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HEAVY OIL PROGRAM
QUARTERLY PROGRESS REPORT NO. 1
APRIL 1 TO JUNE 30, 1980

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EXECUTIVE SUMMARY

In this first quarterly report for Sandia National Laboratories (SNL) Heavy Oil Program emphasis is placed upon the relationship to DOE Heavy Oil RD&D Program. The SNL heavy oil activity is in Reservoir Access as defined in the Heavy Oil Program Plan. This program includes six tasks: 1) survey heavy oil drilling problems and solutions, 2) assess water jet drilling of horizontal holes, 3) survey state-of-the-art for controlling disintegrating heavy oil sand formations, 4) survey fracturing techniques in heavy oil formation, 5) develop a high-temperature packer, and 6) perform scoping studies of alternate techniques of heavy oil extraction.

The survey of heavy oil drilling is being done in conjunction with Prof. Keshava Acharya, New Mexico Institute of Mining and Technology at Socorro, New Mexico. This program, when completed, will help to identify problems that can be most profitably studied. By having a firm basis of past activity, new nonconventional techniques can be evaluated.

A literature search of water jet drilling in heavy oil formations has been initiated. In addition, detailed discussions have provided contact with current research in heavy oil sands jet drilling programs. A review of the correlation of laboratory and field work done by Canadian researchers indicates poor agreement. This identifies the need for additional baseline data on oil sands cutting.

The survey of present sand control technology has been most productive in identifying areas where additional research is needed. In working with George Suman of Completion Technology Company over 175 new references have been identified and characterized. These are references since 1975, the year when Mr. Suman wrote the Sand Control Handbook.

Discussions with leaders in the field will be conducted during the second quarter.

The survey of fracturing techniques in heavy oil formations has just begun. The considerable previous activity in this area is well documented in numerous review articles. These reviews and recent literature will be examined for techniques (if any) that are unique to heavy oil formations.

The high temperature packer development first initiated under the DEEP STEAM Project has been associated with this program since May 1980. The second phase, being performed by L'Garde, Inc., of Newport Beach, CA, will design, fabricate and test an engineering model of the L'Garde packer concept. Phase II consists of three basic tasks: a) seal simulation tests, b) design, analysis and fabrication of an engineering model, and c) room temperature seal tests of the engineering model.

The use of controlled source audio magnetotelluric (CSAMT) survey techniques for tracking in situ combustion and steam drive thermal fronts is an important aspect of improved alternate techniques of heavy oil extraction. The benefit of the CSAMT to the heavy oil program will be to better enable assessment of the efficiency of and the control applied to thermal recovery of heavy oils. The survey method that is used in the first phase of the program involves the measurement of fields around a grounded bipole. By examining the behavior of the electromagnetic field with distance and frequency from the source it is possible to obtain an apparent resistivity of the geologic formations. The change in resistivity will indicate the presence of the thermal front. The experiment chosen for the first test of this approach is a steam injection experiment in the tar sands outside of Vernal, Utah. The preliminary results are very encouraging but must now be carefully analyzed before detailed conclusions can be drawn.

ABSTRACT

Research and development efforts in support of the DOE Heavy Oil RD&D Program in reservoir access were initiated. Preliminary activities in the survey of sand control, drilling, and fracturing techniques in heavy oil formations are described. The continued development of a high temperature packer for use in steam injection applications is presented. A new application of controlled source audio magnetotelluric survey to developing thermal fronts from in situ combustion and steam drive is described.

I. Introduction

Previously the heavy oil program at Sandia National Laboratories (SNL) has been closely related to the Tar Sands Program because of monetary and personnel restraints. With this report, the heavy oil program will assume a new and separate direction that will benefit from the past association and also establish a program to meet the goals and objectives of the heavy oil RD&D program management plan. The SNL heavy oil activity is in Reservoir Access as defined in the Heavy Oil Program Plan.¹ This is especially important because improvement in this technology can have a strong and key impact on the economic feasibility of heavy oil recovery. The objective of the Reservoir Access Program is to improve the extraction of the heavy oil either by drilling and associated activities or by mining or by some combination of both.

After the stage of primary production (if any), the remaining heavy oil requires enhanced oil recovery (EOR) techniques. Most of the economically feasible methods require additional drilling, both of injection wells and in denser spacing of production wells. Thus consideration of improved directional control and increased drilling rates is sometimes required. Often the heavy oil resource is located in unconsolidated formations. This presents special problems in borehole stability and lost circulation. The complex stratigraph of the pay zone can require the use of directional drilling for infill drilling programs. The use of new concepts for establishing well-to-well communication, e.g., horizontally drilled holes, could be important. Thus the objectives of the drilling subactivity include: development of new, improved economically viable drilling techniques to reduce costs, and establishing new concepts of increased reservoir access for higher oil recovery.

The production stage of heavy oil extraction can be critical in the development and operation of a field. Problems associated with

corrosive gases and liquids on tubular materials, sandscreens, packers and downhole pumps are well known. Wellbore heat losses in surface steam injection limit exploitation of reservoirs deeper than about 2500 ft. The need for improved thermal efficiency is concentrated on downhole steam generators, high-temperature packers and steam string insulation. The physical stimulation for increased flow involves the use of fracturing techniques and the use of stimulants such as acid to open the reservoir. The EOR methods often introduce significant corrosion and physical erosion problems for the casing and associated hardware. Also, the associated trouble of sand control will enhance erosion and cavitation around the well. The better emplacement of sand control materials is a needed area of study for improved formation integrity around the wellbore. The objectives of this subactivity are: improved techniques for use in the corrosive, erosive and thermal environs of EOR methods, develop increased heavy oil productions by better physical stimulation, and the application of higher quality steam in the reservoir.

