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AN INNOVATIVE DRILLING SYSTEM

Final Report

By
John Nees
Eric Dickinson
Wade Dickinson
Herman Dykstra

May 1991

Performed Under Contract No. DE-AC22-89BC14203

Petrolphysics
San Francisco, California

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
Bartlesville, Oklahoma

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Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Thomas B. Reid, Project Manager
Bartlesville Project Office
P. O. Box 1398
Bartlesville, OK 74005

Prepared by
Petrolphysics
2101 Third Street
San Francisco, CA 94107

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EXECUTIVE SUMMARY

This project was established to evaluate four objectives for the Petrolphysics Ultrashort Radius Radial System:

1. That the Ultrashort Radius Radial System was capable of drilling and completing multiple horizontal radials in a heavy oil formation which had a production history of thermal operations.
2. That the horizontal radials would serve as effective conduits for directing steam in specific azimuths and at specific elevations within the producing formation.
3. That radials would help alleviate the deleterious effect of steam override.
4. That the horizontal radials could be utilized for cyclic production, i.e. for purposes of steam injection as well as for oil production.

Each of these DOE objectives was successfully achieved in the project.

To provide a means of fulfilling these objectives, a site was selected on the west side of the San Joaquin Valley in the Bremer Lease in the Midway-Sunset Field. In April, 1989, a total of four radials were successfully drilled and completed utilizing Petrolphysics' Ultrashort Radius Radial System. The radials were placed in the Potter "C" sand in a newly drilled vertical well (Bremer RI-53) located in the Midway-Sunset Field at a depth of 1,200 feet. The Potter Sand is a fairly clean quartz sandstone in the Upper Miocene Reef Ridge formation. About 10% shale is present in this zone. Porosity is 9 to 45% with an average porosity of 25%. Permeability ranges from millidarcies to 3 darcies with an average of 1 darcy in this zone. Structurally, the Potter dips at 35 degrees northwest-southeast. Pay thickness ranges from 450 net feet of pay to zero at pinchout.

Temperature profiles indicate the zone to be particularly cold and the oil to be very viscous (11.4 degrees API average for the lease). Average daily production from the vertical wells in the lease after thermal stimulation is 20 barrels of oil.

During placement of the four radials to be completed for injection-production, lengths in excess of 68 to 105 feet were achieved. Each of the radials was completed with a horizontal gravel pack; a Flexible Sand Barrier (FSB) completion was also placed in one of the four radials. Four additional calibration radials were placed for experimental purposes. They were not completed. The vertical well was subsequently gravel packed throughout the 30 foot open hole interval. Upon completion of the well, steam was injected for a period of twelve days. RI-53 was then placed on production. After placement and completion of the radials, 17,085 barrels of cold water equivalent (5390 MMBTU) were injected into the well. This is consistent with injection practice in offset Bremer wells. There were no difficulties.

Observations from the injection and production results of Bremer RI-53 offset wells and the observation well (Bremer O-5) document the following conclusions:

(1) The steam injected into the radials in RI-53 remained at the elevation as injected for a distance of at least 100 feet from the vertical wellbore.

(2) Steam override was not observed in Bremer RI-53.

(3) Bremer RI-53 produced oil from a single 30 foot interval at rates equal to or in excess of offset wells having greater than 400 foot gravel packed completions. The production per vertical foot of sand open was about 1.63 barrels per day versus a maximum of .13 barrels per day for a similar stimulated offset producer.

(4) There was a a positive production response in three offset wells. Two of the offset wells were downstructure and one offset well was slightly upstructure.

(5) Temperature surveys indicated that during the pilot test steam went into a portion of the Potter sand that had only been relatively unaffected during previous cyclic operations.

(6) Based on temperature surveys and the response of RI-53 it appears that oil is being produced that might otherwise not be mobilized without additional mechanical or chemical diversion techniques. This would indicate an increase in reserves.

I. INTRODUCTION

A. Project Objectives

In November, 1988, the Department of Energy issued a Request for Proposal (RFP #DE-RP22-88BC14203) to demonstrate an "innovative drilling and completion system" which would be applicable to thermal operations in heavy oil reservoirs in California. Petrolphysics, Inc. (Petrolphysics) submitted a proposal to the Department of Energy in December, 1988 to demonstrate the use of its Ultrashort Radius Radial System (URRS). On September 26, 1989, Petrolphysics was awarded a one year contract to drill and complete four radials utilizing its URRS technology.

The principal project objectives were the following:

1. To demonstrate the capability of the Ultrashort Radius Radial System to drill and complete multiple horizontal radials in a heavy oil formation which had a production history of thermal operations.

2. To study the effects that horizontal radials have on steam placement at specific elevations and on reducing gravity override.

3. To demonstrate that horizontal radials could be utilized for cyclic production, i.e. for purposes of oil production as well as for steam injection.

Each of these DOE objectives was successfully achieved in the project. Early production results indicate that radials positively influenced cyclic performance. This report documents those results. The work was performed according to the project schedule and within the DOE budget guidelines.

The project work was divided into phases: (1) site and well selection, (2) an operation phase including radial placement, and (3) a steam injection and production phase. Each of these phases is separately considered herein.

The site and well selection phase resulted in selection of the Bremer Lease and the drilling and underreaming of a new well, Bremer RI-53, for the project.

In April, 1989, a total of four radial boreholes were successfully drilled and completed utilizing the Ultrashort Radius Radial System. The radials were placed in the Potter "C" sand in the newly drilled vertical well (Bremer RI-53) located in the Midway-Sunset Field. Radial lengths of 68 to 105 feet were achieved. Each of the radials was completed with a horizontal gravel pack; a Flexible Sand Barrier (FSB) completion was also placed in one of the four radials. The vertical well was subsequently gravel packed throughout the 30 foot open hole interval. Upon completion of the well, steam was injected for a period of twelve days. RI-53 was then placed on production.

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II. SITE SELECTION PHASE

A. Introduction

The final selection of the appropriate DOE candidate well involved three principal selection procedures. These procedures involved the optimum selection of an oil company operator, a heavy oil field, and an appropriate lease for URRS operations.

First, it was necessary to associate with an operator that had extensive experience in heavy oil operations as well as a competent geological, engineering, and operational support staff. The selection process focused on a number of qualified operators. Unocal was eventually selected due to its proven expertise in heavy oil operations in the San Joaquin Valley of California as well as the high caliber of the personnel that it was prepared to dedicate to the DOE project.

Secondly, it was desirable to select a major producing field in the San Joaquin Valley which had a successful history of thermal operations. It was also important to introduce new technology to a field in which a number of companies had operations so that these operators could directly benefit from the project results. Based on these criteria, the Midway-Sunset Field was selected to demonstrate the URRS technology.

The Midway-Sunset Field is currently the second largest producing field in California. In excess of 15 major oil companies and independent producers conduct thermal operations in this field. The opportunity for technology transfer is heightened since many of the Midway-Sunset producers also have thermal operations in other San Joaquin Valley locations.

Thirdly, it was necessary for the candidate well to be located on a lease which had existing cyclic producers for comparative analysis. Unocal's Bremer Fee lease in the Midway-Sunset Field provided offset wells for steam injection and oil production comparisons. Lastly, the Bremer Fee was also determined to be an environmentally sound location.

B. The Midway-Sunset Field

1. Overview

The Midway-Sunset Field is one of the largest producing oil fields in the continental United States. It ranks second in California in terms of annual oil production and cumulative production to date.

Located in the southwestern corner of the San Joaquin Valley of Kern County, the Midway-Sunset Field extends from the town of McKittrick in a southeasterly direction along the foothills of the Temblor Range for a distance of almost 25 miles. The field has an average width of approximately 3 miles and covers an area in excess of 22,000 productive acres. Field elevations range from 500 to 1700 feet; the topography consists of gently rolling hills and alluvial fans.

The first recorded oil well in the Midway-Sunset Field was drilled prior to the turn of the century (circa 1890). Discovered at a depth of approximately 100 feet, initial oil production was limited to a low gravity crude from the Tulare sands. It wasn't until 1909 that the potential significance of Midway-Sunset was finally recognized. During that year, the Chanslor-Canfield Midway Oil Company completed the first Midway-Sunset gusher that produced in excess of 3,000 barrels per day. Within seven years, the field had at least 100 wells with daily production rates in excess of 1,000 barrels. The most famous of the early gushers was drilled by the Lake View Oil Company. Dubbed the "Lakeview Gusher", the well flowed approximately eight million barrels of oil during a one-half year period.

Currently, the field has approximately 10,000 producing wells with an average daily production rate of 16 barrels per well. During 1988, production from the Midway-Sunset Field totaled 58 million barrels of oil. As of January 1, 1989, the field had produced nearly 1.9 billion barrels of oil. An estimated 400 million barrels of reserves still remain. Oil gravity varies significantly throughout the field from a low of 8 degrees API to a high of 35 degrees API. Major operators

in the Midway-Sunset Field include: Union Oil Company, Mobil Oil, Sun Oil, Santa Fe Energy, Shell, Phillips, Arco, Chevron, Texaco, Berry Petroleum, and McFarland.

2. Geology of Midway-Sunset

The Midway-Sunset Field is a regional homocline which parallels the eastern flank of the Temblor uplift and trends in a northwest-southeasterly direction. The field has been structurally modified by a series of folds and converging unconformities. Field production/reserve statistics as well as operatorship are often defined in terms of these major substructures.

Production from the Midway-Sunset Field is primarily from the Miocene, although there is some production from the Pliocene and to a much lesser extent from the shallower Pleistocene formations. The upper Miocene sediments are approximately 8,000 feet thick and consist of a series of sandstone and shale formations. The middle and lower Miocene formations are also marked by a sand-shale sequence which reaches a gross thickness in excess of 10,000 feet. The upper Miocene is the major producing interval in the field; the Reef Ridge and the Antelope Shale are its principal oil bearing formations. (The DOE well produces from the upper Miocene Potter Sands.)

C. The Bremer Fee (Midway-Sunset Field)

1. Introduction

The DOE sponsored well (Bremer RI-53) was drilled on the Bremer Fee lease in the Midway-Sunset Field. Operated by the Union Oil Company, the Bremer Fee is situated at the field's northernmost boundary (Section 16, Township 32 South, Range 22 East). A contour map on the productive interval of Midway-Sunset as

well as the location of the Bremer Fee lease is displayed in **Figure** 1. Well site locations for the Bremer Fee are detailed in **Figure** 2; the location of the Bremer RI-53 well is also identified in this figure.

Initial production from the Bremer Fee began in 1968. Since that date, approximately 21 million barrels of oil have been produced. Original oil in place is estimated at 92 million barrels of oil. 23 percent of the OOIP has been recovered to date. Oil gravity for the lease averages 11.4 degrees API. Due to its low gravity, thermal stimulation is required for economic production from the lease. Average daily production per well from the Bremer Fee is less than 20 barrels of oil.

2. Geology

With the exception of limited production tests in the Marvic zone, all Bremer Fee oil production is from the Potter formation. The Potter, the most prolific sandstone within the upper Miocene Reef Ridge formation, is found at a drilled depth of 1000 to 1500 feet on the Bremer lease. Known collectively as the Potter Sands, the Potter formation is divided into four distinct zones, (Potter "A", "B", "C", and "D"). **Figure 3** represents a "Type Log" of the Bremer Fee lease. The four separate Potter sands are highlighted in this figure.

The Bremer RI-53 was completed in the Potter "C" formation. As can be seen from the type log, the Potter "C" is a fairly clean quartz sandstone. Approximately 10 percent shale is present in this zone. Discontinuous shale stringers are common throughout the "C" interval; these shale zones may negatively impact steam distribution and oil productivity.

The "C" sand in the Midway-Sunset Field has a porosity range of 9 to 45 percent with an effective average porosity of 20 to 25 percent. Permeabilities vary sporadically with depth from a few millidarcies to upwards of 3 darcies. The average porosity and permeability for the "C" sand at the Bremer **RI-53** location are estimated at 25 percent and 1 darcy respectively.

Structurally, the Potter dips at an angle of up to 35 degrees in a northwest to southeast trending direction. The Potter "C" ranges in thickness from 450 net feet of pay to the east to zero feet of pay at the updip pinchout to the west. **Figure 4** provides a cross sectional view of the Potter Formation to the east of the Bremer Fee. This figure illustrates the regional dip as well as the updip pinchout. Since oil production from the Potter is dictated by gravity drainage, the relative structural position of Bremer **RI-53** was a key factor in the site selection process.

3. Thermal Operations

Major thermal operations in the Bremer Fee initially occurred from 1976 to 1977 when 60 producing wells and five continuous steam injectors were drilled. The next major drilling activity took place in 1980 when an additional 46 producers were drilled on the lease; these wells were primarily cyclic producers. Four years later, an additional 53 additional wells were drilled, resulting in current well count of nearly 220 producers.

Bremer field production peaked at 7,647 barrels of oil per day in August of 1985. Oil production is currently averaging approximately 5,000 barrels/day (year-end 1989). **Figure 5**

graphically displays the production history of the Bremer Fee during the period from 1974 through 1989.

The existing steamdrive is located in the northeast portion of the field. This steamdrive is isolated from the southwestern portion of the Bremer fee where the wells are all cyclic producers. Structurally, the Potter formation dips at an angle of up to 35 degrees in a southeasterly direction, thereby providing a strong gravity drainage to the downdip wells in both regions.

Significant potential exists to enhance oil recovery in the southwest portion of the Bremer fee in the area of the DOE well. As of January 1, 1989, recovery in the southwestern sector was only 18 percent of the original oil in place. This compares unfavorably with a recovery of approximately 35 percent in the downdip steamdrive portion of the reservoir.

Recent reservoir studies indicate that recovery from the lowermost Potter "C" zone may be particularly low. Temperature profiles show the basal portion of the Potter "C" to be particularly "cold". The temperature stratification within the Potter Sand is due to a combination of long producing intervals and the gravity override of the injected steam. As a result, the oil in the Potter "C" is very viscous and the recovery has been relatively poor. One of the primary objectives of the DOE project was to stimulate production from the Potter "C" sand by injecting steam into horizontal radials drilled into the "cold" Potter "C" interval.

D. The Bremer RI-53 Well Selection Criteria

1. Reservoir Considerations

The Bremer RI-53 well was drilled in April of this year. The well was drilled to a total depth of 1,200 feet. Eight radials were drilled in the Potter "C" sand of which four radials were completed with gravel pack. **Figure** 6 is a montage of selected well logs in the Bremer Fee trending in a northeast-southwest direction along the strike of the structure, and through the Bremer RI-53 location. The attached reference map **(Figure** 2) shows the areal extent of the montage as it traverses the Bremer Fee from " A to A' " through the DOE location (Bremer RI-53). The interval of the Potter "C" zone in which the radials were placed is also indicated in this figure. Bremer RI-53 was unique to the Bremer Fee since it was only completed in a 30 foot section of the Potter "C" sand. Typically, injectors and cyclic producers are completed throughout the entire 400 foot Potter "C" interval.

Two particular reservoir characteristics of the Potter "C" at the Bremer RI-53 location made it a good candidate for horizontal radials.

First, the Potter "C" zone at the RI-53 location appeared to be "cold". Therefore, steam needed to be injected directly into the "C" in order to enhance production from this zone.

Secondly, due to its excellent vertical permeability, steam override generally occurs very near the vertical wellbore in the Potter formation. Radials could be utilized to direct steam away from the vertical well thereby providing more heat to the surrounding Potter "C" formation.

At the outset, it was anticipated that by utilizing the radials for steam injection purposes at this location, at least three benefits would inure to the operator.

1. **Radials should help alleviate problems associated with steam override.** The radials would enable the steam to be injected at far greater distances into the formation and away from the vertical wellbore thereby dampening the deleterious effects of steam override.

2. **Radials should improve the steam injection efficiency.** Radials would enable the operator to select the desired direction and elevation for steam injectivity based upon specific geological and reservoir engineering parameters. As a result, radials should optimize costly thermal operations through improved steam injection techniques.

3. **Radials should improve oil production and ultimate recovery. By** placing radials in multiple directions, the effective wellbore diameter would be increased from seven inches to in excess of 100 feet, thereby accelerating oil production. In addition, by stimulating the "cold" section of the reservoir, radials could also increase oil recovery.

2. Operational Considerations

In addition to reservoir engineering criteria, the selection of the Midway-Sunset field and the RI-53 location in particular, was also based on a number of operational considerations.

1. The Midway-Sunset field was initially selected due to its preeminent position in heavy oil and thermal operations. It is also a field in which many major oil companies and

independent producers conduct operations and are interested in learning more about new drilling and completion technologies.

2. The oil oriented infrastructure in the Bakersfield, California area enabled Petrolphysics to optimize the use of subcontracted services and supplies, thereby obtaining reliable oil field services at competitive rates. Petrolphysics also maintains a support facility 60 miles away in Bakersfield which was available if required.

3. The proximity of RI-53 to existing producing and injector wells provided useful data points for comparative injection and production results.

4. The RI-53 well site was not located in an environmentally sensitive area. Oil operations have existed in this field for many years. A Department of Energy representative conducted a site inspection survey of the Bremer Fee to verify the environmental acceptability of the Bremer RI-53 location.

III. RADIAL PLACEMENT OPERATIONS PHASE

A. Overview of the Ultrashort Radius Radial System

The basic Ultrashort Radius Radial System (URRS) uses an erectable whipstock lowered downhole by a 4-1/2 inch workstring into an underreamed cavity or hydraulically slotted opening of 24 inch diameter. The whipstock is designed for use in a 7 inch casing. (Other whipstock systems are available for 5-1/2 inch casing.) The drillstring is made of 1-1/4 inch electric-resistance welded tubing (A-606)

supplied from a coiled tubing truck. The drillstring may be provided from a coiled tubing unit or it may be fabricated by welding on site from 40 foot tubing joints.

A hydraulic drill head is welded to the nose of the first joint of the drillstring (radial tube). If the drillstring is fabricated on site, subsequent 40 foot joints of drillstring are welded by automatic computer-controlled welding on the rig floor to form the drillstring. A hydraulic motion controller that regulates rate of penetration (ROP) is joined to its tail.

As the drillstring is fabricated, it is lowered inside the vertical 4-1/2 inch workstring. The nose (drill head) of the drillstring enters a high-pressure removeable seal at the top of the whipstock. The seal provides the bottom closure of the workstring. Hence, the 1-1/4 inch drillstring is fully contained within the 4-1/2 inch workstring at the outset of drilling (Figure 7).

A wireline cable attached to the tail of the drillstring runs to the surface within the workstring and passes through the top closure of the workstring. Thus, a long sealed chamber containing the 1-1/4 inch drillstring and its connecting cable is created by the 4-1/2 inch vertical workstring.

Water drilling fluid at 8,000 to 10,000 psi is pumped into the long vertical workstring at the surface with a conventional frac pump. The drilling fluid is then pumped down the workstring where i-t enters the drillstring. The internal water pressure of the drilling system propels the drillstring through the high-pressure bottom seal and through the bending and confining slides and rollers of the whipstock. Traversing the 12 inch radius and 90 degree bend of the whipstock, the drill head enters the formation horizontally. The drillstring is not rotated.

The pressure on the water drilling fluid in the system not only propels the drillstring, but also drills the horizontal borehole in the formation. To drill the formation, the water drilling fluid is accelerated through the Conical Jet drill head nozzle, creating a conical shell of water particles traveling at 800 to 900 ft/sec.

Figure 8A shows a schematic of the Conical Jet. At the top of the figure is a standard collimated jet nozzle. The addition of fixed vanes within the nozzle causes a conical shell of high-velocity water particles to form a conical jet. In **Figure 8,** the size of the horizontal borehole is established by the twist of the vanes, which in turn controls the angle of divergence of the cone of water particles.

Figure 9 shows water jets resulting from various degrees of vane twist in 1-microsecond flash photographs of a collimated jet and two different Conical Jets. The conical angle is not affected by drilling-fluid pressure. These Conical Jets function at both ambient and elevated backpressures. At higher backpressures, cavitation does not appear to be an important cutting mechanism.

B. Whipstock

Radial placement operations begin once the well has been underreamed and prepared. The **URRS** horizontal drilling technology employs many proprietary subsystems. Chief among these is the whipstock **(Figure** 10). This device allows the 1-1/4 inch the radial tube to be bent 90 degrees from the vertical to the horizontal in a one foot bend radius. The whipstock assembly is installed at the end of the vertical working string of high pressure tubing. The whipstock is a system of wheels, slides, and guides which are packaged into a downhole tool approximately 19 feet long and 6 inches in diameter. The length of the whipstock can be extended to accommodate a range of open hole section milled conditions. This adjustability allows radials to be placed from five to thirty-five feet beneath the casing shoe or top of the section milled zone. The whipstock provides a set of jaws which engage the casing of the well to keep the whipstock from rotating during use as well as to maintain a constant elevation in the vertical well. The whipstock also provides a reference for the gyro system which provides the azimuth location of the whipstock (description follows). Typically the whipstock is lowered to the depth at which the radials are to be placed at the beginning of the job. The whipstock will remain there

until all the desired radials have been placed in the formation or until the cuttings have to be cleared from the underreamed zone. Because the workstring elongates under internal pressure, and since the workstring must be kept in tension, the workstring and whipstock are held in tension and erect by a set of hydraulic cylinders at the wellhead that maintain constant tension.

