

The Recovery of Heavy Oils from Deep Reservoirs*

by

H. M. Stoller and R. L. Fox

Sandia Laboratories
Albuquerque, NM 87185

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ABSTRACT

The objective of Project DEEP STEAM is to develop the technology required to economically produce heavy oil from deep reservoirs. Two approaches are being pursued: improving the thermal efficiency of injection string components and the development of downhole steam generators to achieve steam injection.

The first approach has seen the testing of commercially available components at a high temperature (650°F)/high pressure (2100 psi) simulation facility. Promising components will be tested shortly in a field test conducted by Husky Oil at Lloydminster, Canada.

The second approach has seen the prototype development and laboratory testing of low-pressure and high-pressure hydrocarbon-fueled downhole steam generators. Concurrently, a modified high pressure steam generator has undergone extensive laboratory combustion studies and is currently being employed in a field test at Chevron's Kern River field. This field test is examining the effects of simultaneous injection of steam and combustion products on the reservoir and oil recovery.

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THE RECOVERY OF HEAVY OILS FROM DEEP RESERVOIRS

Introduction

Current estimates are that of the 300 billion barrels of crude oil which have been discovered in the United States but are presently considered nonrecoverable, approximately 100 billion barrels are heavy oils.¹ Thermal methods of enhanced oil recovery, primarily steam soak and steam drive, have proven relatively effective in the recovery of heavy oils. These techniques, in which surface-generated steam is injected via an injection string to the reservoir face, have an economic depth limit, on the order of 1000 feet, primarily due to the thermal losses encountered by the steam in transit down the wellbore (Figure 1).²

Exact numbers of the amount of heavy oil to be found in deeper reservoirs are difficult to establish; yet the target appears reasonably attractive to support a major technology development program (Figure 2).³ As part of the Department of Energy's Enhanced Oil Recovery Program, Project DEEP STEAM has been established to develop the technology required to economically produce heavy oil from deep reservoirs. Basically, two approaches are being pursued concurrently to achieve this objective. The first is the modification of delivery processes for surface-generated steam; the emphasis in this approach is directed at improving the thermal efficiency of the injection string. The second approach is to develop methods for the production of steam at the sand face, the downhole steam generator approach.