The Sandia Heavy Oil Program for FY80

The requirements for the reservoir access program are extensive and the time, personnel and monetary resources are limited. The first stage of this program is thus restricted to those areas which are most pressing and allow the identification of a more coherent program in the future. This program, as agreed upon by SAN/DOE and Sandia National Laboratories (SNLA) include the following tasks:

The first task will be to develop a high-temperature packer for use in steam EOR to allow prolonged application of high-quality and pressure steam. This will include building an engineering prototype and evaluation by a series of actuation seal tests.

The second task will be a survey of heavy oil drilling problems and solutions. This survey will be maintained as ready reference for helping to define program objectives and tasks.

The third task will be to assess the ability to drill horizontal holes with the Sandia water jet drilling system. A study of heavy oil sand drilling characteristics will be made.

The fourth task will be to accumulate and document fracturing techniques in heavy oil formations. The major benefit will be to identify possible problems and solutions especially as they will fit into the heavy oil program.

The fifth task will be to determine the state-of-the-art for controlling disintegrating sand formations. This will help to establish needed new research in the areas of well completions, physical stimulation and downhole steam production.

The sixth task will be the evaluation of exploration electromagnetic geophysical techniques for use in heavy oil formations. Field tests during a thermal recovery process will be performed.

The last task will be the scoping studies of alternate extraction techniques of heavy oil. SNLA will review and perform required analyses to evaluate each process to help establish those with the greatest promise.

II. Drilling Technology

A. Survey of Heavy Oil Drilling

The area of drilling problems in heavy oil formations is an old topic with many recent and continuing developments. The specific formation applications are often unique but allow the development of an overview that should be most useful in the evaluation of new concepts. Thus, the background information from a careful literature survey will identify problems that can be most profitably studied. This survey will also give insight into solutions that have been attempted in the past. The background information then forms a basis for the evaluation of new nonconventional techniques. To these objectives, a survey of heavy oil drilling has begun.

This work is a joint program between SNLA (J. R. Wayland) and New Mexico Institute of Mining and Technology (NMIMT) at Socorro. Prof. Keshava Acharya is directing the NMIMT program. The survey will include

- (1) drilling technology
 - (a) method used
 - (b) new and novel concepts
- (2) size of well and relationship to formation characteristics
 - (a) diameter
 - (b) stress-strain characteristics of formation
- (3) purpose of well
 - (a) injection
 - (b) production
- (4) rate of penetration
 - (a) formation effects
 - (b) rock mechanics
 - (c) fracture characteristics

- (5) directional drilling
- (6) type of drilling fluid used
 - (a) density
 - (b) chemical composition
 - (c) physical characteristics
 - (d) penetration into formation
- (7) type of bit used
 - (a) weight of bit
 - (b) wellbore hydraulics
 - (c) characteristics of bits
- (8) surface terrain effects
 - (a) transportation effects
 - (b) operation time effects
- (9) casing used for
 - (a) surface
 - (b) intermediate
 - (c) production
- (10) drill collars and pipe characteristics
- (11) formation temperature effects
- (12) interaction with mud-filtrate effect
- (13) drilling costs

The first phase of collecting all the current literature has begun. This is being organized in terms of the above outline. Careful attention is being given to the problems of heavy oil production to help identify areas in which new efforts in drilling might be most usefully investigated.

B. Water Jet Drilling in Heavy Oil

Work was initiated on water jet drilling evaluation during the last two weeks of the quarter. Attempts were initiated to search the literature to find appropriate technical literature applicable to

- (a) R&D Activities in Water Jet Drilling
- (b) Directional Drilling Results in Heavy Oil Sands
- (c) Performance Data on Jet Drilling of Oil Sands

Detailed discussions of ongoing research activities sponsored by Sandia in jet drilling of coal for methane drainage have provided contact with researchers who are currently participating in development of jet drilling programs, particularly in oil sands.

The jet drilling program of cavern development in oil sands is supported at Flow Industries by the Bureau of Mines. Two small caverns (up to 20' diameter) were developed off a central hole in a formation near Bakersfield, CA. The project is completed and a report has been submitted to USBM for approval. A copy will be provided by Jim Reichman of Flow Industries upon approval.

Numerous papers were reviewed which, although interesting, were not too valuable since they concentrated upon economic productivity of various heavy oil regions and provided little in the way of useful engineering data on drilling experience.

The feasibility of jet cutting of oil sands has been established by both the Flow Industries and limited laboratory and field work done by Canadian researchers.² Single nozzles were used to traverse oil sands specimens while water and energy requirements and performance data were obtained. Depth of cut, Z , was empirically related to nozzle diameter, D , jet pressure, P_d , and traverse speed, U , by the relation

$$Z = D \left[A \left(1 - \frac{B}{P_d} \right) \left(1 - e^{-C \frac{P_d}{U}} \right) \right]$$

where A , B , and C are constants. Similar relations for water and energy requirements were offered and the correlation of the laboratory data with field observations is shown in attached Figure 1. Clearly, the

correlation is inadequate. These data are being used to assess the needed additional baseline data on oil sands cutting rates and to plan needed tests.

Efforts this next quarter will concentrate upon detailing the laboratory and field tests needed for assessing the applicability of jet drilling, especially in horizontal holes. Material specimens will be obtained in parallel with the test matrix development to facilitate rapid implementation of the testing program.

