FOSSIL ENERGY

DOE/BETC/2628-1

STATUS OF WATER JET DRILLING R&D

Final Report

Date Published—September 1980

Work Performed for the Department of Energy
Under Contract No. ET-78-C-01-2628

Booz, Allen & Hamilton, Inc.
Bethesda, Maryland

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma

DISCLAIMER

DOE/BETC/2628-1
Distribution Category UC-92a

STATUS OF WATER JET DRILLING R&D

Final Report

Leonard Breitstein, *Principal Investigator*
Booz, Allen & Hamilton, Inc.
4550 Montgomery Avenue
Bethesda, Maryland 20014
301/951-2598

C. Ray Williams, *Project Manager*
Drilling and Offshore Technology
U.S. Department of Energy
Bartlesville Energy Technology Center
P.O. Box 1398
Bartlesville, Oklahoma 74003
918/336-2400, Ext. 359

Prepared for the Department of Energy
Under Contract No. ET-78-C-01-2628

Date Submitted—July 1980
Date Published—September 1980

U.S. DEPARTMENT OF ENERGY

FOREWORD

The application of water jet drilling techniques has received much attention in recent years. Some experts believe it will contribute greatly to future drilling technology while others hold that it is not practical for oil field application, but has most of its merits toward other drilling, or tunnelling, applications.

This study was funded by the U.S. Department of Energy, Headquarters section of Drilling and Offshore Technology, Division of Oil, Gas and Shale Technology. The purpose was to document the ongoing research and development and to identify where, and if, the DOE Drilling Technology group should provide funds or other assistance. This report identifies some areas where water jet drilling can assist toward increasing energy development.

C. Ray Williams
Project Manager,
Drilling and Offshore Technology
Bartlesville Energy Technology
Center

TABLE OF CONTENTS

ABSTRACT

A study was made to determine the status of R&D activities in the area of water jet drilling (WJD). Several computerized data bases were searched, and telephone interviews were conducted with nearly 100 experts in drilling R&D. The following information was obtained for each organization engaged in WJD R&D: program descriptions, program status, future plans, level of effort, source of funds, and problems encountered in WJD programs.

For convenience, WJD programs were classified in terms of surface pressure requirements. A total of 18 downhole-WJD programs were identified, with 9 using high surface pressures (5,000 psi or higher) and 9 requiring only conventional or low surface pressures (generally below 3,500 psi). The high-pressure approach to WJD has been investigated much more intensively than the low-pressure approach, with about $25 million spent by private industry on high-pressure programs. Most drilling experts consider the lack of reliable surface equipment such as mud pumps and swivels to be the most critical problem associated with high-pressure WJD. Several programs to develop improved surface equipment for high-pressure operation were also identified. In addition, 28 organizations investigating non-downhole uses of water jets, such as mining or excavation, were also identified.

Several large WJD programs were terminated during the 1970's because of a variety of problems. Two significant field programs are planned for 1980. Shell will conduct high-pressure field tests, while Hydronautics, NL Hycalog, and Smith Tool will jointly conduct low-pressure tests with cavitating jets. Most other plans for smaller-scale R&D involve low-surface-pressure approaches to WJD, including the use of compact intensifiers to increase drilling fluid pressure downhole.

Several opportunities for joint government/industry R&D programs to accelerate the development of WJD technology were identified. Such programs could include the development of downhole intensifiers and the collection of additional WJD performance data, as well as the development of high-pressure pumps and swivels.

1. INTRODUCTION

The economic and strategic consequences of the Nation's dependence on foreign, unreliable sources of energy have become increasingly obvious in recent years. The potential benefits of increasing domestic reserves and production of petroleum and natural gas, and thereby of reducing this dependence on imported oil, are indeed great.

In order to increase significantly domestic oil and gas production, the annual numbers of wells and drilling footage must be substantially increased. The benefits to be gained by improvements in drilling technology that increase penetration rates and reduce costs are well documented.(1,2,3) Maurer has estimated that increasing drilling capabilities of existing rigs by 30 percent would result in the drilling of more than 12,000 additional wells and the discovery of an additional one billion barrels of oil reserves annually.(1) Improvements in drilling technology will also be required for the utilization of geothermal energy on a large scale.

In view of the obvious need to improve drilling technology, a wide variety of novel drilling techniques have been studied, tested, and/or evaluated over the past two decades. Many of these techniques have employed rather exotic means, such as the use of lasers, electron beams, projectiles, and plasmas to enhance rock breakage, but have been found to be impractical under downhole conditions. Some authorities consider high-pressure or cavitating water jets to have the greatest near-term potential for substantially increasing drilling rates (1,4) while others doubt their commercial feasibility.

---

[1] W. C. Maurer, "Near-Term Needs in Drilling Technology," Presentation to the U.S. House of Representatives Fossil and Nuclear Energy Research, Development, and Demonstration Subcommittee of the Committee on Science and Technology, March 1, 1977.

[2] U.S. Department of Energy, Division of Oil, Gas, Shale, and In-Situ Technology, "Blueprint for a Comprehensive Federal Drilling Technology Development Program," February, 1978.

[3] National Research Council, "Drilling for Energy Resources," PB-259 206, 1976.

[4] W. J. McDonald et al., "Drilling Technology Assessments and Future Needs," Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery and Improved Drilling Technology, August 22-24, 1979.

For the purposes of this study, the term "water jet drilling" is used to designate all drilling technologies that utilize the destructive energy of water (or drilling mud) jets to increase rock removal rates relative to conventional drilling techniques. Water jet drilling generally has the advantage over many other advanced drilling techniques under consideration of being an extension or extrapolation of current drilling technology, rather than an entirely different concept that the drilling industry might be unable or unwilling to implement.

Three major oil companies conducted substantial R&D programs in the area of water jet drilling during the 1960's and 1970's. For a variety of reasons discussed in Section 3, these programs have either been terminated or reduced in scope in recent years. Private industry has, in fact, reduced its efforts in drilling R&D in general during the past decade because the structure and fragmentation of the drilling industry are such that the large companies with sufficient resources to develop a technology such as water jet drilling no longer see a clear competitive advantage in doing so.

The study described herein was undertaken to determine the level and scope of R&D activities by industry, research organizations, and universities in the area of water jet drilling, and to identify possible opportunities for joint industry/government efforts in this area. While the emphasis of this study is on deep, downhole drilling with water jets, R&D activities in other related areas of water jet technology have also been identified.

2. DISCUSSION AND SUMMARY

2.1 BACKGROUND

Nearly all oil and gas drilling is today performed with jet drill bits and carefully planned hydraulics programs. The use of nozzles to produce drilling-fluid jets to clean the drill bit and hole bottom was, in fact, introduced more than three decades ago. A typical configuration of a modern drilling system is illustrated schematically in Exhibit 1. The drilling fluid is pumped through surface equipment, down the drill string and bit at the bottom of the hole, and back up the wellbore to a holding tank, before being recirculated to the mud pump. A principal objective of any hydraulics program is to optimize the effectiveness of the bit and hole cleaning functions, and thereby to maximize the drilling rate. It is important to note that, in the case of a conventional drilling system, rock breakage in relatively hard formations is accomplished by the mechanical action of the drill bit, with the jets being employed primarily for cleaning purposes.

Rotary drilling is usually carried out with pump discharge pressures below 3500 psi, and with nozzle pressure drops below 2500 psi as a result of pressure losses in surface equipment and the drill string. Operating pressures are generally limited to the above values because of excessive wear of pump components at higher pressures. In order to actually cut rocks with water jets, higher nozzle pressure drops are generally required. Many studies have shown that rocks have a pressure "threshold" below which no cutting occurs. Some relatively weak rocks have been cut by water jets at nozzle pressure drops down to approximately 2000 psi, while stronger rocks might require 10,000 to 20,000 psi or more. Once the threshold pressure for a rock is exceeded, the rate of rock cutting is generally found to increase rapidly as the nozzle pressure drop is increased.

The key distinction between conventional and water jet drilling (WJD) is that the energy in the drilling fluid actually contributes to rock cutting in the latter case. Two basic approaches have been pursued in WJD programs. The first approach employs relatively high surface pressures to produce high jet velocities for effective rock cutting. Gulf, Exxon, and Shell have conducted the most extensive WJD programs to date, each involving elevated surface pressures. The major problem with this approach has been found to be a lack of reliable, high-pressure surface equipment, especially mud pumps and swivels.

The second basic approach to WJD would require only conventional surface pressures, so that commercially available mud-circulation equipment could be employed. The principal low-pressure

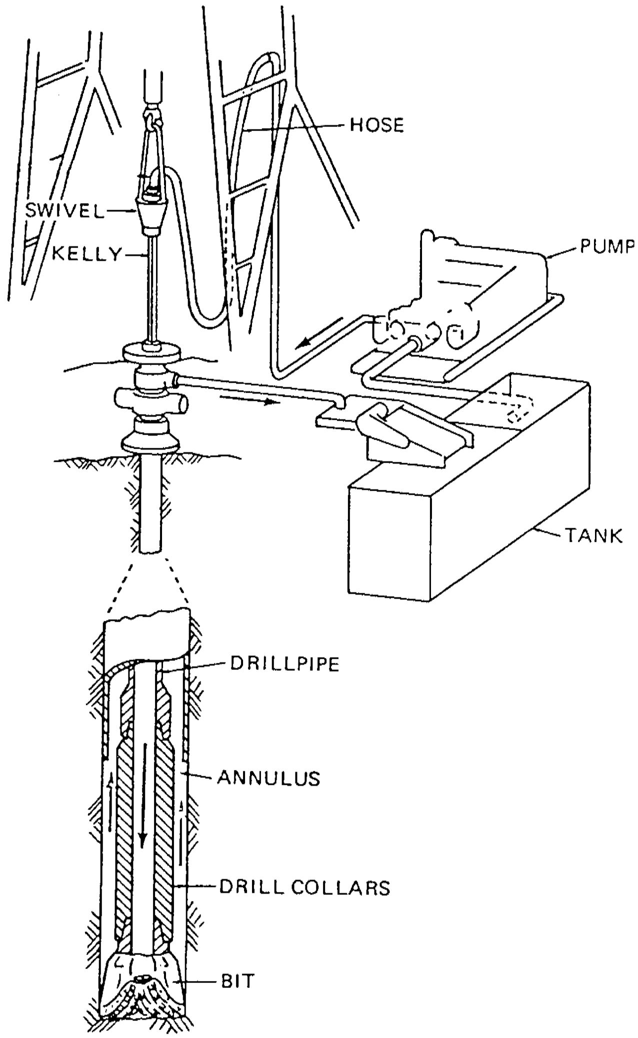

EXHIBIT 1

TYPICAL CONFIGURATION OF DRILLING EQUIPMENT AND MUD CIRCULATION SYSTEM (Reproduced from "Hughes Practical Hydraulics," Hughes Tool Co., 1976) technique pursued to date employs cavitation for rock cutting. Special nozzles are used to induce bubble formation in the drilling fluid, with bubble collapse at the rock surface then resulting in increased rock breakage. Another approach under consideration would employ a downhole device to increase the pressure of the drilling fluid. A high pressure drop across the nozzles would then enhance rock cutting, without entailing the problems associated with high surface pressures.

2.2 WATER JET DRILLING PROGRAMS AND ACTIVITIES

Past, present, and planned efforts in WJD R&D are summarized in Exhibits 2 through 4. Exhibit 2 presents those organizations involved in WJD programs and activities oriented towards downhole (i.e., oil, gas, or geothermal) drilling applications. These organizations have been divided into two groups according to surface-pressure requirements. A third group of organizations shown in Exhibit 2 has been involved in programs to develop the required high-pressure equipment. Organizations involved in programs oriented towards other uses of water jets, such as mining or rock excavation, are presented in Exhibit 3. It can be seen that several organizations are shown in both Exhibits 2 and 3 since they have conducted R&D activities in both the downhole-drilling and non-downhole rock-cutting areas.

Program information such as the nature, status, level of effort, and source of funds for WJD R&D efforts is summarized in matrix form in Exhibit 4. For simplicity and convenience, each organization is listed only once in this matrix. Organizations are classified in terms of their R&D programs and activities (i.e., downhole drilling programs, mud pumps and swivel development, and non-downhole drilling programs). Organizations participating in both downhole and non-downhole programs are included in the former group, since the emphasis of this study relates to downhole water-jet drilling. Similarly, organizations involved in both downhole WJD R&D and high-pressure equipment development are included in the "downhole drilling" group whereas organizations pursuing only equipment development are listed separately. The report sections describing the programs and activities of each organization are also presented.

Exhibit 4 shows that many organizations have participated in a wide range of water-jet R&D programs and activities. Several significant programs have been conducted and completed (or terminated due to problems). Close examination of Exhibit 4 reveals that the high-pressure approach to downhole drilling has been the subject of much more extensive investigation than the lower or conventional-pressure approach. Approximately $25 million has been spent by Gulf, Exxon, and Shell in major downhole WJD programs.

EXHIBIT 2

ORGANIZATIONS INVOLVED IN WATER JET DRILLING
R&D PROGRAMS AND RELATED ACTIVITIES

Downhole Drilling Programs - High Surface Pressures

- Gulf Research and Development
- Exxon Production Research
- Shell, Netherlands
- Hughes Tool
- University of Missouri-Rolla
- University of Tulsa
- NMIMT/University of Oklahoma/IPEC
- Flow Industries
- Colorado School of Mines

→

Programs to Develop High-Pressure Equipment

- Halliburton Services
- Exxon Production Research
- Shell, Netherlands
- TRW Mission
- U.S. Steel - Oilwell Division
- Terra Tek
- Jet Propulsion Laboratory
- Gardner - Denver
- Flow Industries

Downhole Drilling Programs— Conventional Surface Pressures

- Hydronautics/NL Hycalog
    - Terra Tek
    - Smith Tool
- Flow Industries
- Kobe/Reed Tool
- Scire
- Daedalean Associates
- Scientific Associates
- Lawrence Livermore Laboratory
- Physics International
- Sandia Laboratories

EXHIBIT 3

ORGANIZATIONS INVOLVED IN WATER-JET R&D PROGRAMS
FOR MINING, ROCK EXCAVATION, AND OTHER APPLICATIONS

University of Missouri - Rolla
Flow Industries
Colorado School of Mines
The Robbins Company
IIT Research Institute
Dresser Industries
Scire Corporation
Science Applications, Inc.
U.S. Bureau of Mines
Daedalean Associates
Scientific Associates
University of California, Davis
TRW
University of California, Los Angeles
Hydronautics
Ingersoll-Rand Research, Inc.
Continental Oil Company
Institute of Gas Technology/University of Waterloo
Oak Ridge National Laboratory
Georgia Institute of Technology
Bendix Research Laboratories
U.S. Army Cold Regions Research and Engineering Laboratory
National Research Council of Canada
University of Wisconsin - Milwaukee
McCartney Manufacturing
Gas Research Institute
Exotech
Terraspace

EXHIBIT 4. SUMMARY OF ORGANIZATIONS AND PROGRAM IN WATER JET DRILLING AND RELATED ACTIVIITES

ORGANIZATIONS	REPORT SECTIONS	NATURE OF PROGRAMS: Deep Drilling—High Pressure	Deep Drilling—Low Pressure	Equipment Development	Mining	Rock Breakage (e.g., Excavation)	Shallow-Hole Drilling	Basic Research	Industrial Cutting or Cleaning	Others	STATUS⁺: Planned	On-Going	Completed	LEVEL OF EFFORT# $ x 10^6	SOURCE OF FUNDS: INTERNAL	GOVERNMENT	EXTERNAL, PRIVATE INDUSTRY	COMMENTS
DOWNHOLE DRILLING PROGRAMS																		
Gulf	3.1.1	X											X	15	X			Featured abrasives (steel shot) in drilling fluid
Exxon	3.1.2, A.2	X		X									X	6	X			Major problems with mud pumps
Shell (Netherlands)	3.1.3, A.3	X		X								X		2 to 4	X			Major field tests planned for 1980
Hughes Tool	3.1.4	X											X	0.40	X			Proprietary, no published information
University of Missouri-Rolla*	3.1.5, 3.3.1	X			(X)	(X)		(X)		(X)		(X)	X	0.35(>1.6)		X		Very active in many different areas of water jet technology
University of Tulsa	3.1.6	X											X	0.085			X	Laboratory simulations of downhole conditions
NMIMT/Univ. of Oklahoma/IPEC	3.1.7	X										X	X	—	X		X	Generally small—scale tests
Flow Industries*	3.1.8, 3.2.2, 3.3.2, A.9	X	X	X		(X)	(X)		(X)		X	(X)	X	0.15(>1.2)		X	X	Plans to develop downhole intensifier
Colorado School of Mines*	3.1.9, 3.3.3	X			(X)	(X)	(X)				X	(X)		0.00(>0.5)		X		Interest in initiating R&D for downhole drilling
Hydronautics/Hycalog/Terra Tek/Smith*	3.2.1, 3.3.15		X		(X)	(X)			(X)	(X)		X	(X)	>0.25(—)	X	X		Cavitating water jets; major field—drilling tests underway
Kobe/Reed	3.2.3		X								X		X	—	X			Patents for downhole intensifier; plans to develop and combine with drill bits
Scire*	3.2.4, 3.3.7		X		(X)		(X)				X	(X)		— (—)		X	X	Plans to develop downhole intensifier
Daedalean*	3.2.5, 3.3.10		X						(X)		X	(X)		— (—)		X		Plans to develop cavitating-jet system for downhole drilling
Scientific Associates	3.2.6, 3.3.11		X		(X)		(X)				X	(X)		—(>0.6)		X		Percussive water jets (high frequency pulses)
Lawrence Livermore Lab.	3.2.7		X										X	0.20		X		Investigation of "far-zone" cutting at reduced pressures
Physics International	3.2.8		X										X	0.05		X		Feasibility study of downhole propellants to create high-velocity jets
Sandia Laboratories	3.2.9		X										X	—		X		Investigation of downhole electric arcs to create high-velocity jets
MUD PUMP, SWIVEL DEVELOPMENT																		
Halliburton	A.1			X									X	—	X			Long-Stroke pumps developed in support of Gulf's WJD program
TRW Mission	A.4			X								X		—			X	Support to Exxon and Shell for high-pressure pump components
U.S. Steel - Oilwell Division	A.5			X								X		—			X	Support to Exxon and Shell for high-pressure pumps
Terra Tek	A.6			X									X	0.055	X	X		High-Pressure pump development
Jet Propulsion Lab	A.7			X									X	0.035	X			Conceptual design and marketing efforts for Long-Stroke pump
Gardner-Denver	A.8			X								X		—	X			Efforts to extend pressure limits of swivels

