in the estimated values of absolute porosity are approx. ± 0.002 for Zone 1 and ± 0.02 Zone 2. The estimated values of porosity appear to be primary in nature because the sonic log will record the fastest transit time, and will thus bypass any vertical fractures which give rise to secondary porosities.

The calculated values of porosity, listed above, are in good agreement with Schlumberger's computerized log analysis in Figure 2-5.

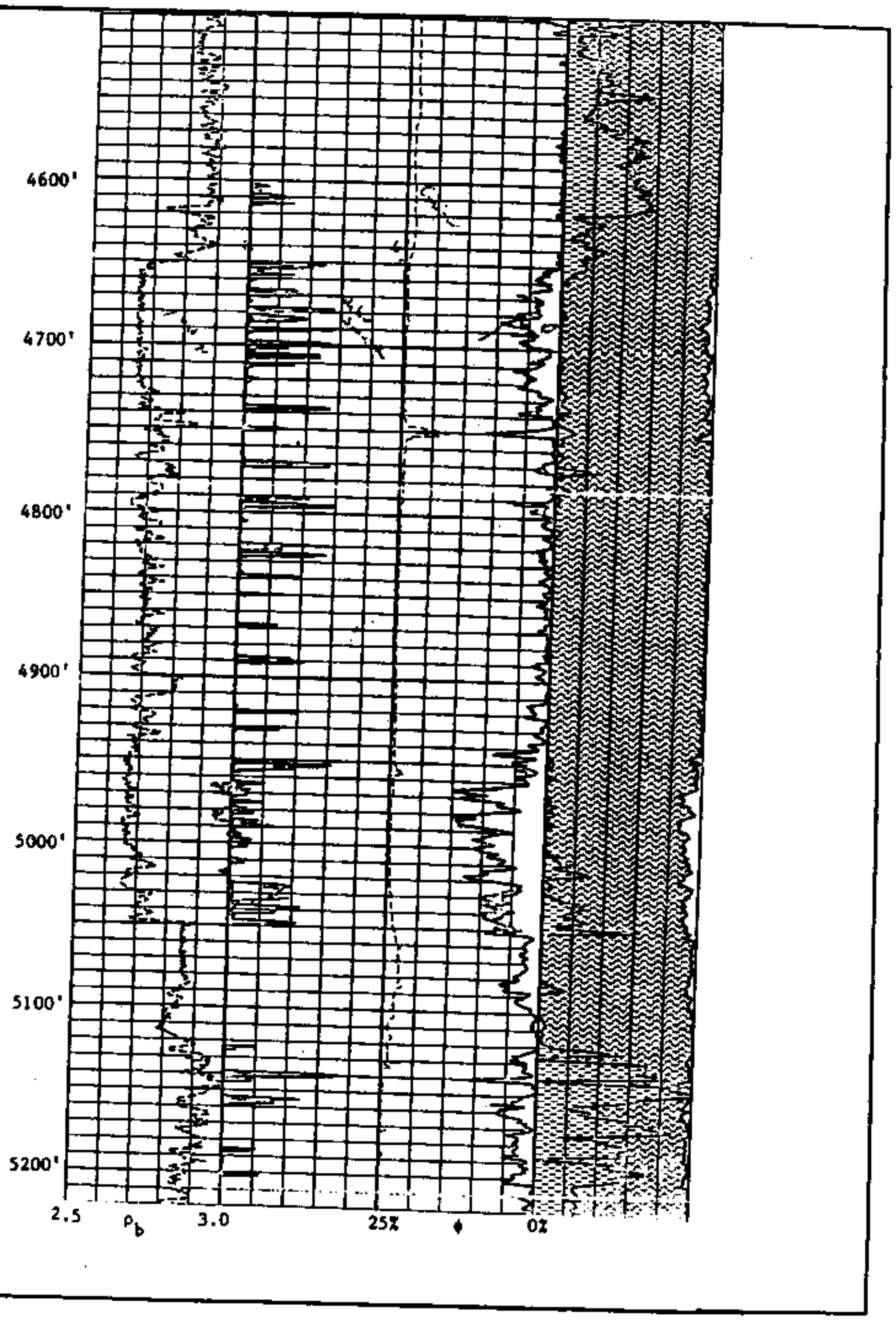


Figure 2-5. Auburn Geothermal Well - Coriband Formation Analysis by Volume (Schlumberger, 1982)

Borehole Televiewer Log

The USGS ran borehole televiewer logs prior to and after making open-hole hydrofracturing stress measurements in April 1982.

The borehole televiewer (manufactured by Simplec, Inc.) is a wireline logging tool that provides a continuous, oriented, ultrasonic image of a borehole wall (Zemanek et al, 1970). Characteristic patterns are produced on the borehole televiewer log by fractures, voids, washouts, and other wall features. The orientation of these features relative to magnetic north may be determined from this log. In particular, planar features such as natural fractures will produce a sinusoidal signature which is utilized to determine their strike and dip. In the Auburn well, the resolution of the borehole televiewer is probably on the order of 3 to 5 mm.

The density of planar features in the Auburn well as revealed by the borehole televiewer log is quite high, and attains values up to 9 features/m (Figure 2-6). The great majority of these features were low-angle and indistinct. Most of these indistinct features are either bedding-plane washouts or drill-bit scour marks since the bedding planes at Auburn are nearly horizontal. The density of distinct natural fractures detected by the borehole televiewer in the Auburn well (Figures 2-6 and 2-7), however, is much lower and averages only 0.077 fractures/m. There is, however, considerable depth variation in this density and localized maximums can be seen in the Queenston Sandstone, the Trenton Limestone, the Black River Limestone, the Theresa Sandstone, and the Pre-Cambrian Basement. There is a persistence of distinct natural fractures, many with apparent apertures on the order of several centimeters, to depths of 5,250 ft. (∿1.6 km). These natural fractures will impact the in situ permeability of the Auburn well.

The orientations of all of the distinct natural fractures seen in the Auburn well using the borehole televiewer log are plotted in Figure 2-7. Although there is a fair amount of scatter in these orientations, these fractures show a strong tendency to separate into either steeply dipping or gently dipping clusters, with the steeply dipping cluster striking in an approximately ENE to SE direction. In the lower part of the sedimentary section in the Auburn well, the steeply dipping natural fractures show a marked tendency to strike in a direction parallel to the current direction of maximum horizontal compression. Fractures in the upper part of this well, however, as well as those in the Pre-Cambrian Basement, exhibit more variability in orientation and show no such tendency to strike parallel to the horizontal stress plane.

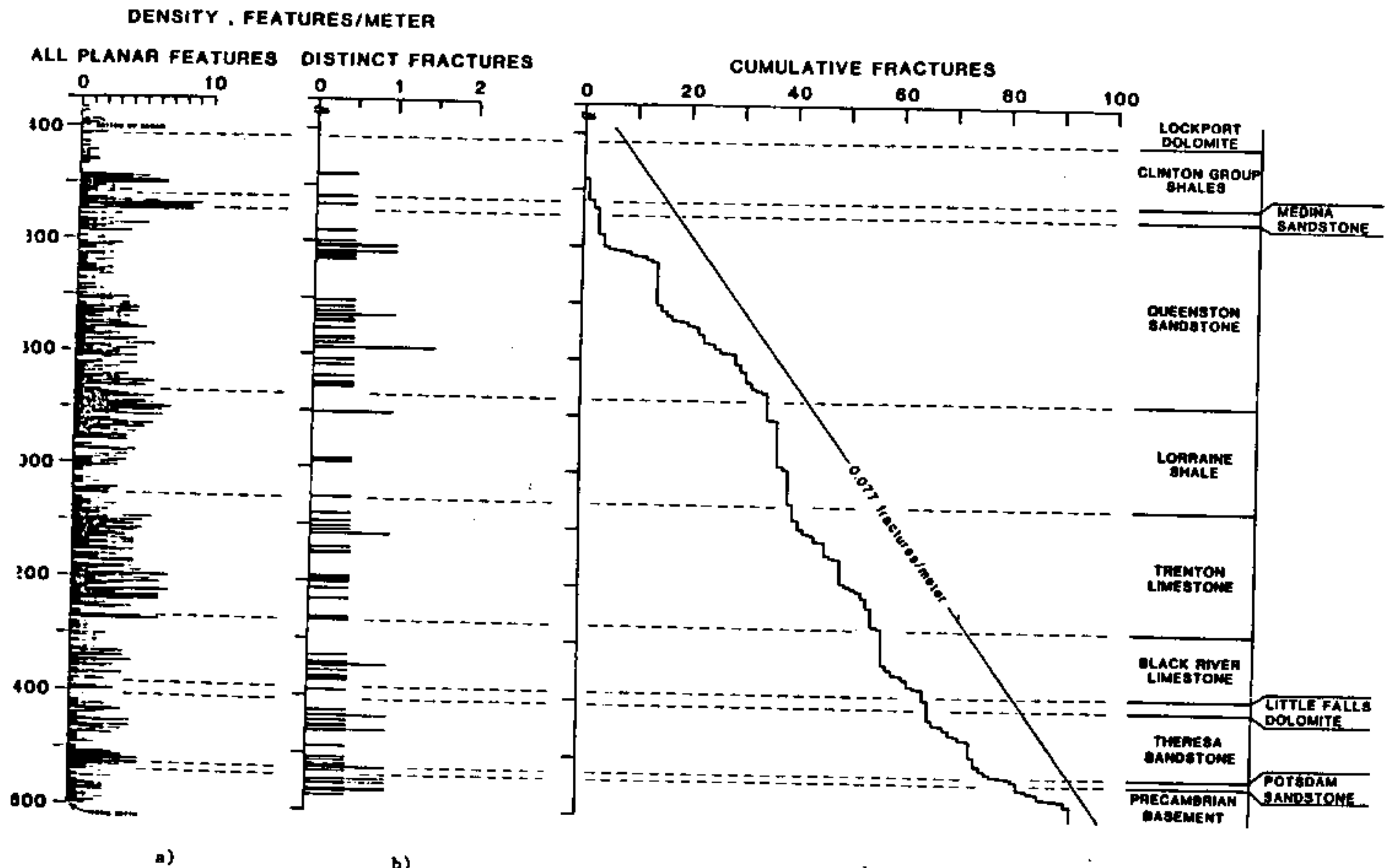


Figure 2-6. Auburn Geothermal Well - Density of Natural Fractures and Planar Features Versus a Simplified Stratigraphic Section. a) All Planar Features; b) Distinct Natural Fractures only; c) The Cumulative Number of Distinct Natural Fractures Versus Depth. The Inverse Slope of the Cumulative Fracture Plot Over a Given Depth Range is Equal to the Average Fracture Density (Hickman, Healy, and Zoback, 1983)

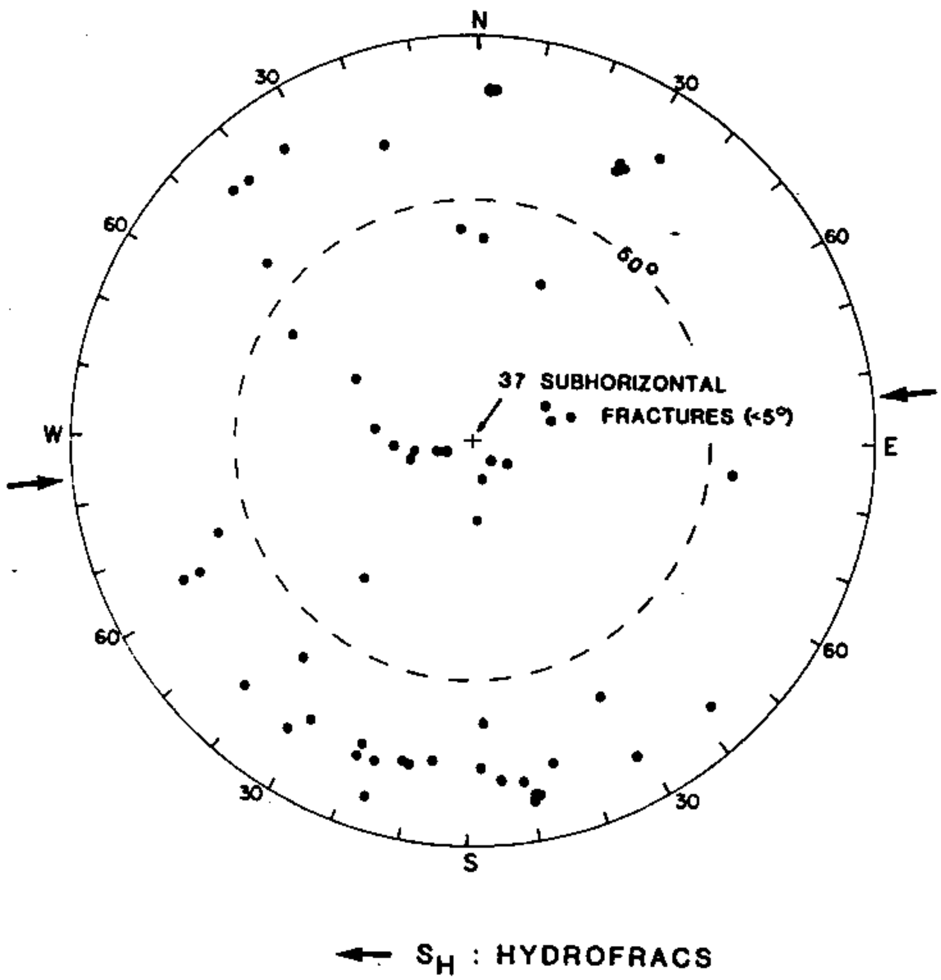


Figure 2-7. Low Hemisphere, Equal Area Sterographic Projection of Poles to All of the Distinct Natural Fractures Seen in the Borehole Televiewer Log at Auburn After Having Been Corrected for a Magnetic Declination of 11°W. Also Indicated is the Average S_H Orientation as Determined from the Hydraulic Fracturing Tests. Points Lying Outside of the Dashed Circle Represent Fractures with Dips >50° (Hickman et al., 1983)

Production Logs

Schlumberger ran a series of production (PLT) logs during the conduct of the preliminary flow tests which are discussed under Reservoir and Well Testing.

Five production logs were run over the period April 5, 1982 to April 8, 1982. Each PLT log included the following measurements: gamma ray and tool travel speed on the left hand tract; and pressure (psig), temperature (^{o}F), differential temperature (^{o}F), and flow rate (rps) on the right hand tract. The logs were run with the tool descending and ascending; the flowmeter log was calibrated for both flow directions. Figure 2-8 is the bottom section of the PLT log taken on April 7, 1982.

The production logs tests were evaluated to determine the major water-producing zones of the Auburn well. The major water-bearing zones of the Auburn geothermal well were identified to occur over the interval 4,740 - 4,950 ft. spanning the Theresa and Potsdam formations. These zones were identified from correlations between the production, formation and lithologic logs (ENG, INC., 1983). The major water-producing zones were identified from Table 2-5.

Table 2-5

EVALUATION DATA IDENTIFYING MAJOR WATER-PRODUCING ZONES

Formation	Interval	ΔFlow (rps)	ΔT (^{o}F)	T (^{o}F)
Theresa	4740-4800	+ 0.60	+ 0.030	123.0-123.6
Theresa	4800-4900	+ 0.45	+ 0.005	123.6-124.5
Theresa	4900-5008	+ 0.50	+ 0.010	124.5-125.0
Potsdam	5008-5050	+ 0.60	+ 0.010	125.0-125.4

RESERVOIR AND WELL TESTING

The Auburn low-temperature geothermal well was thoroughly tested to determine its near wellbore and far wellbore, or reservoir, characteristics. The reservoir and well tests, their timing, and primary goal are listed in Table 2-6.

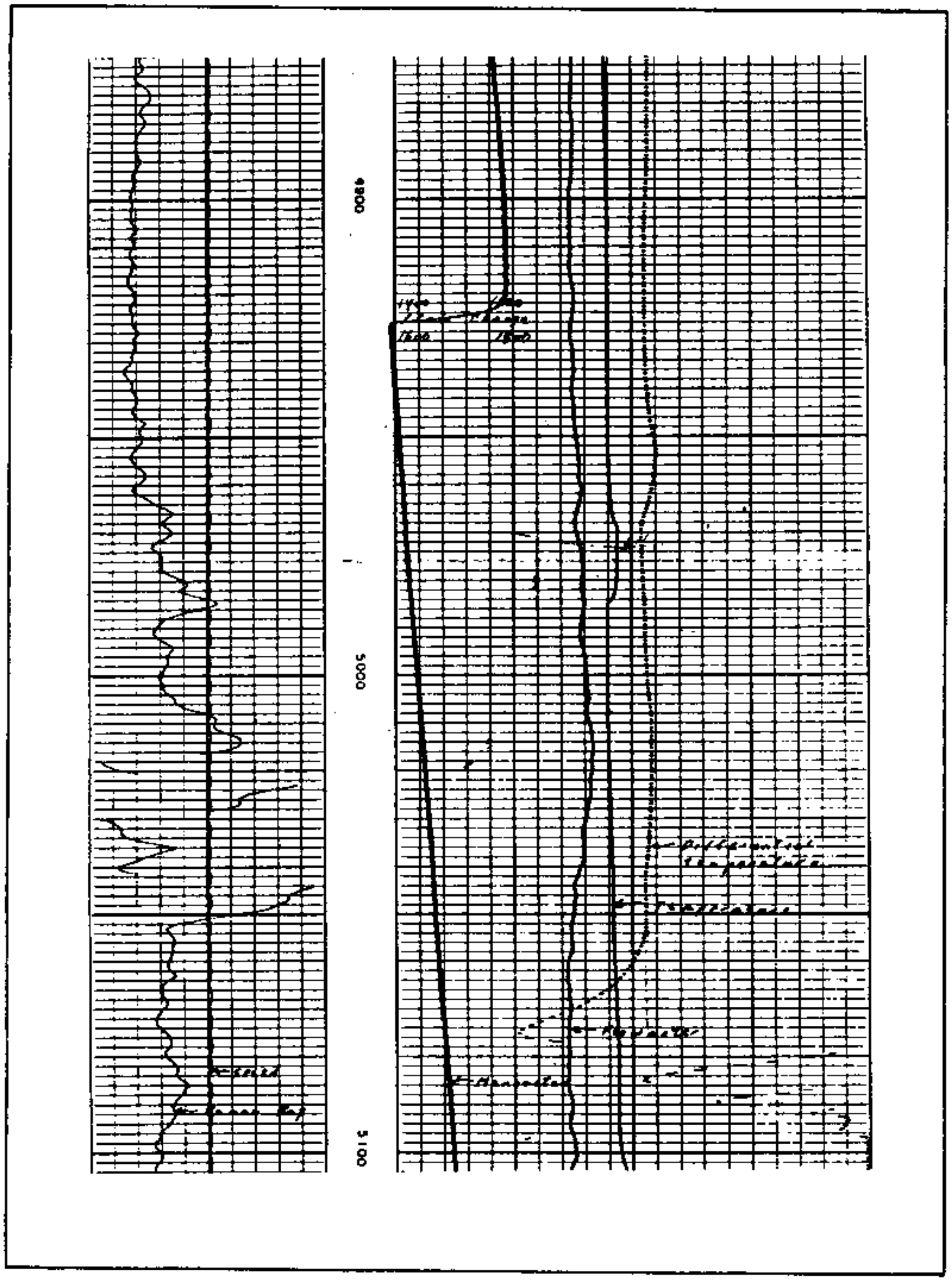


Figure 2-8. Production Log (PLT) Over the Theresa and Potsdam Formations

Table 2-6

RESERVOIR CHARACTERISTICS

Test	Period	Primary Goal
Preliminary Flow	04/05/82-04/09/82	o To identify the volume contribution of the major water-producing zones
Stress (Hydrofracture)	04/12/82	o To assess the state of stress in the Auburn region
Hydraulic Stimulation	04/07/83	o To increase the well's productivity, extend its radius of influence and decrease drawdown
Pressure Transient	08/01/83-08/08/83	o To define the hydrothermal resources and reserves

The reservoir and well tests are described in terms of their major objectives, design bases, and conduct in the sub-sections below.

Preliminary Flow Tests

A preliminary flow test on the geothermal test well in Auburn was conducted over the period April 5 to 9, 1982. The purposes of this preliminary flow test were as follows:

- o Assess the initial productivity of the well.
- o Identify the volume contribution of the major water-producing zones.
- o Forecast decline rates and recoverable reserves in terms of volume and heat.
- o Project surface temperature of the produced brine stream over a range of flow rates.

The preliminary flow tests were conducted by unloading the well with compressed air, establishing a state of equilibrium between brine produced from the formation and compressed air injected, and measuring the discharge flow rates as a function of depth, i.e., the location of the bottom of the air injection pipe. The preliminary flow tests were conducted in a fashion similar to that described by Schafer, 1980. The conduct of the preliminary flow tests is detailed further in Appendix B; the results are discussed under Hydrological Conditions.

Stress (Hydrofracture) Testing

NYSERDA and ESEERCO contracted with DA&M to provide rig support and well access to USGS. USGS used this opportunity to conduct in situ geophysical measurements aimed at assessing the state of stress in the Auburn region, and to define the fracture distribution at depth. This data serves as an aid to finding the most potentially useful procedures for geothermal energy production and brine injection. The techniques utilized and the results of this work are published in a final report by S. H. Hickman, J. H. Healy and M. D. Zoback, June 1983. This work was conducted from April 12 to 19, 1982.

Hydraulic Stimulation

The Auburn well was hydraulically stimulated to increase its productivity and to extend its radius of influence. A "staged" stimulation program was designed by Halliburton Services of Bradford, Pennsylvania, to maximize zonal coverage because of the thickness of the completed interval.

The hydraulic treatment program was designed as a three-stage process which places acid and water between two diversion stages with rock salt. An acid spearhead was selected to clean the fracture face and to etch in any dolomite stringers. A large-volume over-displacement phase was selected to place the acid far from the wellbore area, and to induce a hydraulic fracture. The over-displacement phase was made up of water with a gelled proppant for increasing the flow capacity in the induced fractures. Rock salt in a gelled brine was selected as a diversion between stages in order to maximize zonal coverage.

The Auburn well was hydraulically fractured by Halliburton on April 7, 1983. The well was fractured in three stages, with each stage containing the following:

- 3,000 gallons of acid (15% HCL)
- 10,000 gallons of gelled water containing 10,000 lbs. 20/40 sand (1.0 # sand/gallon)
- 1,000 lbs. rock salt in 3,333 gallons gelled water.

The maximum treatment pressure was 2,450 psi at a rate of 14.7 barrels/minute in the third stage; the instantaneous shutin pressure (ISIP) was 2,000 psi.

Pressure Transient (Pump) Testing

The pump test was designed to meet one of the primary objectives of this study, i.e., the definition of the hydrothermal resource of the Auburn low-temperature geothermal well within a commercialization perspective. The pump-test design was based on the results of the flow test, and on values of net capacity estimated from geophysical logs, regional stratigraphy, and estimated values of fluid and reservoir parameters (ENG, INC., 1982).

The pump test was executed over a seven-day period from August 1 to 8, 1983. Three sets of pressure drawdown and buildup tests were conducted as follows:

- PRELIMINARY DRAWDOWN AND BUILDUP - three-stage preliminary drawdown at 52.4, 74.9 and 133.9 gpm over a 7.27-hour period, followed by a 14.40-hour buildup.
- 24-HOUR DRAWDOWN AND BUILDUP - 127.4 gpm for 24.02 hours followed by a 27.15-hour buildup.
- MULTIRATE DRAWDOWN AND BUILDUP - a four stage drawdown test (124.1 gpm for 1.5 hours; 152.5 gpm for 24.15 hours; 133.1 gpm for 7.88 hours; and 115.5 gpm for 7.97 hours) followed by a buildup period of 48.90 hours.

The schedule of events, conduct of the field test, data and results are detailed in Appendix B. The pressure drawdown and buildup data are used as the basis of the reservoir characterization and reserve estimations under Reservoir Characteristics and Reserve Analysis, respectively.

Section 3

ASSESSMENT OF GEOTHERMAL POTENTIAL

The low-temperature geothermal potential of the Auburn reservoir is assessed in terms of: geological environment; hydrological conditions; the reservoir characteristics and recoverable hydrothermal resources (ENG, INC., 1983).

The geological environment of the Auburn geothermal well is in general conformance with the local and regional geological conditions. The average geothermal gradient in the Auburn well was measured to be as high as 14.7° F/1,000 ft. (26.7°C/km). Hodge (1983) believes that the anomalous gradient at Auburn is partially caused by hydrothermal convection in the fractured Pre-Cambrian Basement and by radiogenic decay. The latter theory is supported by traces of radiogenic material found in the Basement marble. The hydrological conditions were found to be favorable in that a major water-producing zone was found with a net productive sand of 310 ft. spanning the Theresa and the Potsdam formations.

The Auburn low-temperature geothermal reservoir appears to be finite and bounded, and to be made up of as many as six different storage and flow regions. These regions consist of a low-porosity, dolomitic, water-production zone and a high-porosity sandstone zone both of which are naturally fractured and both of which were hydraulically fractured and propped prior to the test. The two producing zones of contrasting porosity are assumed to be in perfect communication with each other, and viewed to be one producing interval with volume-averaged properties. This assumption simplifies the reservoir analysis by characterizing the Auburn reservoir by three distinct regions, each of which will become dominant at different times during reservoir drainage and during system shutdown.

The Auburn well can produce a wellhead water temperature in excess of 125°F. Consequently, the geothermal potential is defined in terms of the thermal energy recoverable by a wellhead temperature drop from 125°F to an operating temperature of 70°F with an 80% overall heat recovery efficiency. The recoverable hydrothermal resources or reserves result from two components: a volumetric, or in situ component based on the thermal capacity of the formation brine, and a reinjection component in which heat is recovered from the reservoir rock by reinjection of the spent brine. The proved hydrothermal reserves of the Auburn low-temperature geothermal well are estimated to be 4.13 x 10^{10}Btu for volumetric depletion, and 17.45 x 10^{10} Btu under specific recharge conditions for a total of 21.58 x 10^{10}Btu. The possible and probable reserves are estimated to be 54.68 x 10^{10} Btu and 70.75 x 10^{10} Btu. respectively.

Without spent brine reinjection and reservoir recharge, the maximum sustained production rate of the Auburn well over the 3.5-year lifetime of its volumetric reserves is ∿100 gpm. The maximum recoverable thermal energy over a 6-month period is thus, ∿1.15 x 10^{10} Btu or ∿40% of the schools' Btu demand. Preliminary injectivity tests performed during the pump tests, together with log analysis, indicate that the spent geothermal brine can be reinjected down the annulus into the adjacent Black River formation.

The production rate for tapping the geothermal potential by reinjecting or recirculating the spent geothermal brine was selected to be 286 gpm. This flowrate was averaged from the maximum drawdown rate for a pump setting at 4,000 ft., and the minimum drawdown rate which can meet the schools' average daily Btu demand. The selected production rate would supply 3.3 x 10^{10} Btu over a 6-month period, or 117% of the schools' Btu demand. The proved lifetime of the reinjection reserves is estimated to be just in excess of 10 years.

Thus, the conclusion can be made that the Auburn low-temperature well can be utilized to provide space heating to the Auburn East Middle School and the Cayuga Community College. This conclusion is made primarily on the reservoir's capacity and productivity. The engineering and economics of developing, constructing and operating a geothermal-energy surface facility are yet to be evaluated. The assessment of the downhole geothermal potential is discussed in the following sections:

- GEOLOGICAL ENVIRONMENT
- HYDROLOGICAL CONDITIONS
- RESERVOIR CHARACTERISTICS
- RESERVE ANALYSIS

The discussions in these sections are based on ENG, INC.'s Hydrothermal Reserves and Evaluation Report attached as Appendix B.

GEOLOGICAL ENVIRONMENT

The geological environment of the Auburn low-temperature geothermal well is in general conformance in terms of lithology and stratigraphy, with the local and regional geological conditions described under Geological Conditions. The formation tops were located, for the most part, at depths predicted by the hypothetical stratigraphic cross-section in Appendix C. The average geothermal gradient in the Auburn well was measured to be as high as 14.7°F/1,000 ft. (26.7°C/km), a value which is just under the high of 16°F/1,000 ft. (30°C/km) identified by Hodge et al. (1981), for the Cayuga County geothermal anomaly. The localized, bottom-hole geothermal gradient of 91.7°F/1,000 ft. (168.1°C/km) is most likely a disequilibrium effect due to drilling disturbance superposed on hydrothermal convection in the Pre-Cambrian Basement (Hodge, 1983). The bulk chemical composition of the Basement marble supports the contention by Hodge et al. (1981) that the radiogenic heat from the granitic rocks may be, with localized hydrothermal convection, the source of the thermal anomalies.

The geologic environment is discussed in terms of the following:

- LOCATION OF FORMATION TOPS
- STRATIGRAPHY AND LITHOLOGY
- AVERAGE AND LOCAL GEOTHERMAL GRADIENTS

Location of Formation Tops

The targeted lithological horizons, the Theresa, the Potsdam, and the Pre-Cambrian Basement, were located at 4,616 ft., 5,002 ft., and 5,050 ft. respectively. The formation tops were picked from drill cuttings and formation logs by NYSERDA's wellsite geologist, Mr. Foster, in conjunction with Mr. Lynch of DA&M. The formation tops and their depths in feet are noted in Table 3-1.

Table 3-1

FORMATION TOPS, DEPTH AND TYPES

Formation Tops	Depth (ft.)	Formation Types
Lockport	1,238	Limestone/Dolomites
Medina	1,710	Sandstone
Queenston	1,792	Sandstone/Shale
Lorraine	2,860	Shale/Siltstone
Trenton	3,460	Limestone
Black River	4,163	Limestone
Little Falls and Knox Unconformity	4,546	Dolomites
Theresa	4,616	Sandstone/Dolomite
Potsdam	5,002	Sandstone
Basement	5,050	Marble

The listed formations were encountered at depths which, for the most part, correspond to the hypothetical cross-section in Appendix C. The major divergence occurred at the Medina horizon due to the greater-than-expected thickness of the Lockport formation. Also, the Potsdam formation was much thinner than projected by the hypothetical cross-section.

Stratigraphy and Lithology

The Theresa formation is a coarse, white-to-medium-gray calcareous dolomite which, in some areas, is predominantly sandstone with traces of pyrite, anhydrite, limonite, and chlorite grains. The composition of the Theresa formation varies from 67% dolomite/33% sandstone in the top horizon to 0% dolomite/100% sandstone in the bottom horizon. The Theresa, which spans the interval from 4,616 ft. to 5,008 ft., is estimated to have a net productive interval of 268 ft. The average absolute porosity varies from 0.2% in the predominantly dolomitic horizons to 9.8% in the 100% sandstone zone at the bottom of the interval.

The Potsdam formation is a white, coarse orthoquartzite with trace amounts of white angular feldspar, rounded frosted quartz grains, and zircon. The Potsdam, which spans the interval 5,008 ft. to 5,050 ft., was shown to be a 100% sandstone from the formation logs. The entire interval, which has an average absolute porosity of 6.8%, is considered productive.

The net producing interval is envisioned as being made up of two major zones:

- Zone 1, which spans the interval 4,740 ft. - 4,950 ft. and which comprises the dolomitic portion of the Theresa has an average of 80.3 ft.-porosity percent and an average porosity of 0.38%.
- Zone 2, which spans the interval 4,950 ft. - 5,050 ft. and which straddles the Theresa and Potsdam, has an average of 832.3 ft. - porosity percent and an average porosity of 8.32%.

The Pre-Cambrian Basement is a coarsely crystalline marble containing angular to subangular quartz grains, frosted quartz grains, hornblende and trace quantities of phlogopite. The Pre-Cambrian Basement rock and the formation brine were found to contain traces of potentially radioactive elements, strontium and potassium. This finding partially supports Hodge et al.'s (1981) contention that radiogenic decay could be the source of the thermal anomalies in the Basement.

Average and Local Geothermal Gradients

The average geothermal gradient of the Auburn well was measured to be as high as 14.7°F/1,000 ft. (26.7°C/km). This gradient is based on a bottom-hole temperature measurement of 127.0°F (52.8°C) by the USGS on March 16, 1982 and a surface temperature of 50.0°F (10.0°C). The bottomhole temperatures, calculated from Schlumberger's wireline logs, ranged from 123.5°F immediately after drilling to 126.0°F during the preliminary flow testing phase. The temperature profile measured by Schlumberger on March 2, 1982 is shown in Figure 3-1 in tracks running from 3,600 ft. to 4,500 ft. (left), and from 4,500 ft. to 5,250 ft. (right).

The temperature profile of the Auburn low-temperature geothermal well indicates a relatively constant thermal gradient of 14.4°F/1,000 ft. (26.4°C/km) just to the top of the Potsdam formation with the temperature rapidly increasing thereafter. The temperature perturbations, just prior to the rapid increase in geothermal gradient, occur over the major water-productive zone in the Theresa formation. These perturbations could have resulted from localized circulation of fluid between the warmer, high-porosity sandstone at the bottom and the cooler, upper portion of the Theresa which is dominated by lower-porosity, dolomitic zones.

The temperature, as shown in Figure 3-1, rapidly increased from 110°F at 5,002 ft.

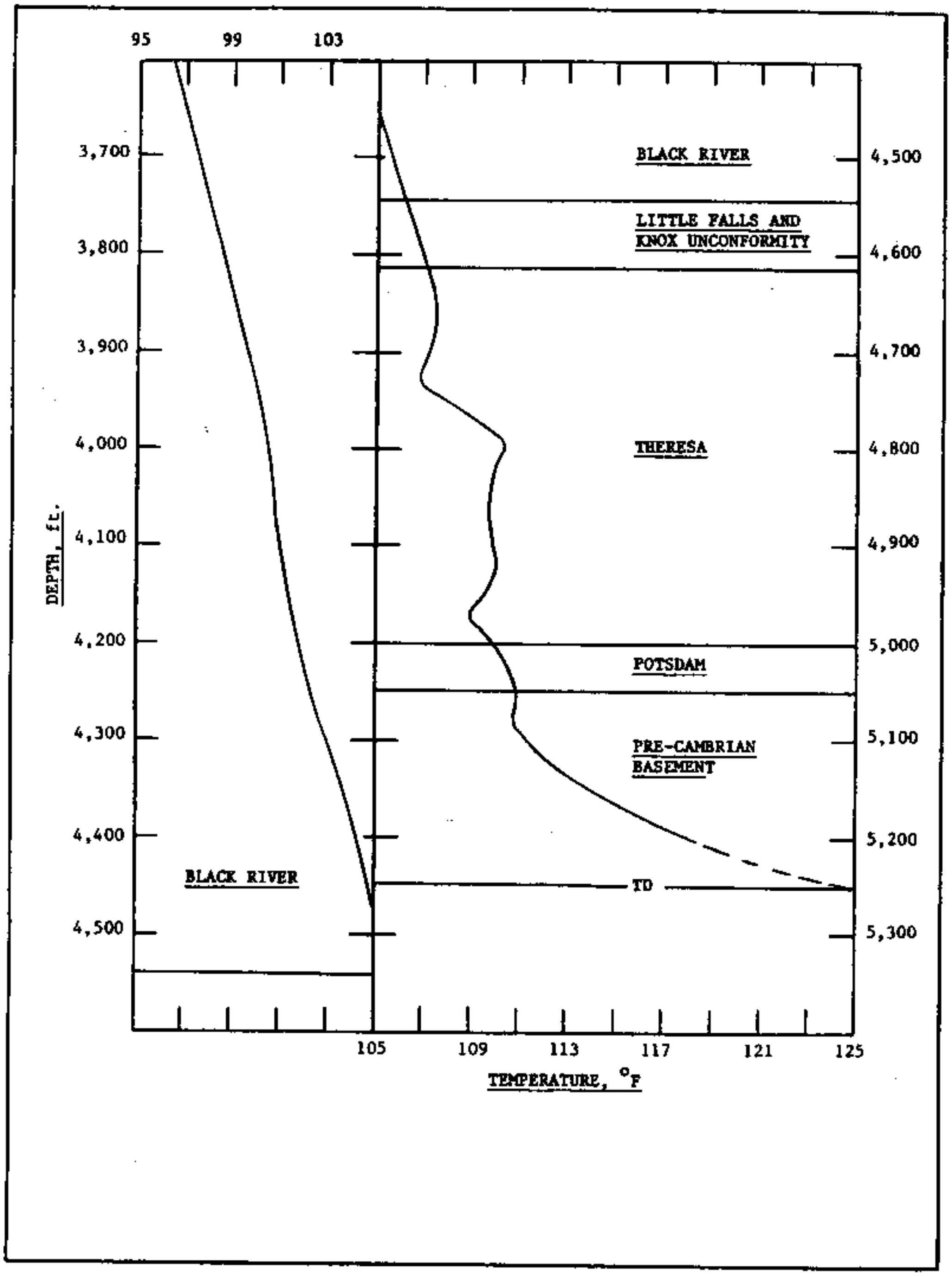


Figure 3-1. Geothermal Gradient of the Auburn, Lot 39, #1 Well (03/02/82)

at the top of the Potsdam to ∿125°F at TD in the Pre-Cambrian Basement. This asymptotic increase in temperature gives rise to a bottom-hole geothermal gradient of 91.7°F/1,000 ft. The sharp increase in temperature across the Potsdam corresponds to the increase in gamma ray counts to over 100 - 200+ API units over a background count of 20 - 50 API units as shown in the left-hand tract of the formation evaluation log suite in Figure 2-4.

The occurrence of a local "hot spot" across the Potsdam and into the Pre-Cambrian Basement supports the theory of Hodge et al. (1981) that the Pre-Cambrian Basement may be, in part, the source of the geothermal anomaly in central New York State.

HYDROLOGICAL CONDITIONS

The Auburn low-temperature geothermal well was found to be hydrostatic with a fluid level at ∿350 ft. below the surface. Six water-bearing zones have been identified. The four upper water-bearing zones, identified during the drilling operation, included two surface water shows, one show in the Queenston, and one show in the Trenton. Hydrocarbon shows were also qualitatively identified during the Auburn well's drilling phase.

The major water-producing intervals were identified as a consequence of the preliminary flow testing of the well. These zones were: a 30-ft. interval in the Black River limestone; and a 310-ft. interval spanning the Theresa and the Potsdam formation. The latter zone was selected for further evaluation because it offered the highest temperature and water production potentials. The well was, consequently, open-hole completed with 7-in. casing set and cemented at ∿4,700 ft. just into the Theresa formation. The interval from 4,700 ft. to TD in the Pre-Cambrian Basement, with a net productive sand of 310 ft., is considered the Auburn low-temperature, geothermal reservoir.

The Auburn reservoir appears to be fully saturated with formation brine with a total dissolved solids concentration of ∿300,000 ppm. The formation brine contains some dissolved natural gas (>90% CH_4), estimated to be >2.0 SCF/STB at the hydrostatic reservoir pressure of 2,260 psi. The ensuing discussions on hydrological conditions refer, for the most part, to the Auburn reservoir. The hydrological conditions are described below in terms of:

- WATER AND HYDROCARBON SHOWS
- MAJOR WATER-PRODUCTIVE ZONES
- HYDROSTATIC LEVELS AND RESERVOIR PRESSURE

o CHEMICAL COMPOSITION OF FORMATION FLUIDS

Water and Hydrocarbon Shows

During the drilling phase, four water-producing zones were identified by the Baroid personnel and noted on the mud log. Two surface water zones were identified at 199 ft. and 106 ft. Water shows were identified at 2,030 ft. in the Queenston and at 4,160 ft. in the bottom of the Trenton. No other water shows were identified because drilling was switched over from air to mud at 4,160 ft. Continuous monitoring of gas flows and pressures was also done by Baroid during the drilling phase. The locations of hydrocarbon shows and their concentrations observed during drilling are shown in Table 3-2.

Table 3-2

HYDROCARBON LOCATIONS AND CONCENTRATIONS

Depth (ft.)	No. of Units	Source
290	NA	Daily Drilling Report
410	NA	"
1,618	18	Lithologic Log
1,651	40	"
2,046	12	"
4,150	600	"
4,160	1,500	"

Gas readings from 0 to 3,000 units (U) measure gas in air mixtures of 0 to 100%. A small gas show of 40 units (1.3% gas in air) was seen from a depth of 1,651 ft. to 1,668 ft. There was a larger gas show in the zone from about 4,160 ft. in which an instanteneous gas reading of 1,500 U (50% gas in air) with a downhole pressure of 350 psi were measured. The composition of this gas show was measured to be 99.3% methane and 0.7% ethane by gas chromatography. These measurements were made while drilling on air at a rate which is on the order of 10^3 standard cubic feet per minute.

Major Water Producing Zones

Two major water-producing zones were identified from production (PLT) logs taken during the first preliminary flow test on April 7, 1982. The preliminary flow tests were conducted prior to well completion with the intermediate 9 5/8-in. casing string set at 1,287 ft. The major water-producing zones were identified as (ENG, INC., 1982):

- A 30-ft. interval from 4,150 ft. - 4,180 ft. in the Black River limestone. It is estimated that this interval contributed 10% of the produced water at a temperature of 121.6°F.
- The 4,650 ft. - 5,050 ft. interval with approximately 310 ft. net productive sand spanning the Theresa and the Potsdam sandstones. It is estimated that this interval contributes 90% of the water (produced during the flow tests) between temperatures of 123.6 to 125.0°F.

The instantaneous, initial well productivity was estimated to be 300 and 365 gpm at 4,000 ft. and 5,000 ft., respectively from the preliminary flow test data. The initial well productivity and maximum deliverability were further quantified from the pump test data in Appendix B.

Hydrostatic Levels and Reservoir Pressure

The Auburn low-temperature geothermal reservoir is hydrostatic with the fluid level occurring ∿350 ft. from the surface or ∿358 ft. above sea level. The hydrostatic gradient is estimated to 0.512 psi/ft. from field-measured, specific gravity values of 1.18, and from downhole pressure measurements and fluid levels. The hydrostatic levels in the wellbore varied from phase to phase during the development operations, depending on the wellbore's condition and the gravity of the stored fluid. At different developmental phases, the hydrostatic levels in the wellbore were measured as shown in Table 3-3.

Table 3-3

HYDROSTATIC LEVELS

Date	Phase	Level (ft.)
03/16/82	Pre-Hydrofracture	345
04/07/82	Flow Test	590
05/24/82	Post-Flow Test	320
04/12/83	Post-Hydraulic Fracturing	363
08/01/83	Pre-Pump Test	50

The pre-pump test level represents the hole loaded with fresh water from the continuous flushing to remove the frac sand subsequent to the aborted attempt at pump testing the well in April, 1983. The hydrostatic gradient was computed to be 0.448 psi/ft. for the conditions which existed just prior to the pump test phase. This gradient, and the measured downhole pressure of 1,757.9 psi at 3,973 ft. below the surface, was used to compute the average reservoir pressure of 2,260 psi because: the wellbore conditions appeared to be optimum just prior to the pump test as a result of the hydraulic fracturing and the continuous swabbing; and the shut in time of four months, prior to the pump test, was sufficient for reservoir stabilization.

Chemical Composition of Formation Fluids

The total dissolved solids (TDS) of the brine from the Theresa and Potsdam formations is approximately 300,000 ppm. The major anionic species is chloride (Cl^-) at a concentration of approximately 180,000 ppm; the major cationic species is sodium (Na^+) at a concentration of approximately 70,000 ppm; and the concentration of Ca^{++} and Mg^{++} ions is approximately 22,500 ppm. The concentration of iron is approximately 55 ppm and silica as SiO_2 is approximately 10 ppm. The pH of the geothermal brine is approximately 5.5. The chemical composition of the formation brine is further discussed in Appendix B and summarized in Table 3-4.

Table 3-4

AUBURN WELL FORMATION WATER ANALYSIS

	08/06/83/13:00 (mg/l)	08/06/83/13:15 (mg/l)	08/07/83/02:45 (mg/l)
pH	5.50	5.22	5.72
Total Dissolved Solids (TDS) @125^{O}F	294,000	283,000	299,000
Alkalinity as $CaCO_3$	96	62	74
Chlorides	179,000	180,000	179,000
Carbonate	<.1	<.1	<.1
Bicarbonate	96	62	74
Sulfate	<1	<1	<1
Sulfite	<0.01	<0.01	<0.01
Sodium	68,300	72,500	71,800
Calcium	18,800	19,800	19,800
Magnesium	2,950	3,000	3,050
Iron	68.5	43.0	50.0
Silica as SiO_2	10.4	12.2	10.9

The chemical composition of the produced brine appears to be relatively consistent over and beyond the seven days of pump testing and the 100,000 plus barrels of produced brine. The observed consistencies in the composition and concentration of the geothermal brine suggest that the Auburn geothermal well is draining a singular source bed because the composition and concentration of brines usually vary with depth and depositional environment.

The analyses in Appendix B indicate that the geothermal fluid contains ~2.25 SCF/STB of dissolved gas at 577 psi and 125^{O}F with a methane concentration in excess of 90%. The measured volume of dissolved gas is approximately 55% of the estimated saturation volume of 4.1 SCF/STB. The laboratory measured gas composition is consistent with behind-the-pipe values measured uphole prior to well completion at 4,700 ft. Chromatographic analysis of gas flows, sampled by Baroid during the drilling phase, indicate 99.3 volume percent methane and 0.7% ethane by volume.

RESERVOIR CHARACTERISTICS

The Auburn low-temperature geothermal reservoir appears to be finite and bounded. Within these physical constraints, the net producing interval is made up of two communicating layers or zones -- a low-porosity dolomitic zone and a medium-porosity sandstone zone -- both of which are highly fractured. The two producing zones are in communication with each other vis-a-vis cross-flow in the intersecting fractures. In addition to the natural fracture system, the producing interval was hydraulically fractured and propped prior to the pump test. Thus, the Auburn reservoir is comprised of as many as six different storage and flow regions as shown in Appendix B.

The two productive zones are assumed to be in perfect communication with each other and are viewed to be one producing interval with volume averaged properties. The naturally fractured Auburn reservoir is thus, divided into three distinct regions:

- REGION 1 - an improved near wellbore region resulting from a vertical mega-fracture created by the pre-pump test hydraulic stimulation.
- REGION 2 - a set of interconnecting fractures and fissures which represents foramenular secondary porosity, and which contributes a low-storage but a high-flow capacity.
- REGION 3 - a matrix of well-defined fine pores which represents intergranular primary porosity and which contributes a high-storage but low-flow capacity.

The three distinct storage regions will result in the development of three different flow regimes, each of which becomes dominant at different times during reservoir drawdown, and well shut-in periods. During drawdown, the vertical hydraulic fracture (Region 1) drains first, followed by the natural fractures (Region 2) and finally, the flow will become limited or controlled by the lower permeability but higher porosity matrix (Region 3). During drawdown, the duration of each flow regime is determined by the pumping rate. During shut-in, the durations of the different flow regimes are determined by the storage capacities of the individual regions.

The reservoir characteristics were readily identifiable and, for the most part, quantifiable from the analysis of the pump test and supporting data (ENG, INC., 1983). The quantifiable reservoir characteristics are briefly summarized in the following.

Matrix Region (3)

The reservoir matrix (dolomites and sandstones) controls the volumetric capacity of the reservoir and will limit the production rate as a result of its low permeability. The reservoir properties, which were calculated by pressure transient analysis, represent the average composition of all three regions. The average composition of the reservoir is, however, controlled and dominated by the reservoir matrix.

The product of effective porosity and effective compressibility was determined to be 2.0×10^{-8} psi^{-1}, on the average, from four data points. These values were computed from log-log type curve matches between the actual ΔP-Δt relationships and theoretical curves of dimensionless P_D-t_D relationships for both the pressure drawdown and buildup data. Based on an estimated value of 7.5×10^{-6} psi^{-1} for the effective compressibility of the reservoir and its contained fluids, the effective porosity computes out to be 0.27%. It should be noted that this value is about 10 times less than the average log-determined value of absolute porosity (2.82%). Such differences between effective and absolute porosities have been reported in the literature, e.g.: Strobel, Gulati and Ramey (1976) calculated effective permeability and porosity of 48.3 millidarcys (md) and 0.22% within a drainage area of 54 square miles for interference test data in a dry-gas reservoir producing from a naturally fractured orthoquartzite zone; cores from the other orthoquartzites were reported to have an average absolute porosity of 2.5% and less than 0.1 md permeability to air.

The effective transmissivity was estimated to be 3,100 md-ft. on the average, from a data set of six. These values were computed from the slopes of the semi-log straight line of a Horner type plot for pressure buildup data and a Miller-Dyes-Hutchinson plot for pressure drawdown data.

For a net productive interval of 310 ft., the effective reservoir permeability is computed to be 10 md. The permeability of a core sample of the Theresa, as discussed in Coring and Core Analyses, was considered too low to be measurable by a petroleum production laboratory in Salt Lake City. There is some uncertainty about the sample's integrity or the laboratory's contention because core samples from the Theresa formation in the Buffalo region have been reported to have permeabilities ranging from 10 to 100 md. based on laboratory measurements. The effective permeability of 10 millidarcys, for lack of sufficient core data, is assumed to be an average of the permeabilities of the reservoir matrix and the natural fracture system.

Natural Fracture Region (2)

The natural fractures and fissures or microcracks are estimated to be ∿26% of the total effective porosity from semilog drawdown and buildup data analyses which are detailed in Appendix B. This estimate is consistent with the observed density of planar features and distinct natural fractures as discussed under the sub-section on Borehole Televiewer Log in Logging Activities and Log Analyses. The density of planar features, mostly low-angle and indistinct, are shown to be ∿3 features/ft. in Figure 2-6 whereas the density of the distinct natural fractures averages only ∿0.02 features/ft. (Hickman et al., 1983). These measurements were made by the USGS utilizing hydraulic fracturing stress techniques and borehole televiewer surveys to evaluate the natural fracture distribution and borehole elongation of the Auburn geothermal well. The USGS concluded that: there is a persistence of natural fractures with apertures on the order of several centimeters to depths of 5,250 ft.; distinct natural fractures, of which approximately one third dip less than 5°, persist to the measured TD; and the strike of steeply dipping natural fractures, which occur in the Cambrian rock (Theresa and Potsdam), shows a strongly developed E-W preferred orientation.

The in situ stress and fracture distribution of the Auburn geothermal well was also investigated by Schlumberger-Doll Research (Plumb and Singer, 1983) utilizing the borehole televiewer log run by the USGS, a dipmeter/fracture identification log and an assortment of other logs including a long-space sonic log which measured compressional as well as shear wave velocities. Schlumberger found: the highest fracture density occurred between depths 4,700 ft. - 4,850 ft., with fractures oriented between N80E and N100E and with the majority having a dip $> 60^{\circ}$; and fractures of similar strike and dip spanned the interval from 4,850 to 5,100 ft. in the Theresa and Potsdam formations, and extended into the Pre-Cambrian Basement. The fracture distribution, in number of fractures per 5-ft. interval, is shown in Figure 3-2, which also shows their orientation or strike. The natural fracture density was found to be as high as 2/ft., around 100 times the depth averaged values obtained by the USGS.

The persistence of distinct natural fractures in the Theresa and the Potsdam formations has made a significant contribution to the reservoir's permeability and the well's productivity. The latter, as well as the reservoir's drainage radius, were artificially enhanced by hydraulic stimulation as discussed below.

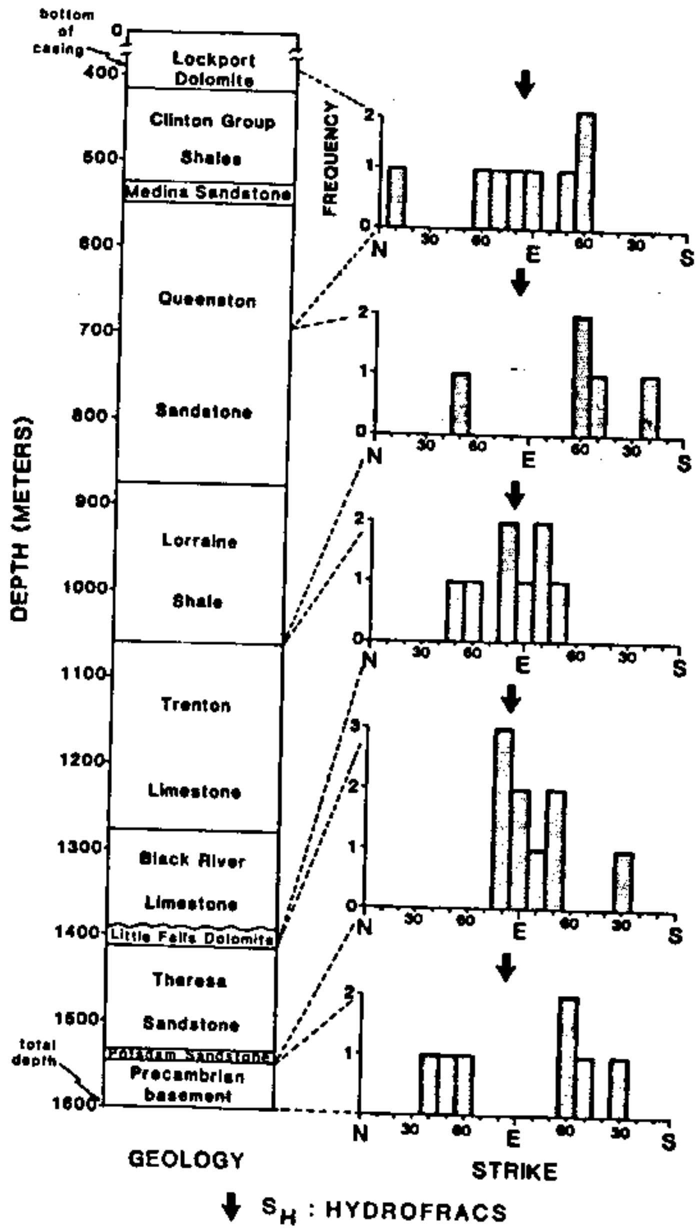


Figure 3-2. Distribution and Orientation of Natural Fractures (Plumb and Singer, 1983)

Hydraulic Fracture Region (3)

The induced hydraulic fracture is most likely vertical with a N85E strike. The intrinsic permeability should be anistropic with maximum, intermediate and minimum permeability oriented N85E, vertical, and N05W, respectively (Plumb and Singer, 1983).

The vertical hydraulic fracture was identified by the 1/2 slope of the log-log plot of ΔP versus Δt, and was computed to have a half-length of $\sim$150 ft. (ENG, INC., 1983).

RESERVE ANALYSIS

The reserves of the Auburn low-temperature geothermal well are quantified in terms of the number of Btus recoverable at the wellhead with and without reinjection of the spent brine to recharge the reservoir. The volumetric resources and areal extent are first identified to determine the in situ thermal capacity of the reservoir brine and the contacted rock masses. The recoverable volumetric resources, or the volumetric reserves, are subsequently estimated in terms of capacity and productivity. The hydrothermal resources and reserves, with and without a reinjection component, are then defined for a surface temperature of 125°F which is projected from measured and estimated wellhead temperatures. The reserve analysis is detailed in the following sub-sections:

- VOLUMETRIC RESOURCES AND AREAL EXTENT
- VOLUMETRIC RESERVES
- HYDROTHERMAL RESOURCES W/WO REINJECTION
- HYDROTHERMAL RESERVES W/WO REINJECTION

Volumetric Resources and Areal Extent

The proved volumetric resources of the Auburn low-temperature geothermal well are estimated to be $3.0 \times 10^6 \pm 0.3 \times 10^6$ STB; the possible resources are estimated to be $7.0 \times 10^6 \pm 1.0 \times 10^6$ STB; and the probable reserves are estimated to be $23.0 \times 10^6 \pm 5.0 \times 10^6$ STB. Correspondingly, the areal extent of the resource is estimated to be 463, 1,080, and 967 acres, respectively, for the proved, possible and probable categories.

The volumetric resources were estimated from reservoir limit tests utilizing pressure drawdown data plotted on cartesian coordinates for the 24-hour drawdown and the multirate drawdown tests. The slope of the pseudosteady-state straight line was used to compute the connected reservoir drainage volume or the volumetric resources. The volumetric resource computation was found to be very sensitive to the total effective compressibility, c_t of the producing formation, whereas the areal extent of the reservoir (and the mass of its rocks) is very sensitive to the product of effective porosity and effective compressibility, ϕc_t. The categorization of resources into proved, possible and probable is based on their sensitivities to c_t and ϕc_t. The probable and possible resources are estimated in the limiting condition of zero-fluid withdrawal. The dependency of volumetric resource or connected reservoir drainage volume on pumping or drawdown rates is a direct consequence of the nature of the Auburn reservoir and the reservoir characteristics.

The "double-porosity" characteristics of the Auburn well gives rise to a connected reservoir drainage volume which is inversely dependent on the pumping rates, i.e., the effective drainage area decreases with increasing flowrate. An unbalance is created between the rate of fracture drain and fracture refill by the porous matrix, i.e., the permeability of the porous matrix is rate-limiting. This unbalance results in the flushing of the natural fracture channels and their disconnection from the porous matrix. The unbalance in intra-porosity flow and the degree of disconnection increases with increasing pumping rates. The radius of influence or reservoir volume, thus, decreases with increasing flowrate. In the limit of zero flowrate, the downhole pressure is only influenced by the total connected pore volume of natural fractures and porous matrix voids.

Volumetric Reserves

The volumetric reserves of the Auburn low-temperature geothermal reservoir are based on the estimated volumetric resources, and are shown in Table 3-5.

Table 3-5

AUBURN VOLUMETRIC RESERVES (STB)

Category	Resources (STB)	Reserves (STB)
Proved	3.0×10^6	2.25×10^6
Possible	7.0×10^6	5.25×10^6
Probable	23.0×10^6	17.25×10^6

The reserves are based on an estimated recovery efficiency of 75%, an assumption which is considered valid for continuous drainage of the resources at pumping or drawdown rates which are less than or equal to the well's long-term or continuous deliverability.