C. Gyro

A small diameter (1-3/4 inch O.D.) gyroscope is used to provide the initial azimuth to which the whipstock is set. The gyro is lowered to the whipstock level inside the working string via a single conductor wireline. It engages a pin in the whipstock. The orientation of the whipstock is then read directly by the wireline truck's operator and directions are then given to operator personnel for the adjustment of the whipstock's orientation. Once the correct azimuth is achieved, the whipstock is locked into place by a combination at uphole slips and downhole jaws on the whipstock.

D. Radial Placement

Once the whipstock assembly is at the required depth and is at the correct azimuth, the 1-1/4 inch radial tube is placed in the formation. Depending on the formation and desired radial length, this drilling process can take from ten minutes to two hours. Radial placement employs a Conical Jet drill head which operates at a surface pressure of 10,000 psi and a flow rate of 140 to 320 gpm. In order to achieve the 10,000 psi operating pressure at 320 gpm flow, two or more high pressure pumps must be manifolded together. The high flow rate within the 1-1/4 inch radial tube is made possible by the addition of friction reduction additives to the drilling fluid (typically water). The radial tube is placed at a nominal velocity of 5-10 feet per minute. While the radial tube is being placed, a real-time Control While Drilling and data acquisition system provides information about the placement process. This information includes penetration of the radial

tube into the formation, inlet pressure, inlet flow, out flow or returns, and control system current. Additionally, the tension of the drillstring in the hole is monitored while the radials are being placed.

E. Control While Drilling

A drillstring can move in four directions (degrees of freedom in movement). In the URRS, three of these movement directions (degrees of freedom) are controlled while drilling.

The first direction of motion, penetration (axial), is controlled by a sealed piston (Motion Controller) attached to the 1-1/4 inch drillstring. This piston, which is analogous to a fluid shock absorber consists of a set of seals and fluid drain orifices. There are no moving parts. The rate of penetration of the drill is preset by the orifice size. This unit is shown as part of the URRS in Figure 7.

Inclination (up/down) is the second direction of motion. It is determined in real-time by an electromechanical inclinometer contained within the 1-1/4 inch drill head. This device, which also compensates for roll (the third direction of motion), switches the power among a set of small locking solenoids. The actual up/down control mechanism consists of four small side thruster jets placed at 90 degrees to each other on the drill head. The thruster jets are valved by flow actuated valves, powered by the high pressure 10,000 psi water drilling fluid. These valves are either held open by the small locking solenoids or allowed to close as required to correct variations in the trajectory inclination. Azimuth (right/left) movement, the fourth direction of motion, is not directly controlled. The Control While Drilling concept is shown in **Figure 11.**

In field applications in a variety of formations and depths, the Ultrashort Radius Radial System with Control While Drilling demonstrates a $\pm$ 2 to 6 degrees vertical deviation. (This results in about a 3.5 to 10 foot vertical deviation per typical 100 foot of horizontal trajectory). A schematic of the forces applied by the

control system of a typical radial is shown in Figure 12. The system is run from a control truck by a single operator. There is no one on the rig floor during drilling operations which normally take only a few minutes to place a 100 to 200 foot radial in an unconsolidated formation.

F. URRS Data Acquisition and Analysis

The URRS data acquisition system can be divided into several functional entities. A schematic is shown in Figure 13. These entities are: signal waveform transporters, signal conditioning, digital converters, mathematical regression equations, database integration and interpretation techniques, information system interface, use input and control messages, data storage, replay and hard copy output.

The signal waveform transporters or "data nervous systems" are comprised of a number of transducers and sensors. The transducers monitor important environmental system parameters and provide real-time analog signals. The incoming signals are conditioned to eliminate system noise and scaled to meet analog/digital input span specifications. Downhole signals can be channeled through a microprocessor and analog multiplexed or frequency shift keyed to the surface. Additional enhancements include power, data signals, and communications transported concurrently over a single wireline.

The conditioned signals are processed by an analog/digital converter at rates up to 5000 Hz and up to 16 channels of simultaneous data. Rate of penetration is currently acquired through optical encoders and a four axis quadrature counter. Distances can be preset for key event diagnostics. All incoming data is imprinted with real-time clock information for post analysis.

A computer processes the large amount of data for immediate interpretation. Computer-simulated filters buffer the digital data to extract specific data for analysis. Mathematical models and algorithms organize the data into easily understandable and relatable parameters. The data is then displayed to the

operator on a single console using overlay techniques. Background waveforms are scrolled across the screen to give an immediate account of the interpreted data as well as an historical record of past data. Foreground information displays scaled windows and modeled information such as effective nozzle areas and system runtime information. Warning flags are implemented for abnormal operations to prevent system failure.

The operator can control various parameters which effect system interpretations as well as control data display. Post analysis of the data includes interfaces with databases of past drilling operations for establishing comparative models for the present drilling assignment. The data is permanently stored for post analysis of run history including playback and hard copy **(Figure** 13).

G. Positional Logging

Positional logging of each radial tube is performed after it is placed. A flexible inclinometer on the end of a wireline is pumped into the radial tube. This inclinometer and its associated equipment including the wireline winch and computer provide graphical and tabular output representations of the radial tube as it lies in the borehole once the radial is placed. All of the radials were positionally logged. Inclinometer surveys of all four completed radials are shown in **Figures 14-17.**

H. Radial Completions

Several options are available for completion of the radials once they have been placed in the formation and positionally logged. Typically, completions could include some or all of the following items: electrolytic cutting off of the drill head, gravel packing of the radial borehole, installation of the Flexible Sand Barrier, and removal of the radial tube. Each of these procedures will be described separately.

1. Electrolytic cutting

Once the positional logging of the radial tube is completed, the drill head portion of the radial tube is cut off with the Electrolytic Cutting System. This system utilizes an insulated single conductor wireline and D.C. welding power supply in conjunction with a flowing electrolyte to provide a localized electrochemical cutting action at the drill head.

The cutoff tool is an insulated metal disk connected by an electrical cable to an electric well or power source. A cable stop is placed on the cable that will stop at the top of the drillstring and accurately locate the cutting tool at the desired position.

Electrochemical cutoff is essentially a controlled corrosion process by which a current is passed between a cathode (tool) and an anode (drillstring). In the presence of power and an electrolyte (e.g., brine and DC), an electrochemical reaction occurs that puts iron from the drillstring into a solution, forming a precipitate (sludge) and gaseous byproducts (H_2 and O_2). (The volume of precipitate is very small.)

Typical parameters are 10 to 15 gpm of potassium chloride (KC1) in a 12-15% by weight solution and the power supply providing 55 amps at 50 volts. By removing the drill head and exposing the open end of the radial tube to the formation, the remaining completion techniques can then be performed on the radial borehole.

2. Horizontal Gravel Packing

Gravel packing can be accomplished by a two-lift borehole filling process with a water/gravel slurry. In the first lift, gravel is pumped down the drillstring and out of its cutoff nose. Conventional

surface gravel-packing equipment is used. After leaving the open nose of the drillstring, the gravel slurry flows back toward the wellbore through the horizontal borehole annulus around the drillstring. **Figure 18** shows the gravel movement and placement for the first lift of the gravel pack.

To gravel pack successfully during the first lift, the material must be pumped at a sufficient rate to ensure transport of the gravel within the 1-1/4 inch drillstring. A suitable pumping rate is in excess of 7 ft/sec. Once the slurry mixture passes out of the drillstring at its open (cutoff) nose, the gravel slurry enters the annulus of the horizontal radial borehole, which is typically about 4 inches in diameter. This larger diameter of the radial borehole causes the slurry mixture to slow and the gravel to settle, forming a dune within the annulus that moves from the nose of the drillstring back toward the vertical wellbore. As the dune partially fills the radial borehole annulus, an ullage (a flow space with a flat bottom and curved top) is created between the top of the radial borehole and the deposited gravel dune.

The ullage is the foundation of the self-regulating characteristics of this horizontal gravel-packing process. If gravel gradually closes off the ullage in a sandoff, it causes the fluid velocity to increase and thus erode out, carrying more of the gravel back toward the wellbore. If the ullage enlarges, the velocity of the slurry slows and more gravel settles, forming a higher dune. In effect, if the water maintains a velocity of about 3 ft/sec in the ullage, it remains open. Hence, gravel transport is self-regulating.

This self-regulation process was proved successful over a wide range of conditions, including 5 to 60 mesh screen sizes of gravel, drillstring inclinations $\pm$ 20 degrees off horizontal, and radial borehole diameters of 4 to 12 inches. For the process to work, it is necessary to keep the viscosity of the slurry liquid at or near that of water and the gravel concentration at about 0.1 to 4 lbm/gal.

The volume of gravel used in the first lift is arbitrarily sized to fill to about 80% of the normal 4 inch borehole provided by the Conical Jet. There is no measurement of the fill percentage provided in the first lift because overfill or underfill is not important.

The second lift of horizontal gravel packing occurs after all radial boreholes on a level are drilled and gravel packed separately in a first lift. At that point all radials are partially gravel packed (70 to 90% or greater fill). The second lift, estimated as essentially total gravel packing of all radial boreholes, occurs automatically while the vertical underreamed zone of the vertical wellbore is conventionally gravel packed. The second lift uses the same type of fluid and slurry concentration as the first lift, but the gravel slurry flows out of the ullages of the all the radials. **Figure 19** shows the interim gravel movement in the second lift. The water enters the formation and gravel progressively sands off each radial. Hence, it progressively fills back toward the vertical wellbore until all radials are fully packed.

Figure 20 shows the completed radial production system also incorporating the Flexible Sand Barrier.

3. Flexible Sand Barrier

The Flexible Sand Barrier (FSB) is a flexible, jointed permeable tube constructed of a helically wound metal strip as shown

in Figure 21. The tube is formed from a single thin narrow metal strip which is folded and wrapped into itself. The degree of infolding or interlock of this joint influences both the filtering properties and the axial or tensile strength of the FSB. As well, the degree of interlock determines the flexibility or allowable bend radius of a particular diameter FSB tube. Because the FSB is formed of a single metal strip, the FSB can be constructed of any ductile material which can be plastically deformed into the interlocking joint.

The Flexible Sand Barrier interlocked structure was developed after extensive trials with many varieties of slotted liner or wire wrapped screen. Neither of these structures provided an adequate combination of mechanical flexibility to go around a one foot radius and filtering capability.

Much laboratory and field research has been accomplished with the Flexible Sand Barrier toward evaluation of pressure drops with water and with oil of various viscosities. In general, the 3/4 inch Flexible Sand Barrier passes 20 to 40 bbl/day of 1,000 centipoise oil per 100 feet of length in a 30 psi reservoir. Higher pressure and lower viscosity will enhance throughput.

The FSB can provide a range of varying passageway shapes, which are dependent upon the construction of the interlocking strip material. The passage shape can vary, but in general, the flexible joint provides a helical passage with an S-shaped cross section. The joint configuration can be wide or narrow depending upon whether the flexible tube is pulled into an open or closed position. The degree of openness is adjusted by tension load on the FSB. The selected degree

of openness is then fixed by an internal structure attached within the FSB. Normal operating specification is 30 to 70% openness.

Considering the FSB as a filter, the fluid flows from outside through the passageway into the interior of the FSB. The sand or formation material collects on the outside and builds a particle bridge over the helical joint. Based upon extensive laboratory tests, this particle bridge acts as an efficient sand filter. Some fine formation sand may pass through the helical joint depending upon the size of particles, the viscosity of the fluid, and the degree of the joint openness. In general, the filter efficiency with the Flexible Sand Barrier is high down to micron size grains. As an option in the event that the outside of the FSB becomes plugged with particles, the FSB can be used as a reverse flow path for fluid or steam. This flow reversal would tend to break up the plugging or sand bridging effect and allow increased flow.

Because of capability for movement, the FSB can adjust to temperature changes and thus should preclude damage therefrom in thermal recovery applications.

The final configuration of the FSB in a multiple set of gravel packed horizontal radial boreholes is shown in **Figure** 20.

a. Application

The FSB can be applied as a sand barrier for horizontal, deviated, and vertical wells.

In placing the FSB, it is pumped down the 1-1/4 inch radial tube and out of the cutoff end, as previously described. To provide the placement and pumpdown mechanism, three components are placed at the anterior or nose of the FSB. The

first is an expanding set of barbs on a spear as shown in the bottom sketch in **Figure 21.** The barbs are compressed when it is pumped down. When it exits the open end of the 1-1/4 inch radial tube, the barbs spring open and engage the formation, thus anchoring the FSB to the formation.

In order to pump down the FSB, a set of chevron seals is also provided at its nose, posterior to the barb anchor. these seals provide the means by which the FSB can be pulled down the radial tube Under fluid pressure. When the FSB reaches the open end of the radial tube, the barbs exit followed by the sliding chevron seal. At that point there is no longer any sealing means by which fluid can pull the FSB along the radial tube and the FSB stops. Upon exit of the FSB from the radial tube, the barbs expand into the formation and anchor the FSB to the formation.

The next step in placement is to withdraw the 1-1/4 inch radial tube by pulling on its posterior with an overshot placed onto its open tail. This overshot is lowered down the vertical workstring via sucker rods. Upon engagement with the open tail of the radial tube, the sucker rods are pulled back and draw back the 1-1/4 inch radial tube. The result is that the bare FSB is left in place as a conduit and sand filter within the horizontal borehole. Suitable sized screens are placed on both ends of the FSB shown as a Tail Filter in **Figure 21.** The net result is a suitably flexible, permeable casing which also serves as a sand barrier.

Once the 1-1/4 inch radial tube has been completely withdrawn, the whipstock can be reoriented and another radial can be placed.

IV. OPERATIONS AT BREMER RI-53

A. Operations Prior to Radial Placement

1. Drilling, Casing, and Cementing the Vertical Well

The well was drilled to 1250 feet for 7 inch casing and 7 inch, 23 pound casing was run to 870 feet. At the bottom of the casing, a guide "shoe" was placed. (The guide shoe is a piece of casing which is slightly belled to allow the whipstock to reenter the casing easily when operations are completed.)

After running the casing, the well was cemented using a class "G" cement. The well was plugged back to 1060 feet leaving an open interval from 1060 feet to 870 feet.

Drilling, casing, and cementing the Bremer RI-53 well took approximately three days to complete. A perspective of the well radial placement is shown in **Figure** 22.

2. Underreaming the Wellbore to 24 Inches in Diameter

Once the vertical well had been drilled, cased, and cemented, and the cement was given sufficient time to set, the well was then underreamed. These operations proceeded without event and were typical of drilling operations that occur in the Midway-Sunset Field.

Underreaming is a process whereby a zone or zones are created that are larger than the drilled size of the well. This process

can be completed on cased or uncased zones and can be done when the well is drilled or at a later date.

The Petrolphysics drilling technology employed at the Bremer (RI-53) well requires the underreaming of a 24 inch diameter zone. The minimum height of this underreamed zone is 10 feet. For this particular well, Unocal opted to underream a 30 foot high zone from 870 to 900 feet.

The 30 foot high zone allowed Unocal to position the whipstock elevation in the selected position and to provide sufficient clearance to allow the whipstock to be removed in the event that this soft unconsolidated formation were to collapse in the underreamed zone.

The underreaming is done by third party contractors who supply the requisite tools and personnel. Underreaming for the Bremer RI-5 was performed by Tri-State Oil Tool of Bakersfield, California. (The underreaming is done with the assistance of the drilling/production rig and crews). The production rig uses many of the same components as a drilling rig, i.e., mud, rotary table, power swivel, mud pump, etc.

For Bremer RI-53 the underreaming was accomplished in 4 steps or changes in successive diameters.

1. 7" to 13" diameter
2. 13" to 15" diameter
3. 15" to 20" diameter
4. 20" to 24" diameter

Each required change in diameter necessitated that the underreaming tool be brought out of the hole (tripped) and new arms

installed to allow the next diameter to be cut. Additionally, the underreaming tool body was changed after the 15 inch diameter pass was made.

Underreaming Bremer RI-53 took approximately two days.

3. Caliper Logging of the Underreamed Zone

After a well is underreamed, it is calipered. Caliper logging is the process of measuring the average diameter of the underreamed cavity zone. It gives both the height and diameter of the underreamed zone. Caliper logging is done by an outside vendor who provides this service. Welenco of Bakersfield, California calipered this underreamed well.

The caliper log of the underreamed portion of Bremer RI-53 showed that it was at least 24 inches in diameter throughout.

B. Radial Placement Operations

After the vertical well was prepared, Petrolphysics moved its equipment onto the location. This included the wireline truck, high pressure frac pump, coiled tubing unit, and equipment trailer. The site arrangement is shown in **Figure** 23. Once all the equipment was set up, the downhole assembly and tubing were run into the well. The downhole assembly included the whipstock and motion controller tubing comprising 260 feet of the required 995 feet of equipment and tubing required to place radials at approximately 985 feet below the surface. The remainder of the string length (725 feet) was comprised of 4-1/2 inch, 24.6 lb/ft Atlas Bradford TC4S tubing.

The high pressure TC4S string was rented from Blue Marlin Specialty Tools in Bakersfield, California.

The radial placement operations at Bremer RI-53 required that the whipstock and high pressure tubing string be run into the well twice. The first time

was prior to placing calibration radials 1-3. The second time was prior to placing calibration radial 4.

Once the whipstock and high pressure tubing were run in the hole to a depth of 985 feet, the whipstock was oriented with the gyroscope. The gyroscope was used to set the azimuth of each radial. This orientation was done prior to each radial being assembled and placed in the formation. Eight radials were placed. The first four were short calibration radials and were not completed. The second four were completed for injection and production usage. **Figure** 22, a perspective view of radial placement, gives the orientations of the four radials that were completed in Bremer RI-53.

After the azimuth of each radial was established by the gyroscope, the radial tubes were assembled. This assembly included the joining of the Conical Jet nozzle, vertical control system, and the motion controllers to the 1-1/4 inch tubing. The radial tubes were then ready to be run to the bottom of the high pressure tubing string via the single conductor wireline.

Upon reaching the bottom of the high pressure tubing string, the Ultrashort Radius Radial System was pressured up via the frac pump and upon reaching 10,000 psi operating pressure the radials progressed through the whipstock and into the formation. The water flow out of the nozzle at this point was approximately 160 gpm. As the radial tubes passed through the whipstock and into the formation the radial's rate of penetration (as well as pressure), flow and other parameters were monitored, displayed, and recorded via the data acquisition system.

Selected graphical displays are attached in **Figures 14-17.** These include pressure, flow, and distance vs. time for each of the four completed radials. Radial placement average velocities can be calculated from the distance vs. time graph as follows:

Radial 1: 5.6 ft/min

Radial 2: 3.5 ft/min

Radial 3: 5.2 ft/min

Radial 4: 0.8 ft/min

When the radials reached approximately 7 feet beyond the exit of the whipstock, the control system was energized and remained on until the maximum radial distance was reached.

After the radials had been placed in the formation, the control system cable was removed from inside the radial tube. This allowed access to the radial for positional logging and completion operations.

After each of the radials was placed in Bremer RI-53, it was positionally logged. Typical positional logging surveys from the work at Bremer RI-53 are shown in **Figures** 19-22.

C. Radial Completions

Several options are available for completion of the radials once they have been placed in the formation and positionally logged. Typically, completions would include electrolytically cutting off the drill head, gravel packing of the radial borehole, installation of the Flexible Sand Barrier, and removal of the radial tube.

For the radials in Bremer RI-53 all the above options were tried. Radial number 1 had its drill head cut off and the radial borehole was first lift gravel packed with 3 ft^3 of gravel. Radial number 2 was completed the same way, except that it was packed with 4 ft^3 of gravel. For both radial numbers 1 and 2 in turn, the radial tube was removed by sucker rod pullback.

Radial number 3 had its drill head cut off and was then first lift gravel packed with 4 ft^3 of gravel. Additionally, a Flexible Sand Barrier 97 feet long was installed in radial number 3 before removing its radial tube.

Radial number 4 was completed the same as radials 1 and 2 and was packed with 3 ft^3 of gravel before removing its radial tube. The four initial short calibration radials were not completed.

The amount of gravel placed in each radial is determined by the estimated borehole volume of each radial. A portion of this volume is then placed in the borehole during the first lift gravel pack. For the radials in Bremer RI-53, 50% of the calculated volume was placed in the first lift process and the remainder during the second lift process.

D. Second Lift Gravel Packing and Vertical Well Completion of Bremer RI-53

After all the radials were placed, the well was checked for accumulated fill from radial placement which was found to be sufficient for the 30 foot length of slotted liner.

The slotted liner (50 mesh, 48 row, 25 slot with 6 inch centers) was run in the hole attached to the over-the-top gravel packing assembly which allows gravel (8-12 mesh) to be pumped to the annulus between the liner and the vertical wellbore. Upon reaching the required depth, the well was gravel packed using a conventional gravel packing technique which had been employed by Unocal in other vertical completions. The gravel pack machine and downhole tools were supplied as a service by R&H Gravel Packing of Bakersfield, California. In order to accommodate the reduced gravel mass requirements of horizontal gravel packing of the radial bores, the gravel packing machine was adjusted to provide a more appropriate water flow and gravel mass rate. For this well these parameters were reduced to approximately one-half those used for vertical gravel packing in the two foot vertical interval where the radial bores intersect the vertical bore. **Figure 20** shows the completed gravel packed, underreamed zone and radial bores incorporating Flexible Sand Barriers.