EXHIBIT 4. (Continued)

ORGANIZATIONS	REPORT SECTIONS	NATURE OF PROGRAMS: Deep Drilling—High Pressure	Deep Drilling—Low Pressure	Equipment Development	Mining	Rock Breakage (e.g., Excavation)	Shallow—Hole Drilling	Basic Research	Industrial Cutting or Cleaning	Others	STATUS+: Planned	On-Going	Completed	LEVEL OF EFFORT# $x10^6	Source of Funds: INTERNAL	GOVERNMENT	EXTERNAL, PRIVATE INDUSTRY	COMMENTS
NON-DOWNHOLE DRILLING PROGRAMS																		
The Robbins Company	3.3.4					X							X	2 M-Y	X	X		Water-jet assisted tunnel boring machine
IIT Research Institute	3.3.5				X	X	X	X				X	X	1.2	X	X	X	Very wide range of activities in water jet R&D
Dresser Industries	3.3.6						X				X			——				Plans relate to drill bits for blast holes
Science Applications (SAI)	3.3.8				X		X					X		0.15	X	X		Patents for blast-hole drill bits; borehole mining of oil shale
USBM	3.3.9				X							X	X	——		X		R&D conducted in-house, and by contractors
University of California, Davis	3.3.12							X				X		——	X	X		Mathematical modeling of water jet rock cutting
TRW	3.3.13				X			X			X		X	0.25		X		Optimized nozzle and flow-inlet design for improved jet coherence
University of California, Los Angeles	3.3.14							X					X	0.09		X		Developed and tested rock-cutting model
Ingersoll-Rand Research	3.3.16				X	X							X	——	X	X		Design study of hydraulic mining, and proprietary R&D
CONOCO	3.3.17				X							X	X	"Many" M-Y	X			Developed nozzle to drill holes in coal seams
IGT/University of Waterloo	3.3.18					X						X	X	0.43			X	Developed and tested pulsed-jet system to break concrete
Oak Ridge National Laboratory	3.3.19					X							X	0.10		X		Small-scale, rock-cutting tests
Georgia Institute of Technology	3.3.20					X						X		0.19		X	X	Development and testing of techniques to quarry granite
Bendix Research Laboratories	3.3.21					X							X	0.13		X		Designed and tested machine for rock excavation
U.S. Army	3.3.22					X			X				X	0.20		X		Cutting of ice and frozen ground
National Research Council (Canada)	3.3.23					X			X			X		0.40		X		Ice and rock-cutting experiments
University os Wisconsin—Milwaukee	3.3.24							X			X		X	0.04		X		Small-scale laboratory tests
McCartney Manufacturing	3.3.25					X		X				X		——	X		X	Manufactures precision-cutting systems; proprietary tests on granite
Gas Research Institute	3.3.26								X		X			——				Plans to support R&D for directional drilling in coal seams
Exotech	3.3.27				X	X		X					X	——	X	X		Development of water cannons and pulsed-jet systems
Terrospace	3.3.28					X							X					Development of water cannons

* All numbers and indicators in ( ) refer to non-downhole-drilling (e.g., mining, etc.) programs conducted by organizations also active in downhole-drilling R&D

\# Level of effort is presented as millions of dollars, unless otherwise indicated. M-Y represents man-years of professional labor.

\+ Multiple status designations (e.g., "planned" and "completed") refer to different programs and activities conducted by an organization.

Hughes Tool also has had a significant R&D program. In addition, the University of Missouri and Flow Industries have also conducted programs related to downhole drilling, although most of their water-jet R&D efforts can be seen to involve the non-downhole drilling applications, such as mining or rock excavation. The consensus of opinion among experts in the above and other organizations is that the most critical deficiency that must be resolved before high-pressure WJD can be implemented commercially is the lack of reliable surface equipment such as mud pumps and swivels.

Only two major downhole-drilling programs are currently on-going or active. Field tests planned by Shell for 1980 will be limited to surface pressures of 5000 to 6000 psi because of the current status of mud pump technology. The joint program being conducted by Hydronautics and NL Hycalog under the sponsorship of DOE's Division of Geothermal Energy features the use of cavitating jets to enhance rock-cutting ability while requiring only conventional surface pressures. Field tests in which Smith Tool will actively participate with Hycalog and Hydronautics are planned for 1980, and laboratory simulations of downhole conditions will be continued at Terra Tek.

Most planned activities related to downhole drilling involve the low-pressure approach to WJD. Techniques under consideration include the use of cavitating jets, pulsed or percussive jets, and intensifiers to increase the pressure of the drilling fluid downhole. The term "intensifier" is commonly used to designate a device employed to increase the pressure of a fluid, as opposed to a "pump" that is used to transport a fluid. Since both an intensifier and a pump generally result in both an increase of fluid pressure and fluid motion, these terms are often used interchangeably. For the purposes of this discussion, relatively compact devices that could be employed to increase drilling-fluid pressures downhole are designated as "intensifiers". Kobe, Flow Industries, and Scire have plans to develop different types of intensifiers for use in downhole drilling.

Organizations active in areas of water-jet technology other than downhole drilling are also presented in Exhibit 4. Water-jet R&D programs conducted by IIT Research Institute, Colorado School of Mines, University of Missouri-Rolla, Flow Industries, Scientific Associates, and Hydronautics are among the most significant of such efforts in the areas of mining, tunneling, rock excavation and industrial cleaning and cutting. Water-jet systems are now employed by industry in a wide variety of applications including the precision cutting of relatively soft materials such as plastics and wood puzzles, and the cleaning of scale and other materials from industrial surfaces. In addition, steeply dipping coal seams have been successfully mined with low-pressure (i.e., less than 2000 psi) water jets in several countries including Russia, China, and Canada. The use of water jets for mining or rock cutting at higher pressures, however, is generally still in the R&D stage.

2.3 OPPORTUNITIES FOR JOINT INDUSTRY/GOVERNMENT R&D

The research findings summarized in Exhibit 4 were reviewed and evaluated to identify potential opportunities for joint R&D programs with industry (or universities and research institutes) in the area of water jet drilling. Several program areas where future government participation in joint R&D efforts appears to be of potential benefit in accelerating the development and commercialization of WJD technology are summarized below in Exhibit 5.

EXHIBIT 5
Summary of Identified Joint
Industry/Government R&D Opportunities

- High-Pressure Program Areas
  - Development of Improved High-Pressure Equipment
    - Mud Pumps
    - Swivels
  - Collection of Additional Drilling Performance Data
  - Systems Analysis of Required Safety Precautions
  - Feasibility Study of Dual-Pipe Systems
- Conventional-Pressure Program Areas
  - Development of Cavitating-Jet Systems
  - Development of Downhole Intensifiers
  - Feasibility Study of Percussive or Pulsed Cavitating-Jet Systems

As was the case in Exhibits 2 and 4, the identified R&D program areas are organized in terms of the pressure requirements of surface equipment. Each of the program areas in Exhibit 5 is discussed briefly in this section, and in more detail in Section 4.

As discussed previously, the results of major field tests conducted by Gulf, Exxon, and Shell clearly demonstrate a need for reliable surface equipment, especially mud pumps and swivels, which are either not commercially available or too costly to operate for commercial drilling at elevated pressures (e.g., above 4000 to 5000 psi). A ready market for mud pumps and swivels capable of operating reliably at pressures up to 10,000 psi or more does not exist. Thus, equipment manufacturers lack incentive to conduct the required development efforts. A potential role for Government, therefore, appears to be indicated to accelerate the development of the required mud pumps and swivels.

Additional data generally appear to be required to reliably predict drilling performance over important ranges of formation depth (or corresponding confining or overburden pressures), nozzle pressure drop, and other variables for several types of rocks and for a variety of drill bit-nozzle configurations. Such data would be valuable for planning and designing large-scale field tests, as well as for use in systems analyses to determine economic feasibility and optimum WJD conditions.

Several experts consider safety problems and their associated costs to be major obstacles to the implementation of high-pressure drilling. In order to address and possibly mitigate the above safety-related perceptions, a systems study focusing on alternative approaches to protecting rig personnel and their overall impacts on drilling costs would be useful.

Dual-pipe systems have been considered by Flow Industries and others. In such systems, a relatively small volume of clean water for rock cutting would be pumped downhole through a high-pressure line, while drilling mud to clean the hole would be pumped through a second line at conventional pressures. Problems associated with high-pressure surface equipment and required safety precautions would be greatly simplified. Difficulties in field assembly and other related problems might, however, preclude the development of dual-pipe systems. In view of their potential advantages, a feasibility study focusing on the possible alleviation of the problems of dual-pipe systems appears to be warranted.

The potential advantages of cavitating-jet systems, downhole intensifiers, and other possible approaches to low or conventional-pressure water jet drilling include the elimination of high-pressure surface equipment and reduced safety concerns. While cavitating-jet systems currently being developed and tested with Government support for hard-rock drilling could be adapted for use in softrock formations, the optimum operating conditions and drill bit-nozzle configurations might be significantly different for geothermal versus oil and gas drilling. Government support for testing cavitating-jet bits in softer rocks might, therefore, accelerate their development for oil and gas drilling.

Several different types of intensifiers to increase drilling-fluid pressures downhole are currently being considered by Flow Industries, Kobe and Scire Corporation. The use of a downhole intensifier would entail several possible design problems, including space limitations in the borehole, the need for remote controls, and erosion due to abrasives in the drilling fluid. Rotary devices under consideration should generally be less sensitive to abrasives or solids in the drilling fluid than piston-type intensifiers.

Another possible approach to enhancing a water jet's ability to cut rocks downhole might utilize intermittent or discontinuous water jets, which have generally been found to cut rock much more effectively than continuous jets at similar pressures. Both percussive (very high frequency) and pulsed (low frequency) jets have been tested for mining and other near-surface applications, but not under downhole conditions.

No attempt has been made to prioritize the above R&D opportunities in terms of benefits and costs, since this was not within the scope of the present investigation. Nevertheless, some general observations concerning possible benefits from government participation in joint R&D programs and potential constraints to the successful development and implementation of WJD technologies are presented above and in Section 4.

3. ORGANIZATIONS, PROGRAMS, AND RELATED ACTIVITES IN WJD

The various water jet drilling (WJD) programs and activities summarized in Exhibit 4 are described briefly below. Organizations and programs oriented towards downhole drilling are discussed in Sections 3.1 and 3.2, whereas water jet activities oriented towards other applications such as mining or rock excavation are discussed in Section 3.3. As discussed in Section 2, the downhole drilling programs have been classified in terms of surface pressure requirements. The high-pressure WJD programs are presented in Section 3.1, while the downhole drilling programs requiring only conventional surface pressures are presented in Section 3.2. Current deficiencies in surface equipment such as mud pumps and swivels required to implement high-pressure drilling and programs to correct such deficiencies are discussed in Appendix A.

The information presented in this report was obtained by means of a thorough literature search and review of pertinent documents, and by telephone conversations with WJD experts in government, industry, research institutes, and universities. The methodology employed in identifying the "key players" in WJD and in obtaining the required program information is described in detail in Appendix B.

The emphasis of this study involves R&D activities in the United States. Most of the organizations discussed, therefore, are located in the United States. The only exceptions are the National Research Council of Canada and the University of Waterloo (in Canada), which participated in joint R&D programs with organizations located in the United States, and Shell Oil Company (in the Netherlands), which is conducting an extensive R&D program that is especially pertinent to this study.

The following information, where available, is presented for each of the organizations engaged in WJD R&D: program description; status/future plans; level of effort/source of funds; and problems/constraints. Pertinent references are listed at the end of each of the following sub-sections to serve as a convenient bibliography for each of the organizations under consideration.

3.1 DOWNHOLE DRILLING - HIGH SURFACE PRESSURES

Organizations employing relatively high surface pressures (i.e., approximately 5000 psi or more at the discharge of the mud pump) in their WJD programs are discussed on the following pages.

3.1.1 Gulf Research and Development Company

Program Description

The Gulf program featured the use of abrasives (steel shot) added to the drilling fluid to increase drilling rates in hard rock in deep formations. Bits with carbide wedges or buttons to crush weakened ridges of rock remaining between grooves cut by the abrasive-laden jets were developed and used in all full-scale testing.

Laboratory testing of the abrasive jet drilling concept began in 1960, with field tests being initiated in 1964. Severe problems with surface-handling equipment to treat the steel shot and rock cuttings in the drilling fluid were experienced in field tests between 1964 to 1969. A full-scale drilling test facility was then established in Bedford, Pennsylvania, to further develop the process and eliminate remaining technical problems. Several holes were drilled at the Bedford facility, with major improvements being made in the reliability of the abrasives-handling system and in pump performance. Drilling rates 7 to 12 times those of conventional bits were achieved during these tests. Most field tests were performed at surface pressures between 10,000 and 15,000 psi.

Status/Future Plans

For reasons discussed below, the program was officially terminated in 1975. Gulf has no plans to resume efforts in WJD R&D. Note that both Halliburton, which developed and provided the high-pressure mud pumps for this program, and Parker Drilling Company, which provided the drilling rigs, have expressed interest to Gulf concerning possible participation in future WJD programs.

Level of Effort/Source of Funds

Total expenditures by Gulf were about $15 million. Halliburton also provided funds for pump development.

Problems/Constraints

Reasons for program termination include the following:

> Unresolved technical problems related to unacceptable life of the swivel packing, equipment for treating the abrasive-laden mud, and development of a satisfactory drilling fluid necessary to suspend the steel shot without making fine solids separation impossible.

While pump performance was generally considered to be satisfactory in the later field tests, additional development to extend the life of pump plungers and packings for commercial use would be required. The development and performance of the mud pumps are discussed in more detail in Appendix A.1.

- Generally "hard times" for petroleum industry, with retrenching by Gulf in drilling R&D.
- Due to results of risk assessment and projected market limitations resulting from high system costs, probability of receiving an acceptable rate of return on additional expenditures needed to eliminate the above technical problems was concluded to be low.
- A fire that destroyed hundreds of thousands of dollars worth of equipment was the program's "coup-de-grace".

REFERENCES

J.C. Fair, "Development of High Pressure Abrasive Jet Drilling", SPE 8442, presented at 54th Annual Fall Technical Conference and Exhibition of SPE of AIME, Las Vegas, Nevada, September 23-26, 1979.

U.S. Patent No. 3,924,698, "Drill Bit and Method of Drilling", Hans C. Juvkam-Wold, December 9, 1975.

U.S. Patent No. 3,838,742, "Drill Bit for Abrasive Jet Drilling", Hans C. Juvkam-Wold, October 1, 1974.

G. Weber, "Gulf's New Abrasion Drill: Is it the Breakthrough?", Oil and Gas Journal, July 26, 1971.

G. Weber and G. L. Farrar, "World Petroleum Congress Reflects Oil's Rapid-Paced Tempo in All Areas", Oil and Gas Journal, June 21, 1971.

G. Weber and G. L. Farrar, "New Gulf Method of Jetted Particle Drilling Promises Speed and Economy", Oil and Gas Journal, June 21, 1971.

3.1.2 Exxon Production Research Company

Program Description

After initiating its WJD program in 1967, Exxon spent approximately five years in collecting threshold-pressure data, designing and testing components, and in conducting field tests. Exxon's original objective was to develop a WJD system for pressures up to 15,000 psi. To accomplish this, Exxon undertook extensive efforts to develop mud pumps, swivels, and other components for high-pressure use. The equipment development, which represented a substantial portion of the overall R&D program, is discussed in Appendix A.2.

A series of seven full-scale field tests prior to 1973 indicated that water jets at pressures up to 15,000 psi could drill two to three times faster than conventional bits in many formations. Roller-cone, drag, and diamond bits were tested at high pressure in the field. Exxon formed a consortium with several other oil companies in 1973 to conduct additional field tests. The other companies shared costs, observed tests in some cases, and reviewed results. In general, though, technical participation by the other companies was quite limited. A series of five field tests was carried out between 1973 and 1975. Both conventional and extended-nozzle roller-cone bits were tested at elevated pressures. Due to problems with mud pumps, most tests were performed at pressures of 6000 psi or lower.