The initial or maximum deliverability of the well was determined to be ∿338 gpm (∿11,600 STB/D) at TD and ∿328 gpm (∿11,200 STB/D) at a pumping depth of 4,000 ft. It should be noted that the preliminary flow-test's estimate of 365 gpm at TD is within 10% of the values determined by the pressure transient. The initial productivity index, J_o', of the Auburn well was determined to be 0.56 STB/D/psia^2 for a Fetkovich exponent, n = 0.642.

$$q_o = 0.5612\ (\bar{P}^2 - P_{wf}^{\ 2})^{0.642} \qquad (3\text{-}1)$$

$\bar{P}$ and P_{wf} are respectively the average reservoir pressure and the flowing wellbore pressure at the reservoir sandface; q_o is the initial production rate in STB/D.

Hydrothermal Resources W/WO Reinjection

The hydrothermal resources of the Auburn low-temperature geothermal reservoir are estimated in Table 3-6.

Table 3-6

AUBURN HYDROTHERMAL RESOURCES (Btu)

Category	Volumetric	Reinjection	Total
Proved	5.50×10^{10}	34.89×10^{10}	40.39×10^{10}
Probable	12.84×10^{10}	89.95×10^{10}	102.79×10^{10}
Possible	42.20×10^{10}	78.20×10^{10}	120.40×10^{10}

The volumetric hydrothermal resources are based on the thermal capacity of the in situ formation brine. The thermal capacity is defined by a wellhead temperature drop from 125°F to an operating temperature of 70°F, and an overall heat recovery of capture efficiency of ∿80%.

The wellhead temperature of ∿125°F is based on estimated, measured and projected surface temperatures (for a production rate of 150 gpm). Surface temperatures of

$\sim 123^{\circ}F$ were estimated for steady-state heat transfer in the wellbore, and unsteady radial conduction in the earth from an insulated tubing string with a perfect downhole pump. Surface temperatures of $\sim 130^{\circ}F$ were measured during the 150 gpm stage of the multirate drawdown test. The measured surface temperatures were strongly influenced by the following factors: production of higher temperature fluids from the lower-producing formations; downhole generation of heat by the pump and motor; and reinjection of warm, produced brine into the annulus adjacent to the production tubing string. The effects of these factors on the measured surface temperatures were quantified, and then combined with the theoretical estimations to predict the wellhead surface temperatures under different operation conditions. The projected surface temperature of $126 \pm 1^{\circ}F$ is for the production of formation brine at 150 gpm through an uninsulated tubing string from a setting depth of 4,000 feet.

The hydrothermal resources include a reinjection component in which heat is recovered from the reservoir rock by the reinjection of the produced brine. The extent of the reinjection resources are defined by the breakthrough time of the thermal front because the wellhead temperature and the recoverable heat will decrease rapidly with breakthrough of the cooler thermal front. The reinjection resources were evaluated in terms of the relative volumetric heat capacities of the formation brine, the reservoir matrix (rock and brine), and the caprock as well as the reinjection rate, and the separation distance between the injection and production well. The latter is taken as the outer limit of a right cylindrical reservoir; the reinjection rate is taken to equal the production rate which is selected to be 286 gpm.

Hydrothermal Reserves W/WO Reinjection

The hydrothermal reserves without fluid reinjection are estimated to be 75% of the hydrothermal resources. The reinjection reserves are estimated to be 50% of the reinjection resources, based on the areal sweep efficiency of 70% and a vertical displacement efficiency of 70%. The hydrothermal reserves of the Auburn low-temperature geothermal well are estimated in Table 3-7.

Table 3-7

AUBURN HYDROTHERMAL RESERVES (Btu)

Category	Volumetric	Reinjection	Total
Proved	4.13×10^{10}	17.45×10^{10}	21.58×10^{10}
Possible	9.63×10^{10}	44.98×10^{10}	54.61×10^{10}
Probable	31.65×10^{10}	39.10×10^{10}	70.75×10^{10}

Section 4

RECOMMENDATIONS

The recommended future course of action is the pursuit of the Auburn low-temperature geothermal project to its logical conclusion, i.e., the extraction of the geothermal energy to provide/supplement the space and hot water heating requirements of the East Middle School, and the Cayuga Community College of the City of Auburn's Enlarged School District. The extraction process is conceptually discussed in Appendix B.

The steps required for future action are as follows:

- STEP 1: Perform an engineering and economic feasibility evaluation on the extraction of geothermal energy for space heating and hot water requirements. This study should include an evaluation of the project site, determination of the current heat load and variability, as well as integration of the surface extraction facilities into the existing HVAC systems. The deliverables should include the feasibility of the project under different operating scenarios such as conditions of discharge and recharge in terms of rate and duration. This study should also consider health, safety and environmental factors. These feasibility studies should be within ± 10% of final engineering specifications with cost-benefit analyses which include investment and energy tax credits.

- STEP 2: Conduct a final engineering design with detailed equipment specifications, piping and instrumentation diagrams, electrical and process control logic diagrams, and operating procedures. The deliverables should include a complete suite of architectural, mechanical, structural, and HVAC drawings, supporting specifications and documentations, and a final cost schedule.

- STEP 3: Construct surface facilities, shake down system and evaluate operations for a minimum period of 30 days.

- STEP 4: Operate and maintain the geothermal energy-extraction facility at Auburn.

Section 5

REFERENCES

1. American Association of Petroleum Geologists and the United States Geological Survey "Subsurface Temperature Map of North America," Arlington, Virginia U.S. Geol. Survey, 1976.

2. Diment, W.H., Urban, T.C. and Revetta, F.A.: "Some geophysical anomalies in eastern United States": The Nature of the Solid Earth, New York: McGraw Hill, 1976 pp. 544-572.

3. Dunn Geoscience, Inc. "Drill Cutting, Core and Formation Water Analysis", Latham, New York, June 1982.

4. ENG, INC. "Letter Communications to Mr. Robert S. Lynch, Manager of Operations, Donohue Anstey & Morrill", Boston, Massachusetts, 1982.

5. ENG, INC. "Hydrothermal Resources and Reserves of the Auburn Low Temperature Geothermal Well, Cayuga County, New York", Boston, Massachusetts, December 1983.

6. Fisher, D.W., Isachsen, Y.W., and Rickard, L.V. Generalized tectonic-metamorphic map of New York, New York State Museum and Science Service Map and Chart Series Number 15, 1971.

7. Hickman, S.H., Healy, J.H. and Zoback, M.D. "In-Situ Stress, Natural Fracture Distribution, and Borehole Elongation at Depth in the Auburn Geothermal Well, Auburn, New York," United States Geological Survey, NYSERDA Report 84-1, Part 1, 1984.

8. Hodge, D.S., and Hilfiker, K. Resource Confirmation for Resource Engineering and Economic Study of Direct Application of Geothermal Energy, Friendship Dairies, State University of New York at Buffalo, Department of Geological Sciences, ERDA Report 82-1, Appendix A, 1981.

9. Hodge, D.S., De Rito, R., Hilfiker, K., P. Morgan and Swanberg, C.A. "Investigations of Low-Temperature Geothermal Potential in New York State", LA-8960-MS, UC-66b, Los Alamos National Laboratory, Los Alamos, New Mexico, September 1981.

10. Hodge, D.S., personal communications, 1983.

11. Long, G. and Chierici, G. "Salt Content Changes Compressibility of Reservoir Brines," Petroleum Engineer, B-25 to B-31, July 1961.

12. Plumb, R.A. and Singer, J. "Insights into the Mechanical Properties of Tight Formations: A Study of In-Situ Stress and Fracture Distribution at Auburn, New York," Schlumberger-Doll Research, NYSERDA Report 84-1, Part II, 1984.

13. Revetta, F.A. and Diment, W.H. "Simple Bouguer Gravity Anomaly Map of Western New York", New York State Museum and Science Service Geol. Sur., 1971 Map No. 17.

14. Schafer, D.C. "Pumping Test Analyses for Low Yield Formations," The Johnson Driller's Journal Nov.-Dec., 1980 pp. 3-4.

15. Strobel, C.J., Gulati, M.S. and Ramey, H.J., Jr. "Reservoir Limit Tests in a Naturally Fractured Reservoir--A Field Case Study Using Type Curves," J. Pet. Tech. Sept. 1976, 1097-1106.

16. Swanberg, C.A. and Morgan, P. "The Linear Relation Between Temperature Based on the Silica Content of Groundwater and Regional Heat Flow: A New Heat Map of the United States", PAGEOPH, Vol. 117, Nos. 1/2, 227-241, 1979.

Section 6

GLOSSARY OF TERMS

Resources	refer to the quantity of fluid or energy which is contained within an underground reservoir.
Reserves	refer to the quantity of resources which is recoverable by known and standard techniques. The recovery technique is usually specified for unconventional or nonstandard methods.
Proved Reserves	refer to the quantity of resources which geological and engineering data, reservoir testing, and/or production data demonstrate with reasonable certainty to be recoverable in the future from known reservoirs under existing economic and operating conditions.
Probable Reserves	are those reserves which are supported by favorable engineering and geological data, but which are subject to a greater degree of risk which prevents classification as proved reserves. Risk refers to the risk of inaccurancies due to insufficient confirmatory information.
Possible Reserves	are speculative reserves where risk is relatively high. Possible reserves usually depend on some favorable development or extent which is not predictable with good accuracy.

GLOSSARY OF TERMS USED IN APPENDIX A

BBLS	barrels
BOP	blow out preventer
fish	an object left in the wellbore during drilling or workover operations
JTS	joints or single lengths (30 ft.) of drill pipe, tubing, or casing
KB	kelly bushing, a drive bushing fitted to the rotary table of a rig
mouse hole	an opening through the rig floor, usually lined with pipe, into which a length of drill pipe is placed temporarily for later connection to the drill string
poz	pozzolan, a siliceous material added to portland cement mixtures
rat hole	a hole that is drilled in the bottom of the main hole; sometimes used to to collect fishes, and thus keep the producing formation clear
reamer	a tool used in drilling to smooth the wall of a well
rig up	to prepare the drilling rig for making hole
spud in	to begin drilling; to start the hole
sub	a short, threaded piece of pipe used to adapt parts of the drill stem

Appendix A

DAILY ACCOUNT OF WELLSITE ACTIVITY

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL

DATE	ACTIVITY
02/01/82	Move in; rig up.
02/02/82	Rig up; dig rat hole and dig mouse hole.
02/03/82	Finish mouse hole; spudded hole with 17 1/2" OWVJ Bit #1 at 12:20 pm (2/3/82); drilling at 59'.
02/02/82	Drilled to 84'; trip for 17 1/2" x-33 Bit #2; drilling at 87'.
02/05/82	Drilled to 99'; rig broke down at 5:00 am (right angle drive).
02/06/82	Rig broke down; commence drilling at 11:00 am; drilled to 117'; rig broke down at 3:45 pm (drive shaft); commenced drilling at 10:30 pm; drilling at 126'.
02/07/82	Drilled to 151'; rig broke down at 9:15 am (drive shaft); commenced drilling at 6:00 pm; drilling at 197'.
02/08/82	Drilled to 306'; shut down to haul water at 2:45 pm; commenced drilling at 5:00 pm; drilling at 398'.
02/09/82	Reaming and cleaning hole; mix mud (6 am-12 pm); wait on mud (12:30 pm-3 pm); change over to air/mud; rig broke down (6:30-9:00 pm); mix mud.
02/10/82	Rig broke down (12 am - 4:30 pm); commence drilling at 4:30 pm; drilling at 413'.
02/11/82	Drilled to 492'; trip for casing; ran 13 3/8" casing to 320' and would not go; pulled casing; trip in hole with 17 1/2" Bit #2.
02/12/82	Finished trip; rig broke down 5:30 am to 6:30 am; reamed 10' to bottom; trip out of hole; run 13 3/8" casing to 320' and would not go; pulled casing; wait on reamer (3:30 pm to 12:00 am).

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
02/13/82	Trip in hole with reamer; ream 304' to 492'; trip out of hole; ran guide shoe (1.15') and 11 JTS (465.70') 13 3/8" O.D.; 48#, H-40 API; Seamless R III Casing and set at 477.85'. Dowell cemented with 135 sacks Class A cement and 195 sacks RFC. Plug down at 5:20 pm; waiting on cement.
02/14/82	Nipple up BOP; go in hole with 12 1/4" J-33 Bit #3; drilled to 478'; trip to clean bit; drilling at 680'.
02/15/82	Drilling at 1085'.
02/16/82	Drilled to 1287'; trip for casing; ran float shoe (1.15) and 31 JTS (1273.00') 9 5/8" O.D.; 36#, J-55 API R III casing and set at 1287.15'. Dowell cemented with 125 sacks Class A cement. Plug down at 11:00 pm. Waiting on cement.
02/17/82	Wait on cement (2 am); go in hole with 8 3/4" J55R Bit #4; drilling at 1903'.
02/18/82	Test BOP (OK); drilling at 2537'.
02/19/82	Drilled to 2758'; trip for bit; go in hole with 8 3/4" J-77 Bit #5; drilling at 2930'.
02/20/82	Drilling at 3775'.
02/21/82	Drilling at 4342'.
02/22/82	Drilled to 4446'; trip for bit; go in hole with 8 3/4" J-77 Bit #6; drilling at 4500'.
02/23/82	Drilled to 4700'; trip for core barrel.
02/24/82	Trip for core barrel; rigged up core barrel; go in hole with 7 27/32" MC4-RS core Bit #7; cut 1 1/2' of core; trip out of hole; recovered 3" of core; wait on bit.
02/25/82	Wait on bit; go in hole with 8 3/4" J-99 Bit #8; drilling at 4719'.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
02/26/82	Drilling at 4897'.
02/27/82	Drilled to 5117'; trip for core barrel.
02/28/82	Trip for core barrel; rigged up core barrel go in hole with 8 23/32" MC-23 Core Bit #9; took weight at 2026'; reamed 30' with core bit; trip out for 7 27/32" core barrel; rigged up core barrel; go in hole with 7 27/32" Chris MC-4RD Bit #10; coring at 5126'.
03/01/82	Cored to 5126'; trip out of hole; recovered 3' of core; go in hole with 8 3/4" J-99 Bit #11; wash down 79' (last two stands); ream hole for 30'; ream cored hole; drilling at 5186'.
03/02/82	Drilled to TD of 5250'; circulate up bottoms for 1 hr. 15 min. trip out of hole; rig up Schlumberger run Diff. Temp. Log; running Form. Den. Comp./Comp. Neutron/GR/Cal. Bottom hole temperature 123.5°F. Fluid level at 128'.
03/03/82	Finish above log; run Dual Laterolog, run Comp. Sonic Log; run FIL Log; rig down Schlumberger; laying down drill collars.
03/04/82	Finish laying down drill collars; run one stand drill pipe in hole on kelly; close BOP; rig on security status.
03/05/82	Rig on security status.
03/06/82	Rig on security status.
03/07/82	Rig on security status.
03/08/82	Rig on security status.
03/09/82	Rig on security status
03/10/82	Rig on security status.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
03/11/82	Rig on security status.
03/12/82	Rig on security status.
03/13/82	Rig on security status.
03/14/82	Rig on security status.
03/15/82	Rig on security status; move in and rig up USGS.
03/16/82	8:00am-5:45am: run temperature log to 5250'; bottom hole temperature of 127^{o}F; fluid level at 345'. 5:45pm-10:30pm rig up and run televiewer log to a total depth of 2000'.
03/17/82	8:00am-11:00am:test packers. 11:00am-3:15am:trip packers in hole to 1945'. 3:15pm-5:45pm:set packers; pressure up and breakdown at 1100 psi. 5:45pm-8:00pm:trip packers out of hole and lay down packers.
03/18/82	8:00am-1:00pm:dress and test packers. 1:00pm-2:00pm:trip in hole with packers to 1980'. 2:00pm-5:45pm:attempt to test - could not build up pressure. 5:45pm-7:00pm:trip out of hole with packers. 7:00pm-10:52pm:work on Borehole Televiewer Logging Tool. 10:52pm-11:48pm: ran Televiewer to 2000' Log not operating properly - came out of hole.
03/19/82	8:00am-3:30pm: dress and test packers. 3:30pm-9:00pm: log with Televiewer 2000' to 4000'.
03/20/82	8:00am-10:30am: pick up packers and trip in hole to 2450'. 10:30am-1:30pm: attempt to test packer at 2450' - maximum pressure 200 psi. 1:30pm-3:15pm: trip out of hole and lay down packers 3:15pm-4:30pm: rig up to log with Televiewer. 4:30pm-12:00am: log with Televiewer from 5250'.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
03/21/82	12:00am-10:00am: log with Televiewer. 10:00am-12:00pm: pick up packers and trip in hole to 2450'. 12:00pm-3:30pm: attempt to test packer at 2450' - maximum pressure 200 psi. 3:30pm-5:00pm: trip out of hole and lay down packers. 5:00pm-6:00pm: rig up to log with Televiewer.
03/22/82	8:00am-10:00am: dress and test packers. 10:00am-11:30am: pick up packers and trip in hole to 2450'. 11:30am-5:15pm: test packer at 2450' - Breakdown at 1150 psi. 5:15pm-7:00pm: trip out of hole and lay down packers. 7:00pm-9:00pm: rig up to log and log to 2450'.
03/23/82	8:00am-12:00pm: pick up packers and trip in hole to 3010'. 12:00pm-6:00pm: test packers at 3010' - breakdown at 1650 psi. 6:00pm-7:00pm: trip out of hole and lay down packers.
03/24/82	8:00am-9:00am: finish trip out of hole and lay down packers. 9:00am-2:00pm: dress packers. 2:00pm-6:00pm: run temperature log to 3200' - log would not work.
03/25/82	8:00am-11:45am: pick up packers and trip in hole to 4858'. 11:45am-7:30pm: test packers at 4858' - breakdown at 2900 psi. 7:30pm-8:00pm: trip out 2 1/2 stands of drill pipe shut down for night.
03/26/82	8:00am-10:30am: finish trip out of hole. 10:30am-12:00pm: dress and test packers. 12:00pm-2:00pm: pick up packers and trip in hole to 3877'. 2:00pm-9:00pm: attempt to test packers at 3877' - pressure built up to 3000 psi and has instantaneous pressure drop to 500 psi (note: equipment on surface had to be thawed out which caused excess testing time). 9:00pm-12:00am: fish for cluster gauge with USGS wireline inside drill pipe.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
03/27/82	12:00am-3:00am: fish for cluster gauge with USGS wireline inside drill pipe. 3:00am-8:00am: shut down. 8:00am-12:30pm: attempt to trip packers out of hole left bottom packer assembly in hole. 12:30pm-6:00pm: inform appropriate parties and discuss alternatives.
03/28/82	8:00am-1:00pm: pick up drill collar and trip in hole. 1:00pm-3:00pm: wait on orders. 3:00pm-6:00pm: continue trip in hole - tag top of packer assembly at 3854' - trip out of hole - order fishing tools, Fishing Engineer and milling bit from Tri-State, Wooster, Ohio.
03/29/82	8:00am-12:00pm: wait on fishing tools. 12:00pm-4:30pm: pick up fishing tools and trip in hole. 4:30pm-5:00pm: fish for bottom packer assembly 5:00pm-8:00pm: trip out of hole - partial recovery of fish (all but packer rubber element).
03/30/82	8:00am-6:00pm: wait on fishing tools.
03/31/82	8:00am-12:00pm: pick up rotary shoe and trip in hole. 12:00pm-2:00pm: work on rig (replace hydraulic hoses) 2:00pm-5:00pm: continue trip in hole. 5:00pm-9:00pm: drill on packer rubber at 3877' packer released; chased packer to 4750'. 9:00pm-12:00am: trip out of hole.
04/1/82	12:00am-1:00am: finish trip out of hole. 9:00am-1:00pm: pick up fishing tool and trip in hole. 1:00pm-3:00pm: fish for packer element. 3:00pm-8:00pm: trip out of hole with fish. 8:00pm-10:30pm: rig up Schlumberger to run dipmeter log and long spaced sonic log. 10:30pm-12:00am: logging.
04/02/82	12:00am-1:00pm: logging and pump pit water down annulus. 1:00pm-6:00pm: secure hole and wait on orders.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
04/03/82	Rig on security status.
04/04/82	Rig on security status.
04/05/82	8:00am-9:30am: lay down drill collars. 9:30am-2:30pm: wait on frac tanks and flow rate measurement hook up. 2:30pm-3:00pm: trip in hole with open-ended drill pipe to 1518'. 3:00pm-9:00pm: rig up Schlumberger temperature log and flowmeter log; unload hole with air compressors and flow test at 1518'. 9:00-10:00pm: rig down loggers and trip out of four stands of drill pipe.
04/06/82	8:00am-6:00pm: wait on frac tanks.
04/07/82	7:00am-8:00am: crip in hole to 1669' with open ended drill pipe. 8:00am-12:00pm: rig up loggers to perform flow test. 12:00pm-7:00pm: flow test hole. 7:00pm-8:00pm: rig down loggers. 8:00pm-9:00pm: trip drill pipe back up into casing.
04/08/82	8:00am-10:00am: trip in hole to 3863' and rig up loggers to perform flow test. 10:00am-1:30pm: try to unload hole; unable to maintain flow. 1:30pm-2:15pm: trip out of hole to 3044'. 2:15pm-9:15pm: flow test hole. 9:15Pm-9:45pm: rig down loggers. 9:45pm-12:00am: trip drill pipe back up into casing.
04/09/82	7:00am-0:30am: trip in hole to 3990'. 9:30am-1:00pm: try to unload hole; unable to maintain flow. 1:00pm-6:00pm: trip out of hole.
04/10/82	Rig on security status.
04/11/82	Rig on security status.
04/12/82	8:00am-2:30pm: dress packers and trip in hole to 1187'. 2:30pm-6:00pm: dress packers.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
04/13/82	7:00am-5:45pm: trip in hole to 5201'; attempt to test; no results. 5:35pm-6:00pm: rig down logging tools and release packers. 6:00pm-11:00pm: chain out of hole to 1187'.
04/14/82	8:00am-9:00am: trip out of hole. 9:00am-6:00pm: dress packers.
04/15/82	8:00am-12:15pm: pick up impression packers and trip in hole to 3100'. 12:15pm-6:00pm: take impression at 3100'. 6:00pm-8:00pm: trip out of hole to 1187'.
04/16/82	8:00am-9:00am: trip out of hole. 9:00am-12:30pm: dress impression packers and trip in hole to 1900'. 12:30pm-6:15pm: take impression at 1900;. 6:15pm-9:00pm: trip out of hole.
04/17/82	8:00am-4:30pm: dress packers and log with Televiewer log. 4:30pm-5:00pm: rig down logging tool 5:00pm-6:00pm: pick up packers and trip in hole to 1187'.
04/18/82	8:00am-10:00am: trip in hole to 5105'. 10:00am-6:00pm: attempt to test at 5105'; no results; parted packer at 4300 psi and left bottom packer in hole. 6:00pm-12:00pm: chain out of hole and lay down one packer.
04/19/82	8:00am-3:00pm: wait on orders. 3:00pm-6:00pm: trip in hole to 1187'. 6:00pm: released rig, plug back total depth 5105'.
05/24/82	SUNY Buffalo (Dr. Hodge) found the water level at 320' using his temperature tool.
05/31/82	SUNY Buffalo (Dr. Hodge) found the water level at 320' using his temperature tool.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
07/15/82	GFS, Inc. on location: 1) tighten swage with tongs and dozer; 3) graded and raked location; and 3) spread stone around wellhead.
08/12/82	7:30am-wellhead pressure 225 psi.
01/06/83	Schlumberger on location at 9am; rigged up mast truck and ran Gamma/Caliper log PBTD (5102') to bottom of 9 5/8" casing (1287'). Off location at 3:30pm.
01/07/83	Moved in 7" casing; placed on pipe racks and assembled miscellaneous equipment. Rig arrived 5:00pm. Spotted substructure and shut down because of darkness.
01/08/83	7:00am: rigged up Devonian Drilling Company Rig #1; waited on center pipe tub; tub arrived 3:00 p.m.; spotted tub; tallied pipe and shut down because of darkness.
01/09/83	7:00am: picked up packer (7" Butler Larkin hook-wall tension packer) ran in hole on 7", N-80, 26#, LT&C (USS), API Range III casing. Attempted several times to set packer at 4621' (KB). Packer would not grab hole wall. Determined that hole diameter was approximately 10" setting area (caliper log). Lowered packer to 4663' (hole measured 9.0675" caliper log) and attempted to set. Packer would not grab wall. Lowered packer to attempt to set into smaller hole size (8.9675"). Attempted LBS tension. Held Tension on packer for 30 minutes. Installed wellhead, slips and seal. Set casing in slips. Released rig at 5:30pm. Packer set at 4722.43' (KB) with casing measuring 4707.43' (112 Jts.). Packer measuring 6.31' (5' to top of rubber element).

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
03/30/83	9:30am: 2 frac tanks, dozer, 2 pipe racks on location - GFS on location, spot tanks, dig and line pit - call Bros. hauling water fill tks 10:00am: Birdwell on location (logging truck & mast truck) 11:00am: Run GR/CCL to PBTD 5074 (measured from top of collar) - packer located at 4700'-4707'. 1:10pm: bridge plug set at 4704'. 2:00pm: perforation at 4701'-4702' (4 holes - .53") - tagged top of bridge plug at 4703' 4:00pm: finished digging and lining pit.
03/31/83	5:00am: Halliburton cement crew on location. 7:00am: Hookup - ready to squeeze cement (note: casing pressure 560 psi). 8:00am: load hole, establish circulation with 91 bbls of fresh water. 8:40am: mix cement and cement with 100 SKs of poz with 10% salt. 8:50am: Displace 7" plug to 4650' followed with wireline. 10:50pm: well shut-in.
04/01/83	Waiting on cement.
04/02/83	Waiting on cement.
04/03/83	Waiting on cement.
04/04/83	Move in and rig up GFS service rig with mud pump, power swivel and 2 7/8" 8rd EUE tubing; Kay-R electric hook up electrical.
04/05/83	Waiting on change over sub (bit to 2 7/8" tubing); fill pit with drilling water; hook up annulus for disposal; Hipot test on wiring for pump; sub arrived 3 pm, run bit (6 1/8"), sub and tubing in hole; top of cement at 4622', drilling started at 8 pm; drilled to 4650'; shut down at 9:30 pm.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
04/06/83	Commenced drilling at 4650' at 6:30am; 9:25am hit top of bridge plug at 4712' drilled ahead; fill frac tanks with water (1200 BBLS fress, 350 BBLS brine); bridge plug drilled out and fell to bottom at 4:25pm; pulled bit and tubing; shutdown at 9pm.
04/07/83	Halliburton frac crew on location at 8am; rigged up for frac (3 stage, 9000 gals. HCL (15%), 3000# Rock salt, 30,000# 20/40 sand, 40,000 gals water); start acid down hole at 11am; frac complete at 1:32pm max treating pressure 2450 psi; rate 15 BPM; ISIP 2000 psi; 5 min SIP 1620 psi; 10 min SIP 1370 psi (total job 1204 BBLS); rig down Halliburton; flow back frac to the pit (approx. 100 BBLS); pump arrived.
04/08/83	Swabbed well; reinjected pit water into annullus (Black River).
04/09/83	Shut down.
04/10/83	Swab well; removed approximately 170 BBLS.
04/11/83	Rigged up Centrilift Hughes downhole motor; seal and pump; rigged up Lynes probes; ran in 10 joints of tubing; shutdown for the night.
04/12/83	Continue to run pump and probe on tubing; cut probe cable; tripped out pump and probe to repair cable; run pump and probe to 4607.43' (154 (jts.); started pump; pump ran for 14 min. at full production and pump shutdown due to Hi Amperage; several attempts to re-start pump were unsuccessful; shutdown for the night.
04/13/83	Circulated water and reverse circulated to try and free pump; several attempts to start pump yielded no production; 2pm start tubing pump and probe out of the hole; pump disassembled and found motor shaft twisted off.
04/14/83	Placed pump in shipping boxes for return to Centrilift; disassembled pump equipment and prepared to circulate.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
04/15/83	Ran tubing to 4956' (168 jts) to tag bottom; tubing stuck in sand and plugged; pull back to 4927' with 30,000 lbs.; reverse circulated at 500 psi; lost circulation; circulate down tubing; return 20% sand; pulled back 6 jts; shut down for the night.
04/16/83	Ran tubing down to 4927'; circulate for 1½ hours; wash down to 4956'; pulled back to 4927' and circulate down to 4956'; found 4' of fill up; losing 50 BBLS/hr. during circulation; shut down for the night.
04/17/83	Shutdown for Sunday
04/18/83	Start circulating down hole at 4984'; circulate down to top of packer at 5104'; no sand fill up; circulate for 2 hrs. with no sand returning; shut down.
04/20/83	Rig down and move off service unit; well shut-in.
08/01/83	Pump test crew is onsite. Crew included reps from Lynes, Centrilift-Hughes, gas field specialists (rig crew), ENG, INC. and DA&M. Water level is at ∿40'-50'; TD is 5094'. Annulus is depressurized from 600 psi in about 2 min. Centrilift Hughes' pump is laid in at 14:00 hrs; Lynes' P&T sensors are attached. By 19:30, 2857' of 2 7/8" EUE 8rd tubing was in hole with pump and sensor.
08/02/83	Decision is made to set pump at 4,000'. Tubing string (3978.16') is completed by 09:15. Power on by NYSEC. Tubing head assembled. System checked out and ready to go by 11:00. P_{BH} = 1758 psi. Preliminary drawdown test started at 11:49:00. Flowed at 60 gpm for 100 mins until water clears up. Rate increased to 80 gpm, 100 gpm, then to 130 gpm. System is shutdown at 18:26.

Table A-1

DAILY DRILLING REPORT OF AUBURN LOW TEMPERATURE GEOTHERMAL WELL (Cont'd)

DATE	ACTIVITY
08/03/83	Christmas tree is changed around to include thermal well and 3/4" bore orifice valve. P_{BH} = 1,687.9 psi. 24-hour test started at 09:18 with choke setting at 1/4". Inconsistencies are discovered in flowmeter measurements. Test is continued until next day.
08/04/83	WELL SHUTIN for buildup test. Echometer shots give fluid level at 08:57 to be 14.00.5' versus a calculated fluid level of 1420.5'. Flowrates of pump are checked against frac tank voidage, and theoretical pump curves. Decision made by NYSERDA to repeat the 24-hour drawdown test at design rate of 150 gpm.
08/05/83	Christmas tree is re-piped to include flowmeter and high pressure sampling port on the upstream side of the variable size choke used in controlling back pressure and maintaining flowrate at specified levels. Thermometers and temperature probes are recalibrated. Second 24-hour test started at 12:40; system shutdown because of leaks at control valve. Test started at 12:59:37; P_{BH} = 1618.89 psi. Downstream flowmeter is calibrated against upstream flowmeter.
08/06/83	Second 24-hour drawdown test (considered as the first part of the multirate drawdown test) being continued.
08/07/83	Multirate drawdown test is being continued. Ends at 06:30:30; P_{BH} = 340.28 psia. Build up test started.
08/08/83	Multirate buildup test continued. Crew is preparing to leave site.
08/09/83	Multirate buildup continues to 07:24:00. Well remains shutin. Site is partially restored and rig crew departs.

HYDROTHERMAL RESOURCES AND RESERVES OF THE AUBURN LOW-TEMPERATURE GEOTHERMAL WELL CAYUGA COUNTY, NEW YORK

Appendix B

Prepared for

NEW YORK STATE
ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

Project Manager
Dr. Burton Krakow

and

U.S. DEPARTMENT OF ENERGY

Project Manager
Dr. David Lombard

Prepared by

ENG, INC.
Boston, Massachusetts

Principal Investigator
Dr. Trevor P. Castor

449-ET-AES-82

DECEMBER 1983

ABSTRACT

The Auburn low-temperature geothermal well was pump tested to define the hydrothermal reserves, and to assess the geothermal potential of the Auburn reservoir. The pump test design was based on: the results of preliminary flow tests; values of net capacity estimated from geophysical logs; regional stratigraphy; and estimated values of fluid and reservoir parameters. The results of pressure transient analyses indicated that the Auburn reservoir can be characterized by as many as six different storage and flow components consisting of two contrasting porosity zones and three distinct permeability regions. The net producing interval is made up of two communicating layers or zones -- a low-porosity dolomitic zone and a medium-porosity sandstone zone -- both of which are highly fractured. The two producing zones are in communication with each other vis-a-vis cross-flow in the intersecting fractures. In addition to the natural system, the producing interval was hydraulically fractured and propped prior to the pump test. The average reservoir properties are estimated to be: net sand thickness of 310 ft.; an effective permeability of 10 millidarcys; an effective porosity of 0.0027; a reservoir pressure of 2,260 psi; an initial productivity index of 0.56 STB/D/psia^2; and proved hydrothermal reserves of 21.58 x 10^{10} Btu.

CONTENTS

CONTENTS (Cont'd)

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

ILLUSTRATIONS (Cont'd)

TABLES

TABLES (Cont'd)

SUMMARY

The Auburn well, located in Cayuga County, New York, penetrates the top of the Pre-Cambrian Basement at ∿5,100 ft. and intercepts an anomalous geothermal gradient of 14.65°F/1,000 ft. The major water-bearing zones were identified from PLT logs correlated with formation and lithology logs, to occur over the interval 4,700 ft.-4,950 ft. spanning the Theresa and the Potsdam formations. The well was subsequently open-hole completed over a gross interval of 434 ft. from a 7-in. casing point at 4,700 ft. to the pre-pump test measured T.D. of 5,094 ft. The Auburn low-temperature geothermal well has a bottom-hole temperature of 125.0°F and a net productive interval of 310 ft. which intercepts a heat flux of ∿0.5 Btu/hr-ft^2 from the Pre-Cambrian Basement.

The hydrothermal resources of the Auburn well, estimated from pump test and supporting data, are listed in Table B-1.

Table B-1

HYDROTHERMAL RESOURCES (Btu)

Category	STB	Volumetric	Reinjection
Proved	$3.0 \pm 0.3 \times 10^6$	5.50×10^{10}	34.89×10^{10}
Possible	$7.0 \pm 1.0 \times 10^6$	12.84×10^{10}	89.95×10^{10}
Probable	$23.0 \pm 5.0 \times 10^6$	42.40×10^{10}	78.20×10^{10}

The volumetric hydrothermal resource is based on the thermal capacity of the formation brines which is realized by a wellhead temperature drop from 125°F to 70°F and a capture efficiency, based on direct-contact heat-exchange efficiencies and transmission losses, of ∿80%. The wellhead temperature is based on a production rate of 150 gpm by a submersible pump, with downhole heat generation due to mechanical and electrical energy losses, through a non-insulated tubing string. The wellhead temperature is based on theoretical estimates, field measurements, and semiempirical projections.

The hydrothermal resources include a reinjection component in which the thermal capacity of the contacted rock masses can provide additional Btu. The extent of the reinjection resources is defined by a wellhead temperature of 125^{o}F and the breakthrouoh time of the thermal front which is a function of the reinjection rate. The latter was selected to be 286 gpm, the same as the injection rate, based on 117% of the schools' Btu demand of 2.8 x 10^{10} over a six-month period.

The volumetric resources were estimated from reservoir limit tests utilizing pressure drawdown data. The estimates of volumetric resources and areal extents are sensitive to the estimated values of effective compressibility and effective porosity as well as drawdown rate. The possible and probable resources were computed for the total effective and formation brine compressibilities, respectively, both in the limit of zero drawdown rate; the proved resources are defined in terms of the pump test's drawdown data. The dependency of volumetric resource or connected reservoir drainage volume on pumping rates is a direct consequence of the nature of the Auburn reservoir. This dependency is, thus, best discussed after some consideration is given to the reservoir characteristics.

The Auburn low-temperature geothermal reservoir can be characterized by as many as six different storage and flow components consisting of two contrasting porosity zones and three distinct permeability regions. The net producing interval is made up of two communicating layers or zones -- a low-porosity dolomitic zone and a medium-porosity sandstone zone -- both of which are highly fractured. The two producing zones are in communication with each other vis-a-vis cross-flow in the intersecting fractures. In addition to the natural system, the producing interval was hydraulically fractured and propped prior to the pump test.

The net producing zones were identified from log analysis to be as follows:

- o Zone 1, which spans the interval 4,740 ft. - 4,950 ft. has an average of 80.3 ft. porosity percent and an average absolute porosity of 0.38%.
- o Zone 2, which spans the interval 4,950 ft. - 5,050 ft. and which straddles the Theresa and the Potsdam, has an average of 832.3 ft. porosity percent and an average absolute porosity of 8.32%.

The three distinct flow regions, identified from the pump test analysis, are as follows:

- REGION 1 - an improved near wellbore region resulting from a vertical macro-fracture created by the pre-pump test hydraulic stimulation.
- REGION 2 - a set of interconnecting fractures and fissures which represents foramenular secondary porosity, and which contributes a low-storage but a high-flow capacity.
- REGION 3 - a matrix of well-defined fine pores which represents intergranular primary porosity and which contributes a high-storage but low-flow capacity.

The two contrasting porosity zones consist of a high-permeability, low-capacity component (Zone 1) and a low-permeability, high-capacity component (Zone 2). Zone 1 will control the initial productivity of the well vis-a-vis its fracture permeability; Zone 2 will control the deliverability of the reservoir and define its reserves vis-a-vis its capacity (∿90% of total). To simplify analysis, the two producing zones are assumed to be in perfect communication with each other and are viewed to be one producing interval with volume-averaged properties, e.g., the absolute porosity of the net producing interval is estimated to be 2.82%.

The "double-porosity" characteristic of the Auburn well gives rise to a connected reservoir drainage volume which is inversely dependent on the pumping rates, i.e., the effective drainage area decreases with increasing flowrate. An unbalance is created between the rate of fracture drain and fracture refill by the porous matrix, i.e., the permeability of the porous matrix is rate-limiting. This unbalance results in the flushing of the natural fracture channels and their disconnection from the porous matrix. The unbalance in intra-porosity flow and the degree of disconnection increase with increasing pumping rates. The radius of influence or reservoir volume, thus, decreases with increasing flowrate. In the limit of zero flowrate, the downhole pressure is only influenced by the total connected pore volume of natural fractures and porous matrix voids.

The reservoir characteristics can be quantified by the following:

- Net sand thickness of 310 ft. and an absolute porosity of 0.0282.
- An effective formation compressibility of 7.5×10^{-6} psi^{-1}.
- An effective transmissivity of 3100 millidarcy-feet, and an effective permeability of 10 millidarcies.
- A product of effective compressibility and effective porosity of 2.0×10^{-8} psi^{-1}; and an effective porosity of 0.0027.

- An average reservoir pressure of 2,260 psi.
- A hydraulic fracture length of approximately 150 ft.
- A natural fracture system which is ∿26% of the total pore volume.
- An initial productivity index of 0.56 STB/D/psia^2 i.e:

$$q_o = 0.5612\ (\overline{P}^2 - P_{wf}^2)^{0.642}. \qquad \text{(B-1)}$$

$\overline{P}$ and P_{wf} are respectively the average reservoir pressure and the flowing wellbore pressure at the reservoir sandface.

The maximum initial deliverability of the well, q_o, was determined to be ∿338 gpm (∿11,600 STB/D) at T.D. and ∿328 gpm (∿11,200 STB/D) at a pump depth of 4,000 ft. Drawdown analysis indicates that these rates cannot be sustained for more than a few hours without the reinjection of fluids into the producing formation in order to maintain reservoir pressure. The continuous deliverability of the well's proved reserves is just in excess of 100 gpm.

The hydrothermal reserves are the recoverable hydrothermal resources. The volumetric hydrothermal reserves are estimated to be 75% of its resources whereas the reinjection reserves are estimated to be 50% of its resources. The hydrothermal reserves of the Auburn low-temperature geothermal well are estimated to be:

Table B-2

HYDROTHERMAL RESERVES (Btu)

Category	STB	w/o Reinjection	w/ Reinjection
Proved	2.25×10^6	4.13×10^{10}	21.58×10^{10}
Possible	5.25×10^6	9.63×10^{10}	54.61×10^{10}
Probable	17.25×10^6	31.65×10^{10}	70.75×10^{10}

Without spent brine reinjection and reservoir recharge, the maximum recoverable thermal energy over a six-month period is ∿1.15×10^{10} Btu or ∿40% of the schools' Btu demand at a withdrawal rate of ∿100 gpm. The lifetime of the proved hydrothermal reserves will be limited <3.5 years without reinjection; the spent geothermal brine can be reinjected down the annulus into the adjacent Black River formation. With reinjection of the spent brine at its production rate of 286 gpm, designed to exceed the schools' Btu demand by $\sim$17%, the proved lifetime of the reinjection reserves is estimated to be just in excess of 10 years. Thus, the Auburn low-temperature reservoir has the capacity and the productivity to provide space heating to the Auburn Middle School and the Cayuga Community College.

Section 1

RESOURCE DESCRIPTION

The Auburn geothermal well was drilled by Arlington Exploration Company under contract with the New York State Energy Research and Development Authority (NYSERDA) to estimate the geothermal potential of central New York State. The well was drilled at the outer margin of the Appalachian Fold and Thrust Belt in the Appalachian Plateau. The well, with an original T.D. of ∿4,250 ft., penetrates about 5,050 ft. of lower Palezoic rocks (a flat-lying sequence of carbonates, dolomites, shales and sandstones) into the Pre-Cambrian marble basement. A cross-section of the well and its most recent completion are shown in Figure B-1.

Zones or intervals of interest can be described as follows:

- The Trenton is a dark shaly limestone (∿20% shale) which appears wet from 4,100 - 4,160 ft. and which has definite gas showings from 4,152 - 4,160 ft. The USGS's televiewer indicates a very vuggy characteristic for this 8 ft. gas show which substantiates that porosity is created by small lenses of fossil residue generating void spaces in the Trenton.

  These observations and qualifications suggest that porosity is not contiguous in the Trenton and that the Trenton could not be used as a reinjection zone without artificial stimulation.

- The Black River is a carbonate formation which has been described by the wellsite geologist, Mr. Brayton P. Foster, as a sugar, fine-grained, brown lime, mudstone. The upper part of the Black River is limestone with traces of calcite while the lower part is a mixture of limestones and dolomites with the dolomitic character increasing in depth. These two parts are separated by a low-porosity limestone zone with traces of calcite, shale, and anhydrite. The Black River, like the Trenton and the Theresa, is considered a blanket formation with regional dips of 50 - 100 ft. per mile to the south; there is no reported faulting in the area.

  The neutron porosity log indicates that the Black River has two water-saturated or wet zones. These zones occur between 4,164 - 4,186 ft. and 4,464 - 4,510 ft. The upper zone has a finite gas saturation which crosses over from the lower 8 ft. of the Trenton. The lower zone is not gas-saturated and is questionably wet. The dolomite in the lower zone is radioactively hot, as indicated by the Gamma Ray Log. Note that this radioactive heat transcends in the Knox Unconformity Gamma Ray which has a reading of 80 API units and in the Potsdam Gamma Ray which has a reading of 150 API units.

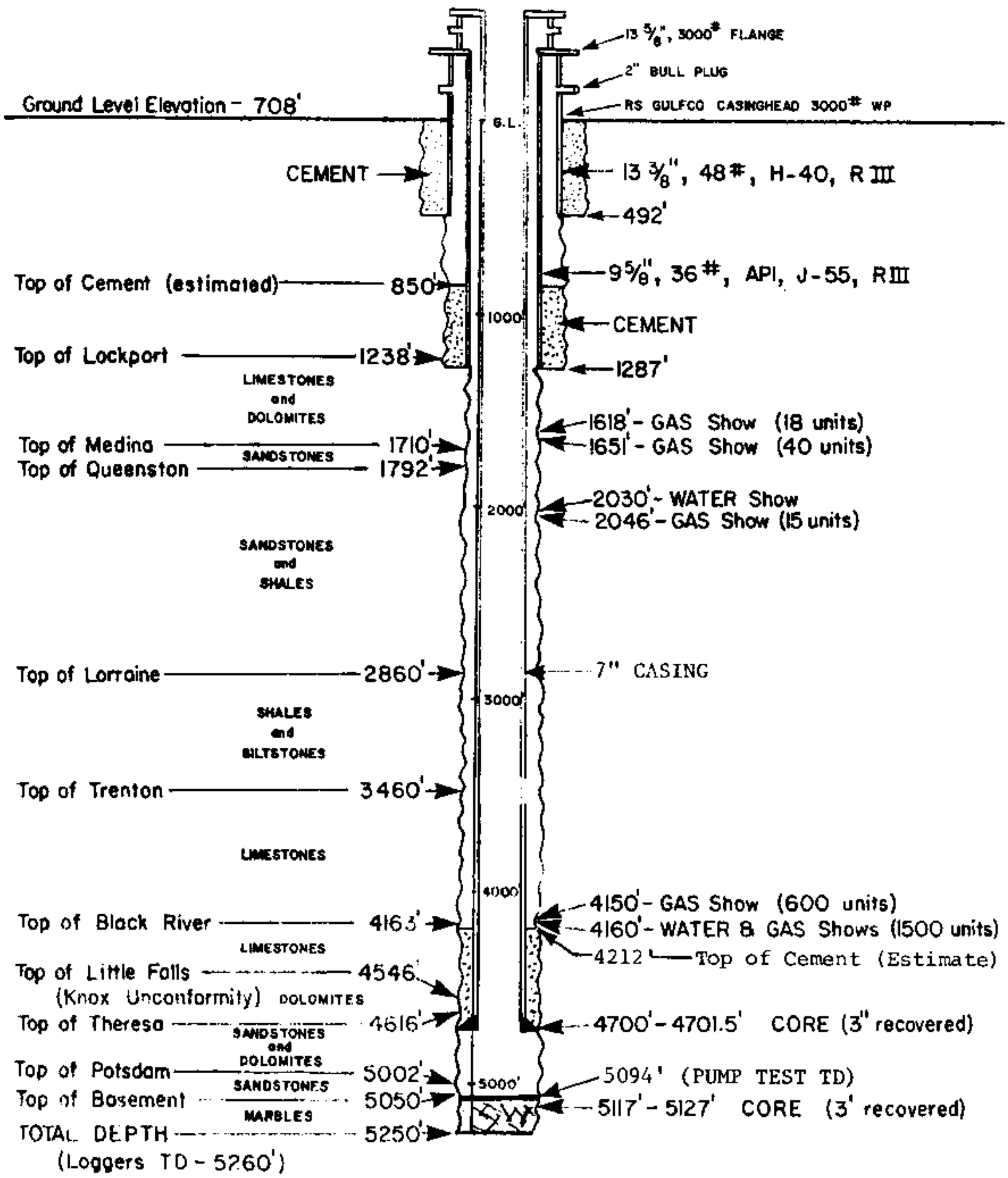


Figure B-1. Auburn Geothermal Well - Completion and Lithological Cross-Section (Donohue, Anstey & Morrill, 1983)

The spent geothermal brine can be injected into the gas-bearing zones of the Black River.

- The Theresa, one of the primary water-producing zones, is a mixture of sandstones and dolomites with the dolomitic character decreasing with depth. Dunn Geoscience (1982) describes the Theresa formation as "a coarse, white limey dolomite with abundant and equally proportioned amounts of rounded, frosted quartz grains and angular, clear quartz grains ... may be predominantly sandstone in some areas." The Theresa core matrix consists of a very fine to extremely fine grained quartz with some larger rounded grains and iron sulfides. The bedding planes, with a dip of $\sim 2^{\circ}$, were represented by numerous thin laminae (1-3mm thick) composed of light- and dark-stained grains. The bottom 58 ft. of the Theresa, from 4,950 - 5,008 ft., is its major water-producing interval.

- The Theresa's major water-producing interval is extended by the Potsdam which runs from 5,008 - 5,050 ft. The Potsdam is an interesting formation because it is very radioactively hot ($\sim$150 API units compared to the $\sim$120 API units reading of the Lorraine's shale line). The Potsdam is predominantly a sandstone with some carbonates and traces of pyrite and hematite. Dunn Geoscience (1982) suggests "that the Basal Potsdam may be an altered chloritic quartz sandstone derived from the basement ...." The Potsdam appears to have good porosity and to be water saturated. The Potsdam appears to be partly responsible for the observed geothermal anomaly because shifts in the T and ΔT profiles at the top of the Potsdam denote the cooling effects of the water-bearing zones, just before and after the Potsdam.

- The Basement can be divided into the Pre-Basement and the Basement. The Pre-Basement occurs between 5,050 ft. and 5,120 ft., consists of a mixture of limestone, quartzite and sandstone, and is radioactively cool ($\sim$10 API units). The Pre-Basement appears to have good secondary and/or fractured porosity and to be water saturated in the first 50 ft. The Basement is slightly hot ($\sim$60 API units), is fractured and is made up of dolomitic marble. Dunn Geoscience (1982) describes the Basement as "metamorphised sedimentary rock containing hornblende, hematite and altered chlorite."

Section 2

RESERVOIR TESTING AND EVALUATION PROGRAM

A preliminary flow test was conducted on the Auburn geothermal well in April 1982 to assess the well's productivity and to make a rough cut evaluation of the reservoir's characteristics and its geothermal potential. This flow test identified two water-producing zones: a 30-ft interval from 4,150 ft. - 4,180 ft. in the Black River limestone formation; and a 310-ft. interval from 4,740 ft. - 5,050 ft., spanning the Theresa and Potsdam, which appeared to contribute 90% of the produced water with temperatures between 123.6°F and 125.0°F. The maximum deliverability was estimated to be 365 gpm at 5,000 ft., and a wellhead temperature of 124.9°F was projected for this flowrate from a lumped parameter heat balance.

The results of the flow tests and preliminary log analyses were utilized to design a pump test for evaluating the hydrothermal resources and reserves of the low-temperature geothermal reservoir. The pump test plan recommended setting the pump at 5,000 ft. (bottom of the Theresa and top of the Potsdam) and included the following:

- A preliminary 4-hour drawdown test pumping @ 150 gpm, followed by a 4-hour buildup test after well shutin.
- A 24-hour drawdown test pumping @ 150 gpm, followed by a shutin and stabilization period.
- Three 8-hour multirate tests @ 150, 140, and 120 gpm.

Provisions were suggested for an extended pump test (10 days @ 150 gpm) in order to establish reservoir limits and thermal characteristics of the geothermal resource.

The pump tests were conducted, over a seven-day period in August 1983, as follows: a preliminary drawdown test in three stages (@ ∿50, ∿75, and ∿135 gpm) in ∿7.3 hours followed by a buildup period of ∿14.4 hours; a 24-hour drawdown test at 127.4 gpm followed by a shutin or buildup period of 27.2 hours; and a four-stage multirate test (@ 124.1, 152.5, 133.1, and 115.5 gpm) which spanned a period of 41.5 hours and which included 24.2 hours of pumping at 152.5 gpm; the multirate drawdown test was followed by a buildup period of 48.9 hours.

The reservoir evaluation methodology is based primarily on pressure transient analysis of slightly compressible fluids.

PRELIMINARY FLOW TEST AND EVALUATION

A preliminary flow test on the geothermal test well in Auburn, New York, was conducted over the period April 5 to 9, 1982. The purposes of this preliminary flow test were as follows:

- Assess the initial productivity of the well.
- Identify the volume contribution of the major water-producing zones.
- Forecast decline rates and recoverable reserves in terms of volume and heat.
- Project surface temperature of the produced brine stream over a range of flow rates.

The preliminary flow tests were conducted by unloading the well with compressed air, establishing a state of equilibrium between brine produced from the formation and compressed air injected, and measuring the discharge flow rates as a function of depth, i.e., the location of the bottom of the drill stem. The preliminary flow tests were conducted in a fashion similar to that described by Schafer, 1980.

The results of the flow tests, conducted at 1,680 ft. and 3,030 ft. under 170 psi and 340 psi, respectively, are shown in Figure B-2 a&b.

The data obtained from the preliminary flow tests are at best ±50% accurate with measured values deviating ±25% from the mean. Deviations from mean values were inherent to the method of "pumping" or unloading the well; inaccuracies in the measured data resulted from the methods of measuring volume differences and time deltas. The results, which were considered gross estimates at best, are in fair agreement with the results of a 7-day pump test.

The measured and estimated rates of flow are as follows:

Table B-3

PRELIMINARY FLOW TEST DATA

Depth (feet)	Initial Rate (gpm)	Comment
1300	100	Flow test of 04/07/82 under 170 psi @ 1,680 ft.
2100	160	Flow test of 04/08/82 under 340 psi @ 3,030 ft.
3000	225	Assuming Darcy's law and flow allocation based on net capacity
4000	300	Ditto
5000	365	Ditto

Major water-producing zones were identified from the PLT log taken during the first flow test on April 7, 1982 and were correlated with formation logs taken on March 2, 1982 and with lithology logs. The PLT log measured temperature, geothermal gradient, differential flow in revolutions per second and gamma radiation as a function of depth. The first major water-producing zone is encountered between 4,150 ft. - 4,180 ft. in the Black River limestone. The producing zone is identified by a ΔT of + 0.15°F in both the PLT and TΔT logs. During the first flow test, the flowmeter indicated + 0.3 rps from the baseline; pressure at 4,180 ft. was 1210 psia; and temperature at 4,180 ft. was 121.6°F. The second major water-producing zone occurs over the interval 4,740 ft. - 5,050 ft. spanning the Theresa and the Potsdam.

The major water-producing zones were identified:

- A 30-ft. interval from 4,150 ft. - 4,180 ft. in the Black River limestone. It is estimated that this interval contributed 10% of the produced water at a temperature of 121.6°F.
- The 4,740 ft. - 5,050 ft. interval with approximately 310 ft. net productive sand spanning the Theresa and the Potsdam sandstones. It is estimated that this interval contributes 90% of the produced water between temperatures of 123.6 to 125.0°F.

The preliminary flow test data (plotted in Figure B-2 a&b) was statistically insignificant and could not be used to estimate reservoir parameters or define decline rates; recoverable reserves could not be estimated from the available flow test data.

The projected surface temperatures were obtained from a simple, lumped parameter heat balance assuming linear temperature profiles in the tubing string and the earth and arithmetic temperature averages (Ramey, 1962):

$$\Delta Q = U_o \, r_{to} \, \pi \, z \left[(T_{out} - T_{surf}) + (T_{in} - T_{res}) \right]. \tag{B-2}$$

also

$$\Delta Q = \dot{m} \, c_p \, (T_{in} - T_{out}) \, . \tag{B-3}$$

with

$$\frac{1}{U_o} = \frac{1}{h_c + h_r} + \frac{r_{to} \ln (r_{co}/r_{to})}{k_{ins}} + \frac{r_{to} \ln (r_h/r_{co})}{k_{cem}} \, . \tag{B-4}$$

Produced brine temperatures were estimated for a 7-in.-cased, cemented hole and a 3½-in. tubing string with air in the annulus acting as an insulator, $U_o \simeq 0.1574$ Btu/hr-ft^2-^{o}F for h_c = 1,650 Btu/hr-ft^2-F (water flow is turbulent for the stipulated pumping rates); h_r = 1.0Btu/hr-ft^2-^{o}F; k_{ins} = 0.0161 Btu/hr-ft-^{o}F; k_{cem} = 0.51 Btu/hr-ft^{o}F; r_{to} = 1.75-in.; r_{co} = 4.5-in.; and r_h = 4.5-in.

For a pump setting of 5,000 ft. at which $T_{in} = 125^oF$, with the assumption that $T_{res} = 126^oF$ and $T_{surf} = 60^oF$, the outlet wellhead temperatures for a perfect pump and an insulated tubing string are as follows:

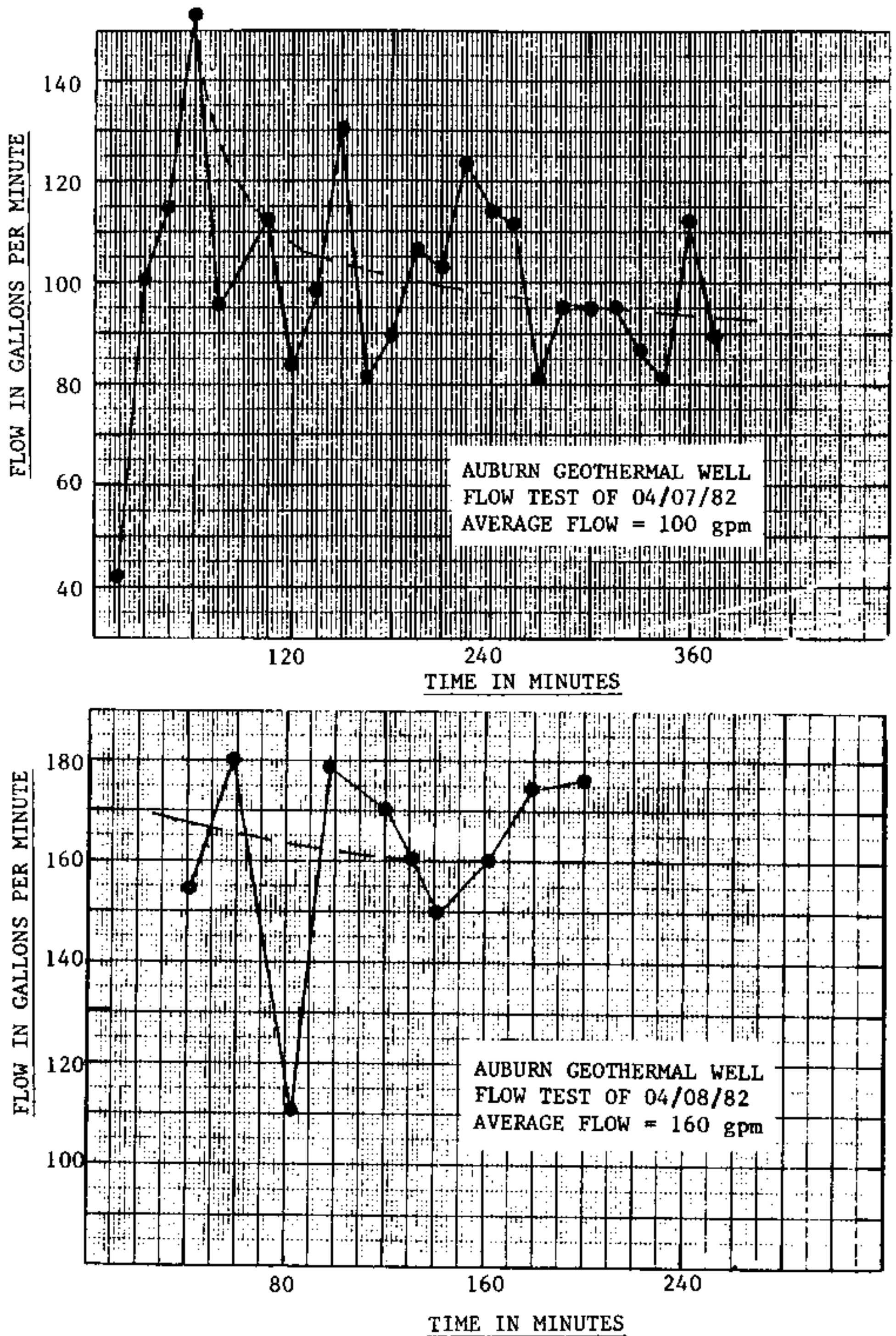


Figure B-2a&b. Auburn Geothermal Well - Preliminary Flow Rates Under "Unloaded" Conditions.