III. Well Completions, Physical Stimulations and Downhole Steam Generation

A. Survey of Present Sand Control Technology

The controlling of disintegrating sand formations is one of the most pressing problems in heavy oil EOR. The current methods of EOR place a heavy burden upon the formation in the environ of the injection and production wellbore. Often there is a synergistic effect from the elevated temperatures, heavy oil flow, corrosive agents and gases introduced. Thus the need to extend the useful period of production of the surrounding sandstone requires consideration of heat-resistant materials used for formation stabilization and the best methods of application. The survey includes

- (1) effects of EOR methods on heavy oil sandstones
- (2) materials for improved sand control
 - (a) heat-resistant resins
 - (b) other materials
- (3) application of consolidation materials
 - (a) method of implanting
 - (b) depth of penetration
- (4) maintenance of sand consolidation
 - (a) non-thermal applications

(b) thermal applications

(c) structural integrity of formation

This work is being done in conjunction with George Suman of Completion Technology Corp. of Houston, TX. Mr. Suman is the author of the authoritative World Oil's Sand Control Handbook.³ This handbook is a survey of the sand control state-of-the-art up to 1975. Thus our survey is concentrating upon developments after 1975. The initial collection of the literature is complete. The next step after digesting this rather voluminous series of articles will be to conduct interviews with universities, national laboratories, oil companies, oil service companies and other sources to determine the current state-of-the-art. This work is on schedule and should give valuable guidance to identifying meaningful problems that need more study.

B. Survey of Fracturing Techniques in Heavy Oil Formations

EOR techniques need to provide well-to-well communication for effective application. Thus one of the most important well stimulation techniques is the fracturing of heavy oil formations. To understand the phenomenon requires site specific formation characterization. The survey will include:

- (1) formation characteristics
 - (a) thickness
 - (b) permeability
 - (c) porosity
 - (d) type of over- and underburden
 - (e) rock mechanics
 - (f) existing fractures
 - (g) clay content in the reservoir
 - (h) formation temperature and pressure
 - (i) formation fluids

- (2) injection fluids
 - (a) physical properties
 - (b) chemical additives
 - (c) leak-off rates
 - (d) propping agent carrying ability
 - (e) friction losses
 - (f) extent of formation damage
 - (g) formation of coke
 - (h) gases, e.g., CO₂, N₂
- (3) propping agents
 - (a) fracture conductivity
 - (b) density of propping agents
 - (c) spacing of propping agents
 - (d) nature of propping material
 - (i) sand
 - (ii) metallic pellets
 - (iii) organic waste
 - (e) selection of propping agent
- (4) fracture characteristics
 - (a) initiation of fracture
 - (b) mechanics of rock fracturing, fracture lengths, etc.
 - (c) angular orientation (vertical, horizontal, etc.)
 - (d) multiple fracture formation
- (5) equipment
 - (a) surface equipment and wellhead equipment
 - (b) downhole tools and packers
 - (c) valves, surface and downhole
- (6) explosive fracturing
- (7) modeling of fractures
- (8) economics of fracturing

This work is being done corporately between SNLA and NNIMT. The principals, J. P. Wayland, K. Acharya and C. Morgan, have almost completed a survey of the state-of-the-art literature from 1975 to the present. As soon as this is completed, the most promising areas will be followed up with on-site interviews.

C. High Temperature Packer Development

In EOR, it is often important to have a packer that will withstand the temperatures and pressures encountered in the long periods of application associated with thermal production techniques. The packer development program is divided into elastomeric and alternate sealing material development. We will be concerned with the latter materials. The first phase of this work was initiated under the DEEP STEAM Project and was associated with this program in May of 1980. Phase I was confined primarily to characterization of seal materials for the packer sealing elements. The materials surveyed included metals and inorganic fibers. These materials are to be used in the development of metal packer seals for minimum stress packers. This work is being done by L'Garde, Inc., of Newport Beach, CA. The first phase provided a conceptual design of the high temperature enhanced recovery packer (ERP), material properties of several candidate seal materials and a structural analysis of the L'Garde concept to help establish feasibility of the concept. They are now into Phase II.

The basic objective of Phase II is to design, fabricate and test an engineering model of the L'Garde packer concept. The hardware proof-of-concept tests will establish a seal against a simulated casing at room temperature. This will involve preliminary developmental testing on the component level. The one area where analysis cannot be exact and indicates testing is in sealing. The amount of sealing pressure required, seal surface finish requirements and need of a sealing pad

at the surface must be established prior to designing and fabricating the demonstration model. Phase II consists of three basic tasks: a) seal simulation tests, b) design, analysis and fabrication of an engineering model, and c) room temperature seal tests of the engineering model.

The tests of Phase I provided material properties--tensile, compressive, shear, friction and creep--for several candidate materials. These data were used to identify the most acceptable material candidates. These materials will be subjected to seal simulation tests in July 1980 to assess sealability. In these tests, a washer-shaped material specimen is pressed between two plates simulating a casing surface. A center volume (washer hole) in the sample is pressurized with water and the leakage determined as a function of squeeze force on the two plates (packer setting force) and water pressure in the washer hole (differential pressure across the packer).

The design and fabrication of a one-half scale engineering model requires seal element and setting mechanism structural analysis, detailed design, preparation of fabrication drawings, and fabrication and assembly of the hardware. First, a finite element analysis will define the optimum shape and force of the actuators to provide constant seal pressure about the circumference. The necessary trade-off between seal thickness and the sealing pressure will be established. Where necessary, manual analysis will be used to check consistency of design. Then a design layout of the engineering model will be generated. Detailed fabrication drawings of the seal configuration and actuating mechanisms will be made. After part fabrication, the assembly will be tested prior to installation of the seal element. Then the engineering model will be ready for room temperature seal tests.