Exxon concluded from the field tests that overall penetration rates with both conventional and extended nozzles were substantially increased at elevated pressures. Limited testing at 10,000 psi resulted in penetration rates about double those at standard pressures. Data at 6000 psi showed that overall increases of 55 to 60 percent in penetration rates are possible. In some cases, the increase in penetration rates was sharply reduced at increasing depths, especially when drilling in sandstone below 7500 feet. This effect of depth was not observed when drilling in shales.

Status/Future Plans

For reasons discussed below, the program was officially terminated in 1977. Exxon currently has no plans for future WJD R&D.

Level of Effort/Source of Funds

Total expenditures by Exxon and the other consortium members was about $6 million, most of which was contributed by Exxon.

Problems/Constraints

The principal problem that caused Exxon to terminate the program involved its unsuccessful attempts to develop a mud pump for high-pressure operation. These attempts are described in Appendix A.2. Another technical problem that remained unresolved related to tool joints. Since o-ring seals are very susceptible to damage in the field, resulting in failure at high pressures, better sealing techniques would be needed for commercial use at high pressures.

Exxon employed special structures to protect rig personnel, which resulted in inefficient drilling operations. A total system concept is needed to protect personnel and still conduct drilling operations efficiently.

REFERENCES

F. H. Deily et al., "A Study of High Pressure Drilling," Transactions of the 1977 International Association of Drilling Contractors, Drilling Technology Conference, New Orleans, LA, March, 1977.

"Drilling Research & Development in the United States," Petroleum Times, Special Feature, pp. 13-16, September 2, 1977.

W. C. Maurer, "Drilling Research to Pay Off by 2000", Petroleum, August, 1977.

F. H. Deily et al., "Fine Wells Test High Pressure Drilling", Oil and Gas Journal, July 4, 1977.

W. Maurer, Technical Paper in Proceedings of the Workshop on the Application of High Pressure Water Jet Cutting Technology, Missouri University, PB-254-316, pp. 51-62, 1975.

J. L. Kennedy, "Oil Firms Join for High Pressure Drilling Tests", Oil and Gas Journal, July 23, 1973.

W. C. Maurer et al., "High Pressure Drilling", Journal of Petroleum Technology, pp. 851-859, July 1973.

W. C. Maurer and J. K. Heilhecker, "Potential of High Pressure Drilling in Exploration", Proceedings of the Southwestern Legal Foundation, Exploration and Economics of the Petroleum Industry, Vol. 11, Bender and Company, 1973.

W. C. Maurer and J. K. Heilhecker, "Hydraulic Jet Drilling", SPE 2434, Preprint, Society of Petroleum Engineers, 1969.

3.1.3 Shell (Koninklijke/Shell Exploratie & Produktie Laboratorium Rijswijk, The Netherlands)

Program Description

Shell's WJD program, including laboratory and field tests, has been conducted in the Netherlands. Shell Oil in Houston has contributed a minor amount of design work and component testing.

While Shell has placed a strong emphasis on laboratory testing and simulation, several field tests have also been carried out. A series of field tests was performed prior to 1974 with a rig designed for pressures up to 5000 psi. The high-pressure jets were incorporated into diamond bits. A technique employing downhole strainers was developed to prevent the nozzles from plugging. The use of strainers for nozzle protection was, in fact, found to be essential. The results of these field tests showed that additional laboratory research was needed to establish design criteria for further bit development. Performance data were then obtained in the laboratory for a wide variety of rocks. Shell's laboratory facilities in the Netherlands permit simulation of downhole drilling conditions with full-size bits and pump pressures up to nearly 15,000 psi. It was found that the increase in drilling rate with bit pressure drop was much lower for impermeable than for permeable rocks.

Full-scale field tests were conducted over a six-week period from November 1976 to January 1977. Roller-cone bits with extended nozzles and diamond bits were tested at pressures up to 5000 psi. The extended-nozzle bits were found to drill approximately twice as fast as lower pressure conventional rotary bits. The high-pressure diamond bits drilled at least 30 percent faster than similar bits at conventional pressures. A 25-percent savings in overall drilling costs resulted from operation at the elevated pressures. The mud pumps employed for the laboratory simulations are discussed in Appendix A.3.

Status/Future Plans

During the past 18 months or so, Shell has been preparing for additional full-scale field tests planned for the second half of 1980 and expected to run for at least one year. Objectives of these tests include the confirmation of previous penetration rates and better estimates of the economics of WJD. The tests will be carried out at approximately 5000 to 6000 psi because of current pump limitations. Based on previous field tests, Shell believes that improvements in drilling performance should be worthwhile at this moderate pressure level.

Level of Effort/Source of Funds

Shell's expenditures are reported to be in the $2 million to $4 million range.*

Problems/Constraints

Shell perceives the major problem to be the maintenance costs for mud pumps at elevated pressures.

REFERENCES

A. J. R. Van Strijp and R. Feenstra, "Higher Pump Pressures Can Reduce Drilling Costs", 1977 Energy Technology Conference, ASME, Houston, Texas, September 1977.

A. C. Pols, "Tests Show Jet Drilling Hard-Rock Potential", Oil & Gas Journal, January 31, 1977.

A. C. Pols, "Rock Type Decides Jetting Economics", Oil & Gas Journal, February 7, 1977.

R. Feenstra et al., "Tests Show Jet Drilling Has Promise", Oil & Gas Journal, July 1, 1974.

U.S. Patent 3,881,561, "Rotary Bit for Hydraulically Drilling Holes Into Underground Formations", A. C. Pols and R. Feenstra, May 6, 1975.

R. Feenstra et al., "Rock Cutting by Jets", Mining Engineering, Vol. 26, No. 6, June 2, 1974.

3.1.4 Hughes Tool Company

Program Description

Hughes Tool investigated the feasibility of high-pressure WJD from 1970 to 1974. As the program was proprietary, no information related to its work was published. While the emphasis of this program related to bit performance, the entire drilling system was also evaluated. Downhole drilling conditions were simulated in Hughes' drilling laboratory. Drilling rates were

* W. J. McDonald et al., "Drilling Technology Assessment and Future Needs", Fifth Annual DOE Symposium on Enhanced Oil and Gas Recovery & Improved Drilling Technology, August 1979.

measured for a variety of bit configurations and downhole conditions. Tests were performed on both pure jet cutting and hybrid bits with jets to augment mechanical cutting. Nozzle pressure drops up to 20,000 psi were considered. While Hughes definitely concluded that the drilling rate is significantly increased at elevated jet velocities and pressures, the program was terminated for reasons discussed below.

Status/Future Plans

This program was terminated during 1974. Hughes has no plans to resume WJD R&D in the future.

In spite of the proprietary nature of this work, Hughes would consider providing DOE with more detailed information if DOE were to "make specific requests for information related to evaluations of proposals, or for some such specific needs."

Level of Effort/Source of Funds

Total funding by Hughes was about $400,000.

Problems/Constraints

Despite the increased drilling rates that Hughes measured at elevated pressures, Hughes concluded that high-pressure WJD is not economically feasible due to high capital costs for equipment, high maintenance costs, and costs related to the elimination of safety problems.

3.1.5 University of Missouri - Rolla

The University of Missouri, under the direction of Professor David A. Summers, has participated in a variety of water jet cutting programs. A program in the area of downhole drilling is discussed below. Other pertinent programs are discussed in Section 3.3.1.

Program Description

The University of Missouri initiated a program involving the downhole drilling of relatively hard rocks in 1975. Tests were conducted with both pure jets and hybrid water jet/roller-cone bits. A dual orifice nozzle with one orifice at the center and another inclined towards the outer edge of the bit was developed and patented in the early stages of the program. Tests were performed both in the laboratory, under downhole-simulated conditions, and in the field. The hybrid jet/roller-cone tests demonstrated that the high-pressure jets are most effective when located on the outside of the bit. A variety of jet orientations were considered. Typical test conditions included pressures of 10,000 psi and water flow rates of 25 gpm.

Status/Future Plans

Program was most active during the 1978-78 period, and was terminated during the summer of 1979. While the University of Missouri has no specific plans for future downhole drilling work, Professor Summers has found "a growing level of interest and activity" in WJD by private companies.

Level of Effort/Source of Funds

This program was initially funded by ERDA, and subsequently by DOE/Division of Geothermal Energy under contract to Sandia Laboratories. Total funding was about $450,000.

Problems/Constraints

Professor Summers considers the lack of a reliable swivel to be a major problem. Although he has experienced satisfactory swivel performance under well-controlled conditions in the laboratory, the reliability of swivels in the field has been inadequate.

REFERENCES

S. G. Varnado, Editor, "Geothermal Drilling and Completion Technology", Monthly Progress Report, Sandia Laboratories, July 1979.

S. G. Varnado, Editor, "Geothermal Drilling and Completion Technology Development Programs", Semi-Annual Progress Report, October 1978-March 1979, SAND 79-1499, September 1979.

D. A. Summers et al., U.S. Patent No. 4, 119, 160, "Method and Apparatus for Water Jet Drilling of Rock", October 10, 1978.

D. A. Summers et al., "Water Jet Drilling in Sandstone and Granite", Proceedings of the 18th Symposium on Rock Mechanics, Colorado School of Mines, June 1977.

3.1.6 University of Tulsa

Program Description

The University of Tulsa conducted relatively small-scale tests to determine the effects of confining (i.e., overburden) pressure on the effectiveness of high-pressure water jets for rock cutting. A triaxial, high-pressure cell was employed to simulate downhole conditions in the drilling research laboratory of the university. Tests were carried out with samples of limestone rock and with both tap and salt water as the drilling fluid. All experiments were of the single-nozzle type, with no augmentation by mechanical cutting. The maximum nozzle pressure drop employed in this program was 8,200 psi. Water flow rates were typically around 40 gpm.

The limited data collected in this program indicated that confining or overburden pressure can significantly reduce the effectiveness of water jets. Threshold pressures were also measured for the limestone samples.

It should also be noted that proprietary tests were performed on cavitating nozzles for Hydronautics and NL Hycalog (see Section 3.2.1).

Status/Future Plans

The program was terminated during 1975 because the level of research had reached the limits of the available high-pressure equipment. Funds were not available to extend the high-pressure capability of the research facilities.

There are currently no plans to resume WJD research. All personnel involved in the WJD tests have since left the university.

Level of Effort/Source of Funds

The total program funding of about $85,000 was obtained from university research grants provided by a group of oil companies on a cooperative basis.

Problems/Constraints

The high-pressure capability of the available equipment was limited, as discussed above.

REFERENCES

J. F. Melaugh, "The Effect of Confining Pressure on the Jet Erosion Cutting of Rock", M.S. Thesis, University of Tulsa, 1972.

J. F. Melaugh and B. J. Livesay, "Confining Pressure Affects Jet-Erosion Drilling Rates", Oil & Gas Journal, November 10, 1975.

3.1.7 NMIMT/University of Oklahoma/IPEC

WJD programs have been carried out by A.A. Sheshtawy at the New Mexico Institute of Mining and Technology (NMIMT), the University of Oklahoma, and International Petroleum Engineering Corp. (IPEC). The programs at these three organizations have been grouped since they effectively represent a continuous effort by Sheshtawy.

Program Description

Sheshtawy initially conducted WJD R&D at NMIMT in 1974 for an M.S. Thesis, and later directed research there as an Assistant Professor in 1975-76. This research was generally carried out with relatively small-scale laboratory equipment. A test cell was used to simulate bottom-hole depths to 10,000 ft. Rock cutting was performed by a single rotating nozzle with pressure drops up to 15,000 psi. In addition, a novel drill bit (IPEC Trademark, Tri-Max) with the shape of an inverted cone was developed and patented. Although this bit was reportedly designed as a hybrid high-pressure-jet/mechanical cutting device, it is currently used at conventional pressures only due to the lack of required high-pressure surface equipment, as discussed in Appendix A.

Status/Future Plans

The research program at NMIMT was terminated in 1976 when Sheshtawy left the Institute. Research at the University of Oklahoma was terminated prior to January 1980, when Sheshtawy left the university. There are currently no plans to resume WJD R&D at NMIMT or the University of Oklahoma.

Current activities at IPEC are proprietary. However, Sheshtawy indicated he is still active in WJD R&D at IPEC, with emphasis on hardware development, and has two active patent applications in the area of WJD.

Level of Effort/Source of Funds

Support at NMIMT was obtained from university grants. Research at the University of Oklahoma was sponsored by several oil companies on a cooperative basis.

REFERENCES

A. A. Sheshtawy, "Advanced Drill Bit Designed for Minimum Cost Drilling", SPE 7751, presented at Middle East Oil Technical Conference of SPE, Bahrain, March 25-29, 1979.

A. A. Sheshtawy et al., "Applicability of High Pressure Fluid Jet to Oil Well Drilling", Proceedings of the 18th Symposium on Rock Mechanics, Colorado School of Mines, June 1977.

U.S. Patent No. 3,915,246, "Rotary Drilling Bit", by A. A. Sheshtawy, October 28, 1975.

3.1.8 Flow Industries

Flow Industries has participated in a variety of water jet cutting programs. A program involving high-pressure WJD is discussed below. Other pertinent programs and activities are discussed in Sections 3.2.2 and 3.3.2 and Appendix A.9.

Program Description

A two-phase study was conducted to evaluate the use of high-pressure water jets for coring and drilling in hard rock formations. The first phase consisted of a conceptual design and system feasibility study. A laboratory-scale coring bit was developed and tested under simulated downhole conditions during the second phase. While the study was oriented towards core cutting with high pressure jets, the techniques considered would generally be applicable to water jet drilling of boreholes, as well.

The basic concept considered in detail in this program involved the use of a dual-pipe system in which only one pipe would be at high pressure. A relatively small volume of water would be passed through the high-pressure pipe for use in rock cutting. Drilling mud at standard pressures would be passed through the second pipe for use in cleaning the hole bottom. A significant advantage of such a system would be the relative simplicity of the high-pressure surface equipment.

Status/Future Plans

The program was terminated during the spring of 1978. There are no current plans to resume work on the dual-pipe concept.

Level of Effort/Source of Funds

Total funding of $150,000 was provided by DOE/Division of Geothermal Energy.

Problems/Constraints

The major problem of the dual-pipe concept concerns expected resistance by industry to implement such a system. A dual-pipe system would generally be more difficult to assemble and disassemble than a standard drill string. In addition, better sealing techniques than are presently available would be required to isolate the two pipes from each other downhole.

REFERENCES

J. M. Reichman, "Research and Development of a High Pressure Water Jet Coring Device for Geothermal Exploration and Drilling", Final Report, Flow Technology Report No. 106, prepared by Flow Industries for DOE, January 1978.

J. M. Reichman and J. B. Cheung, "Feasibility of Water Jet Coring", Task I Report, TID-28700, July 1976.

3.1.9 Colorado School of Mines

The Colorado School of Mines has conducted a number of water jet R&D programs under the direction of Professor Fun den Wang, none of which specifically involves the downhole drilling application. These programs are discussed in Section 3.3.3.

Description of Activities

Confidential discussions are currently being held between the Colorado School of Mines and several private companies concerning possible research programs involving downhole drilling with water jets. These discussions appear to involve the use of a dual-pipe system similar to that discussed in Section 3.1.8 with regard to Flow Industries. Professor Wang previously discussed his ideas concerning a dual-pipe system with technical staff of DOE's Division of Fossil Fuel Extraction.

3.2 DOWNHOLE DRILLING - CONVENTIONAL SURFACE PRESSURES

Research and development programs employing downhole techniques such as cavitation-inducing nozzles or pressure intensifiers to enhance rock cutting and increase drilling rates while requiring only conventional surface pressures are described below.

3.2.1 Hydronautics/NL Hycalog/Terra Tek/Smith Tool

Hydronautics, NL Hycalog, Terra Tek, and Smith Tool are involved in a variety of interrelated activities involving the use of cavitating jets. Since all of these activities involve the development of the CAVIJET (trademark of a cavitation-inducing nozzle developed and patented by Hydronautics) for use in downhole drilling, they will be considered as a single program for purposes of this discussion. These activities are being carried out with DOE funds as part of Sandia Laboratories' Geothermal Drilling and Completion Technology Development Program.

The CAVIJET produces a turbulent jet that promotes the nucleation of vapor and gas bubbles near the nozzle orifice and encourages growth of the bubbles in the jet streams. By proper adjustment of the standoff distance, the bubbles can be made to collapse at the rock face. The erosive power of the low velocity jet is then enhanced by the high impact pressures caused by the collapse of the bubbles.

Program Description

The first phase of a program to demonstrate the feasibility of CAVIJETS for drilling in hard-rock, geothermal formations was recently completed. Single-nozzle, small-scale tests were generally performed at Hydronautics' test facility, whereas larger-scale downhole simulations were conducted at Terra Tek's Drilling Research Laboratory. Hycalog participated in a cost-sharing arrangement with Sandia, providing drill bits hardware, and engineering to the joint effort. The effects of high ambient downhole pressures and drilling muds on rock cutting were studied in these tests. The performance of roller-cone bits modified to incorporate CAVIJET nozzles was compared to that of standard roller-cone bits. Results are reported to be very encouraging with drilling rates being increased by up to 40 percent. In addition to the laboratory simulations, field tests have also been initiated.