In a typical vertical gravel pack the well is allowed to circulate and flow to the surface. This was done during the majority of the vertical gravel pack of Bremer RI-53. Petrolphysics' two lift gravel packing techniques require that the well be closed in once the gravel in the vertical well reaches the intersection of the radial bores. By "squeezing" the well in this way water is forced into the formation thereby transporting gravel into the radial bores along with the water.

Once the calculated volume of gravel has been delivered to the radial wellbores the flow is once again allowed to go to the surface and the remainder of the underreamed zone is gravel packed.

E. Cost of Radial Placement and Completion Operations

In normal commercial operations, four radials may be placed and completed in seven to eight 12-hour days made up of the following tasks:

Task 1 - Underream and Caliper	1 day
Task 2 - Set Up Petrolphysics Equipment	1/2 day
Task 3 - Place and Complete Radial #1	1-1/2 days
Task 4 - Place and Complete Radial #2	1-1/2 days
Task 5 - Place and Complete Radial #3	1-1/2 days
Task 6 - Place and Complete Radial #4	1-1/2 days
Task 7 - Remove Petrolphysics Equipment	1/2 day
Total	8 days

For this work a number of specially requested tasks involving safety reviews and placement of short calibration radials were included. These tasks extended the work period.

V. STEAM INJECTION AND PRODUCTION PHASE

One of the principal project objectives was to demonstrate that a well completed with radials could be utilized for the dual purpose of steam injection as well as oil production. Injection and production results from the first cycle of Bremer RI-53 have been quite encouraging. In addition to the very favorable impact on Bremer RI-53 well itself, radials appear to have positively affected production results from offset locations as well. The following section briefly describes the steam injection and production phases and the initial conclusions thereof. An interpretation of the effectiveness of radials as cyclic producers is discussed in the next section of this report.

A. Steam Injection Phase

The steam injection phase was conducted solely at Unocal's direction and control. Petrolphysics did not participate in designing the steam injection program nor was it involved in monitoring the injection results. The steam injection information is provided for the first cycle only.

Following the completion of Bremer RI-53 and prior to steam injection, the well was placed on primary production for three days. During this period, the well had an average daily production of one barrel of oil and a total of five barrels of gross fluid.

Steam Cycle #1 was subsequently initiated on May 31, 1990 and continued for a total of twelve days. During this twelve day period, 17,085 barrels of cold water equivalent (5,390 MMBTU) were injected into the well. The quantity and quality of the injected steam was consistent with the volume and quality of steam injected into offset wells on the Bremer lease.

Unocal encountered no difficulties during the injection phase. No abnormal injection response nor reservoir receptivity to the injected steam was observed. The following table substantiates this observation.

Bremer RI-53 Injection

Steam Cycle #1

	Bbls Inj	Ht Inj	Cum Wtr	Cum Ht
05/31/90	1068	340	1068	340
06/01/90	1131	365	2199	705
06/02/90	1501	496	3700	1201
06/03/90	1228	412	4928	1613
06/04/90	1392	422	6320	2035
06/05/90	1333	423	7653	2458
06/06/90	1253	395	8906	2853
06/07/90	1421	430	10327	3283
06/08/90	1568	491	11895	3774
06/09/90	1613	493	13508	4267
06/10/90	1802	562	15310	4829
06/11/90	1775	561	17085	5390

Prior to injecting steam into Bremer RI-53, an observation well (Bremer O-5) was drilled approximately 100 feet to the northwest. A temperature profile from the Bremer O-5 location was taken before and after the steam injection phase. A temperature log from the updip Bremer O-5 location is displayed in **Figure 28.**

The temperature log from Bremer O-5 substantiates the capability of radials to direct steam in specific azimuths and within specific elevations within a formation. The attached log also documents that steam has been effectively transported throughout the entire length of the radial, i.e., horizontal distance of at least 100 feet can be substantiated by the O-5 response. As can be noted from the

attached log, there is a substantial temperature increase at an elevation of minus 800 to minus 875 feet. This temperature spike corresponds with the elevation of Radial #3 which terminated approximately 50 feet to the south of the observation well. Therefore, the steam has been effectively contained within the target interval.

The temperature log also indicates that the background temperature in the well, both above and below the radial effected zone, is at least 90 degrees cooler. Oil in these colder areas has not been yet mobilized since typical steam injection procedures have been ineffective in heating these zones. Normally, steam is injected into the entire 400+ foot Potter interval. While the upper portion of the Potter is heated by this process (as indicated by the attached temperature profile from minus 550 feet to minus 700 feet), the basal portion of the Potter remains unaffected. As a result, oil reserves attributable to the lower Potter sands remain "cold" and relatively immobile. Therefore, one of the principal benefits of an injector or a cyclic producer completed with radials appears to be the ability to selectively provide heat to specific zones thereby accelerating production or perhaps even mobilizing additional oil in place.

Another key objective of the DOE project was to utilize radials to eliminate the deleterious effects of steam override near the vertical wellbore. The steam appears to stay within the selected interval and there would be localized growth override within that limited zone. Nevertheless, there have been no indications of steam override over the total Potter interval in Bremer RI-53 at this point. Subsequent cycles will be necessary to determine if steam override in the total Potter interval is eliminated.

Steam injection response was encouraging; however, subsequent testing is required to verify the long term usefulness of the radials. In conclusion it appears:

1. **Radials can be utilized as effective conduits for purposes of steam injection.**

2. Steam override has not been observed in the vertical well completed with radials.

3. Radials can provide steam to specific zones within a producing formation and provide heat to that particular zone.

4. Radials may direct steam in specific azimuths, including downdip. Offset wells did respond to the RI-53 steam cycle; however, this is common in closely spaced cyclical operations.

5. Radials may provide a combination of vertical and areal heat placement efficiency not attainable by conventional vertical wells.

B. Production Phase

Production from Bremer RI-53 was monitored by Unocal and it was measured on various dates throughout Production Cycle # 1. Early production results are very favorable on an absolute and on a comparative well basis. Bremer RI-53 is early in its productive life.

During the first week of production following the steam injection, production from Bremer RI-53 was quite low; production averaged less than 5 barrels of oil per day. By comparison, a typical cyclic producer has a relatively high initial production rate. However, during the subsequent three week period, Bremer RI-53's production began to ramp up dramatically and peaked at approximately 60 barrels of oil per day. This production level was higher than "typical" producing wells drilled at a similar time and spacing. This comparatively high level of oil production was also accompanied by a correspondingly low level of water production; a 30.5 per cent water cut was measured.

Oil production remained at a relatively high plateau during approximately three months of observation from mid-July through the first of October. This consistent level of oil production was considered to be anomalously high, relative to the typical producer in the field. Notwithstanding variations in reservoir

characteristics and oil quality throughout the Bremer Fee, the operator considered early production results from RI-53 to be very encouraging. Bremer RI-53, which was originally slated to be converted into an steam injector after the conclusion of first production, will remain a cyclic producer for further testing. Future injection and production cycles will now be available for additional evaluation. The pattern of relatively constant or unusually slow production decline has been observed in other heavy oil wells. (Reference Well 378 reported in Figure 15 on page 253 of the September, 1989 issue of SPE Drilling Engineering. This well with four URRS radials had very similar properties and completions to the Bremer well. It similarly showed an unusually prolonged period of slow decline.)

In light oil wells wherein multiple ultrashort radials have been placed in areas such as Wyoming and Louisiana, a similar production pattern of low or minimal oil production decline has been observed for extended periods. This desirable condition may be caused by several properties including penetration of the near wellbore damage, penetration of reservoir heterogeneity, and a reduced convergence or a different flow condition with the multiple radials as compared to a conventional vertical well.

For both heavy and light oil, multiple radials probably have two flow characteristics which are different from a vertical well. First, with long multidirectional, high permeability flow channels, the fluid velocity is lower and in turn the pressure gradients within the reservoir are lower. This would explain both reduced water/oil ratio or a lesser tendency to water cone. Second, with multidirectional radials, deleterious reservoir heterogeneity and anisotropy effects will be less pronounced and some oil which was heretofore immobile may become producible.

Figure 29 graphically displays the initial production results from RI-53. Gross fluids, oil production and temperature were recorded at various intervals.

These data have been charted for the period from June 27 through October 1, 1990. [Oil production continued beyond that date but recordation was beyond the scope (due date) of the final report to the DOE.]

Bremer RI-53 was open hole completed in a 30 foot zone. Both the horizontal radials, as well as the vertical wellbore, were gravel packed upon completion of the URRS operations. By comparison, a typical producer in the Bremer Lease produces from a 400+ foot open hole, gravel packed interval. In general, the first cycle production from RI-53 exceeded production rates from the typical producers having a much more extensive open hole completion.

The following observations can be documented for the first cycle of production operations in RI-53:

1. **On average, the well completed with radials had initial production rates after thermal stimulation in excess of typical producers in the lease.**
2. **The well completed with radials maintained a relatively level production profile throughout the observation period.**
3. **Although the well with radials was only completed in a 30 foot open hole zone, its daily production was equal to or exceeded recently completed producers with 400+ foot open hole completions.**
4. **The radials appear to be beneficial to the performance of cyclic producers. However, we do not know if improved cyclic response is due to improved placement of heat or improved inflow performance of the radial.**

VI. CONCLUSIONS

The primary project objectives set forth in the Department of Energy's Request for Proposal (RFP#DE-RP22-88BC14203) have been successfully accomplished. Results to date demonstrate that all of the stated DOE objectives have been achieved, specifically:

1. Petrolphysics has successfully demonstrated that its Ultrashort Radius Radial System is capable of drilling and completing multiple horizontal radials in a heavy oil formation.
2. Field results preliminarily show that URRS radials are effective conduits for directing steam at specific elevations within a producing formation.
3. URRS radials appear to be effective in eliminating the negative effects of steam override conditions.
4. URRS radials can be utilized for cyclic production; radials have demonstrated their effectiveness for steam injection.

In addition to these observations, additional analysis of the production data from Bremer RI-53 and from the surrounding wells was conducted. While still preliminary, the analysis to date indicates that radials are having a positive impact on the production results from RI-53 as well as on the production from the surrounding wells.

Mr. Herman Dykstra, petroleum engineering consultant with extensive experience in heavy oil, thermal operations, was asked to analyze the results to date. The text of Mr. Dykstra's report can be found in Appendix A. Based on his observations of the relevant production data, the following conclusions have been excerpted from Mr. Dykstra's report:

1. There was a positive response in three wells to (steam) injection into RI-53; two wells were downstructure and one well was slightly upstructure.
2. There did not appear to be a response in the highest upstructure well (Bremer 106) in the pilot area.
3. Temperature surveys indicated that during the pilot test steam went into a portion of the Potter sand that had only been affected to a small extent during previous cyclic operations.

4. Based on temperature surveys and the response of RI-53, it appears that oil is being produced that would otherwise not be mobilized. This would indicate an increase in reserves.

5. Based on temperature surveys and on response at Bremer 42, it appears that steam entered the reservoir at the far end of at least two of the four radials.

6. Average maximum rates of production per foot of sand open are about 1.63 for RI-53 versus a maximum of .13 for an offset producer.

VII. RECOMMENDATIONS FOR FUTURE WORK

The initial results from Bremer RI-53 have demonstrated the practical utility of URRS radials as steam injectors and as oil producers. These positive results have been documented during the first cycle of RI-53. By comparison, offset wells on the Bremer lease have experienced in excess of ten steam cycles. Since Unocal has made the decision to convert RI-53 into a cyclic producer, it is recommended that the steam injection and production results from this well continue to be monitored. It is also recommended that the production results from the offset wells to RI-53 be analyzed to further document the potential benefits of radials on the production performance of surrounding wells.

Since Bremer RI-53 has performed well, it is recommended that a five or ten well package embodying the same technology be placed to provide better statistical support for the production and related results. This set of wells should provide a good statistical basis for the long term analysis of decline to confirm the indicated increase in reserves. The vertical location of the radials in the additional wells should be selected so as to optimize the production of heretofore immobile oil, such as placement low in the zone.

ACKNOWLEDGMENT

Petrolphysics wishes to acknowledge the excellent cooperation and well document data acquisition that was provided by Unocal throughout its organization.

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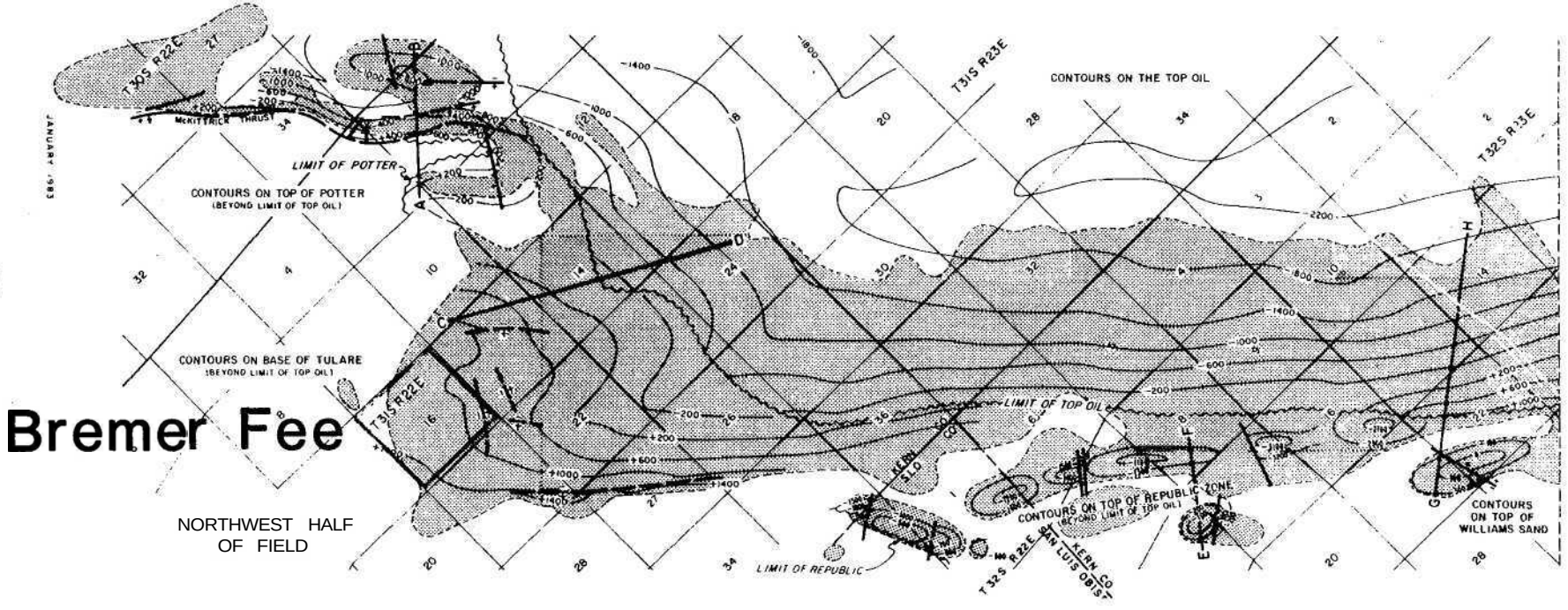

Bremer Fee
NORTHWEST HALF OF FIELD
CONTOURS ON THE TOP OIL
CONTOURS ON TOP OF POTTER (BEYOND LIMIT OF TOP OIL)
LIMIT OF POTTER
CONTOURS ON BASE OF TULARE (BEYOND LIMIT OF TOP OIL)
LIMIT OF TOP OIL
CONTOURS ON TOP OF REPUBLIC ZONE (BEYOND LIMIT OF TOP OIL)
LIMIT OF REPUBLIC
CONTOURS ON TOP OF WILLIAMS SAND
McKITTRICK THRUST
T 30S R22E
T 31S R22E
T 31S R23E
T 32S R22E
T 32S R23E
KERN FLD
SAN LUIS OBIS T
KERN CO
JANUARY 1985

Figure 1

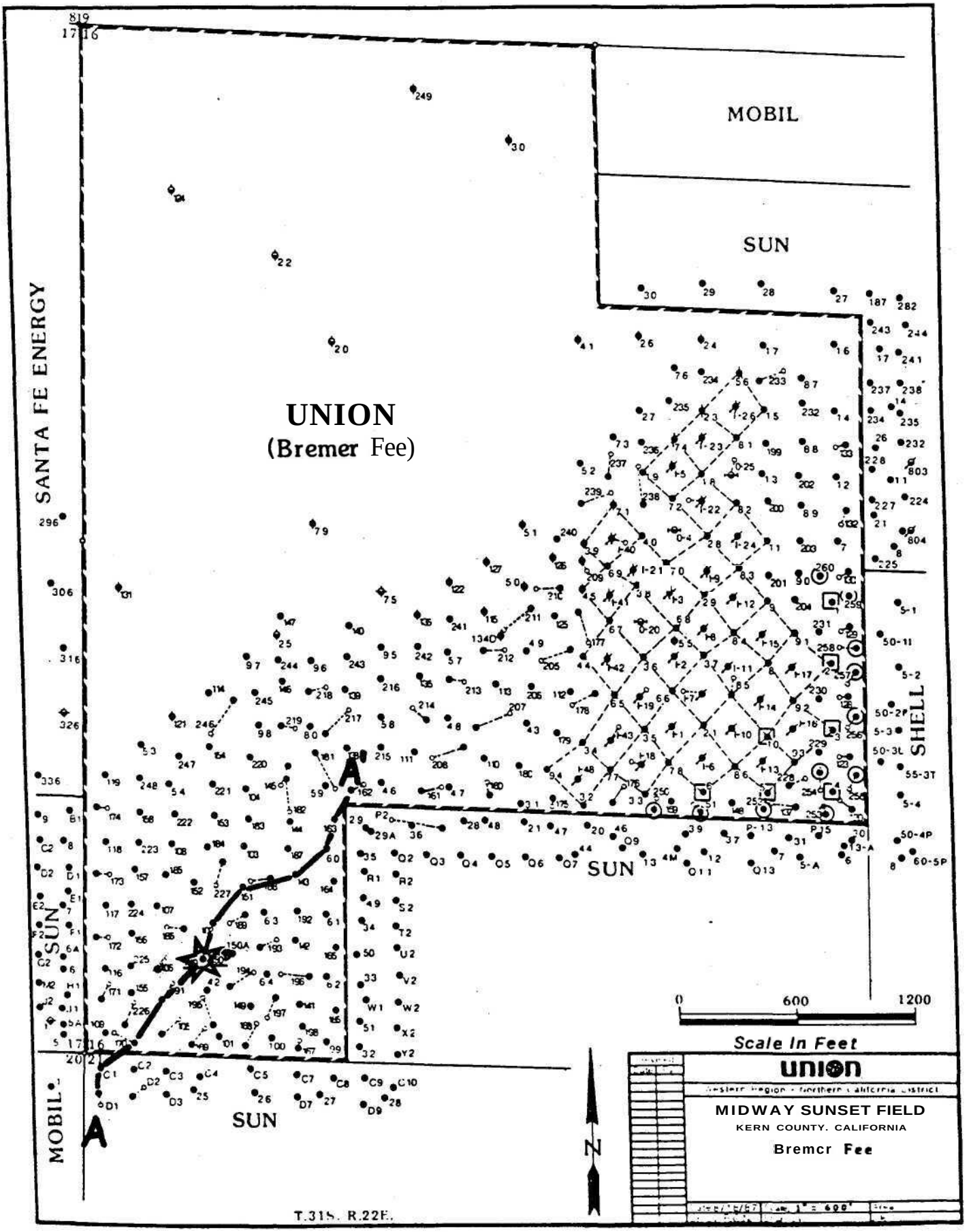

MOBIL
SUN
SANTA FE ENERGY
UNION
(Bremer Fee)
SHELL
SUN
SUN
MOBIL
A
A
0
600
1200
Scale In Feet
union
MIDWAY SUNSET FIELD
KERN COUNTY, CALIFORNIA
Bremer Fee
N
T.31S. R.22E.