Table B-4

PROJECTED SURFACE TEMPERATURES

Depth (feet)	Flow Rate (gpm)	Outlet Temperature (°F)
5000	100	124.6
5000	200	124.8
5000	365	124.9

PUMP TEST DESIGN

The pump test was designed to meet the objectives of this study, i.e., the definition of the hydrothermal resources of the Auburn low-temperature geothermal well within a commercialization perspective. The pump test design was based on the results of the flow test, on values of net capacity estimated from geophysical logs, stratigraphy, and on estimated values of fluid and reservoir parameters.

The following assumptions were made in designing the pump test (ENG, INC., 1982):

- The pump test should be adequate to evaluate a reservoir with the capability to produce up to 150 gpm over a six-month period for a period of 20 years. Under this assumption, the volumetric capacity of the producing formation should be about 18.77×10^6 barrels.

- The producing formations include the Theresa and the Potsdam with a net $h\phi$ of 1,718 ft.-%, an average thickness of 434 ft. and an average porosity of 3.96%.

- The geothermal reservoir is unbounded, and it is a right-circular cylinder with uniform and isotropic properties. Based on this and the two previous assumptions the areal extent of the reservoir should be at least 6.14×10^6 sq. ft. or 141 acres.

- The average permeability of the reservoir is assumed to be 10 millidarcies. This assumption is made to be conservatively limiting; based on present information, permeabilities are estimated to be in the 10-100 md range. Permeability is included as a variable in the calculations below.

- Based on measured salinities of 240,000 ppm TDS, the brine viscosity is estimated to be 1.722 cp at 120°F, and fluid compressibility is estimated to be 2.21×10^{-6} psi^{-1}. Fluid density is assumed to be that measured in the field during the initial flow tests, i.e., 1.07 gms/cc. Formation compressibility is assumed to be 3.4×10^{-6} psi^{-1}. Conservatively, the wellbore skin factor, s, is assumed to be zero in most calculations. In all probability, $s < 0$ (estimated to be -2) because of the highly fractured nature of the water-productive zones.

These assumptions were all revised subsequent to the conduct of the pump test.

Based on the above assumptions, the following calculations were made to support the pump test design:

1) Near wellbore effects will not influence measured pressure transients at early times in the pressure drawdown test if:

   $t \text{ (mins)} > 35 / k \text{ (md)}$

   that is, the semi-log straight line will begin at $t > 0.35$ minutes for $k = 100$ md.

2) Pressure buildup transients will respond to reservoir parameters and not wellbore characteristics if and only if:

   $t \text{ (mins)} > 3.3 / k \text{ (md)}$

3) The time required to reach the end of the semi-log straight line of the infinite acting period and achieve the psuedo-steady state response is:

   $t \text{ (hrs)} > 89.97 / k \text{ (md)}$

   Under the above listed assumptions, the minimum time required to delineate the reservoir limits is 3.8 days if $k = 1.0$ md and 0.38 days or $\sim$9 hours if $k = 10.0$ md.

4) The pressure measurement device should have a resolution of ¼ psi for measurement of ΔP's at Δt's of 15 seconds as is planned for the very early wellbore drainage period and at Δt's of 15 minutes as is planned for the transient and psuedo-steady state periods.

During a continuous 150 gpm drawdown, the estimated flowing bottom-hole pressure during the transient period is as follows:

Table B-5

ESTIMATED FLOWING BOTTOM-HOLE PRESSURES

Assumed Conditions of k and s	P_{wf} (psia) at time Δt 0 hr.	1 hr.	4 hrs.	24 hrs.
k = 1, s = 0	1756	432	232	-26
k = 1, s = -2	1756	1008	808	550
k = 10, s = 0	1756	1590	1570	1554
k = 10, s = -2	1756	1648	1628	1620
k = 100, s = 0	1756	1736	1734	1731
k = 100, s = -2	1756	1744	1742	1739

The above calculations indicate the range and sensitivity requirements of the bottom-hole pressure-measuring device; that the geothermal well could not maintain a productivity of 150 gpm over an extended period of time with an extremely low permeability reservoir; and the effects of matrix permeability and wellbore fractures on early pressure transients.

The pump test design and length were dependent upon the assumption that the average permeability of the producing formations (Theresa and Potsdam) is 10 millidarcies. Under estimated and assumed conditions, a four hour test will allow determination of in situ reservoir and fluid parameters as well as wellbore conditions; and a 24-hour test will allow delineation of specified reservoir limits. Pressure transient calculations indicate the need for downhole pressure-measuring instrumentation with a range of 200-2000 psi and a resolution of ¼ psi.

The pump test plan recommended setting the pump at 5000 ft. (bottom of the Theresa and top of the Potsdam) and included the following:

- A preliminary 4-hour drawdown test pumping @ 150 gpm, followed by a 4-hour buildup test after well shut in.
- A 24-hour drawdown test pumping @ 150 gpm, followed by a shut in and stabilization period.
- Three 8-hour multirate tests @ 160, 140, and 120 gpm.

Provisions were suggested for an extended pump test (10 days @ 150 gpm) in order to establish reservoir limits and thermal characteristics of the geothermal resource.

Reservoir analysis indicates that the large volumes of produced fluids could be reinjected into the Medina or Black River. The preliminary pump test, the 24-hour drawdown test and the multirate tests were scheduled for seven days.

PUMP TEST FIELD EXECUTION

The pump test was executed over a seven-day period from August 1 to 8, 1983. The schedule of events is listed with pressure conditions in Table B-6 and with temperature conditions in Table B-7. The listed pressures and temperatures are respectively analysed in Sections 4 and 5 of this report. The pump test layout is shown by a process flow diagram in Figure B-3a and a piping and instrumentation diagram in Figure B-3b.

The equipment utilized in the field test is as follows:

- Centrilift-Hughes submersible pump, Model #S-175 for a 7-in. O.D. well casing. The 97.92 ft. unit consisted of a PhD (pressure and temperature) sensor, two motors (100 and 200 HP) in tandem, a sealing section, and two pumps with 152 stages. The intake of the pump was protected by a Johnson screen and located 4,016 ft. (as determined by the pipe tally) from the surface. The submersible pump was hung on a string of 2 7/8 ft. tubing and driven by a 300 KVA power supply on an amperage draw of 100 amps. The primary Centrilift-Hughes representative onsite was Mr. Chuck Reynolds who was assisted by field service area manager Mr. John Schoonover.

- Lynes pressure and temperature-sensing instrumentation was used to record downhole and surface conditions continuously over the seven-day period. The downhole sensing devices were side-mounted on a 5-ft. sub right on top of the submersible pump; the downhole sensor was positioned 3,972.2 ft. from the surface. The surface probe was placed on the wellhead as per Figure B-3b; the surface temperature probe measured ambient conditions. The wireline conductor probe, CWL-300, utilizes quartz-crystal transducer technology with an accuracy of 0.05% FS (2.5 psia) and a resolution of 0.005% FS (0.25 psia) over an operating pressure range of 0 - 5,000 psia; the accuracy and the resolution of the temperature sensing device are 1.8^{o}F over the operating range of 32^{o}F to 212^{o}F. The surface probe (Model SP-380-PTX-5K) utilized similar quartz-crystal transducer technology over an operating range of 32^{o}F to 175^{o}F. The probes were calibrated just prior to the field test. Pressures and temperatures were recorded continuously at preprogrammed intervals ranging from 20 seconds to one hour. Lyne's wellsite representative was Mr. Robert "Butch" Guthrie.

Table B-6

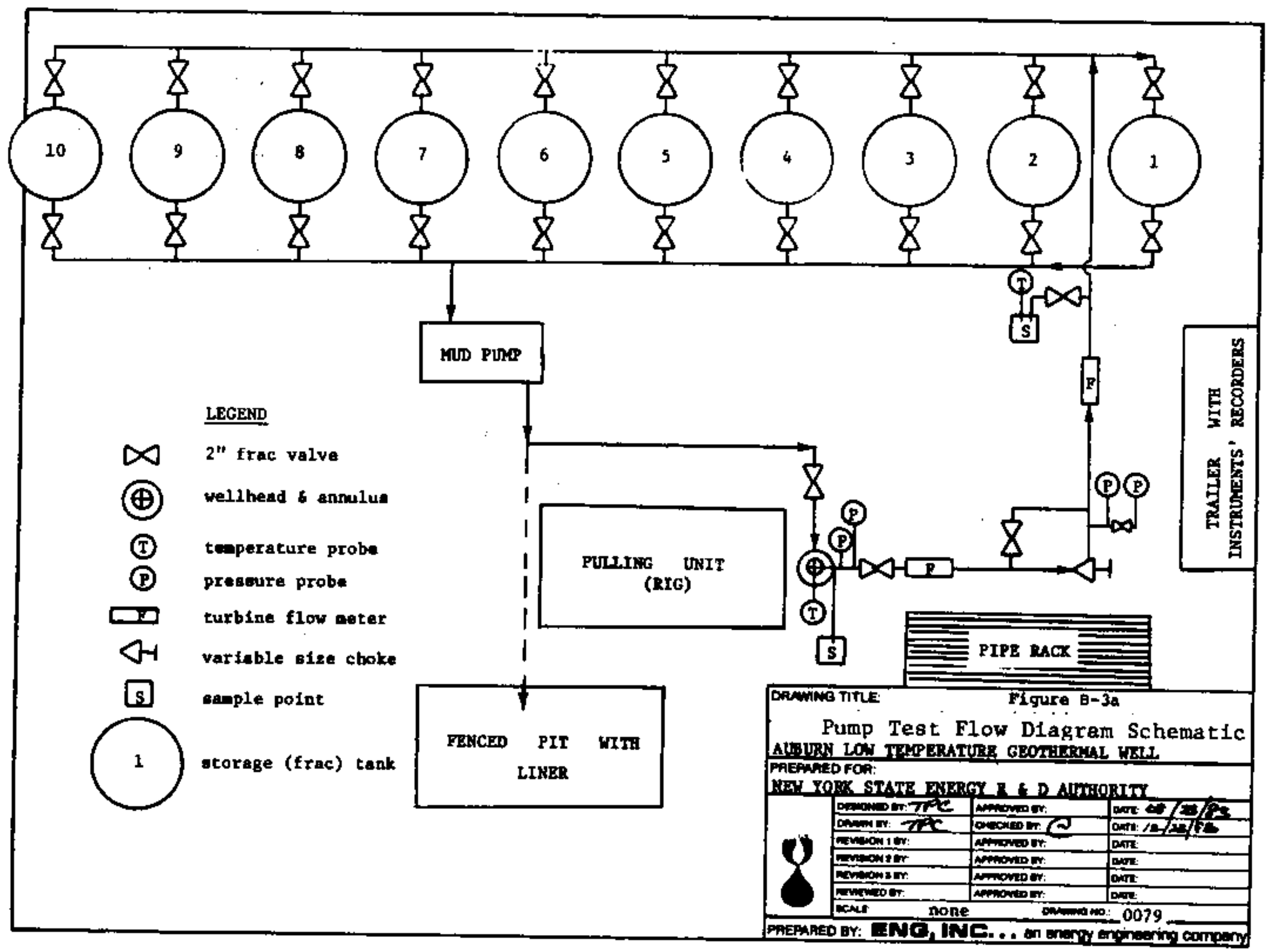
AUBURN GEOTHERMAL WELL--SCHEDULE OF PUMP TEST EVENTS WITH PRESSURES LISTED

TEST TYPE	DURATION (HRS)	VOLUME (GALLONS)	AVG. RATE (gpm)	$P_{BH,i}$	$P_{BH,f}$	ΔP_{BH}
PRELIMINARY DRAWDOWN						
FIRST STAGE	1.67	4,719	52.4	1,757.9	1,631.24	-126.66
SECOND STAGE	1.83	8,236	74.9	1,631.24	1,541.50	-89.74
THIRD STAGE	3.77	30,292	133.9	1,541.50	1,335.51	-205.99
	7.27	43,247	99.2	1,757.9	1,335.51	-422.39
PRELIMINARY BUILDUP	14.40	—	—	1,335.51	1,690.22	+354.71
24-HOUR DRAWDOWN	24.02	183,636	127.4	1,690.22	1,101.25	-588.97
24-HOUR BUILDUP	27.15	—	—	1,101.25	1,618.69	+517.44
MULTIRATE DRAWDOWN						
FIRST STAGE	1.50	11,170	124.1	1,618.69	1,206.31	-412.38
SECOND STAGE	24.15	221,000	152.5	1,206.31	403.76	-802.55
THIRD STAGE	7.88	62,960	133.1	403.76	320.91	-82.85
FOURTH STAGE	7.97	55,190	115.5	320.91	340.28	+19.37
	41.50	350,320	140.7	1,618.69	340.28	-1,278.41
MULTIRATE BUILDUP	48.90	—	—	340.28	1,509.00	+1,168.72
PUMP TEST	163.24	577,203	52.4- 152.5	1,757.9	1,509.00	-248.90

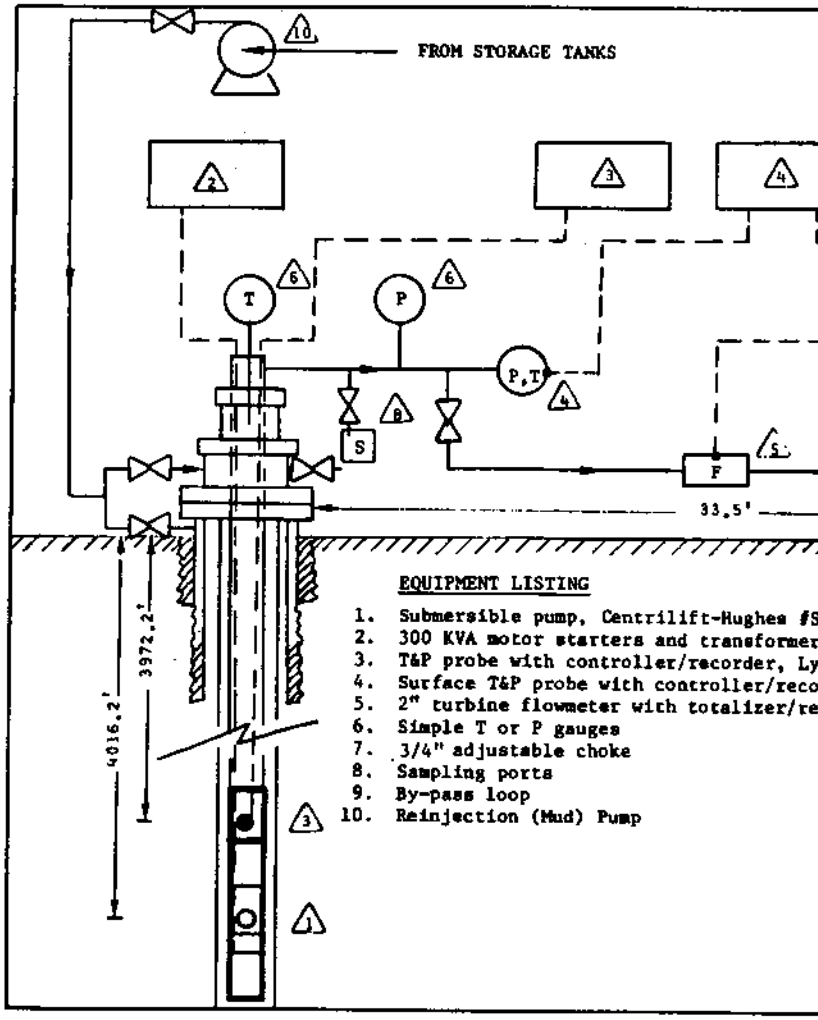
Table B-7

AUBURN GEOTHERMAL WELL--SCHEDULE OF PUMP TEST EVENTS WITH TEMPERATURES LISTED

TEST TYPE	DURATION (HRS)	AVG. RATE (gpm)	$T_{BH,i}$	$T_{BH,f}$	$T_{w,f}$	$T_{s,f}$
PRELIMINARY DRAWDOWN	7.27	99.2	110.4	130.19	88.35	122.0
PRELIMINARY BUILDUP	14.40	—	130.19	114.18	—	—
24-HOUR DRAWDOWN	24.02	127.4	114.18	132.52	123.0	126.0
24-HOUR BUILDUP	27.15	—	132.52	114.84	—	—
MULTIRATE DRAWDOWN						
FIRST STAGE	1.50	124.1	115.47	123.97	115.0	115.0
SECOND STAGE	24.15	152.5	123.97	130.88	132.5	131.0
THIRD STAGE	7.88	133.1	130.88	132.89	134.0	133.0
FOURTH STAGE	7.97	115.5	132.89	134.89	135.0	134.0
	41.50	140.7	115.47	134.89	135.0	134.0
MULTIRATE BUILDUP	26.00	—	134.89	116.57	—	—
PUMP TEST	140.57	—	110.4	116.57	—	—



10
9
8
7
6
5
4
3
2
1
MUD PUMP
TRAILER WITH INSTRUMENTS' RECORDERS
PULLING UNIT (RIG)
FENCED PIT WITH LINER
PIPE RACK
F
P
T
S
LEGEND
2" frac valve
wellhead & annulus
temperature probe
pressure probe
turbine flow meter
variable size choke
sample point
storage (frac) tank
DRAWING TITLE:
Figure B-3a
Pump Test Flow Diagram Schematic
AUBURN LOW TEMPERATURE GEOTHERMAL WELL
PREPARED FOR:
NEW YORK STATE ENERGY R & D AUTHORITY
SCALE none
DRAWING NO.: 0079
PREPARED BY: ENG, INC. . . an energy engineering company



EQUIPMENT LISTING

1. Submersible pump, Centrilift-Hughes #S-175A
2. 300 KVA motor starters and transformers
3. T&P probe with controller/recorder, Lynes #CWL-300
4. Surface T&P probe with controller/recorder, Lynes #SP-380 PTX-5K
5. 2" turbine flowmeter with totalizer/recorder, Halliburton
6. Simple T or P gauges
7. 3/4" adjustable choke
8. Sampling ports
9. By-pass loop
10. Reinjection (Mud) Pump

DRAWING TITLE: Figure B-3b

PROJECT NAME: Pump Test Field Setup

AUBURN LOW TEMPERATURE GEOTHERMAL WELL

PREPARED FOR: NEW YORK STATE ENERGY R&D AUTHORITY

DESIGNED BY: TPC	APPROVED BY:	DATE: 03/13/83
DRAWN BY: TPC	CHECKED BY:	DATE: 11/22/85
REVISION 1 BY:	APPROVED BY:	DATE:
REVISION 2 BY:	APPROVED BY:	DATE:
REVISION 3 BY:	APPROVED BY:	DATE:
REVIEWED BY:	APPROVED BY:	DATE:
SCALE: none	DRAWING NO. 0080	

PREPARED BY: ENG, INC. . . an energy engineering company

- Halliburton's 2-in. turbine flow meters were used upstream and downstream of the choke as in Figure B-3b. The meters are designed to operate accurately to within ± 0.5% over the entire flow range (40-400 gpm) with a repeatability of 0.05%. The meters were pre-calibrated at 130 gpm and appear to have a drift of less than 2%. Flows were continuously recorded and totalized. The meters were calibrated and their installation checked by Halliburton's senior field engineer, Mr. Steve Novakawski.

- The wellsite rig and crew were supplied by Gas Field Specialists under the direction of Mr. Groves West.

- The entire pump test was conducted under the management of Mr. Robert S. Lynch, now of Lynch Consulting Company with technical direction by Dr. Trevor P. Castor of ENG, INC.

Prior to the start of the pump test, the downhole pressure (@ 3,972.2 ft.) was 1757.9 psia, and the water level in the well was ∿40-50 ft. from the surface yield-an initial gradient of 0.448 psi/ft. T.D. was measured at 5,094 ft. versus 5,104 ft. after cleaning and 5,250 ft. before hydraulic fracturing. This discrepancy in T.D. is due to a packer which seals off ∿150 ft. of the bottom of the well. The preliminary tests were conducted with a 2-in. frac valve for flow control and a downstream flowmeter. Recorded flowrates were corrected for gas liberated at the lowered downstream pressures; the correction factor of ∿1.19 was based on upstream-downstream calibration checks during the multirate drawdown test. Flowrates were adjusted likewise for the 24-hour drawdown test. In this test, the 2-in. frac valve was changed over for an adjustable choke with a 3/4-in. bore. The multirate test was conducted with a field hookup as sketched in Figure B-3a. Temperatures were measured at the wellhead with an immersion type, bimetalic thermometer in a thermowell, and with a mercury thermometer at the sample point; both thermometers were calibrated at 212°F. Periodically throughout the test, the fluid level in the annulus was checked with an echometer, and the barometric pressure was recorded. Wellsite conditions are depicted in Figure B-4.

RESERVOIR EVALUATION METHODOLOGY

The hydrothermal resources and reserves of the Auburn geothermal well were evaluated from pressure transients measured as a function of time in both the drawdown and buildup phases of the pump tests.

Pressure transients measured during the pump testing lead to an estimation of reservoir properties (such as average pressure, the product of effective permeability and net formation thickness, effective permeability and total compressibility), reservoir geology (presence of faults or barriers, fractures, boundary conditions),

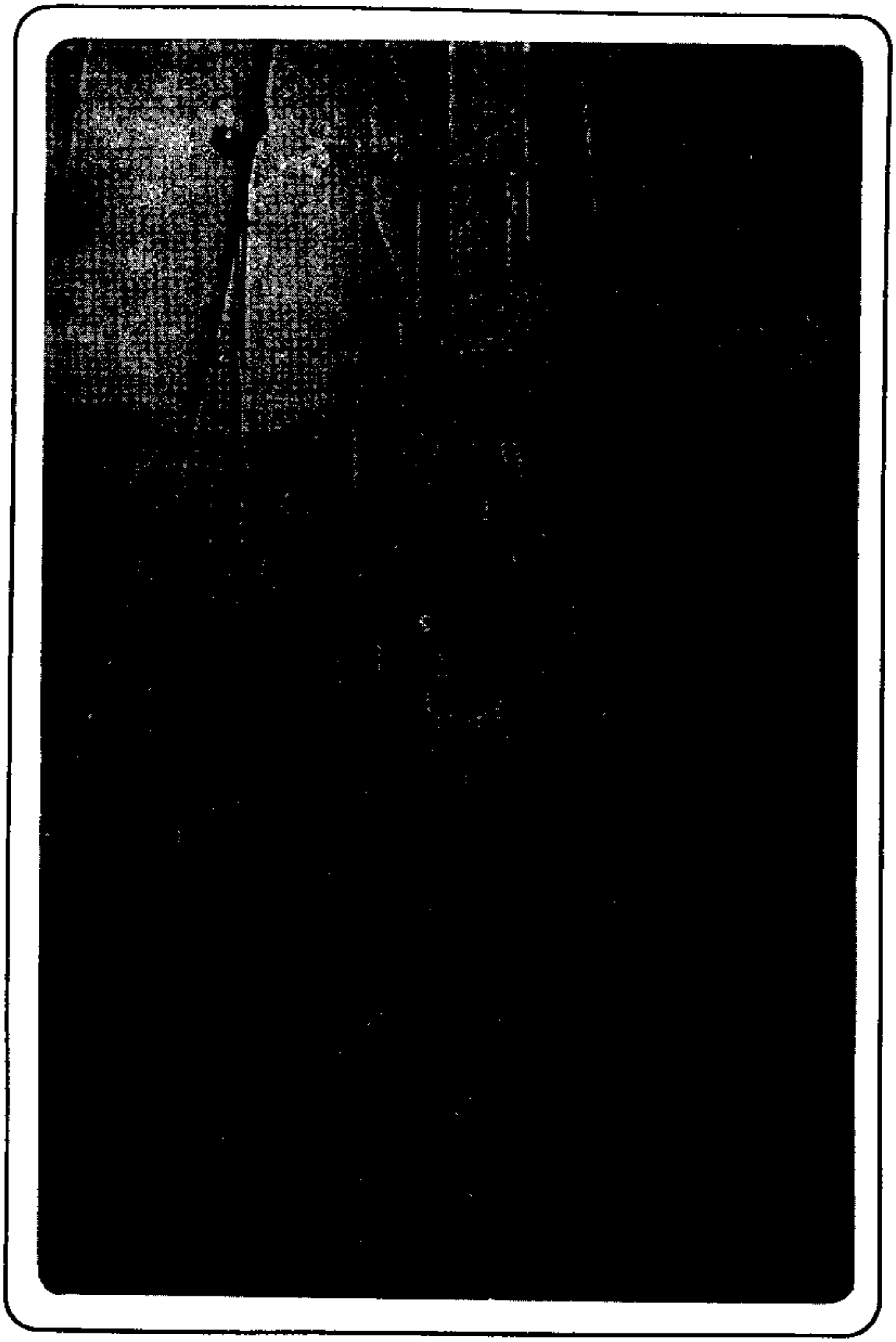


Figure B-4. Auburn Geothermal Well--Wellsite Activity and wellbore conditions (such as drainage volume, skin effects, and productivity or injectivity changes due to hydraulic stimulation). Results of the pressure transient analysis, together with reservoir temperature data, were used to estimate the low-temperature geothermal resource potential of the Auburn reservoir.

Pressure transients during pump-testing or pressure drawdown are most commonly analyzed by solving the equations describing radial flow of a slightly compressible liquid into a wellbore from finite/infinite reservoirs.[1/] The equations of motion and of conservation can be combined to yield the following partial differential equation:

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} = \frac{\phi\mu c}{k}\frac{\partial P}{\partial t} \quad . \qquad \text{(B-5)}$$

If the well is assumed negligibly small in an infinitely large reservoir (conditions applicable during the early transient region of a newly drilled prospect), and the fluid and reservoir properties are isotropic and independent of pressure, the following line source approximation can be made for transient pressures occurring at the sandface of the wellbore (referred to as the "Theis solution"):

$$P(r,t) = P_i + \frac{q\mu B}{4\pi kh}\left[Ei\left(-\frac{\phi\mu c r^2}{4kt}\right)\right]. \qquad \text{(B-6)}$$

P = pressure at any r, atmospheres
P_i = initial reservoir pressure, atmospheres
q = constant rate of production of well, cc/sec. at reservoir conditions
μ = fluid viscosity, centipoises
B = fluid formation volume factor, barrels per stock tank barrel
k = formation permeability, darcys
h = formation thickness, cm
c = fluid or composite fluid-rock compressibility in volume per volume per atmosphere, atm^{-1}
r = distance from centerline of the well, cm .

The Theis solution is sometimes represented in dimensionless form ($r_D > 20$, $t_D/r_D^2 > 0.5$):

1/ Mathews and Russell, 1967; Ramey, 1976; and Earlougher, 1977.

$$P_D = -\frac{1}{2}\left\{Ei\left(-\frac{r_D^2}{4t_D}\right)\right\} \approx \frac{1}{2}\left\{\ln\left(\frac{t_D}{r_D^2}\right)\right\} + 0.80907 \quad \text{(B-7)}$$

where

$$P_D = \frac{P_i - P_{wf}}{q\mu B/2\pi kh}$$

$$r_D = \frac{r}{r_w}$$

$$t_D = \frac{kt}{\phi\mu c r_w^2} .$$

Now, $E_i(-x) \approx \ln x + 0.5772$ for $x > 0.02$. Thus, for $\frac{\phi\mu c r^2}{4kt} < 0.02$ (after a few minutes in most reservoirs), the Theis solution reduces to:

$$P(r,t) = P_i + \frac{q\mu B}{4\pi kh}\left[\ln\left(\frac{\phi\mu c r^2}{4kt}\right) + 0.5772\right] . \quad \text{(B-8)}$$

During the transient flow period of pressure drawdown testing, a plot of flow pressure versus ln $[t]$ will yield a straight line with a negative slope, $m = \frac{q\mu B}{4\pi kh}$. From the calculated slope and measured properties, the effective reservoir transmissivity, kh can be calculated, and knowing the net sand thickness, h, the effective permeability can be determined (Miller, Dyes and Hutchinson, 1950).

Assume that the well is shut in for an elapsed time, Δt after production at a stabilized rate, q for a time, t. Then neglecting afterproduction - a period of time during which the formation produces fluid into the wellbore at a decreasing rate until equilibirum is established in the wellbore - the new well pressure can be obtained by superposing two solutions at t and Δt:

$$P(r,t) = P_i - \frac{q\mu B}{4\pi kh}\left\{\ln\left(\frac{t + \Delta t}{\Delta t}\right)\right\} . \quad \text{(B-9)}$$

A plot of $P(r,t)$ versus $\ln\left(\frac{t + \Delta t}{\Delta t}\right)$ will give a straight line, and is referred to as the "Horner" plot after D. R. Horner (1951). The gradient of the line, $m = \frac{q\mu B}{4\pi kh}$, can be used to determine kh and knowing h, the effective formation permeability.

The effective transmissivity, kh, as well as the product of effective porosity and compressibility, ϕc_t, can also be determined from matching the pressure drawdown for buildup data with the theoretical curves which are computed for a variety of assumed reservoir conditions but which are very similar to the described Theis solution. This method is popularly called log-log type curve matching, (Ramey,1976). The product of ϕc_t is utilized more to calculate the effective porosity, ϕ from the effective total compressibility, c_t than vice-versa.

Extrapolating the Horner semilog straight line to infinite shut in time yields a reservoir pressure, P* which equals the initial reservoir pressure P_i and the average reservoir pressure, $\overline{P}$ in an infinite acting reservoir, i.e., $P^* = \overline{P} = P_i$.

Deviation from the straight line on the Horner plot can be caused by wellbore storage and skin effects. Skin effects are reflected as a substantial pressure drop around the wellbore due to reduced permeability caused by the invasion of drilling fluids, dispersion of clays, presence of mudcake, high gas saturation around the wellbore, partial well penetration, and limited and/or plugged perforations as well as acidization and/or hydraulic fracturing. Skin effects can be defined as a constant pressure drop, non-dimensionalized by the flow-rate:

$$s = \frac{\Delta P_s}{qB\mu/2\pi kh} \quad . \qquad \text{(B-10)}$$

Subtracting the skin pressure drop from both sides of the Theis solution at transient times, we have:

$$P(r,t) - P_i = \frac{qB\mu}{4\pi kh}\left\{ \ln\left(\frac{\gamma\phi\mu c r_w^2}{4kt}\right) - 2s \right\} \qquad \text{(B-11)}$$

where

$$\gamma = 1.78 = \text{Euler's constant } (\ln \gamma = 0.5772) \quad .$$

s can be calculated, from the straight line portion of the pressure build-up curve, one hour after shutting in the well ($\Delta t << t$ and $\left|\frac{t + \Delta t}{t}\right| \approx 1.0$):

$$s = \frac{P_{ws(\Delta t = 1\ hr.)} - P_{wf}}{m} - \frac{1}{2} \ln \left\{ \frac{k}{\phi \mu c r_w^2} \right\} + \frac{1}{2} \ln \left\{ \frac{\gamma}{4} \right\} \qquad \text{(B-12)}$$

P_{ws}, P_{wf} = shut in and flowing bottom-hole pressures.

The early time-flow behavior in vertical fractures, in either infinite systems or in closed systems with relatively short vertical fractures ($x_e/x_f > 1.5$), is linear from the formation to the fracture. For example, the dimensionless pressure at the well for a uniform flux vertical fracture is computed from:

$$P_{Dxf} = \sqrt{\pi t_{Dxf}}\ \text{erf} \left(\frac{1}{2 \sqrt{t_{Dxf}}} \right) - \frac{1}{2} \text{Ei} \left(\frac{-1}{4 t_{Dxf}} \right) . \qquad \text{(B-13)}$$

Where dimensionless time, based on the half-fracture length, is defined by:

$$t_{Dxf} = t_D \, (r_w/x_f)^2 \ .$$

at short times, for $t_{Dxf} < 0.1$,

$$P_{Dxf} = \sqrt{\pi\ t_{Dxf}} \ . \qquad \text{(B-14)}$$

For long times, for $t_{Dxf} > 10$,

$$P_{Dxf} = \frac{1}{2} \left[\ln t_{Dxf} + 2.80907 \right] . \qquad \text{(B-15)}$$

The early time solution of the vertical fracture indicates that the flow behavior is linear, i.e., $\Delta P \ \alpha \ \sqrt{t}$. Thus, the early time log-log slope of ΔP versus Δt for a vertical fracture should yield a slope of one-half (Earlougher, 1977).

The solutions for infinite reservoirs can be modified to take care of the boundaries of closed and partially closed reservoirs. The influence of a fault in an otherwise infinite reservoir can be determined by the Method of Images. Thus, early in the buildup:

$$P_{ws} = P_i - \frac{q\mu B}{4\pi kh} \left\{ \ln \left(\frac{t + \Delta t}{\Delta t}\right) - Ei \left(- \frac{\phi\mu ca}{kt}\right)\right\} \tag{B-16}$$

where a = linear distance from fault .

The distance of the fault from the well can be determined from graphical representation of the above solution; the exact type of barrier boundary can be determined from log-log type analysis of the experimental data versus theoretical curves similar to those governed by the Theis solution.

As Δt becomes large, the above equation reduces to:

$$P_{ws} = P_i - \frac{q\mu B}{2\pi kh} \ln \left(\frac{t + \Delta t}{\Delta t}\right). \tag{B-17}$$

Thus, the late slope is exactly double of the early slope; this doubling effect is the distinguishing feature of pressure behavior of a well near a barrier (Horner, 1951).

In finite reservoirs, the boundary conditions are assumed to be 1) no influx over the drainage radius or 2) constant pressure at the drainage radius. In 1950, Miller, Dyes and Hutchinson published exact mathematical solutions (in the form of complicated Bessel functions) which can be used to determine kh and the average pressure in the reservoir. In this analytic solution, a psuedo-steady state assumption is used because reservoir conditions usually change very slowly in time.

Pressure behavior in non-symmetrical drainage areas have been estimated by Matthews, Brons and Hazebroek by the Method of Images in terms of a drainage area and a shape-dependent time function.

For a variable rate drawdown test, the pressure drawdown test can be divided into intervals during which the production rate is considered constant. The principle of superposition is applied to the Theis solution for transient flow. The resulting solution is the pressure drop as a function of reservoir properties (assumed constant) and fluid flow (summation of the product of interval rate and the logarithm of interval length).

Nominal wellbore storage is defined by a constant:

$$C = \Delta V/\Delta P,\ \text{bbl/psi} \tag{B-18}$$

ΔV = change in volume of fluid in wellbore, bbl

ΔP = change in bottom-hole pressure, psi .

For a wellbore which is completely filled with a single-phase fluid:

$$C = V_w c_w \tag{B-19}$$

V_w = total wellbore volume, bbls

c_w = compressibility of the fluid in the wellbore at wellbore conditions, psi^{-1} .

A dimensionless wellbore storage coefficient can be defined:

$$C_D = \frac{C}{2\pi\phi c_t h r_w^2} \tag{B-20}$$

c_t = total compressibility, psi^{-1} .

At early times and constant c_t, ΔP versus ΔV yields a straight line on a linear or log-log plot. Thus a log-log plot of dimensionless time yields a curve which has a straight line portion (slope of 1) and which is representative of C_D. Thus, a log-log plot can be used to determine early effects such as wellbore storage and to determine the start of the semi-log straight line (Mathews and Russel, 1967).

Section 3

FLUID AND ROCK PROPERTIES

The relevant fluid and rock properties were measured and/or estimated by semi-empirical correlations.

The specific gravity of the produced-formation brine, of which more than three dozen samples were taken during the course of the seven-day pump test, is relatively constant at ∿1.19. The total dissolved solids of the brine is ∿250,000 ppm and the pH is ∿5.3.

The observed consistencies in the composition and concentration of the geothermal brine suggest that the Auburn geothermal well is draining a singular source bed constituting the Theresa and Potsdam formations and possibly the Pre-Cambrian Basement.

The absolute viscosity of the produced brine is estimated to be ∿1.16 centipoise at a reservoir temperature of 125^{o}F. The water formation volume factor is estimated to be ∿1.01 at 2,400 psia and 125^{o}F. The formation brine appears to be undersaturated with natural gas containing ∿94% methane by volume.

The net producing interval is estimated to be 310 ft. spanning the Theresa and the Potsdam formations from 4,740 ft. - 5,050 ft. This interval is made of two zones: Zone 1 which has an average of 80.3 ft. porosity percent and an average, absolute porosity of 0.38%; and Zone 2 which straddles the Theresa and the Potsdam, and which has an average of 832.3 feet-porosity percent and an average porosity of 8.32%. Research by the USGS and Schlumberger-Doll Research indicates that both zones are naturally fractured with a fracture density as high as 10 per 5-ft. interval, with an orientation between N80E and N100E, and dips ranging from $< 5^{o}$ to $> 60^{o}$. The formation compressibility of Zone 2 is estimated to be 7.5×10^{-6} psi^{-1}.

CHEMICAL COMPOSITION OF GEOTHERMAL BRINE

The total dissolved solids (TDS) of the brine from the Theresa and Potsdam formations is approximately 250,000 ppm. The major anionic species is chloride (Cl^-) at a concentration of approximately 150,000 ppm, and the concentration of major divalent ions (Ca^{++} and Mg^{++}) is approximately 20,000 ppm. The concentration of iron is approximately 60 ppm and silica as SiO_2 is approximately 15 ppm. The geothermal brine pH is approximately 5.3, and its specific gravity is approximately 1.19 at reservoir conditions.

The described chemical composition is based on samples taken during the pressure-transient testing of the Auburn reservoir; the sampling schedule of the produced brine is listed in Table B-8. Certifiable chemical and spectrophotometric analyses were made on selected samples by three different laboratories. The average chemical compositions of the Auburn formation brine, as measured by the different laboratories, are listed in Table B-9.

The analysis by Cambridge Analytical Associates (CAA), Watertown, MA, is an average of three formation brine samples taken at the tail ends of the preliminary, 24-hour, and multirate drawdown tests. The samples (14, 24, and 34) are identified in Table B-8 by date, time and temperature at the time of sampling. In addition to the elements listed above, CAA also measured the following cations: lithium (∿63 mg/l); vanadium (∿1.1 mg/l); boron (∿15 mg/l); silver (∿0.20 mg/l); tin (∿64 mg/l); cobalt (<5 mg/l); zinc (∿0.65 mg/l); and arsenic (<5 mg/l). The anions were measured utilizing a combination of electrometric, gravimetric, titrimetric and turbidimetric techniques. For analysis of cations, the sample was boiled to re-solubilize crystallized salts; an aliquot was withdrawn and acidified with nitric acid to a pH <2. Analyses were then performed on appropriate dilutions by inductively coupled argon plasma emission spectroscopy (ICP); zinc and silver were measured by flame atomic absorption, and silver by graphite furnace atomic absorption. The analytical techniques used by CAA, and the results of their chemical analyses on the three brine samples, are detailed in Appendix B.2.

The brine composition, listed in the third column of Table B-9, is based on a certified analysis by the Erie Testing Laboratory Division of Microbac Laboratories, Inc. (MLI) of Erie, PA. The chemical composition is based on the analysis included as Appendix B.3, of three high-pressure samples which were taken during the multi-rate drawdown test and which are identified in Table B-8 by date and time. A mass balance indicates that non-closure between the TDS and the individual chemical components is approximately 10.0% low; an electroyte balance between the major

Table B-8

AUBURN GEOTHERMAL WELL--SCHEDULE OF WATER SAMPLES TAKEN DURING THE PUMP TEST

SAMPLE NO.	TEST TYPE	DATE	TIME	COMMENT
1	PRELIMINARY DRAWDOWN	08/02/83	11:53:30	
2			12:06:00	
3			12:17:00	
4			12:28:30	
5			12:41:00	
6			12:57:00	
7			13:12:00	
8			13:27:00	
9			13:56:00	
10			14:25:00	T= 100°F
11			15:05:00	
12			15:45:00	T= 112°F
13			16:42:00	T= 118°F
14			17:55:00	T= 119.5°F
15			19:00:00	T= 122°F
16	24-HOUR DRAWDOWN	08/03/83	09:37:00	
17			10:30:30	T= 108°F
18			11:33:00	T= 117°F
19			13:30:00	T= 122°F
20			16:45:00	T= 116°F; ρ = 1.18
21			20:37:00	T= 123°F
22			23:30:00	T= 124°F
23		08/04/83	02:17:00	T= 126°F; ρ = 1.17
24			05:30:00	T= 126°F
25			08:30:00	T= 126°F; ρ = 1.19
26	MULTIRATE DRAWDOWN	08/05/83		
27			14:30:00	T= 115°F; ρ = 1.18
			14:35:00	Samples For Galson
28			16:31:00	T= 123°F; ρ = 1.18
29	MULTIRATE DRAWDOWN		20:32:00	T= 126°F; ρ = 1.18
30		08/06/83	00:32:00	T= 127°F
31			04:32:00	T= 128°F
32			08:32:00	T= 130°F
33			12:32:00	T= 130°F
			13:00:00	Pressurized Samples
			13:15:00	(@ 577 psi) Taken For Erie Testing Laboratory
34			16:30:00	T= 131°F
35			22:30:00	T= 133°F
36		08/07/83	02:30:00	T= 134°F
			02:45:00	Pressurized Sample (@ 980 psi & 134°F) Taken For Erie Testing Laboratory

Table B-9

AUBURN GEOTHERMAL WELL - CHEMICAL COMPOSITION OF FORMATION BRINE

CONSTITUENT	CONCENTRATION (mg/l)		
	CAA	MLI	GTS
pH	5.1	5.5	5.4
Total Dissolved Solids @ 125°F	308,000	292,000	303,000
Total Alkalinity as $CaCo_3$	9	77	78
Chloride	179,000	179,000	169,000
Bromide	NM	NM	2,200
Carbonate	NM	<.1	NM
Bicarbonate	NM	77	NM
Sulfate	<10	<1	<3
Sulfite	< 1	<0.1	<0.1
Sodium	60,000	70,800	38,750
Calcium	19,000	19,500	24,250
Magnesium	2,600	3,000	3,480
Iron	90	54	90
Silica as SiO_2	24	11	14
Manganese	16	NM	NM
Strontium	1,500	NM	NM
Potassium	2,200	NM	1,600
Barium	140	NM	NM

CAA - Cambridge Analytical Associates, Watertown, MA

MLI - Microbac Laboratories, Inc., Erie, PA

GTS - Galson Technical Services, Inc., E. Syracuse, NY

NM - Not Measured

cationic and anionic species indicates approximately 12% excess Cl^- ions. The latter was measured by colorimetric titration utilizing one cc sample whereas the cationic concentrations were measured by atomic absorption (AA) emission spectrophotometry utilizing 1:1000 dilutions. The non-closure in the mass and ion balances appears to be inherent in the analytic techniques used in their measurements. Erie Testing Laboratory reports a mean relative error of ∿8.8% with a standard deviation of 3.9% for recently measured Pennsylvania brine samples which are similar to the Auburn brine in concentration and composition.

Galson Technical Services, Inc. (GTS) of East Syracuse, N.Y., analysed four samples taken ∿90 minutes into the multirate drawdown test; the results of their analyses are attached as Appendix B.4 with the arithmetic mean average values listed in Table B-9. The chemical analyses in Table B-9 all exhibit different degrees of non-closure in mass and ionic balances. The reasons for these non-closures could be as follows:

- Positive errors in the analytic techniques used in the cationic species coupled with negative errors in the spectrophotometric techniques used in the measurement of the anionic species.
- The presence of unidentified anionic species.
- The aging of the samples, e.g., CAA's analysis was performed ∿3 months after the analyses by MLI and GTS.

The mass balance on the chemical constituents of the Auburn geothermal brine closes between 2-7% if the CAA and MLI analyses are combined; the closure on the ionic balance is ∿8.5%. These discrepancies may be resolved with further analyses of fluid and rock samples by Arc Spark Atomic Emission Spectroscopy and Energy Dispersive X-Ray techniques with Electron Microscopy.

Apart from the discrepancies discussed above, the chemical composition of the produced brine appears to be relatively consistent over and beyond the seven days of pump testing and the 100,000 plus barrels of produced brine. The brine analyses, certified by Microbac Laboratories, Inc., were taken 24.00 hours and 37.75 hours into the multirate drawdown test. These samples are about the same as those of nearer wellbore samples taken 90 minutes into (within the natural fracture flow regime of) the multirate drawdown tests and analysed by Galson Technical Services. It should also be noted that: (1) formation water of the Hooker Chemical Corporation's waste disposal well in Buffalo, NY, was field tested to have a TDS of 300,000 ppm and a specific gravity of 1.2; and (2) formation water of Bethlehem

Steel's waste disposal well in Erie County, New York was tested to have a TDS of ∿322,000 ppm of which the Cl^- content was 84,200 ppm and the divalent ions (Mg^{++} and Ca^{++}) concentrations were ∿35,000 ppm.

The observed consistencies in the composition and concentration of the geothermal brine suggest that the Auburn geothermal well is draining a singular-source bed constituting the Theresa and Potsdam formations and possibly the Pre-Cambrian Basement. The observed similarities in the produced brines of the Auburn, Hooker Chemical and Bethlehem Steel wells suggest that the producing formations may extend regionally on a hydrological basis. The differences in the concentrations of the produced brines of these three widely spaced wells result from the differences in the local geothermal gradients and, thus, in the geochemistry of the three locations.

VISCOSITY AND SPECIFIC GRAVITY OF GEOTHERMAL BRINE

The absolute viscosity of the produced brine is estimated to be ∿1.16 centipoise at reservoir conditions of temperature and pressure.

Viscosity of the produced brine was extrapolated from Matthews and Russell's correlation between absolute viscosity, temperature, brine salinity in the form of weight percent NaCl and reservoir pressure. This correlation is shown in Figure B-5; the pressure correction factor was estimated to be 1.003.

The viscosity measurements made by Erie Laboratories in Pennsylvania and presented in Appendix B.3 are incorrect. The measurements were in Saybolt seconds and presented as absolute viscosities in centipoises. The presented values are actually kinematic viscosities in centistokes, i.e., absolute viscosity in centipoise divided by gravity in gms/cc. The measured values are incorrect because they show little or no temperature dependency; typically, liquid viscosity is a decaying exponential function of temperature. The room temperature measurement, at 77°F, appears reasonable. The value of 2.00 centipoise is within 10% of Matthews and Russell's correlation value of 1.85 centipoise at 77°F and 1 atmosphere pressure.

The specific gravity of the produced brine is estimated to be ∿1.19 at reservoir conditions of temperature and pressure. The specific gravity as a function of

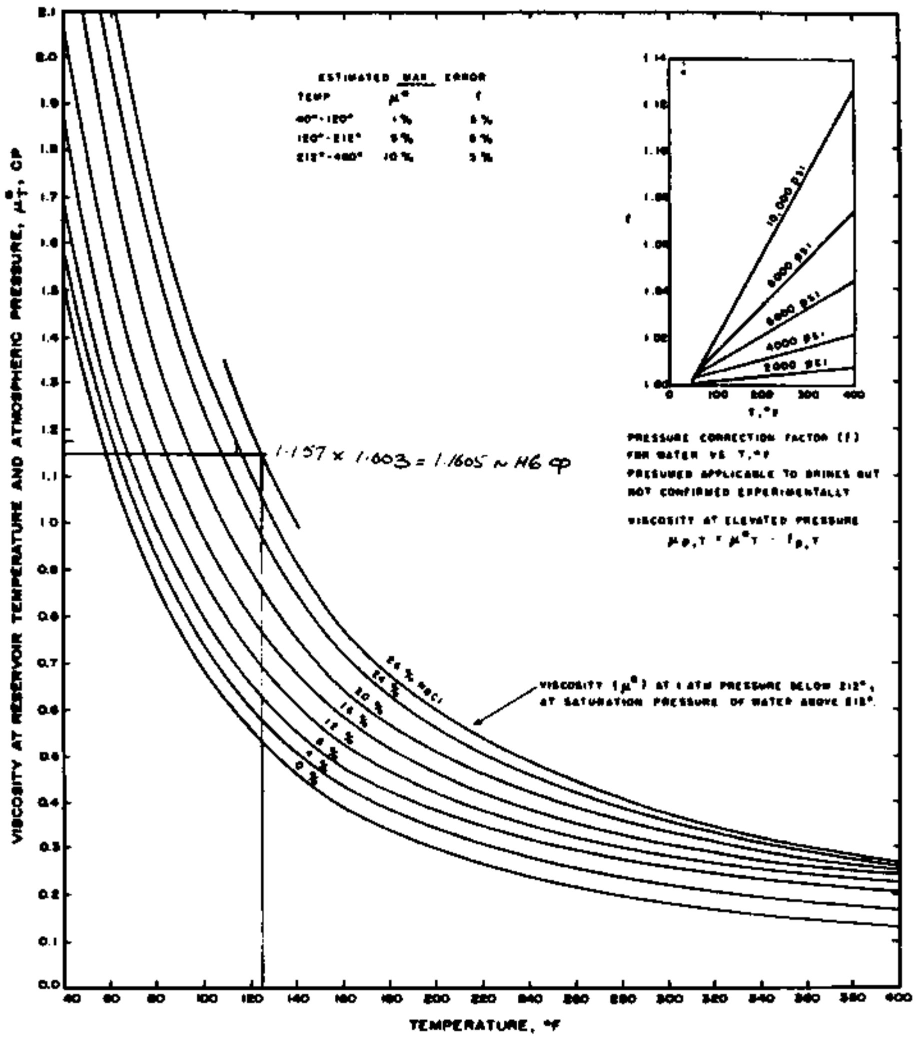


Figure B-5. Water Viscosity at Various Salinites and Temperatures (after Matthews and Russell, data of Chestnut, 1967) temperature is tabulated in Appendix B.3. The values given in Table B-8, which were measured under field conditions, indicate that the specific gravity of the produced brine was relatively constant.

WATER FORMATION VOLUME FACTOR

The water formation volume factor (B_w) is estimated from the correlation in Figure B-6 below. For water plus natural gas at 2,400 psia and 125°F, $B_w \simeq 1.01$ reservoir barrels per stock tank barrel (RB/STB).

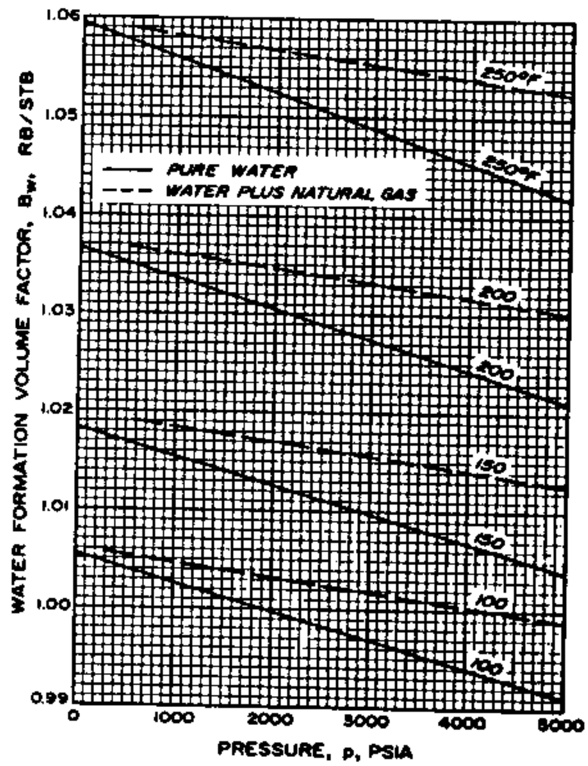


Figure B-6. Water Formation Volume Factor as a Function of Pressure and Temperature w/wo Natural Gas in Solution (Dodson and Standing, 1944)

COMPOSITION AND CONCENTRATION OF DISSOLVED GASES

The pressurized fluid analyses by Erie Testing Laboratory indicate that the geothermal brine contains finite quantities of natural gas. The analyses, in Appendix B.5, indicate 2.25 SCF/STB of solution gas at 577 psi and 125°F with a methane concentration in excess of 90% by volume. The measured volume of dissolved gas is approximately 50% of the saturation volume as shown in Figure B-7 below.

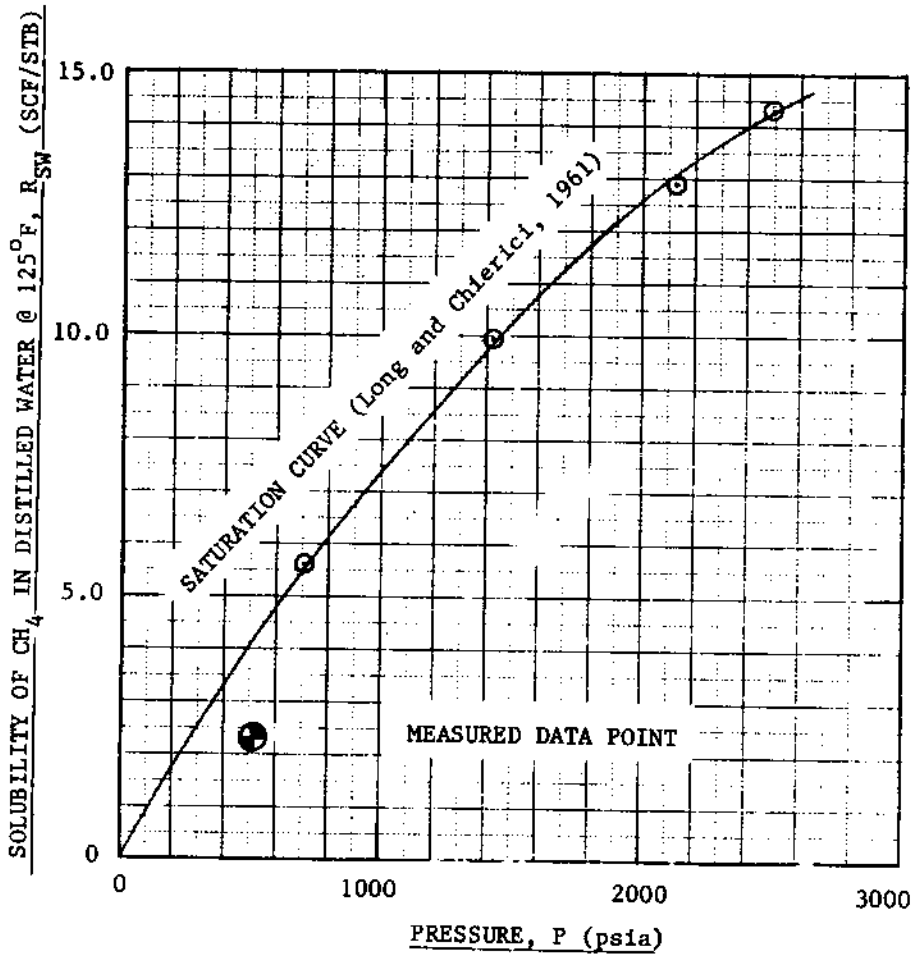


Figure B-7: Solubility of Methane in Distilled Water as a Function of Pressure @ 125°F

The component analysis of the 8/6/83/13:15 sample, with a methane concentration of 73.3 volume %, appears to have been diluted by air as indicated by the proportionately high concentration of oxygen (3.8 vol %) and nitrogen (17.7 vol %).

Correcting this sample and the 8/6/8/13:00 sample, with a methane concentration of 88.8 volume %, for air dilution yields methane concentrations of 93.4 and 94.5 volume %, respectively. Lower pressure air bag samples taken by Galson Technical Services, Inc. at 8/5/83/14:35 in the earlier stages of the multirate drawdown test indicate a corrected methane concentration of 67.2 vol % (as per the GC thermal conductivity analysis in Appendix B.4). The second inconsistency in the data relates to the volumetric analysis of the 8/7/83/02:15 sample (@ P = 980 psi & T = 125°F) by Erie Testing Laboratory which indicated ∿0.10 SCF/STB of solution gas. This extremely low value could have resulted because of gas leakage across the valve stems of the sample bomb at the field sampling pressure of 980 psi, i.e., there is no record of the sample pressure just prior to testing in the Pennsylvania laboratory.

The measured gas volume of ∿2.25 SCF/STB appears to be consistent with observed differences between the pumping rates measured upstream and downstream of the wellhead choke. The downstream measurements were ∿20% greater than the upstream values at ∿125 gpm as a consequence of the rapid drop in pressure and the subsequent flash liberation of gas at the downstream side of the choke. The difference between the downstream and the upstream measurements of flow rate appears to decrease with increasing flow rate and to increase with decreasing flow rate because higher downstream pressures are associated with the higher flow rates.

The laboratory measured value of 40 volume % gas at 577 psi exceeds the field measured values because of the differential solubility between the downstream and atmospheric pressures. The measured gas composition is consistent with behind-the-pipe values measured uphole prior to well completion at 4,700 ft. Chromatographic analysis of gas flows, sampled by Baroid in the development of the litho log on 3/2/82, indicate 99.3 volume % methane and 0.7% ethane by volume. It should be noted that gas shows below the Black River formation were not discernible because of the changeover from drilling with air to drilling with mud at 4,163 ft.; a small gas show (∿1.3% gas in air) was seen in the Lockport between 1,651 ft. and 1,668 ft., and there was a larger gas show (50% gas in air with a localized downhole pressure of 500 psi) in the Trenton and Black River formations between 4,150 ft. to 4,215 ft.