The objective of the room temperature seal tests will be to demonstrate that a seal against a typical casing section can be made. The seal test will consist of the engineering model being set in a section of 3-1/2 inch API tubing using L'Garde's 200-ton press. The lower end of the tubing will have a fitting that provides a pressure chamber for applying pressure to the bottom of the seal. Two test runs will be made. At the conclusion of the first run, the test data will be evaluated and the model modified as needed. The second run will be to verify the design modification.

In summary, this task consists of design and fabrication of the test casing, redesign of the engineering model after the first run, fabrication of the changed components, performance of the test and documentation of the tests.

D. Controlled Source Audio Magnetotelluric Survey

The tracking of in situ combustion and steam drive thermal fronts by surface measurement techniques is an important aspect of improved reservoir stimulation. There are numerous electrical and electromagnetic geophysical techniques that might be applicable. Almost all depend upon the fact that the oil zone will usually be of a higher electrical resistivity than the surrounding strata because of the resistive nature of the oil. During a steam drive EOR process, the heated region will be of a lower resistivity because of the presence of hot steam, the heated groundwaters and the absence of oil. During a fire flood EOR process, the combustion region will be of a lower resistivity because of the hot carbonaceous material, the nearby heated groundwater, and the absence of oil. The oil front will probably be a high resistivity region because of the presence of excess oil and absence of groundwater. The objectives of this project are to evaluate and improve the effectiveness of surface electromagnetic exploration geophysical techniques that can be used to:

- 1) map and monitor the thermal recovery process for heavy oil sands, and

2) explore and map shallow heavy oil deposits. More specifically, field tests of controlled source audio magnetotelluric and pulsed or transient EM techniques will be conducted for evaluation of their applicability to this objective.

The benefit of the controlled source audio magnetotelluric (CSAMT) to the heavy oil program will be to better enable assessment of the efficiency of and the controls applied to the thermal (steam and fire floods) recovery of heavy oils. The CSAMT method may allow one to map and monitor the progress of the recovery process. In addition, to adequately plan the recovery of the heavy oils in a particular field requires knowledge of the areal extent and depths of the reservoirs. Seismic reflection data cannot alone supply this information. There is speculation among various exploration geophysicists that the proposed EM techniques may be used to directly indicate the presence of hydrocarbons. The proposed project will address the evaluation of the use of EM techniques to map shallow deposits and monitor thermal recovery process.

The survey method that is used in the first phase of the program involves the measurement of fields around a grounded bipole. Without a detailed examination of the electric and magnetic fields associated with a grounded bipole, it is impossible to make accurate prediction from an analysis of field data. Many solutions exist for different geometries but all require reformulation into a form that will allow analysis of site specific measurements. One example that indicates the approach is given by Foster⁴ for the case of the bipole grounded into a layer of given thickness and resistivity over a half-space of given resistivity. By examining the behavior of the field with distance from the source, it is possible to calculate the apparent resistivity, ρ_a ,

$$\rho_a = \frac{1.26 \times 10^5}{f} (E/H)^2$$

where E is the electric field in volts/m and H is in amp turns/m for a source of frequency f . When measurements are made at distances greater than three skin depths, the apparent resistivity calculated by the above equation corresponds to the actual apparent resistivity. The skin depth is given by

$$d = 503 \sqrt{\rho_a / f}$$

More detailed solutions will solve Maxwell's equations for the components of the Hertz vector Π , i. e., each component of the Hertz vector satisfies

$$\nabla^2 \Pi_{ik} - \delta_i^2 \Pi_{ik} = 0$$

where

$$i = 0, 1, 2$$

$$k = x, z$$

$$\delta = \text{propagation constant}$$

Then the electric field E is given by

$$E_i = c \nabla \nabla \cdot \Pi_i - c \gamma_i^2 \Pi_i$$

and the magnetic field H is given by

$$H_i = \frac{-jc}{\omega} \gamma_i^2 \nabla \times \Pi_i$$

where c is the velocity of light and ω is the angular frequency, and

$$\gamma_i^2 = j 4\pi\omega\sigma_i - \omega^2 \epsilon_i$$

where σ is the conductivity and ϵ the electric permeability. The solution of these equations gives a near and far field solution that is frequency dependent. Thus the analysis of measurements must include this effect and a proper interpretation of measured E and H fields. At the present time, calculations are being set up for analysis purposes.

The experiment chosen for a first test of this approach is a steam injection experiment in the tar sands outside of Vernal, Utah. This test is being run by Laramie Energy Technology Center (LETC). The site for the LETC TS-1S, four miles west of Vernal, Utah, in the Northwest Asphalt Ridge deposit, is on Sohio National Resource Company property. Based upon steam injection tests and modeling, two concentric five spot production patterns were chosen (Figure 2). The outer four production wells (3P1-3P4) are on the perimeter of 0.25 acres production pattern and the inner four production wells (3P5-3P8) bound 0.1 acres production pattern with a common injection well (3I1) located in the middle. The wells (3M1-3M4) are temperature monitor wells. There is a greater permeability in the North-South direction than in the East-West direction. Also, the top 45 ft of the pay zone averaged about 10 md, while the bottom 5 feet had about 2 darcies of saturated permeability. The bottom layer appears to be unconsolidated. The overlying and underlying shales have less than 10 md of permeability for reasonable pay zone isolation.

Steam injection began on 22 April 1980. After the initial shakedown, the steam injection rate is about 400 equivalent barrels of water per day (BWPD). The steam quality is about 50 to 80% at approximately 500 psig and 460°F. A steam break-through to production well 3P6 has occurred and 3P6 is now shut-in with periodic low level steam bleed-off. The best producers have been production wells 3P7 and 3P8, with 3P8 giving about twice the amount of oil as 3P7. The production well 3P5 is not producing any oil.