COST OF OIL PRODUCTION AS FUNCTION OF RESERVOIR DEPTH

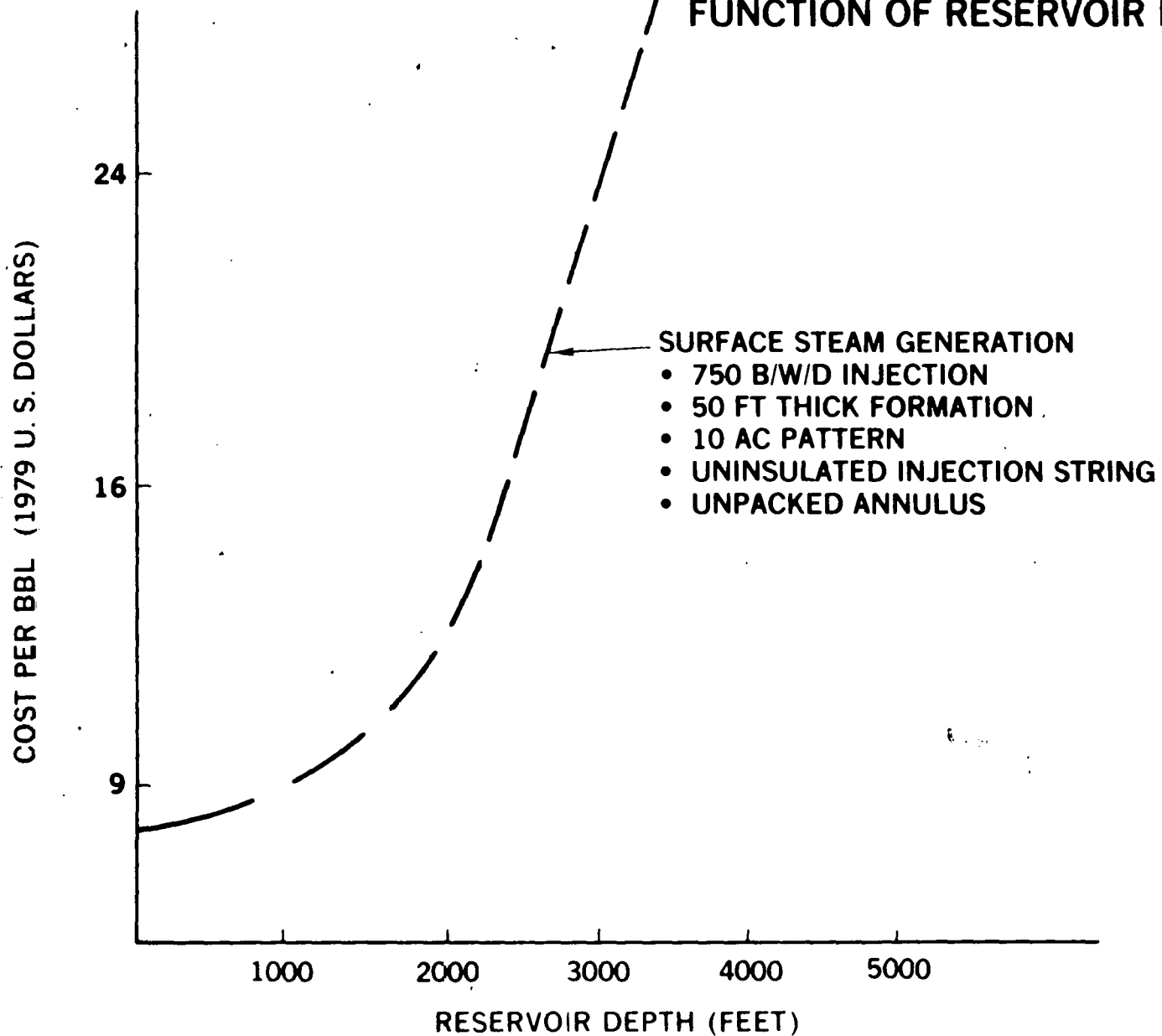
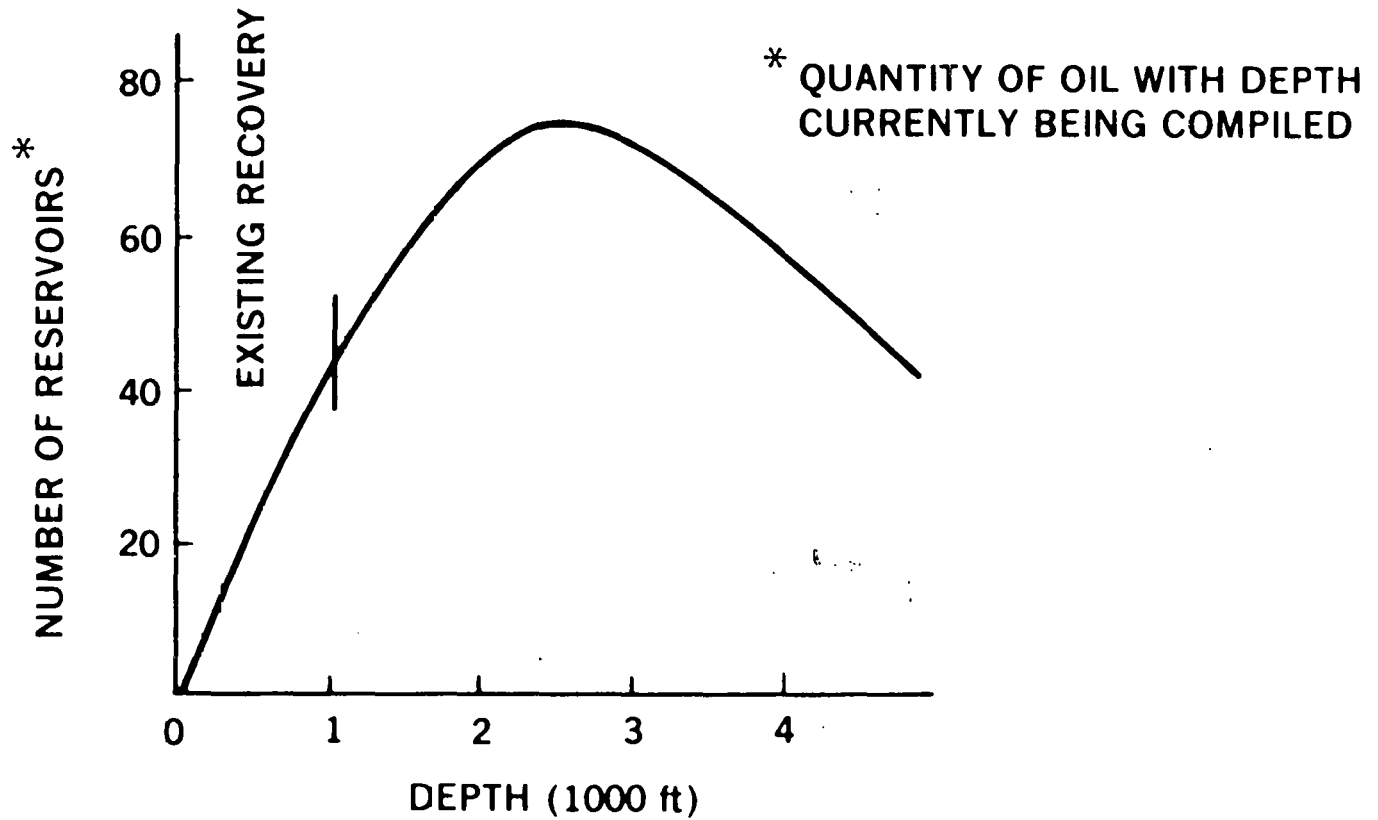


FIGURE 1

DEEP STEAM

EXTEND THE APPLICATION OF STEAM DRIVE TO DEEPER RESERVOIRS



DEPTH OF HEAVY OIL RESOURCES IN CALIFORNIA
(Ca. OIL AND GAS CONSERVATION COMMISSION)