Figure 2

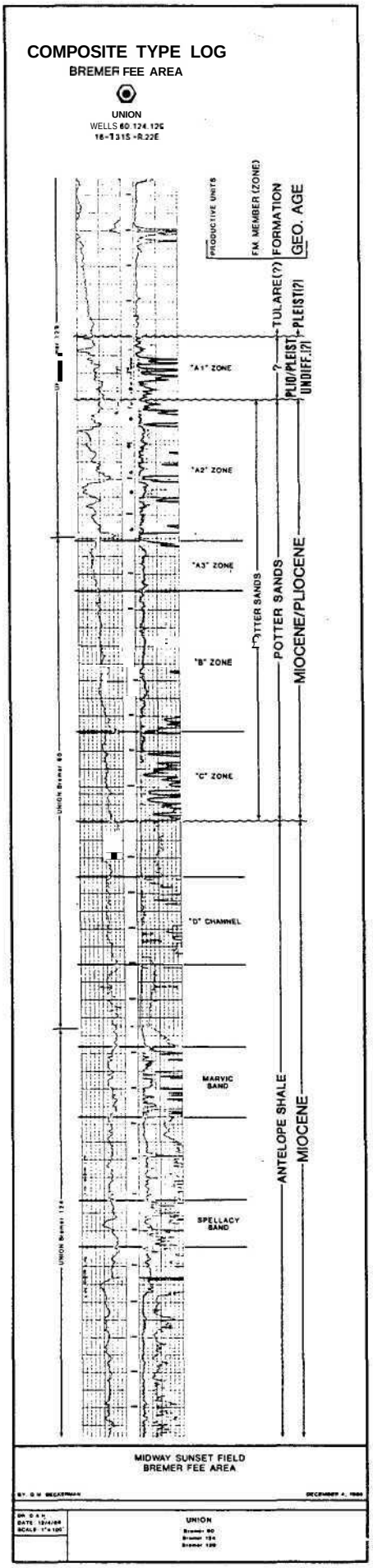

COMPOSITE TYPE LOG
BREMER FEE AREA
UNION
WELLS 60.124.126
18-T31S-R22E
PRODUCTIVE UNITS
FM. MEMBER (ZONE)
FORMATION
GEO. AGE
"A1" ZONE
"A2" ZONE
"A3" ZONE
"B" ZONE
"C" ZONE
"D" CHANNEL
MARVIC SAND
SPELLACY SAND
POTTER SANDS
TULARE(?)
PLIO/PLEIST.
UNDIFF.(?)
PLEIST(?)
POTTER SANDS
ANTELOPE SHALE
MIOCENE/PLIOCENE
MIOCENE
MIDWAY SUNSET FIELD
BREMER FEE AREA
UNION

Figure 3

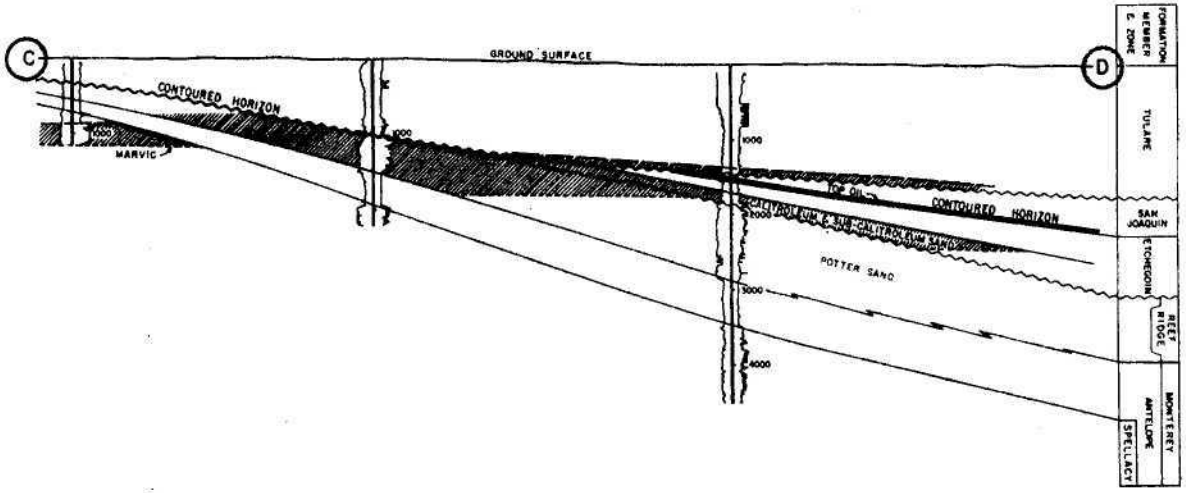

FORMATION
MEMBER
E. ZONE
TULARE
SAN JOAQUIN
ETCHEGOIN
REEF RIDGE
MONTEREY
ANTELOPE
SPELLACY
C
D
GROUND SURFACE
CONTOURED HORIZON
MARVIC
1000
2000
3000
4000
OIL
CONTOURED HORIZON
POTTER SAND

Figure 4

MIDWAY SUNSET FIELD
BREMER FEE
Potter

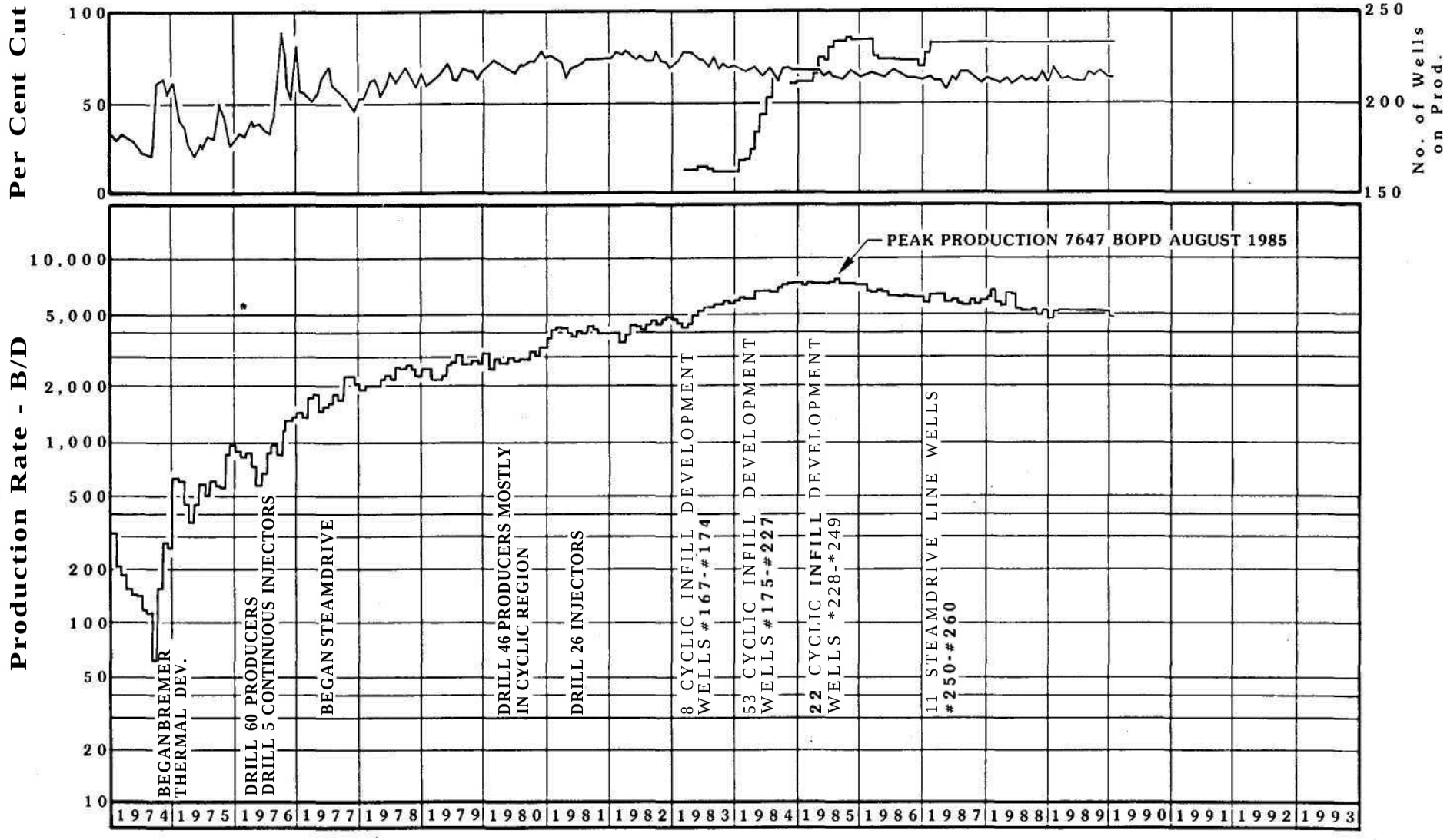


Figure 5

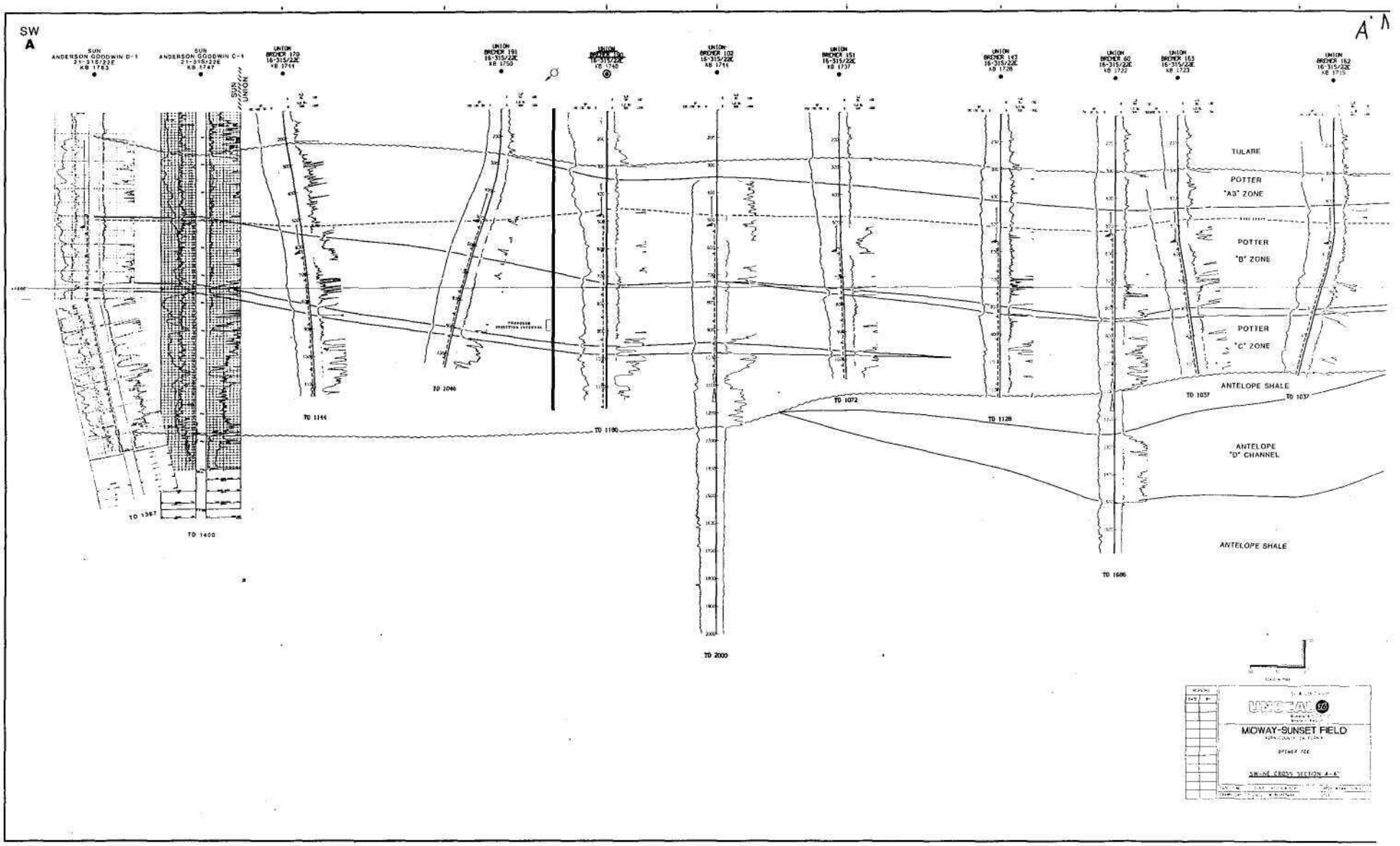

SW
A
A'
TULARE
POTTER
"A3" ZONE
POTTER
"B" ZONE
POTTER
"C" ZONE
ANTELOPE SHALE
ANTELOPE
"D" CHANNEL
ANTELOPE SHALE
MIDWAY-SUNSET FIELD
SW-NE CROSS SECTION A-A'

Figure 6

ULTRASHORT RADIUS RADIAL SYSTEM

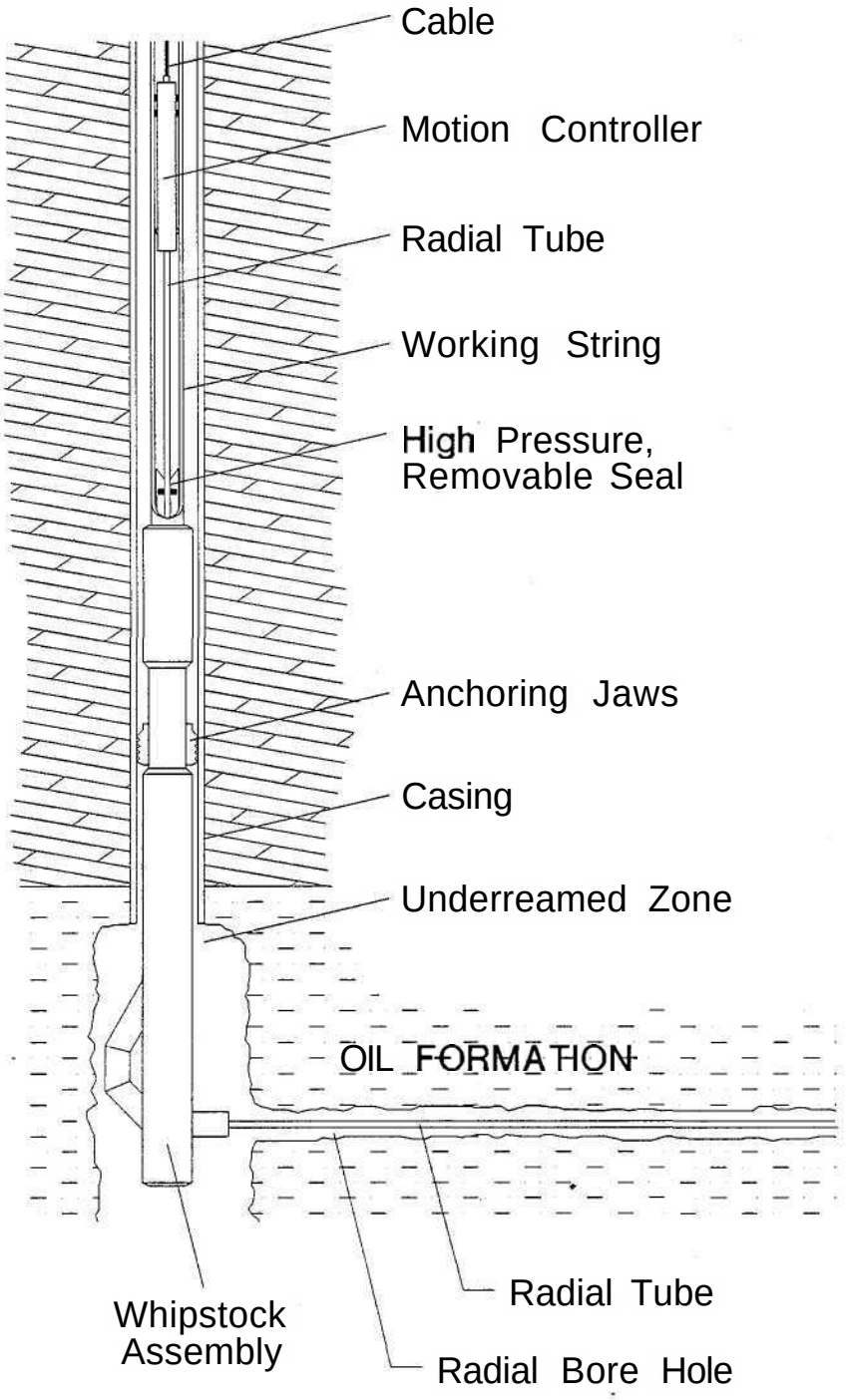
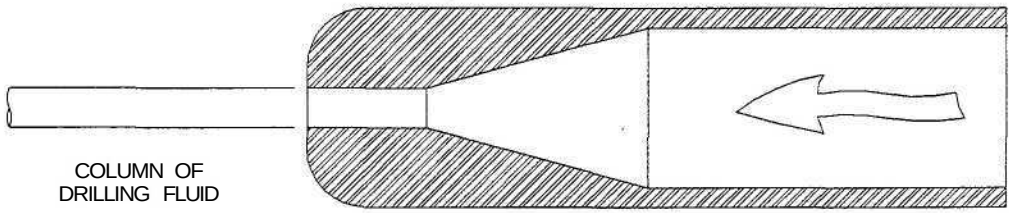
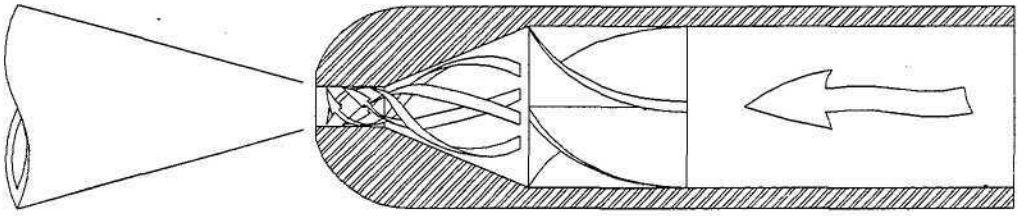