FORMATION (FLUID AND ROCK) COMPRESSIBILITY

The formation compressibility (c_t) is a composite made up of the compressibilities of the porous rock and its contained fluids:

$$c_t = c_r + S_w c_w \quad . \tag{B-21}$$

The compressibility of the brine was estimated to be 1.95×10^{-6} psi^{-1} at reservoir conditions of temperature (125°F) and pressure (∿2,400 psia). The estimate was based on a correlation by Long and Chierici:

$$c_w = (c_w)_{o,n} \left[1 + 0.0088 \times 10^{-Kn} (R_{sw}) \right] . \tag{B-22}$$

where

c_w = compressibility of a gas-free brine containing solution gas and n gram-equivalents of dissolved solids, psi^{-1}.

$(c_w)_{o,n}$ = compressibility of a gas-free brine containing n gram-equivalents of dissolved solids, psi^{-1}.

n = dissolved solids concentration in gram-equivalents/litre, i.e., ppm/58,443.

K = Secenov's coefficient at reservoir temperature, 0.123.

R_{sw} = gas solubility in distilled water at reservoir pressure and temperature, 14.3 SCF/STB.

For a 300,000 ppm, brine, $(c_w)_{o,n}$ and c_w were computed to be 1.90×10^{-6} and 1.956×10^{-6} psi^{-1} respectively.

The pore volume compressibility is estimated to be 5.5×10^{-6} psi^{-1} for the Zone 2 average porosity of 8.3% from Hall's correlation in Figure B-8. Assuming a 100% saturation, $S_w = 1$, the formation compressibility of Zone 2 is estimated to be 7.5×10^{-6} psi^{-1}.

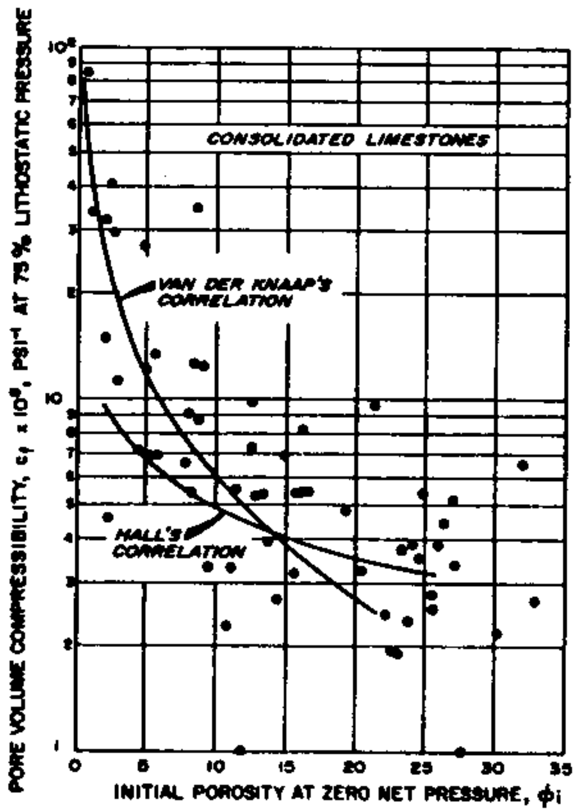


Figure B-8. Pore-Volume Compressibility at 75-Percent Lithostatic Pressure Versus Initial Sample Porosity for Limestones (Newman, 1973)

RESERVOIR CAPACITY - FORMATION THICKNESS AND ABSOLUTE POROSITY

The Auburn geothermal well is producing brine over a gross interval of 434 ft. from 7-in. casing point at 4,700 ft. to the pre-pump test measured T.D. of 5,094 ft. This open-hole completion penetrates the Theresa and Potsdam formations into the Pre-Cambrian Basement.

The major water-bearing zones of the Auburn geothermal well have been identified to occur over the interval 4,740 ft. - 4,950 ft. spanning the Theresa and Potsdam formations. These zones were identified from PLT logs taken on April 7, 1982, and correlated with the formation logs taken on March 2, 1982 and with lithology logs (c.f. Appendix B.6). Producing zones were identified as follows:

Table B-10

MAJOR WATER PRODUCING ZONES OF THE AUBURN GEOTHERMAL WELL

Interval	ΔFlow (rps)	Δa'max (^{o}F/ft.)	T_{Wb} (^{o}F)
4740-4800	+ 0.60	+ 0.030	123.0-123.6
4800-4900	+ 0.45	+ 0.005	123.6-124.5
4900-5008	+ 0.50	+ 0.010	124.5-125.0
5008-5050	+ 0.60	+ 0.010	125.0-125.4

The gross values of feet-porosity over the interval 4,740 ft. - 5,050 ft. range from 712.7 to 1,033.0 ft-percent yielding an average, composite porosity of 2.82%.

The estimated values of porosity and feet-porosity are listed in Table B-11. The cross-plotted values were estimated from sonic transit times and values of apparent limestone porosity taken from sonic/gamma ray and compensated neutron density/gamma ray logs taken March 2, 1982 by Schlumberger. The values of apparent limestone porosity are listed under neutron in Table B-11; these values are not included in the average and net computations of ϕ and $h\phi$. The cross-plots, with the lithological logs, were used to estimate the gross bulk compositions of the intervals listed in Table B-11. The calculated values of porosity from the formation density and sonic logs (under ρ_b and Δt, respectively, in Table B-11)were made from mean

Table B-11

AUBURN GEOTHERMAL WELL COMPOSITE POROSITIES AS A FUNCTION OF DEPTH FROM FORMATION LOGS AND LITHOLOGICAL ANALYSIS

FORMATION COMPOSITION	INTERVAL	h (ft)	POROSITY, ϕ				GROSS h ϕ			
			NEUTRON	X-PLOT	ρ_b	Δt	NEUTRON	X-PLOT	ρ_b	Δt
THERESA										
33%ss/67%dol	4616-4650	34	0.010	0.000	0.000	0.000	0.340	0.000	0.000	0.000
80%ss/20%dol	4650-4736	86	0.010	0.010	0.033	0.010	0.860	0.860	2.838	0.860
74%ss/26%dol	4736-4900	164	0.000	0.005	0.000	0.001	0.000	0.820	0.000	0.164
63%ss/37%dol	4900-4950	50	0.010	0.010	0.009	0.010	0.500	0.500	0.450	0.500
100% ss	4950-5008	58	0.060	0.105	0.081	0.109	3.480	6.090	4.703	6.322
	4616-5008	392	0.013	0.021	0.020	0.020	5.180	8.270	7.991	7.846
POTSDAM 100%ss	5008-5050	42	0.040	0.070	0.047	0.070	1.68	2.940	4.991	7.846
TOTAL NET	4740-5050	310		0.033	0.023	0.032		10.330	7.127	9.922
ZONE 1	4740-4900	210		0.006	0.002	0.003		1.300	0.450	0.660
ZONE 2	4950-5050	100		0.090	0.067	0.093		9.030	6.677	9.262

averages of logged values and composite estimates of matrix bulk densities and transit times. The estimated values of porosity appear to be primary in nature because the sonic log will record the fastest transit time and will thus bypass any vertical fractures which give rise to secondary porosities.

Dunn Geoscience Corporation measured the porosity of the Theresa and the Basement by counting the voids of thin sections which were vacuum-saturated with blue-stained epoxy. The Theresa was determined to have a primary porosity of 2 ± 2%; the Pre-Cambrian basement was determined to have 0.3 + % secondary porosity which was described as "open fractures which are partially impregnated with blue epoxy." For comparison reasons, dolomite and sandstone cores taken from similar horizons were measured by the Washburn - Bunting method to have effective porosities of ~5.5% and ~10.0%, respectively. The cores were taken from the Theresa and Potsdam formations between depths of 3,818 ft. - 4,163 ft. of the Lackawanna WPL Test Well #1 - a waste disposal well drilled, completed and tested for the Bethlehem Steel Corporation in Hamburg Township, Erie County, New York. Another waste disposal well, which encountered the Theresa and the Potsdam, was drilled and cored for Hooker Chemical Company in Niagara County, New York. The porosity of 38 samples over the interval 2,849 ft. - 3,032 ft. in the Theresa and Potsdam formations averaged ~5.1%. The calculated values of porosity, listed in Table B-11, are in good agreement with Schlumberger's computerized logging and analysis as per Figure B.6-2 in Appendix B.6.

The net producing interval is made of two zones:

- Zone 1, which spans the interval 4,740 ft. - 4,950 ft. has an average of 80.3 ft.-porosity percent and an average porosity of 0.38%.
- Zone 2, which spans the interval 4,950 ft. - 5,050 ft. and which straddles the Theresa and Potsdam, has an average of 832.3 ft-porosity percent and an average porosity of 8.32%.

Thus, Zone 2 contributes 91.2% of the primary pore volume. Yet, per the PLT logs, Zone 1 was identified to be a good, and maybe a better, producer than Zone 2. This identification was correct in the time frame of the spinner survey because both zones are highly fractured.

The in situ stress and fracture distribution of the Auburn geothermal well was investigated by Schlumberger-Doll Research (Plumb and Singer, 1983) utilizing a borehole televiewer log run by the USGS, a dipmeter/fracture identification log and an assortment of other logs including a long-space sonic log which measured compressional as well as shear wave velocities. The number of fractures per 5-ft. interval is represented as Figure B-9. The highest fracture density was found between depths 4,700 ft. - 4,850 ft. with fractures oriented between N80E and N100E with the majority having a dip > 60°. As shown in Figure B-9, the fracture density was as high as 10/5ft or 1/6 in. Fractures of similar strike and dip were found to extend from 4,850 ft. to 5,100 ft. spanning the Theresa and Potsdam formations and extending into the Pre-Cambrian Basement. The United States Geological Survey (Hickman, 1983) utilized hydraulic fracturing stress measurement techniques and the borehole televiewer survey to evaluate the natural fracture distribution and borehole elongation of the Auburn goethermal well. The USGS concluded that distinct natural fractures, approximately one-third of which have dips less than 5°, persist to the measured T.D. of 5,250 ft. and that the strike of steeply dipping natural fractures, which occur in the lower sedimentary section (Theresa and Potsdam), show a strongly developed E-W preferred orientation.

In addition to the natural fracture system, the Auburn geothermal well was hydraulically stimulated in April 1983. Plumb and Singer (1983) predicted that:

- The induced hydraulic fractures will be vertical and strike N85E.
- Intrinsic permeability should be anisotropic with maximum, intermediate and minimum permeability oriented N85E, vertical and N05W, respectively.

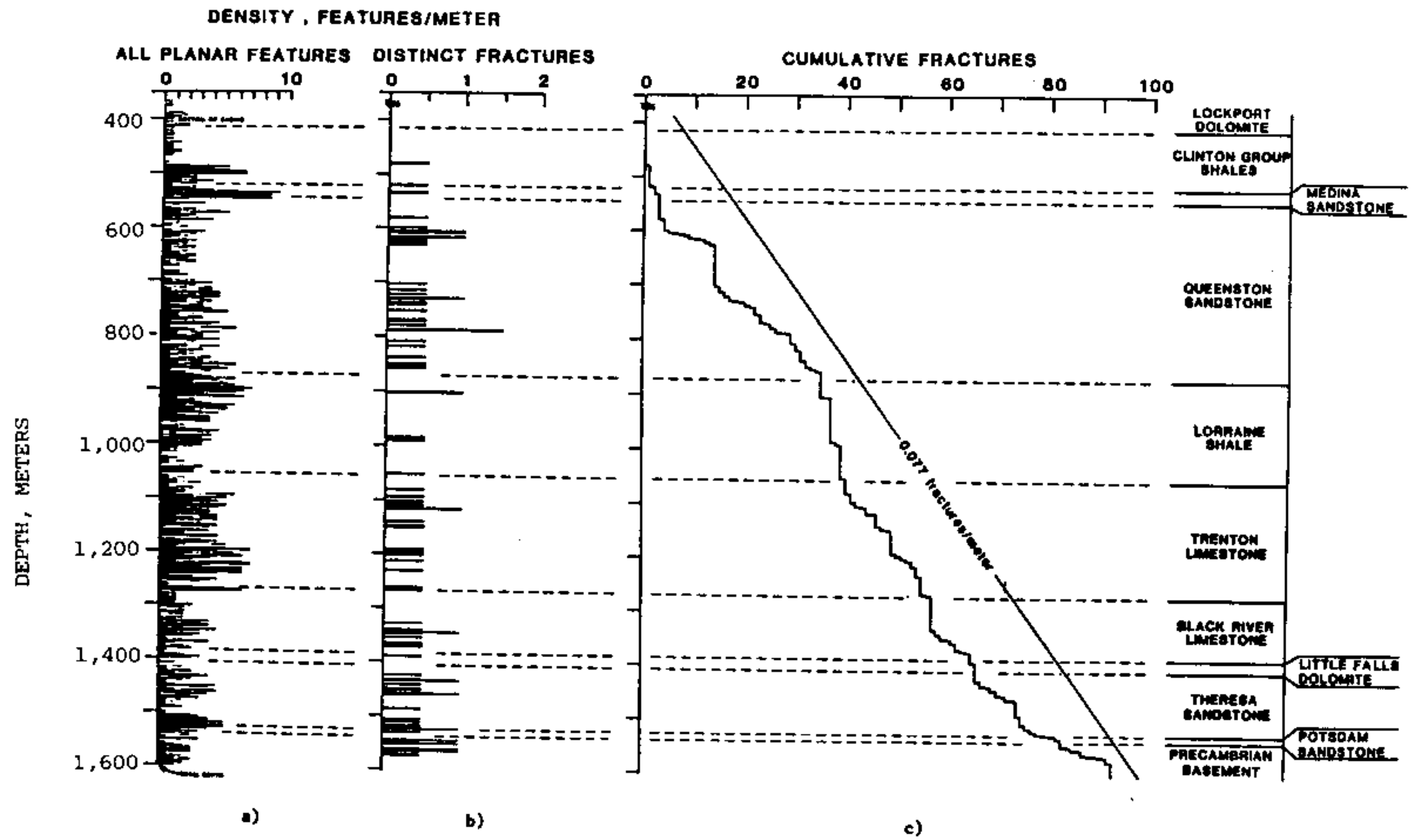


Figure B-9. Auburn Geothermal Well Density of Natural Fractures and Planar Features Versus a Simplified Stratigraphic Section. a) All Planar Features; b) Distinct Natural Fractures Only; c) The Cumulative Number of Distinct Natural Fractures Versus Depth. The Inverse Slope of the Cumulative Fracture Plot Over a Given Depth Range is Equal to the Average Fracture Density. (Hickman, Healy, and Zoback 1983)

Section 4

RESOURCE AND RESERVE ANALYSIS

The Auburn low-temperature geothermal reservoir appears to be finite and bounded, and to be made up of as many as six different storage and flow regions. These regions consist of a low-porosity, dolomitic, water production zone and a high-porosity sandstone zone both of which are naturally fractured and both of which were hydraulically fractured and propped prior to the test. The two producing zones of contrasting porosity, are assumed to be in perfect communication with each other and are viewed to be one producing interval with volume averaged properties. This assumption simplifies the reservoir analysis by characterizing the Auburn reservoir by three distinct regions, each of which becomes dominant at different times during reservoir drainage and reservoir buildup. The reservoir characteristics were readily identifiable and, for the most part, quantifiable from the analysis of the pump test and supporting data.

The effective transmissivity and the effective permeability are estimated to be 3,100 millidarcy-feet and 10 millidarcies, respectively, on the average; the effective transmissivity and the effective permeability were computed from the slopes of the semilog straight line of a Horner-type plot for pressure buildup data and a Miller-Dyes-Hutchinson plot for pressure drawdown data.

The effective porosity and the effective compressibility are estimated to be 0.0027 and 7.5×10^{-6} psi^{-1}, repectively. These values were computed from log-log type curve matches between the actual ΔP-Δt relationships and theoretical curves of dimensionless P_D-t_D relationships for both the pressure drawdown and buildup data.

The three distinct storage regions of the Auburn reservoir are quantified as follows: Region 1, the vertical hydraulic fracture, identified by the 1/2 slope of the log-log plot of ΔP versus Δt, and computed to have a half-length of ~150 feet; Region 2, the natural fractures and fissures or microcracks, identified from the semilog drawdown and buildup plots and estimated to be ~26% of the total effective porosity; Region 3, the porous matrix, computed to have an absolute porosity of 0.0282 (from log analysis) and an effective porosity of 0.0027 (from the analysis of pump test data). The average reservoir pressure, $\bar{P}$ in these three regions was estimated to be 2,260 psi prior to the pump test.

The areal extent, volumetric resources, and reserves of the Auburn low-temperature geothermal reservoir are estimated to be as follows:

Table B-12

AREAL EXTENT, VOLUMETRIC RESOURCES AND RESERVES (STB)

Category	Area (acres)	Resources (STB)	Reserves (STB)
Proved	462.7	3.0×10^6	2.25×10^6
Possible	1,079.5	7.0×10^6	5.25×10^6
Probable	967.3	23.0×10^6	17.25×10^6

The volumetric resources were estimated from reservoir limit tests utilizing pressure drawdown data. The estimates of volumetric resources and areal extents are sensitive to the estimated values of effective compressibility and effective porosity as well as drawdown rate. The possible and probable resources were computed for the total effective and formation brine compressibilities, respectively, both in the limit of zero drawdown rate; the proved resources are defined in terms of the pump test's drawdown data. The volumetric reserves are based on an estimated recovery efficiency of 75%.

The maximum initial deliverability of the well was determined to be ∿338 gpm (∿11,600 STB/D) at T.D. and ∿328 gpm (∿11,200 STB/D) at a pump depth of 4,000 ft. Drawdown analysis indicates that these rates cannot be sustained for more than a few hours without the reinjection of fluids into the producing formation in order to maintain reservoir pressure. Similar analysis indicates that the reservoir could sustain a production rate of 150 gpm for approximately six months without fluid reinjection and a production rate of 100 gpm indefinitely over the lifetime of the resource.

The intermittent deliverability of the Auburn low-temperature geothermal well also was evaluated to determine the response of the reservoir, its "recovery factor", under cyclic operating conditions without fluid recharge. For pumping at 150 gpm, the reservoir is drawndown in 6.3 months under intermittent withdrawal (6 months pumping - 6 months shut-in) versus 6.1 months for continuous withdrawal. For each six months of pumping at 100 gpm, the six-month shut-in recovery factors are estimated to be $\sim$0.71, $\sim$0.58, and $\sim$0.49 before full depletion of the estimated, proved reserves of the Auburn reservoir.

RESERVOIR CHARACTERIZATION

The Auburn low-temperature geothermal reservoir appears to be finite and bounded. Within these physical constraints, the net producing interval is made up of two communication layers or zones -- a low-porosity dolomitic zone and a medium-porosity sandstone zone -- both of which are highly fractured. The two producing zones are in communication with each other vis-a-vis cross-flow in the intersecting fractures. In addition to the natural fracture system, the producing interval was hydraulically fractured and propped prior to the pump test.

Thus, the Auburn reservoir is comprised of as many as six different storage and flow regions as shown in Figure B-10. To simplify analysis, the two producing zones are assumed to be in perfect communication with each other and are viewed to be one producing interval with volume averaged properties. The naturally fractured Auburn reservoir is characterized by three distinct regions:

- REGION 1 - an improved near-wellbore region resulting from a vertical macro-fracture created by the pre-pump test hydraulic stimulation.
- REGION 2 - a set of interconnecting fractures and fissures which represents foramenular secondary porosity, and which contributes a low-storage but a high-flow capacity.
- REGION 3 - a matrix of well-defined fine pores which represents intergranular primary porosity and which contributes a high-storage but low-flow capacity.

The existence of these distinct regions results in the development of three flow regimes, each of which becomes dominant at different times during reservoir drainage and reservoir buildup. During the drainage, the vertical hydraulic fracture (Region 1) drains first, followed by the natural fractures (Region 2), and finally the flow becomes limited or controlled by the lower-permeability but higher-porosity matrix (Region 3). The time constants are determined by the storage capacity of the individual regions instead of the drawdown or pumping rates.

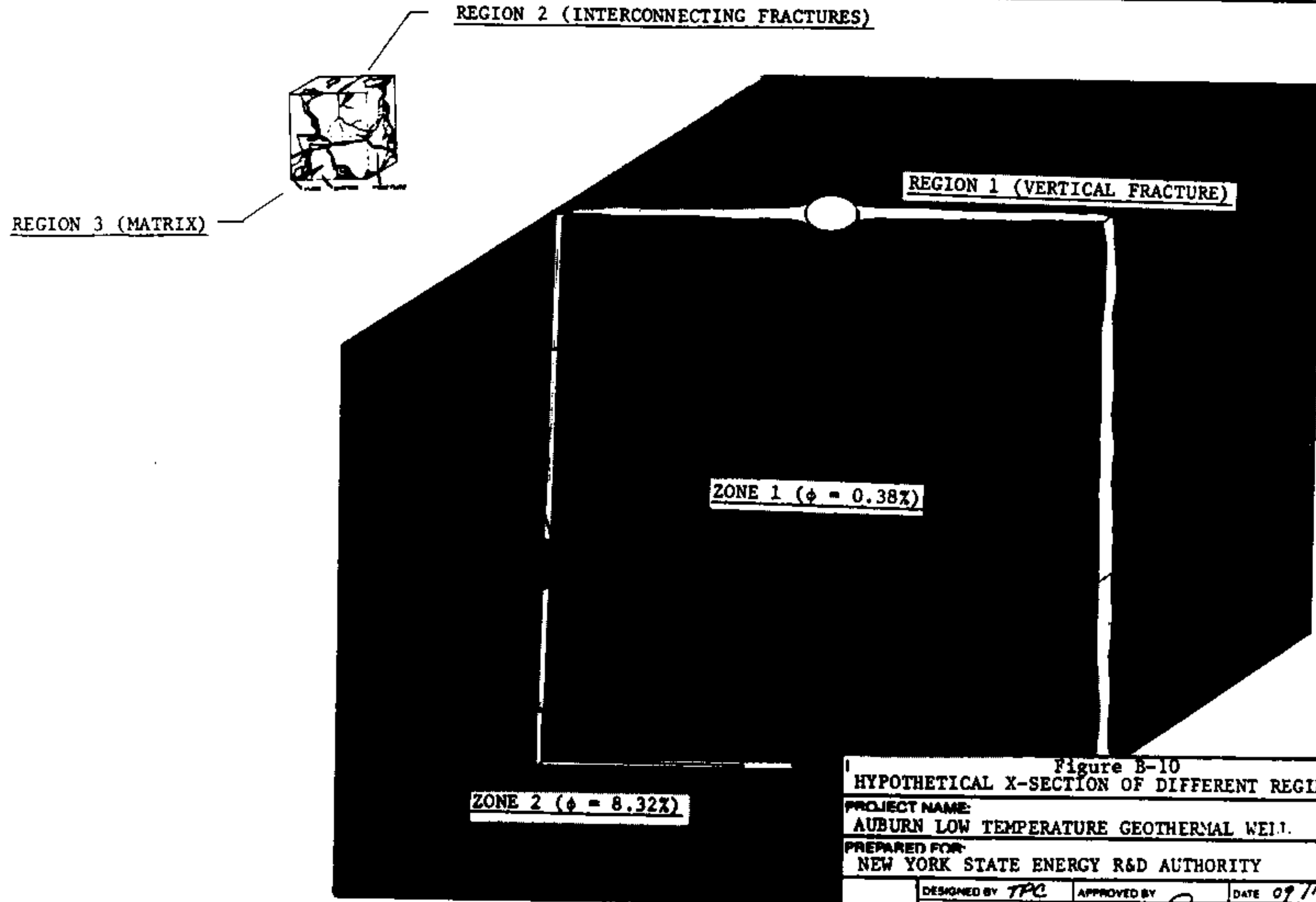


Figure B-10
HYPOTHETICAL X-SECTION OF DIFFERENT REGIMES

PROJECT NAME:
AUBURN LOW TEMPERATURE GEOTHERMAL WELL

PREPARED FOR:
NEW YORK STATE ENERGY R&D AUTHORITY

DESIGNED BY TPC	APPROVED BY	DATE 09/15/82
DRAWN BY TPC	CHECKED BY	DATE 12/23/83
REVISION 1 BY	APPROVED BY	DATE
REVISION 2 BY	APPROVED BY	DATE
REVISION 3 BY	APPROVED BY	DATE
REVIEWED BY	APPROVED BY	DATE
SCALE none	DRAWING NO. 0078	

PREPARED BY ENG, INC. . . an energy engineering company

The characteristics of the Auburn low-temperature geothermal reservoir were defined from the anlaysis of the pump test and supporting data. The latter was used to identify, delineate and quantify the two-zone model which is detailed under "Reservoir Capacity - Formation Thickness and Absolute Porosity." The three distinct storage regions and flow regimes, although identifiable in most of the pressure-transient tests, can be readily illustrated by the 24-hour drawdown and buildup data.

The log-log type curve match of the 24-hour pressure buildup data in Figure B-11 indicates a skin factor, s, of -5. This negative skin factor is representative of a highly stimulated wellbore region. Additionally, the early transients between 10^{-2} and 10^{-1} hours have a $\Delta P/\Delta t$ slope of approximately one-half. This early time slope is indicative of fracture flow because the flow is akin to Hagen-Poiseuille flow between planar walls in which pressure is proportional to the square root of time. These early pressure transients usually disguise wellbore storage effects which are characterized by a $\Delta P/\Delta t$ slope of 1 on a log-log plot. Wellbore storage effects should theoretically precede fracture flow effects but are either obscured by the wellbore storage-fracture flow transition regime or just not recorded. As demonstrated in the discussion of storage regions, the hydraulic fracture is vertical. At the producing interval depth of $\sim$4,700 - 5,100 ft., the plane of maximum prinicpal stress is horizontal. The well would thus fracture in the vertical plane. The induced hydraulic fracture's preferred orientation is N85E as discussed under "Reservoir Capacity - Formation Thickness and Absolute Porosity" and as predicted by Plumb and Singer, 1983.

The 24-hour pressure drawdown data exhibits behavior which is similar to the buildup data but which has different time constants. The 24-hour pressure drawdown data is typed curve matched on log-log coordinates in Figure B-12. The negative skin effect (-5) is shown because skin effects are representative of an additional pressure drop in the near wellbore region and are not dependent on the residence time of an individual fluid particle. The early transients, representative of fracture flow and wellbore storage, ends about 0.5 hours in Figure B-12. This time interval is substantiated in the Miller-Dyes-Hutchinson (MDH) type semi-log plot in Figure B-24. Just prior to the beginning of the transient period of flow, the 1/2-slope regime typical of fracture flow is established. The psuedosteady flow regime begins at approximately 10 hours as indicated in Figure B-12. This flow regime is identified from the linear plot of the 24-hour pressure drawdown data in Figure B-25.

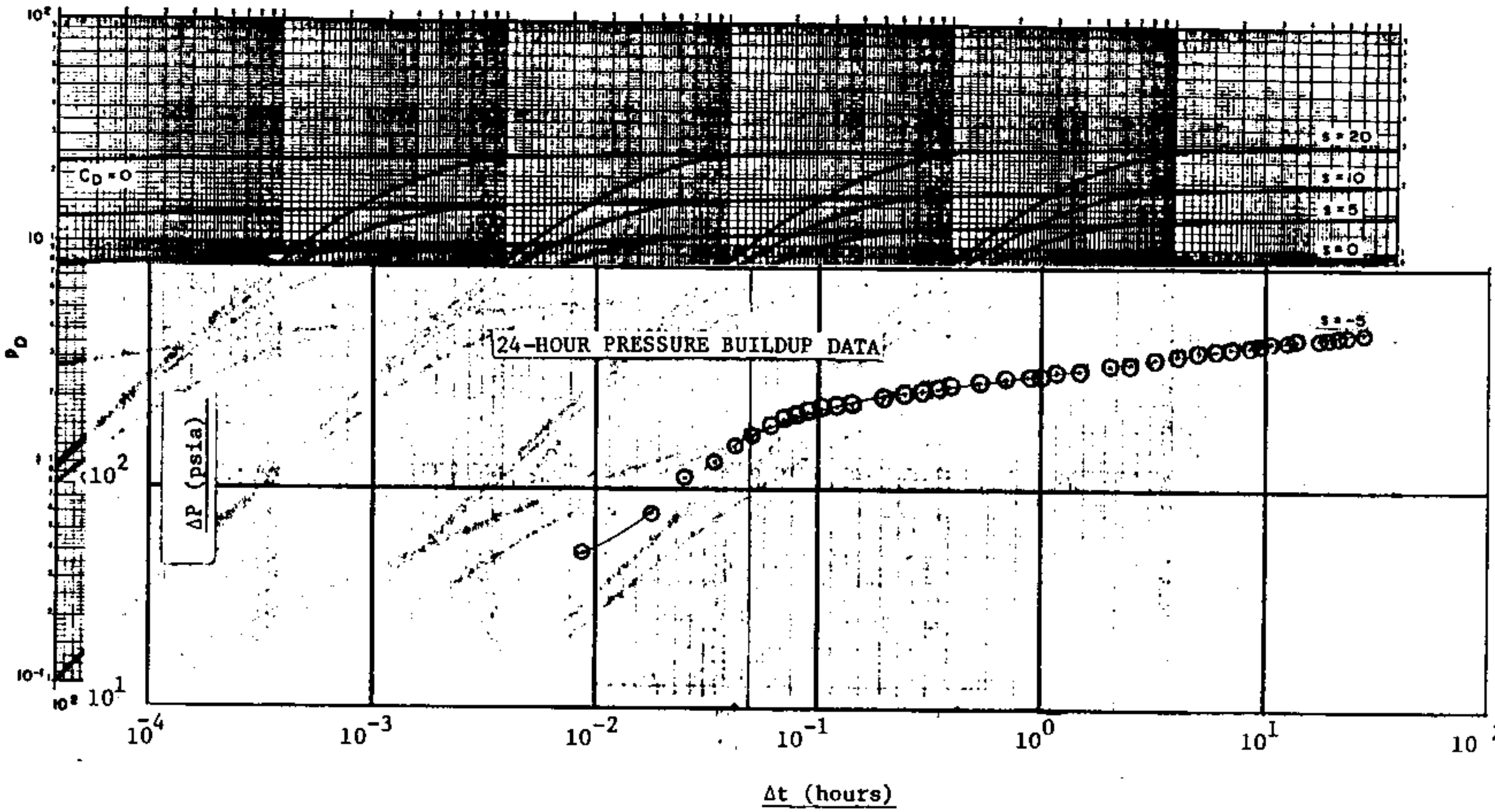


Figure B-11. Auburn Geothermal Well Log-Log Type Curve Match Between 24-Hour Pressure Buildup Data and Dimensionless Pressure Transients for a Single Well in an Infinite System, Wellbore Storage and Skin Included (Agarwal, Al-Hussainy, and Ramey, 1970)

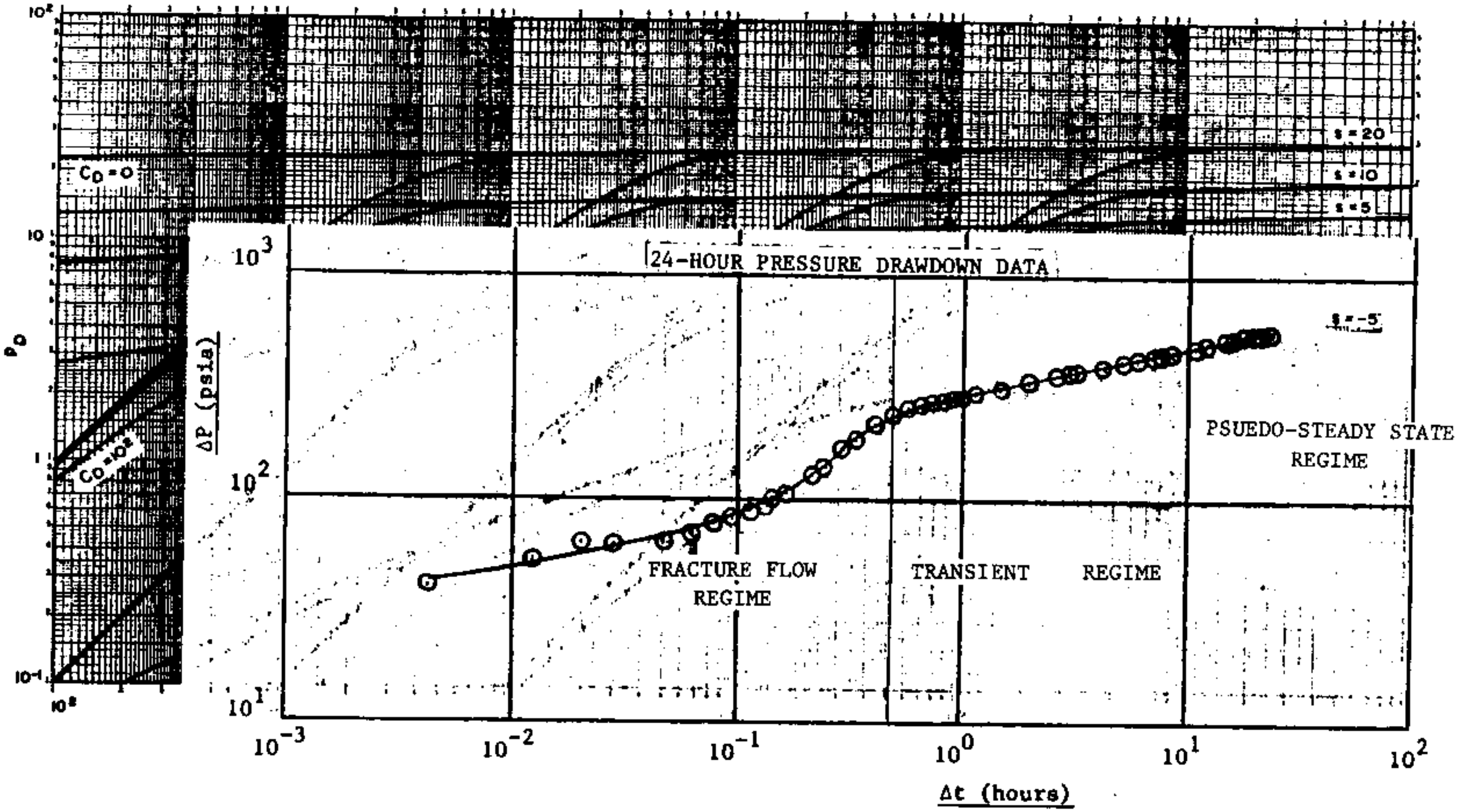


Figure B-12. Auburn Geothermal Well Log-Log Type Curve Match Between 24-Hour Pressure Drawdown Data and Dimensionless Pressure Transients for a Single Well in an Infinite System, Wellbore Storage and Skin Included (Agarwal, Al-Hussainy, and Ramey, 1970)

The hydraulic fracture flow regime is identified in Figure B-13 which is a semi-log (Horner) plot of downhole pressure, ΔP versus $(t+\Delta t)/\Delta t$ during the 24-hour pressure buildup test. Subsequent to this flow regime, the pressure transients trace a sigmoidal-shaped curve in which an early straight line slope decreases by approximately 50%, then doubles at later times to form a second straight line which is approximately parallel to the first straight line. This type of semi-log behavior is representative of the flow characteristics of a naturally fractured medium (Warren and Root, 1963; Kazemi 1969; Kazemi, Seth and Thomas, 1969; and Earlougher, Jr., 1977). The sigmoidal semi-log curve is typical of flow in a "double-porosity" medium comprised, as described earlier, of Regions 1 and 2. These regions are respectively identified as the natural fracture flow regime and the porous matrix flow regime in Figure B-13.

It should be noted that the behavior of a fractured reservoir is almost identical with the behavior of a multilayer reservoir with crossflow (Kazemi, 1969). Warren and Root (1963) warns that "since the buildup curve associated with this type (double porosity) of porous medium is similar to that obtained from a stratified reservoir, an ambiguous interpretation is not possible without additional information." The reader is reminded that the net productive interval was first modeled as two contrasting porosity zones, and then simplified to a single, comingled zone with volumetric-averaged properties. The interpretation of double-porosity effects is qualitatively unambiguous in face of the evidence, presented in "Reservoir Capacity - Formation Thickness and Absolute Porosity", that the reservoir is naturally fractured. The quantitative contribution of reservoir stratification to the sigmoidal curve's vertical separation will remain an unknown because of the commingling of the produced fluids. The natural fracture flow regime is assumed to include the effects of stratification and fracture flow with the latter dominating or controlling because both zones are intersected with a high density of natural fractures.

The Auburn low-temperature geothermal reservoir appears to be finite and bounded because of the slight divergence of the psuedosteady state portion of the semi-log, porous matrix flow regime straight line shown in Figure B-14. This graph is a type-curve match between the 24-hour pressure buildup data and the dimensionless pressure transients for single wells in various rectangular shapes with one or more constant pressure boundaries and no wellbore storage or skin effects (Ramey et al, 1973). The curve match suggests that the reservoir is rectangular (of length = 2 x width) with three no-flow boundaries and one constant-pressure boundary on the shorter side. This interpretation is very sketchy because the

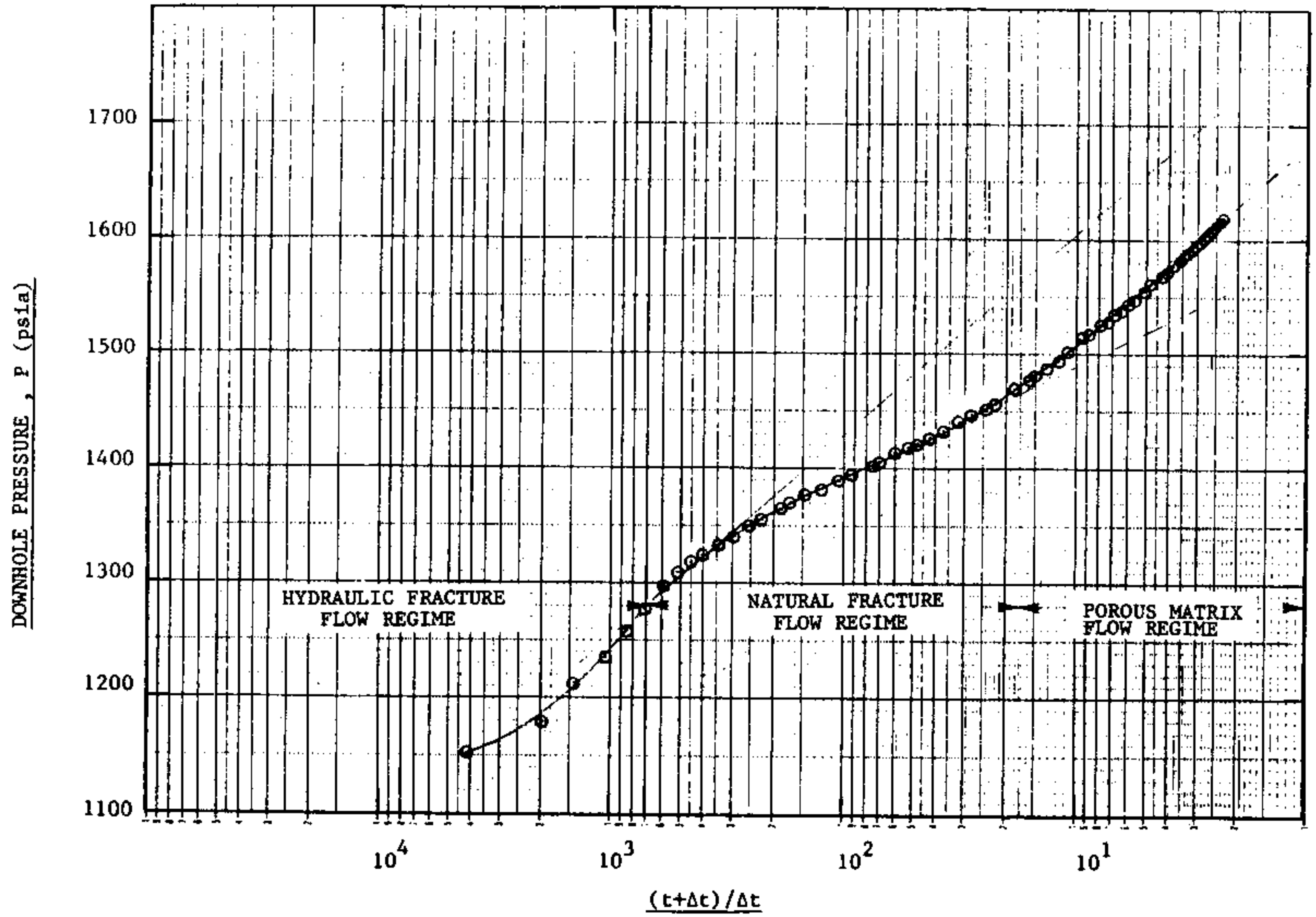


Figure B-13. Auburn Geothermal Well Horner Plot of 24-Hour Pressure Buildup Data

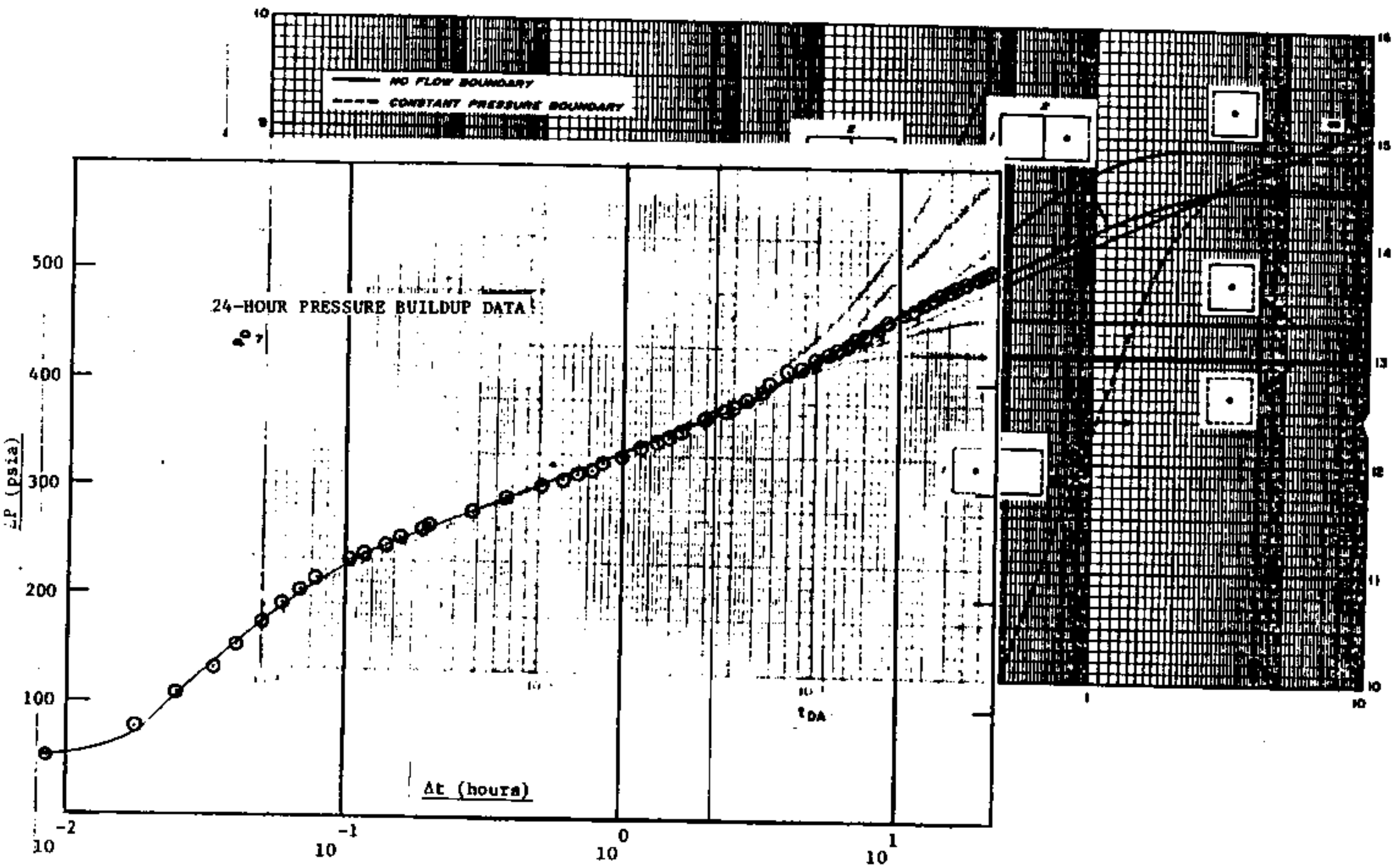


Figure B-14. Auburn Geothermal Well Semi-log Type Curve Match Between 24-Hour Pressure Buildup Data and Dimensionless Pressure Transients for Single Wells in Various Rectangular Shapes with one or More Constant Pressure Boundaries, No Wellbore Storage, No Skin (Ramey et al, 1973) buildup data is not extensive enough and because the slight divergence in the $\Delta P/\Delta t$ slope could have been caused by the double-porosity effect. Further evidence which suggests that the reservoir is finite and bounded is discussed under "Volumetric and Areal Resources."

EFFECTIVE TRANSMISSIVITY AND PERMEABILITY

The effective transmissivity is defined as the product of effective permeability, k, and net thickness, h; the product kh is usually expressed in millidarcy-feet. The effective transmissivity was computed from drawdown and buildup data to be approximately 3,100 millidarcy-feet yielding, for a net productive interval of 310 ft., an effective permeability of 10 millidarcy.

The effective transmissivity was computed from the slope of the semi-log straight line of a Horner-type plot (ΔP versus log $(t+\Delta t)/\Delta t$) for pressure buildup data and a Miller-Dyes-Hutchinson plot (ΔP versus log Δt) for pressure drawdown data.

$$kh = \frac{162.6\ qB\mu}{m} \qquad \text{(B-23)}$$

where

m = slope in psi/cycle

q = effective flow rate, STB/D

B = water formation volume factor, bbl/STB

μ = absolute viscosity of brine, centipoise .

The semi-log straight line, which represents the hydraulic transmissivity of the porous matrix, can be misinterpreted because of near-wellbore and fracture-flow effects. The start of the correct semi-log straight line is best defined 1-1½ cycles after the end of the early transients caused by wellbore storage and hydraulic fracture flow effects. The latter can be most readily identified from log-log plots of ΔP versus Δt. The natural fracture flow effects are identifiable by the existence of two parallel semi-log straight lines connected by a transition (or fracture flow) regime with a slope which is one-half of the other two straight lines. Either of the two parallel straight lines can be used to define m; the late time parallel straight line is, however, more representative of flow in the porous matrix.

The Horner-type plot of preliminary pressure buildup data in Figure B-15 exemplifies the difficulties which can be associated with defining the correct semi-log straight line. The log-log plot in Figure B-19 under "Effective Porosity and Compressibility" indicates that the hydraulic fracture flow regime ends around 10^{-1} hours or 6 minutes, and the correct semi-log straight line begins between Δt of 1-5 hours. The latter corresponds to a $(t+\Delta t)/\Delta t$ between 8.3 - 2.45. The correct slope is thus identified as m_1 = 95 psi/cycle yielding a kh = 7,090 md-ft with k = 22.9 md for h = 310 ft. Note that m_2 = 47 psi/cycle. The two parallel straight lines are not very well defined in Figure B-15 because of the relatively short production time (∿7.27 hours) prior to the buildup period. The preliminary pressure buildup data may not be representative of aggregate reservoir properties because of the limited withdrawal (∿1,000 STB) and the small radius of drainage or influence (∿16 ft.) seen during the preliminary pressure drawdown test.

The parallel, semi-log straight lines, which represent double-porosity flow effects, are well defined in the Horner plot of the 24-hour pressure buildup data shown in Figure B-13. In this plot, production time and rate prior to the buildup period were averaged from the beginning of the preliminary drawdown using a modified-Horner plot method suggested by Odeh and Selig, 1967.

$$t_p^* = 2 \left\{ t_p - \frac{\sum_{j=1}^{N} q_j \left(t_j^2 - t_{j-1}^2\right)}{2 \sum_{j=1}^{N} q_j \left(t_j - t_{j-1}\right)} \right\} \qquad \text{(B-24)}$$

$$q^* = \frac{1}{t_p^*} \sum_{j=1}^{N} q_j \left(t_j - t_{j-1}\right) \qquad \text{(B-25)}$$

The conventional Horner analysis is used with t_p^* and q^* in place of t_p and q. In Figure B-13, the late slope, m_1 equals 180 psi/cycle and the early slope, m_2 equals 90 psi/cycle. From the late slope, kh = 3,866 md-ft and k = 12.47 md.

A semi-log plot of the 24-hour drawdown data demonstrates the same type of double-porosity flow behavior. This plot is shown in Figure B-24. The transition and late slopes of this Miller-Dyes-Hutchinson (MDH) type semi-log plot are -165 psi/cycle and -300 psi/cycle, respectively. From the latter kh = 2,774 md-ft and k = 8.95 md for h = 310 ft.

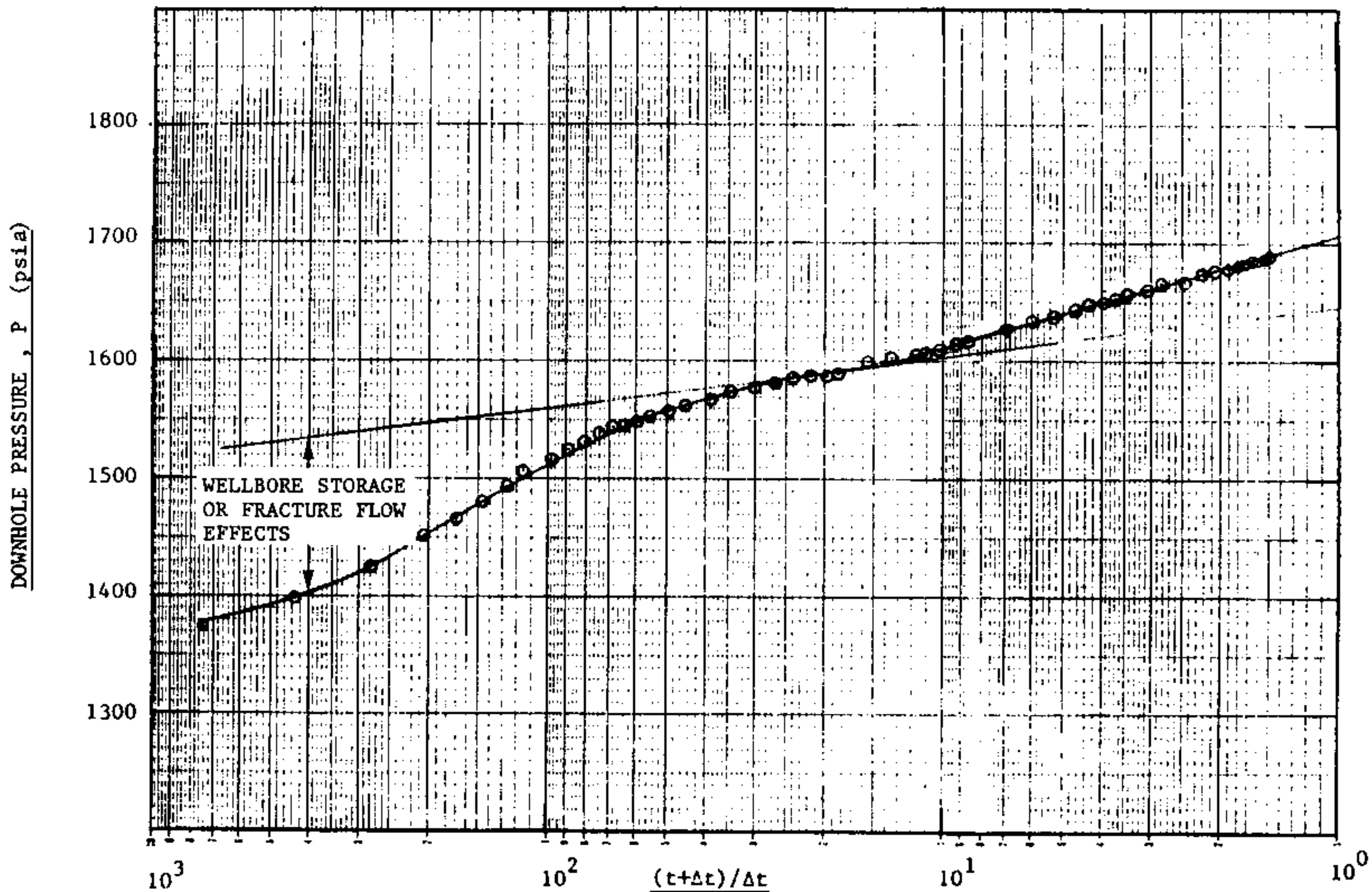


Figure B-15. Auburn Geothermal Well Horner Plot of Preliminary Pressure Buildup Data

The first two stages of the multi-rate drawdown data are shown in Figure B-16. The early slope of the 152.5 gpm stage is 325 psi/cycle, and yields a kh of 3065 md-ft making k = 9.89 md for h = 310 ft.

The third stage of the multi-rate drawdown test is graphically analyzed in Figure B-17 by a two-rate flow test analysis method. From the slope of 360 psi/cycle, kh = 2415 md-ft and k = 7.85 md for h = 310 ft.

Finally, the multi-rate pressure buildup data is plotted in Figure B-18. The upper curve utilizes the method of Odeh and Selig, 1967 and the lower curve utilizes the more rigorous approach in which the following equation is valid:

$$P_{ws} = P_i - m \sum_{j=1}^{N} \frac{q_j}{q_N} \log \left[\frac{t_N - t_{j-1} + \Delta t}{t_N - t_j + \Delta t} \right]. \qquad \text{(B-26)}$$

The lower curve is a plot of P (or P_{ws})

$$\text{versus } \log \sum_{j=1}^{N} \frac{q_j}{q_N} \log \left[\frac{t_N - t_{j-1} + \Delta t}{t_N - t_j + \Delta t} \right]. \qquad \text{(B-27)}$$

The slope of the two curves, which are parallel, is 230 psi/cycle yielding kh = 2,899 md-ft and k = 9.35 md for h = 310 ft.