FIGURE 2

This project was initiated in early CY 1978. The first six months were devoted to a variety of systems analysis, reservoir modeling and technical feasibility studies to establish the relative merits of pursuing one or both approaches and, in the case of the downhole steam generator, which concepts appeared economically the most attractive. The decision was made to pursue both approaches. In the thermally efficient well completions approach, the initial direction was the construction of a high temperature, high pressure simulation facility in which commercially available components could be evaluated. As proven necessary, appropriate materials development and component development activities then would be undertaken. The concepts of low-pressure and high-pressure steam generators utilizing hydrocarbon fuels appeared to be the most promising and contracts were initiated for engineering studies and prototype fabrication. Concurrently, a commercially available steam generator was procured and modified for high pressure combustion studies at Sandia.

Economic analyses continue to indicate that both approaches have economic merit. This paper presents the technical status of Project DEEP STEAM to date as well as outlining planned activities.

Thermally Efficient Well Completions

The computational simulation of heat loss during transportation of steam through concentric tubulars has been the

object of many investigations.⁴⁻⁸ These existing computational methods have been verified in laboratory simulations and field testing. The heat loss due to eccentric installation of the injection string has been shown to be negligible unless the string is in contact or very close to contact with the casing.⁹ Hence, it is relatively easy to compute the improvements in steam quality and the economic payoff resulting from improving the thermal efficiency of the injection string.

With an uninsulated injection string, 85% quality steam at the surface degrades to 50% quality steam at a 2500 foot depth. The addition of $\frac{1}{2}$ inch of foam insulation to the injection string along with a thermal packer to eliminate steam escape up the annulus achieves a 75% quality steam at the same depth. Critical components include the tubular insulation, a means to insulate the joints of the injection string, and a thermal packer that can survive temperatures of 700°F and pressures of 3000 psi. If attainable, this approach could extend the economic viability of heavy oil recovery to depths on the order of 2-3000 feet.

An experimental approach for obtaining quantitative performance characteristics of these critical components is being conducted. An above ground thermal simulation test facility capable of simulating reservoir pressures of 3000 psi and steam temperatures of 700°F has been constructed by General Electric at their Takoma, Washington, location (Figure 3).