Figure 7

A CONICAL JET NOZZLE

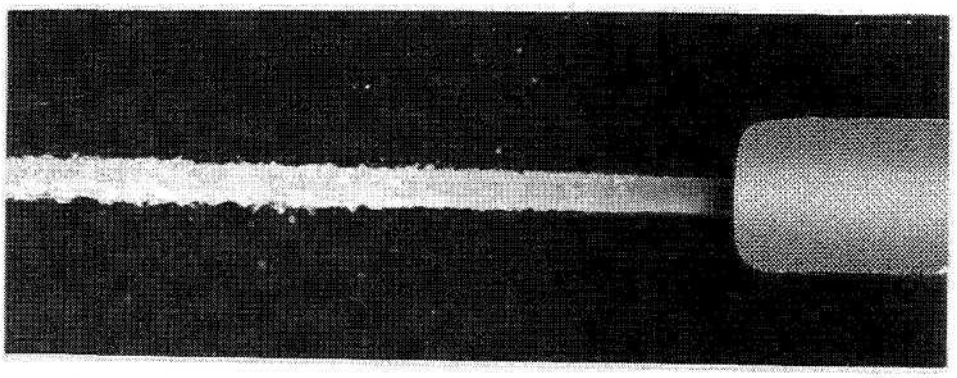


LEACH AND WALKER NOZZLE

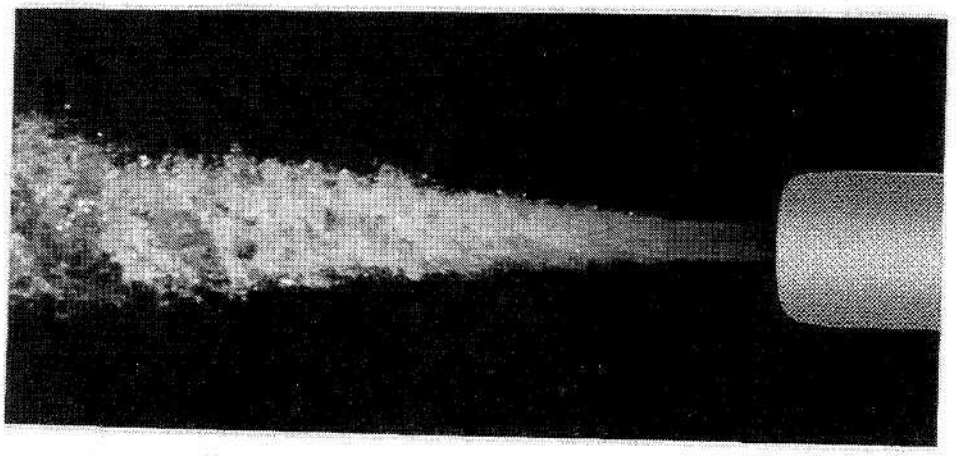


**A CONICAL JET NOZZLE
AND FIXED VANE INSERT**

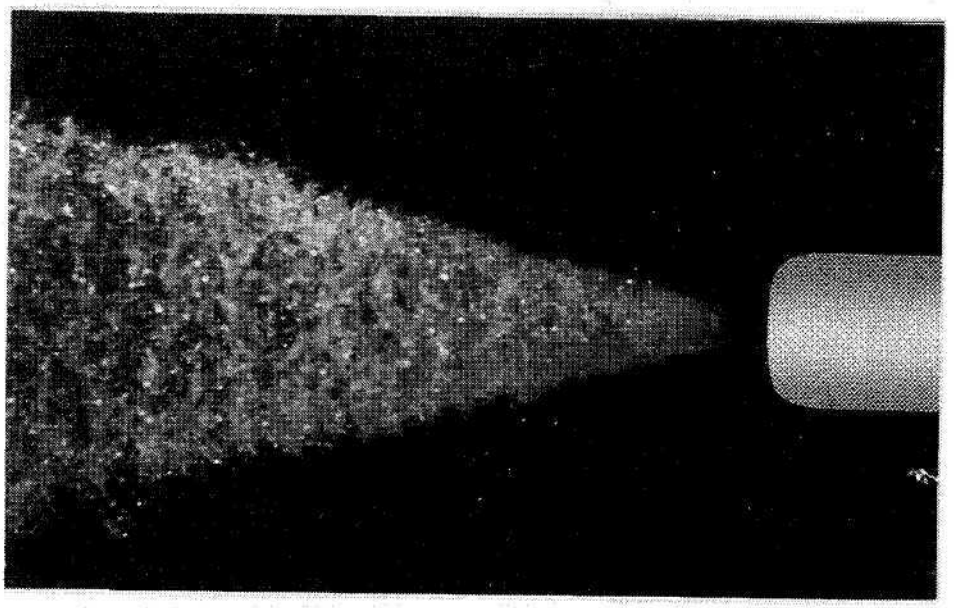
Figure 8



a) Leach and nozzle at 0.4 MPa



b) 14° Jet nozzle at 0.4 MPa



c) 30° Conical Jet nozzle at 0.4 MPa

Figure 9

MARK III WHIPSTOCK

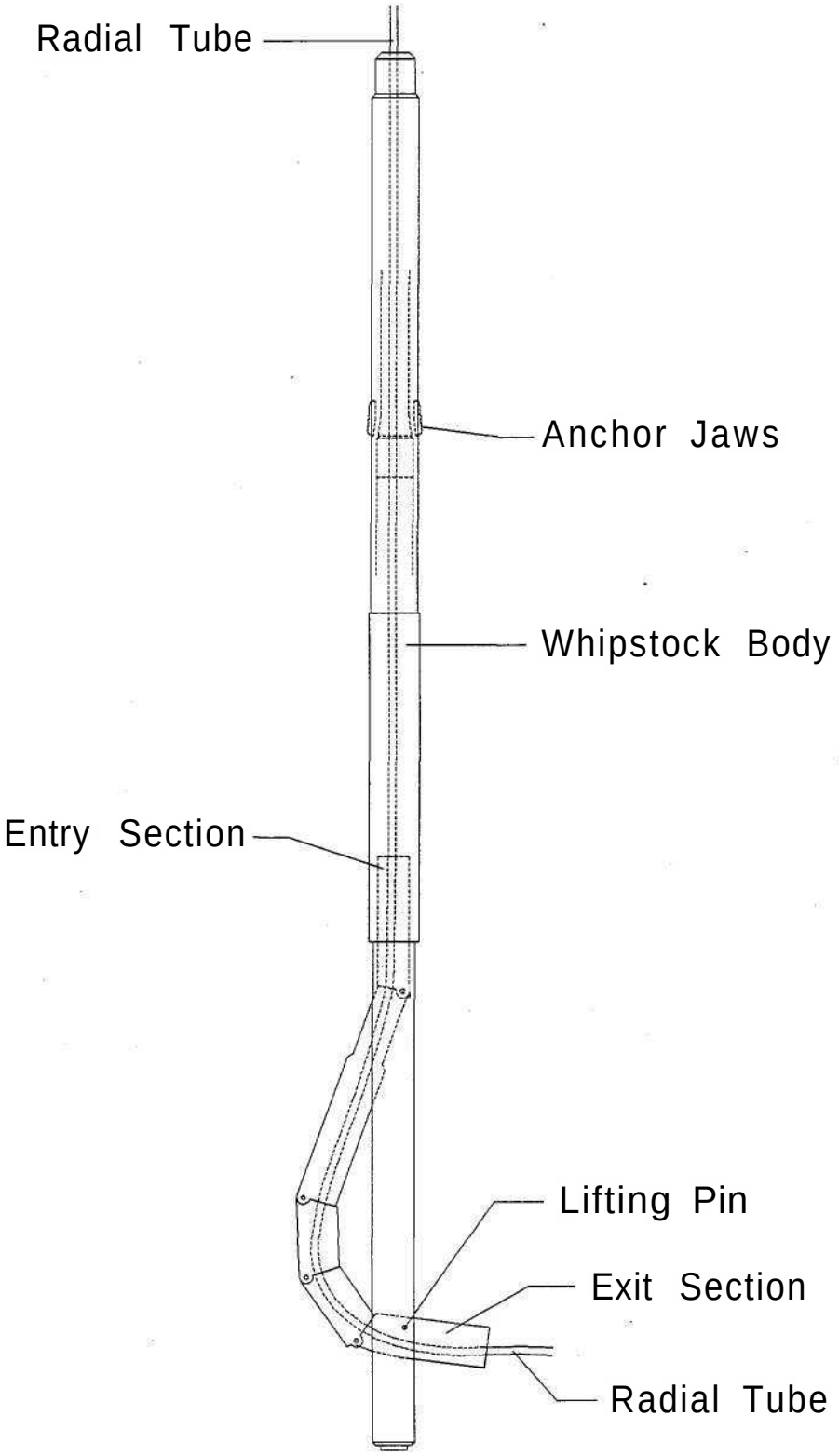


Figure 10

VERTICAL DEVIATION CONTROL WHILE DRILLING

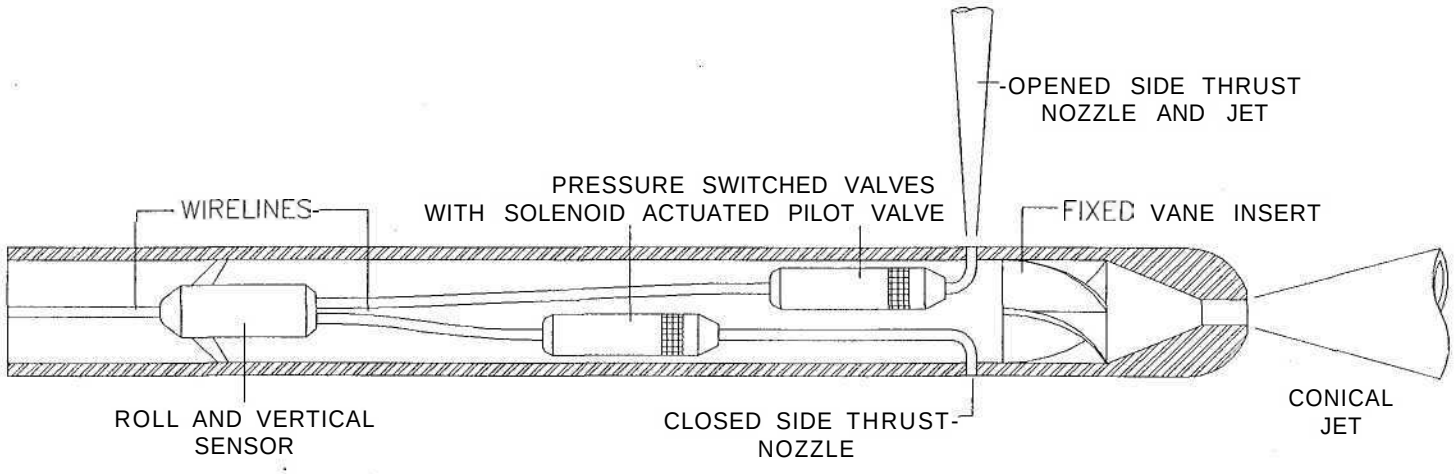


Figure 11

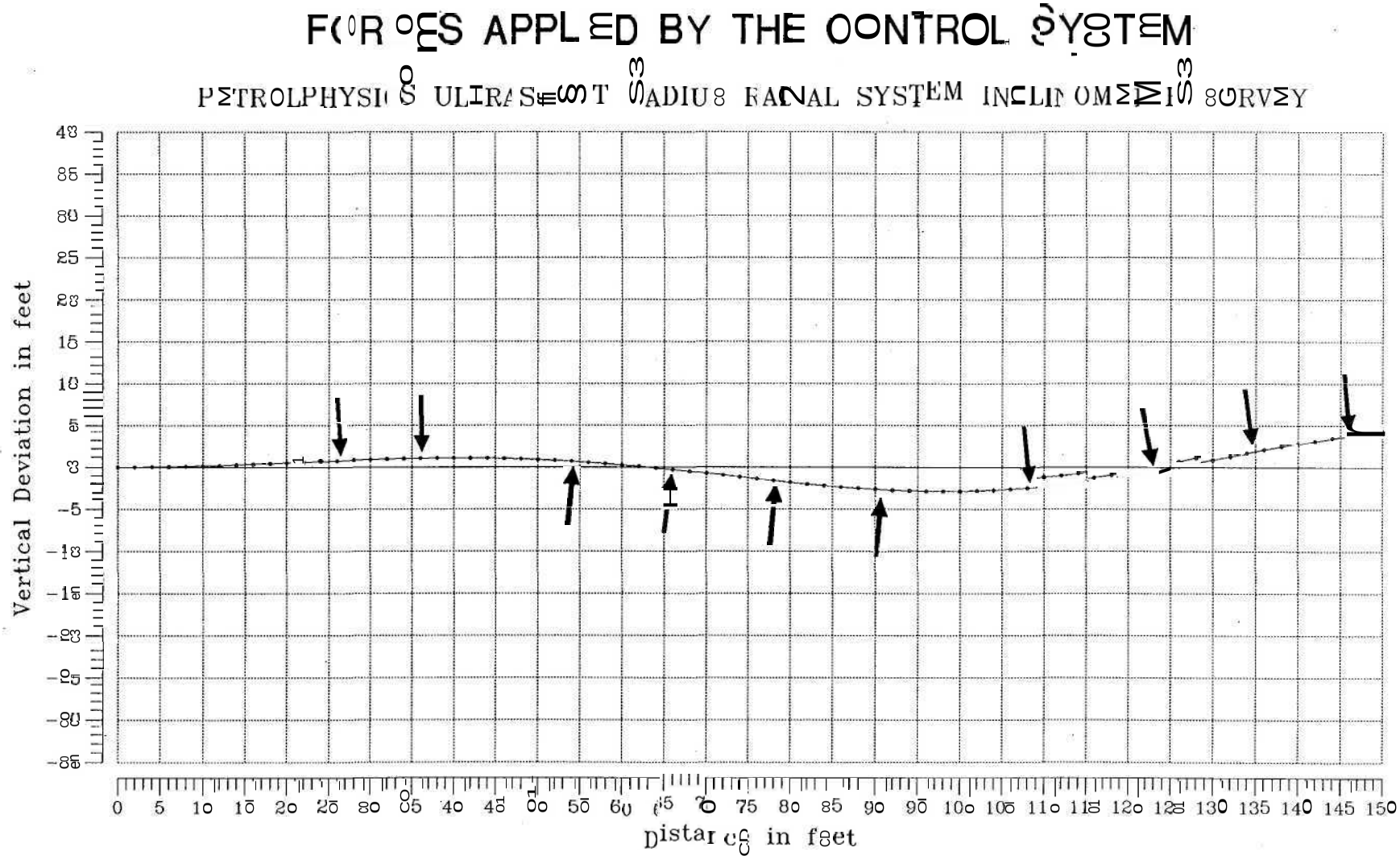
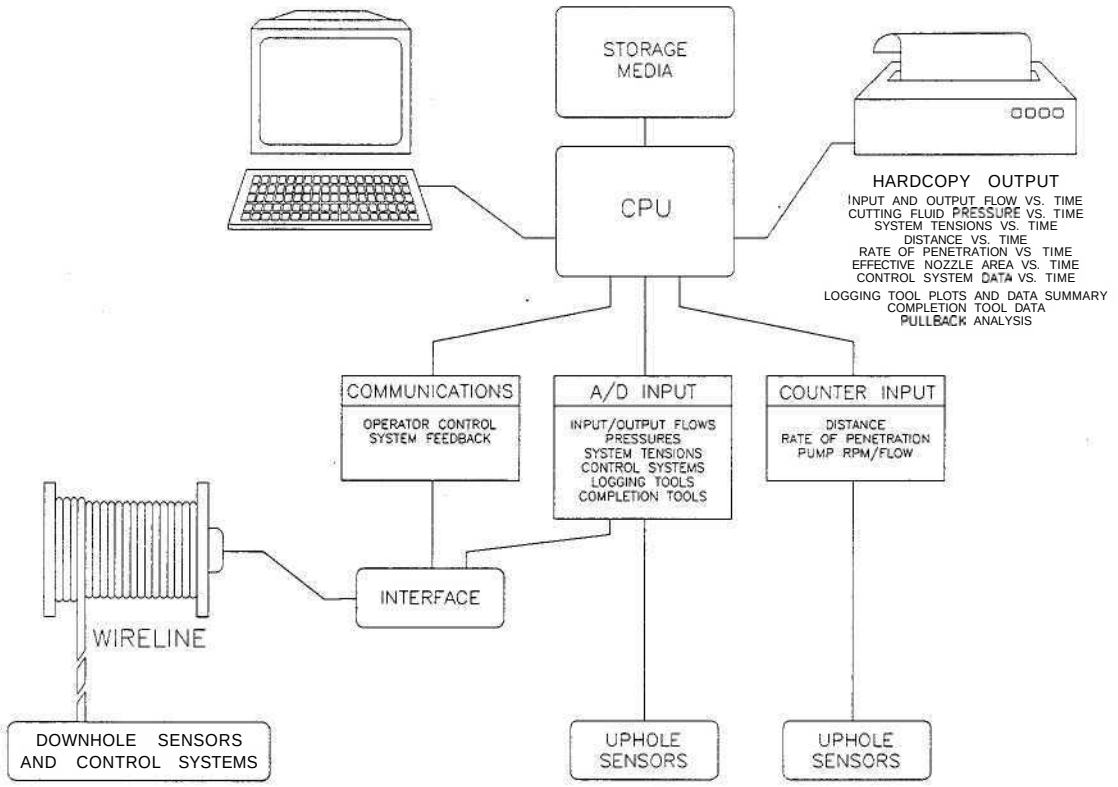
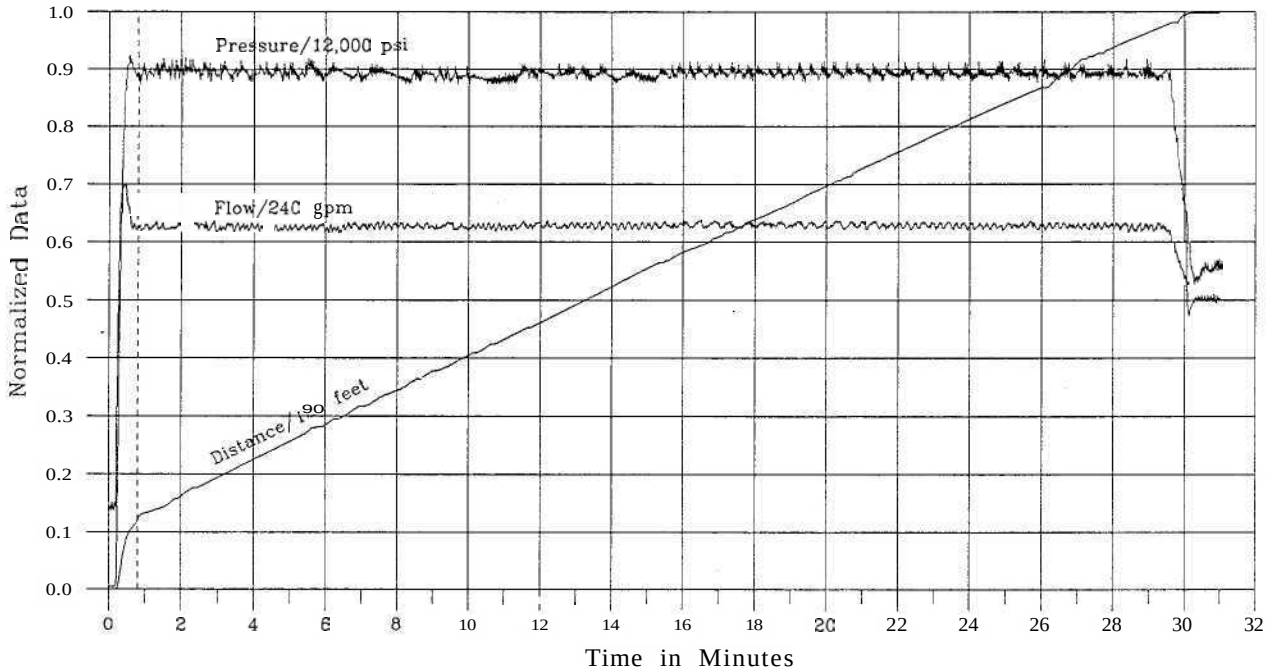

FORCES APPLIED BY THE CONTROL SYSTEM
PETROLPHYSICS ULTRASONIC RADIUS CANAL SYSTEM INCLINOMETER SURVEY
Vertical Deviation in feet
Distance in feet

Figure 12

DATA ACQUISITION SYSTEMS SCHEMATIC



Example of Petrolphysics URRS Data



Note: Vertical dashed line indicates kick-off point.

Figure 13

Petrolphysics Inclinometer Survey Unocal Bremer RI-53, Radial 1. 4/9/90

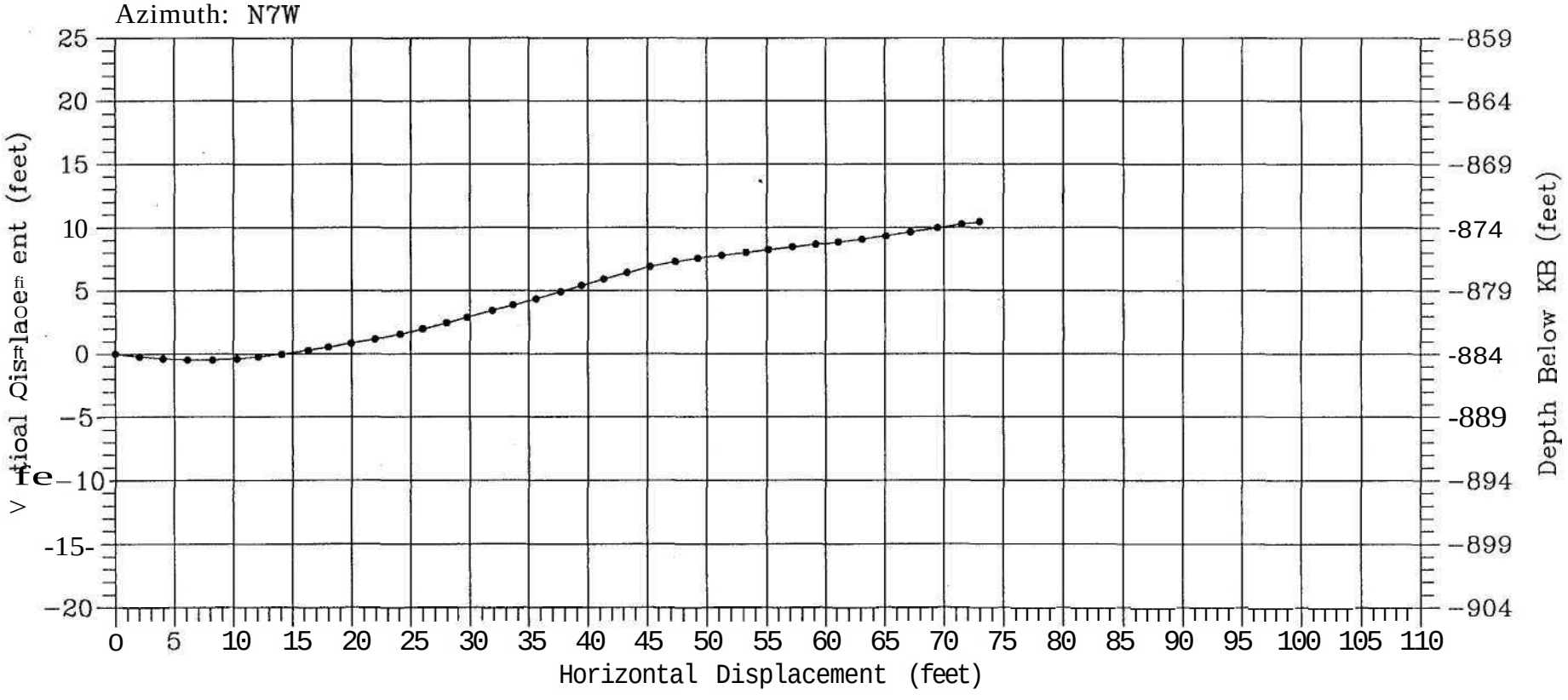


Figure 14

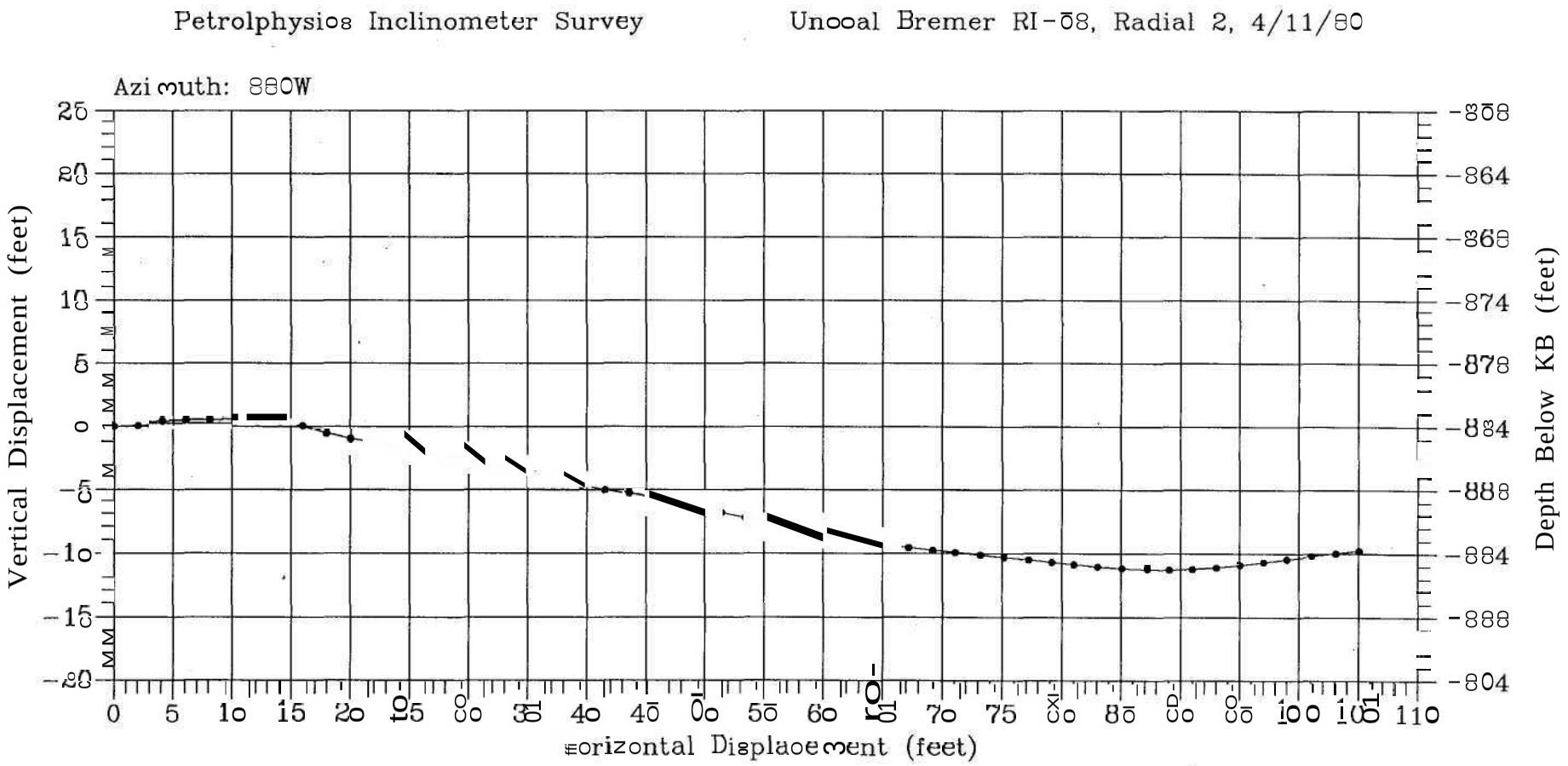

Petrolphysics Inclinometer Survey
Unocal Bremer RI-58, Radial 2, 4/11/80
Azimuth: 880W
Vertical Displacement (feet)
Depth Below KB (feet)
Horizontal Displacement (feet)
25
20
15
10
5
0
-5
-10
-15
-20
-850
-860
-870
-880
-890
-900
-910
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110

