

National Advanced Drilling  
and  
Excavation Technologies Program

Summary of the Fifth Meeting  
of  
Interested Federal Agencies

January 17, 1995

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# **National Advanced Drilling and Excavation Technologies Program**

## **Fifth Meeting of Interested Federal Agencies**

### **Meeting Summary**

The fifth meeting of Federal agency representatives interested in advanced drilling and excavation technologies took place on January 17, 1995. The Geothermal Division of the U.S. Department of Energy (DOE) hosted the meeting at the Washington, D.C., offices of DOE. Representatives from the National Science Foundation, U.S. Bureau of Mines, National Aeronautics and Space Administration, U.S. Army and various offices within the Department of Energy attended. The meeting agenda is provided in Appendix A and a list of attendees can be found in Appendix B.

Allan Jelacic, Acting Director of the Geothermal Division, opened the meeting by welcoming the participants and having attendees introduce themselves. He explained the purpose of the meeting was to exchange information on the various FY 1995 research efforts in drilling and excavation underway or planned by the agencies and to discuss a prospective research coordination agreement under consideration in the Department of Energy.

Dr. Jelacic reported that a coordination agreement had been negotiated among five DOE offices (Fossil Energy, Environmental Management, Civilian Radioactive Waste Management, Energy Efficiency, and Energy Research). The agreement represents an initial attempt to coordinate the various research interests of the offices under the auspices of the National Advanced Drilling and Excavation Technologies (NADET) program. Under the terms of the agreement, each office retains independent control over its research program but shares information with the other offices. The five offices have identified research projects totalling over \$10 million in FY 1995 funds that come under the agreement. Other Federal agencies may participate in the agreement, and Dr. Jelacic invited them to do so.

Dr. Jelacic reported that a new survey had been mailed out the previous week seeking volunteers to participate in planning, peer review, and research for the NADET Program. Apart from the survey, he reported, NADET is being promoted through a newsletter, industry meetings, technical presentations and papers, and a brochure currently in preparation.

Two studies being co-funded by the Geothermal Division and Morgantown Energy Technology Center - a review of Russian technical drilling literature by Maurer Engineering and a drilling

systems study underway at Sandia National Laboratory were mentioned. The report on Russian drilling is virtually done, but requires editing before publication sometime this spring. The Sandia report will evaluate advanced technologies against basic drilling functions and should also be completed this spring.

**Bill Luth**, DOE Office of Energy Research, was recognized for his efforts in "jump starting" the research and development (R&D) phase of NADET through the inclusion of an advanced drilling category in the Small Business Innovative Research (SBIR) solicitation. The solicitation, which closes March 1, 1995, was sent to all 300 persons on the NADET mailing list.

According to Dr. Jelacic, the ultimate cost of the NADET program could be \$250 - \$500 million over eight years, with the government contributing up to 60%. Appendix C contains a copy of Dr. Jelacic's slides.

**Peter Smeallie**, ROM, asked about the current status of the proposed "NADET Institute." Dr. Jelacic answered that DOE has received an unsolicited proposal from the Massachusetts Institute of Technology to establish such an institute and that a decision should be reached in 4 to 6 weeks.

**Roy Long**, DOE Yucca Mountain Project, presented an overview of DOE's radioactive waste isolation project in Nevada. He reported the project's 25-foot diameter tunnel boring machine (TBM) is currently operating and is 450 feet down an inclined tunnel. The tunneling was very slow initially due to unexpected rock types for which the TBM was not designed. Efforts are underway to speed the progress of the TBM. Mr. Long also briefly outlined the project's surface drilling activities involving the LM300 rotary rig and dual-wall drilling system designed for the project. The system, which incorporates air as the drilling fluid, is designed to protect the borehole environment to obtain uncontaminated core samples. Their office, Mr. Long stated, is interested in developing improved polycrystalline diamond compact (PDC) bits, thermally stable polycrystalline diamond (TSP) bits, tubular technology, directional drilling, and the ability to know the exact drill bit location at all times. Mr. Long's handouts are presented in Appendix D.

**Al Yost**, of the Morgantown Energy Technology Center (METC), described the Center's program as focussing on the development of an advanced evolutionary drilling system that results in significant cost reductions by the year 2005. The program seeks to be sensitive to the market, attempting to balance technology and market pull. In studying underbalanced drilling fluids, including air, mist, foam and aerated muds, METC has found significant improvements in cost and penetration rates over traditional water based muds. Tests in Alberta, Canada, achieved faster penetration rates using an air rotary system and even faster rates using an air hammer system. Mr. Yost pointed out that underbalanced systems perform differently in differing geological environments and would need to be tested in many different geologic basins. Drilling systems under investigation by METC include percussion drilling, high-pressure jet-assisted drilling, and air motor drilling. Other projects being pursued by METC include slim hole electro-magnetic measurement while drilling, slim hole high-speed, high-torque systems, near-bit

sensors, a study of Russian downhole motor technology, an advanced drilling system study, motorless directional drilling and high pressure rotating head. A copy of Mr. Yost's view graphs is presented in Appendix E.