A series of CSAMT measurements have been made at the Vernal site. The electromagnetic field was produced by a grounded bipole source. The two ends of a 2000 ft antenna were grounded with transmitter located at the center of the bipole. The electric field was measured by a dipole receiver (5 m spacing) in contact with the ground, and the magnetic

field measured with a ferrite coil magnetometer. Soundings were made by varying the frequency from 4 to 2048 Hz and lateral variations by moving the receiving antenna.

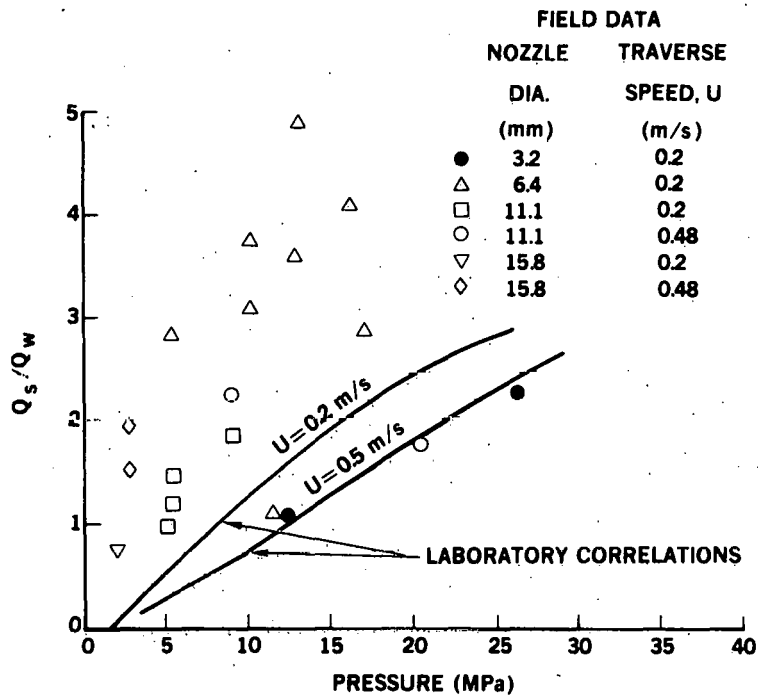
When measurements of the electric and magnetic fields (E parallel to and H perpendicular to the transmitting bipole antenna) are made at distances greater than three skin depths (far field region) from the transmitting antenna, the apparent resistivities calculated using the equation given above correspond to the "true" apparent resistivities. In the far field region plane wave solutions are appropriate. Measurements made at distances less than three skin depths (near field region) yield an apparent resistivity which will be higher than the "true" apparent resistivity. Even though the near field resistivity values do not represent the "true" apparent resistivities, the near field measurements can be used to delineate subsurface variations if there are sufficient resistivity contrasts. For the most part, the measurements made at the Vernal site were in the near field region.

Because of the steam breakthrough, the first set of measurements in late May 1980 concentrated upon measurements between 3I1 and outpost 3P6. A resistivity low found near 3I1 increased to a maximum away from the injection well and then decreased to a background value further away from 3I1. Later tests indicate that the presence of plumbing does not have detrimental effects on CSAMT measurements.

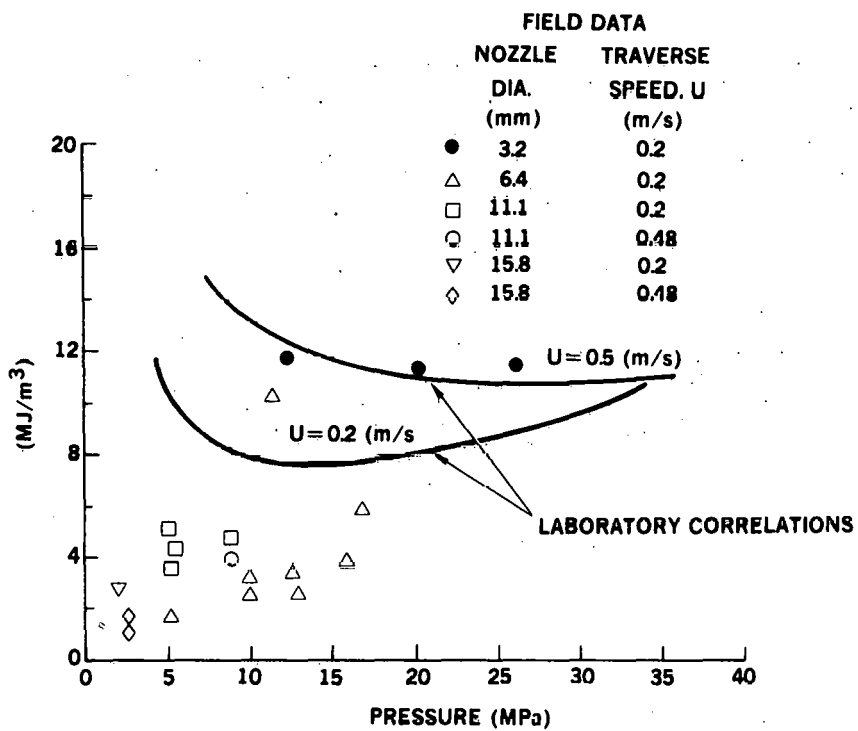
This set of preliminary results encouraged us to make a complete survey of the injection site on 20 to 22 June 1980. The results of this survey are shown in Figures 3 to 7. Each data collection point is shown by a dot overlain upon the well pattern of Figure 2. The numbers beside each dot are the apparent resistivity in ohm-meters at the indicated frequency. The contours are best estimates of the constant resistivities (indicated by the circled numbers). The analysis of the