In summary, the effective transmissivities and permeabilities were computed to be as follows:

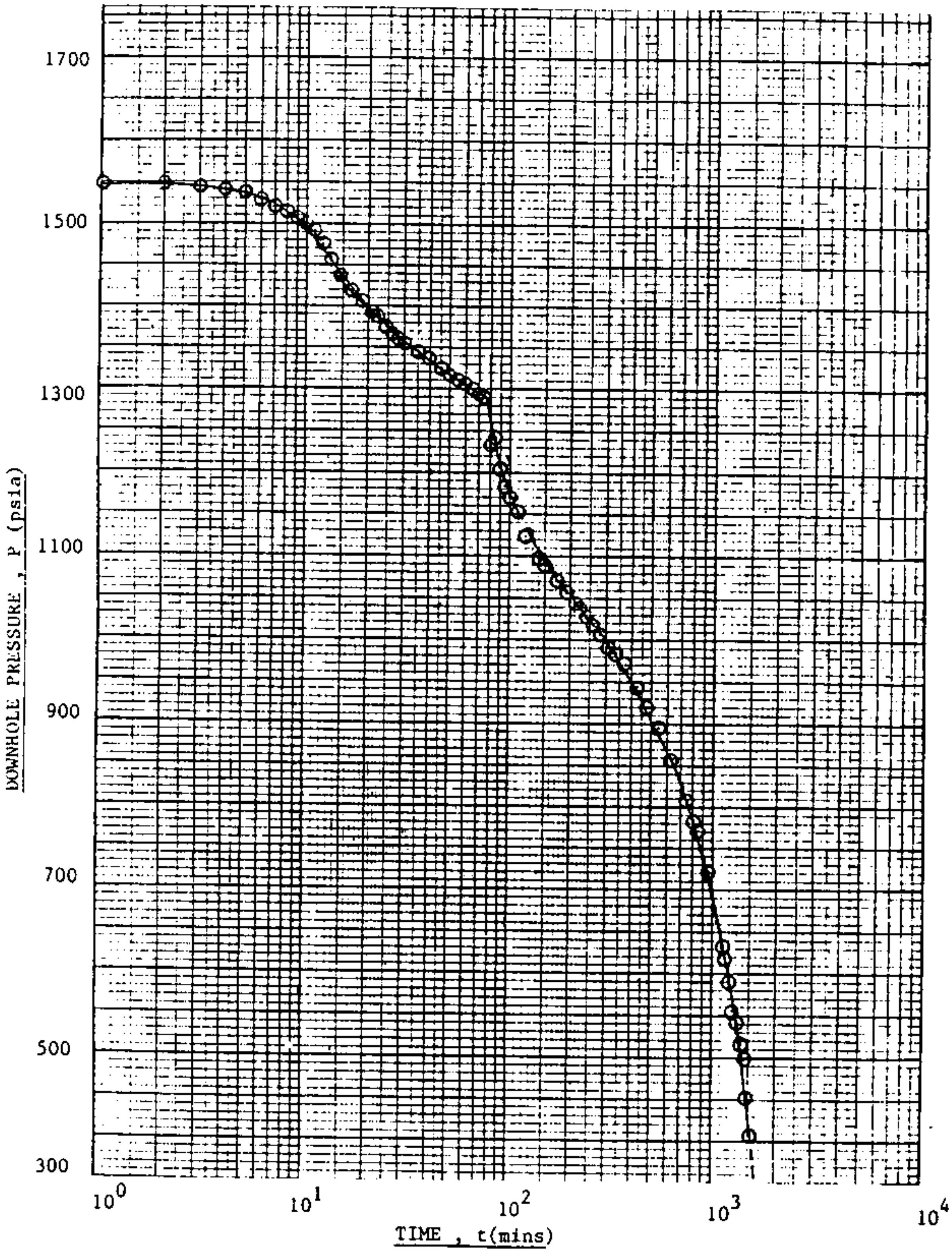


Figure B-16. Auburn Geothermal Well MDH Semilog Plot of Multirate Drawdown Data

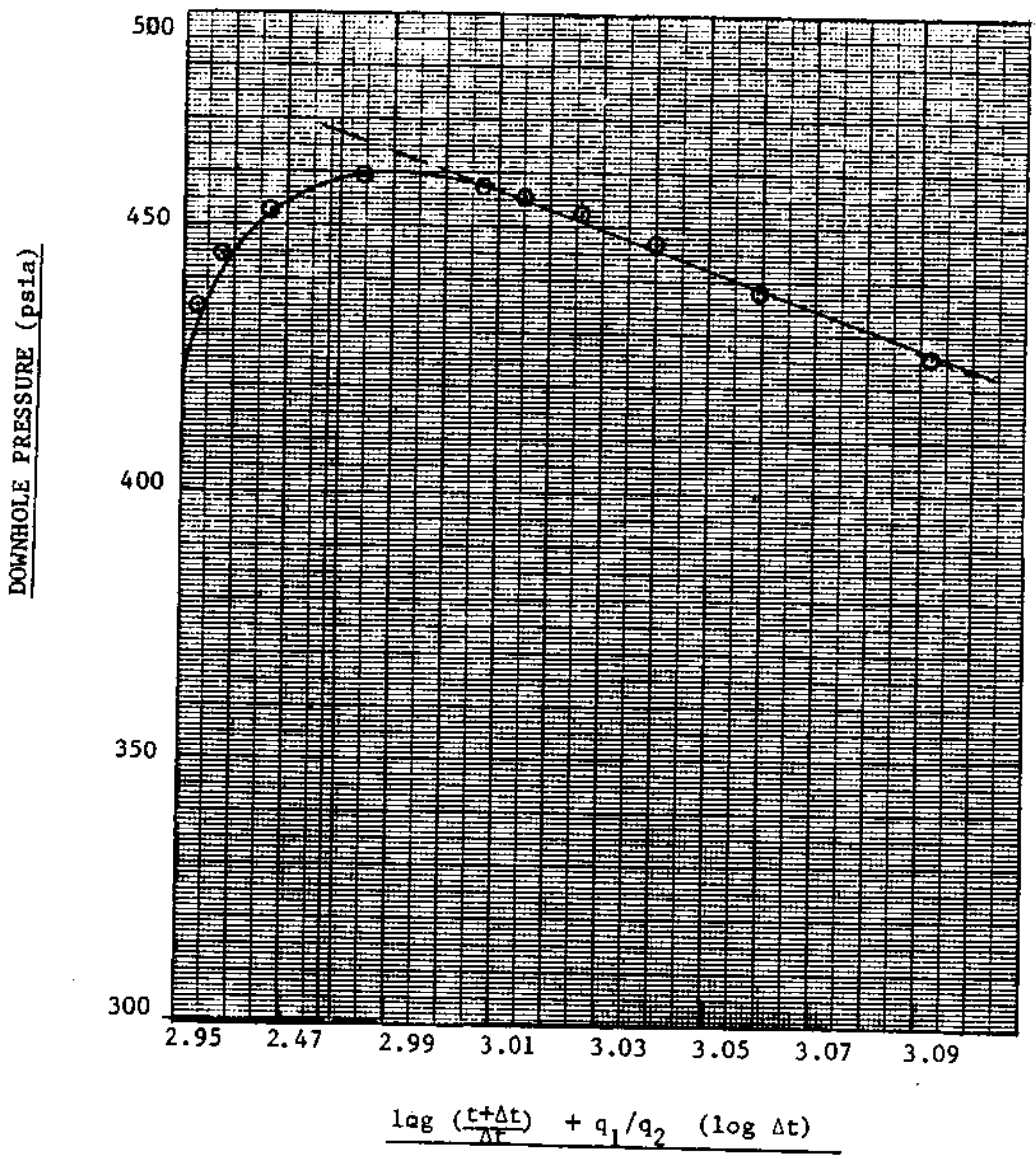


Figure B-17. Auburn Geothermal Well Two-Step Rate Analysis of 2nd and 3rd Stages of Multirate Drawdown Data

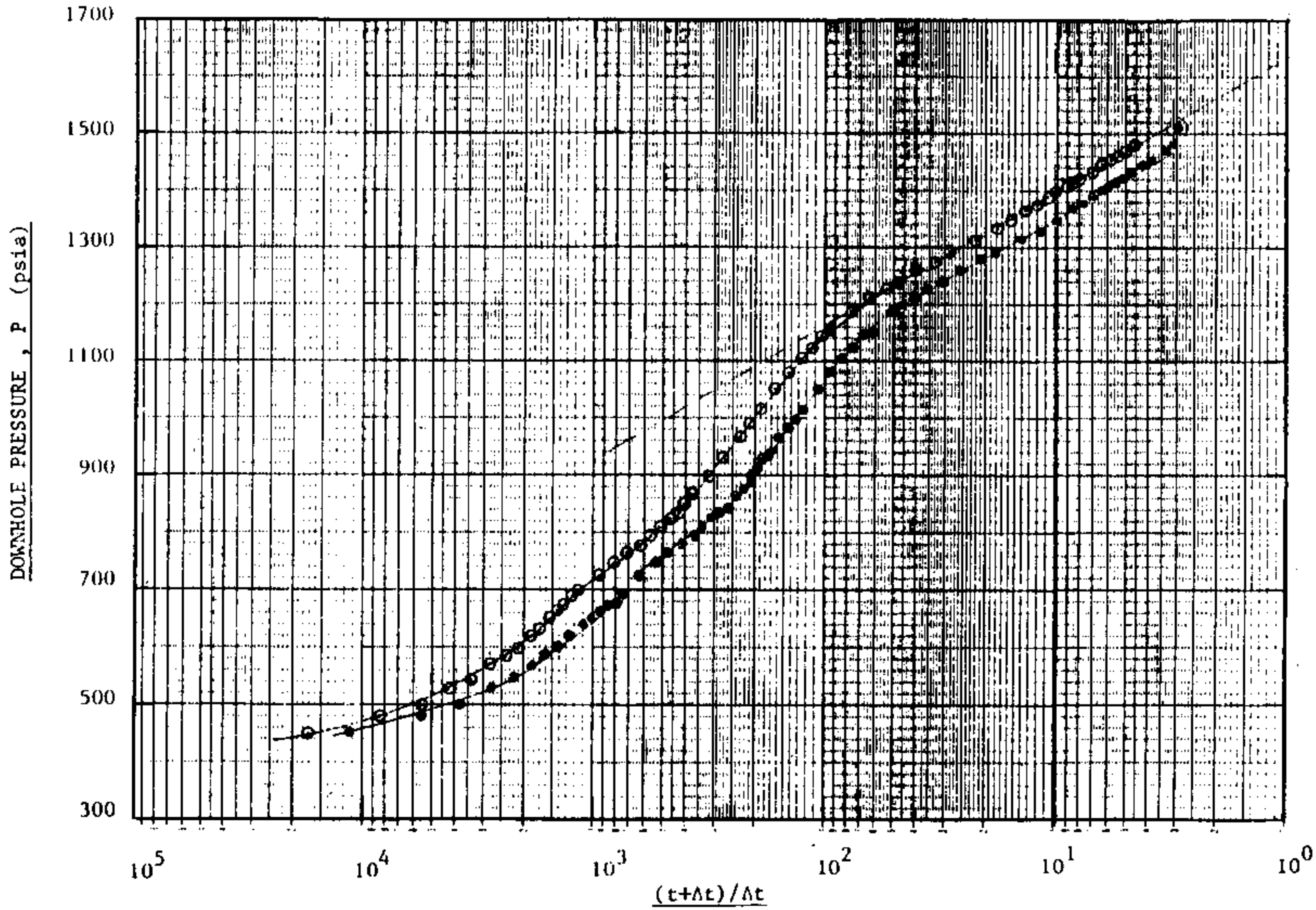


Figure B-18. Auburn Geothermal Well Horner Plot of Multirate Pressure Buildup Data

Table B-13

EFFECTIVE TRANSMISSIVITIES AND PERMEABILITIES

Test	kh (millidarcy-feet)	k (millidarcy)
Preliminary Buildup	7,090	22.9
24-Hour Buildup	3,866	12.47
24-Hour Drawdown	2,774	8.95
Multirate Drawdown Second Stage @152.5 gpm	3,065	9.89
Multirate Drawdown Third Stage @131.7 gpm	2,415	7.85
Multirate Buildup	2,899	9.35
Average	3,151	10.16

The average values of kh and k were made after exclusion of the low and high values due to the two-step rate analysis of the multi-rate drawdown (third stage) test, and the preliminary pressure buildup test, respectively.

EFFECTIVE POROSITY AND COMPRESSIBILITY

The product of effective porosity and effective compressibility, ϕc_t, is usually expressed in fractional psi^{-1}. The effective porosity-compressibility product was computed from drawdown and buildup data to be approximately 2.0×10^{-8} psi^{-1}. For an estimated effective compressibility of 7.5×10^{-6} psi^{-1}, the average producing interval's effective porosity is 0.27%.

The effective compressibility was computed from log-log type curve matches between the actual ΔP - Δt relationships and theoretical curves of dimensionless P_D - t_D relationships for both the pressure drawdown and buildup data. From the match points of $\Delta P/P_D$ and $\Delta t/t_D$, the effective transmissivity (kh) and the product of effective porosity and compressibility (ϕc_t) are computed from the following:

$$kh = \left[141.2\ qB\mu\right] \frac{P_D}{\Delta P} \qquad \text{(B-28)}$$

and

$$\phi c_t = \left[\frac{0.0002637\ k}{\mu r_w^2}\right]\frac{\Delta t}{t_D} \quad . \qquad \text{(B-29)}$$

From a log-log type curve match of the preliminary pressure buildup data in Figure B-19, kh = 14,066 md-ft and k = 45.3 md for h = 310 ft. Note that the calculated permeability is approximately twice that computed by the semi-log method described under Effective Transmissivity and Permeability. This doubling suggests that a best fit was obtained around the transition or natural fracture flow regime. In general, log-log type curve matching will provide order of magnitude parameters because of the subjectivity of the technique. Consequently, log-log type curve matching is more useful in defining the reservoir characteristics and in the dilineation of flow regimes. The preliminary pressure buildup data, which, as discussed in the previous section, does not represent the aggregate characteristics of the reservoir, yields a ϕc_t of 6.67×10^{-8} psi^{-1} for a correspondent k = 45.3 md.

The log-log type curve match of the multirate pressure buildup data in Figure B-20, indicates the following:

$$\underline{\text{MATCH POINTS}} \begin{cases} \circ \quad s = -5;\ C_D = 10^4 \\ \circ \quad \Delta t/t_D = 10^0 \ /\ 5.5 \times 10^5 \\ \circ \quad \Delta P/P_D = 10^2 \ /\ 2.5 \times 10^{-1} \quad . \end{cases} \qquad \text{(B-30)}$$

The match points yield: kh = 2164 md-ft; k = 6.98 md; and $\phi c_t = 2.052 \times 10^{-8}$ psi^{-1}.

The computed values of ϕc_t can be summarized as follows:

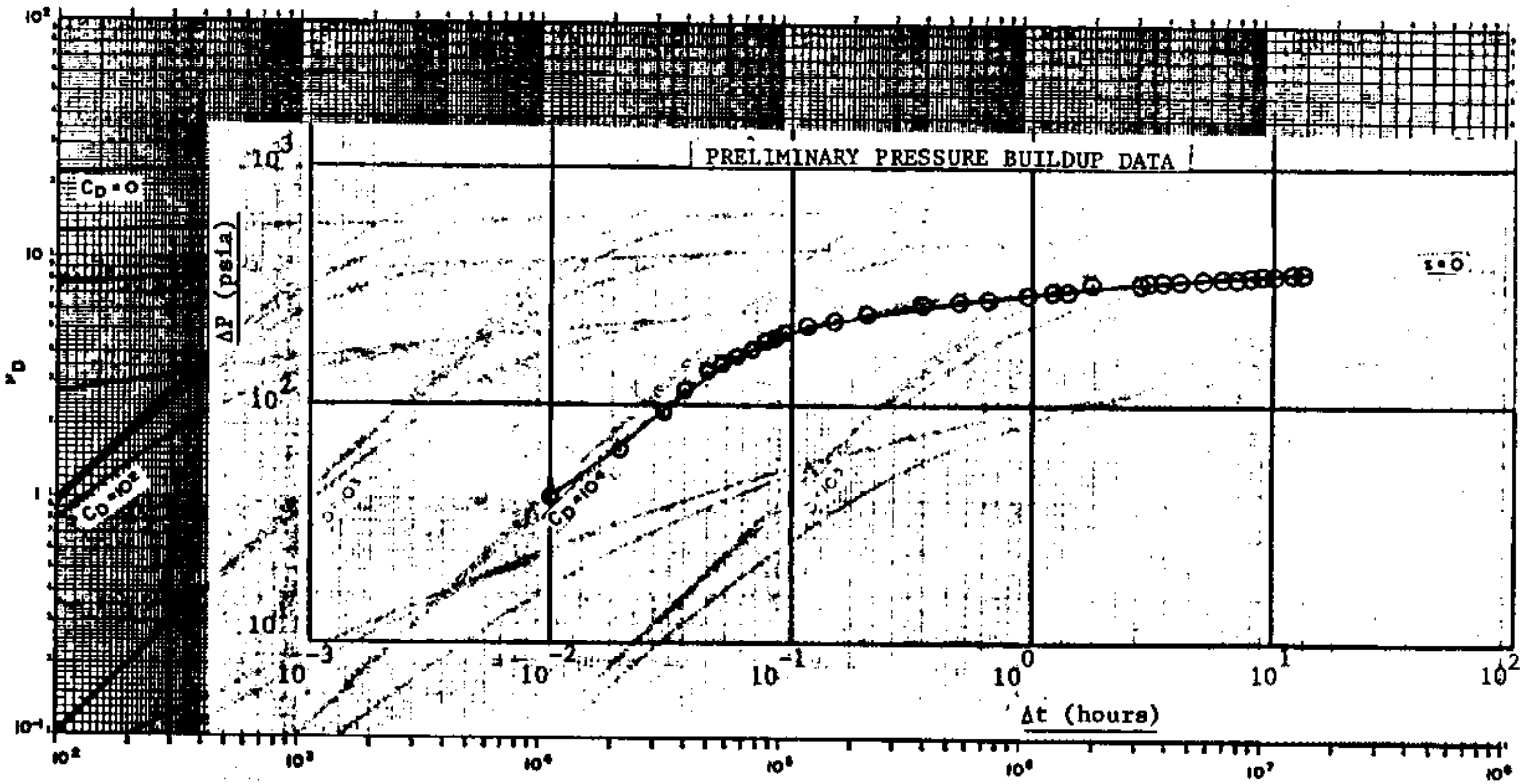


Figure B-19. Auburn Geothermal Well Log-Log Type Curve Match Between Preliminary Pressure Buildup Data and Dimensionless Pressure Transients for a Single Well in an Infinite System, Wellbore Storage and Skin Included (Agarwal, Al-Hussainy, and Ramey, 1970)

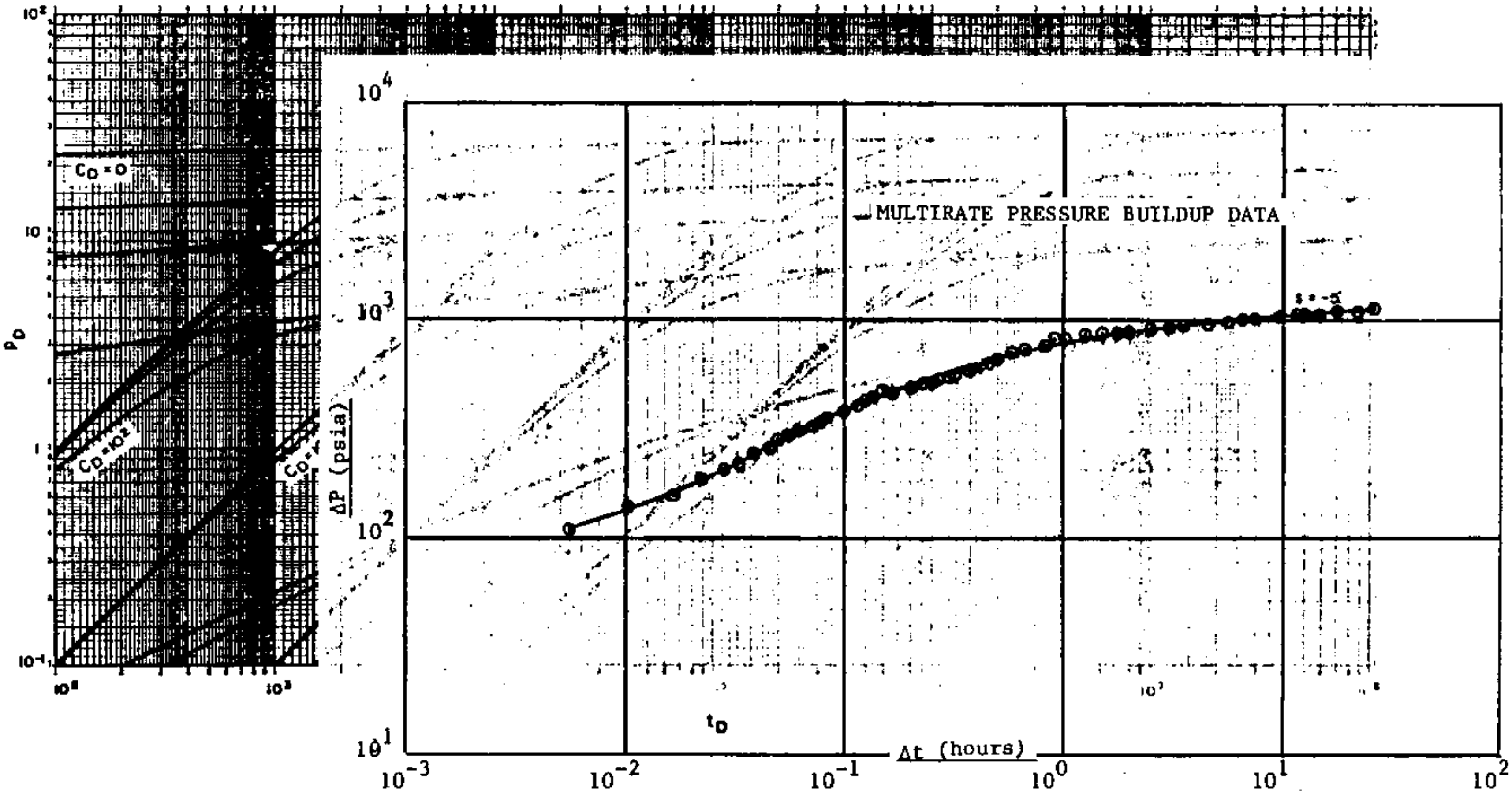


Figure B-20. Auburn Geothermal Well Log-Log Type Curve Match Between Multirate Pressure Buildup Data and Dimensionless Pressure Transients for a Single Well in an Infinite System, Wellbore Storage and Skin Included (Agarwal, Al-Hussainy, and Ramey, 1970)

Table B-14

PRODUCTS OF EFFECTIVE POROSITY AND COMPRESSIBILITY

Test Type	Figure No.	k (md)	ϕc_t (psi^{-1})
Preliminary Buildup	B-19	45.30	6.67×10^{-8}
24-Hour Buildup	B-22	18.65	1.18×10^{-8}
24-Hour Drawdown	B-12	16.55	2.43×10^{-8}
Multirate Buildup	B-20	6.98	2.05×10^{-8}
Pump Test Average		14.06	1.89×10^{-8}

Note that the 24-hour buildup permeability of 18.65 md calculated by the log-log curve match is approximately the same as the arithmetic mean, (12.47 + 24.94)/2 = 18.71 md, of the values computed from the slopes of the semi-log plots. The log-log match thus represents an average fit of a broad range of the 24-hour buildup data spanning the transient and psuedosteady state regimes. The 24-hour drawdown log-log computed permeability of 16.55 md corresponds more to the natural fracture-flow transition regime value of 16.26 md computed from the second slope in Figure B-24 than to the first slope value of 8.95 md. The 24-hour drawdown log-log fit, thus, corresponds more to the transition-regime data points. The multirate buildup log-log computed permeability of 6.98 md corresponds more to the late permeability, 9.35 md, measurements of the semi-log Horner plot in Figure B-18. The multirate log-log computed value of the product ϕc_t of 2.05×10^{-8} psi^{-1} is thus assumed to represent the porous matrix flow conditions.

The ϕc_t product is assumed to be 2.0×10^{-8} psi^{-1}; the average value listed for the pump test does not include the preliminary pressure buildup value. With an effective compressibility of 7.5×10^{-6} psi^{-1}, as estimated in Formation (Fluid and Rock) Compressibility, the effective porosity of the producing interval computes to be 0.27%. This value is approximately one tenth the value of absolute porosity, 2.82%, estimated in Reservoir Capacity - Formation Thickness and Absolute Porosity.

Strobel, Gulati and Ramey (1976) calculated effective permeabilities and porosities of 48.3 md and 0.22% within a drainage area of 54 square miles for interference test data in a dry gas reservoir producing from a naturally fractured orthoquartzite zone; cores from the other orthoquartzites were reported to have an absolute porosity of 2.5% and less than 0.1 md permeability to air. Similar differences between the effective and absolute values of porosity and permeability were observed in the Auburn reservoir. It should be noted that measurements of Strobel et al. (1976) were also consistent with published values of fracture porosity and permeability in naturally fractured reservoirs (Stearns and Friedman, 1972; and Elkins, 1953).

AVERAGE RESERVOIR PRESSURE

The average reservoir pressure, $\bar{P}$, was estimated to be 2,260 psi.

This estimate of reservoir pressure is based on a measured value of 1757.9 psi at 3,973 ft. just prior to pump testing and a computed gradient of 0.448 psi/ft. The semi-log Horner plot usually indicates an average pressure, P*, for infinite shut-in time by extrapolating the straight line portion of the buildup curve to log $(t+\Delta t)/\Delta t = 1$ since $(t+\Delta t)/\Delta t \rightarrow 0$ as $\Delta t \rightarrow \infty$. The calculated values of P* are as follows:

Table B-15

AVERAGE RESERVOIR PRESSURE

Test Type	Figure No.	P* (psia)
Initial Value		1757.9
Preliminary Buildup	B-15	1706.0
24-Hour Buildup	B-13	1684.0
Multirate Buildup	B-18	1580.0

HYDRAULIC FRACTURE, NATURAL FRACTURE, AND MATRIX STORAGE REGIONS

The Auburn low-temperature geothermal reservoir has been characterized in "Reservoir Capacity - Formation Thickness and Absolute Porosity" and "Reservoir Characterization" by as many as six different storage and flow components consisting of two contrasting porosity zones and three distinct regions.

The two contrasting porosity zones consist of a thick, low-porosity zone, Zone 1, and a thinner, medium-porosity zone, Zone 2, both of which are naturally fractured. Zone 1 is considered the high-permeability, low-capacity component whereas Zone 2 is the low-permeability, high-capacity component. Zone 1 will control the initial productivity of the well vis-a-vis its fracture permeability; Zone 2 will control the deliverability of the reservoir and determine its reserves vis-a-vis its capacity (∿90% of total). These zones are grossly simplified into an aggregate of a natural fracture region and a porous matrix region, with volumetric averaged properties over the net producing interval.

The low-porosity matrix of Zone 1 ($\phi \simeq 0.38\%$) and the medium-porosity matrix of Zone 2 ($\phi \simeq 8.32\%$) are mixed to yield a volumetric averaged absolute porosity of 2.82% which is considered a Region 3. The natural fractures and fissures or micro-cracks, Region 2, are assumed to be evenly distributed over the net producing interval. The propagation of the hydraulically induced fracture is assumed to have similar dependencies in both Zone 1 and Zone 2. The hydraulic fracture is identified as Region 1.

The vertical hydraulic fracture was identified in Reservoir Characterization by the 1/2-slope of the log-log plot of ΔP versus Δt. During the early time period, the flow behavior from the formation into the fracture is linear and the pressure of the wellbore (Bixel, Larkin and van Pollen, 1963) is given by:

$$P_{WS} = P_i - m_{vf} \sqrt{t} \qquad \text{(B-31)}$$

where

$$m_{vf} = \frac{-4.064\ q\ B}{h} \sqrt{\frac{\mu}{k\phi c_t x_f^2}} \; .$$

This relationship is valid for early times, little or no wellbore storage effects, and if $x_e/x_f > 1.5$ where x_e and x_f are respectively the half lengths of the reservoir and the fracture.

The linear portion of the plot of ΔP versus $\sqrt{\Delta t}$ in Figure B-21 has a slope of 775 psi/hr$^{1/2}$ for the 24-hour pressure buildup data. Utilizing log-log computed values of k, 18.65 md and ϕc_t, 1.182×10^{-8} from Effective Porosity and Compressibility, the half length of the vertical fracture, x_f, is $\simeq$ 171 feet. A curve

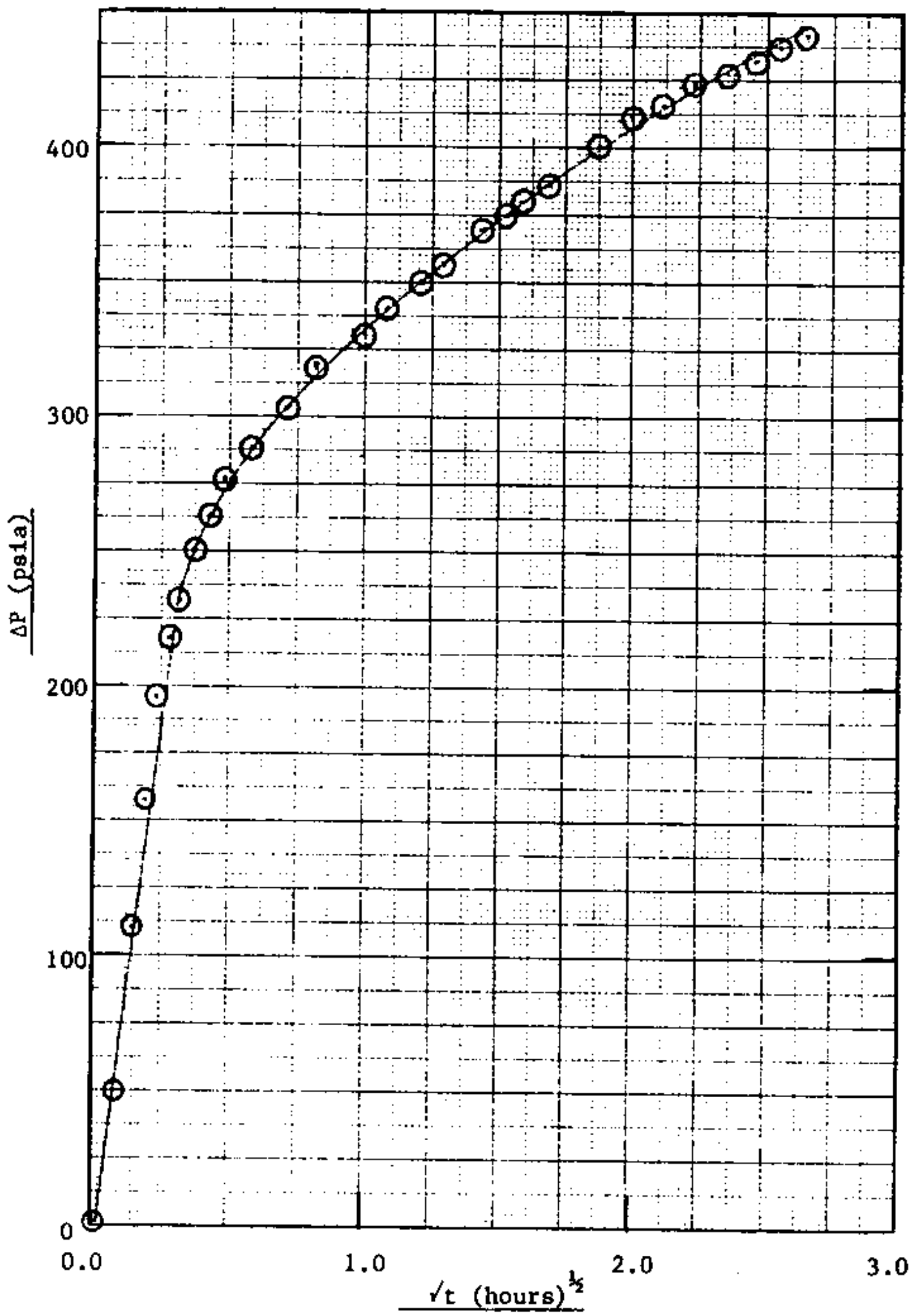


Figure B-21. Auburn Geothermal Well Linear Plot of Pressure Difference Versus the Square Root of Shut-In Time for Early 24-Hour Pressure Buildup match of the 24-hour buildup data in Figure B-22 yields a value of 87.4 ft. for x_f and 18.65 for k. The multirate drawdown data, from a log-log curve match in Figure B-23. yields the following: $x_e/x_f = 1$; $k = 15.91$ md; and $x_f = 132.8$ ft. The vertical hydraulic fracture (1) is a high-porosity (∿30-36%) storage region with an estimated wing span of 150 ft., on the average; the permeability of this region is estimated to range from 1,000-10,000 millidarcys. The vertical hydraulic fracture thus provides a stimulated wellbore radius with an average, estimated negative skin factor of 5.

The natural fracture storage region (2) can be characterized by a storativity factor, ω, which is the ratio of ϕc_t for the natural fracture region to ϕc_t for the total system (primarily the natural fracture and matrix storage regions). ω is usually estimated from the separation of the two parallel straight lines in an MDH plot of pressure drawdown data (Kazemi, 1969). As shown in Figure B-24, $\omega = 0.26$ for a δ_P of ∿175 psi and a slope of ∿300 psi/cycle. Under the assumption that c_t is the same for all regions, the natural fracture region (2) is ∿26% of the total pore volume.

VOLUMETRIC RESOURCES AND AREAL EXTENT

The proved volumetric resources of the Auburn low-temperature geothermal well are estimated to be $3.0 \times 10^6 \pm 0.3 \times 10^6$ STB; the possible resources are $7.0 \times 10^6 \pm 1.0 \times 10^6$ STB; and the probable reserves are $23.0 \times 10^6 \pm 5.0 \times 10^6$ STB. Correspondingly, the areal extent of the resource is estimated to be 463, 1,080, and 967 acres, respectively, for the proved, possible and probable categories.

The volumetric resources were estimated from reservoir limit tests (Jones, 1956) utilizing pressure drawdown data. A cartesian plot of bottom-hole flowing pressure versus time yields a straight line, with slope m*, during psuedosteady state flow. This slope is used to estimate the connected reservoir drainage volume from the following relationship:

$$W = \phi hA = -\left[\frac{0.0417qB}{c_t m^*}\right] \quad \text{(B-32)}$$

where

W = resource in stock tank barrels, STB .

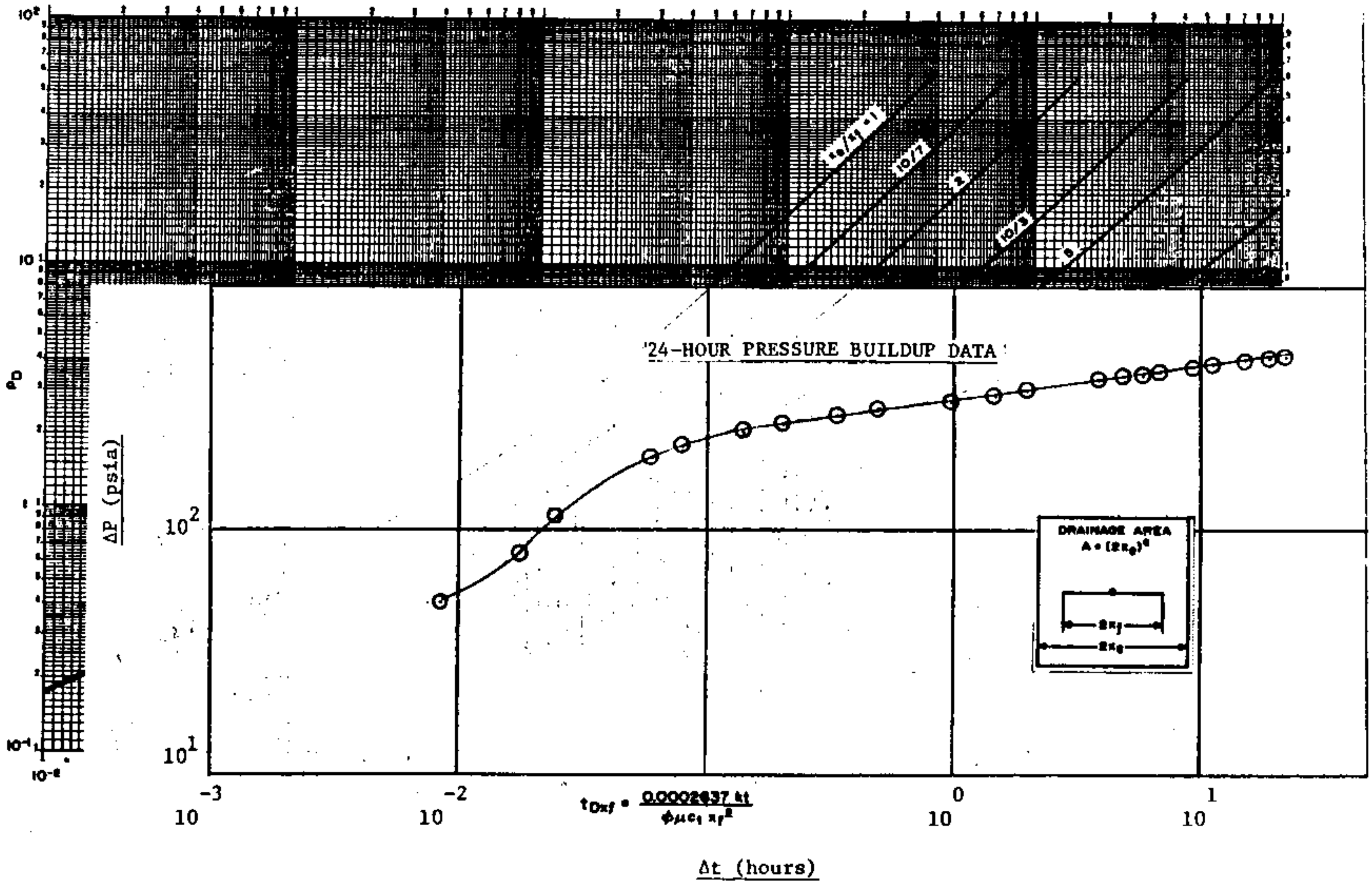


Figure B-22. Auburn Geothermal Well Log-Log Type Curve Match Between 24-Hour Pressure Buildup Data and Dimensionless Pressure Transients of a Vertically Fractured Well in the Center of a Closed Square, No Wellbore Storage, Infinite-Conductivity Fracture (Gringarten, Ramey, and Raghavan, 1974)

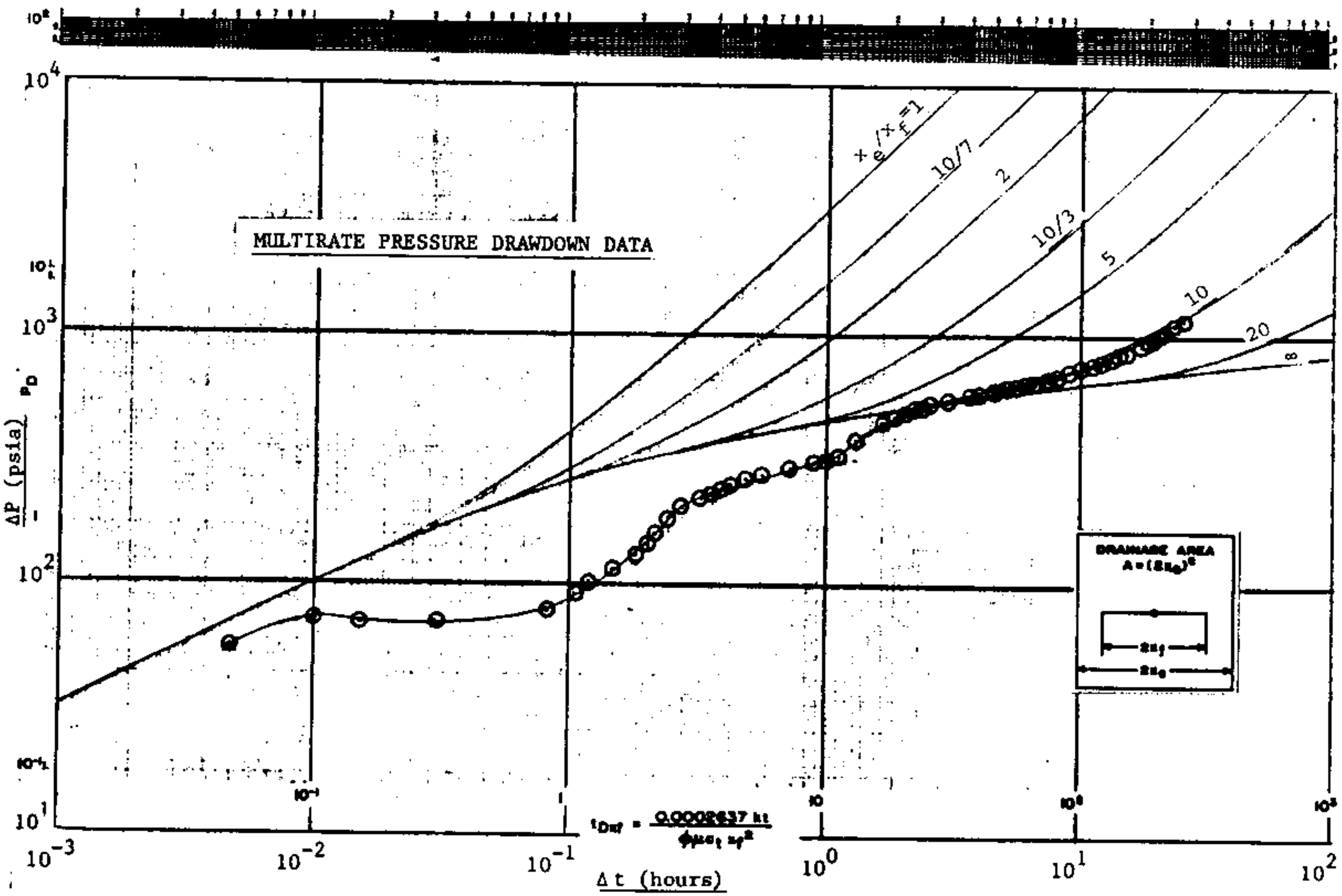


Figure B-23. Auburn Geothermal Well Log-Log Type Curve Match Between Multirate Pressure Drawdown Data and Dimensionless Pressure Transients of a Vertically Fractured Well in the Center of a Closed Square, No Wellbore Storage, Uniform Flux Fracture (Gringarten, Ramey and Raghavan, 1974)

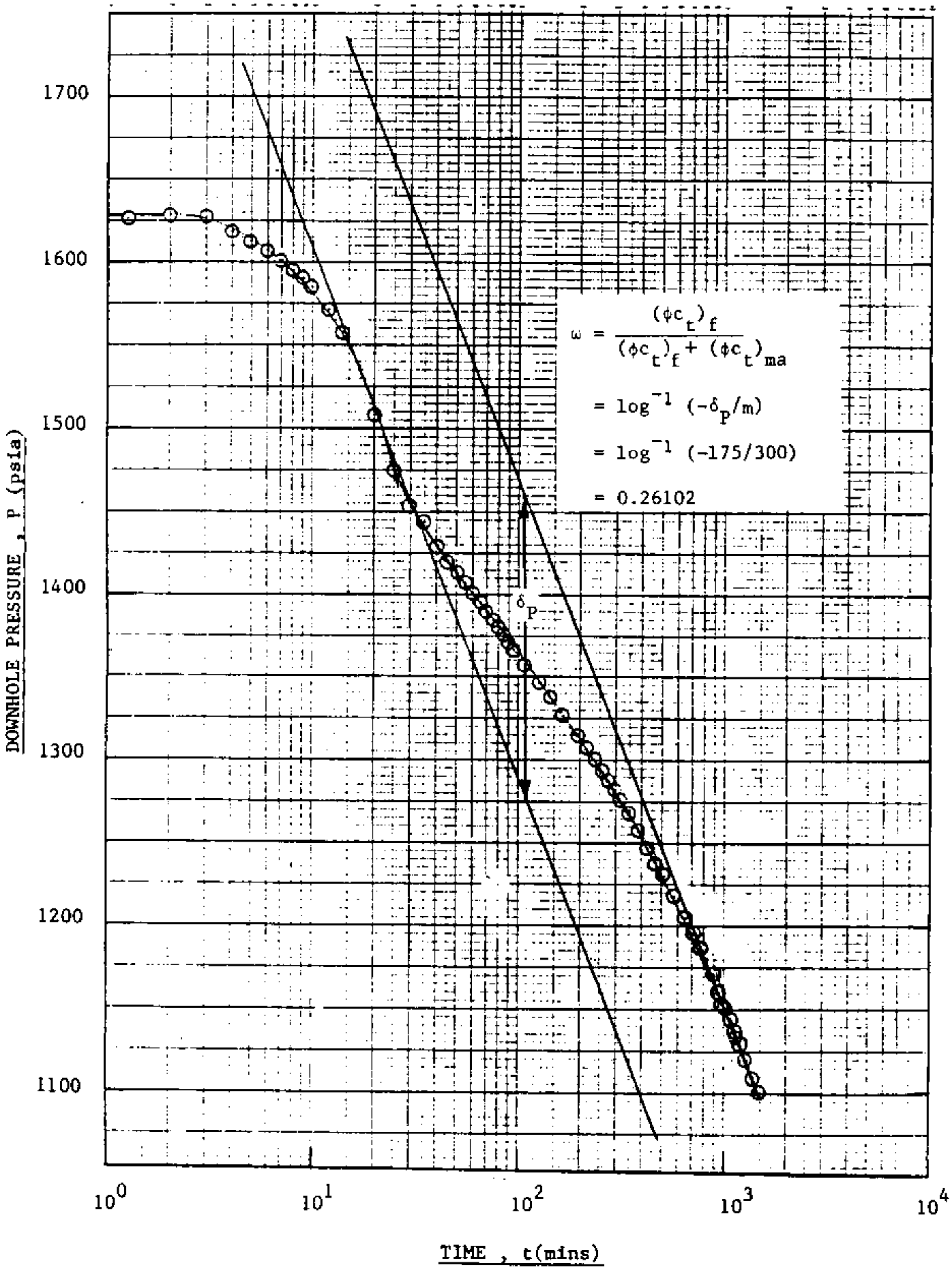


Figure B-24. Auburn Geothermal Well MDH Semi-log Plot of 24-Hour Drawdown Data

The estimated volumetric resource is very sensitive to the total effective compressibility, c_t; the areal extent of the resource is sensitive to the product ϕc_t.

The cartesian plot of the 24-hour drawdown data, Figure B-25, has a psuedosteady state slope of -8.357 psi/hr. The resulting volumetric resources and their areal extents, for different values of ϕ and c_t, are as follows:

Table B-16

VOLUMETRIC RESOURCES AND THEIR AREAL EXTENTS
AS A FUNCTION OF POROSITY AND COMPRESSIBILITY

ϕc_t (psi^{-1})	ϕ	c_t (psi^{-1})	Area (acres)	Volumetric Resource (STB)
2.0×10^{-8}	0.0027	7.5×10^{-6}	452.2	2.93×10^6
2.0×10^{-8}	0.0100	2.0×10^{-6}	456.9	10.97×10^6
0.2×10^{-8}	0.0282	7.5×10^{-6}	43.3	2.93×10^6

The first estimate is based on the computed value of ϕc_t as per Effective Porosity and Compressibility, and the estimated value of c_t as per Formation (Fluid and Rock) Compressibility. In the second estimate, the computed value of ϕc_t is used with c_w under the assumption that the rock's compressibility is negligible. In the third row above, the estimated value of total compressibility is utilized with aggregate value of absolute porosity; this estimate is most unlikely. The first estimate is most likely because the effective values of porosity, compressibility and ϕc_t appear to be consistent.

The multirate drawdown data is plotted on cartesian coordinates in Figure B-26 with the last three stages expanded in Figure B-27. The computed values of volumetric resource, for $\phi c_t = 2.0 \times 10^{-8}$, are as follows:

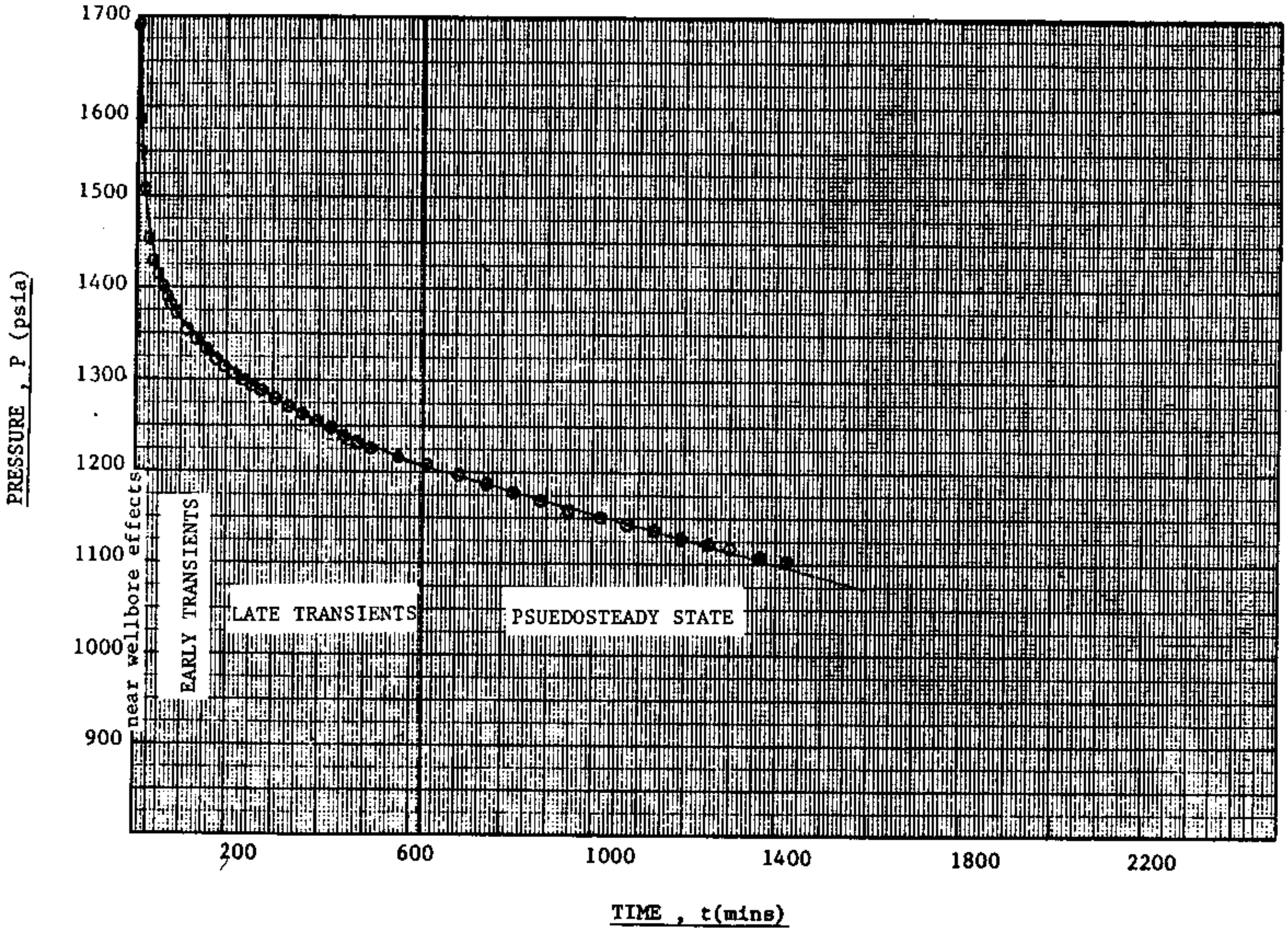


Figure B-25. Auburn Geothermal Well Linear Plot of 24-Hour Drawdown Data

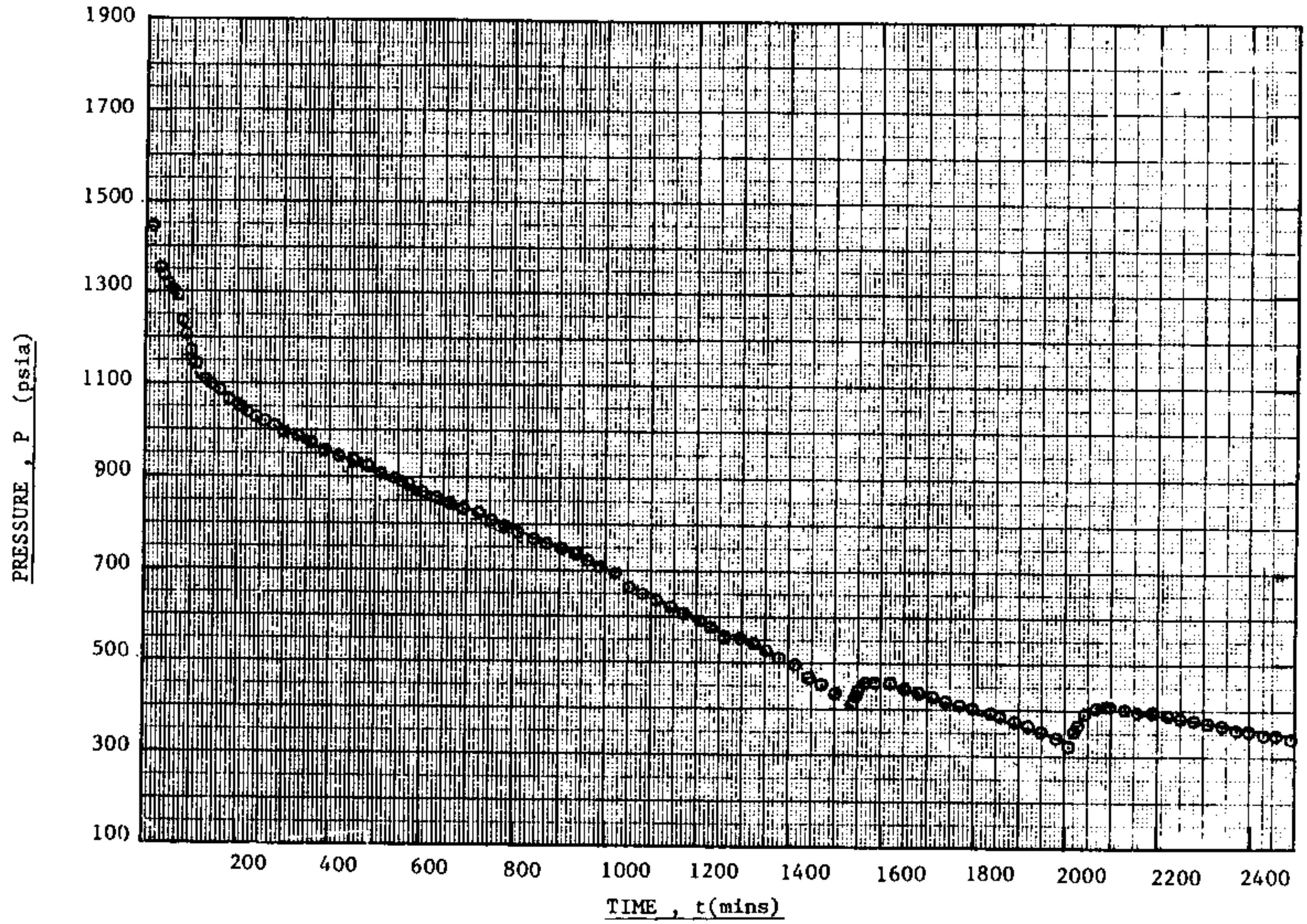


Figure B-26. Auburn Geothermal Well Linear Plot of Multirate Drawdown Data

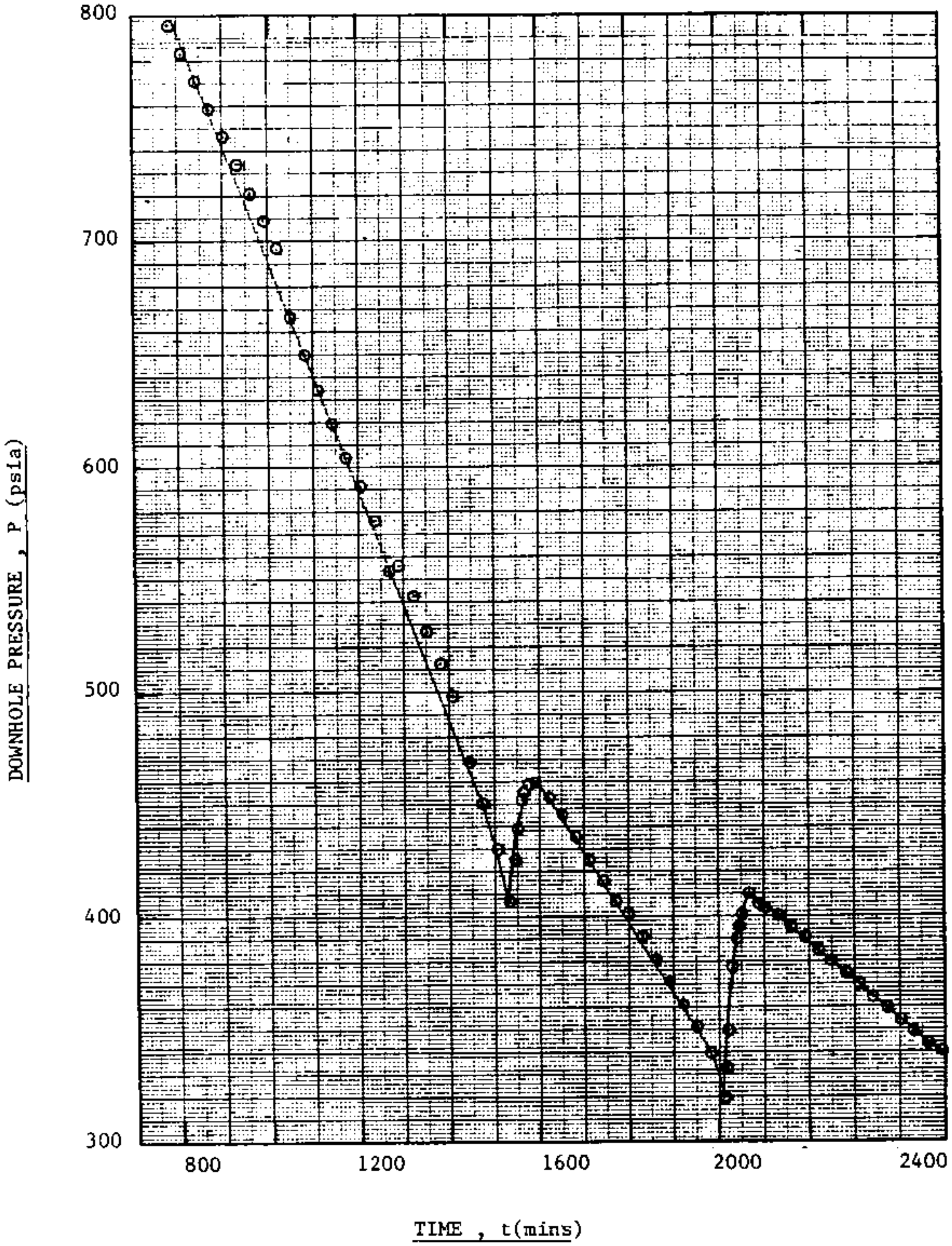


Figure B-27. Auburn Geothermal Well Linear Plot of Multirate Drawdown Data (Expanded Scale Version)

Table B-17

VOLUMETRIC RESOURCES AS A FUNCTION OF DRAWDOWN RATE AND COMPRESSIBILITY

q (gpm)	m* (psi/hr)	Resource (STB)	
		$c_t = 7.5 \times 10^6$	$c_t = 2.0 \times 10^{-6}$
115.1	-9.73	2.3×10^6	8.5×10^6
133.1	-18.46	1.4×10^6	5.2×10^6
152.5	-29.63	1.0×10^6	3.7×10^6

The data suggests that the volumetric resource or the connected reservoir drainage volume is inversely dependent on the pumping rates, i.e., the effective drainage area decreases with increasing flowrate. This inverse relationship suggests that an unbalance is created between the rate of fracture drain and fracture refill by the porous matrix, i.e., the permeability of the porous matrix is rate-limiting. This unbalance results in the flushing of the natural fracture channels and their disconnection from the porous matrix. The unbalance in intra-porosity flow and the degree of disconnection increases with increasing pumping rates. The radius of influence or reservoir volume thus decreases with increasing flowrate. Conversely, in the limit of zero flowrate, the downhole pressure is only influenced by the total connected pore volume of natural fractures and porous matrix voids.