**Stan Calvert**, DOE Geothermal Division, presented the Geothermal Division's drilling R&D program. He said the Division is providing joint funding with DOE's Fossil Energy Office for a 50/50 industry cost shared project to improve PDC/TSP drill bits. The newly developed rolling float meter is proving successful in the early detection of drilling fluid lost circulation episodes. The program is also evaluating a Doppler flow meter for the same purpose. For treating lost circulation zones, the Division is developing a drillable straddle packer, a wireline porous packer, and cementitious muds. Other areas Mr. Calvert described included acoustic telemetry and slimhole drilling. Appendix F contains a copy of his presentation.

**Garrett Hyde**, U.S. Bureau of Mines, reported that his agency's mission has evolved from mineral extraction to remediation of environmental problems resulting from mineral extraction. The agency does not currently support any drilling R&D. He characterized his organization as more of a user rather than a developer of technology. The agency does fund about \$6 million per year to develop in situ extraction methods.

**Steve Brody** and **Al Willoughby**, both of the National Aeronautic and Space Administration, briefly described the Mission from Planet Earth program and its interest in drilling and excavation technologies. The program is interested in the long term commercial use of the solar system. One possible NASA application of drilling and excavation technology is a launch system incorporating a long tunnel in a mountain, through which a missile would be accelerated by magnets along the walls of the tunnel. Their presentation can be found in Appendix G.

**Rhonda Lindsey**, DOE Bartlesville Project Office, outlined her office's drilling related R&D. She reported they are supporting programs in synthetic diamond drill bits, top drive rig failures, wellbore stability, underbalanced drilling, advanced horizontal coiled tubing drilling, and paraffin control. Ms. Lindsey's handout material is included in Appendix H.

**Ian MacGregor**, National Science Foundation, reported his agency supports a number of drilling projects. He anticipated they will sign an agreement with Germany on February 23, 1995 to begin a multilateral scientific drilling program. Japan and France are expected to also join soon, and possibly Britain, Canada and Mexico later. The program will be science driven and drilling projects will be selected based on a review of scientific merit.

**Bill Luth**, DOE Office of Energy Research, reported on the Continental Scientific Drilling program of his office. He pointed out that the Salton Sea Scientific Drilling Project, a deep exploration of the Salton Sea geothermal field in California, was sponsored by his program. The program is proposing to drill across the San Andreas fault at a number of locations and depths to determine whether or not the fault is a high pressure one. Dr. Luth's office is interested in basic research into interaction between drill bits and rock and sensing ahead of the bit while drilling.

**George Gazonas**, Army Research Laboratory, reported that his office does not support drilling R&D, but that some of their research overlaps drilling research. His program's three areas of research include interior ballistics (the inside of the gun), exterior ballistics (the path of projectiles) and terminal ballistics (target penetration mechanics). A paper authored by Mr. Gazonas, Appendix I, describes the possible applications of military technologies to drilling.

**Jeffrey Mora**, Federal Transit Administration, said that while his agency does not support research and development, it is interested in NADET because of the great amount of money spent for mass transit tunneling. His office sees its role as a transfer agent of technology rather than a developer of technology.

The meeting was then opened for general discussion.

**Dan Entingh**, Princeton Economic Research, Inc., recommended if the NADET interagency group is intended to evolve into a cohesive group of R&D managers, then the process should start soon.

In response, Allan Jelacic stated that the focus of NADET has been to attract as many interested parties as possible, improve communications between those parties, and evolve the relationships amongst the parties toward those outlined in the coordination agreement. As far as R&D management, he envisioned that being left to the individual sponsoring agencies.

Bill Luth said that everyone needs to feel they win, and that the collaborative effort will evolve as trust evolves amongst the collaborators.

Allan Jelacic displayed a slide of organizational options (Figure 1) and noted that the group seemed to be in the mid range of the options listed.

Peter Smeallie asked if any private industry organization is devoted to the advancement of drilling R&D or if anyone is making presentations before Congress on behalf of NADET. He noted that Congress is currently interested in research that crosses agency lines and suggested that the Drilling Engineering Association (DEA) could approach Congress.