data is not complete, so interpretation cannot be made at this time. However, a number of observations can be made to indicate possible interpretations. Temperature measurements in 3M1-3M4 indicate that the steam has developed most strongly along the lower layer of the pay-zone with some heat toward the top of zone at 500 ft. The higher temperatures on 20-22 June 1980 were in 3M2 and 3M3. Thus the 4 Hz results shown in Figure 3 follow a pattern that is consistent with the observations from the production and monitor wells. (3P2 and 3P3 were not operational at the time of these measurements.) The same general phenomena is seen up to about 128 Hz (see Figures 3, 4 and 5). However, at 256 and 512 Hz, the contour pattern changes and the interpretation is less clear. At 256 and 512 Hz the resistive high near P2 is still present. The higher frequencies (1024 and 2048 Hz) are not shown because of pattern breakup.

As a hypothesis, if we assume that the pattern shown for 4 Hz is the steam front, then 3P7 and 3P8 should be the best producers. But also then the next two wells to start up should be 3P2 and 3P3. By the end of July, the steam front was at 3P8 to the extent that there was sufficient pressure to produce without pumping. Also 3P3 had produced for awhile but sand control problems had shut it down. The well 3P5 has not yet produced oil.

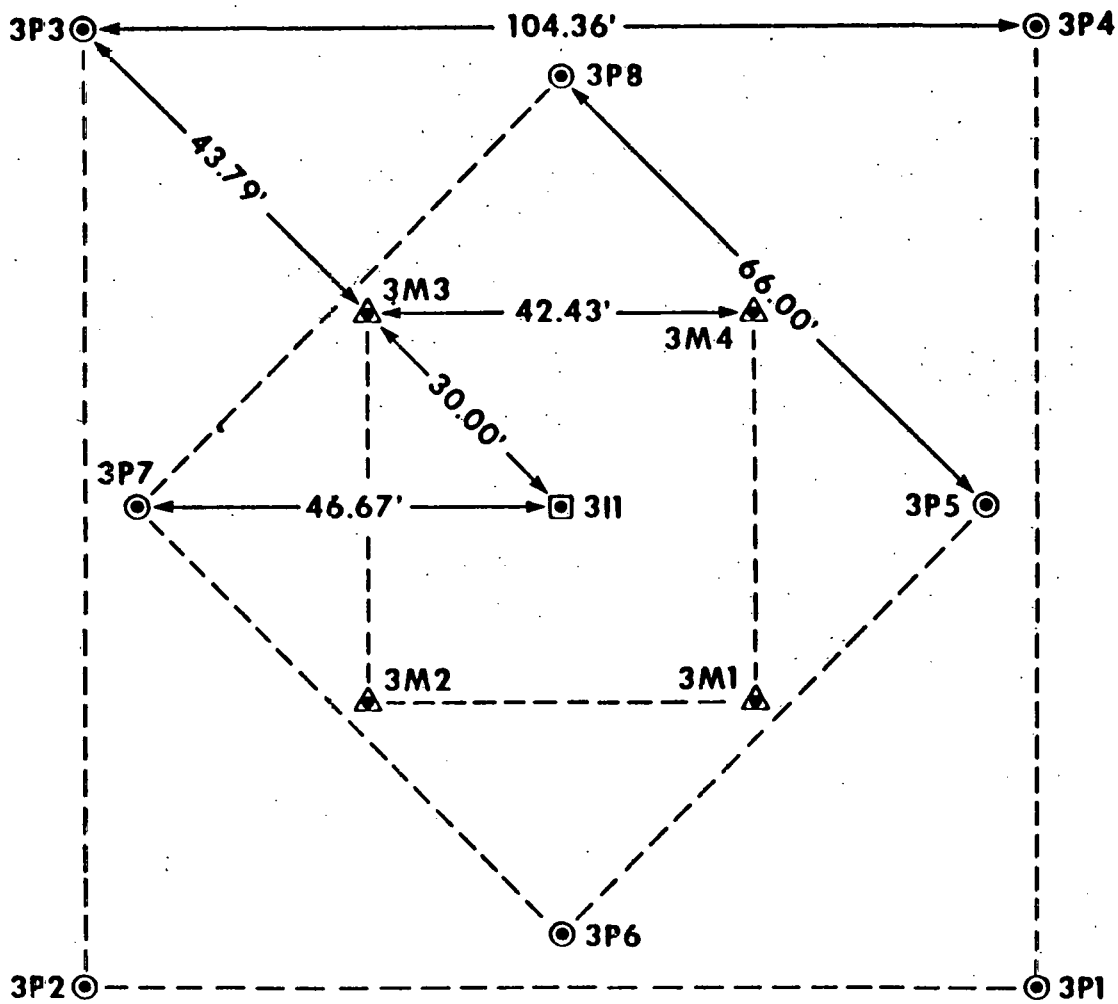


a. VOLUMETRIC CUTTING RATIO (OIL SANDS CUT TO WATER REQUIRED)