Status/Future Plans

The Phase I feasibility study was initiated in January 1978, and completed in September 1979. Phase II studies, also under Government support, are being initiated to optimize drilling parameters for relatively hard rocks.

Plans for the next year include 12 to 14 days of testing at Terra Tek, with 8 days involving hard-rock tests and the balance oriented towards tests with softer rocks typical of oil and gas drilling. Hydronautics and Hycalog would like to perform more intensive soft-rock testing, which is funded internally, but are limited by available budgets. The planned laboratory simulations will include the following types of bits modified to contain CAVIJET nozzles: two-cone, extended-nozzle bits; tri-cones with extended nozzles; Stratapax bits; and natural diamond drill bits.

In addition to the planned laboratory simulations, field tests will also be conducted. Smith Tool has recently signed a contract for a joint field program with Hydronautics and Hycalog. Smith's extended-nozzle bits will be combined with CAVIJET nozzles and tested. Whereas Smith simply provided bits and conventional nozzles for previous tests, it will actively participate in this program to develop an optimum bit design. Hycalog plans to publish a paper next October that will be the first public disclosure of the results of the field tests, which are now underway.

Hycalog and Hydronautics also plan to hold discussions with several other bit companies (Reed, Dresser, Hughes and others) with regard to their possible participation in CAVIJET tests with various types of bits.

Level of Effort/Source of Funds

Funding of $250,000 for the Phase I feasibility study was provided by DOE/Division of Geothermal Energy under contract to Sandia. In-house funds were also provided. With regard to the planned Phase II simulations, the hard-rock tests will be supported by DOE, under contract to Sandia, whereas the soft-rock tests will be funded internally by Hydronautics and Hycalog.

All field tests will be funded internally without Government support.

Problems/Constraints

Space limitations complicate the replacement of standard nozzles with CAVIJET nozzles in certain types of bits, especially tri-cones. In some cases, nozzle sizes may have to be reduced, with the effects on performance not yet known.

REFERENCES

A. F. Conn and R. P. Radtke, "CAVIJET Cavitating Jets for Deep-Hole Rock Cutting," Presented at the Energy Technology Conference and Exhibition, ASME, New Orleans, Louisiana, February 3-7, 1980.

A. F. Conn et al., "The Fluid Dynamics of Submerged Cavitating Jet Cutting," Preprint from the Fifth International Symposium on Jet Cutting Technology, BHRA, to be held June 2-4, 1980.

A. F. Conn and R. P. Radtke, "Elevated Ambient Pressure Effects on Rock Cutting by Cavitating Fluid Jets," Proceedings of the Fifth International Conference on Erosion by Solid and Liquid Impact, pp. 68-1 through 68-8, 1979.

A. F. Conn and R. P. Radtke, "Rock Cutting with Cavitating Jets under Simulated Deep-Hole Conditions," Geothermal Resources Council, Transactions, Vol. 3, September 1979.

A. F. Conn and R. P. Radtke, "Evaluation of Cavitating Jets for Increased Geothermal Drilling Rates," Geothermal Resources Council Transactions, Vol. 2, pp. 113-114, July 1978.

A. F. Conn and R. P. Radtke, "CAVIJET Augmented Deep-Hole Drilling Bits," Trans ASME, Journal of Pressure Vessel Technology, Vol. 100, pp. 52-59, February 1978.

A. F. Conn and R. P. Radtke, "Cavitating Bit Jets Promise Faster Drilling for Deep-Hole Operations," Oil & Gas Journal, October 31, 1977.

3.2.2 Flow Industries

Program Description

The feasibility of using a downhole intensifier for core cutting with high pressure jets was considered under the program described in Section 3.1.8. Various combinations of different fluids were considered for hydraulically powering the intensifier and for drilling. It was concluded that the ideal system would use standard muds for both powering the intensifier and for drilling, but that abrasives in drilling muds would make the development of such a system difficult. Flow Industries has developed a commercial line of intensifiers to produce low-flow water jets at pressures up to 60,000 psi for use in cutting a wide variety of industrial materials such as shoe leather and plastics.

A major advantage of a downhole intensifier is the elimination of any need for high-pressure surface equipment, since the high pressures required for rock cutting would be generated downhole. In addition, a downhole intensifier would be more readily accepted by industry than the dual pipe system described in Section 3.1.8, since it would require no novel field assembly techniques.

Status/Future Plans

Flow Industries has been holding discussions and negotiating with several different organizations including the Gas Research Institute (Section 3.3.26) and some oil companies with regard to an R&D program for downhole piston-type intensifiers. The objective is to test the intensifiers under downhole conditions.

Problems/Constraints

The use of a downhole intensifier would entail several possible problems, including space limitations in the borehole, the need for remote controls, and erosion due to abrasives in the drilling fluid. Flow Industries' existing line of intensifiers would have to be redesigned to withstand elevated downhole temperatures, as well as the drilling fluids. Flow believes a downhole intensifier could be developed in three to four years, but considers the effort too costly to be carried out with only in-house funds.

3.2.3 Kobe/Reed

Description of Activities

Kobe, Inc. has been developing axial-flow turbo-pumps for several years to increase oil production from a well by increasing the oil pressure at the bottom of the hole. Field tests of these pumps were conducted for several months, and they have recently entered the marketplace for well production. While the turbo-pumps have not been tested specifically for downhole drilling, Kobe believes they are applicable for use as downhole intensifiers to generate the high pressures required for jet erosion drilling.

Kobe has obtained patents for a multistage, downhole, turbo-powered intensifier for use in WJD, which is very similar to the device employed for well production. A centrifugal cleaner to remove particles from the drilling fluid is incorporated as an integral part of the intensifier design. This cleaner is located upstream of the turbo-pump, thereby reducing erosion of the turbine blades. The intensifier system contains turbines powered by the cleansed drilling fluid, with the turbine shaft power then being used to drive rotary pumps. Several stages of the turbines and pumps can be employed to achieve the desired drilling fluid pressures. The intensifier unit is located downhole directly above the drill bit. The last pump stage, therefore, exhausts the high pressure drilling fluid to the bit nozzles to produce high velocity jets.

Kobe believes that the maximum downhole pressure will be much higher for the above turbo-pump, than for piston-type intensifiers, since "the pressure is limited only by the number of pump stages." In addition, abrasives would probably be less troublesome in the downhole turbo-pump than in a piston-type intensifier, due to the latter's very close clearances.

Status/Future Plans

As indicated above, the turbo pump and associated centrifugal cleaner have been patented by Kobe for downhole drilling applications.

Kobe has held "active discussions" with Reed Tool about a possible joint program to combine the Kobe downhole intensifier with Reed's drill bits, but there are no "concrete plans" for such a program. Field tests of the downhole turbo-pump for drilling are probably "at least two years away," since Kobe is devoting its resources to producing the turbo-pump for well production.

Level of Effort/Source of Funds

All pertinent R&D has been conducted with in-house funds.

REFERENCES

J. W. Erickson, Kobe, Inc., U.S. Patent No. 4,103,749, "Downhole Cleaner Assembly for Petroleum Wells," August 1, 1978.

J. W. Erickson, Kobe, Inc., U.S. Patent No. 4,047,581, "Multi-State, Downhole, Turbo-Powered Intensifier for Drilling Petroleum Wells," September 13, 1977.

H. Petrie and J. W. Erickson, "Field Testing the Turbo-Powered Intensifier for Drilling Petroleum Wells," September 13, 1977.

H. Petrie and J. W. Erickson, "Field Testing the Turbo-Lift™ Production System," SPE 8245, Presented at the 54th Annual Fall Technical Conference and Exhibition of SPE, Las Vegas, Nevada, September 23-26, 1979.

Francis Barton Brown, Kobe, Inc., U.S. Patent No. 3,847,512, "Free Turbine Pump," November 19, 1974.

3.2.4 Scire Corporation

In addition to its non-downhole programs described in Section 3.3.7, Scire is currently involved in the development of an intensifier for increasing the pressure of drilling fluids downhole.

Program Description

Scire's objective is to develop a prototype downhole intensifier with a capability of increasing the pressure of a drilling fluid to 60,000 psi. The basic concept is to utilize a "high speed, rotary device," rather than the more conventional piston-type intensifier, such as that under consideration by Flow Industries (see Section 3.2.2). Scire believes that the small volume flow per revolution at high speeds would result in many advantages, including reduced bearing loads.

In addition, the rotary design would eliminate the need for troublesome packing, mechanical seals, and valves, which often cause problems in piston-type intensifiers.

Status/Future Plans

Scire has submitted a proposal to an industrial firm for developing the downhole, rotary-type intensifier for the drilling of blast holes. Scire "has not had a chance" to pursue possible activities related to deep-downhole use of this device, but believes it would be suitable for such applications.

3.2.5 Daedalean Associates, Inc.

Daedalean Associates is involved in a variety of activities that center around the use of cavitating water jets for cleaning and cutting difficult materials. In addition to these activities, which are described in Section 3.3.10, Daedalean is also interested in the possible utilization of cavitating jets for downhole drilling.

Program Description

Daedalean recently prepared a proposal involving the use of pure cavitating jets for downhole drilling without any augmentation by mechanical cutting devices. The approach is generally designed to minimize fluid flow requirements in a high-pressure cutting operation. Other details were not available.

Daedalean's cavitating jet activities (see Section 3.3.10) generally feature low flows of 2.5 gpm or less and pressures up to 10,000 psi or more, as compared to the generally higher flows and lower pressures used in Hydronautics' cavitating jet programs (see Section 3.2.1).

Status/Future Plans

The proposal discussed above was submitted to the Applied Technology Development Branch of DOE during January 1980. Daedalean's interest apparently involves the use of cavitating jets for drilling in geothermal formations and in fossil fuel extraction.

3.2.6 Scientific Associates, Inc.

Scientific Associates has been involved for nearly ten years in the development of percussive water jets to enhance rock cutting effectiveness at reduced pressures. The term "percussive" jet is used by Scientific Associates to describe a jet that strikes a target in the form of a high-frequency, short-duration series of impacts, rather than as a continuous liquid stream. By use of a rotating, variable-area valve or "modulator" just upstream of the nozzle, small pressure perturbations can be created in the jet stream. A discontinuous jet consisting of discrete liquid slugs is thereby produced. The "waterhammer effect" produced by these high-frequency (2,000 to 20,000 slugs per second) impacts enhances rock fracturing and erosion.

The major programs conducted by Scientific Associates have employed percussive jets for cutting in air, not under downhole drilling conditions. These programs are described in Section 3.3.11. Activities related to the downhole use of percussive jets are discussed below.

Description of Activities

While Scientific Associates has not conducted any tests specifically oriented towards downhole drilling, it has conducted some limited in-house experiments under submerged (i.e., underwater) conditions at atmospheric pressure. Percussive jets were generally effective under submerged conditions, with cutting ability being very sensitive to standoff distance.

Status/Future Plans

Scientific Associates believes that percussive jets would be effective under downhole conditions at high pressure, and is interested in pursuing work in this area. Although the downhole application has been "considered" for several years, no formal proposals have been prepared due to a lack of outside interest. Discussions were held with DOE's Division of Geothermal Energy several years ago concerning the possible use of percussive jets downhole. In addition, a major oil company has recently expressed interest in this subject.

Problems/Constraints

The control and reliability of modulating devices appear to be potential problems in utilizing percussive jets under downhole drilling conditions.

3.2.7 Lawrence Livermore Laboratory

Program Description

Lawrence Livermore Laboratory (LLL) conducted a program to determine the effects of nozzle shape and flow conditions on the ability of water jets to cut rock. During this investigation, LLL detected a "far zone" at a downstream distance of 300 nozzle diameters, where jet erosion potential appeared to reach a second peak. In general, threshold pressures for cutting in this far zone were found to be only 10 to 25 percent of those in the near zone (e.g., up to 20 nozzle diameters downstream from the nozzle). While the reason for this behavior was not determined during this program, a likely explanation appears to involve the physical breakdown of the jet into discrete droplets in the far zone. As discussed previously, repeated pressure pulses due to impacts of droplets on a rock face result in enhanced jet cutting.

The above tests were conducted in air, whereas downhole drilling obviously is carried out with the bit submerged in drilling fluid at high pressures. Since jet momentum dissipates rapidly in a liquid, the above far zone effect is not experienced under submerged conditions. However, in conducting tests with submerged jets, LLL was able to achieve reduced threshold pressures in the far zone by employing a shroud or duct around the nozzle that extended nearly to the rock surface. As a result, LLL speculated that the use of large standoff distances with a shrouded jet might reduce pressure requirements for effective downhole drilling. In the latter stages of its program, LLL assembled equipment to test shrouded jets under simulated deep downhole (to 15,000 ft.) conditions.

Status/Future Plans

This program was initiated in 1974 and terminated around 1977 due to a lack of funds to continue work. The planned tests to simulate downhole conditions were never carried out. Much of the assembled equipment is apparently still in-place.

Since drilling is not within the mainstream of its activities, LLL has no plans for future R&D in the water jet area. The above program was originally initiated with the hope of attracting outside funds, but this was not accomplished.

Level of Effort/Source of Funds

About $200,000 of in-house LLL funds was spent.

Problems/Constraints

While threshold pressures required to initiate rock cutting are greatly reduced in the far zone, LLL also found that jets cut rock much more slowly in the far zone than at distances closer to the nozzle, as long as the threshold pressure is exceeded in the near zone. The potential use of far zone cutting to increase downhole drilling rates would appear, therefore, to be limited to relatively hard rocks with high threshold pressures.

REFERENCES

E. A. Platt, "Fluid Jets, Enhanced Cutting in the Far Zone at Lower Pressures," Energy and Technology Review, Lawrence Livermore Laboratory, UCRL - 5200-75-11, November 1975.

3.2.8 Physics International Company

Program Description

Physics International conducted a conceptual design and feasibility study of a novel WJD system. The basic approach investigated in this study involved the use of downhole propellants to create high-pressure pulses and high-velocity jets. In this approach, propellant capsules would be inserted into the drilling fluid at specified time intervals and carried downhole. The capsules would then be ignited near the bottom of the hole, thereby creating the high-pressure pulses. Ignition of the propellant would be accomplished by use of a material (e.g., lithium aluminum hydride) that is hypergolic with water. An ignition canister would be pierced by a stainless steel spike in the combustion chamber, thereby exposing the hypergolic material to water in the drilling fluid. The resulting hot flash would then initiate the combustion process. The system evaluated in this study consisted of a hybrid bit using jet erosion to cut grooves in the rock and a conventional rotary device to mechanically crush the remaining ridges. The study concluded that this system would be economically attractive under certain drilling conditions.

Status/Future Plans

Program was completed in 1977. Physics International has no plans for future work related to this concept or WJD in general.

Level of Effort/Future Plans

Funding of $50,000 was provided by DOE/Division of Geothermal Energy.

Problems/Constraints

Program was terminated without any "follow-on" study to test the system experimentally since DOE concluded that the concept was not practical.

REFERENCES

"A Feasibility Study of a Hybrid Erosion Drilling Concept," prepared by Physics International Company for the U.S. DOE, Geothermal Energy, TID-28699, June 1977.

3.2.9 Sandia Laboratories

In addition to managing several of the WJD programs described elsewhere in Section 3, Sandia also conducted an in-house R&D program in the area of WJD, as described below.

Program Description

Sandia conducted a theoretical and experimental investigation into the possible use of electric arcs to create high-velocity liquid jets downhole. In this concept, the drill bit would consist of a downhole electric spark generator. The spark discharges would create high-pressure shockwaves in the drilling fluid, thereby producing the high-velocity jets. Theoretical analyses and rock-cutting experiments were performed.

Status/Future Plans

Program was terminated at the end of 1977. Sandia currently has no plans to resume R&D related to the above concept.

Problems/Constraints

The principal technical problems involved generation of the arc discharges. Rather complex equipment is required for this technique. In general, the concept was concluded to be impractical.

REFERENCES

G. F. Huff and A. L. McFall, "Investigation Into the Effects of an Arc Discharge on a High Velocity Liquid Jet," SAND 77-1135C, August 1977.

A. Narath, "Advanced Drilling Technology," Geothermal Energy Magazine, June 1975.

3.3 MINING, ROCK EXCAVATION, AND OTHER WATER JET APPLICATIONS

As discussed in Section 2, many organizations have conducted R&D programs directed at a wide variety of possible applications of water jets. Such applications include mining, rock excavation, tunneling, ice breakage, and the cutting and cleaning of many different materials by means of water jets. Organizations involved in these "non-downhole-drilling" R&D programs are discussed briefly on the following pages.

3.3.1 University of Missouri - Rolla (UMR)

In addition to the downhole drilling program described in Section 3.1.5, the University of Missouri has also conducted a number of programs involving the cutting of a variety of materials with water jets. The most significant programs are discussed below.

3.3.1.1 Program to Drill Long Horizontal Holes in Coal

Program Description

This program involves the drilling of long horizontal holes in coal seams for the purpose of methane drainage or the linking of wells for underground gasification. The general approach is to drill a vertical hole by conventional means, make a 90° turn, and then drill horizontally with pure water jets. Operation is typically at a pressure of 10,000 psi with a water flow rate of 25 gpm.