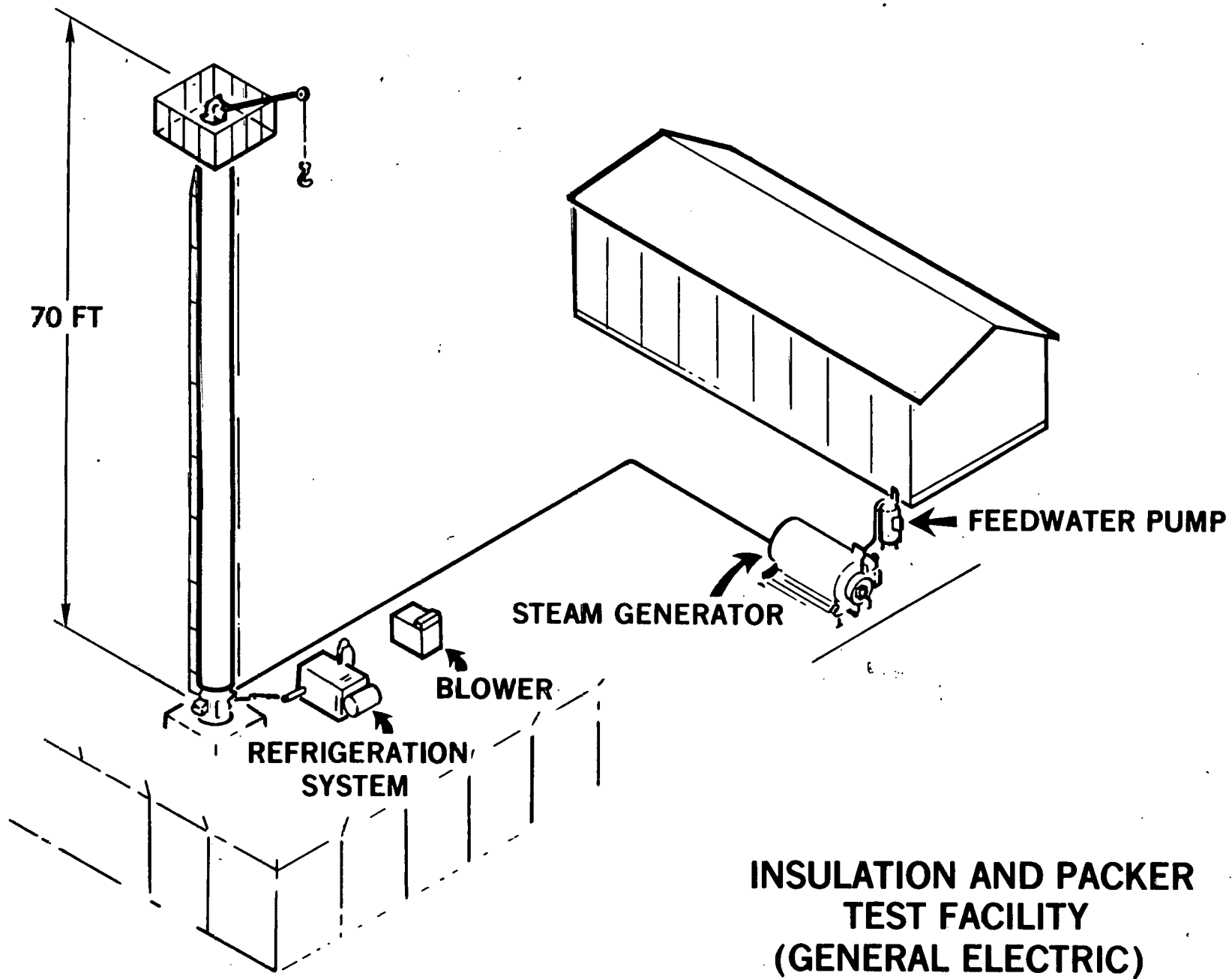


FIGURE 3

The test facility is a 70 foot vertical tower which contains a variety of diagnostic instrumentation and can test a complete section of injection tubular with joints at both ends along with a thermal packer.

To date, as illustrated in Figure 4, a variety of commercially available tubular insulations and thermal packers have been tested. Test conditions have been 650^oF and 2100 psi, not the maximum conditions for Project DEEP STEAM, but certainly realistic starting conditions for this screening program. Of the three insulations tested, the calcium silicate tubular insulation performed satisfactorily. However, none of the insulation concepts tested provided thermal protection at the joints; this problem area will require subsequent development activities. Four commercial packers were tested under the above stated test conditions. One packer, with an advanced seal design, successfully withstood the test conditions on a four day test.

As part of Project DEEP STEAM, Husky Oil will be testing components of the thermally efficient well completion which perform satisfactory. These field tests will be conducted at their Lloydminster, Canada, operations at a reservoir depth of 1500-2000 feet. Testing is planned to begin in February 1980.

As a result of these initial screening tests in the GE facility, it does not appear encouraging that thermal packers

GENERAL ELECTRIC TEST TOWER

STEAM, 650°F, 2100 psi

INSULATION

UNI-THERM MINERAL WOOL - hot spot near coupling and severe degradation of jacket.

CONCO CALCIUM SILICATE - hot spot at coupling. Insulation performance satisfactory.

GE THERMO CASE III - 1st test (< 24 hours) satisfactory.
- 2nd test, steam leak at lower joint.

PACKERS

BROWN EMJAY - seal held for 5 days;
difficult to pull.

HALLIBURTON CT - set in tension, failed
in 2 hours @ 1000 psi; set in compression,
seal failed @ 2100 psi in ≤ 24 hrs.

GUIBERSON UNI-VI - seal blew after 48 hrs.
@ 2100 psi; seal blew @ 2100 psi overnight.

BAKER HB-1 (with advanced seal) - seal held for
4 day test (twice).

FIGURE 4

employing elastomeric- or asphaltic-material seals can survive the maximum DEEP STEAM conditions for extended time periods. Foster-Miller, of Waltham, Mass., as part of their high-pressure downhole steam generator activities has initiated the development of a thermal packer employing an aluminum metal seal. This design has survived preliminary laboratory testing at nominal test conditions. The design also allows for subsequent removal. Project DEEP STEAM will emphasize this approach to thermal packers in its subsequent development activities.

Downhole Steam Generation

Contracts for engineering design and prototype fabrication of downhole steam generators were placed with the Rocketdyne Division of Rockwell International Corp., Canoga Park, CA, for the low-pressure concept and with Foster-Miller Associates of Waltham, MA, for the high-pressure concept. Subcontractors include the Doschers Group for Rocketdyne and MIT, Gulf Oil Corp. and Cash and Jenkins for Foster-Miller. Figure 5 lists the various approaches to steam generation which were subjected to systems and economic analyses which led to the selection of the low-pressure and high-pressure, hydrocarbon-fueled steam generators. Concurrently, Sandia procured a commercially available, low-pressure steam generator, capable of a thermal output of 5×10^6 Btu's/hour, modified it for high pressure operations and undertook a series of combustion studies to determine clean burning conditions.