b. SPECIFIC ENERGY REQUIREMENT FOR HYDRAULIC CUTTING OF OIL SANDS

Figure 1. Water Jet Nozzle Performance



**LETC TS-15
Well Pattern**

- ⊙ Production Well
- ▣ Injection Well
- ▲ Monitor Well



Figure 2

AMT RESISTIVITY AT 128Hz
FOR THE TS-IS EXPERIMENT
ON 20-22 JUNE 1980

128Hz

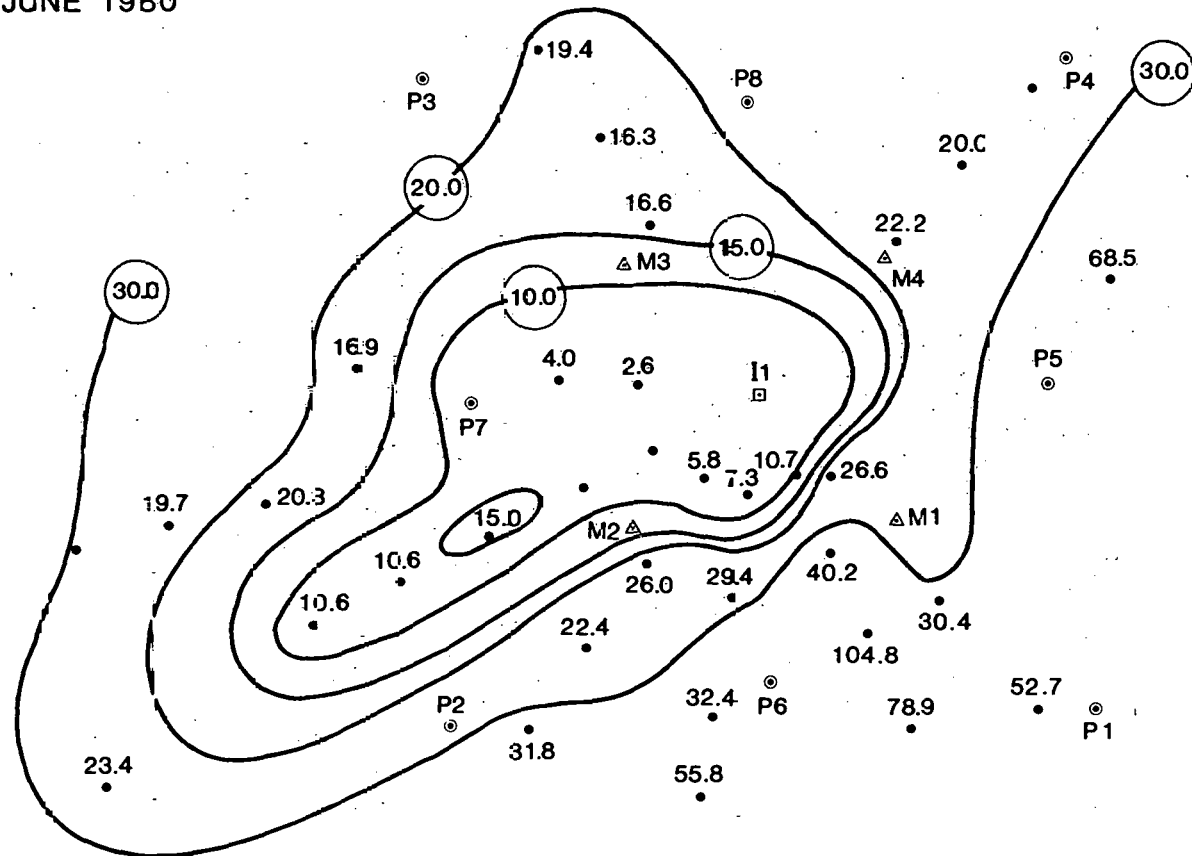