Status/Future Plans

A feasibility study was completed by UMR in 1978. As a result of this study, Sandia Laboratories has contracted with DOE's Morgantown Energy Technology Center (METC) to develop the system. Sandia, the principal investigator, has awarded a subcontract to UMR to develop the water-jet drilling head. The ultimate objective is to drill a 1,000-ft long hole with an 8-in. diameter.

Level of Effort/Source of Funds

Funding of $120,000 for the feasibility study was provided to UMR by DOE/METC under contract to Sandia. Total funding to Sandia for the development phase is $700,000, with $180,000 subcontracted to UMR.

3.3.1.2 Underreaming Program

This program involves the underreaming or widening of an existing hole by means of water jets. Program objectives include the enlargement of holes from a 9-in. to a 6-ft diameter over a 200-ft length at a depth of 6,000-ft.

A test procedure is being developed within this program to measure a rock's resistance to cavitating jets and to better understand mechanisms of rock failure.

Status/Future Plans

A feasibility study for a water-jet underreaming device was initiated in February 1979 and completed in April 1980. Results of this study are currently being reviewed.

Level of Effort/Source of Funds

Funding of $120,000 was provided by DOE/Division of Geothermal Energy under contract to Sandia Laboratories.

3.3.1.3 Longwall Coal-Cutting Program

A jet-augmented longwall coal-cutting machine was developed. A prototype "Hydrominer", which is similar to a jet-augmented plow, was built and field tested. Typical pressures and flow rates are 10,000 psi and 45 gpm, respectively.

Status/Future Plans

Program was active between 1973 and 1978, and has generally been inactive since 1978. Program has not been officially terminated, however.

Level of Effort/Source of Funds

Total funding by the U.S. Bureau of Mines and DOE/Division of Fossil Fuel Extraction is approximately $750,000.

REFERENCES

In addition to the references presented in Section 3.1.5, the following references are pertinent to the programs discussed in this section:

D. A. Summers, "The Use of High Pressure Water Jets in the Mining Industry", Colliery Guardian International, pp. 40-48, October 1978.

C. R. Barker et al., "Considerations in the Development of a Water Jet Cutting Head", Proceedings of the 18th U.S. Symposium on Rock Mechanics, Colorado School of Mines, June 1977.

D. A. Summers, "Recent Advances in Water Jet Coal Mining", Colliery Guardian, September 1979.

D. A. Summers et al., "The Effect of Stress on Water Jet Performance, "Symposium on Rock Mechanics, Lake Tahoe, Nevada, May 1978.

3.3.2 Flow Industries

Flow Industries has conducted many different R&D programs involving the use of water jets for mining and rock cutting. Two on-going programs are described below. Other recent programs involved the hydraulic borehole mining of uranium ores and the use of water jets to augment mechanical cutting devices on tunnel boring machines. In addition, Flow Industries is commercially producing high-pressure water jet systems for cutting a wide variety of industrial materials such as shoe leather and plastics. These systems typically employ pressures of 60,000 psi and very low water flow rates.

3.3.2.1 Program to Drill Roof Bolt Holes

Program Description

This program involves the drilling of small diameter holes in mines for roof stabilization. Such holes are typically 1 inch in diameter and 6 ft deep. Typical conditions include pressures of 15,000 psi and water flows of 10 gpm. Extensive laboratory testing was performed in an earlier phase of the program. Equipment testing and prototype design are to be carried out.

Status/Future Plans

Program is scheduled for completion around June 1981.

Level of Effort/Source of Funds

Program was initially funded by the U.S. Bureau of Mines, and subsequently by DOE/Division of Fossil Fuel Extraction. Total funding is approximately $800,000.

3.3.2.2 Near-Surface Directional Drilling Program

The objective of this program is to develop and test prototype equipment for drilling holes for burying transmission cables several feet underground. The design condition for directional control is to hit a 2-ft-diameter target with a 1000-foot-long hole. Components are currently being evaluated. Water jets will be used to assist an air-driven impactor hammer in drilling relatively hard rocks and soils.

Status/Future Plans

Program is scheduled for completion by mid-1981.

Level of Effort/Source of Funds

Funding by the Electric Power Research Institute is $400,000.

REFERENCES

In addition to the references presented in Section 3.1.8, the following references are pertinent to Flow Industry's programs discussed in this section.

S. D. Veenhuizen, J. B. Cheung, and J. R. M. Hill, "Water Jet Drilling of Small Diameter Holes", Fourth International Symposium on Jet Cutting Technology, Paper C3 BHRA, April 12-14, 1978.

J. M. Reichman and J. B. Cheung, "An Oscillating Waterjet Deep-Kerfing Technique", International Journal of Rock Mechanics, Mineral Science and Geomechanical Abstracts, Vol. 15, No. 4, pp. 135-144, August 1978.

3.3.3 Colorado School of Mines

The Colorado School of Mines has conducted a variety of programs in the area of water-jet R&D since 1973. Two on-going programs are discussed below. Other previous programs include water-jet slotting experiments related to quarrying and the drilling of blast holes in hard rock.

3.3.3.1 Program to Drill Roof Bolt Holes

Program Description

A high-speed rotary drag bit augmented by high-pressure water jets was designed, fabricated, and tested for drilling small diameter (e.g., 3/4-in) holes several feet deep. Drilling tests have been conducted in several different types of soft and hard rocks. Typical water pressures and flow rates are 20,000 to 40,000 psi and 1 gpm.

Status/Future Plans

Program is scheduled for completion during May 1980.

Level of Effort/Source of Funds

Total funding of $300,000 was initially provided by the U.S. Bureau of Mines, and subsequently by the DOE/Division of Fossil Fuel Extraction.

3.3.3.2 Tunnel Boring Machine Evaluation

Program Description

The feasibility of tunnel boring machines (TBM) with mechanical cutters augmented by high-pressure water jets is being determined. This program involves rock cutting to open large diameter holes for tunneling and mine-entry development. Laboratory simulations of TBM's are being used to collect data.

A similar study was previously conducted by the Colorado School of Mines together with Flow Industries and the Robbins Co. This program is discussed in the following section.

Status/Future Plans

Program is on-going.

Level of Effort/Source of Funds

Funding of $250,000 is being provided by DOE/Division of Fossil Fuel Extraction.

REFERENCES

G. Zink, Fun den Wang, and J. R. M. Hill, "Augmentation of Small-Hole Rock Drilling With Water Jets," Preprint No. 78-AV-93, presented at the 1978 AIME Annual Meeting, Denver, CO, February 28 through March 2, 1978.

Fun den Wang, Technical Paper, pp. 148-170, Proceedings of the Workshop on the Application of High Pressure Water Jets Cutting Technology, Missouri University - Rolla, PB-254, 316, 1975.

3.3.4 The Robbins Company

Program Description

Robbins conducted a joint program with Flow Industries and the Colorado School of Mines to design, fabricate and test a water-jet assisted tunnel boring machine (TBM) to open holes up to 20 ft in diameter. Flow Industries provided the water jet system, the Colorado School of Mines carried out supporting laboratory tests of high-pressure water jets to augment mechanical disk cutters, and the Robbins Company supplied the TBM and the cutting face for the tests. A full-scale water-jet assisted TBM was field tested at a granite quarry. Optimum water pressures and flows were estimated to be 30,000 to 40,000 psi and 10 to 30 gpm.

Status/Future Plans

This one-year program was completed during January 1976. For reasons described below, Robbins has no plans for future R&D in this area.

Level of Effort/Source of Funds

Support was provided by the U.S. Bureau of Mines, the National Science Foundation, and the U.S. Department of Transportation. In-house funds were also provided by the Robbins Company. In addition to the equipment, Robbins contributed about 2 man-years of engineering.

Problems/Constraints

Since this program was completed, Robbins has developed a heavy-duty mechanical cutter that penetrates rock faster than the chips can be removed from the rock face. Thus, Robbins sees no need for water jets to assist its heavy-duty line of machines. Robbins suggested that the use of water jets to assist mechanical cutters might be useful with relatively lightweight, low-thrust, pick cutters.

REFERENCES

Fun den Wang, R. Robbins, and J. Olsen, "Water Jet Assisted Tunnel Boring", Third International Symposium on Jet Cutting Technology, BHRA, Paper E6, May 11-13, 1976.

R. Robbins, "Big-Hole Drilling, Raise-Boring and Tunneling", Background Papers for a Drilling Technology Workshop, PB-253-378, June 1975.

3.3.5 IIT Research Institute (IITRI)

The IIT Research Institute has conducted a wide variety of R&D programs in the water jet area for more than ten years. Both basic and applied research have been carried out. Three representative and pertinent programs are presented. Other relevant programs have included: field demonstrations of high-pressure jets to cut granite in quarries, sponsored by the Quarry Association of America; in-house studies of nozzles to induce cavitation for use in underwater excavation; experimental and field demonstrations of water jets for strip mining operations for the U.S. Bureau of Mines; and fundamental studies employing high-speed photography and other sophisticated experimental and theoretical techniques to investigate the phenomena of deformation and fracture of various materials by water jets for the National Science Foundation. Total expenditures for all water-jet R&D programs conducted by IITRI amount to $1.2 million.

3.3.5.1 Program to Resurface Roads

Program Description

A field study was conducted to demonstrate the use of high-pressure water jets to break concrete and resurface roads. Pressures and water flow rates were typically around 45,000 psi and 5 gpm, respectively.

Status/Future Plans

Program was initiated in December 1977, and was completed during February 1980.

Level of Effort/Source of Funds

The National Science Foundation provided $120,000 for this program.

3.3.5.2 Hydraulic Coal Mining Program

A hydraulic coal mining device for use underground was designed and field-tested. High-pressure jets to 100,000 psi and low-volume flows of water below 2 gpm were used in the tests.

Status/Future Plans

Program was completed around 1975.

Level of Effort/Source of Funds

The U.S. Bureau of Mines provided about $100,000 for this program.

3.3.5.3 Water-Jet Augmented Tri-Cone Bits

A conceptual design of a tri-cone roller bit augmented by high-pressure water jets was developed for drilling relatively shallow blast holes. Preliminary laboratory tests related to the incorporation of such jets into standard tri-cone bits were also performed.

Status/Future Plans

A proposal was submitted by IITRI to Dresser Industries in June 1978 to conduct laboratory and field tests of the jet-augmented tri-cone bit. Dresser decided not to fund this work, as discussed in Section 3.3.6. IITRI plans additional efforts related to the above hybrid bit in the future.

Level of Effort/Source of Funds

IITRI spent approximately $5,000 of in-house funds in the preliminary design and testing of the hybrid bit.

REFERENCES

T. J. Labus and J. A. Hilaris, "Highway Maintenance Application of Jet Cutting Technology," Fourth International Symposium on Jet Cutting Technology, BHRA, Paper G1, April 12, 14, 1978.

I. M. Daniel, "Experimental Studies of Water Jet Impact on Rock and Rocklike Materials," Third International Symposium on Jet Cutting Technology, BHRA, Paper 3, May 11-13, 1976.

T. J. Labus, "Energy Requirements for Rock Penetration by Water Jets," Third International Symposium on Jet Cutting Technology, BHRA, Paper E3, May 11-13, 1976.

T. J. Labus, I. M. Daniel, and R. H. Cornish, Technical Paper, Proceedings of the Workshop on the Application of High Pressure Water Jet Cutting Technology, Missouri University-Rolla, PB-254-316, 1975.

I. M. Daniel, "Experimental Study of Mechanics of Rock Fracture by Water Jet," PB-242-436, April 1975.

P. J. Huck and M. M. Singh, "Rock Fracture by High Speed Water Jet," PB-197-651, December 1970.

3.3.6 Dresser Industries

Program Description

While Dresser Industries has not been actively involved in any specific water jet R&D programs, its Mining Services and Equipment Division is interested in the use of high-pressure water jets for mining operations. As discussed in Section 3.3.5, Dresser encouraged IIT Research Institute to submit a proposal for designing and testing a hybrid roller-cone/ water-jet bit. Dresser's interest is related to the possible augmentation of its standard line of commercial roller-cone bits employed in drilling blast holes.

Status/Future Plans

Although the IITRI proposal was not accepted, Dresser is still interested in investigating water jet technologies for use in mining. Dresser has no interest in pursuing water jet R&D programs related to deep downhole drilling, however, because of the problems experienced by Gulf and Exxon in their programs.

3.3.7 Scire Corporation

In addition to two on-going programs described below, Scire is conducting proprietary programs for industry. One such program involves an evaluation of techniques to mechanically interrupt or break jets so as to increase their effectiveness for cutting rocks. The objective is to develop a portable tool for cutting concrete.

3.3.7.1 Borehole Mining Program

Program Description

Scire is participating as a subcontractor to SAI in a program involving the borehole mining of oil shale. Scire's role in this effort is to design experimental tests, analyze data, and conduct economic analyses. The overall program is described in Section 3.3.8.

Status/Future Plans

Program is scheduled for completion around June 1980.

Level of Effort/Source of Funds

The value of SAI's subcontract to Scire is $12,000.

3.3.7.2 Program to Develop Roof Bolt Drill

Program Description

This program involves the design, fabrication, and testing of a prototype pure jet device (i.e., with no mechanical cutting) for drilling roof bolt holes 1-in. in diameter and 8-ft deep. Pressures and flow rates are typically 60,000 psi and 4 gpm, respectively.

Status/Future Plans

Current fabrication of device will be followed by laboratory and field tests. Program is scheduled for completion during the summer of 1981.

Level of Effort/Source of Funds

Since program is proprietary, this information is not available.

REFERENCES

T. J. Labus, "High-Pressure Water Jet Applications in Drilling Observations," Sixth AIRAPT Conference, Vol. 2, Applications and Mechanical Properties, High Pressure Science and Technology, Boulder, CO, 1977.

3.3.8 Science Applications, Inc. (SAI)

3.3.8.1 Borehole Mining Program

Program Description

SAI is conducting a program involving the borehole mining of oil shale. The technique employed is generally similar to that developed by the U.S. Bureau of Mines (see Section 3.3.9) for mining coal and uranium. The objective of the program is to cut a hole of 30-ft radius and 4-ft thickness at a depth of 1,200 ft. A 15 to 30 percent void volume will thereby be created for subsequent use in retorting oil shale. Both laboratory and field experiments are being performed. Typical pressures and flow rates are 6,000 to 10,000 psi and 40 gpm.

Status/Future Plans

This program was recently initiated, and is expected to be completed in about one year.

SAI also plans to test the borehole mining device in Devonian shale around the summer of 1981. Support is to be provided by DOE/METC.

Level of Effort/Source of Funds

Total funding of the current oil shale program of $100,000 is being provided by DOE/LETC.

3.3.8.2 Blasthole Drilling Program

Program Description

A hybrid mechanical/water-jet cutting device was developed for drilling relatively small blast holes. Typical operating conditions are 10,000 to 12,000 psi and flow rates of 5 gpm or less.

Status/Future Plans

The above device was developed and patented by SAI three years ago.

Level of Effort/Source of Funds

Development program was conducted with in-house funds amounting to about $45,000.

3.3.9 U.S. Bureau of Mines (USBM)

The U.S. Bureau of Mines has conducted water jet R&D programs since the 1950's. Programs have been conducted both in-house and on a contract basis. Work performed by USBM contractors is discussed throughout Section 3. Major current programs involve the use of water jets for the borehole mining of uranium ores, oil sands, and phosphates. The borehole mining device employed in these programs is similar to that previously developed for mining coal, as described below.

Program Description

The Twin Cities Mining Research Center conducted an in-house program to design, fabricate, and test a device for mining coal from a borehole. The general approach involves the drilling of a borehole several inches in diameter by conventional techniques, after which a nozzle is lowered into the borehole and rotated. The objective is to mine out a volume 30 to 60 ft in diameter by means of water jets at pressures between 4,000 and 5,000 psi.

In addition to coal-cutting experiments in both the laboratory and the field, USBM conducted a series of tests to determine the effects of nozzle design and chemical additives on jet coherence and cutting effectiveness at standoff distances up to 15 feet.

Status/Future Plans

The program described herein was conducted during the mid-1970s.

REFERENCES

G. A. Savanick and J. M. Franck, "Force Exerted By Water Jet Impact at Long Standoff Distance," Third International Symposium on Jet Cutting Technology, BARA, P B5, May 11-13, 1976.

G. A. Savanick, Panel Discussion, Proceedings of the Workshop on the Application of High Pressure Water Jet Cutting Technology, p. 295, PB-254-316, 1975.

G. A. Savanick et al., "Cutting Experiments Using a Rotating Water Jet in a Borehole," Report of Investigations 8095, VSBM, 1975.

3.3.10 Daedalean Associates, Inc.

Several programs involving the use of high-pressure cavitating jets for cleaning and cutting have been conducted by Daedalean. Some specialized cleaning equipment employing cavitating jets has been sold commercially. All of Daedalean's cavitating jet activities feature low flows of approximately 2.5 gpm per nozzle or less.

Daedalean recently completed a program to remove scale from the inside of boiler tubes at pressures of 5,000 psi for the Fossil Fuel Utilization Division of DOE. Another program to develop an underwater cleaning tool for the Navy is currently in progress. In addition, a program involving the descaling of geothermal wells is being conducted, as described below.