Figure 15

Petrolphysics Inclinometer Survey Unocal Bremer RI-53, Radial 3, 4/13/90

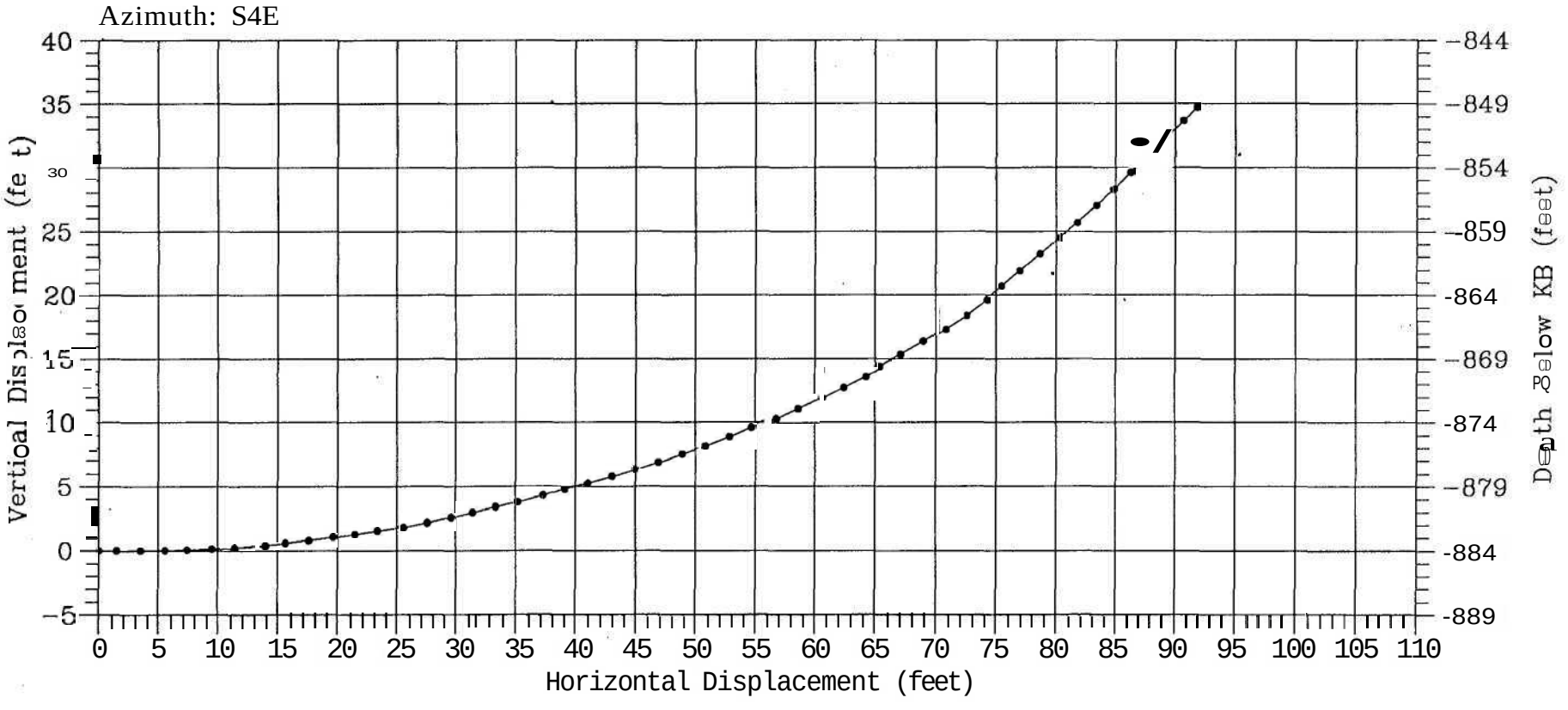


Figure 16

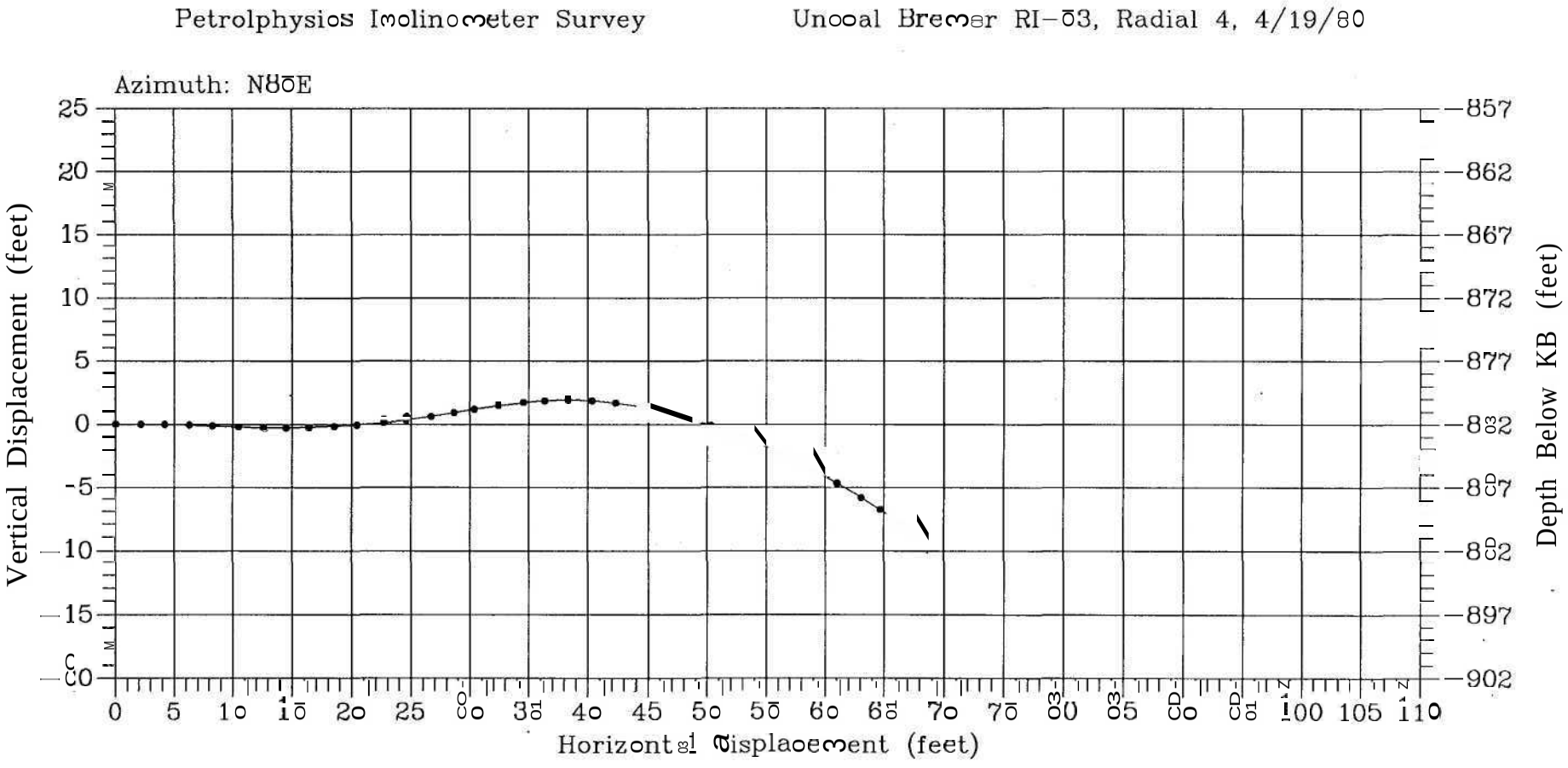

Petrolphysics Inclinometer Survey
Unocal Bremer RI-03, Radial 4, 4/19/80
Azimuth: N80E
Vertical Displacement (feet)
Depth Below KB (feet)
Horizontal Displacement (feet)
25
20
15
10
5
0
-5
-10
-15
-20
857
862
867
872
877
882
887
892
897
902
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110

Figure 17

GRAVEL MOVEMENT IN FIRST LIFT

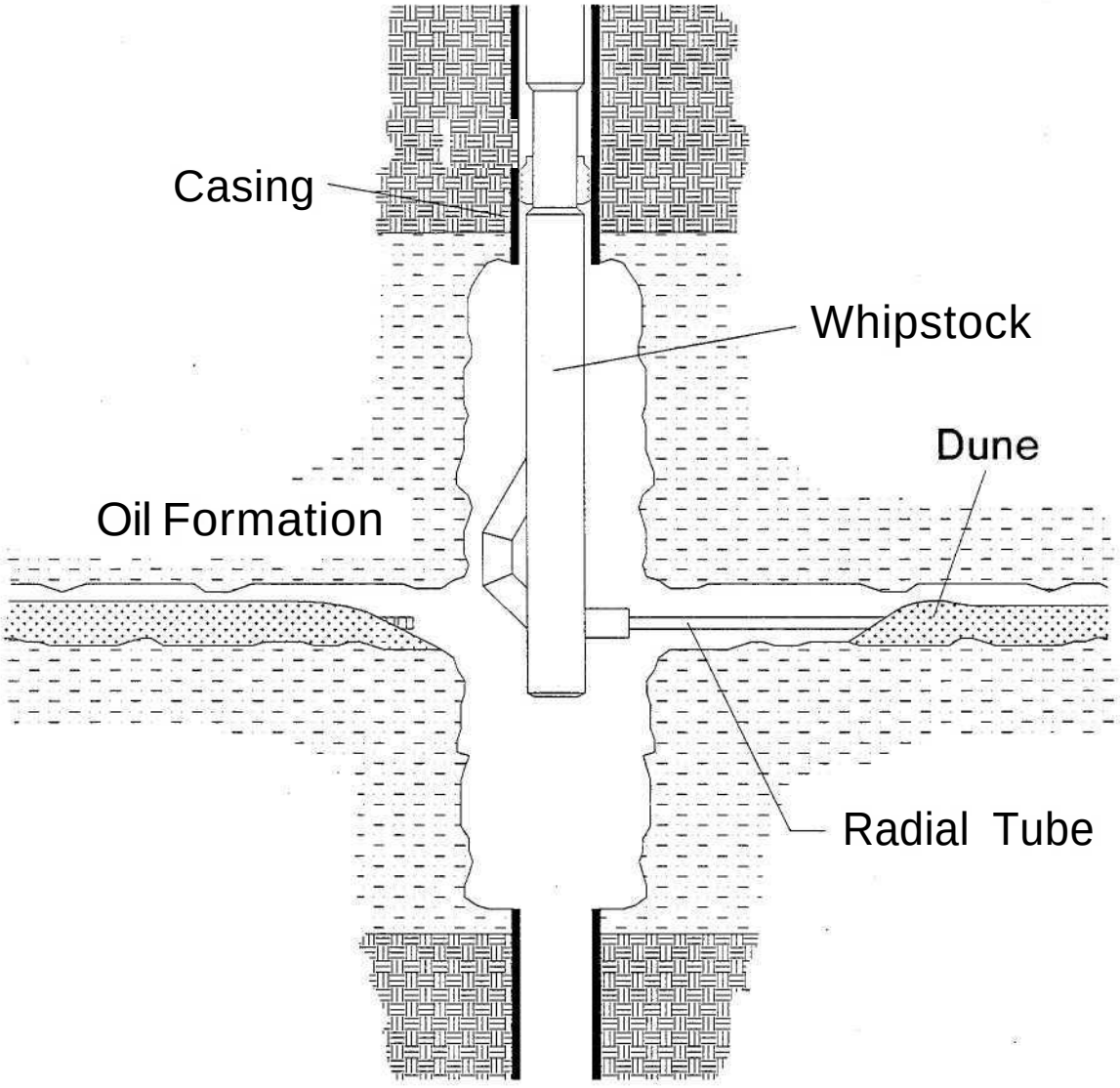


Figure 18

INTERIM GRAVEL MOVEMENT IN SECOND LIFT

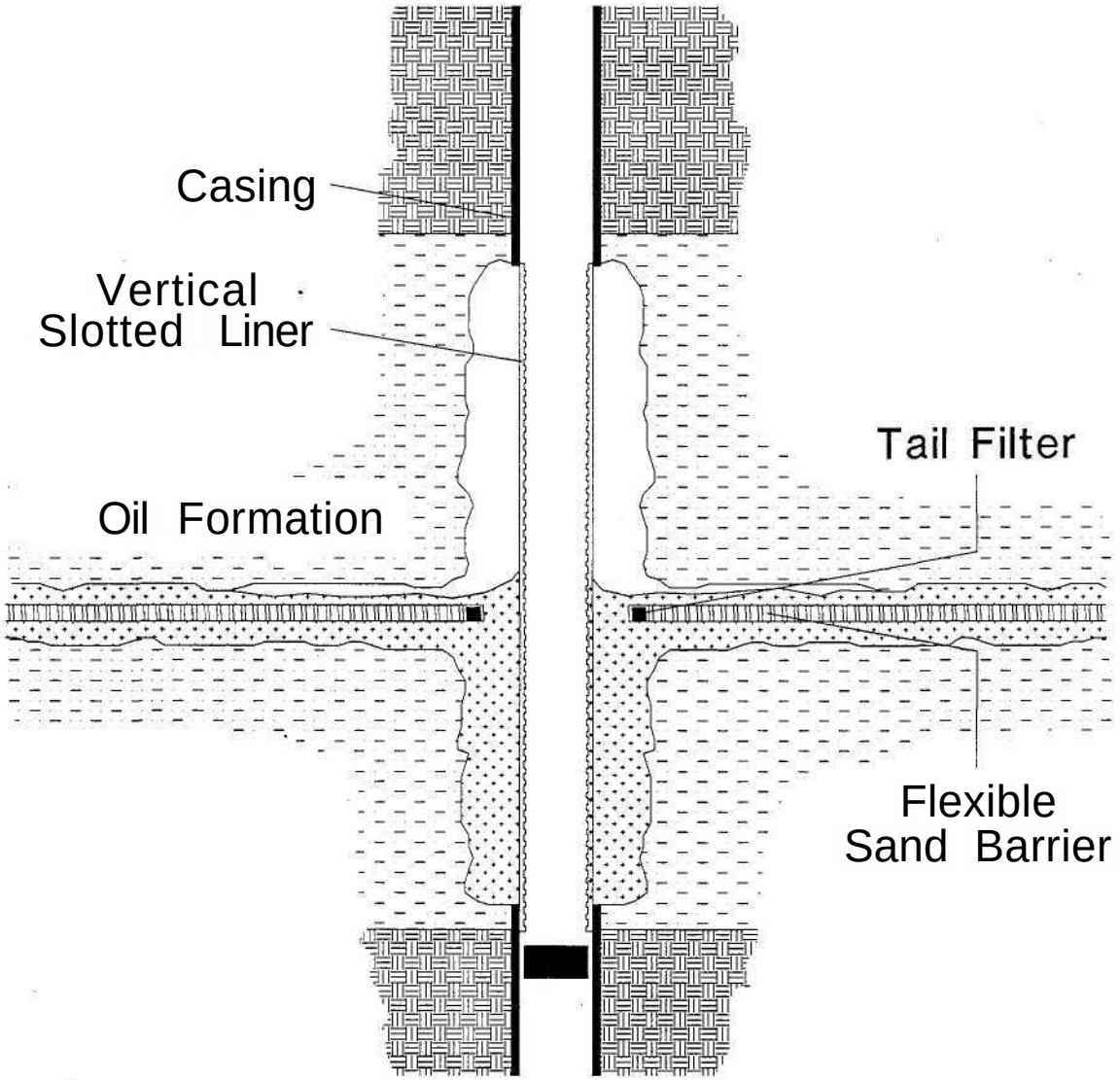


Figure 19

COMPLETED RADIAL PRODUCTION SYSTEM
WITH GRAVITY DRAINAGE

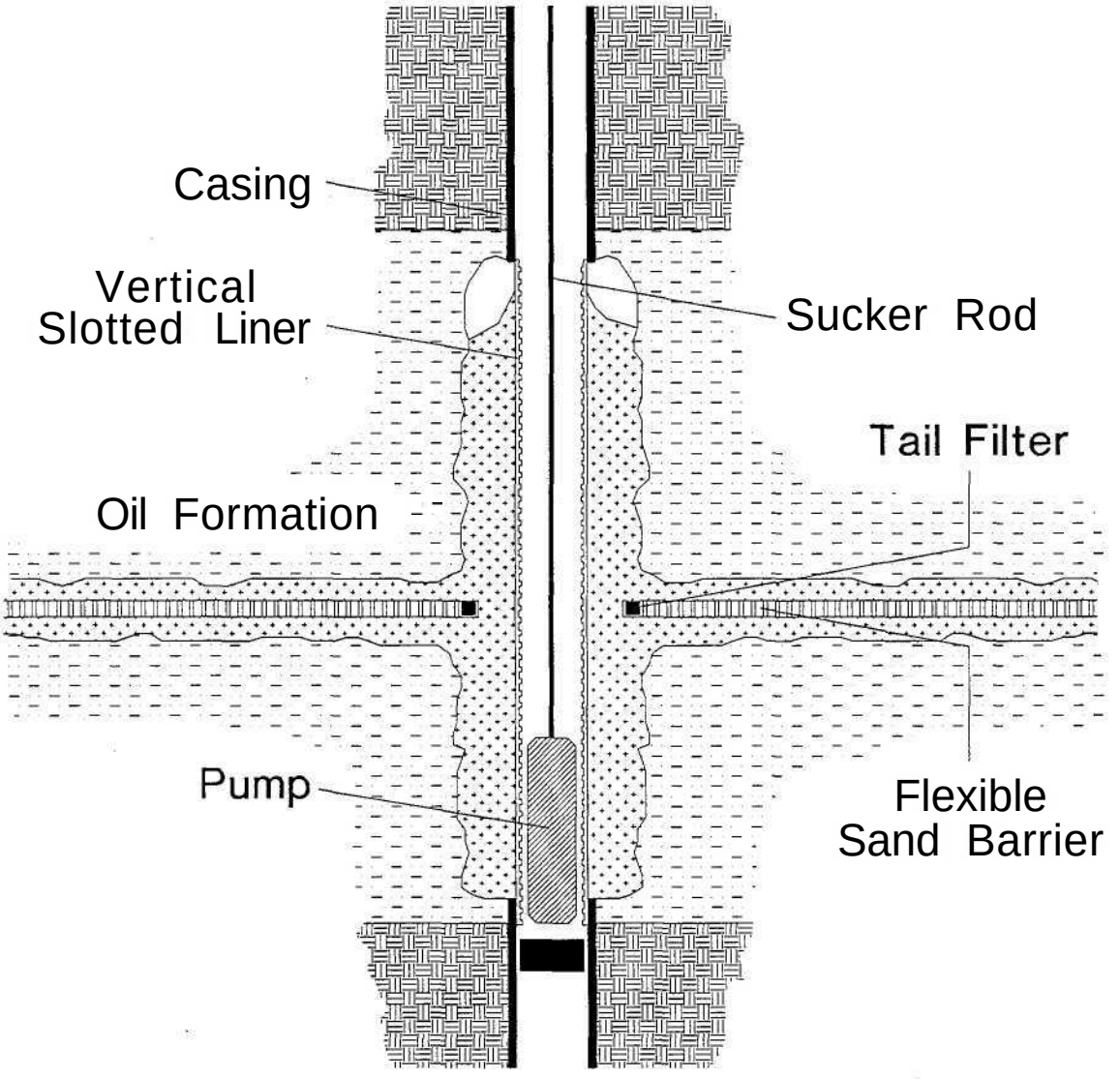
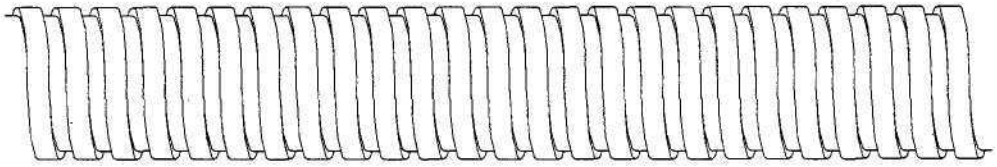
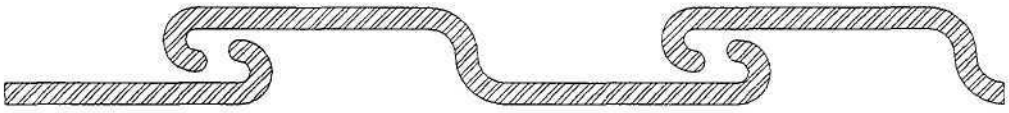