Figure 5

AMT RESISTIVITY AT 256Hz
 FOR THE TS-IS EXPERIMENT
 ON 20-22 JUNE 1980

256Hz

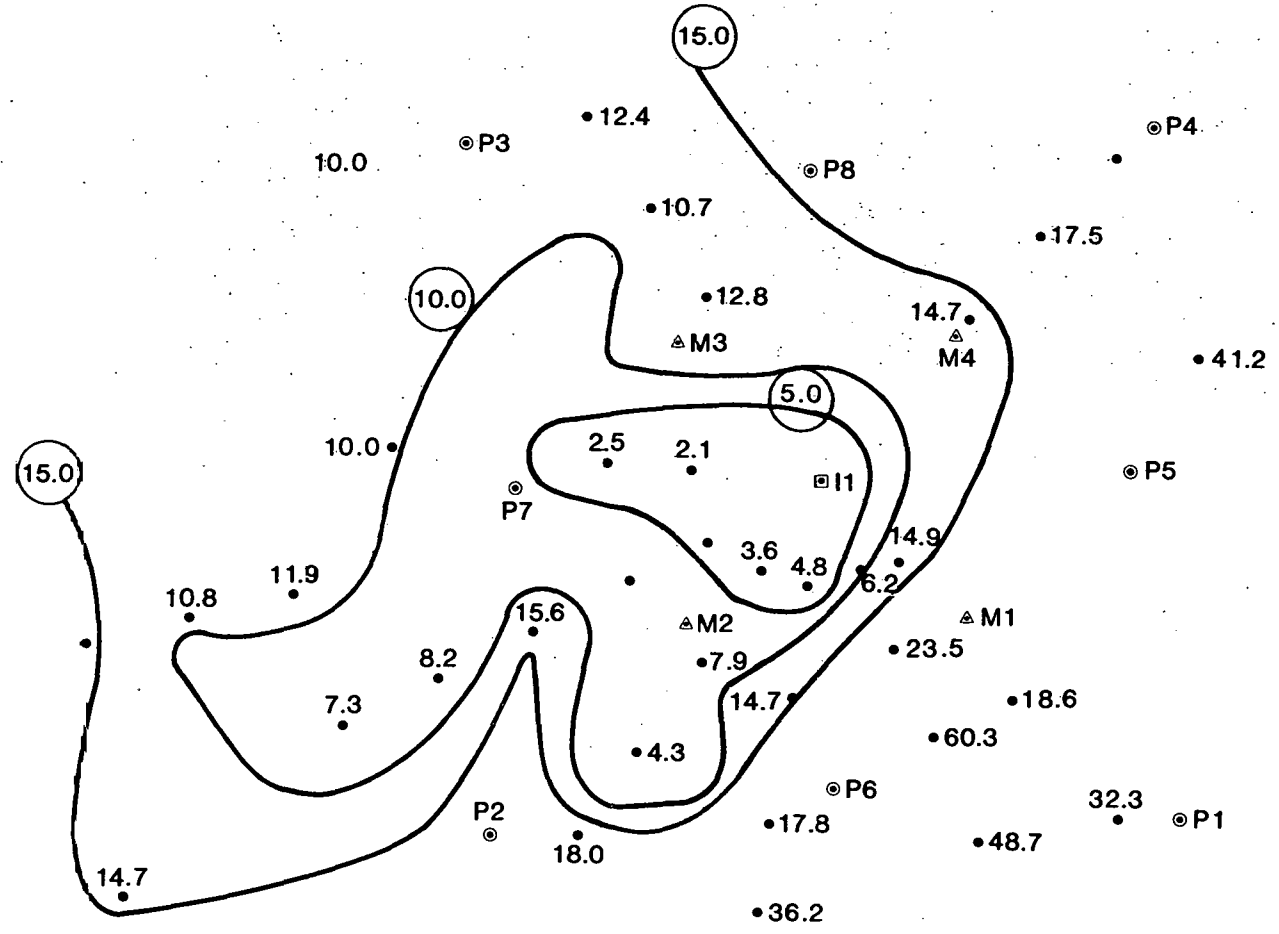


Figure 6

AMT RESISTIVITY AT 512 Hz
FOR THE TS-IS EXPERIMENT
ON 20-22 JUNE 1980

512 Hz

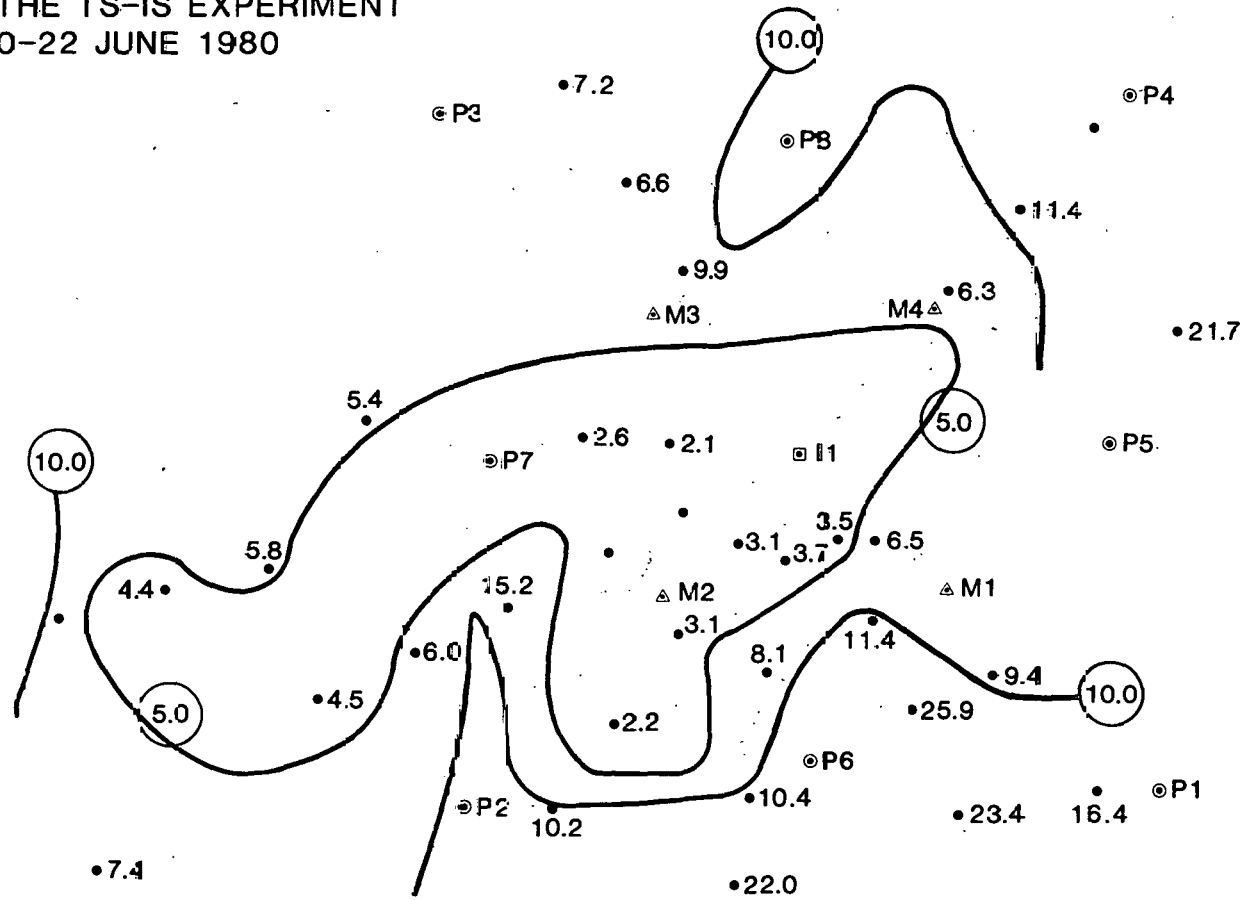


Figure 7

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