The computed values of resource are plotted as a function of flowrate and c_t in Figure B-28 for $\phi c_t = 2.0 \times 10^{-8}$ psi^{-1}. Extrapolating these curves to q = 0 yields estimated resources of 23.0×10^6 and 7.0×10^6 STB, respectively, for c_t = 2.0×10^{-6} and 7.5×10^{-6} psi^{-1}, respectively. The error bound on the reserve estimates is suggested by the 24-hour drawdown estimates at 127.4 gpm. The areal extent of the resources are estimated to be as follows:

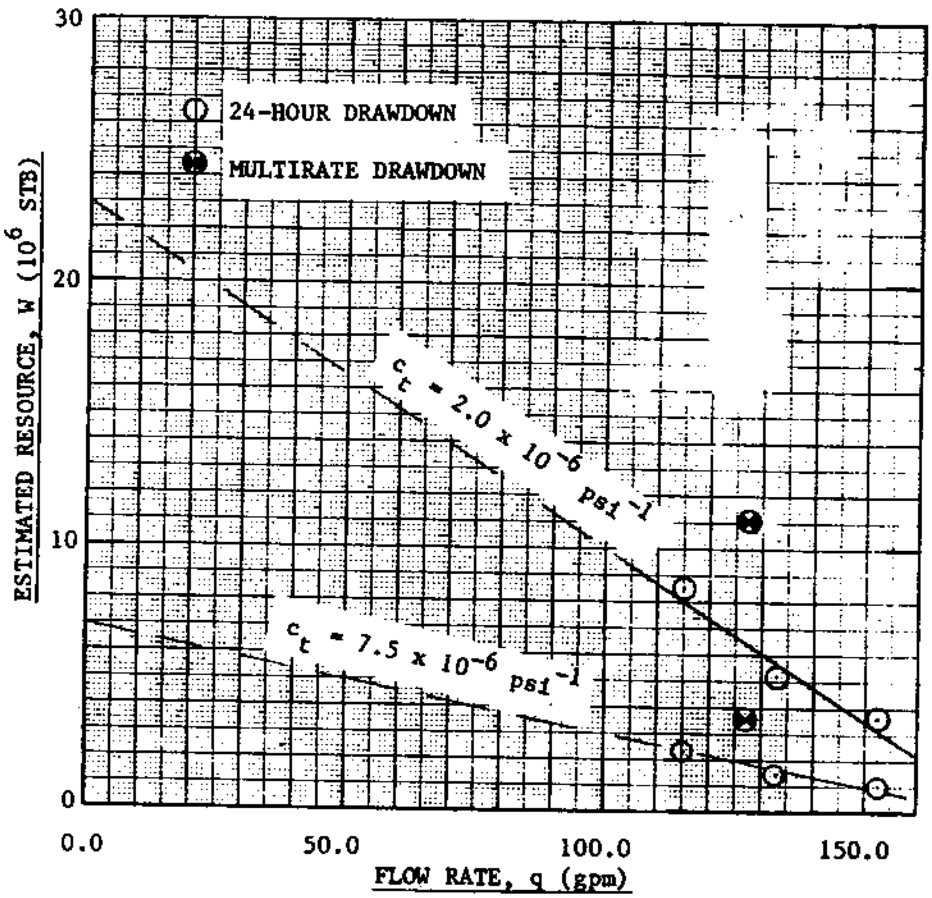
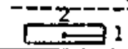


Figure B-28. Auburn Geothermal Well - Estimated Resource (As Determined by Reservoir Limit Tests) as a Function of Flow Rate

Table B-18

PROVED, POSSIBLE AND PROBABLE AREAL EXTENTS OF THE AUBURN GEOTHERMAL RESERVOIR

Category	ϕ	Area (acres)	r_e (feet)	
				
Proved	0.0027	462.74	3,188	2,544
Possible	0.0027	1,079.53	4,870	3,885
Probable	0.0100	967.27	4,586	3,659

VOLUMETRIC RESERVES

The volumetric resources and reserves of the Auburn low-temperature geothermal reservoir are estimated to be as follows:

Table B-19

PROVED, POSSIBLE AND PROBABLE VOLUMETRIC RESOURCES AND RESERVES

Category	Resources (STB)	Reserves (STB)
Proved	3.0×10^6	2.25×10^6
Possible	7.0×10^6	5.25×10^6
Probable	23.0×10^6	17.25×10^6

The volumetric reserves are based on an estimated recovery efficiency of 75% because the reservoir will drain to its irreducible water saturation which is estimated to be ∿0.25. This assumption is considered valid for continuous drainage of the resources at pumping or drawdown rates which are less than or equal to the well's long-term or continuous deliverability. The initial or maximum deliverability of the well was determined to be ∿338 gpm (∿11,600 STB/D) at T.D. and ∿328 gpm (∿11,200 STB/D) at a pumping depth of 4,000 ft. It should be noted that $q_{o,max}$

corresponds to within 10% of the preliminary flow test estimate of 365 gpm. The initial productivity index, J_o' of the Auburn well was determined to be 0.56 STB/D/psia^2 for a Fetkovich exponent, n = 0.642, i.e.,

$$q_o = 0.5612\ (\overline{P} - P_{wf}^{\ 2})^{\ 0.642} \qquad \text{(B-33a)}$$

The initial or maximum deliverability curve is shown in Figure B-29 which is a plot of the modified isochronal data from the preliminary drawdown test, shown in Figure B-30. The first three stages of the preliminary drawdown test provided estimates of ΔP^2 versus q where $\Delta P = \overline{P} - P_{wf}$, the difference between the average reservoir pressure and the flowing bottom hole pressure. Figure B-30 indicates that the well stabilizes after $\sim$100 minutes in the first stage yielding a P_{wf} = 2,205.1 psia; the second and third stages were extrapolated to 200 and 300 minutes, respectively, to determine their psuedo stabilized values of P_{wf}. The average reservoir pressure, $\overline{P}$ was estimated to be 2,295.5 psia from the measured value of 1757.9 psi at 3,973. ft.

The continuous deliverability is defined by the well's capability to maintain flush production over the lifetime of the reserves, i.e., the continuous maintenance of a positive liquid head above the pump's suction. The forecasted pressure drawdown rates as a function of time are shown in Figure B-31 for 100, 150 and 328 gpm. These projections are based on the same assumptions made in the analysis of the pump test data, and are made for a pump setting depth of 4,000 ft. with the following reservoir parameters: kh = 3,100 md-ft; $\phi c_t = 2.0 \times 10^{-8}$ psi^{-1}; and s = -5.

At its maximum deliverability of 328 gpm, the well would have produced < 0.1% of its proved resources before total drawdown in $\sim$4.0 hours. The well's deliverability, at a production rate of 150 gpm, is continuous for about six months, after which time the well would have produced $\sim$30% of its proved resources before total drawdown. As shown in Figure B-31, the well will sustain a production rate of 100 gpm (3429 STB/D) over the lifetime of the reserves. The continuous deliverability of the well's proved reserves lies between 100 and 150 gpm.

The intermittent deliverability of the Auburn low-temperature geothermal well was also evaluated to determine the response of the reservoir, its "recovery factor," under cyclic operating conditions, e.g., six months pumping during the winter demand season, and six months shut-in during the low-heat demand seasons. The evaluation of "recovery factors" was made with the assumption that the Auburn

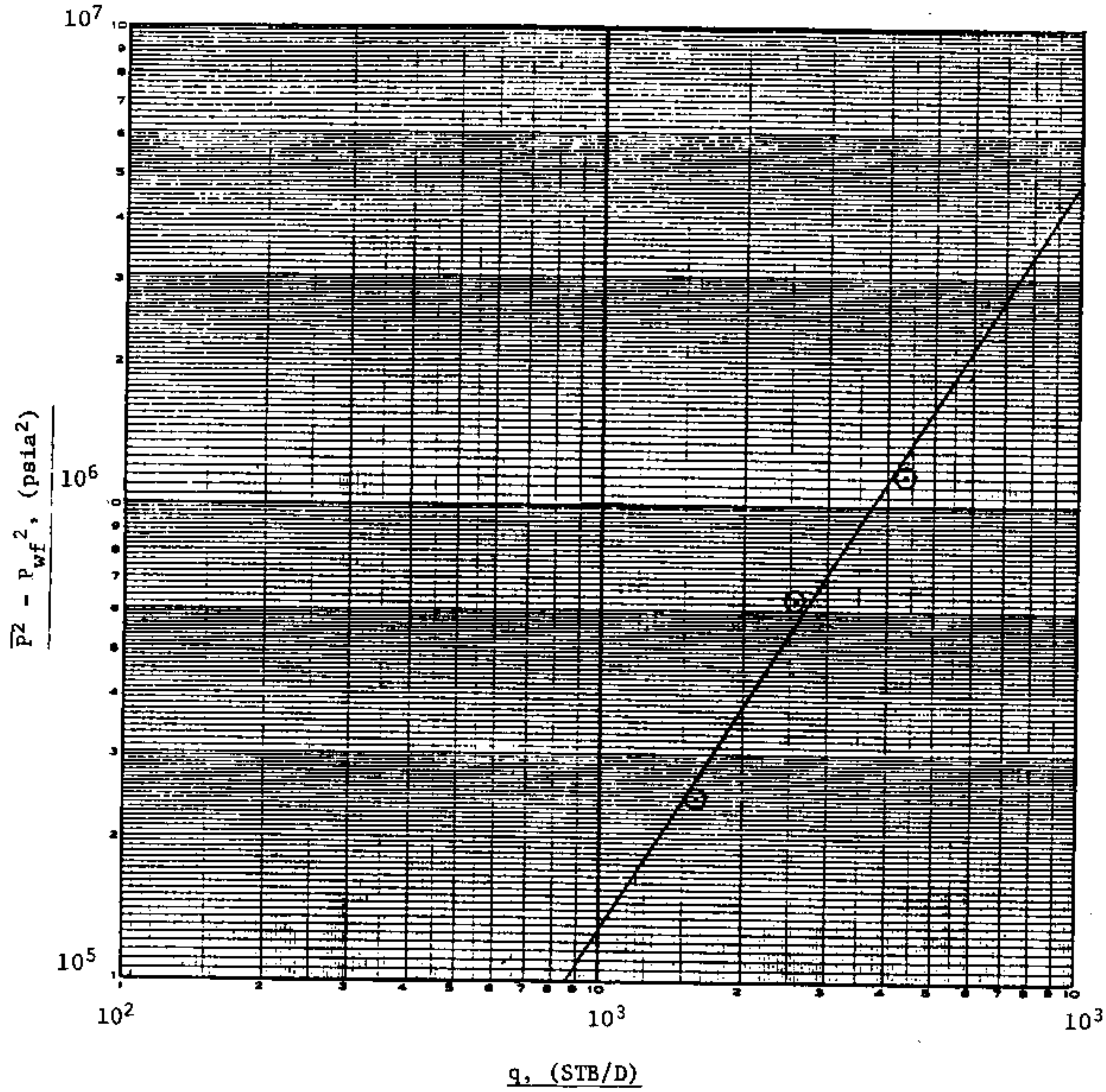


Figure B-29. Auburn Geothermal Well Initial Deliverability Curve from Preliminary Pressure Drawdown Data

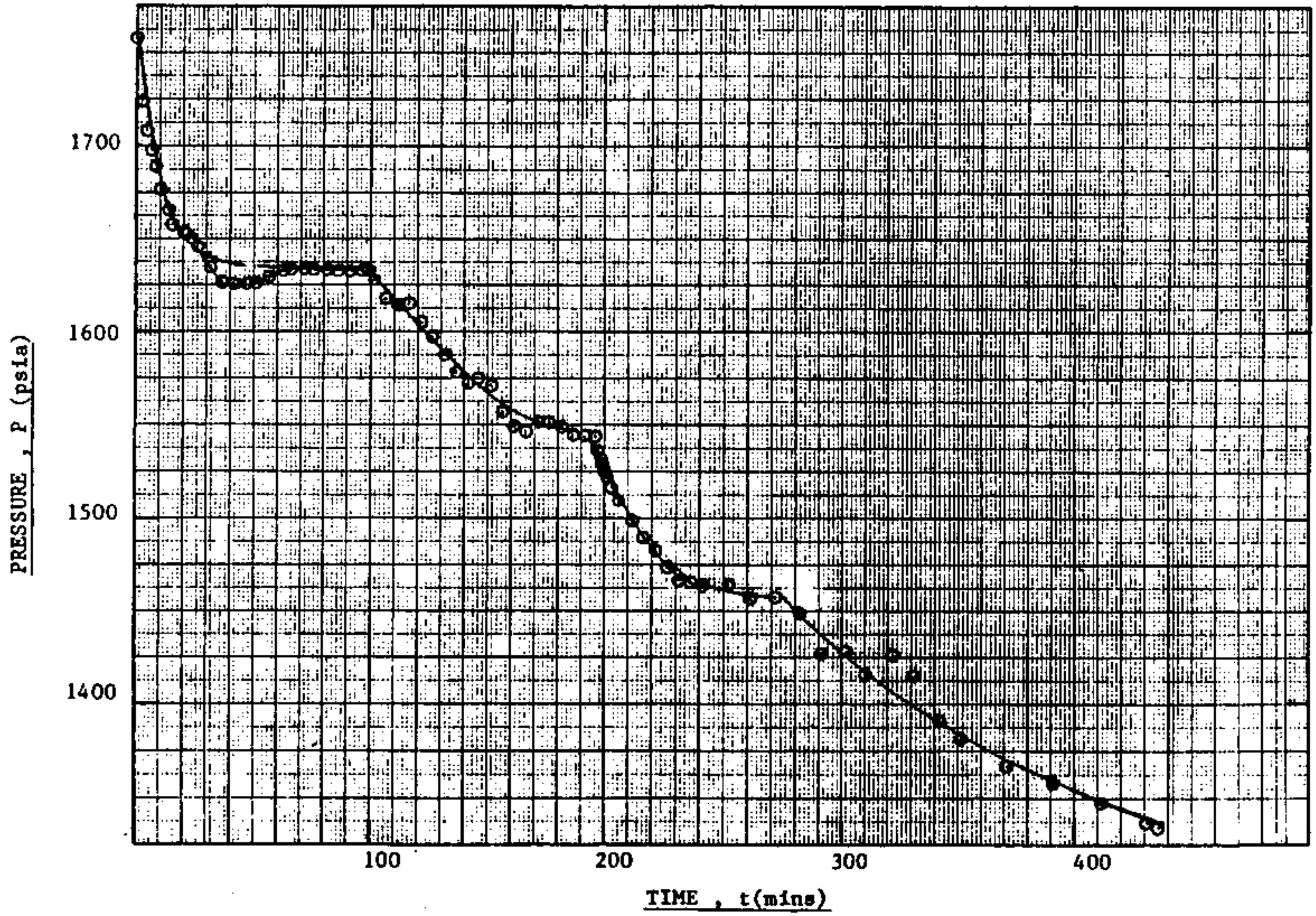


Figure B-30. Auburn Geothermal Well Linear Plot of Preliminary Drawdown Data

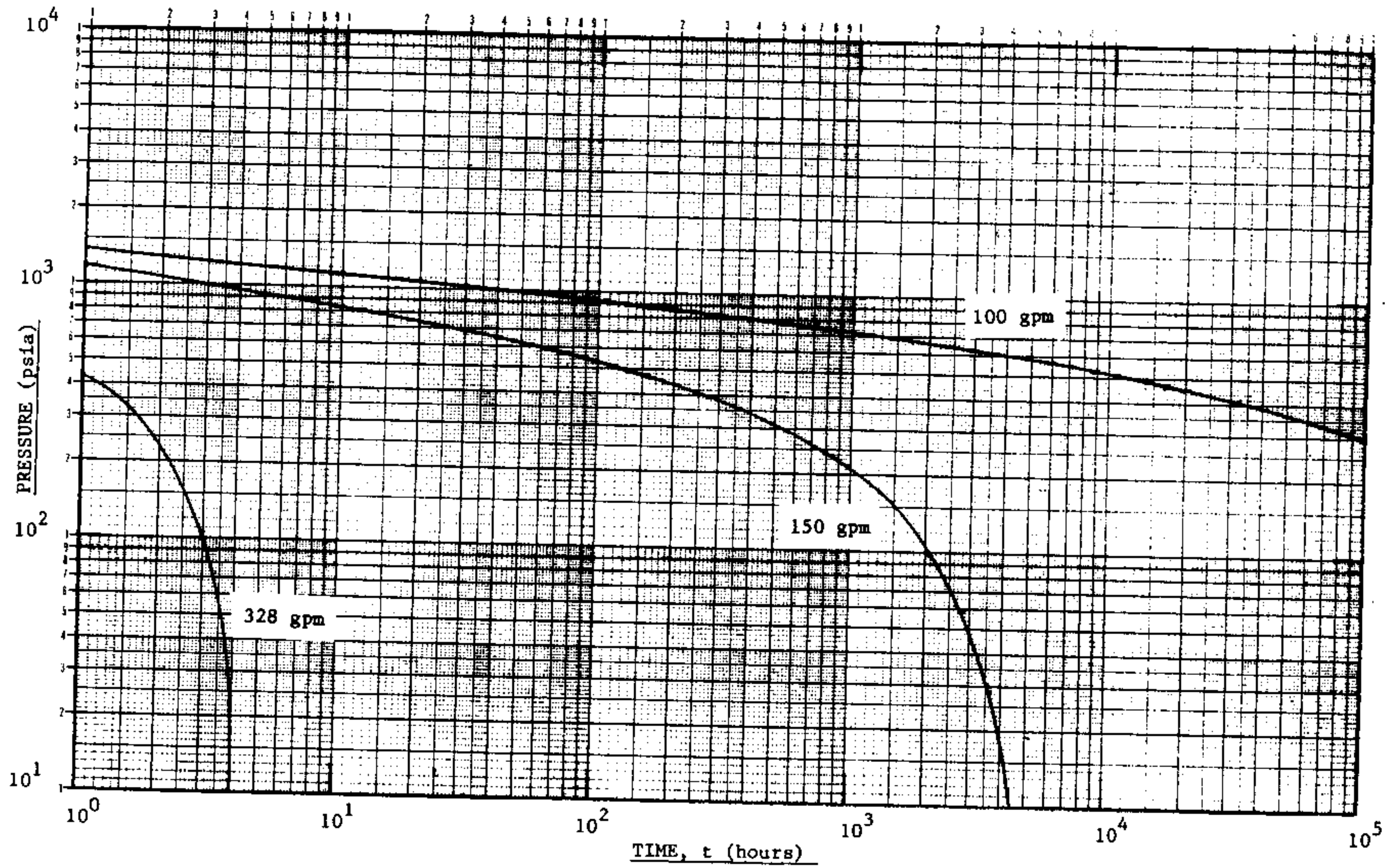


Figure B-31. Auburn Geothermal Well Forecasted Pressure Drawdown Versus Time as a function of Pumping Rates reservoir, as previously discussed in Reservoir Characterization, is made up of three different flow regimes: a vertical hydraulic fracture; a natural fracture or fissure system; and a porous matrix. Under psuedosteady state conditions, the dimensionless pressure (P_{WD}) is described by the following relationships, provided that t_{DA}/ω >0.1 and $\lambda = 0$; 1/

$$P_{WD} = \frac{2\pi t_{DA}}{\omega} + \tfrac{1}{2} \ln \left\{ \frac{2.2458A}{C_A r_f^2} \right\} \qquad \text{(B-33b)}$$

where

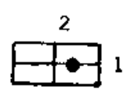
$$P_{WD} = \frac{k_f h \ (P_i - P)}{141.2qB\mu}$$

$$t_{DA} = \frac{2.637 \times 10^{-4} k_f t}{\left[(\phi vc)_m + (\phi vc)_f\right] \ \mu r_w^2}$$

$$\omega = \frac{(\phi vc)_f}{(\phi vc)_m + (\phi vc)_f}$$

A = drainage area in acres

B = shape factor, 4.15141 for



$r_f = r_w e^{-s}$, where s is the skin factor .

The "recovery factors" were determined for the reservoir parameters developed in Resource and Reserve Analysis for two flowrates, 100 and 150 gpm. The performance of the reservoir under six-month periods of depletion at 150 gpm, (with a pump and pressure sensor setting at 4,000 ft) is as follows:

1/The interporosity flow factor, λ, is negligible if $k_f \gg k_m$.

Table B-20

RESERVOIR PERFORMANCE UNDER INTERMITTENT OPERATING CONDITIONS
(6-MONTH DRAWDOWN PERIODS AT 150 GALLONS PER MINUTE)

Elapsed Time (months)	Status	P (psia)	Fluid Level (ft)	Recovery Factor
0	Virgin	1,757.9	368	1.00
6	Pumping	3.2	3,994	-
12	Shut-In	1,348.2	1,367	0.73
12.3	Pumping	4.7	3,991	-

The proved reserves of 2.25 x 10^6 STB will deplete just after the end of the first year for continuous pumping at 150 gpm or 5,142 STB/D. The reservoir is, however, drawndown in 6.3 months of intermittent withdrawal (6 months pumping - 6 months shut-in) versus 6.1 months for continuous withdrawal at 150 gpm without spent brine reinjection.

The performance of the reservoir under six-month periods of depletion at 100 gpm, with a pump and pressure sensor setting at 4,000 ft., is as follows:

Table B-21

RESERVOIR PERFORMANCE UNDER INTERMITTENT OPERATING CONDITIONS
(6-MONTH DRAWDOWN PERIODS AT 100 GALLONS PER MINUTE)

Elapsed Time (months)	Status	P (psia)	Fluid Level (ft)	Recovery Factor
0	Virgin	1,757.9	368	1.00
6	Pumping	568.8	2,854	-
12	Shut-In	1,483.2	1,103	0.71
18	Pumping	312.1	3,390	-
24	Shut-In	1,208.7	1,639	0.58
30	Pumping	37.6	3,927	-
36	Shut-In	934.2	2,175	0.49

The estimated proved reserves of the Auburn well will be depleted at the end of the third six-month interval, i.e., at the end of the third year of intermittent operation at 100 gpm without fluid recharge.

RESOURCE CHARACTERIZATION

The Auburn low-temperature geothermal reservoir is characterized as being made up of as many as six different storage regions and flow regimes. These reservoir characteristics were readily identifiable and, for the most part, quantifiable from an integrated analysis of the pump test and supporting data such as geophysical logs, core analyses and completion history. The resources of the Auburn reservoir can be characterized as falling into one of the following categories:

- Unbounded or infinite
- Finite with natural recharge
- Finite and bounded by a fault zone, gas barrier and/or permeability pinchout
- Finite and limited by the connected reservoir pore volume.

The Auburn reservoir may be unbounded or infinite in that central New York State consists of a sequence of flat-lying carbonates, dolomites and shales which dip very gently to the south in the Appalachian Plateau. This contention does not appear valid in that the Auburn reservoir showed signs of depletion during the conduct of the pump test. For example, there was a decrease in the average reservoir pressure, P*, from 1757.9 psia to 1580.0 psia obtained from extrapolating buildup data to infinite shut-in time. This decrease, which reflects a decrease in average reservoir pressure, resulted from a volumetric drawdown of approximately 14,000 barrels of fluid. The Auburn reservoir thus appears to be finite and bounded without significant recharge from natural sources.

Pressure transient analysis of the pump test data does not categorically identify the location and/or orientation of reservoir boundaries. There is no geological evidence to the occurrence of fault zones or permeability pinchouts within the estimated reservoir boundaries. The occurrence of solution gas (primarily methane) in the brine suggests the presence of a gas cap to the water producing formations. There are, however, no viable gas wells producing from the Theresa and Potsdam formations in the immediate vicinity of the wellsite and thus, no viable evidence of a gas/water contact within the estimated limits of the reservoir. The volumetric and hydrothermal resources of the Auburn reservoir appear to be limited to a reservoir drainage volume which is connected by natural fractures.

Section 5

HYDROTHERMAL RESOURCES AND RESERVES

The hydrothermal resources of the Auburn low-temperature geothermal reservoir are estimated to be as follows:

Table B-22

HYDROTHERMAL RESOURCES (Btu)

Category	Volumetric	Reinjection	Total
Proved	5.50×10^{10}	34.89×10^{10}	40.39×10^{10}
Probable	12.84×10^{10}	89.95×10^{10}	102.79×10^{10}
Possible	42.20×10^{10}	78.20×10^{10}	120.40×10^{10}

The volumetric hydrothermal resources are based on the thermal capacity of the in situ formation brine. The thermal capacity is defined by the realization of a wellhead temperature drop from 125°F to an operating temperature of 70°F and an overall heat recovery or capture efficiency of ∿80%.

The wellhead temperature of ∿125°F is based on estimated, measured and projected surface temperatures (for a production rate of 150 gpm). Surface temperatures of ∿123°F were estimated for steady-state heat transfer in the wellbore and unsteady radial conduction in the earth from an insulated tubing string with a perfect downhole pump. Surface temperatures of ∿130°F were measured during the 150 gpm stage of the multirate drawdown test. The measured surface temperatures were strongly influenced by the following factors: production of higher-temperature fluids from the lower producing formations; downhole generation of heat by the pump and motor; and reinjection of warm-produced brine into the annulus adjacent to the production tubing string. The effects of these factors on the measured surface temperatures were quantified, and then combined with the theoretical estimations to predict the wellhead surface temperatures under different operation conditions. The projected surface temperature of $\sim 126 \pm 1^{\circ}F$ is for the production of formation brine at 150 gpm through an uninsulated tubing string from a setting depth of 4,000 ft.

The hydrothermal resources include a reinjection component in which heat is recovered from the reservoir rock by the reinjection of the produced brine. The extent of the reinjection resources is defined by the breakthrough time of the thermal front because the wellhead temperature and the recoverable heat will decrease rapidly with breakthrough of the cooler thermal front. The reinjection resources were evaluated in terms of the relative volumetric heat capacities of the formation brine, the reservoir matrix (rock and brine), and the caprock as well as the reinjection rate, and the separation distance between the injection and production well. The latter is taken as the outer limit of a right cylindrical reservoir; the reinjection rate is taken to equal the production rate which is selected to be 286 gpm. Table B-22 indicates that the probable reinjection resources are greater than the possible even though the reverse is true for the volumetric hydrothermal resources. As shown in Table B-18, the probable and possible volumetric resources are based on approximately the same areal extent ($\sim$ 1,000 acres) but on different average effective porosities (0.27% for probable and 1.00% for possible). The probable volumetric reserves are approximately three times smaller than the size of the possible because of its lower pososity or connected pore volume. The probable reinjection hydrothermal resources are, however, greater than the possible because of the larger rock volume available for contacting during the reinjection process.

The hydrothermal reserves are the recoverable hydrothermal resources. The volumetric hydrothermal reserves are estimated to be 75% of the resources whereas the reinjection reserves are estimated to be 50% of the resources. The hydrothermal reserves of the Auburn low-temperature geothermal well are estimated to be:

Table B-23

HYDROTHERMAL RESERVES (Btu)

Category	Volumetric	Reinjection	Total
Proved	4.13×10^{10}	17.45×10^{10}	21.58×10^{10}
Possible	9.63×10^{10}	44.98×10^{10}	54.61×10^{10}
Probable	31.65×10^{10}	39.10×10^{10}	70.75×10^{10}

ESTIMATED, MEASURED, AND PROJECTED SURFACE TEMPERATURE

The wellhead temperatures of the geothermal well were estimated prior to, and measured during, the pump test. Since the latter was accomplished under variable field conditions, for example, the reinjection of hot brine ($\sim 125^{\circ}F$) down the annulus of the production tubing to a depth of 4,700 ft., the measured wellhead temperatures will be adjusted to reflect an operational environment. Consequently, the estimated surface temperatures of the geothermal brine will be discussed first.

The wellhead temperatures were estimated assuming that heat transfer in the wellbore is steady-state, while heat transfer to the earth is unsteady radial conduction with allowances made for varying heat transfer resistance in the wellbore (Ramey, 1962).

Assumptions used in the heat transfer calculations are as follows:

- Heat flows radially from the wellbore, is unsteady state, and can be represented by:

  $$\Delta Q = 2\pi k_e (T_{Wb} - T_e) dz / f(t). \quad \text{(B-34)}$$

- f(t) can be estimated from solutions for radial conduction from an infinitely long cylinder, i.e., the wellbore is considered a line source in an infinite radial medium.
- For open-hole conditions, the wellbore boundary temperature is assumed to be the same as the wellbore center-line temperature because the thermal resistance of a water-filled wellbore is negligible and the overall heat transfer coefficient can be assumed to be infinite.
- For insulated tubing completions, the wellbore boundary is assumed to be at a constant heat flux condition.

- Axial heat flow in the wellbore is rapid compared to radial heat flow to the formation; axial heat flow in the wellbore can thus be represented by steady-state solutions, e.g.,

$$\Delta Q = \dot{m} c_p \ (T_{in} - T_{out}) \ . \tag{B-35}$$

- Geothermal gradients between calculated values are linear and constant, i.e.,

$$T_e = a' z + b \ . \tag{B-36}$$

- Thermophysical properties are constant and evaluated at $125^{\circ}F$.

- Temperatures and pressure of the reservoir are constant over time.

Center-line temperature, with depth referenced from the producing formation, can be calculated from the following equations:

1) $$T_{out}(z,t) = a'z + b - a'A' + \left[T_{in}(z,t) + a'A' - b \right] e^{-z/A'} \ . \tag{B-37}$$

2) $$A' \left[U_o, f(t) \right] = \frac{\dot{m} c_p \left[k_e + r_{to} U_o \ f(t) \right]}{2\pi r_t U_o \ k_e} \ . \tag{B-38}$$

3) $$f(t) = -\ln \left\{ \frac{r_{Wb}}{2\sqrt{\alpha t}} \right\} - 0.290 + O \left[r_{Wb}^2 \ / \ 4\alpha t \right] \tag{B-39}$$

.... for $\log_{10} \left[\alpha t \ / \ r_{Wb}^2 \right] > 4.0$

$f(t)$ is usually represented as a function of $r_t U_o \ / \ k_e$

.... for values of $\log_{10} \left[\alpha t \ / \ r_{Wb}^2 \right] < 4.0$.

4) $$\frac{1}{U_o} = \frac{1}{h_c + h_r} + r_t \frac{\ln \ (r_{Wb}/r_1)}{k_{cem}} + r_t \ \frac{\ln \ (r_1/r_2)}{k_w} + r_t \ \frac{\ln \ (r_2/r_3)}{k_w} + r_t \ \frac{\ln \ (r_3/r_t)}{k_{ins}} \ . \tag{B-40}$$

5) $$h_c = \frac{k_w}{d_t} \left\{ Nu \right\} = \frac{k_w}{d_t} \left\{ 0.023 \ Re^{0.8} \ \ Pr^{0.4} \right\} . \tag{B-41}$$

Figures B-32a,b illustrate the temperature profiles for fluid flowing from a 9-in. open hole at 150 gpm. Figure B-32a also illustrates the temperature profile for fluid flowing in the wellbore during the preliminary flow testing at 100 gpm on April 7, 1982, and the assumed geothermal gradient at steady-state conditions. It

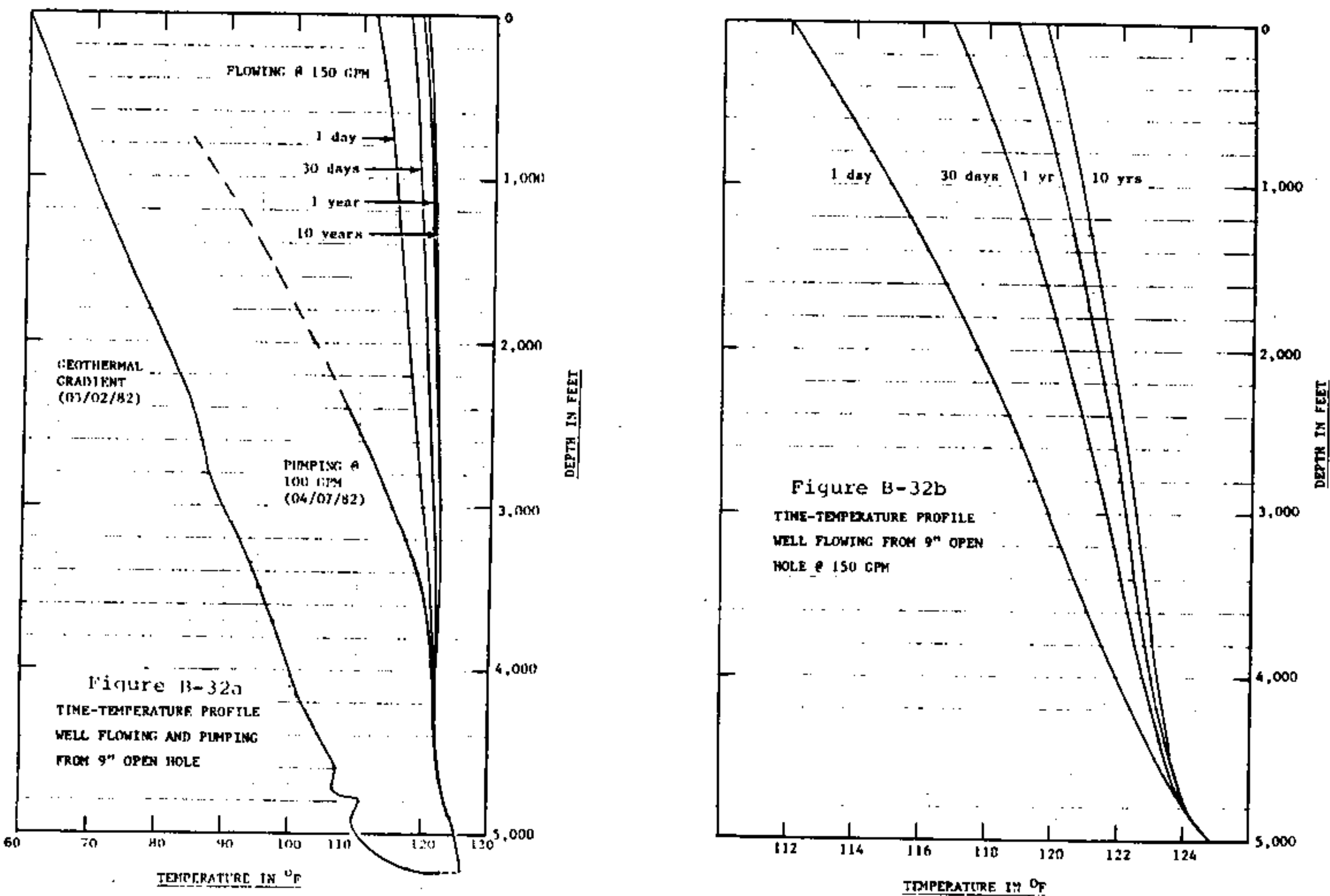


Figure B-32 a & b. Auburn Geothermal Well Projected Time-Temperature Profile Under Flowing, Open-Hole Conditions

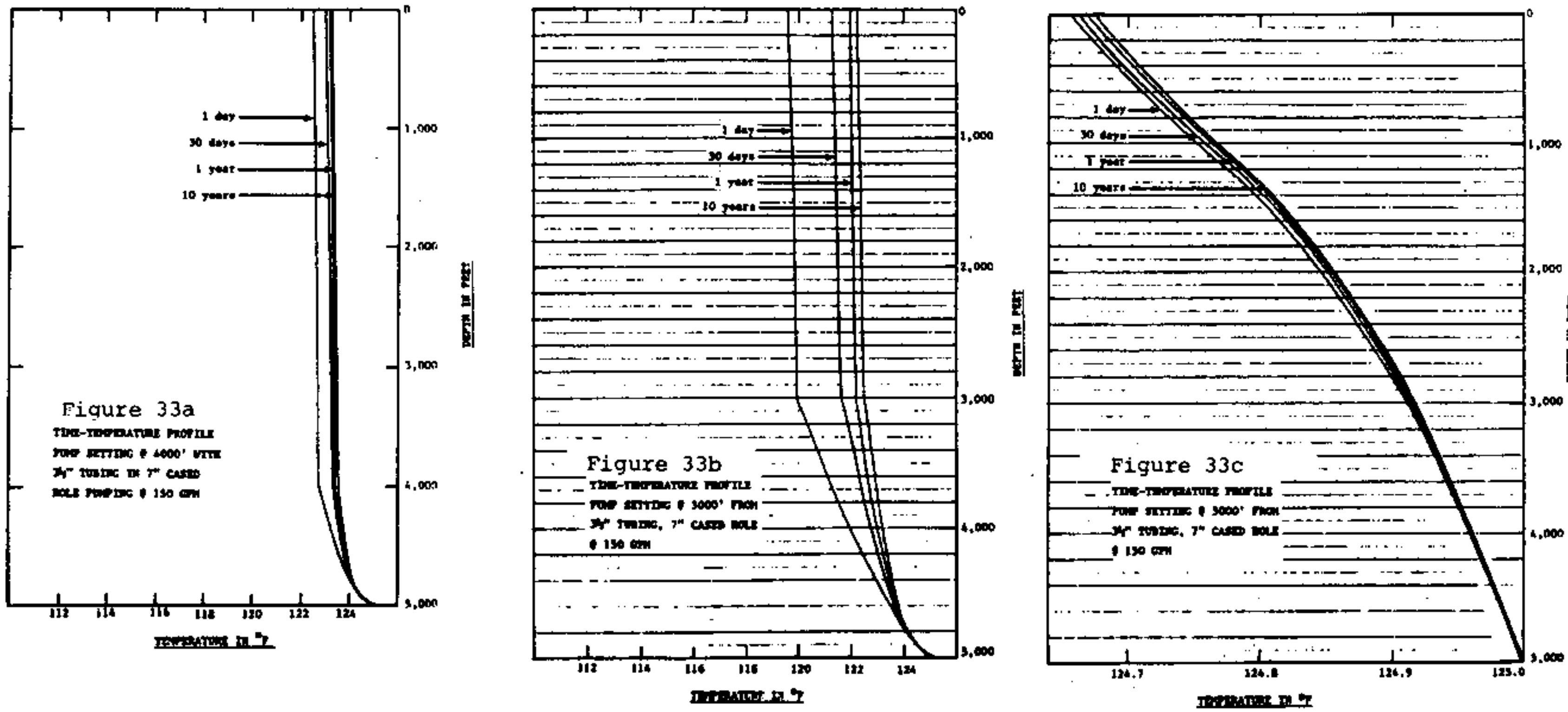


Figure B-33 a, b & c. Auburn Geothermal Well Projected Time-Temperature Profile Under Pumping, Cased-Hole Conditions was assumed that 90% of the water is produced from 4,810 ft. at 124.2°F and 10% of the water is produced from 4,165 ft. at 121.6°F with ideal thermal mixing occurring between the two streams on contact; point sources were located by averaging flows on the basis of formation thickness, flowmeter response and average values of porosity. The temperature profiles in Figures B-32a,b are used to determine center-line water temperature in the wellbore at various pump setting depths.

Temperature profiles at various setting depths (illustrated in Figures B-33 a,b,c) were made for 150 gpm flowing through 3½-in. 12½# tubing in a 7-in, 26#, J-55 casing with air in the annulus acting as the primary insulator. In lieu of this configuration, an insulated tubing string can be used (General Electric's Thermocase™ or Baker Packers' HeatSaver™) or the annulus between the casing and tubing strings could be filled with perlite or compressed air. For a pump setting at 5,000 ft., the casing was assumed cemented at 4,000 ft. and perforated over the 4,720 ft. - 5,008 ft. interval. For a pump setting at 3,000 ft., the casing was assumed cemented back to 2,600 ft. The projected tubing outlet temperatures at the surface for the geothermal well flowing and being pumped @ 150 gpm from 3,000 ft., 4,000 ft. and 5,000 ft. as a function of time are as follows:

Table B-24

PROJECTED WELLHEAD TEMPERATURES AS A FUNCTION OF DEPTH AND TIME

Pump Setting (feet)	Wellhead Temperature (°F)			
	1 day	30 days	1 year	10 year
Well-Flowing	111.98	116.90	118.86	119.73
3000	119.62	121.33	121.97	122.27
4000	122.45	122.98	123.17	123.26
5000	124.66	124.66	124.67	124.68

The estimated values, listed to five significant figures, illustrate time and depth sensitivities and do not reflect the accuracy of the calculations. The temperatures measured during the seven-day pump test are listed in Table B-7 for pre-test bottom-hole conditions, $T_{BH,i}$, post-test bottom-hole conditions, $T_{BH,f}$, flowing wellhead temperatures, $T_{WH,f}$, and sample point temperatures, $T_{s,f}$. The measured temperatures, at stabilized or psuedo-stabilized conditions, are as follows:

Table B-25

MEASURED WELLHEAD TEMPERATURES AS A FUNCTION OF FLOWRATE

Average Flow Rate (gpm)	$T_{BH,f}$ (^oF)	ΔT_{BH} (^oF)	T_{WH} (^oF)	ΔT_{Wb} (^oF)
99.2	130.19	+ 19.79	122.0	- 8.19
127.4	132.52	+ 22.12	126.0	- 6.52
152.5	130.88	+ 20.48	132.5	+ 1.62
133.1	132.89	+ 22.49	134.0	+ 1.11
115.5	134.89	+ 24.49	135.0	+ 0.11

The listed bottom-hole and wellhead temperatures were strongly influenced by the following factors:

- Production of higher-temperature fluids from the lower-producing formations, primarily for the 100 ft. of net pay spanning the Theresa and the Potsdam over the interval 4,950 ft. to 5,050 ft.
- Downhole generation of heat by the pump and motor as a result of mechanical and electrical inefficiencies created under nominal and restricted operating conditions.
- Reinjection of produced brine, with temperatures as high as 126^oF, into the Black River and other uphole formations vis-a-vis the annulus between the 9 5/8-in. and the 7-in. casings.

The bottom-hole measurements were made with a Lynes wireline temperature (c.f. Pump Test Field Execution) probe with a resolution of 1.8^oF and an accuracy of 1.8^oF. The bottom-hole temperature measured at 3,972 ft. was 110.4^oF and 116.57^oF before and after the pump testing of the reservoir. The former value is consistent with open-hole measurements of temperature at the same depth, $T_{BH,i}$ = 111.5^oF, on April 7, 1982 by Schlumberger. The after pump test bottom-hole temperature of 116.57^oF reflects the warming of the near wellbore area by the production of ~577,000 gallons of formation brine.

ΔT_{BH} is the difference between the final bottom-hole temperature at the end of the test, $T_{BH,f}$ and the initial $T_{BH,i}$ of 110.4^oF. The bottom-hole temperatures at the end of each test, $T_{BH,f}$ are made up of a production component and a heat generation component. Under ideal conditions, the production component can raise the $T_{BH,f}$ to a maximum of 125 $\pm$ 1^{o}F. The bottom-hole temperature is a function of pumping rate as shown in Figure B-34. Extrapolating to zero flowrate, the production component lowers the bottom-hole temperature to a minimum of 123 $\pm$ 1^{o}F. Thus, without pumping and heat generation, 123^{o}F < T_{BH} < 125^{o}F within $\pm$ 1^{o}F. T_{BH} @ 4,000 ft. was predicted to reach 122.8^{o}F after 24 hours of pumping at a rate of 150 gpm. The temperature increase due to the heat generation component, plotted as a function of flowrate in Figure B-35, substantiates the miminum bottom-hole temperature at 4,000 ft. in that ΔT due to heat generation goes to zero at $q = 0$. This heat generation component is specific to the wellbore conditions and the submersible pump used, Centrilift-Hughes' Model #S-175.

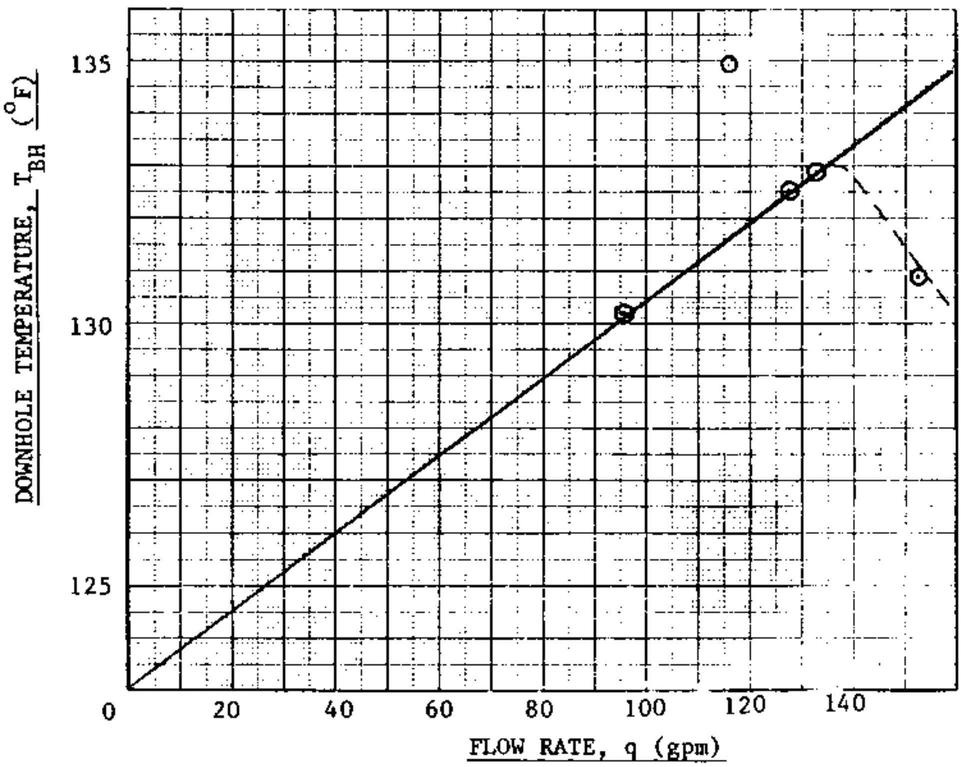
ΔT_{Wb} is the temperature difference between the maximum temperature observed at the surface (either $T_{w,f}$ or $T_{s,f}$) and $T_{BH,f}$. ΔT_{Wb} represents the heat loss (-) or gain (+) to the produced brine between the downhole pump and the wellhead. The listing above indicates that ΔT_{Wb} is negative for the preliminary and the 24-hour drawdown tests at 96.1 and 127.4 gpm, respectively, and positive for the multirate drawdown tests. The latter values are within the accuracy range of the combined downhole and surface temperature sensing devices and for all practical purposes, do not represent any physical heat gain from the wellbore. These values do, however, indicate that an isothermal wellbore condition resulted from the reinjection of geothermal brine into the annulus adjacent to the production string. The following measurements were taken prior to the start of reinjection:

Table B-26

MEASURED BOTTOM-HOLE TEMPERATURES AS A FUNCTION OF FLOWRATE

Test Type	q (gpm)	Δt (hours)	$T_{BH,f}$ (^{o}F)	$T_{w\ or\ s}$ (^{o}F)	ΔT_{Wb} (^{o}F)
Preliminary	99.2	7.3	130.19	122.0	- 8.19
24-Hour	127.4	6.0	131.08	125.0	- 6.08
Multirate	152.5	4.7	128.72	124.0	- 4.72

Figure B-34. Auburn Geothermal Well Downhole Temperature as a Function of Pumping Rate



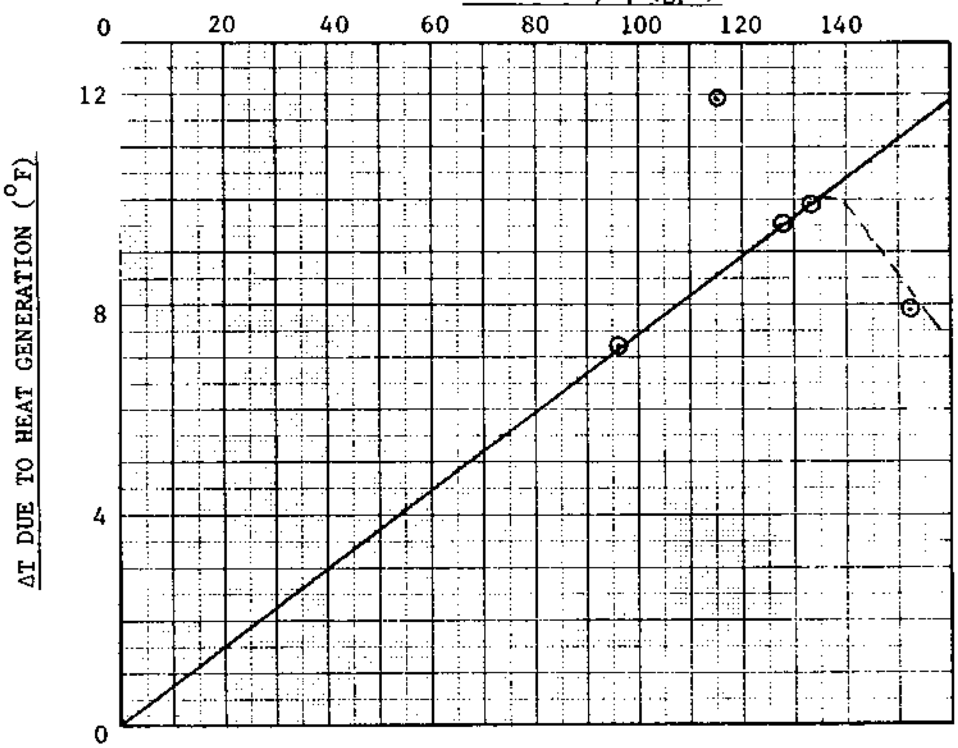


Figure B-35. Auburn Geothermal Well Downhole Heat Generation Due to Pump and Motor as a Function of Pumping Rate

From the above, ΔT_{Wb} is shown to be a strong inverse function of flowrate as shown in Figure B-36. Although this relationship can be theoretically justified in that heat loss decreases with decreased residence time or increased flowrate, the reader should be cautioned to the applicability of this relationship because of the unknown wellbore conditions and the varying values of Δt.

Without reinjection of geothermal brine into the annulus, the wellhead temperature is estimated to reach $\sim 126^{\circ}F$ at a minimum after 24 hours of pumping at 150 gpm with a 175-horsepower pump. Without reinjection, and without heat generation due to mechanical and electrical inefficiencies of the submersible pump, the minimum wellhead temperature is estimated to be $\sim 119^{\circ}F$ after 24 hours of pumping at 150 gpm with a perfect pump. The estimated wellhead temperatures for pumping at 150 gpm from 4,000 ft. through an insulated string with a perfect pump (Case I), through an un-insulated string with a non-perfect pump (Case II), and through an insulated string with a non-perfect pump (Case III) are as follows:

Table B-27

ESTIMATED WELLHEAD TEMPERATURES

Time	I	II	III
1 day	122.5	126.0	129.5
30 days	123.0	126.5	130.0
1 year	123.2	126.7	130.2
10 years	123.3	126.8	130.3

HYDROTHERMAL RESOURCES

The proved, possible, and probable hydrothermal resources of the Auburn low-temperature geothermal well are estimated to be 5.5×10^{10}, 12.84×10^{10}, and 42.20×10^{10} Btus, respectively.

The hydrothermal resources are based on the heat content of the volumetric resources and are computed from the following:

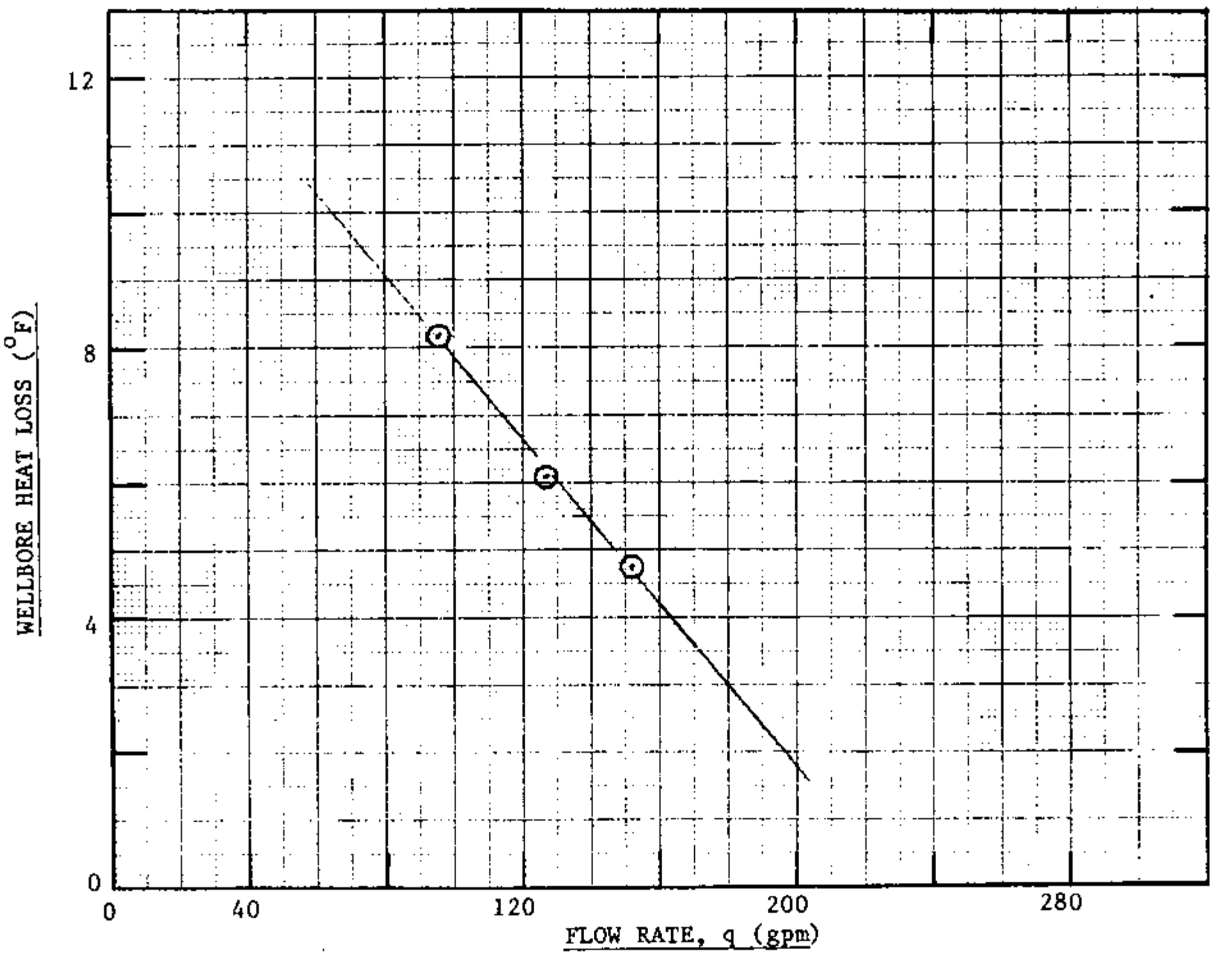


Figure B-36. Auburn Geothermal Well Wellbore Heat Loss as a Function of Pumping Rate

$$W = 5.615 \rho c_p \Delta T E_h \qquad \text{(B-42)}$$

where

W = volumetric resources, STB

ρ = formation brine density, lb/ft^3

c_p = heat capacity of brine, Btu/lb $^{\circ}F$

ΔT = temperature drop at the wellhead, $^{\circ}F$

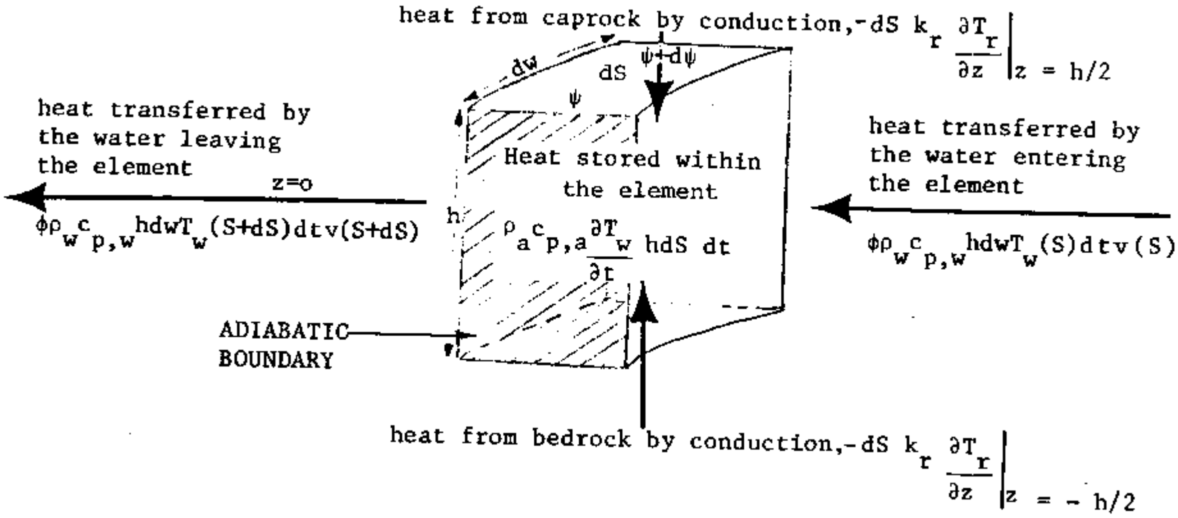
E_h = heat recovery, or capture efficiency .

The volumetric resources are defined and discussed in "Volumetric Resources and Areal Extent". The formation brine density is defined to be 74.3 lbs per cubic foot in "Viscosity and Specific Gravity of Geothermal Brine". The heat capacity of brine is assumed to be that of water 1.0 Btu/lb $^{\circ}F$. The wellhead temperature drop, ΔT, is assumed to be from an estimated wellhead temperature of $125^{\circ}F$, as per the estimates in "Estimated, Measured, and Projected Surface Temperatures", to an operating temperature of $70^{\circ}F$. The heat recovery or capture efficiency, E_h, is assumed to be $\sim$80%; E_h is based on the product of an estimated direct contact heat exchange efficiency of 90% and a transmission efficiency of 90%.

HYDROTHERMAL RESOURCES WITH REINJECTION

The hydrothermal resources of the Auburn reservoir are made up of two components: an in situ component which is made up of the thermal capacity of the recoverable volumetric resources; and a reinjection component in which heat is recovered from the reservoir rock by the reinjection of the produced brine.