SYSTEMS AND ECONOMIC ANALYSIS OF APPROACHES TO DOWNHOLE STEAM PRODUCTION

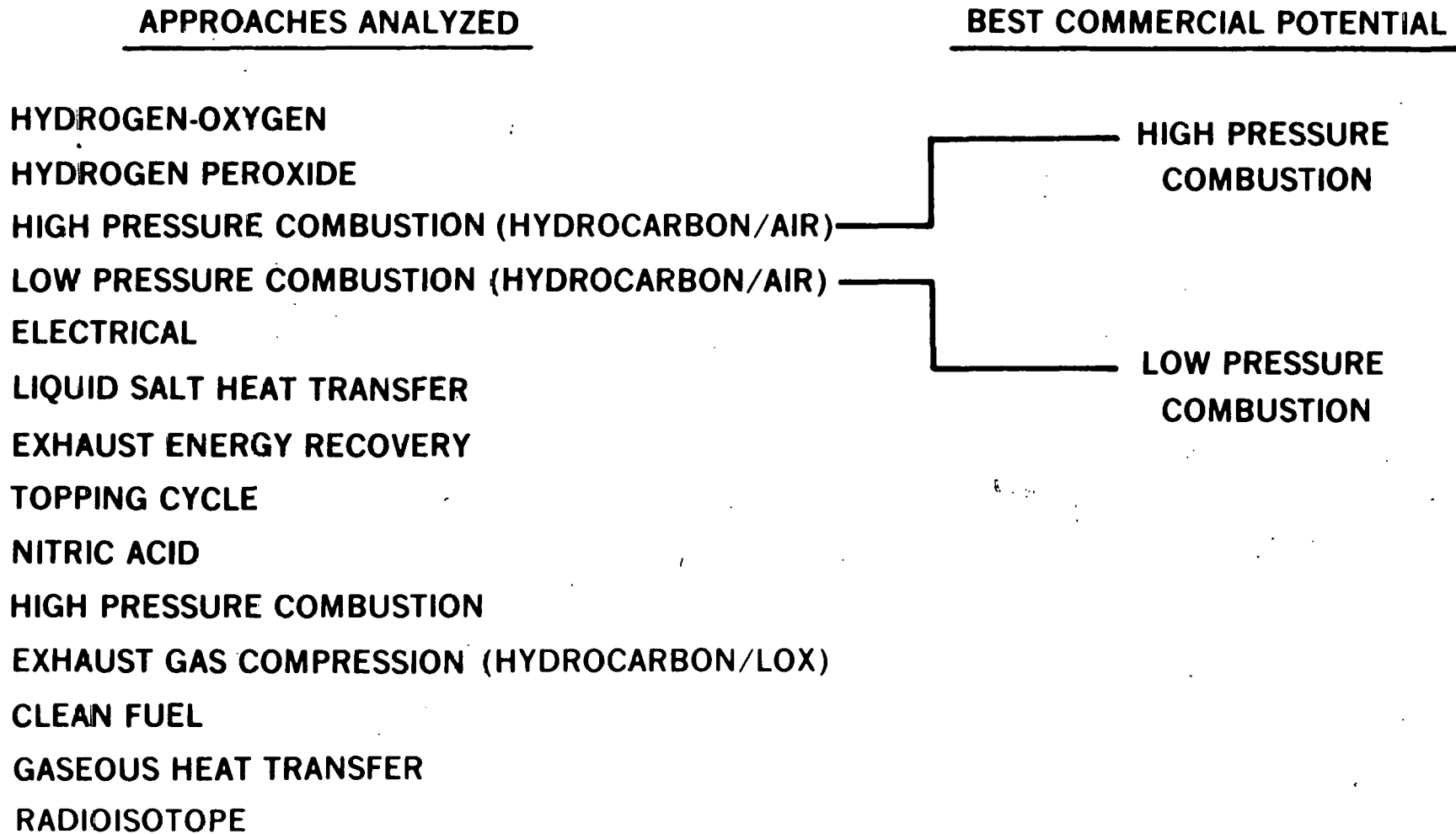


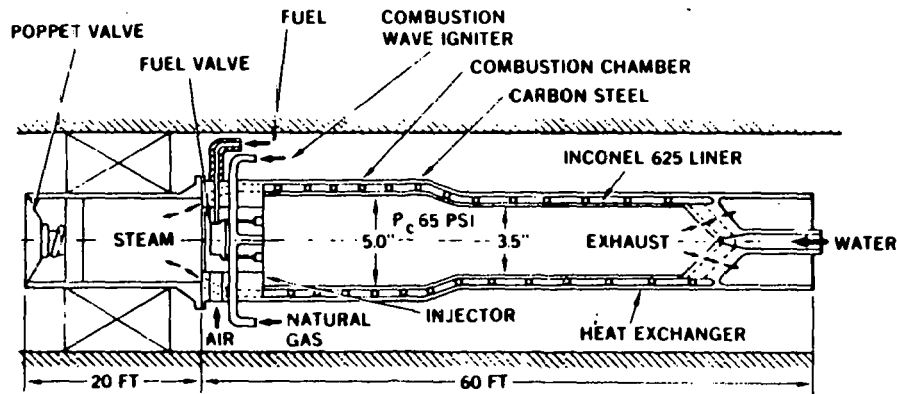
FIGURE 5

Figure 6 presents a schematic of the low pressure design along with the energy usage of the fuel. 92% of the energy in the fuel is delivered to a reservoir at a 2500 foot depth; this represents a 25-50% increase in efficiency over a surface generated steam system. The low pressure combustion downhole generator uses a compact heat exchanger to transfer heat of combustion to water which is delivered from the surface producing high pressure steam at a high quality. The exhaust gases of combustion are transported back to the surface and must be dealt with to satisfy environmental regulations.