Figure 20

FLEXIBLE SAND BARRIER



Schematic Representation



Opened Joint Cross-section

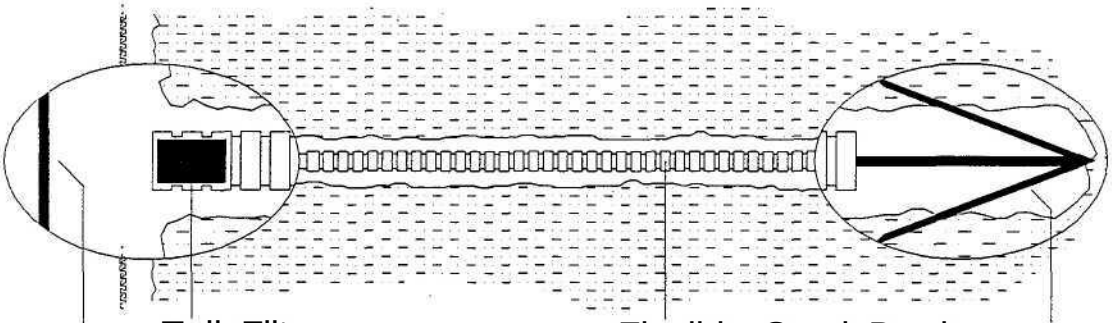


Figure 21

PERSPECTIVE OF BREMER-53 RADIAL PLACEMENT

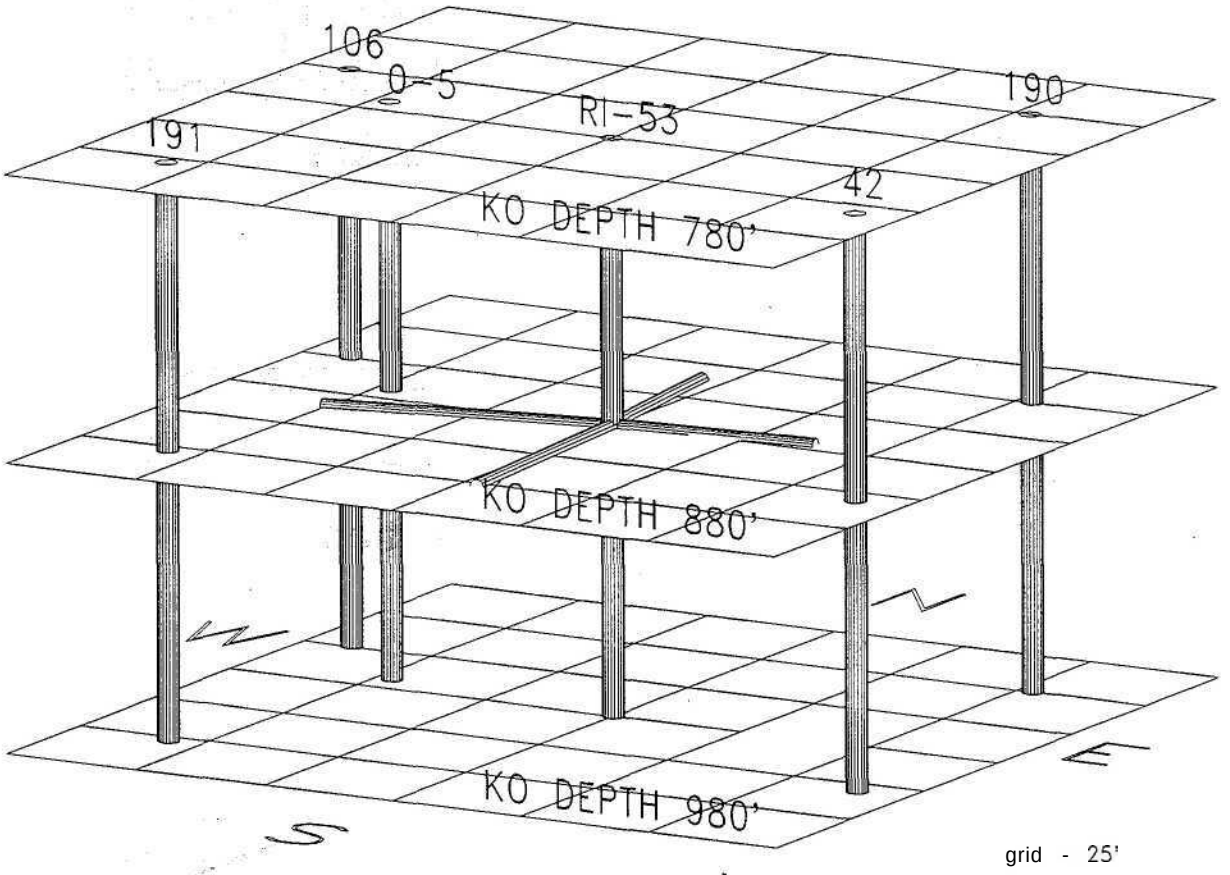


Figure 22

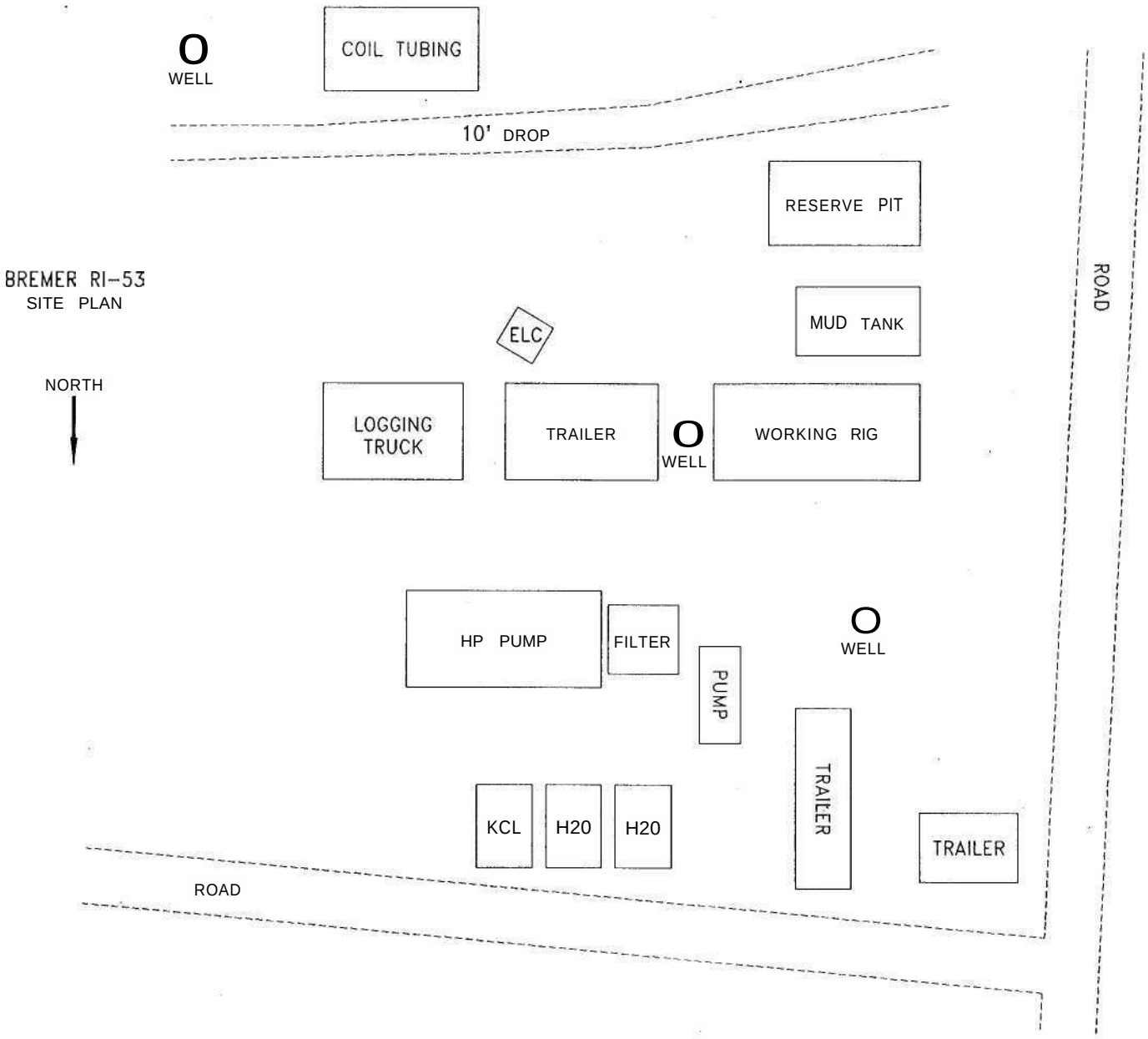

BREMER RI-53
SITE PLAN
NORTH
WELL
COIL TUBING
10' DROP
RESERVE PIT
MUD TANK
ELC
LOGGING TRUCK
TRAILER
WELL
WORKING RIG
HP PUMP
FILTER
PUMP
WELL
TRAILER
KCL
H20
H20
TRAILER
ROAD
ROAD

Figure 23

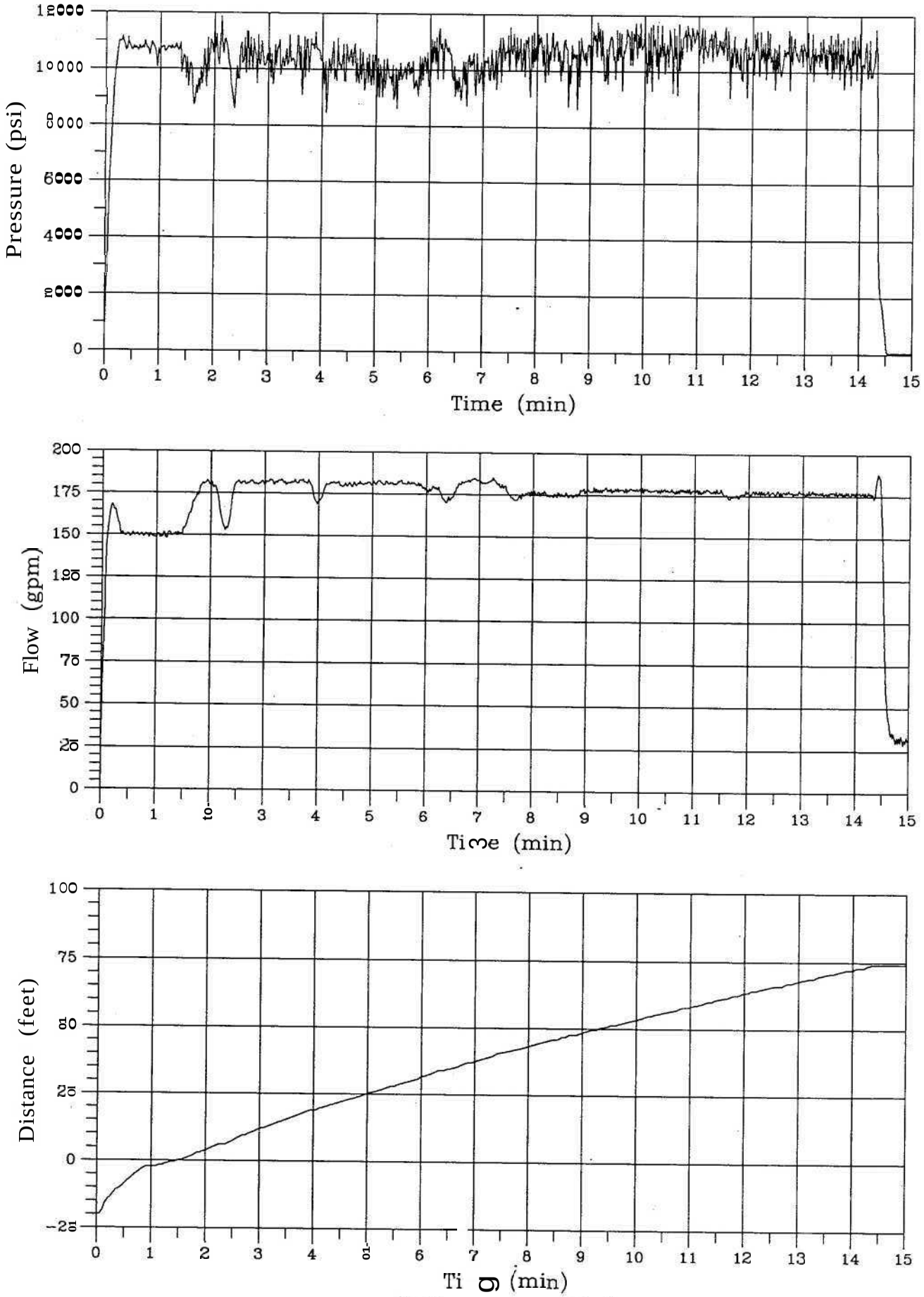

Pressure (psi)
Time (min)
Flow (gpm)
Time (min)
Distance (feet)
Time (min)