Program Description

The objective of this program is to develop a technique using cavitating jets to clean and remove scale downhole in geothermal wells. A variety of nozzle designs have been tested. Pressures up to 10,000 psi have been used in laboratory scale-removal tests.

Status/Future Plans

The program was initiated in February 1979, with completion scheduled for August 1980.

Level of Effort/Source of Funds

Funding is being provided by DOE/Division of Geothermal Energy under contract to Sandia Laboratories.

3.3.11 Scientific Associates, Inc.

All of the programs conducted by Scientific Associates in the water jet area are centered around the development and use of "percussive" jets. The characteristics of such jets are discussed in Section 3.2.6 with regard to their possible application for downhole drilling. Major programs conducted by Scientific Associates are discussed below.

3.3.11.1 Program to Develop Percussive Water Jets

Program Description

This program involves the development and testing of relatively small diameter (0.060 in.) jets to cut a variety of rocks ranging from soft sandstone to hard granite. Pressures ranged from 2,000 to 7,000 psi, with water flow rates around 10 gpm. Test results confirmed that percussive jets are many times more efficient than ordinary jets in cutting rocks.

Status/Future Plans

Program was initiated around 1974 and will be completed early in 1980.

Level of Effort/Source of Funds

Total funding of $250,000 was initially provided by U.S. Bureau of Mines, and subsequently by DOE/Division of Fossil Fuel Extraction.

3.3.11.2 Program to Cut Coal at Large Standoff Distances

Program Description

Relatively large nozzles with diameters up to 0.5 in. will be developed and tested for cutting coal. Applications of interest include the mining of coal in steeply dipping beds and borehole mining. Flow rates up to 300 gpm are to be employed at pressures ranging from 500 to 2,000 psi. Coal cutting effectiveness at standoff distances up to 40 ft will be determined.

Level of Effort/Source of Funds

Funding of $400,000 is being provided by DOE/Division of Fossil Fuel Extraction.

REFERENCES

E. B. Nebeker and S. E. Rodriguez, "Development of Percussive Water Jets," Final Report, prepared by Scientific Associates for U.S. DOE, May 31, 1979.

E. B. Nebeker and S. E. Rodriguez, "Percussive Water Jets for Rock Cutting," Third International Symposium on Jet Cutting Technology, BARA, Paper Bl, May 11-13, 1976.

E. B. Nebeker, Technical Paper, Proceedings of the Workshop in the Application of High Pressure Water Jet Cutting Technology, Missouri University - Rolla, PB-254-316, 1975.

3.3.12 University of California, Davis

Program Description

The University of California is conducting a program to mathematically describe the behavior of liquid jets. A computational model incorporating the dynamics of the jet, mechanical properties of the rock, and the jet-rock interactions is being developed. While theoretical analysis is being emphasized, supporting laboratory tests have also been conducted. Program support in these areas was previously provided to the WJD program of Lawrence Livermore Laboratory (Section 3.2.7).

Status/Future Plans

Program was initiated several years ago and is on-going.

Level of Effort/Source of Funds

Program cost primarily involves computer time, in addition to support of a doctoral program. Lawrence Livermore Laboratory is providing partial support for this work.

3.3.13 TRW

The Defense and Space Systems Group of TRW conducted a program to investigate the effects of flow turns and nozzle design on jet coherence and cutting ability. This work was performed in support of the borehole mining program of the Bureau of Mines (See Section 3.3.9). Due to space limitations in the borehole, the fluid must make a sharp 90° turn before entering the nozzle that performs the hydraulic mining. Jet disintegration caused by this flow turn has been found to be a problem in borehole mining. Based on theoretical analyses and supporting experiments, TRW developed an optimum nozzle and flow-inlet design for maintaining jet coherence and cutting effectiveness up to 30 ft or more from the nozzle.

Status/Future Plans

Program was initiated in mid-1975, and completed during December 1977. TRW is interested in pursuing additional water jet activities in the future, and has some active in-house proposals.

Level of Effort/Source of Funds

The U.S. Bureau of Mines provided $250,000 for this program.

REFERENCES

P. D. Lohn and D. A. Brent, "Design and Test on an Inlet-Nozzle Device," Fourth International Symposium on Jet Cutting Technology, BHRA, Paper D1, April 12-14, 1978.

P. D. Lohn and D. A. Brent, "Inlet Nozzle Performance Study," Final Report by TRW for Bureau of Mines, 27752-6005-TV-00, July 1977.

P. D. Lohn and D. A. Brent, "Nozzle Design for Improved Water Jet Cutting," Third International Symposium on Jet Cutting Technology, BHRA, Paper A3, May 11-13, 1976.

3.3.14 University of California, Los Angeles

Program Description

The University of California, Los Angeles (UCLA) conducted theoretical investigations of the interactions between water jets and rock mechanics. The program involved basic research, with laboratory experiments being conducted in support of the theoretical analyses. A theoretical model of hydraulic rock cutting was developed and tested at pressures up to 20,000 psi. Rock properties such as porosity and permeability were incorporated into the model.

Status/Future Plans

Program was conducted in the 1972-74 period. There have been no water jet programs since then, and are no plans for future programs.

Level of Effort/Source of Funds

The National Science Foundation provided $90,000 in support of this work.

REFERENCES

G. H. Hurlburt et al., "Experiments in Hydraulic Rock Cutting," International Journal of Rock Mechanics, Mineral Science and Geomechanics Abstract, Vol. 12, pp. 203-212, 1975.

S. C. Crow, "The Effect of Porosity on Hydraulic Rock Cutting," International Journal of Rock Mechanics, Mineral Science and Geomechanics Abstract, Vol. 11, pp. 103-105, 1974.

S. C. Crow, "A Theory of Hydraulic Rock Cutting," International Journal of Rock Mechanics, Mineral Science and Geomechanical Abstract, Vol. 10, pp. 567-584, 1973.

3.3.15 Hydronautics, Inc.

As discussed in Section 3.2.1, Hydronautics has developed a cavitating jet with the trademark CAVIJET. In addition to its programs in deep downhole drilling, Hydronautics has also conducted several programs directed at other possible applications of the CAVIJET. These programs have included the use of the CAVIJET to remove explosives from the inside of improperly made shells and to remove barnacles, paint, or rust from the hulls of ships. A recent coal-mining program is discussed below.

Program Description

The feasibility of the CAVIJET for use in hydraulic coal mining was demonstrated in laboratory tests, and system and operating parameters required to cut coal were obtained. In a later phase of the program, both coal and a variety of rocks such as shale, limestone, and granite were cut at jet pressures ranging from less than 2,000 psi in the case of coal to over 10,000 psi for granite.

Status/Future Plans

Program was initiated in 1977, with tests being completed in early 1979. Hydronautics plans to resume work, with emphasis on cutting coal.

Level of Effort/Source of Funds

Program was initiatlly funded by the U.S. Bureau of Mines, and subsequently by DOE/Division of Fossil Fuel Extraction.

REFERENCES

A. F. Conn and S. L. Rudy, "CAVIJET Coal Cutting Parameters, Erosion: Prevention and Useful Applications," ASTM STP 664, W. F. Adler, Ed., A STM, pp. 562-581, 1979.

A. F. Conn, Technical Paper, Proceedings of the Workshop on the Application of High Pressure Water Jet Cutting Technology, Missouri University - Rolla, PB-254-316, 1975.

A. F. Conn and S. L. Rudy, "Parameters for a Ship Hull Cleaning System Using the Cavitating Water Jet Method," prepared for the National Maritime Research Center, July 1975.

3.3.16 Ingersoll-Rand Research, Inc.

Ingersoll-Rand has conducted proprietary R&D programs involving the use of water jets to cut rock in mining and hole-drilling (e.g., shallow blast holes) applications. The following coal mining study has also been performed.

Program Description

A design study was conducted to develop the basic concept of a Hydrominer (i.e., water-jet assisted coal mining device). No tests or experiments were conducted in this program. A variety of geologic conditions and coal seam characteristics were analyzed with regard to Hydrominer feasibility. Based on its analyses, Ingersoll-Rand defined a test plan to obtain required data.

Status/Future Plans

Program was initiated in June 1975 and completed in March 1977.

Ingersoll-Rand has a "continuing interest" in the use of water jets for mining. Information is not available on internally-funded efforts.

Level of Effort/Source of Funds

Program was originally supported by the U.S. Bureau of Mines, and subsequently by DOE/Division of Fossil Fuel Extraction. Total level of effort consisted of about 2 man-years of labor.

REFERENCES

P. du Toit et al., "Study of a Water Jet Continuous Coal Mining System," prepared for USBM by Ingersoll Rand, PB-267-287, March 1977.

W. McGahan and J. W. Adams, "Blast Hole Drilling Technology Workshop, Par City, Vermont, PB-253-387, June 1975.

3.3.17 Continental Oil Company (Conoco)

3.3.17.1 Program to Develop Borehole Miner

Program Description

Conoco conducted a program to develop a water-jet borehole miner for phosphates. Several pilot projects were carried out.

Status/Future Plans

Program was terminated several years ago for non-technical, business-related reasons.

Level of Effort/Source of Funds

Program was internally funded.

3.3.17.2 Program to Develop Methane-Drainage Device

Program Description

The Mining Research Division of Conoco conducted an R&D program to develop a water jet nozzle assembly to drill long holes in coal seams. These holes would then provide openings in the seam through which methane gas can be vented.

Status/Future Plans

The device developed under this program is "close to being commercialized," and is in the process of being licensed by Conoco.

Level of Effort/Source of Funds

Several man-years of effort were devoted to this program over a period of several years. Internal funds were employed.

REFERENCES

U.S. Patent No. 4,031,971, "Jet Nozzle Drilling Assembly," by T. R. Miller, Continental Oil Company, June 28, 1977.

3.3.18 IGT/University of Waterloo

Program Description

The Institute of Gas Technology (IGT) and the University of Waterloo, Ontario, Canada conducted a joint program involving the use of pulsed jets to break concrete pavements quickly and quietly. An experimental high-pressure, pulsed-jet system was developed and tested at IGT. This system employed a pulsed intensifier that generated approximately ten slugs or pulses per minute. Maximum effective pressures up to 100,000 psi were employed.

The Mechanical Engineering Department of the University of Waterloo conducted supporting laboratory experiments and acted as a consultant to IGT.

Status/Future Plans

The above program was initiated in 1974, and completed in 1977. Water jet R&D was terminated at IGT upon completion of the program. IGT has no plans to resume activities in the area. The University of Waterloo has continued small-scale experimentation with the equipment assembled during the joint program with IGT.

Level of Effort/Source of Funds

Total funding of $425,000 was provided by a group of seven gas utility companies.

REFERENCES

Gene G. Yie, "Water Jetting; A New Way to Fracture Concrete and Rock," Pipe Line Industry, pp. 49-52, October, 1978.

3.3.19 Oak Ridge National Laboratory

Program Description

Oak Ridge National Laboratory (ORNL) conducted a program to develop a water-jet assisted tunneling method for utility distribution under cities. Relatively small-scale laboratory tests were carried out to cut rock specimens of sandstone, concrete, and granite with water jets at pressures up to 12,000 psi.

Tests were conducted with both pure jet nozzles, and jet-augmented mechanical cutting devices. Based on the results of this study, a mechanical mole augmented with water jets appeared to be feasible, and further research was recommended.

Status/Future Plans

This one-year program was terminated in 1971. Proposals were then prepared to several Federal agencies and equipment manufacturers for funds to continue this R&D program, but without success. There are no current plans to continue work in this area.

Level of Effort/Source of Funds

Funding of approximately $100,000 was provided by the U.S. Department of Housing and Urban Development.

REFERENCES

W. C. McClain and G. A. Cristy, "Examination of High Pressure Water Jets for Use in Rock Tunnel Excavation," ORNL-HUD-1, UC-38-Engineering and Equipment, January 1970.

3.3.20 Georgia Institute of Technology

The Engineering and Experimentation Station of the Georgia Institute of Technology conducted an evaluation of alternative techniques for quarrying granite. Water jet cutting of granite represented only a portion of this study, which was completed about one year ago for the National Science Foundation. All laboratory testing was subcontracted to the University of Missouri - Rolla and IIT Research Institute.

In addition to this study, a proprietary program is also being conducted, as described on the following page.

Program Description

A program is currently being conducted to test and develop water jet cutting techniques for quarrying granite. This R&D program has employed techniques with continuous water jets at pressures from 15,000 to 60,000 psi. Additional information is not available.

Status/Future Plans

This program was initiated one year ago, and is scheduled for completion in the summer of 1980.

Level of Effort/Source of Funds

Total funding of $190,000 is being provided by private industry.

3.3.21 Bendix Research Laboratories

Program Description

Bendix Research Laboratories conducted a program to design, fabricate, and test mobile machines employing water-jet assisted mechanical cutters for rock excavation and tunneling. Continuous water jets at pressures from 20,000 to 80,000 psi and flow rates of 1 gpm or lower were employed. The program was conducted in two phases, with laboratory tests to define water-jet cutting parameters being performed in the first phase, and field tests of a prototype device at a granite quarry being carried out in the second phase.

Status/Future Plans

Program was initiated in May 1972 and completed in October 1973.

Level of Effort/Source of Funds

The Advanced Research Projects Agency of the U.S. Department of Defense provided about $125,000 in support of this program.

REFERENCES

Ray F. Chadwick, "Continuous High-Velocity Jet Excavation - Phase II Report," NTIS AD-773-417, October 1973.

3.3.22 U.S. Army

Program Description

The Cold Regions Research and Engineering Laboratory of the U.S. Army conducted a program to investigate the feasibility of cutting ice and frozen ground with high-pressure water jets. Water-jet applications under consideration included construction and transportation activities in cold regions such as the Arctic. Some R&D activities were conducted strictly in-house, while others were carried out jointly with the National Research Council of Canada (see Section 3.3.23). Tests were generally carried out at pressures up to 30,000 psi and with small nozzles less than 0.01-in. in diameter.

Status/Future Plans

Water-jet R&D activities were initiated around 1973 and terminated during 1977. The U.S. Army has no current plans to resume work in this area, since mechanical tools developed by the army were found to be more effective for the specific applications under consideration in this program.

Level of Effort/Source of Funds

All water-jet R&D activities were conducted with in-house, U.S. Army Corps of Engineer funds. Expenditures were about $50,000 per year over a 4-year period, amounting to a total of $200,000.

REFERENCES

M. Mellor, Technical Paper, Proceedings of the Workshop of The Application of High Pressure Water Jet Cutting Technology, Missouri University - Rolla, PB-254-316, pp. 411-413, 1975.

H. D. Harris and M. Mellor, "Cutting Rock With Water Jets," International Journal of Rock Mechanics, Mineral Science and Geomechanics, Alstro, Vol. 11, pp. 343-258, 1974.

3.3.23 National Research Council of Canada

Description of Activities

In addition to its joint activities conducted with the U.S. Army Cold Regions Research and Engineering Laboratory (see Section 3.3.22), the National Research Council of Canada has also been involved in a number of other water-jet R&D activities. Such activities include ice breaking with water jets, which is an extension of the joint R&D carried out in cooperation with the U.S. Army, and rock-cutting experiments related to mining, tunneling, and quarrying applications. Laboratory tests are performed to determine rock-cutting efficiencies of continuous water jets and optimum nozzle designs. Due to equipment limitations, most tests are conducted at pressures around 10,000 psi.

Status/Future Plans

Both the ice and rock-cutting activities are on-going.

Level of Effort/Source of Funds

Current expenditures amount to approximately $80,000/yr, including $20,000/yr for the ice-breaking work and $60,000/yr for the rock-cutting R&D. Funding is provided by the Canadian Federal Government.

REFERENCES

M. M. Vijay and W. H. Brierley, "Cutting Rocks and Other Materials by Cavitating and Non-Cavitating Jets," Fourth International Symposium on Jet Cutting Technology, BGRA, Paper C5, April 12-14, 1978.

H. D. Harris, "Data for the Cutting of Vermont Marble With Continuous Water Jets," International Journal of Rock Mechanics, Mineral Science and Geomechanics, Abstract, Vol. 12, pp. 27-31, 1975.

H. D. Harris and M. Mellor, "Cutting Rock With Water Jets, International Journal of Rock Mechanics, Mineral Science and Geomechanics, Abstract, Vol. 11, pp. 343-358, 1974.

H. D. Harris and W. H. Brierley, "A Rotating Water Jet Device and Data on its Use for Cutting Berea Sandstone," International Journal of Rock Mechanics, Mineral Science and Geomechanics, Abstract, Vol. 11, pp. 359-366, 1974.

3.3.24 University of Wisconsin - Milwaukee

Description of Activities

The University of Wisconsin at Milwaukee has conducted a variety of water-jet R&D programs related to industrial cutting applications of plastics, aluminum and other materials. Laboratory tests to measure cutting rates are conducted at maximum pressures of 100,000 psi and flow rates below 1 gpm with very small nozzles less than 0.01 in. in diameter. A high-pressure fluid reservoir is used to achieve these pressures for "quasi-steady" periods of 2 seconds. Basic research has also been conducted to investigate the fluid mechanics of water jets and the resulting thermal effects on material properties (e.g., the degradation of plastics) due to the jet impacts.