The first prototype of the low pressure generator has been fabricated and is presently undergoing testing at Rocketdyne facilities. The prototype is 35 feet in length, 10 inches in diameter and is capable of producing 15×10^6 Btu/hr of steam. Depending on Project DEEP STEAM funding levels, this prototype could be ready for initial field tests by fall, 1980.

The high pressure combustion design oxidizes hydrocarbon fuel at high enough pressures so that the exhaust gases can be injected into the reservoir along with the steam. This simultaneous injection into a reservoir of both steam and combustion gases (primarily carbon dioxide and nitrogen) present totally different physics of oil recovery. Hence, additional data addressing reservoir performance in addition to the cost of steam must be obtained to determine comparative recovery efficiency.

LOW PRESSURE DOWNHOLE GENERATOR



ADVANTAGES

- HIGH THERMAL EFFICIENCY (92%)
- LOW CAPITAL COST
- NO PARTICULATE INJECTED INTO RESERVOIR

DISADVANTAGES

- AIR QUALITY
- SIZE AND NUMBER OF STRINGS
- PARTICULATE IN RETURN GASES

HEAT BALANCE INFORMATION

INJECTION PRESSURE 1500 PSIA, DEPTH 2500 FT
 BASED ON LOWER HEATING VALUE = 18,293 BTU/LB

HEAT INPUT

SOURCE	%
COMBUSTION FUEL (750.02 LB/HR)	81.9
DIESEL FUEL (165.71 LB/HR)	18.1
TOTAL (915.73 LB/HR)	100

HEAT OUTPUT

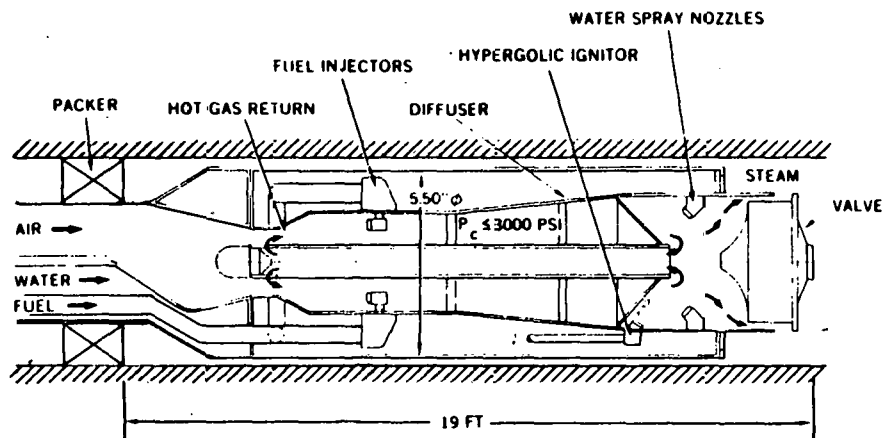
	%
COMBUSTION EXHAUST LOSS	4.1
DIESEL ENGINE EXHAUST LOSS	2.2
DIESEL COOLANT LOSS	0
OTHER: DIESEL STRAY & PUMP WORK	1.0
ABOVE GROUND TOTAL	7.3
WELL BORE LOSS	0.50
INJECTED GAS (EXCLUSIVE OF STEAM)	0
USEFUL HEAT (85% QUALITY STEAM)	92.2
BELOW GROUND TOTAL	92.7
TOTAL	100.0

FIGURE 6

Figure 7 presents a schematic of the high pressure steam generator design along with the energy usage of the fuel. Approximately 81% of the energy is delivered as steam to a 2500 foot reservoir which is less than for the low pressure design. However, as will be shown below, injection of the combustion gases into the reservoir may have a synergistic effect with respect to oil production as well as mitigating air quality problems by being retained in the reservoir. These potential positive advantages may be offset by the deleterious effect of formation damage or plugging if the combustion process is not sufficiently clean to minimize particulate formation.

Figure 8 compares the oil recovery from a hypothesized reservoir via steam injection alone and via steam injection plus combustion gases. This problem was run by the Intercomp Resources Development and Engineering Company, Houston, TX, utilizing their in situ combustion code. Simultaneous injection of both steam and combustion gases recovered the in-place oil in approximately 30% less time than required for steam injection alone. The comparison is essentially between the high pressure and low pressure designs and accounts for the lower energy injection rate of the high pressure generator. A similar modeling effort by the Gulf Oil Corp. confirms the synergistic effect of steam and combustion gases.