The reinjection of the produced brine not only permits the recovery of heat contained in the reservoir rock but also maintains the reservoir pressure and the well's deliverability. The reinjection of spent brine will create a zone of cooler water which will grow with time and eventually reach the production well. After breakthrough of the cooler thermal front, the wellhead temperature and the recoverable heat will decrease rapidly. Gringarten and Sauty (1975) points out that "it is thus important to design such a system in order to prevent injected water breakthrough before a specified time and to maintain the temperature variations at the production wells after breakthrough within reasonable limits." These authors conducted a theoretical study of heat extraction from aquifers with uniform regional flow under reinjection conditions to evaluate the thermal performance of a recharging-discharging well pair. The aquifer is modeled, under these conditions, by the differential stream channel element below:



The flow of heat in the differential element of rock is described in the following partial differential equation (PDE) in which $q = \phi hdwv$.

$$\frac{h}{2} \rho_a c_{p,a} \frac{\partial T(S,t)}{\partial t} + \frac{q}{2} \rho_w c_{p,w} \frac{\partial T(S,t)}{\partial S} = k_r \frac{\partial T_r}{\partial z}(S,z,t) \Bigg|_{z = h/2} . \tag{B-43}$$

The PDE is subject to the following boundary condition:

$$\frac{\partial^2 T_r(S,z,t)}{\partial z^2} = \frac{\rho_r c_{p,r}}{k_r} \frac{\partial T_r}{\partial t}(S,z,t)$$

$$\text{....for } z \geq \frac{h}{2} .$$

The temperatures must also satisfy the following initial conditions:

$$T(z,o) = T_i \quad t \leq o$$

Behind the hydrodynamic front, the following condition is assumed:

$$T(0,t) = T_{inj} \quad t > 0$$

Ahead of the hydrodynamic front but before breakthrough, the following condition is assumed:

$$T(S,z,t) = T(S,t) = T_i \quad t < \phi hS/q$$

In general, the following is also assumed:

$$T(S,t) = T(S,\frac{h}{2}, t)$$

$$\lim_{z \to \infty} T_r(S,z,t) = T_i$$

The flow of heat in the production well is described by the following relationship:

$$\frac{T_i - T_w}{T_i - T_{inj}} = \text{erfc}\left[\frac{(\rho_w c_{p,w})^2}{k_r \rho_r c_{p,r}}\left(\frac{q}{S}\right)^2\left(t - \frac{\rho_a c_{p,a}}{\rho_w c_{p,w}}\frac{hS}{q}\right)\right]^{-\frac{1}{2}} \quad \text{(B-44)}$$

with

$\rho_w c_{p,w}$ = brine heat capacity Btu/ft^3 $^\circ$F

$\rho_m c_{p,m}$ = heat capacity of rock matrix, Btu/ft^3 $^\circ$F

$\rho_a c_{p,a}$ = $\phi\rho_w c_{p,w} + (1-\phi)\rho_m c_{p,m}$, the aquifer heat capacity, Btu/ft^3 $^\circ$F

$\rho_r c_{p,r}$ = heat capacity of caprock, Btu/ft^3 $^\circ$F .

k_r = thermal conductivity of caprock, Btu/lb hr $^\circ$F .

The above solution was made under the following simplifying assumptions:

- The aquifer is assumed horizontal with thickness, h.
- The caprock and the bedrock above and below the aquifer are assumed impermeable to flow and of infinite extent in the vertical direction.

- Flow is assumed steady, since the duration of the transient period is short in comparison with the length of time required to reach thermal equilibrium, with the injection rate constant and equal to the production rate.

- Initially, the water and rock in the aquifer is at the same temperature, T_i; the caprock and the bedrock are at the same temperature T_i.

- At the t = o, the temperature of the injected water is set equal to T_{inj} and is maintained constant thereafter.

- Thermal equilibrium is assumed to take place instantaneously between the water and the rock in the aquifer so that anywhere in the aquifer the rock has the same temperature as the surrounding fluid.

- In the aquifer, the effect of thermal conductivity is neglected in the horizontal direction (high Peclet number) and is assumed infinite in the vertical direction (uniform temperature in the vertical direction).

- In the caprock and the bedrock, the effect of thermal conductivity is neglected in the horizontal direction and is assumed finite in the vertical direction.

- The temperature of the caprock and the bedrock remains constant and equal to the initial temperature T_i at all times.

The results of Gringarten and Sauty's (1975) analysis were also given in terms of dimensionless parameters:

$$T_D = \text{erfc}\left\{ \frac{d\ (S_{max}/D^2)}{d\ (\psi/Q)} \left[\chi \left(t_D - \frac{d\ (S_{max}/D^2)}{d\ (\psi/Q)} \right) \right]^{-\frac{1}{2}} \right\} \qquad \text{(B-45)}$$

where

$$\chi = \left(\rho_w\ c_{p,w}\ \ \rho_a\ c_{p,a} / k_r \rho_r\ c_{p,r}\right)\left(Qh/D^2\right)$$

$$t_D = \left(\rho_w\ c_{p,w} / \rho_a\ c_{p,a}\right)\left(Qt/D^2 h\right) \ .$$

D is a characteristic length, e.g. the separation distance between a discharging-recharging well pair in uniform flow. The above relationship indicates that thermal front breakthrough occurs at the following dimensionless times:

$$t_D = 1.04 \ \ldots \ \text{if } \chi > 10 \qquad \text{(B-46)}$$

$$\chi\ (t_D - 1) = 0.5 \ \ldots \ \text{if } 0 < \chi < 10 \ .$$

For no change in the produced water temperature for a period of time Δt, the useful life of the well doublet, the spacing (D) must at least be equal to the following:

$$D_{min} = \left\{ (2.Q.\Delta t) \middle/ \left[\left(\phi + (1-\phi) \frac{\rho_r c_{p,r}}{\rho_w c_{p,w}} \right) h + \left(\left((\phi + (1-\phi) \frac{\rho_r c_{p,r}}{\rho_w c_{p,w}} \right)^2 h^2 + 2 \frac{k_r \rho_r c_{p,r}}{(\rho_w c_{p,w})^2} \Delta t \right)^{1/2} \right] \right\}^{1/2} . \quad \text{(B-47)}$$

The breakthrough time of the thermal front will define the extent of the available reinjection reserves or the reinjection resources. The reinjection resources are thus a function of the relative volumetric heat capacities of the formation brine, the reservoir matrix (rock and brine), and the caprock as well as the reinjection rate and the distance between the injection and the production well.

The separation distance, D, between the discharging-recharging well pair is defined by the reservoir boundary which is taken as the radius of a right circular cylinder as discussed in "Volumetric Resources and Areal Extent." The reinjection rate, Q, is taken to be equal to the production rate, q, which is selected to be 286 gpm as discussed in "Preliminary Assessment of Geothermal Potential." The dimensionless breakthrough coefficients and the reinjection resources are as follows:

Table B-28

PROVED, POSSIBLE AND PROBABLE REINJECTION RESOURCES (Btu)

Category	r_e (feet)	X	t_D (@ breakthrough)	Reinjection Resources (Btu)
Proved	2,544	5.845	1.086	34.89×10^{10}
Possible	3,885	2.506	1.200	89.95×10^{10}
Probable	3,659	2.826	1.177	78.20×10^{10}

The reinjection resources can be compared to the thermal capacities of the reservoir which are 22.65×10^{10}, 52.84×10^{10}, and 42.73×10^{10} Btu/Δ^{O}F, respectively, for the proved, possible and probable resource categories. Thus, the reinjection resources are made available by drops in rock temperature of approximately 1.54, 1.70 and 1.83^{O}F for the proved, possible and probable resource categories.

HYDROTHERMAL RESERVES W/WO REINJECTION

The hydrothermal reserves without fluid reinjection are estimated to be 75% of the hydrothermal resources, listed in "Hydrothermal Resources", because the volumetric recovery efficiency is estimated to be 75% in "Volumetric Reserves", and because the wellhead temperatures will exceed the values projected in "Estimated, Measured, and Projected Surface Temperatures" at the production rate of 286 gpm. The volumetric recovery efficiency of the reinjected brine is estimated to be made up of an areal sweep efficiency of 70% and a vertical displacement efficiency of 70%. The reinjection reserves are thus estimated to be 50% of the reinjection resources listed in "Hydrothermal Resources with Reinjection".

The hydrothermal reserves of the Auburn low-temperature geothermal well are estimated to be:

Table B-29

PROVED, POSSIBLE AND PROBABLE VOLUMETRIC AND REINJECTION RESERVES (Btu)

Category	Volumetric	Reinjection	Total
Proved	4.13×10^{10}	17.45×10^{10}	21.58×10^{10}
Possible	9.63×10^{10}	44.98×10^{10}	54.61×10^{10}
Probable	31.65×10^{10}	39.10×10^{10}	70.75×10^{10}

Section 6

PRELIMINARY ASSESSMENT OF GEOTHERMAL POTENTIAL

The Auburn low-temperature geothermal well can be utilized to provide space heating to the Auburn Middle School and the Cayuga Community College. This preliminary assessment is based on an evaluation of the hydrothermal resources and reserves in the previous sections of this report; a site visit through the heating, ventilation and air conditioning (HVAC) systems; and a review of the blueprints of the HVAC systems. Preliminary process flow diagrams (PFD) for extracting the geothermal energy are presented in Figures B-37 and B-38.

The key element of the process flow diagram is the countercurrent heat exchanger which can be of the following types:

- o Indirect-Contact Tube and Shell or Plate-and-Frame Heat Exchanger
- o Direct-Contact Heat Exchange Column
- o Indirect-Contact Cascade Heat Exchanger.

The direct-contact heat exchanger system is reported to have a thermal efficiency in excess of 95%. The loss of working fluid such as isobutane to the geothermal brine will be the major operational and cost disadvantage of direct-contact systems. The cascade heat exchanger is reported to have an overall heat transfer coefficient which is as much as five times greater than that of tube-and-shell heat exchangers because of the reduced fouling; this system may prove to be operationally difficult for this application which would necessitate low-pressure operation. The tube-and-shell heat exchanger is operationally the most simple but thermally the least efficient.

The exchanged heat energy in the working fluid can be boosted via a heat pump to enhance the system's thermal efficiency. Such a geothermal heat pump device -- utilizing a bubble tray, direct contact, heat exchange column -- is illustrated in Figure B-38.

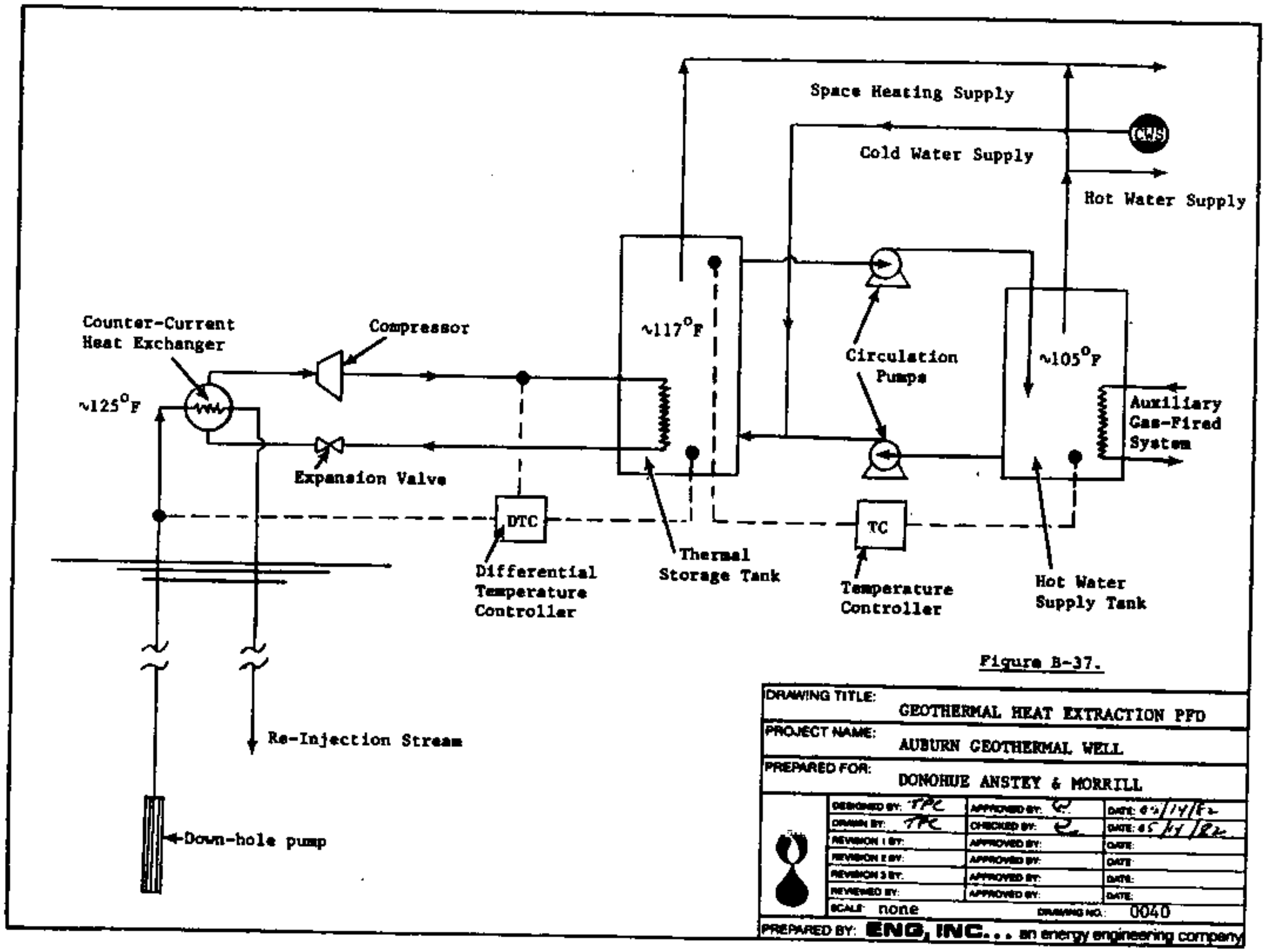

Space Heating Supply
Cold Water Supply
CWS
Hot Water Supply
Counter-Current Heat Exchanger
Compressor
~125°F
~117°F
~105°F
Circulation Pumps
Auxiliary Gas-Fired System
Expansion Valve
DTC
TC
Thermal Storage Tank
Differential Temperature Controller
Temperature Controller
Hot Water Supply Tank
Re-Injection Stream
Down-hole pump
DRAWING TITLE: GEOTHERMAL HEAT EXTRACTION PFD
PROJECT NAME: AUBURN GEOTHERMAL WELL
PREPARED FOR: DONOHUE ANSTEY & MORRILL
SCALE: none
DRAWING NO. 0040
PREPARED BY: ENG, INC. . . an energy engineering company

Figure B-37.

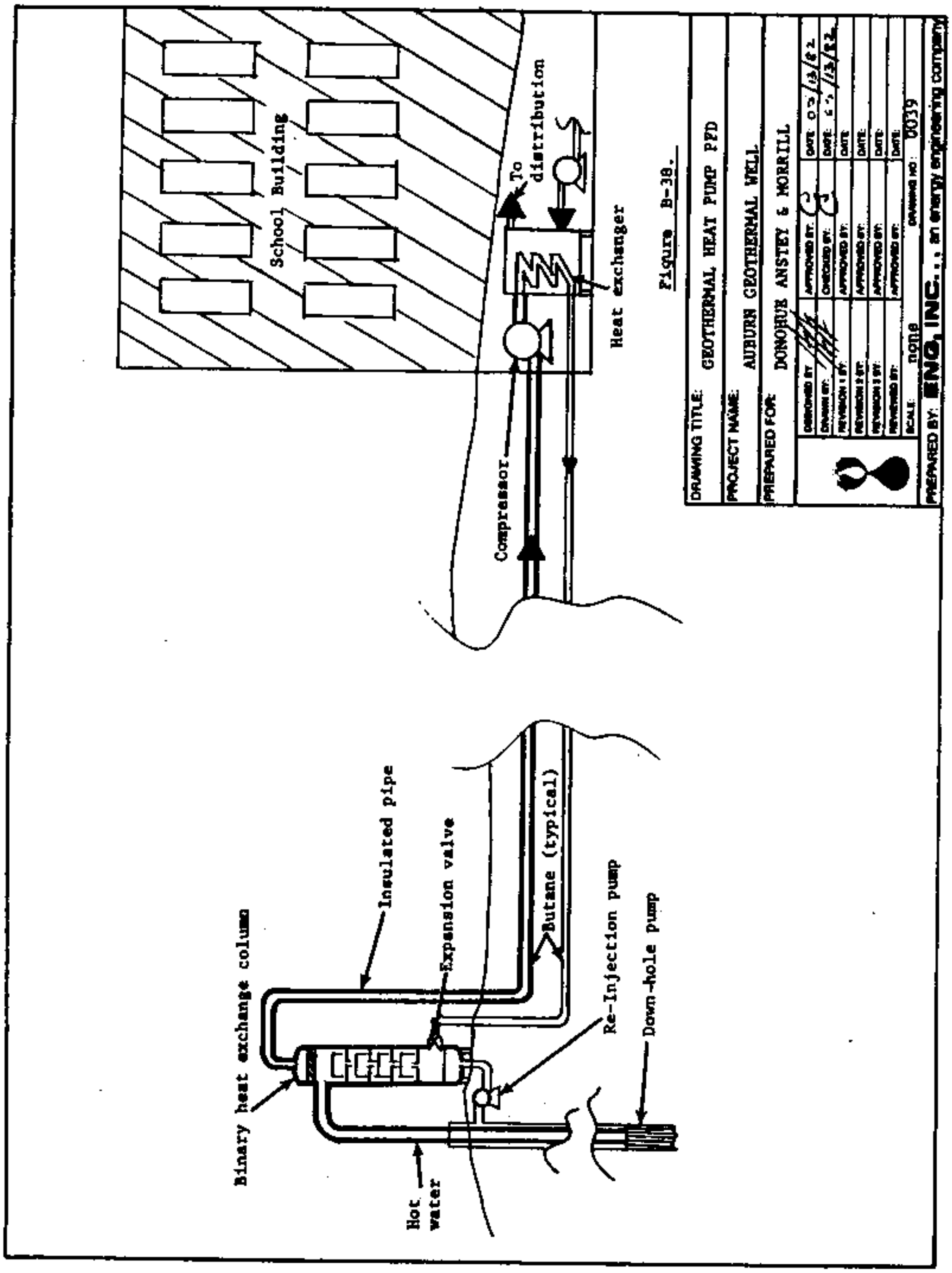

School Building
To distribution
Heat exchanger
Compressor
Binary heat exchange column
Insulated pipe
Expansion valve
Butane (typical)
Re-Injection pump
Down-hole pump
Hot water
DRAWING TITLE: GEOTHERMAL HEAT PUMP PFD
PROJECT NAME: AUBURN GEOTHERMAL WELL
PREPARED FOR: DONOHUE ANSTEY & MORRILL
SCALE: none
DRAWING NO: 0039
PREPARED BY: ENG, INC. . . an energy engineering company

Figure B-38.

The geothermal potential is defined by the recoverable resources or reserves which are detailed in Section 5. The reserves were defined in terms of a volumetric or in situ component and a reinjection component. Without reinjection, the maximum production rate is ∿100 gpm over the volumetric reserves' lifetime, ∿3.5 years. The maximum recoverable thermal energy over a six-month period is, thus, 1.15×10^{10} Btu or ∿40% of the schools' Btu demand. Preliminary injectivity tests performed during the pump tests, together with log analysis, indicate that the spent geothermal brine can be reinjected down the annulus into the adjacent Black River Formation.

The production rate for tapping the geothermal potential by reinjecting or recirculating the spent geothermal brine was selected to be 286 gpm. This flowrate was averaged from the maximum drawdown rate for a pump setting at 4,000 ft., and the minimum drawdown rate which can meet the schools' average daily Btu demand. The selected production rate would supply 3.3×10^{10} Btu over a six-month period, or 117% of the schools' Btu demand. The proved lifetime of the reinjection reserves is estimated to be just in excess of 10 years.

Section 7

REFERENCES

1. Agarwal, Ram G., Al-Hussany, Rafi, and Ramey, H.J., Jr.: "An Investigation of Wellbore Storage and Skin Effect in Unsteady Liquid Flow: I. Analytic Treatment." Soc. Pet. Eng. J., (Sept. 1970) 279-290.

2. American Industrial Disposal Systems, Inc.: "Feasibility Report on Underground Fluid Waste Disposal for the Hooker Chemical Corporation, Niagara Falls, New York: 01 November, 1967.

3. American Industrial Disposal Systems, Inc.: "Completion Report, Waste Disposal Test Well-WPL #1, Lackawanna Plant, Bethlehem Steel Corporation, Erie County, New York," 06 August 1968.

4. Bixel, H.C., Larkin, B.K., and van Pollen, H.K.: "Effect of Linear Discontinuities on Pressure Build-Up and Draw-Down Behavior," J. Pet. Tech. (Aug. 1963) 885-895.

5. Dodson, C.R. and Standing, M.B.: "Pressure-Volume-Temperature and Solubility Relations for Natural-Gas-Water Mixtures," Drill. and Prod. Prac., API (1944) 173-179.

6. Dunn Geoscience Corp.: "Preliminary Report on the Auburn Geothermal Test Well," to Mr. Robert S. Lynch on 16 June 1982.

7. Earlougher, R.C., Jr.: "Advances in Well Test Analysis," Monograph Series, Society of Petroleum Engineers of AIME, Dallas, Texas (1977) 5.

8. Elkins, L.F.: "Reservoir Performance and Well Spacing; Sprayberry Trend Area Field of West Texas," Trans., AIME (1953) 198, 177-196.

9. Gringarten, A.C., Ramey, H.J., Jr., and Raghavan, R.: "Pressure Analysis for Fractured Wells," SPE # 405 presented at the SPE-AIME 47th Annual Fall Meeting, San Antonio, Texas, Oct. 8-11, 1972.

10. Gringarten, A.C., Ramey, H.J., Jr. and Raghavan, R.: "Unsteady-State Pressure Distributions Created by a Well with a Single Infinite-Conductivity Vertical Fracture," Soc. Pet. Eng. J. (Aug. 1974) 347-360.

11. Gringarten, A.C. and Sauty, J.P.: "A Theoretical Study of Heat Extraction from Aquifers with Uniform Regional Flow," J. Geophys. Res., Vol. 80, No. 35 (1975) 4956-4962.

12. Hickman, S.H., Healy, J.H. and Zoback, M.D.: "In-Situ Stress, Natural Fracture Distribution, and Borehole Elongation at Depth in the Auburn Geothermal Well, Auburn, New York," United States Geological Survey, 449A/ET/FUC/82, June 1983.

13. Horner, D.R.: "Pressure Build-Up in Wells," Proc., Third World Pet. Cong., The Hague (1951) Sec. II, 503-523.

14. Kazemi, H.: "Pressure Transient Analysis of Naturally Fractured Reservoirs with Uniform Fracture Distribution," Soc. Pet. Eng. J. (Dec. 1969) 451-562.

15. Kazemi, H., Seth, M.S., and Thomas, G.W.: "The Interpretation of Interference Tests in Naturally Fractured Reservoirs with Uniform Fracture Distribution," Soc. Pet. Eng. J., (Dec. 1969) 463-472.

16. Long, G. and Chierici, G.: "Salt Content Changes Compressibility of Reservoir Brines," Petroleum Engineer (July, 1961) B-25 to B-31.

17. Matthews, C.S. and Russel, D.G.: " Pressure Buildup and Flow Test in Wells," Monograph Series, Society of Petroleum Engineers of AIME, Dallas, (1967) 1.

18. Miller, C.C., Dyes, A.B., and Hutchinson, C.A., Jr.: "The Estimation of Permeability and Reservoir Pressure from Bottom Hole Pressure Build-Up Characteristics," Trans., AIME (1950) 189, 91-104.

19. Newman, G.H.: "Pore-Volume Compressibility of Consolidated, Friable and Unconsolidated Reservoir Rocks Under Hydrostatic Loading," J. Pet. Tech. (Feb. 1973) 129-134.

20. Odeh, A.S. and Selig, F.: "Pressure Build-Up Analysis, Variable Rate Case," J. Pet. Tech. (July 1963) 790-794; also Reprint Series No. 9 - Pressure Analysis Methods, Society of Petroleum Engineers of AIME, Dallas, (1967) 131-135.

21. Plumb, R.A. and Singer, J.: "Insights into the Mechanical Properties of Tight Formations: A Study of In-Situ Stress and Fracture Distribution at Auburn, New York," Schlumberger-Doll Research, NYSERDA (Report 84-1), Part II, 1984.

22. Ramey, H.J., Jr.: "Wellbore Heat Transmission," J. Pet. Tech. (April 1962) 427-434.

23. Ramey, H.J., Kumar, A. and Gulati, M.S.: "Gas Well Test Analysis Under Water-Drive Conditions, " AGA, Arlington, Va (1973).

24. Ramey, H.J., Jr.: "Practical Use of Modern Well Test Analysis," 46th Annual California Regional Meeting of the Society of Petroleum Engineers of AIME SPE #5878.

25. Schafer, D.C.: "Pumping Test Analyses for Low Yield Formations," The Johnson Driller's Journal (Nov.-Dec., 1980) 3-4.

26. Stearns, D.W. and Friedman, M.: "Reservoirs in Fractured Rock," AAPG Memoir 16 (1972) 82-106.

27. Strobel, C.J., Gulati, M.S. and Ramey, H.J., Jr.: "Reservoir Limit Tests in a Naturally Fractured Reservoir--A Field Case Study Using Type Curves," J. Pet. Tech. (Sept. 1976) 1097-1106.

28. Sutter, A.: "Heat Losses During Flow of Steam Down a Wellbore," J. Pet. Tech. (July 1965) 845-851.

29. Theis, C.V.: "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage," Trans. AGU (1935) 519-524.

30. Warren, J.E., and Root, P.J.: "The Behavior of Naturally Fractured Reservoirs," Soc. Pet. Eng. J., (Sept. 1963) 245-255.

Section 8

NOMENCLATURE

A	areal extent, acres
A'	thermal penetration time function, ft
a'	geothermal gradient, $^{o}F/ft$
a	linear distance from fault, ft
B	formation volume factor, bbl/STB
b	geothermal temperature at T_{out}, ^{o}F
C	wellbore storage constant, bbl/psi
c_p	specific heat at constant pressure, Btu/lb - ^{o}F
c	compressibility, psi^{-1}
D	characteristic separation distance between discharging - recharging well pair, ft
d_t; d_{ti}	outer and inner tube diameter, ft
E_h	heat recovery or capture efficiency, dimensionless
f(t)	transient heat conduction time function of earth, dimensionless
H	hydrothermal resources, Btu
h	formation thickness, ft
h_c; h_r	convective and radiative heat transfer coefficients, dimensionless
K	Secenov's coefficient, dimensionless
k	effective permeability, millidarcy
k_s	thermal conductivity of medium s, Btu/lb - ^{o}F
m	slope of semi-log plot such as Horner or Miller-Dyes-Hutchinson
$\dot{m}$	mass flowrate, lbs/hr
N	number of stages or steps
Nu	Nusselts number, $h_c d_t / k_w$, dimensionless
n	dissolved solids concentration, gram-equivalents/litre
P	pressure, psi
Pr	Prandlt number, $c_p \mu_w / k_w$, dimensionless
Q	heat flux, Btu/hr
q	production or pumping rate, gpm, STB/D or ft^3/hr
Re	Reynolds number, $\rho_w v d_{ti} / \mu_w$, dimensionless
R_{sw}	gas solubility in water, SCF/STB
r	radius, ft

rps	revolutions per second
s	fluid streamline, dimensions of area
S_w	water saturation, dimensionless
s	skin factor, dimensionless
T	temperature, ^oF
T.D.; TD	total depth, ft
TDS	totaled dissolved solids, ppm
t	time, hours or days
U_o	overall heat transfer coefficient, Btu/hr - ft^2-F
V	fluid volume, bbl
v	superficial fluid velocity, ft/hr
W	volumetric resources, STB
w	width of stream channel, dimensions of length
x	half length of hydraulic fracture, ft
z	depth from surface, ft

Greek Symbols

α	thermal diffusivity of earth, $k_e/c_e\rho_e$, dimensionless
γ	Euler's constant, 1.78
Δ	difference operator
μ	viscosity, centipoise
$\mathcal{O}$	"on the order of"
ρ	density, lb/ft^3
ϕ	porosity, dimensionless
ψ	stream function, dimensionless
λ,ω	interporosity flow and storage parameters
χ	dimensionless heat transfer parameter

Subscripts

a	aquifer
BH	bottom hole
b	bulk
cem	cement
co	outer edge of casing
D	dimensionless
Dxf	dimensionless half-fracture
e	earth or extent
f	final or fracture
h	outer edge cement
i	initial

in	pump inlet
inj	injection
ins	insulation
j	mathematical counter
ma	matrix
max	maximum function
min	minimum function
o	initial or overall
out	tubing outlet at the wellhead
p	modification
r	rock
res	reservoir
surf	surface
s	sample point
t	total effective or tubing
to	outer edge of tubing
vf	vertical fracture
Wb	wellbore
wf	flowing wellbore
ws	shut-in wellbore

Superscripts

—	average
*	extrapolated or modified value

Appendix B.1

PUMP TEST DATA

Table B.1-1

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF PRELIMINARY TEST

REAL TIME	Δt	P	ΔP
11:49:03	0	1757.93	
11:50:04	1.02	1738.53	19.40
11:51:07	2.07	1724.99	32.94
11:52:03	3.00	1716.10	41.83
11:53:04	4.02	1708.94	48.99
11:54:07	5.07	1703.71	54.22
11:55:03	6.00	1698.64	59.29
11:57:06	8.05	1690.41	67.52
12:00:05	11.03	1677.33	80.60
12:03:05	14.03	1665.26	92.67
12:06:04	17.02	1658.86	99.07
12:09:04	20.02	1654.85	103.08
12:12:00	23.00	1651.21	106.72
12:15:00	26.00	1645.74	112.19
12:20:00	31.00	1635.05	122.88
12:25:00	36.00	1626.83	131.10
12:30:00	41.00	1625.75	132.18
12:35:00	46.00	1626.59	131.34
12:40:00	51.00	1628.31	129.62
12:45:00	56.00	1630.92	127.01
12:50:00	61.00	1632.72	125.21
12:55:00	66.00	1633.69	124.24
13:00:00	71.00	1633.98	123.95
13:05:00	76.00	1634.64	123.29
13:10:00	81.00	1634.69	123.24
13:15:00	86.00	1634.14	123.79
13:20:00	91.00	1633.66	124.27
13:25:00	96.00	1633.08	124.85
13:28:31	99.50	1632.98	124.95
13:30:01	101.00	1627.57	130.36
13:35:07	106.00	1617.54	140.39
13:40:03	111.00	1614.80	143.13
13:45:08	116.00	1615.54	142.39
13:50:05	121.00	1605.30	152.63
13:55:09	126.00	1596.90	161.03
14:00:04	131.00	1587.38	170.55
15:05:01	136.00	1579.46	178.47
14:10:04	141.00	1571.85	186.08
14:15:01	146.00	1574.84	183.09
14:20:01	151.00	1571.75	186.18
14:25:07	156.00	1557.65	200.28
14:31:00	162.00	1548.74	209.19
14:35:00	166.00	1545.69	212.24
14:40:00	171.00	1550.47	207.46
14:45:00	176.00	1550.41	207.52
14:50:00	181.00	1547.25	210.68
14:55:00	186.00	1543.50	214.43

Table B.1-1 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF PRELIMINARY TEST

REAL TIME	Δt	P	ΔP
15:00:00	191.00	1543.65	214.28
15:04:58	196.00	1541.50	216.43
15:05:58	197.00	1536.55	221.38
15:06:58	198.00	1532.02	225.91
15:07:58	199.00	1527.85	230.08
15:09:00	200.00	1524.63	233.30
15:09:58	201.00	1521.82	236.11
15:11:58	203.00	1517.05	240.88
15:14:03	205.00	1511.45	245.48
15:15:01	206.00	1509.36	248.57
15:20:00	211.00	1498.55	259.38
15:25:00	216.00	1490.31	267.62
15:30:00	221.00	1483.09	274.84
15:35:00	226.00	1473.83	284.10
15:40:00	231.00	1467.12	290.81
16:00:00	251.00	1464.68	293.25
16:20:00	271.00	1457.48	300.45
16:40:00	291.00	1426.00	331.93
17:00:00	311.00	1414.77	343.15
17:20:00	331.00	1412.67	345.26
17:40:00	351.00	1379.16	378.77
18:00:00	371.00	1366.64	391.29
18:20:00	391.00	1356.93	401.00
18:40:00	411.00	1346.96	410.97
19:00:00	431.00	1337.25	420.68
19:05:01	436.00	1335.40	422.53

Table B.1-2

AUBURN GEOTHERMAL WELL-PRESSURE BUILDUP DATA OF PRELIMINARY TEST

REAL TIME	Δt (mins)	(t+Δt)/Δt	P (psia)	ΔP (psia)
(08/02/83)				
19:05:01	0.00		1335.40	0.00
19:05:36	0.58	748.40	1375.82	40.42
19:06:01	1.00	437.00	1399.48	64.08
19:06:35	1.56	279.29	1426.50	91.10
19:07:09	2.13	205.37	1450.81	115.41
19:07:35	2.56	170.87	1466.51	131.11
19:08:00	2.98	147.14	1480.55	145.15
19:08:29	3.46	126.76	1498.00	157.60
19:08:59	3.96	110.49	1507.06	171.66
19:09:29	4.46	98.61	1516.05	180.65
19:09:59	4.96	88.78	1526.28	190.88
19:10:29	5.46	80.75	1532.41	197.01
19:10:59	5.96	74.07	1539.11	203.71
19:11:29	6.46	68.42	1543.73	208.33
19:11:59	6.96	63.58	1546.39	210.99
19:12:29	7.46	59.39	1549.88	214.48
19:12:59	7.96	55.72	1552.15	216.75
19:13:59	8.96	49.62	1557.21	221.81
19:14:59	9.96	44.74	1561.97	226.57
19:16:33	11.53	38.80	1568.12	232.72
19:18:00	12.98	34.58	1573.43	238,03
19:20:00	14.98	30.09	1577.68	242.28
19:22:00	16.98	26.67	1580.67	245.27
19:24:00	18.98	23.96	1587.53	252.13
19:26:00	20.98	21.77	1588.11	252.71
19:28:00	22.98	19.97	1589.11	253.71
19:30:00	24.98	18.45	1590.64	255.24
19:35:00	29.98	15.54	1599.55	264.15
19:40:00	34.98	13.49	1602.89	267.49
19:45:00	39.98	11.90	1605.61	270.21
19:47:14	42.21	11.33	1605.40	270.00
19:52:03	47.03	10.27	1609.77	274.37
19:57:03	52.03	9.38	1613.91	278.51
20:02:03	57.03	8.64	1618.97	283.57
20:18:03	73.03	6.96	1628.82	293.42
20:33:03	88.03	5.94	1632.45	297.05
20:48:03	103.03	5.23	1637.12	301.72
21:03:03	118.03	4.69	1642.00	306.60
21:18:03	133.03	4.28	1646.76	311.36
21:33:03	148.03	3.95	1649.61	314.21
21:48:03	163.03	3.67	1651.84	316.44
22:03:03	178.03	3.45	1656.42	321.02
22:33:00	208.03	3.10	1659.67	324.27
23:03:03	238.03	2.83	1663.48	328.08

Table B.1-2 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE BUILDUP DATA OF PRELIMINARY TEST

REAL TIME	Δt (mins)	(t+Δt)/Δt	P (psia)	ΔP (psia)
(08/03/83)				
00:03:03	298.03	2.46	1666.75	331.35
01:03:03	358.03	2.22	1674.09	338.69
02:03:03	418.03	2.04	1667.26	341.86
03:03:03	478.03	1.91	1679.98	344.58
04:03:03	538.03	1.81	1682.33	346.93
05:03:03	598.03	1.73	1684.17	348.77
06:03:03	658.03	1.66	1685.83	350.43
07:03:03	718.03	1.61	1687.27	351.87
08:03:03	778.03	1.56	1688.65	353.25
09:18:00	852.98	1.51	1689.99	354.59
09:30:00	864.98	1.50	1690.22	354.82

Table B.1-3

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF 24 HOUR TEST

REAL TIME	Δt	P	ΔP
09:30:00	0	1690.22	0
09:30:15	0.25	1649.71	40.51
09:30:45	0.75	1636.71	53.51
09:31:15	1.25	1626.39	63.83
09:31:45	1.75	1629.39	60.83
09:32:51	2.85	1626.95	63.27
09:33:49	3.82	1619.32	70.90
09:34:47	4.78	1612.98	77.24
09:35:46	5.77	1606.50	83.72
09:36:45	6.75	1600.58	89.64
09:37:45	7.75	1595.35	94.87
09:38:45	8.75	1590.63	99.59
09:39:45	9.75	1585.65	104.57
09:43:00	13.00	1561.70	238.52
09:44:42	14.70	1553.18	137.04
09:48:13	18.22	1527.13	163.09
09:50:30	20.50	1509.52	180.70
09:55:00	25.00	1474.56	215.66
10:00:04	30.07	1453.50	236.72
10:05:04	35.07	1439.32	250.90
10:10:00	40.00	1428.53	261.69
10:15:00	45.00	1420.09	270.13
10:20:00	50.00	1413.17	277.05
10:25:00	55.00	1406.70	283.52
10:30:00	60.00	1400.69	289.53
10:35:00	65.00	1394.87	295.35
10:40:00	70.00	1389.46	300.76
10:50:00	80.00	1379.74	310.48
11:00:00	90.00	1371.23	318.99
11:17:42	107.70	1358.23	331.99
11:27:03	117.05	1352.19	338.03
11:47:03	137.05	1341.08	349.14
12:07:03	157.05	1332.05	358.17
12:27:03	177.05	1323.05	367.17
12:47:03	197.05	1315.36	374.86
13:07:03	217.05	1307.89	382.33
13:27:03	237.05	1300.73	389.49
13:47:03	257.05	1293.81	396.41
14:07:03	277.05	1287.60	402.62
14:37:03	307.05	1278.52	411.70
15:07:03	337.05	1269.84	420.38
15:37:03	367.05	1262.21	428.01

Table B.1-3 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF 24 HOUR TEST

REAL TIME	Δt	P	ΔP
16:07:03	397.05	1255.05	435.17
16:37:03	427.05	1247.33	442.89
17:07:03	457.05	1239.81	450.29
17:37:03	487.05	1233.93	456.29
18:07:03	517.05	1227.41	462.81
19:07:03	577.05	1217.61	472.61
20:17:03	647.05	1205.12	485.10
21:17:03	707.05	1195.43	494.79
22:17:03	767.05	1186.62	503.60
23:17:03	827.05	1178.73	511.49
00:17:03	887.05	1168.45	521.77
01:17:03	947.05	1159.01	531.21
02:17:03	1017.05	1151.20	539.02
03:17:03	1077.05	1143.35	546.87
04:17:03	1137.05	1136.53	553.69
05:17:03	1197.05	1129.75	560.47
06:17:03	1257.05	1123.37	566.85
07:17:03	1307.05	1116.75	573.47
08:17:03	1367.05	1109.61	580.61
09:17:03	1427.05	1102.61	587.61
09:31:03	1441.05	1101.25	

Table B.1-4

AUBURN GEOTHERMAL WELL-PRESSURE BUILDUP DATA OF 24 HOUR TEST

REAL TIME	Δt (mins)	(t+Δt)/Δt	P (psia)	ΔP (psia)
(08/04/83)				
09:30:41	0.00		1101.25	0.00
09:31:12	0.52	4096.00	1151.36	50.11
09:31:45	1.07	1991.00	1179.96	78.71
09:32:11	1.50	1421.00	1212.61	111.36
09:32:44	2.05	1040.00	1235.72	134.47
09:33:11	2.50	853.00	1258.69	157.44
09:33:44	3.05	699.00	1278.62	177.37
09:34:17	3.60	593.00	1297.11	195.86
09:34:52	4.18	510.00	1309.72	208.47
09:35:26	4.75	449.00	1319.01	217.76
09:36:01	5.33	401.00	1324.86	223.61
09:36:52	6.18	346.00	1333.59	232.34
09:37:51	7.17	298.00	1341.37	240.12
09:39:11	8.50	252.00	1350.35	249.10
09:40:11	9.50	225.00	1356.51	255.26
09:42:11	11.50	186.00	1364.41	263.16
09:43:11	12.50	171.00	1370.16	268.91
09:45:11	14.50	148.00	1377.07	275.82
09:48:11	17.50	123.00	1381.20	279.95
09:51:19	20.63	104.00	1389.34	288.09
09:54:00	23.31	92.40	1395.51	294.26
09:59:41	29.00	74.40	1402.14	300.89
10:02:00	31.32	70.00	1405.30	304.05
10:07:00	36.32	59.60	1412.90	311.65
10:12:00	41.32	52.50	1418.92	317.67
10:17:00	46.32	47.00	1421.16	319.91
10:22:00	51.32	42.50	1426.66	325.41
10:30:00	59.32	36.90	1431.96	330.71
10:40:00	69.32	31.80	1441.32	340.07
10:50:00	79.32	27.90	1446.75	345.50
11:00:00	89.32	24.80	1451.71	350.46
11:10:00	99.32	22.40	1457.53	356.28
11:32:03	121.37	18.50	1470.88	369.63
11:52:03	141.37	16.10	1476.59	375.34
12:02:03	151.37	15.10	1480.90	379.65
12:22:03	171.37	13.40	1487.31	386.06
12:42:03	191.37	12.10	1493.89	392.64
13:02:03	211.37	11.10	1502.42	401.17
13:32:03	241.37	9.82	1513.39	412.14
14:02:03	271.37	8.85	1516.71	415.46
14:32:03	301.37	8.07	1525.01	423.76
15:02:03	331.37	7.43	1528.73	427.48
15:32:03	361.37	6.89	1534.05	432.80
16:02:03	391.37	6.44	1538.98	437.73
16:32:03	421.37	6.05	1543.38	442.13
17:02:03	451.37	5.72	1547.50	446.25
18:03:03	512.37	5.16	1554.84	453.59
19:03:03	572.37	4.72	1561.26	460.01

Table B.1-4 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE BUILDUP DATA OF 24 HOUR TEST

REAL TIME	Δt (mins)	(t+Δt)/Δt	P (psia)	ΔP (psia)
20:03:03	632.37	4.37	1567.06	465.81
21:03:03	692.37	4.08	1572.15	470.90
22:03:03	752.37	3.83	1576.91	475.66
23:03:03	812.37	3.62	1581.28	480.03
(08/05/83)				
00:03:03	872.37	3.44	1585.17	483.92
01:03:03	932.37	3.28	1588.72	487.47
02:03:03	992.37	3.15	1592.27	491.02
03:03:03	1052.37	3.02	1595.46	494.21
04:03:03	1112.37	2.91	1598.50	497.25
05:03:03	1172.37	2.82	1601.19	499.94
06:03:03	1232.37	2.73	1603.88	502.63
07:03:03	1292.37	2.65	1606.45	505.20
08:03:03	1352.37	2.57	1608.86	507.61
09:09:03	1418.37	2.50	1611.35	510.10
10:09:03	1478.37	2.44	1613.56	512.31
11:09:03	1538.37	2.38	1615.65	514.40
12:11:03	1600.37	2.33	1617.79	516.54
12:31:17	1620.60	2.31	1618.42	517.17
12:39:37	1628.93	2.31	1618.69	517.44

Table B.1-5

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF MULTIRATE TEST

REAL TIME	Δt (mins)	P (psia)	ΔP (psia)
(08/05/83)			
12:59:57		1618.89	
13:00:00	0.00		
13:00:17	0.28	1563.37	55.00
13:00:37	0.61	1547.90	70.99
13:00:57	0.94	1549.77	69.12
13:01:57	1.94	1549.77	69.12
13:02:57	2.94	1545.94	72.95
13:04:57	4.94	1541.43	77.46
13:05:57	5.94	1534.49	84.40
13:06:17	6.27	1527.60	91.29
13:06:57	6.94	1521.52	97.37
13:07:17	7.27	1518.15	100.74
13:08:17	8.27	1511.15	107.74
13:09:17	9.27	1504.73	114.16
13:10:17	10.27	1499.23	119.66
13:11:17	11.27	1487.41	131.48
13:11:57	11.94	1475.40	143.49
13:12:17	12.27	1471.12	147.77
13:12:57	12.94	1461.08	157.81
13:13:17	13.27	1457.25	161.64
13:14:17	14.27	1445.39	173.50
13:15:17	15.27	1434.86	184.03
13:16:17	16.27	1425.69	193.20
13:17:17	17.27	1417.42	201.47
13:18:17	18.27	1407.02	211.87
13:20:17	20.27	1396.54	222.35
13:22:17	22.27	1386.05	232.84
13:24:17	24.27	1377.08	241.81
13:26:17	26.27	1367.90	250.99
13:28:17	28.27	1362.47	256.42
13:30:17	30.27	1356.65	262.24
13:33:00	33.00	1349.70	269.19
13:35:00	35.00	1345.25	273.64
13:40:00	40.00	1335.18	283.71
13:45:00	45.00	1326.64	292.25
13:50:00	50.00	1319.02	299.87
13:55:00	55.00	1312.03	306.86
14:00:00	60.00	1305.85	313.04
15:10:00	70.00	1295.36	323.53
14:20:00	80.00	1234.70	384.19
14:21:00	81.00	1233.68	385.21
14:22:00	82.00	1274.33	344.56
13:23:00	83.00	1262.94	355.95
14:24:00	84.00	1252.56	366.33
14:25:00	85.00	1242.90	375.99

Table B.1-5 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF MULTIRATE TEST

REAL TIME	Δt (mins)	P (psia)	ΔP (psia)
14:26:00	86.00	1234.28	384.61
14:27:00	87.00	1226.72	392.17
14:28:00	88.00	1220.01	398.88
14:29:00	89.00	1212.40	406.49
13:30:00	90.00	1206.31	412.58
14:31:00	91.00	1201.86	417.03
14:32:00	92.00	1196.76	422.13
14:33:00	93.00	1192.89	426.00
14:34:00	94.00	1188.66	430.23
14:35:00	95.00	1184.53	434.36
14:36:00	96.00	1180.96	437.93
13:37:00	97.00	1177.88	441.01
14:38:00	98.00	1175.34	443.55
14:39:00	99.00	1173.05	445.84
14:40:00	100.00	1170.74	448.15
14:42:00	102.00	1166.38	452.51
14:44:00	104.00	1162.42	456.47
14:46:00	106.00	1158.55	460.34
14:50:00	110.00	1152.13	466.76
14:55:00	115.00	1140.56	478.33
15:00:00	120.00	1126.75	492.14
15:05:00	125.00	1117.01	501.88
15:10:00	130.00	1109.31	509.58
15:15:00	135.00	1103.29	515.60
15:20:00	140.00	1098.73	520.16
15:25:00	145.00	1094.11	524.78
15:30:00	150.00	1089.49	529.40
15:41:03	161.05	1079.25	539.64
15:51:03	171.05	1071.07	547.82
16:01:03	181.05	1064.22	554.67
16:21:03	201.05	1051.01	567.88
16:41:03	221.05	1039.37	579.52
17:01:03	241.05	1028.55	590.34
17:31:03	271.05	1013.85	605.04
18:01:03	301.05	999.32	619.57
18:32:03	332.05	984.63	634.26
19:02:03	362.05	971.64	647.25
19:32:03	392.05	957.51	661.38
20:02:03	422.05	944.16	674.73
20:32:03	452.05	932.12	686.77
21:02:03	482.05	920.54	698.35
21:32:03	512.05	908.12	710.77
22:02:03	542.05	895.59	723.30
22:32:03	572.05	883.14	735.75
23:02:03	602.05	870.82	748.07
23:32:03	632.05	858.20	760.69

Table B.1-5 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF MULTIRATE TEST

REAL TIME	Δt (mins)	P (psia)	ΔP (psia)
(08/06/83)			
00:02:03	662.05	845.86	773.03
01:02:03	722.05	820.49	798.40
02:02:03	782.05	796.23	822.66
03:02:03	842.05	770.95	847.94
04:02:03	902.05	746.43	872.46
05:02:03	962.05	721.34	897.55
06:02:03	1022.05	696.72	922.17
07:02:03	1082.05	649.73	969.16
08:02:03	1142.05	619.85	999.04
09:02:03	1202.05	590.83	1028.06
10:02:03	1262.05	553.26	1065.63
11:02:03	1322.05	542.84	1076.05
12:02:03	1382.05	513.13	1105.76
13:02:03	1442.05	469.14	1149.75
14:02:03	1502.05	430.03	1188.86
14:32:03	1532.05	407.22	1211.67
14:38:31	1538.52	403.53	1215.36
14:39:11	1539.19	404.55	1214.34
14:39:51	1539.86	407.74	1211.15
14:40:31	1540.53	410.58	1208.31
14:41:31	1541.53	414.30	1204.59
14:42:31	1542.53	418.53	1200.36
14:43:31	1543.53	421.96	1196.93
14:44:31	1544.53	425.10	1193.79
14:45:31	1545.53	427.89	1191.00
14:46:31	1546.53	430.69	1188.20
14:47:31	1547.53	433.51	1185.38
14:48:31	1548.53	435.80	1183.09
14:49:31	1549.53	437.95	1180.94
14:50:31	1550.53	439.93	1178.96
14:52:31	1552.53	442.89	1176.00
14:54:31	1554.53	446.45	1172.44
14:56:31	1556.53	448.52	1170.37
14:58:31	1558.53	450.94	1167.95
15:00:31	1560.53	452.83	1166.06
15:05:31	1565.53	455.97	1162.92
15:10:31	1570.53	458.02	1160.87
15:16:03	1576.05	459.07	1159.82
15:26:03	1586.05	459.57	1159.32
15:36:03	1596.05	458.51	1160.38
15:46:03	1606.05	456.36	1162.53
15:56:03	1616.05	454.33	1164.56
16:02:43	1622.72	452.92	1165.97
16:17:03	1637.05	449.13	1169.76
16:30:03	1650.05	444.58	1174.31

Table B.1-5 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF MULTIRATE TEST

REAL TIME	Δt (mins)	P (psia)	ΔP (psia)
16:45:03	1665.05	439.59	1179.30
17:00:03	1680.05	434.95	1183.94
17:15:03	1695.05	430.28	1188.61
17:30:03	1710.05	425.29	1193.60
17:45:03	1725.05	420.52	1198.37
18:00:03	1740.05	415.46	1203.43
18:30:03	1770.05	407.92	1210.97
19:00:03	1800.05	400.66	1218.23
19:30:03	1830.05	390.97	1227.92
20:00:03	1860.05	381.34	1237.55
20:30:03	1890.05	371.28	1247.61
21:00:03	1920.05	361.98	1256.91
21:30:03	1950.05	351.31	1267.58
22:00:03	1980.05	340.05	1278.84
22:30:03	2010.05	319.73	1299.16
22:31:00	2011.00	319.21	1299.68
22:32:00	2012.00	320.91	1297.98
22:32:30	2012.50	323.25	1295.64
22:33:00	2013.00	324.77	1294.12
22:33:30	2013.50	326.60	1292.29
22:34:00	2014.00	328.00	1290.89
22:34:30	2014.50	330.27	1288.62
22:35:00	2015.00	332.18	1286.71
22:35:30	2015.50	333.53	1985.36
22:36:00	2016.00	335.45	1283.44
22:37:00	2017.00	338.42	1280.47
22:38:00	2018.00	341.44	1277.45
22:39:00	2019.00	345.34	1273.55
24:40:00	2020.00	349.10	1269.79
22:41:00	2021.00	352.64	1266.25
22:42:00	2022.00	355.77	1263.12
22:43:00	2023.00	359.18	1259.71
22:44:00	2024.00	362.05	1256.84
22:45:00	2025.00	364.78	1254.11
22:46:59	2026.98	369.58	1249.31
22:47:59	2027.98	371.97	1246.92
22:48:59	2028.98	374.09	1244.80
22:50:59	2030.98	377.91	1240.98
22:52:59	2032.98	381.34	1237.55
22:54:59	2034.98	384.18	1234.71
22:56:59	2036.98	386.98	1231.91
22:58:59	2038.98	389.23	1229.66
23:00:59	2040.98	391.46	1227.43
23:02:59	2042.98	393.33	1225.56
23:05:59	2045.98	395.79	1223.10
23:10:59	2050.98	399.12	1219.77

Table B.1-5 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE DRAWDOWN DATA OF MULTIRATE TEST

REAL TIME	Δt (mins)	P (psia)	ΔP (psia)
23:15:59	2055.98	401.63	1217.26
23:20:59	2060.98	403.23	1215.66
23:25:59	2065.98	404.37	1214.52
23:30:03	2070.05	405.34	1213.55
23:40:03	2080.05	406.39	1212.50
23:45:03	2085.05	406.31	1212.58
23:50:03	2090.05	405.86	1213.03
23:55:03	2095.05	405.28	1213.61
(08/07/83)			
00:00:03	2100.05	404.60	1214.29
00:15:03	2115.05	403.68	1215.21
00:30:03	2130.05	401.69	1217.20
00:45:03	2145.05	398.61	1220.28
01:00:03	2160.05	395.53	1223.36
01:30:03	2190.05	391.27	1227.62
02:00:03	2220.05	385.68	1233.21
02:30:03	2250.05	380.87	1238.02
03:00:03	2280.05	375.31	1243.58
03:30:03	2310.05	369.47	1249.42
04:00:03	2340.05	364.07	1254.82
05:00:03	2400.05	354.10	1264.79
06:00:03	2460.05	343.59	1275.30
06:15:03	2475.05	340.29	1278.60

Table B.1-6

AUBURN GEOTHERMAL WELL-PRESSURE BUILDUP DATA OF MULTIRATE TEST

REAL TIME	Δt (mins)	(t+Δt)/Δt	P (psia)	ΔP (psia)
(08/07/83)				
06:30:00	0		426.24	85.96
06:30:20	0.33	17,137	449.28	109.00
06:30:40	0.67	8,441	479.32	139.04
06:31:00	1.00	5,656	498.51	158.28
06:31:20	1.33	4,253	526.05	185.77
06:31:40	1.67	3,387	543.41	203.13
06:32:00	2.00	2,828	568.12	227.84
06:32:20	2.33	2,428	583.86	243.58
06:32:40	2.67	2,119	598.64	258.36
06:33:00	3.00	1,886	619.67	279.39
06:33:20	3.33	1,699	632.70	292.42
06:33:40	3.67	1,542	651.16	310.88
06:34:00	4.00	1,415	662.70	322.42
06:34:20	4.33	1,307	673.40	333.12
06:34:40	4.67	1,212	687.64	347.36
06:35:00	5.00	1,132	695.94	355.66
06:36:00	6.00	944	722.93	382.65
06:37:00	7.00	809	744.94	404.66
06:38:00	8.00	708	763.58	423.30
06:39:00	9.00	629	778.70	438.41
06:40:00	10.00	567	793.63	453.35
06:41:00	11.00	515	808.20	467.91
06:42:00	12.00	472	822.28	482.00
06:43:00	13.00	436	837.87	497.59
06:44:00	14.00	405	850.63	510.35
06:45:00	15.00	378	863.40	523.12
06:46:00	16.00	355	875.98	535.70
06:47:00	17.00	334	887.73	547.45
06:48:00	18.00	315	899.30	559.02
06:49:00	19.00	299	912.28	572.00
06:50:00	20.00	284	923.15	582.88
06:51:00	21.00	270	933.88	593.60
06:52:00	22.00	258	944.00	603.72
06:53:00	23.00	247	954.00	613.72
06:54:00	24.00	237	963.49	623.20
06:55:00	25.00	227	973.67	633.39
06:56:00	26.00	219	982.72	642.44
06:57:00	27.00	210	991.19	650.90
06:58:00	28.00	203	999.47	659.19
06:59:00	29.00	196	1007.45	667.17
07:00:00	30.00	190	1015.39	675.11
07:05:00	35.00	163	1051.30	711.02
07:10:00	40.00	143	1081.38	741.10
07:15:00	45.00	127	1105.64	765.37
07:20:00	50.00	114	1126.92	786.64
07:25:00	55.00	104	1144.37	804.09
07:30:00	60.00	95	1156.03	815.75
07:45:00	75.00	77	1191.10	850.79

Table B.1-6 (Cont'd)

AUBURN GEOTHERMAL WELL-PRESSURE BUILDUP DATA OF MULTIRATE TEST

REAL TIME	Δt (mins)	(t+Δt)/Δt	P (psia)	ΔP (psia)
08:00:00	90	63.8	1212.38	872.10
08:15:00	105	54.9	1228.12	887.84
08:30:00	120	48.1	1241.00	900.69
09:00:00	150	38.7	1261.31	921.03
09:30:00	180	32.5	1293.12	952.84
11:00:00	270	21.9	1317.29	977.00
12:00:00	330	18.1	1336.70	996.41
13:00:00	390	15.5	1352.90	1012.61
14:00:00	450	13.6	1366.82	1026.54
15:00:00	510	12.0	1378.95	1038.68
16:00:00	570	10.9	1389.63	1049.35
17:00:00	630	10.0	1399.17	1058.89
18:00:00	690	9.2	1407.72	1067.44
19:00:00	750	8.5	1417.78	1077.50
20:00:00	810	8.0	1420.27	1080.00
22:00:00	930	7.1	1435.52	1095.24
(08/08/83)				
00:00:00	1050	6.4	1446.60	1106.32
02:00:00	1170	5.8	1456.60	1116.32
04:00:00	1290	5.4	1465.80	1125.52
06:00:00	1410	5.0	1474.00	1133.72
08:30:00	1560	4.6	1483.00	1142.72
(08/09/83)				
07:24:00	2934	2.9	1615.60	1275.32

Appendix B.2

FORMATION BRINE ANALYSES BY CAMBRIDGE ANALYTICAL ASSOCIATES (CAA),
WATERTOWN, MA

Cambridge Analytical Associates
222 Arsenal Street / Watertown, Massachusetts 02172 / (617)923-9376

FORMAL REPORT OF ANALYSIS

PREPARED FOR: Eng, Inc.
137 Newbury Street
Boston, MA 02116

CUSTOMER ORDER NUMBER:

CAMBRIDGE ANALYTICAL ASSOCIATES, INC.

REPORT NUMBER: 83-1004

DATE PREPARED: December 7, 1983

Cambridge Analytical Associates

TABLE OF CONTENTS

1. INTRODUCTION

This report summarizes results of chemical analyses performed on samples received by CAA on November 15, 1983. Analytical methods employed for these analyses are described in Section 2 and results are presented in Section 3. The last section contains quality control data and certifications supporting the analytical results.