Status/Future Plans

Water-jet R&D activities were initiated around 1974, and all recent programs were completed during 1979. There is currently no research in the water-jet area. The University of Wisconsin has recently submitted proposals, however, to DOE and the National Science Foundation for water-jet R&D related to both industrial cutting applications and cleaning of industrial surfaces such as heat transfer tubes.

Level of Effort/Source of Funds

Total funding of $40,000 has been provided, in part, by the National Science Foundation.

REFERENCES

K. F. Neusen and S. W. Schramm, "Jet Induced Target Material Temperature Increases During Jet Cutting," Fourth International Symposium on Jet Cutting Technology, BHRA, Paper E4, April 12-14, 1978.

J. L. Bayer and K. F. Neusen, "Specific Energies for Jet Cutting of Polymeric Materials," Third International Symposium on Jet Cutting Technology, BHRA, Paper C2, May 11-13, 1976.

3.3.25 McCartney Manufacturing Company

McCartney Manufacturing, a subsidiary of Ingersoll-Rand, has developed water-jet cutting systems for industrial applications. More than 100 of these systems are reported to be in operation for the precision cutting of a wide variety of materials such as plastics, wood puzzles, and asbestos-brake linings. Water-jet pressures and flow rates are typically 50,000 psi and 0.3 gpm. Very fine nozzles with diameters ranging from 0.005 to 0.010 in. are generally employed. High pressures are achieved by means of hydraulically-driven, piston-type intensifiers also manufactured by McCartney.

In addition to its work with precision-cutting systems, McCartney is currently conducting a proprietary program involving rock cutting, as discussed on the following page.

Program Description

McCartney Manufacturing is conducting an R&D program involving the use of high-pressure water jets to cut granite.

Status/Future Plans

The above program is currently in progress.

Level of Effort/Source of Funds

This proprietary program is being funded by private industry.

3.3.26 Gas Research Institute

Description of Activities

The Gas Research Institute (GRI) plans to support a water jet R&D program in the area of directional drilling to extract methane from coal seams. This program is to include a feasibility study, laboratory experiments, and field tests in outcrops. Drilling specifications are to be developed within the program. A proposal to develop a directional drilling device was solicited and received from Flow Industries (see Sections 3.2.2. and 3.3.2).

In addition to the above directional drilling proposal, GRI has also received an unsolicited proposal from Flow Industries for support of a program to develop a downhole intensifier for possible use in cleaning wellbores, underreaming boreholes, and/or downhole drilling.

Status/Future Plans

The directional-drilling proposal from Flow Industries has not yet been reviewed. However, GRI plans to support such a program.

The unsolicited downhole-intensifier proposal from Flow Industries also has not been reviewed. GRI believes that it is "premature to get involved in this type of activity," but might fund a program on a cooperative basis with industry or government.

Level of Effort/Source of Funds

As indicated above, R&D program(s) by contractors are to be funded by GRI. Details are not available.

3.3.27 Exotech, Inc.

Description of Activities

Exotech was active throughout the past two decades in the development of water cannons and pulsed-jet systems to generate extremely high instantaneous pressures (up to 1 million psi) for cutting hard rock. Seventeen patents related to high-pressure water jet technology are held by Exotech. Most of Exotech's work was of a proprietary nature, and available information is limited. Nevertheless, most of Exotech's activities appear to have centered around the development of water cannons for excavation, tunneling, and mining applications. Several high-pressure pulses or slugs of water could typically be generated each second.

Exotech conducted a program to develop a hybrid system containing pulsed water jets to augment tri-cone bits employed in drilling blast holes. This effort appears to have been unsuccessful, however.

Status/Future Plans

Exotech initiated its water-jet R&D activities in the early 1960's. All such activities were terminated during the summer of 1979 due to a lack of funds.

Level of Effort/Source of Funds

Most of Exotech's programs were funded internally. Some programs were carried out with government support, however.

REFERENCES

U.S. Patent No. 2,927,723, "Apparatus for Drilling Holes Utilizing Pulsed Jets of Liquid Charge Material," by J. M. Hall and L. L. Clipp, Exotech, Inc., December 23, 1975.

L. L. Clipp, Panel Discussion, Proceedings of the Workshop in the Application of High Pressure Water Jet Cutting Technology, Missouri University - Rolla, PB-254-316, 1975.

W. C. Cooley and L. L. Clipp, "High-Pressure Water Jets for Undersea Rock Excavation," Journal of Engineering for Industry, TRANS. ASME, pp. 281-287, May 1970.

3.3.28 Terraspace, Inc.

Description of Activities

Terraspace was active in the early 1970's in the development of water cannons to generate peak stagnation pressures to 650,000 psi. Terraspace's activities centered around the development of such cannons for use in rapid excavation and tunneling through hard rock. Large pulsed-jet systems were designed, fabricated, and field-tested in both mines and quarries.

Status/Future Plans

Terraspace initiated its water-jet R&D activities during 1970. These activities were terminated in 1974 due to a lack of funds.

Level of Effort/Source of Funds

The total level of effort of Terraspace's water-jet R&D activities was about $330,000, with $250,000 being provided by the Department of Transportation and $80,000 by the Bureau of Mines.

REFERENCES

W. C. Cooley, "Water Jets and Rock Hammers for Tunneling in the U.S. and U.S.S.R.", First Rapid Excavation and Tunneling Conference, Chicago, IL, June 5-7, 1972.

W. C. Cooley, "Rock Disintegration Tests of a Water Cannon", Rapid Excavation and Tunneling Conference, San Francisco, CA, June 24-27, 1974.

4. OPPORTUNITIES FOR JOINT INDUSTRY/GOVERNMENT R&D

The research findings presented in Sections 3.1 and 3.2 and summarized in Section 2 were reviewed and evaluated to identify potential opportunities for joint R&D programs with industry (or universities and research institutes) in the area of water jet drilling (WJD). Several program areas where future government participation in joint R&D efforts appear to be of potential benefit in accelerating the development and commercialization of WJD technology are presented below.

As was the case in Section 3, the identified R&D program areas are organized in terms of the pressure requirements of surface equipment. Program areas involving high-pressure surface equipment are presented in Section 4.1, while those employing conventional pressures are presented in Section 4.2.

It should be noted that no attempt has been made in this report to prioritize the identified R&D opportunities in terms of benefits and costs, since this was not within the scope of this investigation. Nevertheless, some general observations concerning possible benefits from government participation in joint R&D programs and potential constraints to the successful development and implementation of WJD technologies are presented below.

4.1 WJD PROGRAM AREAS—HIGH SURFACE PRESSURES

As indicated in Exhibit 4, the high-pressure approach to WJD has been the subject of much more extensive investigation than the lower or conventional-pressure approach. The critical deficiency requiring resolution before high-pressure WJD can be implemented commercially involves the need for reliable surface equipment. Needs to resolve potential safety problems and to obtain additional performance data for downhole WJD have also been identified in this study. Programs to address each of the above problems and needs are discussed below.

4.1.1 Development of Improved High-Pressure Equipment

Private industry has spent about $25 million on the development of high-pressure WJD systems. The results of major field tests conducted by Gulf, Exxon, and Shell clearly demonstrate a need for reliable surface equipment, especially mud pumps and swivels, which are either not commercially available or too costly to operate for commercial drilling at elevated pressures (e.g., above 4,000 to 5,000 psi).

The current status of high-pressure surface equipment and programs to improve such equipment are discussed in detail in Appendix A. Specific equipment deficiencies and possible program areas for government consideration are presented below.

Mud Pumps

The development of mud pumps for reliable, economical operation at pressures up to 5,000 to 6,000 psi appears to be achievable through modest advances in fluid-end technology with currently available triplex mud pumps. The achievement of significantly higher pressures such as 10,000 to 15,000 psi, however, will require major advances in mud pump technology. Some experts consider the best approach to developing such a pump to be an improvement or extrapolation of present mud pump designs, while others consider a suitable long-slow-stroke intensifier-type design to be required. Since a ready market for mud pumps capable of 10,000 psi operation does not exist and, therefore, pump manufacturers lack incentive to conduct the required development efforts, a potential role for government appears to be indicated. Both approaches discussed above should be considered in any future pump-development program.

Swivels

Based on the Exxon and Shell field tests, the Exxon swivel design appears to be adequate for commercial drilling operations at pressures up to 5,000 to 6,000 psi. Reliable swivels for operation up to 10,000 psi or more are not available, however. As in the case of mud pumps, a joint R&D effort between government and private industry could accelerate the development of suitable swivels for operation at the elevated pressures.

4.1.2 Collection of Additional Drilling Performance Data

Experts in water jet drilling expressed conflicting opinions concerning the need for additional drilling performance data. Several experts believe that sufficient data have been collected during previous WJD programs to characterize drilling performance under a variety of conditions. Other experts, however, believe that additional data are required. Based on our review and evaluation of available information, additional data generally appear to be required to reliably predict drilling performance over important ranges of formation depth (or corresponding confining or overburden pressures), nozzle pressure drop, and other variables for various types of rocks and for a variety of drill bit-nozzle configurations.

The required drilling performance data can be most efficiently and economically obtained at drilling research laboratories capable of simulating downhole drilling conditions. Such data would be valuable for planning and designing larger-scale field tests, as well as for use in systems analyses to determine economic feasibility and optimum WJD conditions.

4.1.3 Systems Analysis of Required Safety Precautions

Several experts consider safety problems and their associated costs to be major obstacles to the implementation of high-pressure drilling. The general approach employed by Gulf and Exxon in their field tests was to confine personnel to protective "doghouses" during high-pressure drilling, which can result in inefficient drilling and maintenance operations.

In order to address and possibly mitigate the above safety-related perceptions, a systems study focusing on alternative approaches to protecting rig personnel would be useful. Such a study would identify and evaluate possible safety precautions and procedures such as the use of "doghouses" or automation of certain drilling or maintenance functions, and estimate their impacts on overall drilling costs.

4.1.4 Feasibility Study of Dual-Pipe Systems

Flow Industries (Section 3.1.8) conducted a feasibility study of dual-pipe systems for water-jet coring in geothermal formations. While concluding dual-pipe systems to be technically feasible for coring, Flow identified several problems including increased difficulty of assembling and disassembling the pipes in the field, the need to retrain drilling personnel to handle the dual pipes, and the need for improved downhole sealing techniques.

In the case of a dual-pipe system, only a relatively small volume of water for rock cutting would be pumped downhole at high pressures (possibly up to 60,000 psi), while the drilling mud used to clean the hole would be at conventional pressures. Required safety precautions and problems associated with the high-pressure surface equipment would, therefore, be greatly simplified.

In view of the above advantages, an updated feasibility study focusing on the possible use of dual-pipe systems for WJD in a variety of rock formations and the alleviation of the above problems appears to be warranted. If the results of the feasibility study are encouraging, a program to develop a dual-pipe system could then be initiated.

4.2 WJD PROGRAM AREAS - CONVENTIONAL SURFACE PRESSURES

As discussed previously, a variety of different approaches to WJD have been investigated to eliminate the need for high-pressure surface equipment. The obvious benefit of such approaches is that commercially available mud-circulation equipment could be employed. In addition, special safety precautions due to high surface pressures would not be necessary. The two principal approaches pursued to-date employ cavitation to enhance rock cutting or downhole devices (intensifiers) to increase the pressure of the drilling fluid in the borehole. A third possible approach to low-pressure WJD might employ percussive or pulsed jets to increase the effectiveness of jet cutting.

4.2.1 Development of Cavitating Jet Systems

As discussed in Section 3.2.1, past and current R&D programs involving the use of cavitating jets for downhole drilling emphasize performance in hard rocks characteristic of geothermal formations. While limited laboratory tests are also planned with softer rocks, both Hydronautics and NL Hycalog expressed interest in a joint R&D effort with government to accelerate the development of cavitating-jet systems for oil and gas drilling.

While cavitating-jet systems currently being developed and tested with government support for hard rocks could be adapted for use in soft-rock formations, the optimum operating conditions and drill bit-nozzle configurations might be significantly different for geothermal versus oil and gas drilling.

4.2.2 Development of Downhole Intensifiers

Several different concepts for intensifiers to increase drilling-fluid pressures downhole are currently being considered. Flow Industries (Section 3.2.2) is interested in developing a piston-type intensifier for downhole use. Kobe (Section 3.2.3) has obtained patents for a multi-stage, turbine-powered, impeller-type device for downhole drilling applications. The Kobe intensifier system includes a centifugal cleaner for removing solids from the drilling fluid. A high-speed, rotary device is under consideration by Scire Corporation (Section 3.2.4) for downhole drilling.

The use of a downhole intensifier would entail several possible design problems, including space limitations in the borehole, the need for remote controls, and erosion due to abrasives in the drilling fluid. The rotary devices discussed above should generally be less sensitive to abrasives or solids in the drilling fluid than piston-type intensifiers.

4.2.3 Feasibility Study of Percussive or Pulsed Jets

As discussed in Section 3.2.6, the high-frequency percussive jet system under development by Scientific Associates has not been evaluated or tested for possible use under downhole drilling conditions. Other intermittent or pulsed-jet systems operating at much lower frequencies, such as those developed by IGT (Section 3.3.18) and Exotech (Section 3.3.27), have also apparently not been considered for deep downhole drilling. Hydronautics (Section 3.2.1) is investigating the effects of passively-induced pressure pulses with cavitating jet systems that would require no switching or modulating devices downhole.

Intermittent (i.e., discontinuous) water jets have generally been found to cut rock much more effectively than continuous jets at the same pressures. Thus, a feasibility study to evaluate the possible use of percussive or pulsed jets for downhole drilling appears to be warranted. In the case of percussive jets, the feasibility of powering the modulating device downhole with the drilling mud should be considered.

APPENDIX A

Programs to Develop Surface Equipment for High-Pressure Drilling

In designing a drilling system for operation at high pressure, the entire mud circulation system must be considered. Upgrading of tool joints, rotary hose, and other components would be required. However, the consensus of opinion among experts in the drilling field is that mud pumps and swivels are by far the major problems that need to be resolved before high pressure drilling can be implemented on a commercial basis.

Conventional mud pumps, which are used to force the drilling fluid or mud through the surface equipment, drill string, drill bit, and then back through the annulus of the wellbore, generally operate at discharge pressures below 3,500 psi. Some mud pumps employ pistons and liners in their fluid ends, while others employ plungers and packings. As operating pressures are increased, wear of these and other expendable parts increases dramatically, and the component lives are correspondingly reduced. The costs of expendable parts is the limiting factor in operating mud pumps at higher than conventional pressures.

Swivels are used to suspend the drill pipe, and to connect the stationary hose from the mud-pump discharge to the rotating drill pipes. The stem of the swivel rotates with the drill pipe. The rotating swivel seals must withstand the high mud pressures. Abrasives in the drilling mud can be damaging to the seals. Fines from rock cutting that are not completely removed from recirculated drilling fluids are especially troublesome in causing deterioration of the seals.

Organizations involved in programs to develop the required high-pressure surface equipment for deep downhole drilling are discussed below. It should be noted that several other organizations discussed previously in Section 3, including the Colorado School of Mines, IIT Research Institute, Scire Corporation, and National Research Council of Canada, have also conducted research to develop swivels for a variety of applications. These efforts have generally been oriented towards smaller-scale laboratory or field work where relatively small volumes of clean water are employed for the water jet cutting at pressures well above those typically employed or considered for downhole drilling in the field.

A.1 HALLIBURTON SERVICES

Gulf employed Halliburton intensifier pumps for its field tests (see Section 3.1.1). Halliburton contributed funds for pump development during the Gulf program and, in fact, actually developed its HT-1000 intensifier for use in the high-pressure tests with abrasive-laden drilling fluids. While Gulf appears to have generally been satisfied with the performance of these pumps, problems related to plunger and packing wear were not resolved. Gulf concluded that a development program would be required to solve "plunger wear-life problems". It should also be noted that the final, modified version of the HT-1000 pump employed in the Gulf tests was limited to 70 hours of actual service in the field.

While originally developed for high-pressure drilling, the intensifier pumps have not been used for drilling since the conclusion of the Gulf tests. They are currently employed to pump slurries or acids at pressures up to 20,000 psi for hydraulic fracturing in well stimulation programs. The intensifier pumps are hydraulically powered and designed for long-stroke operation with a corresponding low frequency of pressure cycles to reduce wear on replaceable parts such as packings and valves.

A.2 EXXON PRODUCTION RESEARCH COMPANY

A substantial portion of the Exxon WJD program described in Section 3.1.2 involved the development of equipment for operation at high pressures. While the major portion of the equipment development involved the mud pump, a considerable effort was also made to improve swivel performance. As a result, Exxon developed a technique to better contain swivel packing at high pressures, as well as procedures to change inexpensive packings rapidly without interfering with drilling operations. While the swivel was not considered a major problem at the conclusion of the test program, the packing life was unexpectedly short during some of the later field tests.

An extensive effort was made to increase the reliability of commercially available mud pumps at high pressures. Exxon purchased a conventional mud pump and made several improvements to the fluid end. Although the frequency of failure of expendable parts was reduced, performance was inadequate for subsequent field tests that were planned for pressures of 10,000 psi or more.