HIGH PRESSURE DOWNHOLE GENERATOR



ADVANTAGES

- ADDRESSES AIR QUALITY
- COMBINES THERMAL WITH CARBON DIOXIDE RECOVERY
- COMPACT DESIGN

DISADVANTAGES

- PARTICULATE INJECTION TO RESERVOIR
- HIGH PRESSURE COMBUSTION
- HIGH PRESSURE AIR SUPPLY

HEAT BALANCE INFORMATION

INJECTION PRESSURE 1500 PSIA, DEPTH 2500 FT
 BASED ON HEATING VALUE = 18,293 BTU/LB

HEAT INPUT

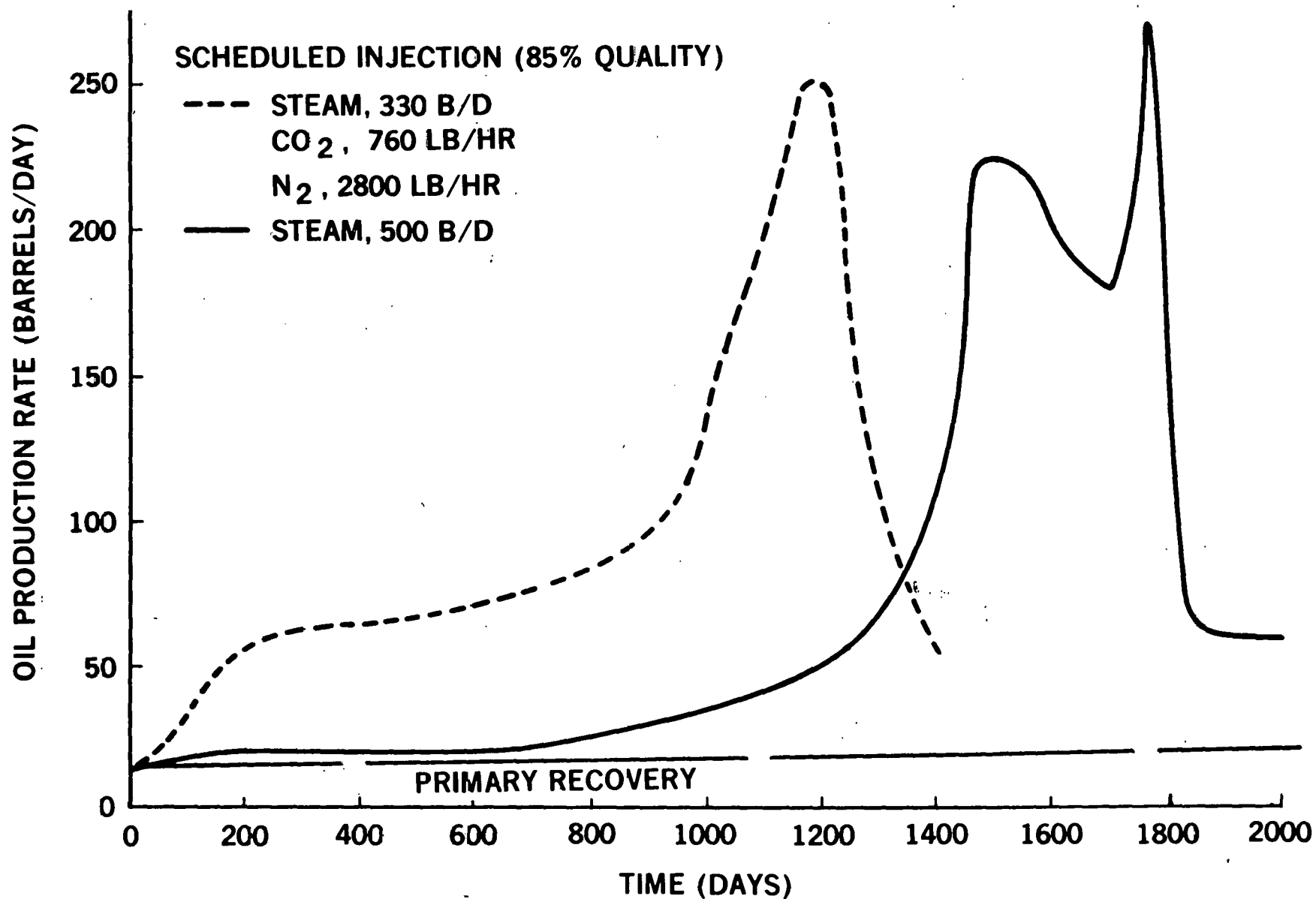
SOURCE	%
COMBUSTION FUEL (676.8 LB/HR)	65.3
COMPRESSOR FUEL (360 LB/HR)	34.7
TOTAL (1036.85 LB/HR)	100

HEAT OUTPUT

	%
COMBUSTION EXHAUST LOSS	0
DIESEL ENGINE EXHAUST LOSS	4.9
DIESEL COOLANT LOSS	7.1
OTHER: DIESEL STRAY & PUMP WORK	0.8
ABOVE GROUND TOTAL	12.8
WELL BORE LOSS	0.2
INJECTED GAS (EXCLUSIVE OF STEAM)	5.6
USEFUL HEAT (85% QUALITY STEAM)	81.4
BELOW GROUND TOTAL	87.2
TOTAL	100

FIGURE 7

FIGURE 8. OIL PRODUCTION RATE VS TIME FOR STEAM DRIVE ALONE COMPARED TO STEAM WITH COMBUSTION GASES



Foster-Miller has also completed the prototype fabrication of their design. This device is 12 feet in length and 6 inches in diameter. They have successfully tested, at atmospheric pressure, the high pressure design utilizing diesel fuel as the hydrocarbon source. The prototype is now at Sandia Laboratories awaiting completion of suitable testing facilities before undergoing high pressure testing. At atmospheric pressure, the high pressure design was demonstrated to be extremely clean burning, producing less than one part per million.