2. ANALYTICAL METHODS

Analytical methods utilized for sample analysis are summarized in Table 1. For analysis of cations, the sample was boiled to resolubize crystallized salts; an aliquot was withdrawn and acidified with nitric acid to pH <2. Analyses were then performed on appropriate dilutions by inductively coupled argon plasma emission spectroscopy (ICP.)

3. RESULTS

Results of analyses are presented in Table 2.

Table 1

SUMMARY OF ANALYTICAL METHODS

Constituent	Method Reference	Method Description
pH	Method 150.1 (1)	Electrometric
Total dissolved solids	Method 160.1 (1)	Gravimetric, 180°C
Total alkalinity	Method 310.1 (1)	Titrimetric, pH 4.5
Chloride	Method 325.3 (1)	Titrimetric, mercuric nitrate
Sulfate	Method 375.4 (1)	Turbidimetric
Sulfite	Method 377.1 (1)	Titrimetric
<u>Metals</u>		
Na, Ca, Mg, Fe, Si, Mn, Sr, K, Ba, Li, V, B, Sn, Co	Method 200.1 (1)	ICP
Zn	Method 289.1 (1)	Flame atomic absorption
Ag	Method 272.1 (1)	Flame atomic absorption
As	Method 206.2 (1)	Graphite furnace atomic absorption

(1)U.S. EPA. 1979. Methods for Chemical Analysis of Water and Waste. EPA 600/4-79-020. EPA/EMSL, Cincinnati, Ohio.

Table 2

RESULTS OF CHEMICAL ANALYSES

Constituent	Client ID: / CAA ID:	14 8/2/83-17:15 8309248	24 8/4/83-05:30 8309249	34 8/6/83-16:30 8309250
pH		4.35;3.57[a]	5.19;4.09[a]	5.66;4.24[a]
Total dissolved solids (mg/l)		297,000	311,000	316,000
Total alkalinity (mg/l as $CaCO_3$)		0	10	17
Chloride (mg/l)		174,000	178,000	184,000
Sulfate (mg/l)		<10	<10	<10
Sulfite (mg/l)		<1	<1	<1
Na (mg/l)		55,000	61,000	64,000
Ca (mg/l)		19,000	19,000	19,000
Mg (mg/l)		2,600	2,600	2,700
Fe (mg/l)		150	78	50
Si (mg/l)		26	22	23
Mn (mg/l)		20	15	12
Sr (mg/l)		1,500	1,500	1,400
K (mg/l)		2,000	2,200	2,300
Ba (mg/l)		176	135	110
Li (mg/l)		62	63	63
V (mg/l)		1.1	1.4	0.70
B (mg/l)		13	16	17
Ag (mg/l)		0.20	0.22	0.19
Sn (mg/l)		63	63	66
Co (mg/l)		<5	<5	<5
Zn (mg/l)		1.2	0.52	0.23
As (mg/l)		<5	<5	<5

[a]Repeat analysis after sample was boiled.

Table 3

QUALITY CONTROL DATA
SPIKE RECOVERIES AND CHECK STANDARDS

Constituent	Client ID CAA ID	CONCENTRATION (PPM) Theoretical Value	Observed Value	Recovery (%)
Ca	Check Standard (EPA 478 #4)	32.0	33.2	104
	8309248 (1/30,000) spike	16.7	16.3	98
Fe	Check Standard (EPA 475 #3)	0.600	0.598	100
	8309248 (1/30,000) spike	3.33	3.29	99
Mg	Check Standard (EPA 478 #4)	7.10	7.76	109
	8309248 (1/30,000) spike	3.33	3.49	105
Mn	Check Standard (EPA 475 #3)	0.350	0.336	96
	8309248 (1/30,000) spike	3.33	3.19	96
Na	Check Standard (EPA 478 #4)	40.	36.4	91
	8309248 (1/30,000) spike	24.4	21.0	86
V	Check Standard (EPA 475 #3)	0.750	0.724	96
	8309248 (1/30,000) spike	3.33	3.27	98
K	Check Standard (EPA 478 #4)	7.20	7.60	106
	8309248 (1/30,000) spike	33.3	34.1	102
Si	Check Standard (Sci. Products)	2.00	1.98	99
	8309248 (1/500) spike	1.0	0.95	95
Zn	Check Standard (EPA 475 #3)	0.20	0.18	90
	8309249 spike	0.50	0.46	92
Ba	Check Standard (EPA 581 #2)	10.0	10.8	108
	8309248 (1/300) spike	1.50	1.45	96
Sr	8309248 (1/300) spike	0.50	0.49	98
Li	8309248 (1/300) spike	5.0	4.5	90
Sn	8309248 (1/300) spike	5.00	4.98	100
B	Check Standard (EPA ICAP-3)	1.00	1.01	101
	8309248 (1/300) spike	5.00	5.06	101
Ag	Check Standard (EPA ICAP-3)	1.0	1.0	100
	8309248 spike	0.25	0.22	88
Co	Check Standard (EPA 475 #3)	0.500	0.495	99
	8309248 (1/300) spike	5.00	4.66	93

4. QUALITY ASSURANCE DOCUMENTATION

4.1 Quality Control Data

Quality control data associated with the cation analyses are summarized in Table 3. These results consist of recoveries of spikes from analyte solutions and analysis of check standards.

4.2 Certification

This work has been checked for accuracy by the following staff personnel:

Director, Inorganic Chemistry Laboratory

Keith A. Hausknecht

Appendix B.3

FORMATION BRINE ANALYSES BY MICROBAC LABORATORIES, INC.

(MLI), ERIE, PA

MICROBAC LABORATORIES, INC.
ERIE TESTING LABORATORY DIVISION
2401 West 26th Street, Erie, Pennsylvania 16506
814/833-4790

AUG 2 5 1983
REC'D

AIR • FUEL • WATER • FOOD • WASTES

Eng., Inc.
137 Newberry Street
Boston, MA 02116

Date Reported: August 24, 1983
Date Received: August 5, 1983
Sample No.: 217-176, 236-05446

Attention: Dr. Trevor Castor

CERTIFICATE OF ANALYSIS

Subject: 3-brine samples for analysis (Arlington Exploration)

	8/6 13:00		8/6 13:15		8/7 2:45	
pH	5.50	units	5.22	units	5.72	units
Total Dissolved Solids @125°C.	294,000	mg/1	283,000	mg/1	299,000	mg/1
Alkalinity as $CaCO_3$	96	mg/1	62	mg/1	74	mg/1
Chlorides	179,000	mg/1	180,00	mg/1	179,000	mg/1
Carbonate	<.1	mg/1	<.1	mg/1	<.1	mg/1
Bicarbonate	96	mg/1	62	mg/1	74	mg/1
Sulfate	<1	mg/1	<1	mg/1	<1	mg/1
Sulfite	<0.01	mg/1	<0.01	mg/1	<0.01	mg/1
Sodium	68,300	mg/1	72,500	mg/1	71,800	mg/1
Calcium	18,800	mg/1	19,800	mg/1	19,800	mg/1
Magnesium	2,950	mg/1	3,000	mg/1	3,050	mg/1
Iron	68.5	mg/1	43.0	mg/1	50.0	mg/1
Silica as SiO_2	10.4	mg/1	12.2	mg/1	10.9	mg/1

Specific Gravity

	8/6 13:00	8/6 13:15	8/7 2:45
70°F.	1.1913	1.1915	1.1937
95°F.	1.1898	1.1901	1.1930
125°F.	1.2016	1.1968	1.2011
150°F.	1.2141	1.2118	1.2141

MICROBAC LABORATORIES, INC. • ERIE TESTING LABORATORY DIVISION

Viscosity	8/6 13:00		8/6 13:15		8/7 2:45	
70°F.	36.6	sec	34.0	sec	34.0	sec
95°F.	37.0	sec	34.4	sec	34.2	sec
125°F.	36.4	sec	33.3	sec	34.0	sec
150°F.	36.4	sec	33.2	sec	34.1	sec
70°F.	3.20	centipoise	2.40	centipoise	2.40	centipoise
95°F.	3.32	centipoise	2.58	centipoise	2.48	centipoise
125°F.	3.14	centipoise	2.15	centipoise	2.40	centipoise
150°F.	3.14	centipoise	2.11	centipoise	2.45	centipoise

Signed Robert A. Horgan

Appendix B.4

FORMATION BRINE ANALYSES BY GALSON TECHNICAL SERVICES, INC. (GTS),

E. SYRACUSE, NY

Galson
Technical Services, Inc.
6601 Kirkville Road
Post Office Box 546
E Syracuse, N.Y. 13057
Tel. (315) 432-0506

Environmental Sciences Division

August 19, 1983

Mr. Bob Lynch
Arlington Exploration Co.
137 Newbury Street
Boston, MA 02116

RE: GTS #G3-260

Dear Mr. Lynch:

Enclosed are the results of the analyses of the air bag samples and the water samples collected by Mr. Paul Strader on 8/8/83. 5

The air bags were analyzed using three different methods:

1) Gas chromatography using a thermal conductivity detector

2) Gas chromatography using a flame ionization detector

3) Orsat

All airbag results are in percent by volume. I have no explanation for the missing percentages.

Four bottles of water were collected. Duplicate analyses were performed, using samples from two different bottles for each duplicate pair.

The water samples were digested in acid before analysis for metal ions. The water was kept at room temperature from the time of receipt to analyses, but analyses were not performed at elevated temperatures. There is a possibility of error in the sulfate results. Because of the high salt content of the samples, the barium chloride used in the sulfate analysis to precipitate sulfate did not dissolve completely. Some of it did go into solution, however. No barium sulfate precipitate was formed.

Total hydrocarbons in the water was determined by purge and trap gas chromatography. The peak areas in the gas chromatogram were summed, and quantified using heptane as a standard.

If you have any questions concerning our results, please feel free to call.

Sincerely,

GALSON TECHNICAL SERVICES, INC.

Eva Galson
Laboratory Director

EG/sl

Enclosure

Galson Technical Services, Inc.
6601 Kirkville Road
Post Office Box 546
E. Syracuse, N.Y. 13057
Tel: (315) 432-0506

LABORATORY ANALYSIS REPORT

Client: Arlington Exploration Job Number: G3-260

Sample Identification: 83080811 Date Received: 8/8/83

Location: NS Date Sampled: 8/5/83

Parameters	Samples #1, #3 GTS # 10251, 10252	Samples #2, #4 GTS # 10253, 10254				
Sodium	38,750	38,750				
Calcium	24,250	24,250				
Potassium	1,550	1,650				
Magnesium	3,350	3,600				
Iron	88	91				
Silicon	14.0	13.7				
Alkalinity (Bicarbonate)	ND	ND				
Alaklinity (as $CaCO_3$)	77.5	78				
Chloride	192,800	144,600				
Total Dissolved Solids	304,000	303,000				
Sulfides	<0.1	<0.1				
pH	5.3	5.4				

(<)—less than
(>)—greater than
NA—Not Applicable
ND—Not Detectable
NS—Not Specified

Units are expressed in mg/ℓ unless otherwise stated.

Submitted by: EAS

Approved by:

Date: 8/13/83

Galson
Technical Services, Inc.
6601 Kirkville Road
Post Office Box 546
E. Syracuse, N.Y. 13057
Tel: (315) 432-0506

LABORATORY ANALYSIS REPORT

Client Arlington Exploration Job Number G3-260

Sample Identification 83080811 Date Received 8/8/83

Location NS Date Sampled 8/5/83

Parameters	Samples #1, #3 GTS # 10251, 10252	Samples #2, #4 GTS # 10253, 10254				
Turbidity (NTUs)	9	16				
Sulfates	<3	<3				
Bromide (ppm)	2,250	2,200				
Total* Hydrocarbons(μg/ℓ)	80	81				

(<)—less than
(>)—greater than
NA—Not Applicable
ND—Not Detectable
NS—Not Specified

*as heptane

Units are expressed in mg/ℓ unless otherwise stated.

Submitted by:

Approved by:

Date: 8/19/83

Page 2 of 4

Galson
Technical Services, Inc.
6601 Kirkville Road
Post Office Box 546
E. Syracuse, N.Y. 13057
Tel (315) 432-0506

Air Bags

LABORATORY ANALYSIS REPORT

Client Arlington Exploration Job Number G3-260

Sample Identification 83080811 Date Received 8/8/83

Location NS Date Sampled 8/5/83

Parameter	GTS #A10255					
GC THERMAL CONDUCTIVITY DETECTOR						
Carbon Dioxide	11.3%					
Oxygen	9.4%					
Nitrogen	20.5%					
Methane	23.1%					
Carbon Monoxide	ND					
GC FLAME IONIZATION DETECTOR						
Methane	29.8%					
Total Hydrocarbons	26.5%					
Non-Methane Hydrocarbons	< 1%					

(<)—less than
(>)—greater than
NA—Not Applicable
ND—Not Detectable
NS—Not Specified

Percentage by volume

Units are expressed in mg/ℓ unless otherwise stated.

Submitted by: ________

Approved by: ________

Date: ________

Page 3 of 4

Galson
Technical Services, Inc.
6601 Kirkville Road
Post Office Box 546
E Syracuse, N.Y. 13057
Tel (315) 432-0506

LABORATORY ANALYSIS REPORT

Client Arlington Exploration Job Number G3-260

Sample Identification 83080811 Date Received 8/8/83

Location NS Date Sampled 8/5/83

ORSAT APPARATUS

Parameters						
Carbon Dioxide	13.8%	13.9%				
Oxygen	8.8%	8.8%				
Carbon Monoxide	ND	ND				

(<)—less than
(>)—greater than
NA—Not Applicable
ND—Not Detectable
NS—Not Specified

Percentage by volume

Submitted by:

Approved by:

Date: 8/19/83

Units are expressed in mg/ℓ unless otherwise stated.

Appendix B.5

PRESSURIZED FLUID AND DISSOLVED GAS ANALYSES BY MICROBAC LABORATORIES, INC. (MLI), ERIE, PA

MICROBAC LABORATORIES, INC.
ERIE TESTING LABORATORY DIVISION
2401 West 26th Street, Erie, Pennsylvania 16506
814/833-4790

AIR • FUEL • WATER • FOOD • WASTES

August 25, 1983

Dr. Trevor Castor
Eng. Inc.
137 Newberry Street
Boston, Ma. 02116

REC'D
AUG 2 6 1983

Dear Dr. Castor,

This report should finalise the work we performed for you and Arlington Exploration concerning the gas well in Auburn, New York.

The tests were performed on three samples of pressurised fluid with gas dissolved in them. The information required is as follows:

I. Amount of gas in fluid

I.D.	Volume Fluid	Volume Gas	Pressure (Sampling pressure)
8/7/83 02:45	300 ml	3 - 5 ml	900 psi
8/6/83 13:15	300 ml	127 ml	577 psi
8/6/83 13:00	300 ml	120 ml	577 psi

II. Analysis of gas dissolved in fluid

Component I.D.:	8/6/83/13:15	8/6/83/13:00	8/7/83/02:15
Oxygen	3.8 %	0.8 %	*
Methane	73.3	88.8	*
Nitrogen	17.7	4.5	*
Carbon dioxide	4.8	5.3	*
Ethane	.5	.56	*
Propane	<.1	<.1	*

* Insufficient gas was produced to obtain an analysis.

The following information was presented on a previous report:

III. Brine Analysis
IV . Viscosity as a function of temperature
V . Specific Gravity as a function of temperature

Two other pieces of information your requested were:

VI . Bubble point (pressure and temp. conditions at which the dissolved gas will bubble out of the fluid.

MICROBAC LABORATORIES, INC. • ERIE TESTING LABORATORY DIVISION

REC'D AUG 26 1983

Eng, Inc. Arlington Exploration

VIII. Water formation volume fraction (defined as reservior volume/surface volume or reservior density/surface density).

As I informed you upon our initial conversation, these two terms were unfamiliar to me. We have attempted to find information on the measurement and calculation of these two pieces of information by contacting several sources. We are currently awaiting assistance from the American Gas Association in this area and when we receive this information, we should be able to provide this final data.

Sincerely,

Mark R. Banister

Mark R. Banister

Appendix B.6

FORMATION LOGS

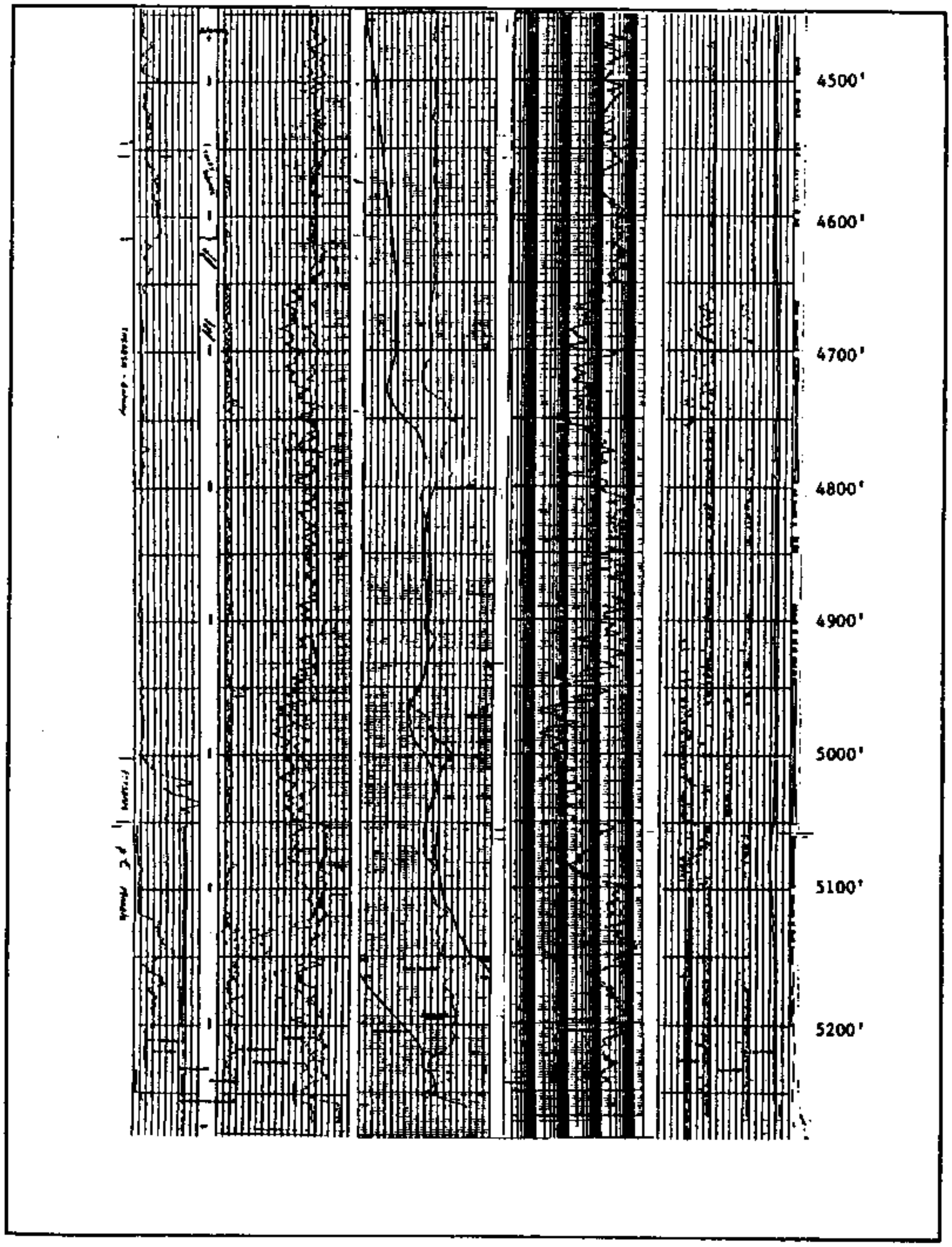


Figure B.6-1. Auburn Geothermal Well - Gamma Ray & Caliper, Compensated Neutron and Bulk Densities, Temperature & Gradient, Deep & Shallow Laterlogs and Fracture Identification Logs (Schlumberger, 1982)

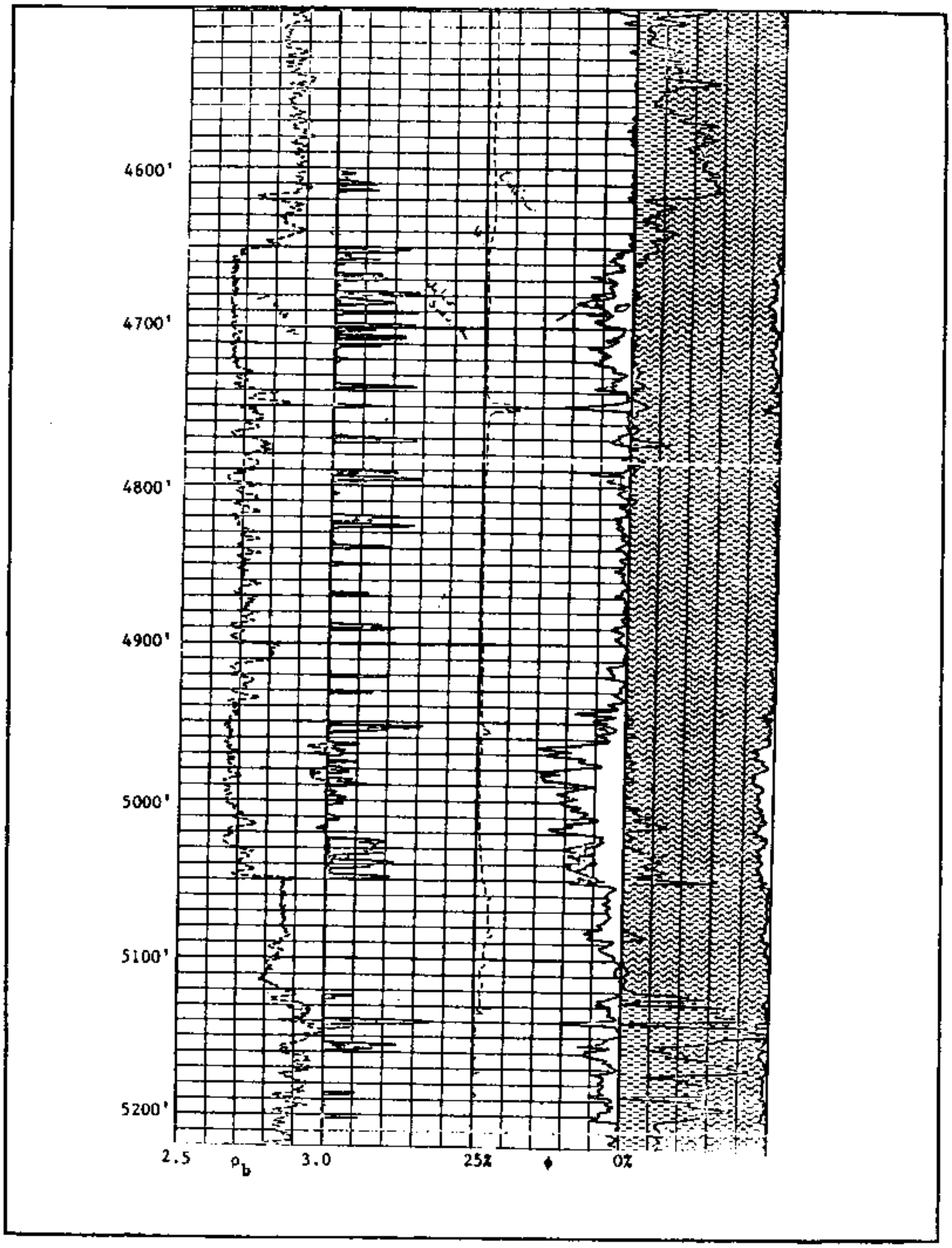


Figure B.6-2. Auburn Geothermal Well - Coriband Formation Analysis by Volume (Schlumberger, 1982)

Appendix C

DUNN GEOSCIENCE, INC.'S DRILL CUTTING, CORE, AND FORMATION WATER ANALYSIS

GEOSCIENCE CORP.

5 NORTHWAY LANE NORTH •
LATHAM, NEW YORK 12110
(518)783-8102

June 16, 1982

Mr. Robert Lynch
Donahue, Anstey & Morrill
137 Newbury Street
Boston, Massachusetts 02116

Dear Bob:

Enclosed is an updated copy of our preliminary report on the Auburn Geothermal Test Well. It includes new information on thermal conductivity and heat flow, water chemistry and porosity.

The Appendices and core description chart were previously sent to you.

If you have any questions, please give me a call.

Sincerely yours,

George M. Banino
Vice President

GMB:pl
Enc.

PRELIMINARY DRAFT

TABLE OF CONTENTS

PRELIMINARY DRAFT

1.0 EXECUTIVE SUMMARY

2.0 INTRODUCTION

2.1 Purpose of Report

The purpose of this report is twofold: (1) to present preliminary data gained from the first phase of the contract, and (2) to make a preliminary assessment of the geothermal resource.

2.2 Personnel

The drilling was performed by Devonian Drilling under the direction of Robert S. Lynch of Arlington Exploration. Vinson Ventors served as the Arlington representative at the drilling site. Dunn Geoscience provided geologic and geothermal analysis information under the direction of George H. Banino, Vice President. Margaret R. Sneeringer provided day-to-day contact with the project, James R. Dunn provided petrographic analyses, and William E. Cutcliffe reviewed the project activity. Water samples were analyzed by Health Research, Inc. under the direction of Robert Weinbloom. Thermal conductivity measurements were performed at Virginia Polytechnic Institute and State University under the direction of Lawrence Perry, and other core tests and analyses were performed at Terra Tek Laboratories in Salt Lake City, Utah. Brayton Foster, an independent consultant, served as the on-site representative of New York State Energy Research and Development Authority and helped direct drilling and coring activities. Other subcontractors on the project included ENG, INC.

2.3 Scope of Report

This report is intended only to collect for and provide to NYSERDA all the available basic information necessary to make a determination about advancing to Phase II - Hydrologic Analysis. It also presents a preliminary assessment of the potential geothermal resource based on the limited data and time available. A more detailed report, with further data and analysis, may be prepared in the future if the project advances beyond the initial phase.

2.4 Post Drilling Work

Under an agreement with the Empire State Electric Energy Research Corporation and NYSERDA, funding was made available for additional studies in the drill hole by the U.S. Geological Survey. This work was in regard to stress analysis in the rock formations and did not have a direct bearing on the geothermal program.

3.0 WELL DRILLING

3.1 Daily Activity

PRELIMINARY DRAFT

3.2 Well Construction

3.3 Problems and Solutions

4.0 WIRE LINE LOGS

4.1 Log Description

4.2 Log Analyses

5.0 STRATIGRAPHY

5.1 Stratigraphic Analysis

5.1.1 Hypothetical Cross-Sections

A hypothetical cross-section was constructed prior to the Auburn drilling for the purpose of projecting expected depths to lithologic horizons. Generalized information was taken from New York State Geological Survey Map and Chart Series reports numbers 1, 2, 3, 8 and 12. Detailed information on nearby deep wells was drawn from Selected Deep Wells and Areas of Gas Production in Eastern and Central New York, Bulletin #373, 1959, and Deep Wells in New York State, Bulletin #418A, 1972, of the New York State Museum and Science Services.

A number of wells have been drilled around the Auburn site in the search for gas. Most have penetrated approximately 1500 to 2000 feet into the Medina or Queenston formations which are known gas-rich zones. These wells are useful for demonstrating a uniform regional dip and formation thicknesses of the Queenston and higher formations. A few nearby wells (within 15 miles) penetrate 3000 to 5000 feet or as far as the Potsdam or basement. These also demonstrate a uniform regional dip and relatively uniform formation thicknesses below the Queenston. Regional dip has historically been assigned the value of 52 feet/mile to the south.

Projection of the four nearest deep wells to the Auburn site, using the regional dip and average formation thicknesses, allowed a hypothetical cross-section to be constructed. Some indication of slight easterly dip was noted from wells to the west. The wells used were the Alnutt #31-011-04715K, Parker #31-011-0499K, Johnson #31-011-04365K (Bulletin 418A), and the Old Auburn No. 1 (Bulletin #373).

The Alnutt and Parker wells are recent wells penetrating the Theresa and Potsdam formations respectively. The Old Auburn No. 1 reaches the Trenton Group, while the Johnson well is an accurately logged well penetrating the Queenston formation. The hypothetical cross-section resulted from best estimates of the predicted regional dip and direction plus the nearest best estimate of the formation thicknesses. Estimated depths to the tops of these formations were:

Salina Group	350 ft
Lockport Group	1100 ft
Clinton Group	1230 ft
Medina Group	1575 ft
Queenston Fm	1665 ft
Oswego Fm	2390 ft
Lorraine Group	2830 ft
Trenton Group	3400 ft
Black River Fm	4150 ft
Little Falls	4550 ft
Theresa Fm	4610 ft
Potsdam Fm	4910 ft
Basement	5010 ft

5.1.2 Stratigraphic Description

These descriptions were compiled from numerous sources in the literature.

POST-SALINA - sequence of limestones and dolomites primarily consisting of the Rondout/Cobleskill dolomite, Manlius dolomitic and Onondaga limestone.

SALINA GROUP

Bertie Formation - Sequence of dolomite with gray or green shale sometimes mixed with anhydrite.

Camillus Member - Predominantly green shale and occasional dolomite beds with anhydrite. Contact between Bertie and Camillus is distinguished by abrupt, predominant shale content rather than dolomite content.

Syracuse Member - Upper unit: dolomite with minor gray or green shales and evaporites. Lower unit: dolomite with gray or green shale and occasional clay or evaporite beds.

Vernon Member -	Upper unit: relatively uniform, fine-textured gray or green shale and siltstone with occasional dolomite beds. Medial unit: dolomite with anhydrite changing to green dolomitic shale downward. Lower unit: fine-textured, red shale in upper 2/3 changing to greenish shale below.
LOCKPORT GROUP -	Sequence of interbedded, fine to medium grained, gray or brown limestone and dolomite. Individual units not generally subdivisable from well cuttings.
CLINTON GROUP -	If present, this is a sequence of gray to white, fine-grained sandstone and gray calcareous shale.
MEDINA GROUP -	Sequence of red to green or gray mottled sandstone with interbedded red shale.
QUEENSTON FORMATION -	Thin interbedded red sandstones and shales with occasional green shale interbeds.
OSWEGO FORMATION -	Thin interbedded greenish-gray to gray, fine to medium grained sandstone and greenish-gray shale.
LORRAINE GROUP -	Sequence of tan to gray shale and siltstone with some light gray sandstone beds.
TRENTON GROUP -	Sequence of medium to coarse grained, brown limestone with black calcareous shale laminae. Dolomite is very rare. Different members are generally not subdivisable from well cuttings.
BLACK RIVER GROUP -	Sequence of gray, medium grained to subcrystalline limestones with

	occasional cherty beds. Sequence is generally not subdivisable from well cuttings.
	---KNOX UNCONFORMITY---
LITTLE FALLS FORMATION -	Sequence of white to very light tan, or cream-colored, sandy dolomite with abundant frosted, rounded and clear angular to subangular quartz grains. Dolomite content decreases downward until basal portion is principally quartz grains supported by a dolomite matrix. Higher in the section may be found thin brown dolomitic laminae or thin laminae of black non-calcareous shale containing pyrite. Chert is commonly noted in the uppermost Little Falls as thin layers in a predominately pure, coarse tan dolomite.
THERESA FORMATION -	A coarse, white, limey dolomite with abundant and equally proportioned amounts of rounded, frosted quartz grains and angular, clear quartz grains. Formation may be predominately sandstone in some areas.
POTSDAM FORMATION -	White, coarse orthoquartzite with trace amounts of white, angular feldspar, rounded, frosted quartz grains, and zircon. Basal Potsdam may be an altered chloritic quartz sandstone derived directly from the basement.
BASEMENT -	Metamorphosed sedimentary rock containing hornblende, hematite and altered chlorite.

5.1.3 Comparison With Well Logs

The correlation between the hypothetical cross-section and the actual results is quite good. Major divergences occur at the Medina horizon due to a greater-than-expected thickness of the Lockport formation. The Potsdam formation was also much thinner than expected.

The major surprise with the lithologies occurred with the Theresa formation which, contrary to the expected limey dolomite with quartz grains, was instead a fine sandstone with a dark carbonaceous coating on the quartz grains.

5.2 Formation Tops

Brayton Foster in conjunction with Arlington Exploration personnel, selected the following formation tops based on well logs and chip descriptions. All measurements are in feet from the rig's Kelly bushing.

1238	Lockport Formation
1710	Medina Sandstone
1792	Queenston Shale
2590	Oswego(?) Shale
2860	Lorraine Shale
3460	Trenton Limestone
4163	Black River Limestone
4546	Knox Unconformity and Little Falls Formation
4616	Theresa
5002	Potsdam Sandstone
5260	TD

5.3 Lithologic Log

The Litho Log or "mud log" was prepared by N.L. Bariod during the course of the drilling. It presents a lithologic description of the chip samples, a graphic log of the lithology, the drilling rate, gas readings, water shows, and notations concerning drill bit replacement, rig down time and similar information.

5.4 Selected Lithologic Descriptions

As a confirmation of the Lithologic Log, Dunn Geoscience Corporation independently developed a detailed description of the lithology of selected drill cuttings. Samples were selected from the following formations:

Medina
Queenston
Lorraine
Trenton
Black River
Little Falls
Theresa
Potsdam
Basement - Marble

The Dunn Geoscience Corporation lithologic descriptions are included in Appendix 10.6. In general, there was a close correlation between the Lithologic Log descriptions and the results of the Dunn Geoscience Corporation analyses.

6.0 WATER

6.1 Water Shows

Four zones were identified where formation water was observed entering the drill hole. These were at 199 feet, 306 feet, 2030 feet, and at 4160 feet. These fluid entry points were identified by Baroid personnel and noted on the mud log.

6.2 Sample Collection Procedure

Drill fluid samples were collected and split into two 500 ml samples and placed in clean Nalgene bottles, each of which had been rinsed three times with the drill fluid. One bottle was then capped and labeled with sample number, depth, and date. Five milliliters of 50% HNO_3 solution was added to the other bottle to fix trace metals in solution. That bottle was then sealed and carefully marked with the same data, and a notation of HNO_3 was added. Samples were to be collected at 100-foot intervals from 500 feet. Water samples were not collected by the Baroid personnel as specified at 100-foot intervals for unknown reasons. Only thirteen samples were collected of a possible forty-seven. Samples collected are tabulated below:

Sample #	Depth(FT)	Date	Time	Water Temp Degrees F
21051	840	2/15	5:24	---
21052	940	2/15	22:15	38
21053	1240	2/16	8:30	55
21054	3740	2/20	21:30	---
21055	3940	2/21	5:00	---
21056	4310	2/21	21:00	---
21057	4620	2/23	12:40	72
21058	4720	2/26	1:00	61
21059	4820	2/26	14:45	70
21060	4920	2/27	4:35	68
21061	5020	2/27	14:30	---
21062	5120	2/28	19:45	---
21063	5220	3/29	4:00	72

6.3 Water Chemistry

Four samples were selected for bulk chemical analysis of major elements. The fluid being circulated during the drilling process contains many additives that add to the chemistry of formation waters entering the hole. The drill fluid is also circulated out of the hole into mixing pits, and an extremely cross-contaminated mixture is then recirculated down the hole as the drilling fluid. At best, a slight change in chemistry is expected as different formations are penetrated. The four samples selected for analysis were from depths of 4310 feet, 4820 feet, 5020 feet, and 5220 feet. The last three samples were each selected because they were collected from well within each of the Theresa, Potsdam and basement formations, respectively. The sample from 4310 feet was selected as representative of fluid before entering those formations, and as the closest sample to the last known location where formation water was entering the hole. The chemical analyses of these samples are in Tables 1 and 2.

6.4 Water Levels

The water level in the drill hole after completion of drilling has decreased from a high of 115 feet below ground level when the first logging took place on 3/2/82, to 333 feet below ground level when the USGS personnel commenced logging operations on 3/16/82. It is not known yet whether the water level has stabilized.

7.0 CORE DESCRIPTION

7.1 Physical Core Description

Two segments of core were retreived during drilling, one each from the Theresa Formation and from the basement. Physical and mineralogic descriptions were made of each, and are listed below.

7.1.1 Theresa Core Description

Statistics:
Length - 2.9" (73.7 mm) along core center
Weight - 810.2 grams (as received)
Width - 3.6" (91.4 mm)

Description:
Medium-dark gray (N3), medium- to very fine - grained sandstone. Grains are subangular to subrounded clear-to-dark quartz with minor plagioclase feldspar. Matrix consists of very fine to extremely fine-grained quartz with some larger rounded grains and iron sulfides. Some evidence of local grain overgrowth is present.

TABLE 1

WATER CHEMISTRY RESULTS

Sample #	21056	21059	21061	21063
Depth	4310 ft.	4820 ft.	5020 ft.	5220 ft.
Total Solids	254000	122000	93900	56400
Sodium	72000	40000	30000	20000
Chloride	140000	65000	48000	23000
Potassium	2000	3200	2500	1500
Sulfate	*	750	650	400
Calcium	13000	6400	5600	3000
Magnesium	42000	880	900	520
Silica	1.4	3.2	4.0	3.7
Alkalinity	420	110	80	310

1. All chemical quantities listed in parts per million (ppm)

*Analysis could not be done because of interference.

TABLE 2

WATER CHEMISTRY RESULTS

Sample #	21065	21066
Depth	1670 ft.	3024 ft.
pH	6.0	6.0
Total Solids	283,000	302,000
Sodium	66,000	66,000
Chloride	150,000	170,000
Potassium	1,900	2,200
Sulfate	*	*
Calcium	14,000	15,000
Magnesium	1,900	2,000
Silica	2.2	3.2
Alkalinity	26	18

All chemical quantities listed in ppm.

*Analysis could not be done because of interference.

Core has one apparent fracture along one edge, oriented 13 degrees from the core axis. Fracture surface shows evidence of polishing or smearing probably resulting from abrasion during coring. Upper core surface is slightly conical with apparent chatter marks. Lower core surface is broken perpendicular to the core axis and shows no signs of mechanical abrasion.

Bedding is represented by numerous thin laminae (1-3 mm thick) composed of light and dark stained grains. Dip bedding is approximately 2 degrees.

7.1.2 Basement Core Description

The chemical composition of the Pre-Cambrian Basement core is described in Table 3; the physical aspects are described in Appendix C.1.

7.2 Petrographic Descriptions

7.2.1 Method

Detailed petrographic descriptions were made of thin sections of the basement and Theresa core samples by James R. Dunn of Dunn Geoscience Corporation and Terra Tek of Salt Lake City. In addition to the petrographic description, a bulk chemical analysis of the basement rock was made by inductively coupled plasma (ICP) spectroscopy analysis. Results are given in oxide weight percent, where applicable, or in parts per million (ppm). It should be noted that the total reported is only 53.108% because the primary mineral constituent, dolomite, is a carbonate, and only oxides are reported. The remainder of the analysis can be assumed to be the carbonate component of the dolomite. Prior to examination, the samples were vacuum saturated with blue-stained epoxy. This allowed ready identification of voids in the samples.

7.2.2 Theresa Sandstone

Rock Type: Quartz Arenite.

General Description:

This sandstone is composed largely of subrounded to well-rounded quartz grains with moderate sphericity. The sand grains range between 0.1 and 0.7 mm,in size averaging about 0.2 mm. Sorting is good. The sand grains have thin rinds, 0.001 - 0.02 mm wide, comprised of a very fine-grained, brownish, platy, semi-opaque material,that are likely Mn-oxides or tar. The sand grains also have traces of pyrite.

TABLE 3

ICP CHEMICAL ANALYSIS OF BASEMENT; DOLOMITIC MARBLE

ELEMENT		CONCENTRATION*	
NA	% OX.		0.052
K	% OX.		0.096
CA	% OX.		27.46
MG	% OX.		21.83
FE	% OX.		1.07
AL	% OX.		0.698
SI	% OX.	<	1.60
TI	% OX.		0.039
P	% OX.		0.046
SR	PPM		93
BA	% OX.		0.043
V	PPM	<	250
CR	PPM		8
MN	% OX.		0.168
CO	PPM		12
NI	PPM	<	5.00
CU	PPM		6
MO	PPM	<	50.0
PB	PPM	<	10.0
ZN	PPM	<	5.00
CD	PPM	<	5.00
AG	PPM	<	2.00
AU	PPM	<	10
AS	PPM	<	25.0
SB	PPM	<	30.0
BI	PPM	<	100
U	PPM	<	2500
TE	PPM	<	50.0
SN	PPM	<	5.00
W	PPM	<	1200
LI	PPM		10
BE	PPM		0.5
B	PPM	<	400
ZR	PPM		5
LA	PPM		10
CE	PPM		22
TH	PPM	<	150
	TOTAL		53.108

* Note: Elemental abundances reported as less than a specific concentration indicate that the element was not present at the detection limit of the instrument.

Secondary quartz partially to completely fills some pores. The secondary quartz covers the brown rims on sand grains and often contains inclusions and fracture fillings of the brown substance. A portion of the core was crushed and heated to 1000°C. The result was a uniform white sand indicating that the brownish material is likely a hydrocarbon. This material was determined to be 0.8% by weight of the sample.

No veins occur in the rock. Most of the pores are primary; some of the larger pores are lined by the brownish material.

Minerals	300 Point Count Volume %	Visual Estimate %	Occurrence
Quartz	77.3 ± 4.5		Sand grains, subrounded averaging 0.2 mm in size
Quartz	9.0 ± 3.3		Secondary, partially to completely fills original pores; often intergrown with semi-opaque, brown substance which appears to occur in plates.
Semi-Opaque to Opaque Material	11.6 ± 3.5		Very fine-grained, brownish, platy material (Mn oxide? or tar?) and pyrite which rim sand grains; the brown material is often intergrown with quartz. Pyrite 0.5-2% of rock; it is often so fine-grained it is not easy to distinguish from other material.

Tourmaline, sphene and feldspar	--	(0.2)	Detrital grains
Pores	2 ± 2		Blue epoxy filled voids; most of the pores are primary.

7.2.3 Basement - Sample 1

Rock Type: Medium-grained Dolomitic Marble

General Description:

This rock is composed largely of equant, subhedral dolomite crystals ranging between 0.3 and 2 mm in size and averaging about 1 mm in size. The dolomite grain contacts are sutured. Clots of chlorite-quartz, or quartz and of chlorite are dispersed throughout the rock; such clots are usually equant and they range between 0.1 and 0.6 mm in size. Minor to trace amounts of pyrite, magnetite, apatite and goethite occur as disseminations.

A parallel set of discontinuous, filled-in microfractures, 0.002-0.03 mm wide, occur with a frequency of about 1 per mm. These fractures are completely filled with clear dolomite which is optically continuous with dolomite grains crossed by the fracture, the vein dolomite is clear because it contains few inclusions. A later set of cross-cutting fractures, 0.002-0.05 mm wide, occur with a frequency of about 1 per 2 cm. These fractures are partially filled with brownish montoillonite or a very fine-grained, 0.001-0.003 mm, biotite and with traces of very fine grained carbonate, goethite and hematite. The only places that the blue-colored epoxy has penetrated this rock is in these late fractures. The porosity as indicated by impregnation of the blue epoxy is less than 1%.

Minerals	300 Point Count Volume %	Visual Estimate %	Occurrences
Quartz	3.7 ± 2	--	Anhedral, 0.01-0.2 mm; usually occurs in multicrystalline aggregates.

Dolomite	88.3 ± 4	--	See above.
Chlorite	7.7 ± 3	--	Occurs in books + quartz 0.1-0.6 mm across and in thickness; usually contains tiny inclusions of rutile.
Apatite	--	--	Subhedral crystals up to 0.1 mm in length.
Montmorillonite/ biotite	--	(0.1)	Very fine-grained brownish material which partially fills late fractures.
Pyrite	--	(0.5-1)	Disseminated, equant crystals, 0.01-0.15 mm in size.
Magnetite	--	(0.1)	Disseminated, 0.005-0.1 mm in size.
Goethite/ hematite	--	(tr)	Very fine-grained material occurs in and near late fractures.
Rutile	--	(tr)	Occurs as tiny inclusions in chlorite books.
Voids	0.3+	--	Open fractures which are partially impregnated with blue epoxy.

7.2.4 Basement - Sample 2

Rock Type: Medium-grained Dolomitic Marble

General Description:

Equant dolomite grains ranging between 0.5 and 7 mm in size from most of this rock. The average grain size is about 1 mm; the grain borders are sutured. Also present are minor amounts of talc, chlorite and quartz. The chlorite is intergrown with talc and is apparently replacing it. Tiny blebs of rutile occur as inclusions in chlorite grains.

A parallel set of discontinous, filled-in microfractures, 0.002-0.03 mm wide, occur with a frequency of about 1 per mm. These fractures are completely filled with clear dolomite which is optically continuous with each of the dolomite grains crossed by the fractures; the vein dolomite is clear because it contains few inclusions relative to the host rock dolomite. No other veins or fractures occur in the sample. No blue epoxy has impregnated the rock.

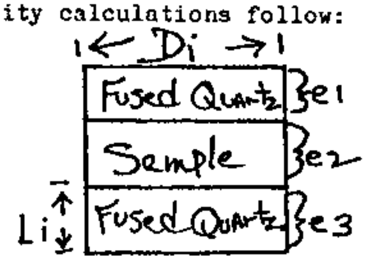
Minerals	300 Point Count %	± %	Visual Estimate %	Occurrences
Quartz	3.3	2	--	Anhedral grains, 0.02-0.1 mm in size, occurring in multicrystalline aggregates 0.1 to 1 mm across.
Dolomite	90.7	3.5	--	Subhedral grains averaging 1 mm in size.
Chlorite	4.3	2.5	--	Colorless; present as both length-fast (abnormal grey-green birefringence) and as length-slow (abnormal blue birefringence) material; usually both types present in each "book" of chlorite.
Talc	1.3	1.5	--	Colorless; occurs as equantly shaped "books" 0.3-0.75 mm

			across; the talc is partially to completely replaced by chlorite; quartz is is usually present in the chlorite + talc clots.
Pyrite	0.3 ± 1	(0.5-1)	Euhedral crystals 0.1-0.4 mm in size, occasionally showing some alteration to limonite.
Apatite	--	(0.3-0.5)	Subhedral crystals 0.1-0.4 mm in size.
Rutile	--	(0.1)	Tiny blebs, < 0.01 mm, which occur as inclusions in chlorites.
Voids/Pores	--	--	No blue epoxy has penetrated the sample.

7.3 Thermal Conductivity and Heat Flow

A section of the basement core was sent to Viginia Polytechnic Institute and State University (VPI and SU) for thermal conductivity measurements. The sample was machined to a 1.5 inch diameter right cylinder by Belanger Industries in Massachusetts, and then sent to the VPI and SU laboratory. Conductivity measurements were made by Margaret McKinney under the direction of Lawrence Perry. Three separate sets of measurements were made on the sample, and the results are shown in Table 4 included in this section. A diagram of the sample stack and the forumula used in the conductivity calculations follow:

Stack Diagram



Differential temperature thermal couples

A stack correction factor (SCF) was calculated to compensate for slight differences in the fused quartz standard's wafer diameters, and the resultant formula for sample conductivity(K2) is:

TABLE 4

Stack Parameters

	Fused Qtz Standard	Basement Sample
Thickness (L_2)*	.651	1.0024
Diameter (D_2)*	1.5	1.5005
SCF	NA	.955921
(Determined using:)		
K_1	1.0	3.359
L_1*	.375	.375
L_3*	.375	NA
D_1*	1.499	1.499
D_3*	1.5085	1.5085

e_1, e_2, e_3 are measured potential differences in microvolts.

*Linear measurements in inches.

$$K_2 = \frac{L_2}{e_2 D^2_2} \cdot \frac{K_1}{L_1} \left(\frac{e_1 D_1{}^2 + e_3 D_3{}^2}{2} \right) \cdot \frac{1}{SCF}$$

where $L_1 = L_3$, and $K_1 = K_3$ = conductivity of quartz at 53°C. Subscripts refer to position in the stack, with position 1 at the top: e is the potential difference in microvolts.

Three separate sets of readings were taken at 20 minute intervals. Each reading has three e_1, e_2, and e_3, and conductivity is determined for each e_1, e_2, and e_3 couple and then averaged for the final figure. The readings are shown in Table 5 in this section.

Averaging the conductivity values for the three readings gives a value of 11.171 mcal/cm sec °C.

Heat flow can be calculated for this site by using the equation

$$q = K\,G,$$

where q = heat flow, K = thermal conductivity, and G = thermal gradient. Since the gradient conductivity vary with rock type, the heat flow calculation for this hole is based on values determined for the basement. The thermal gradient for the basement can be calculated from the Schlumberger log prepared April 7, 1982, on which the temperature was shown to vary from about 124.7°F at 5050 feet (top of basement) to approximately 126°F at 5206 feet. This translates to a gradient of 15.19°C/km. Using the above heat flow equation

$$\begin{aligned} q &= (11.171 \text{ mcal/cm sec } ^\circ C)\ (15.19^\circ C/km) \\ &= 1.697\,\mu \text{cal/cm}^2 \text{ sec} = \pm\, 1.7 \text{ HFU or } 71 \text{ mWm}^{-2}. \end{aligned}$$

This heat flow value is consistent with other values reported by Diment et. al. (1972)* for the area southwest of Syracuse. This value is significantly higher than the norm for the eastern United States, and appears to confirm an area of anomalously high heat flow.

7.4 Permeability and Porosity

7.4.1 Method

Samples of the Theresa and Basement cores were sent to Terra Tek Laboratories in Salt Lake City, Utah for porosity and permeability determinations, under the direction of Dr. Lawrence Owen. Due to the extremely tight nature of the samples, standard porosity and permeability tests were not performed. Instead, the samples were impregnated with a colored epoxy, and made

*Diment, W.H., Urban, T.C., and Revetta, F.A., 1972, Some Geophysical Anomalies in the Eastern United States, in: The Nature of the Solid Earth, New York, McGraw Hill, pp 544-572.

TABLE 5

Measurements and Calculated Conductivity

	Fused Quartz Standard			Basement Sample Reading 1			Reading 2			Reading 3		
e1	129	129	129.5	176.6	175	174	176.1	176.9	176.4	179.6	179.5	179.7
e2	220.9	220	220.9	139	138.9	138.6	138.3	137.2	138	138.8	139.6	138.9
e3	111.5	114.3	112.3	152	152.7	152	150	149.4	152	151	150.9	151.5
calc K2*	.949034	.964264	.954465	11.144	11.127	11.092	11.118	11.209	11.220	11.2298	11.158	11.2409
avg. K2*		.955921			11.121			11.182		11.2096		

* units of thermal conductivity are mcal/cm sec °C.

into thin sections so that a visual determination of the porosity could be made by point count. On the recommendation of Dr. Owen, no permeability measurements were made, as it was obvious that the values would be extremely small and basically insignificant and unworthy of the added expense of obtaining values in that range. Additional description of the pores and fractures are included with the petrographic descriptions.

7.4.2 Theresa Sandstone

Evaluation of the epoxy impregnated thin sections of the Theresa Sandstone indicated a primary porosity of approximately 2 percent. Primary permeability is assumed to be in the low milli-micro-darcy range, and any production from the sandstone would be largely attributable to flow through fractures if they are present.

7.4.3 Basement

Two thin sections were analyzed for the Basement sample since the first one showed no free porosity. One of the thin sections included a prominent fracture that was also evident in the hand specimen.

Based on analysis of both thin sections, it was determined that the dolomite marble has a primary porosity of zero. Secondary porosity, attributable to fractures, is approximately 0.3 volume percent. These values suggest that the primary permeability of this rock is in the low micro- to nano-darcy range. Prominent tertiary fractures, which appeared to be partially open, were also seen. It can be assumed that any production from the marble can be entirely attributed to flow through fractures.

8.0 HYDROCARBONS SHOWS

Continuous monitoring of gas flows and pressures was done by Baroid and plotted in the Litho Log. Gas readings from 0 to 300 units measures gas in air mixtures of 0 to 10%. The scale reading from 0 to 3000 units measures gas in air mixtures of 0 to 100%. A small gas show of 40 units (1.3% gas in air) was seen from a depth of 1651 feet to 1668 feet. There was a major gas show in the zone from about 4150 feet to 4215 feet and average gas readings of 1500 U (50% gas in air) with a downhole pressure of 500 psi were measured. The gas chromatograph analysis indicated 99.3% CH_4 (C1) and 0.7% C_2H_6 (C2).

9.0 FLOW TESTS

The flow tests were performed under the direction of Bob Lynch, Arlington Exploration and Trevor Caster, Reservoir Engineer. Time-discharge measurements taken while conducting the two tests at different discharge rates are to be analyzed to determine the various reservoir parameters characteristic of several distinct water-producing zones.

Each flow test involved pumping compressed air into the well through the drill stem, and forcing a column of water out of the well. Once the hole was unloaded, a state of equilibrium was set up between water discharged from the well due to the continued injection of compressed air and water entering the hole from major water-producing zones located between 4100 and 5250 feet. Discharge measurements were not initiated until equilibrium had been reached and all discharge water was being derived directly from the formation. The flow rate was determined by routing water from the well head through a system of pipes to one of two cylindrical tanks of known dimensions. The height of water in the tank was measured at regular intervals and the measurements converted to volume. The change in volume over time was then reduced to an average flow rate for the measurement interval. Water samples were collected from each successful test and were submitted for chemical analyses. Results are presented in the table in this section.

On April 7, 1982, the first flow test was conducted with the bottom of the drill stem set 1670 feet below ground level. Compressed air was forced down the hole at an estimated 180 psi. The test was run for approximately 8 hours at an average flow rate of about 123 gpm.

Water samples were collected 3 hours after the test started. Although a sampling port was provided, it did not function, having become clogged with formation material carried out of the borehole by the discharging water. Consequently, the sample was collected from the end of the discharge pipe. A portion of the sample was transferred to the appropriate collection bottles, and the remainder was retained for field tests.

The sample pH was measured 6.0. A titration was made which determined alkalinity to be 26. The water was very saline and weighed 9.8 pounds per gallon as compared to 8.4 pounds per gallon for fresh water.

A temperature measurement using a standard mercury thermometer was taken at the top of the collection tank. A temperature of 16.5 degrees celsius was recorded; however, due to the unknown residence time of water in the tank and the low ambient air temperature, the value cannot be considered as an accurate measurement of water temperature at the well head. Schlumberger was running a series of logs in conjunction with the flow tests and recorded a down-hole temperature of 117 to 122 degrees F.

A sample of rust inhibitor used in the borehole was also collected. Manufactured under the trade name MAGCOBAR by Dresser Industries of Houston, Texas. The inhibitor is prepared by mixing it with three parts of diesel fuel.

A second flow test was attempted on Thursday, April 8, 1982. The bottom of the drill pipe was set at 3863 feet below ground level and air pressure was estimated at 394 psi. The test was terminated after 2 1/2 hours when it became evident that the hole would not unload due to the weight of the water column in the well.

The bottom of the drill pipe was raised to 3024 feet below ground level, and the test was restarted with compressed air set at 442 psi. The test was run for approximately 6 hours after the start of the test; water samples were collected in the manner described previously. The pH was measured at 6.0 and the titration measured an alkalinity of 18. No temperature measurement was taken during this test.

On Friday, April 9, 1982, a third flow test was attempted. The drill pipe was set 3990 feet below the surface and compressed air was pumped in at 650 psi. It was theorized that the hole would unload if the density of the water column be reduced through aeration. The mud pump was used to circulate water in the well as compressed air was injected through the drill stem. As the column became aerated, circulation through the mud pump was decreased,and air pressure was increased.

However, before the hole could,unload the relief valve on the booster pump associated with the air compressors malfunctioned. Despite efforts to overcome the problem, the injection of air into the hole was limited to less than 950 psi. Consequently, this final test was terminated when it became evident that the hole would not unload under this limited pressure.

10.0 PRELIMINARY RESOURCE EVALUATION

10.1 Gradient Measurements

Based on the bottom hole temperature measured by the USGS logging personnel on March 16, 1982, a rough geothermal gradient can be calculated for this site. Since the well has been inactive for two weeks, the bottom hole temperature should be relatively close to the actual equilibrium temperature. The bottom hole temperature measured was 127 degrees F, or 52.8 degrees C. If a surface temperature of 50 degrees F or 10 degrees C is assumed, a rough gradient of 26.7 degrees C/km can be calculated.

The gradients and temperatures shown on the Schlumberger Wire Line log were measured within a day after completion of drilling, and represent non-equilibrated temperatures. A gradient can be calculated in two ways from this log, however. The bottom hole temperature indicated on this log was determined to be 123.5 degrees F, or 50.8 degrees C. If a surface temperature of 50 degrees F or 10 degrees C is assumed, the rough gradient that can be calculated is 25.5 degrees c/km. A section of the temperature log shows a fairly constant gradient from just below the casing at 1300 feet to a depth of 4655 feet, where the temperature variation becomes quite irregular. The change in temperature over that interval of 3355 feet is 24.4 degrees C, which is equivalent to a gradient of 23.9 degrees C/km. In this case the calculated gradients from essentially immediately after drilling were close to the gradient calculated after a more reasonable equilibration time.

GENERALIZED NOTES

1. A[illegible] core pieces include:
   a. micaceous [illegible]inerals, including chlorite
   b. occasional garnets (?)
   c. trace amounts of pyrite, chalcopyrite, with bornite and sooty chalcosite along slickenside surfaces
2. Greater potential porosity and permeability is possible due to fracture development than from rock itself
3. All core pieces are stained by drilling mud to varying degrees

Appendix C.1

DUNN GEOSCIENCE CORPORATION
5 Northway Lane North
Latham, N.Y. 12110

BASEMENT CORE DESCRIPTION
AUBURN GEOTHERMAL WELL

CITY OF AUBURN — CAYUGA COUNTY, N.Y.

PROJ. MANAGER: George M. Banino	PROJECT NO. 16-7-2190	MAP NO. 6029
PREPARED BY: William E. Cutcliffe	SHEET 1 OF 1	DATE: March 23, 198[illegible]
DRAFTED BY: Robert W. Shuey	SCALE: IN INCHES 0 1 2	
CHECKED BY:		