While intensifier pumps were available on a rental basis, Exxon considered their expense too high for a long-term research program. Exxon then decided that a long-stroke pump with a slow stroke rate would be needed to extend the life of replaceable parts. Exxon conducted a program in conjunction with Kelsey Hayes to develop a long-stroke, hydraulically-powered intensifier. This pump was generally similar to the Halliburton intensifier pumps described previously, with modifications to adapt pump controls for use in drilling. After pursuing this approach unsuccessfully for about a year and a half, Exxon abandoned its efforts to develop a long-stroke pump.

A.3 SHELL (KONINKLIJKE/SHELL EXPLORATIE & PRODUKTIE LABORATORIUM RIJSWIJK), THE NETHERLANDS

In the 1976-1977 field tests described in Section 3.1.3, Shell employed standard triplex mud pumps provided with fluid ends based on the design Exxon had developed (See Appendix A.2). In general, these pumps operating at 5,000 psi performed with the same downtime for maintenance as conventional pumps operating at 3,000 psi. The high-pressure fluid ends are designed for rapid replacement of worn plungers, packing, and valves. Packing had to be replaced more frequently at elevated than at conventional pressures, however.

The fluid ends to be employed in the field tests scheduled for the second half of 1980 will be slightly modified versions of the Exxon design. TRW Mission is working with Shell on the fluid end design. Tests will be carried out at 5,000 to 6,000 psi, with both piston-liner and plunger-packing arrangements under consideration. Shell will also employ Exxon's swivel design in these tests. Shell does not consider the swivel to be a significant problem, at least at these pressures.

Shell developed a custom-made swivel for its laboratory simulations at pressures up to 14,500 psi. Standard chevron-type packings were found to be inadequate. A hydraulic oil seal was found to be satisfactory for laboratory testing. However, oil consumption and vulnerability to damage because of the small internal clearances were found to be problems.

A.4 TRW MISSION

TRW Mission manufactures expendable parts such as valves, pistons, liners, and packings for mud pumps. It provided assistance to Exxon in the design of high-pressure fluid ends (see Appendix A.2), and is currently working with Shell (see Appendix A.3) in exploring the feasibility of extending mud-pump pressure limits. TRW Mission also does a considerable amount of in-house component testing. Continuous mud pump tests have been run at pressures up to nearly 4,000 psi with very satisfactory life of expendable parts.

A.5 U.S. STEEL-OIL WELL DIVISION

The OILWELL Division of U.S. Steel manufactures mud pumps with maximum pressure ratings of approximately 5,000 psi for short-term, intermittent operation. These pumps are generally used for continuous operation at pressures below 3,000 to 3,500 psi.

U.S. Steel participated in the Exxon pump development program, and is currently participating in Shell's program, both of which were previously described. It considers the next logical step in pump development to be an approximate doubling of the range of reliable operating pressures from 3,000 to 6,000 psi. U.S. Steel does not consider operation at 10,000 to 15,000 psi to be within reach at the present time, since this would require a "quantum leap" in pump design, although such operation might be feasible in three to five years with a well-funded research effort to improve the fluid end and the durability of expendable parts. It considers the best approach to be an extrapolation of present pump design, rather than the development of new concepts such as the use of a long-stroke pump for drilling operations.

A.6 TERRA TEK

Terra Tek developed pumps for operation up to 15,000 psi to simulate deep downhole conditions at its Drilling Research Laboratory. High pressure fluid ends based on the design developed by Exxon (See Appendix A.2) were added to a standard triplex mud pump. Some components were actually purchased from Exxon in making these modifications about a year ago. The modifications were made with the high-pressures drilling application in mind. Terra Tek believes it successfully demonstrated the ability to conduct reliable laboratory simulations at pressure up to 15,000 psi, but that reliability for field operations has not been demonstrated. Total expenditures for this program amounted to approximately $55,000, with support being provided by Sandia Laboratories.

It is interesting to note that Terra Tek has encountered "tremendous interest" in high-pressure pumps, and in high-pressure drilling in general. Several companies have reportedly expressed interest in testing pumps, swivels, and other equipment at elevated pressures. Names of these companies could not be revealed due to confidentiality.

The above expressions of interest by industry are primarily for operation at about 5,000 psi. Terra Tek believes industry will tend to increase operating pressures in relatively small increments, and is confident drilling can be conducted successfully in the field with the pump discussed previously.

A.7 THE JET PROPULSION LABORATORY (JPL), CALIFORNIA INSTITUTE OF TECHNOLOGY

JPL conducted a study* several years ago to evaluate the applicability of aerospace techniques for petroleum exploration. High-pressure drilling was one of the technologies considered. As a result of this investigation, JPL concluded that pump reliability and maintenance costs were the major constraints to the implementation of high-pressure drilling.

In view of the above, JPL developed a conceptual design for an innovative, long-stroke mud pump for high-pressure (up to 20,000 psi or more) operation with direct electrical or mechanical drives. JPL's expenditures for designing and subsequently marketing this pump concept amounted to about $35,000. Discussions were held with many pump and drill bit manufacturers and oil companies with regard to a possible joint development program. In general, manufacturers expressed little interest because of the lack of a ready market for such a pump. JPL's efforts related to this pump were suspended in 1977.

A.8 GARDNER-DENVER COMPANY

The Gardner-Denver PZ line of commercially available mud pumps has a maximum pressure rating of 5,500 psi for short-term operation. These pumps are generally used for continuous operation at pressures in the 1,800 to 2,500 psi range, with pressures rarely exceeding 3,500 psi. A French Company, Forex, reportedly drilled continuously between 3,500 and 5,000 psi with PZ model pumps. There is presently no major development effort to extend the pressure range of these mud pumps, due to the lack of a ready market. It should be noted that Gardner-Denver PZ-9 pumps with modified fluid ends were employed in both the Exxon and Shell water jet drilling programs discussed previously.

*Applications of Aerospace Technology to Petroleum Explorations", JPL Document 5040-32, September 30, 1976.

Gardner-Denver's commercially available swivels are rated at 5,000 to 6,000 psi under static (i.e., non-rotating) test conditions, but are generally operated at 3,000 psi or less in the field. An effort is now underway to certify these swivels for field operation at pressures up to 5,000 psi by means of dynamic tests.

A.9 FLOW INDUSTRIES

Flow Industry has developed high-pressure equipment for a variety of industrial applications. High-pressure intensifiers developed and manufactured by Flow are discussed in Section 3.2.2.

Flow Industries has also conducted R&D on high pressure swivels. Typical design conditions for this R&D include pressures up to 60,000 psi, water flow rates less than 10 gpm, and high rotational speeds (e.g., 1,000 rpm). A high-pressure swivel was developed and employed for laboratory tests of the high-pressure water jet coring system described in Section 3.1.8. It should be noted, however, that Flow has not attempted to develop swivels specifically for use in downhole drilling in the field with high-pressure drilling muds.

APPENDIX B

Literature Search and Telephone Interviews

The information presented in this report was obtained by means of an in-depth search of the published literature, review of pertinent documents, and telephone interviews with identified experts in the area of water jet drilling.

Computerized searches were made of the following data bases:

- Energy Data Base of the DOE/RECON System
- Energyline (which includes the NTIS data base) of the Lockheed/DIALOG System
- Maritime Research Information (MRIS) of the Lockheed/DIALOG System
- Oceanic Abstracts of the Lockheed/DIALOG System
- American Petroleum Institute (API) data base of the System Development Corporation/ORBIT System.

These computerized searches were complemented by manual or in-person searches of the Oil and Gas Abstracts, Petroleum Abstracts (1970-1979), Applied Science and Technology Abstracts (1978-1979), Journal of Petroleum Technology (1979), Drilling (1979), Drilling Contractor (1979), Journal of Canadian Petroleum Technology (1979), Petroleum Engineering International (1979), and Oil and Gas Journal (1979). While each of these listed journals was included in the above computerized data bases, recent issues were individually reviewed to ensure that the most up-to-date information would be available for this study.

As a result of the literature search, approximately 100 relevant papers, articles, and reports were obtained and reviewed. A list of leads or "key players" to be contacted for additional information was thereby assembled. Telephone interviews were subsequently conducted with each of the individuals shown in Exhibit 6. It can be seen from Exhibit 6 that nearly 100 experts in government, industry, universities, research institutes, and other organizations were contacted and interviewed.

EXHIBIT 6

TELEPHONE INTERVIEWS

Government

- Cliff Carwile, U.S. DOE, Division of Geothermal Energy, Washington, D.C.
- Morris Skalka, U.S. DOE, Division of Geothermal Energy, Washington, D.C.
- Lowell Gibbs, U.S. DOE, Division of Fossil Fuel Extraction, Washington, D.C.
- Hamilton Reese, U.S. DOE, Division of Fossil Fuel Extraction, Washington, D.C.
- David Glowka, U.S. DOE, Sandia Laboratories, Albuquerque, New Mexico
- Charles H. Huff, U.S. DOE, Sandia Laboratories, Albuquerque, New Mexico
- Charles C. Carson, U.S. DOE, Sandia Laboratories, Albuquerque, New Mexico
- Marvin Timmerman, U.S. DOE, Sandia Laboratories, Albuquerque, New Mexico
- John Rowley, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
- C. Ray Williams, U.S. DOE, Bartlesville Energy Technology Center, Bartlesville, Oklahoma
- Howard E. Parkinson, U.S. DOE, Carbondale Mining Technology Center, Carbondale, Illinois
- Richard Coryell, National Science Foundation, Washington, D.C.
- William W. Hakala, National Science Foundation, Washington, D.C.
- George Savanick, U.S. Bureau of Mines, Twin Cities Mining Research Center, Twin Cities, Minnesota

EXHIBIT 6
(Continued)

- Don Linger, Office of Research, U.S. Department of Transportation, Washington, D.C.

- Arnold Harak, Laramie Energy Technology Center, Laramie, Wyoming

- G. A. Cristy, U.S. DOE, Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee

- Malcolm Mellor, Cold Regions Research and Engineering Laboratory, U.S. Army, Hanover, New Hampshire

Industry

- Norman Coggeshall, Gulf Research and Development Company, Pittsburgh, Pennsylvania

- John Fair, Gulf Research and Development Company, Pittsburgh, Pennsylvania

- Clinton W. Cole, Section Supervisor, Mechanical R&D Department, Halliburton Services, Duncan, Oklahoma

- Fred Deily, Senior Research Associate, Exxon Production Research Company, Houston, Texas

- Joe Heilhecker, Brandt Co., Houston, Texas

- W. C. Maurer, Maurer Engineering, Houston, Texas

- F. G. Keightley, Manager of Technical Services-Exploration and Production, Shell Oil Company, Houston, Texas

- Edward M. Galle, Vice President, Engineering and Research, Hughes Tool Company, Houston, Texas

- Joseph Vincent, Director of Research, Smith Tool Division of Smith International, Inc., Irvine, California

- Jean Ott, Vice President of Engineering, Mining Service and Equipment Division, Dresser Industries, Dallas, Texas

- Walter E. Littman, Vice President of Research and Engineering, Security Division, Dresser Industries, Dallas, Texas

EXHIBIT 6
(Continued)

- Dewey Theissen, Vice President of Engineering, Reed Tool Company, Houston, Texas
- Bill Schumacher, Manager of Research, Reed Tool Company, Houston, Texas
- John W. Erickson, Vice President, Engineering, KOBE, Inc. Huntington Park, California
- Bruce Walker, Manager of Research, Christiansen Diamond Products, Salt Lake City, Utah
- Kenneth Blenkarn, Research Director, AMOCO Production Co., Tulsa, Oklahoma
- Milton Gravley, Mobil Research and Development Corporation, Dallas, Texas
- T. K. Perkins, Head of Well Mechanics Division, Drilling and Well Completions, Atlantic Richfield Company (ARCO), Dallas, Texas
- Don Carter, Product Manager - Drilling Machinery, Petroleum Machinery Division, Gardner-Denver Company, Dallas, Texas
- Mike Rizzone, Director of Product Engineering and Development, U.S. Steel, Oilwell Division, Dallas, Texas
- Jean Richardson, Chief Project Engineer, Rig and Pump Engineering, Continental Emsco, Houston, Texas
- E. T. Roberts, Chief Engineer, TRW Mission, Houston, Texas
- Samuel L. Collier, Manager of Research and Devleopment, TRW Mission, Houston, Texas
- Sidney Green, Drilling Research Laboratory, Terra Tek, Inc., Salt Lake City, Utah
- James M. Reichman, Director of Applied Technology, Flow Industries, Kent, Washington
- Joan B. Cheung, Flow Industries, Kent, Washington

EXHIBIT 6
(Continued)

- Gene Yie, Flow Industries, Kent, Washington
- Robert P. Radtke, NL/HYCALOG, Houston, Texas
- Andrew F. Conn, Principal Research Scientist, HYDRONAUTICS, Inc., Laurel, Maryland
- B. Bohli, Technical Director of Fluid Systems Daedalean Associates, Inc., Woodbine, Maryland
- Chapman Young, Science Applications, Inc. (SAI), Fort Collins, Colorado
- Gordon French, Science Applications, Inc (SAI) Morgantown, West Virginia
- P. D. Lohn, TRW Defense and Space Systems Group, Redondo Beach, California
- John C. Harding, Foster-Miller Associates, Waltham, Massachusetts
- Peter Albertini, Foster-Miller Associates, Waltham, Massachusetts
- Mukund Gangal, Supervisor of Special Projects, Ingersoll-Rand Research Center, Princeton, New Jersey
- E. T. Moore, Vice President and Director of Applied Sciences, Physics International Company, San Leandro, California
- Eugene Nebeker, Scientific Associates, Inc., Santa Monica, California
- A. A. Sheshtawy,President, International Petroleum Engineering Corporation, Norman, Oklahoma
- J. F. Melaugh, Consultant, Tulsa, Oklahoma
- B. J. Livesay, Livesay Consultalnt, San Diego, California

EXHIBIT 6
(Continued)

- T. J. Labus, Scire Corporation, Downers Grove, Illinois

- Ken Mohrlok, Manager-Domestic Sales, McCartney Manufacturing Company, Inc., Baxter Springs, Kansas

- Bruce Bray, Mining Research Division, Continental Oil Company (CONOCO), Ponca City, Oklahoma

- Elard Haden, Continental Oil Company (CONOCO), Ponca City, Oklahoma

- Ray Chadwick, Electronic and Engine Control Systems Group, Bendix Research Laboratories, Newport News, Virginia

- William Lyle, President, Exotech, Inc., Gaithersburg, Maryland

- L. L. Clipp, Richards Corporation, McLean, Virginia

- William C. Cooley, President, Terraspace, Inc., Rockville, Maryland

- James Friant, Manager of Market Development, the Robbins Company, Seattle, Washington

- James Langley, Sales Manager, Partek Corporation, Houston, Texas

Universities and Research Institutes

- G. B. Clark, Professor Mining Engineering, Colorado School of Mines, Golden, Colorado

- Fun Den Wang, Professor of Mining Engineering and Director of Excavation Engineering and Earth Mechanics Institute, Colorado School of Mines, Golden, Colorado

- B. J. Mitchell, Professor Petroleum Engineering, Colorado School of Mines, Golden, Colorado

- John Sharer, Gas Supply Division, Gas Research Institute, Chicago, Illinois

EXHIBIT 6
(Continued)

- D. A. Summers, Professor of Mining Engineering and Director of Rock Mechanics and Explosives Research Center, University of Missouri-Rolla, Rolla, Missouri

- Ethan Platt, Lawrence Livermore Laboratory, University of California, Livermore, California

- Roger B. DeBar, Lawrence Livermore Laboratory, University of California, Livermore, California

- Paul Brown, Lawrence Livermore Laboratory, University of California, Livermore, California

- Harry Brandt, Professor of Mechanical Engineering, University of California, Davis, California

- Roy Knapp, Chairman of Petroleum, Engineering Department, University of Oklahoma, Norman, Oklahoma

- M. Sturville, Chairman of Mining and Petroleum Department, New Mexico Institute of Mining Technology, Socorro, New Mexico

- J. J. Azar, Chairman of Petroleum Engineering, University of Tulsa, Tulsa, Oklahoma

- Leonard Jaffe, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

- Paul Gordon, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

- William H. Spuck, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

- Robert Henschel, Institute of Gas Technology, Chicago, Illinois

- Lynnard Tessner, Research Engineer, Engineering and Experimentation Station, Georgia Institute of Technology, Atlanta, Georgia

- K. F. Neusen, Associate Professor of Mechanical Engineering and Assistant Dean, University of Wisconsin, Milwaukee, Wisconsin

EXHIBIT 6
(Continued)

- Steven C. Crow, Professor of Mechanics and Structures, University of California, Los Angeles, California

- John Hilaris, Manager of High Pressure Technology Group, Soil and Rock Mechanics, IIT Research Institute, Chicago, Illinois

Miscellaneous (Including Foreign)

- Joseph Yanzig, National Coal Association, Washington, D.C.

- John L. Kennedy, Drilling Editor, Oil and Gas Journal, Tulsa, Oklahoma

- Edwin McGhee, Executive Vice-President, International Association of Drilling Contractors, Houston, Texas

- W. H. Brierley, Division of Mechanical Engineering National Research Council, Ottawa, Canada

- David Burns, Department of Mechanical Engineering, University of Waterloo, Ontario, Canada

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980—671-115/61