At Sandia, the modified high pressure steam generator, 35 inches long by 6.5 inches in diameter, has successfully completed a five day continuous operation test. Through a series of combustor design changes, this laboratory proof test resulted in about 0.1 oz/24 hours of particulate matter being produced with propane as the hydrocarbon fuel. This generator is now at a site in Chevron's Kern River field where, in a surface configuration, steam and combustion products are being injected into a known reservoir at a depth of 800 feet. Steady state injection should be achieved by mid-February. Initial results on the effects of oil production may be available by late March. Monitoring of oil production data is also accompanied by extensive environmental monitoring.

Summary

Figure 9 assesses the economic payoff from these technology developments. Clearly, if either the thermal efficiency well completion approach or the downhole steam generator approach is successful, then the economic depth for the recovery of heavy oils has been extended significantly. More importantly, as these results indicate, if it is possible to achieve the synergistic effects of simultaneous injection of steam and combustion products without deleterious formation effects, then a major breakthrough in the recovery of heavy oils may have been achieved.

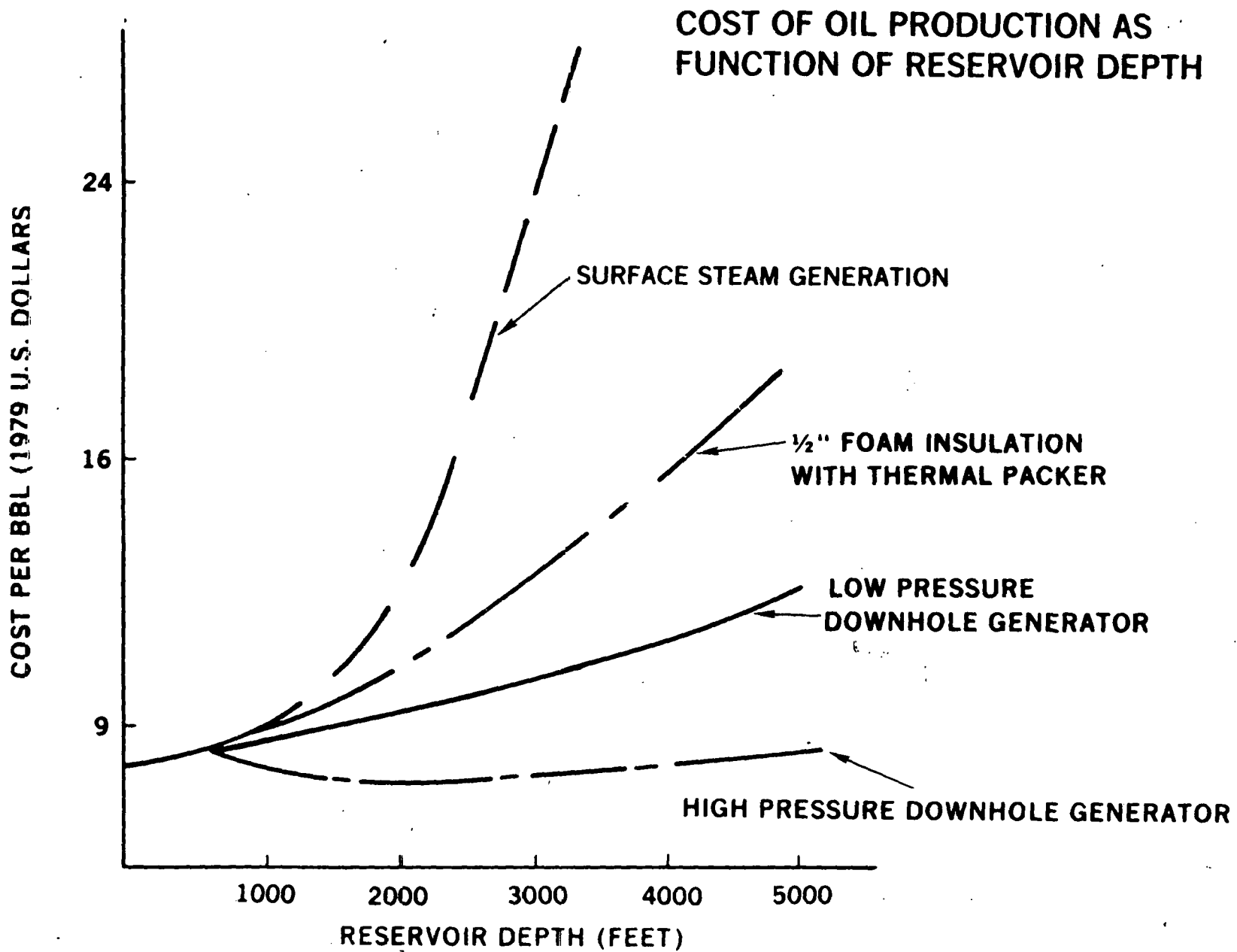


FIGURE 9

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