Figure 24

Petrolphysics URRS Data Unocal Bremer RI-53, Radial 2, 4/11/90

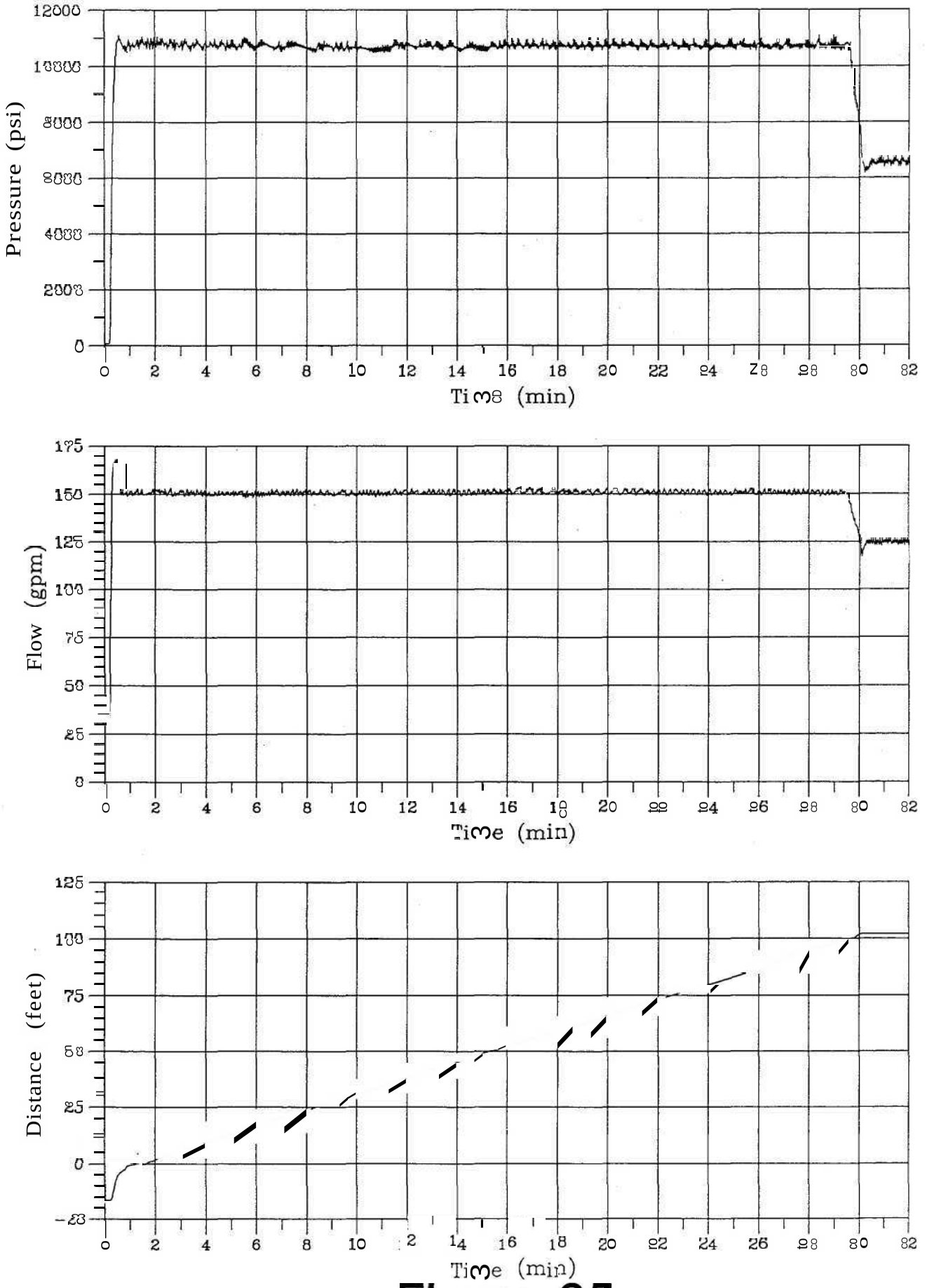


Figure 25

Petrolphysics URRS Data Unocal Bremer RI-53, Radial 3, 4/13/90

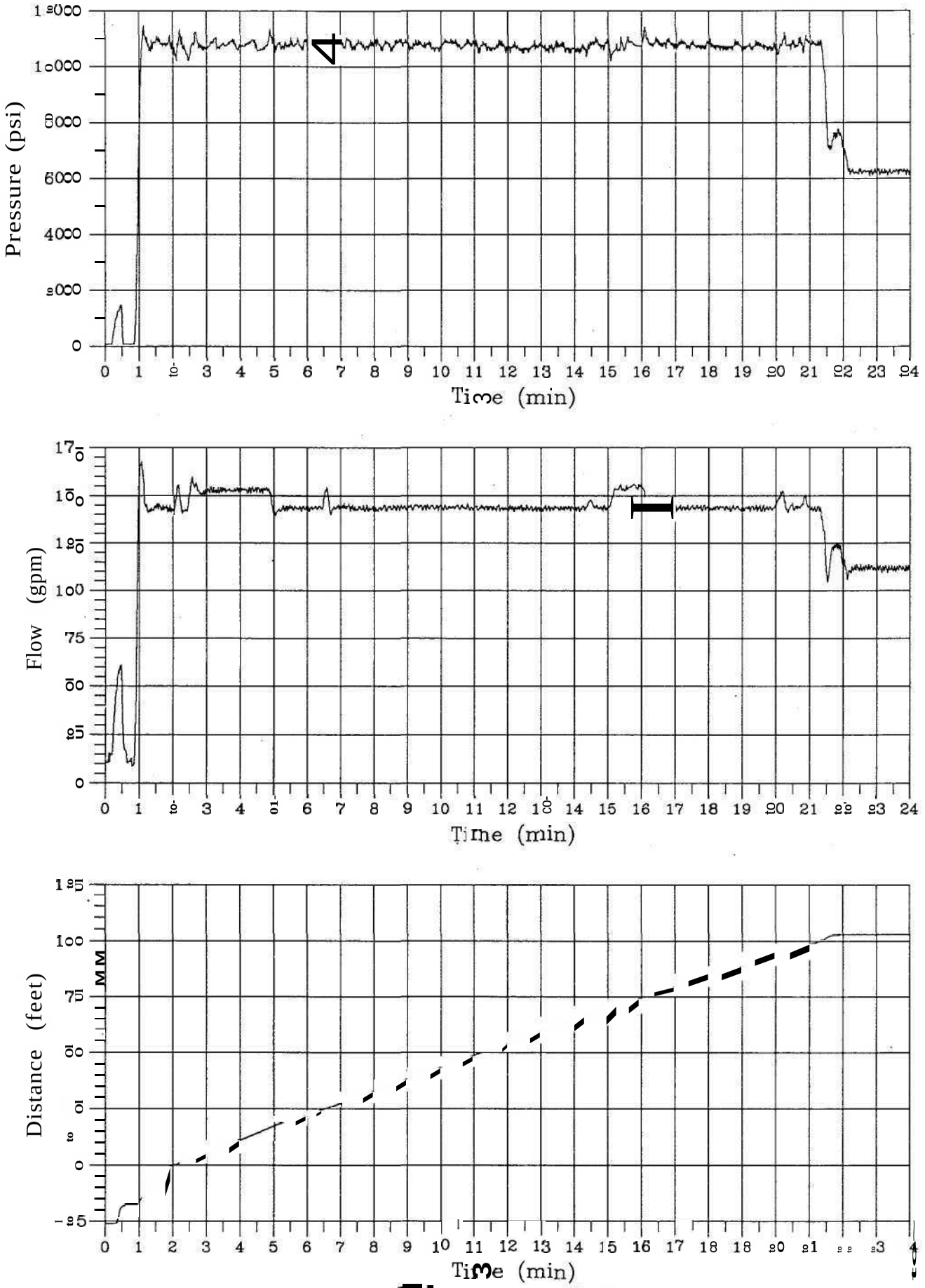


Figure 26

Petrolphysics URRS Data Unocal Bremer RI-53, Radial 4, 4/19/90

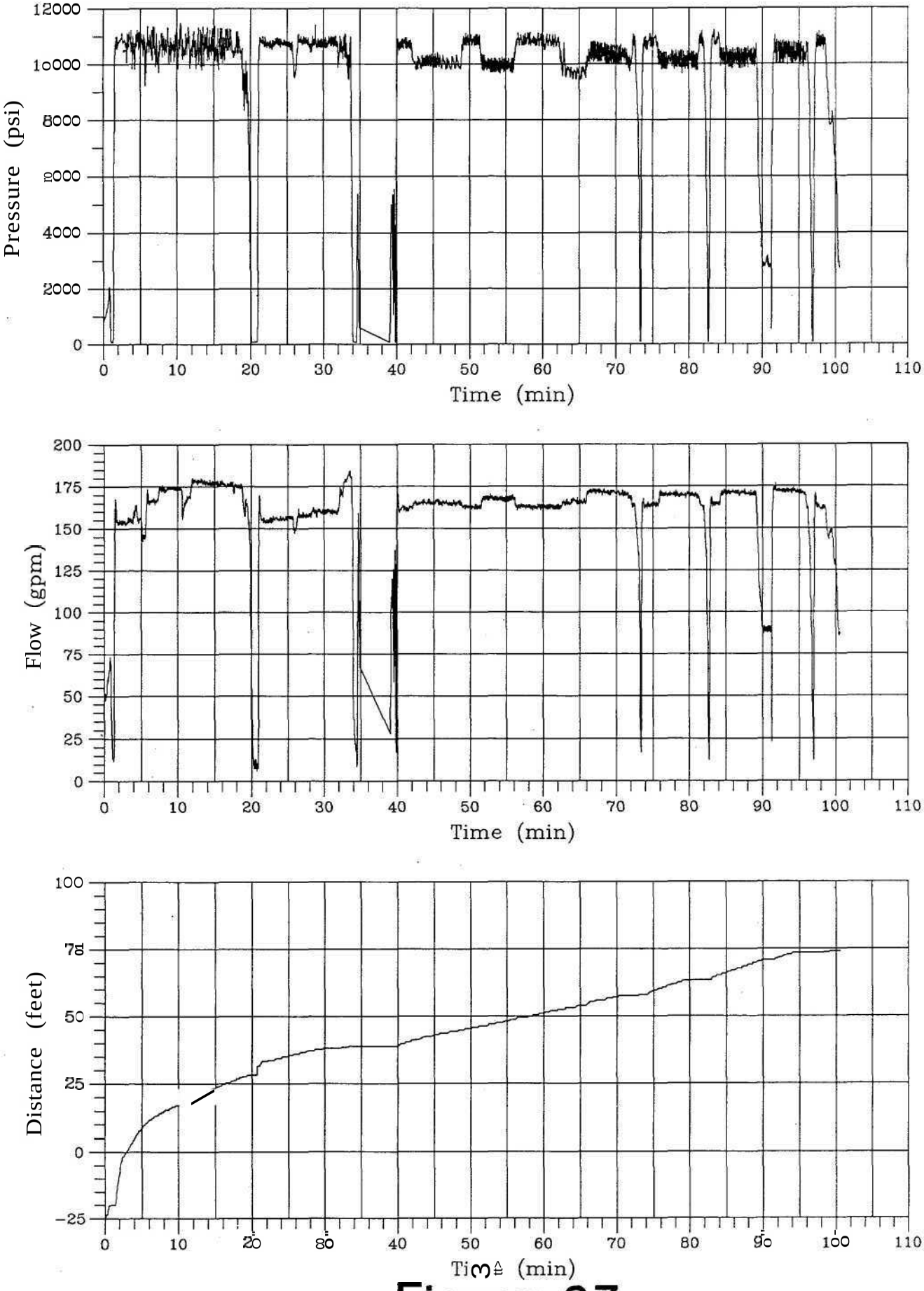


Figure 27

MIDWAY SUNSET FIELD
BREMER FEE
WELL #O-5
TEMPERATURE LOG

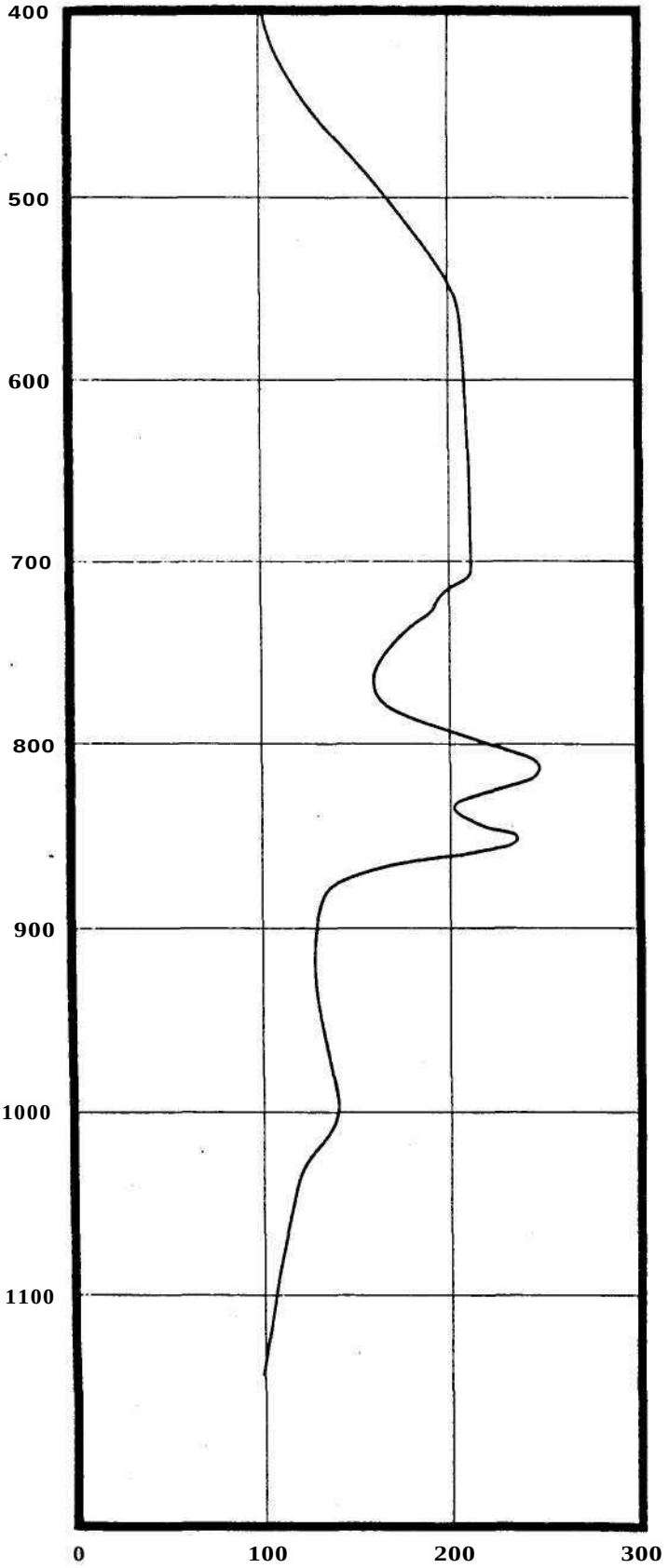


Figure 28

6/11/90

BREMER RI-53
RADIAL WELL

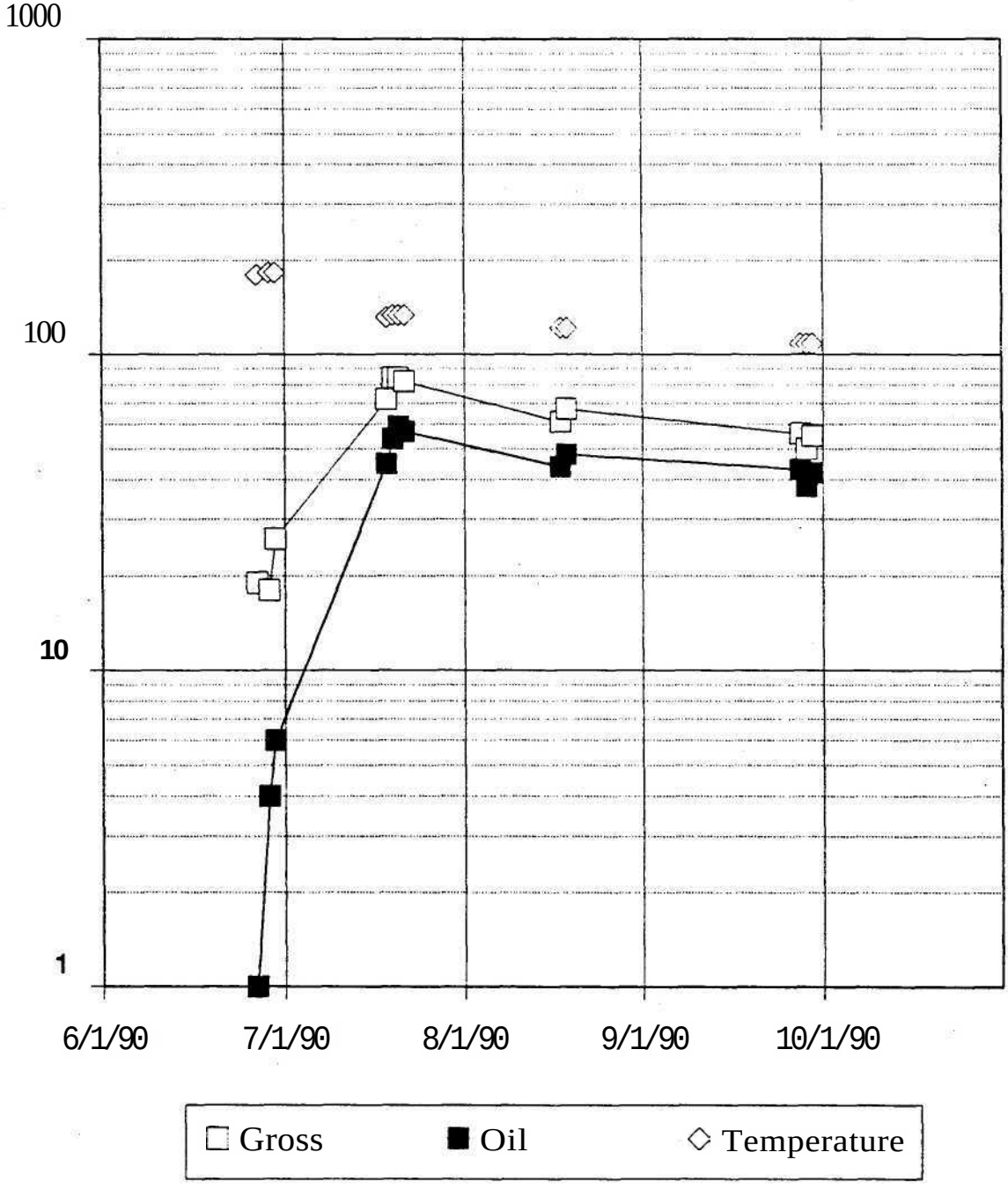


Figure 29

Appendix A

Summary Evaluation

of the

Bremer Lease Pilot Test

by

Herman Dykstra

January 11, 1991

BREMER LEASE PILOT TEST

The following information was available on a five-well pilot test on the Bremer Lease with one well having four radials drilled out at the same level:

1. Dual induction-SP logs of five wells and one observation well in the pilot area.

2. Completion data on each well.

3. Two temperature surveys on the observation well.

4. Contour maps of the top of the Potter sand, the B sand, and the C sand.

5. A Potter net sand map.

6. A summary of the past five steam cycles for four wells in the pilot area.

7. A cross-section through the pilot area.

8. An estimate of oil viscosity versus temperature.

9. Production curves over the period 1980 to Sep 1990 showing production response of wells to cyclic steam injection.

10. Injection and production data on RI-53.

A summary of the well completion data, and depth markers of the top of the Potter sand and of the C sand are given in Table 1. Also shown are the ASL (above sea level) depths. A schematic diagram of the wells and the radials are shown in Fig.1. A plot of the two temperature surveys are shown in Fig.2.

Observation of the performance data indicate the following:

1. All of the wells showed a tendency for the decline rates to decrease with each steam cycle. It was most apparent for Bremer 191 decreasing from about 90 percent per year after the 2nd and 3rd cycles to about 40 percent after the 6th cycle.

2. Three of the wells showed a definite trend of decreasing steam-oil ratio with increasing length of time between cycles.

3. The maximum response to cyclic steam injection is as follows for the pilot well and four surrounding wells:

70-100 bpd	well Bremer	42
45-75		106
50-70		190
60-80		191
59	single cycle in	RI-53

4. The steam-oil ratio of a cyclic test on 3 of the 4 wells showed a decrease in ratio from about 1.5 for a 7 month cycle to about 0.7 for a 20 month cycle.

5. A total of 17085 bbls of steam were injected in RI-53 from 31 May to 11 Jun 1990. The well was gauged 3 days in Jun, 4 in Jul, 2 in Aug, and 3 in Sep 1990 with no data thereafter. The estimated maximum monthly average rate was 49 bpd in Jul 1990.

6. Response of the four wells surrounding RI-53 is as follows:

   a) Bremer 42, downstructure from RI-53; 21,100 bbls steam injected in Jun 90. For the 4 months of history after injection in RI-53 it showed essentially no decline.

   b) Bremer 106, shallowest well upstructure; 13,400 bbls steam injected Jan-Feb 1990. It showed continued steep decline after the cyclic job.

   c) Bremer 190, slightly downstream from RI-53; 12,000 bbls steam injected Mar 1990. A positive response was observed, the oil production rate actually increased after steam was injected into RI-53.

   d) Bremer 191, slightly upstructure from RI-53; 13,200 bbls steam injected Feb-Mar 1990. Initially the well showed typical decline rate after the cyclic steam injection, but after steam was injected in RI-53, the decline was arrested and the oil rate remained about the same.

7. The temperature surveys on the observation well indicated an abrupt decrease in temperature at just above 700 ft which is close to the top of the C sand.

8. The temperature survey which was run the day that steam injection was ended indicated a definite response to steam injection. A maximum of 250 F was reached at 800 ft which appeared to be about an 110 F increase in temperature.

9. Gross interval open was 30 ft in RI-53 but ranged from 530 to 681 ft for the four surrounding wells as shown in Table 1.

10. Average maximum rates of production per foot of sand open are about as follows:

Well	Avg max rate	rate
42	85	.12 bpd/ft
106	60	.10
190	60	.09
191	70	.13
RI-53	49	1.63

Based on the above observations the following conclusions can be drawn:

1. There was a positive reponse in 3 wells to injection into RI-53; two wells were downstructure and one well was slightly upstructure.

2. There did not appear to be a response in the highest upstructure well, Bremer 106, in the pilot area.

3. Temperature surveys indicated that during the pilot test steam went into a portion of the Potter sand that had only been affected to a small extent during previous cyclic operations.

4. Based on temperature surveys and the response of RI-53 it appears that oil is being produced that would otherwise not be mobilized. This would indicate an increase in reserves.

5. Based on temperature surveys and on response at Bremer 42 it appears that steam entered the reservoir at the far end of at least two of the four radials.

6. The production history of RI-53 was too short to determine how effective steam injection was in this well in terms of the ultimate steam-oil ratio, compared to the ratio of the four surrounding wells.

Follow-up recommendations for the pilot area are as follows:

1. A cross-section through the pilot area wells along the dip would be very helpful in evaluating gravity drainage potential. The cross-section should include updip well 172 and downdip wells 149, 198, and 99.

2. It would be very helpful in confirming the response that has been seen to have production data available through Dec 1990.

3. Inasmuch as the lower part of the Potter has been affected only to a small degree by the cyclic steam injection, as indicated by the temperature surveys, consideration should be given to cleaning out the sand plug in RI-53 and putting in radials at around 1000 ft to heat the thick sand interval between 955 and 1050 ft, which apparently was only being slightly affected by cyclic injection.

H. Dykstra

Herman Dykstra
Petroleum
Engineering
Consultant

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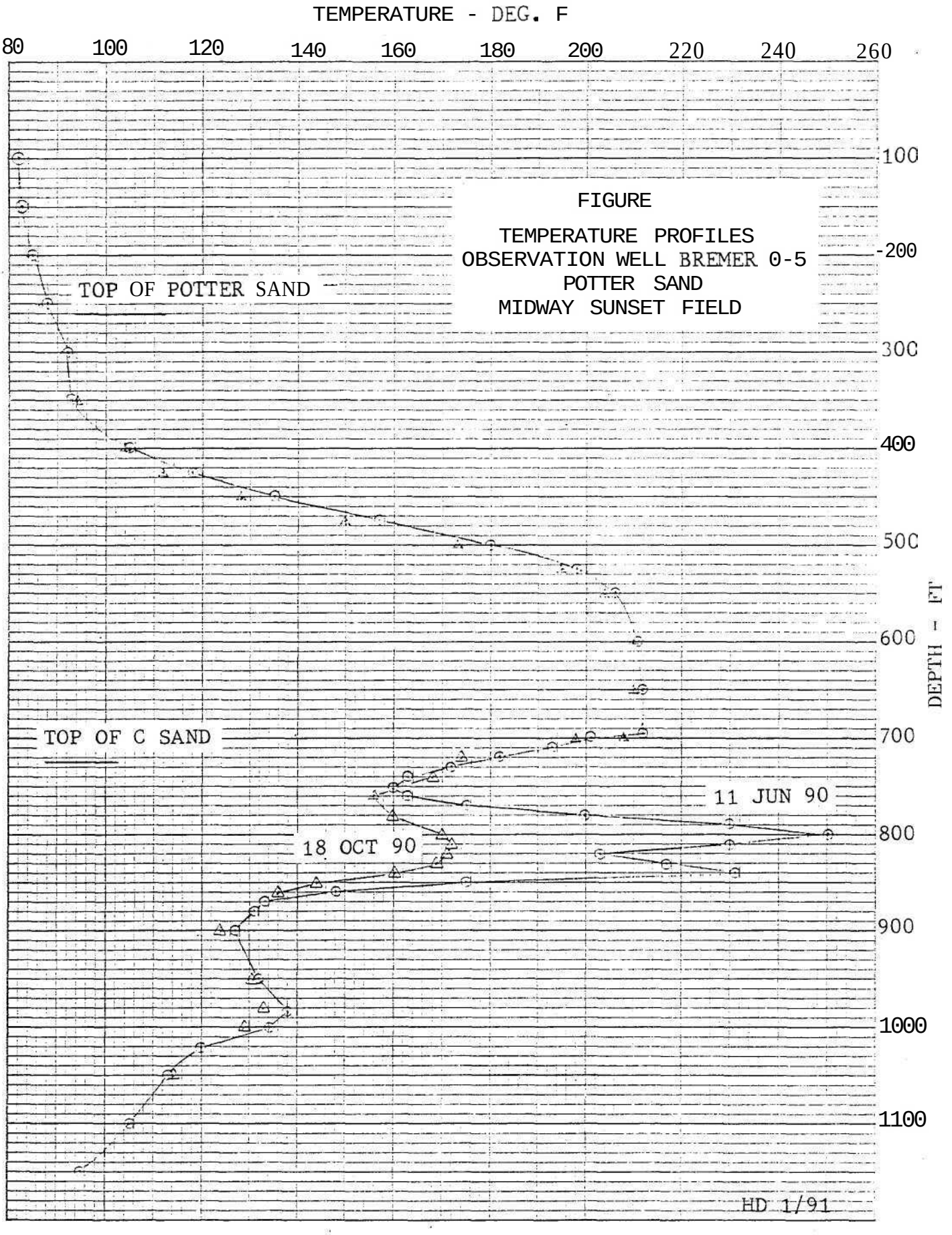
TABLE 1

SAND MARKERS AND COMPLETION
INTERVALS OF POTTER SAND
BREMER LEASE, MIDWAY SUNSET FIELD

WELL	Elev. ft.	csg. Pt. ft.	Total depth ft.	Top of Potter, ft. MD	ASL	C Snd, ft. MD	ASL
Br 42	1743	542	1223	305	+1438	768	+ 975
106	1754	539	1154	253	+1501	667	+1087
190	1740	478	1150	304	+1436	748	+ 992
191	1750	515	1045	268	+1481	691	+1059
RI-53	1750	870 (a)	1253	286	+1464	730	+1020
0-5	1754	(b)	1250	263	+1491	725	+1029

(a) Sand plug to 900'. Radials at 881-885' (+869 to +865)
(b) Observation well cased to bottom



FIGURE

TEMPERATURE PROFILES
OBSERVATION WELL BREMER 0-5
POTTER SAND
MIDWAY SUNSET FIELD