Allan Jelacic noted that a concerted effort is needed to bring in industry groups to participate in NADET and that hosting regional workshops could be key to integrating industry into NADET.

Peter Smeallie announced the creation of the "Advanced Rock Mechanics Association (ARMA)," with himself as the Executive Director. ARMA was established in October 1994 as an umbrella association organized to work for the advancement of the science and practice of rock mechanics and rock engineering. ARMA's objectives include acting as a proponent for all firms involved in rock mechanics and rock engineering, and assisting in technical transfer and information exchange efforts.

**Lynn McLarty**, DynCorp, expressed the opinion that because the success of NADET will depend on the involvement of industry not only for cost-shared funds but also for obtaining appropriations from Congress, the efforts of the NADET interagency group should become focused on soliciting involvement from industry.

Figure 1

## **National Advanced Drilling and Excavation Technologies Program**

### **Organizational Options**

- Informal exchange of information; scheduled meetings
- Loose confederation of agencies; formal information exchange
- Coordinated agency R&D programs; oversight committee
- Integrated Federal R&D program; pooled resources
- Integrated Federal-industry-university R&D program; central manager

## Appendix A

# **National Advanced Drilling and Excavation Technologies Program**

## **Fifth Meeting of Interested Federal Agencies**

**January 17, 1995**

**Hosted by  
Geothermal Division  
U.S. Department of Energy**

1:00 pm	Registration - Room 8E-089 Forrestal Building	
1:30 pm	Welcome/Introductions	John Mock
1:40 pm	Update of Activities Concerning the NADET Program	Allan Jelacic
2:00 pm	Reports of Current Research Interests of the Federal Agencies	All
3:30 pm	Open Discussion	All
4:00 pm	Closing Remarks	John Mock

## **Appendix B**

# **National Advanced Drilling and Excavation Technologies Program**

## **Fifth Meeting of Interested Federal Agencies**

### **List of Attendees**

Steve Brody	National Aeronautics and Space Administration
Stan Calvert	DOE Geothermal Division
Skip Chamberlain	DOE Office of Technology Development
Perle Dorr	Princeton Economic Research, Inc.
Eyob Easwaran	Princeton Economic Research, Inc.
Dan Entingh	Princeton Economic Research, Inc.
Ray Fortuna	DOE Geothermal Division
George A. Gazonas	Army Research Laboratory
Garrett Hyde	Bureau of Mines
Allan Jelacic	DOE Geothermal Division
Ronald Kangas	Federal Transit Administration
John Kerridge	National Aeronautics and Space Administration
Rhonda P. Lindsey	DOE Fossil Energy, Bartlesville Project Office
Roy Long	DOE Yucca Mountain Project
William C. Luth	DOE Office of Energy Research
Ian MacGregor	National Science Foundation
Lynn McLarty	DynCorp
Jeffrey Mora	Federal Transit Administration
Peter Smeallie	Research Opportunities Management
Len Volk	NIPER/BDM, Bartlesville, OK
Ray Wallace	Geological Survey
Allan Willoughby	National Aeronautics and Space Administration
Al Yost	DOE Morgantown Energy Technology Center

## **Appendix C**

# Fifth Meeting of Interested Federal Agencies

## National Advanced Drilling and Excavation Technologies Program

January 17, 1995



Department  
of Energy



National Aeronautics  
and Space Administration



Department  
of Defense



Department  
of Interior



Department  
of Transportation



National Science  
Foundation



Department  
of Commerce



Environmental  
Protection Agency



Nuclear Regulatory  
Commission

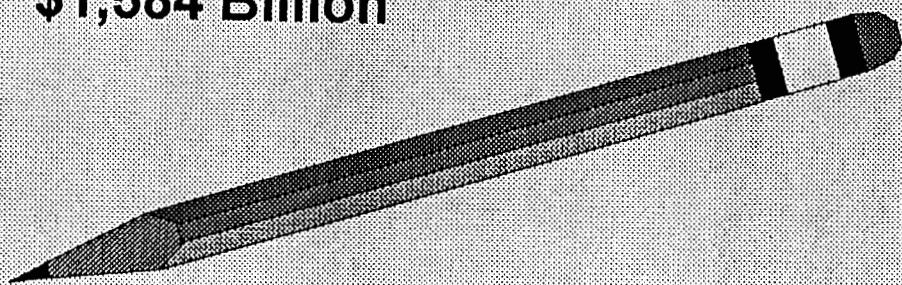
# Estimated Annual Expenditures for Worldwide Drilling and Excavation Activities

**Oil & Gas**      **\$82.2 - 100.2 Billion**

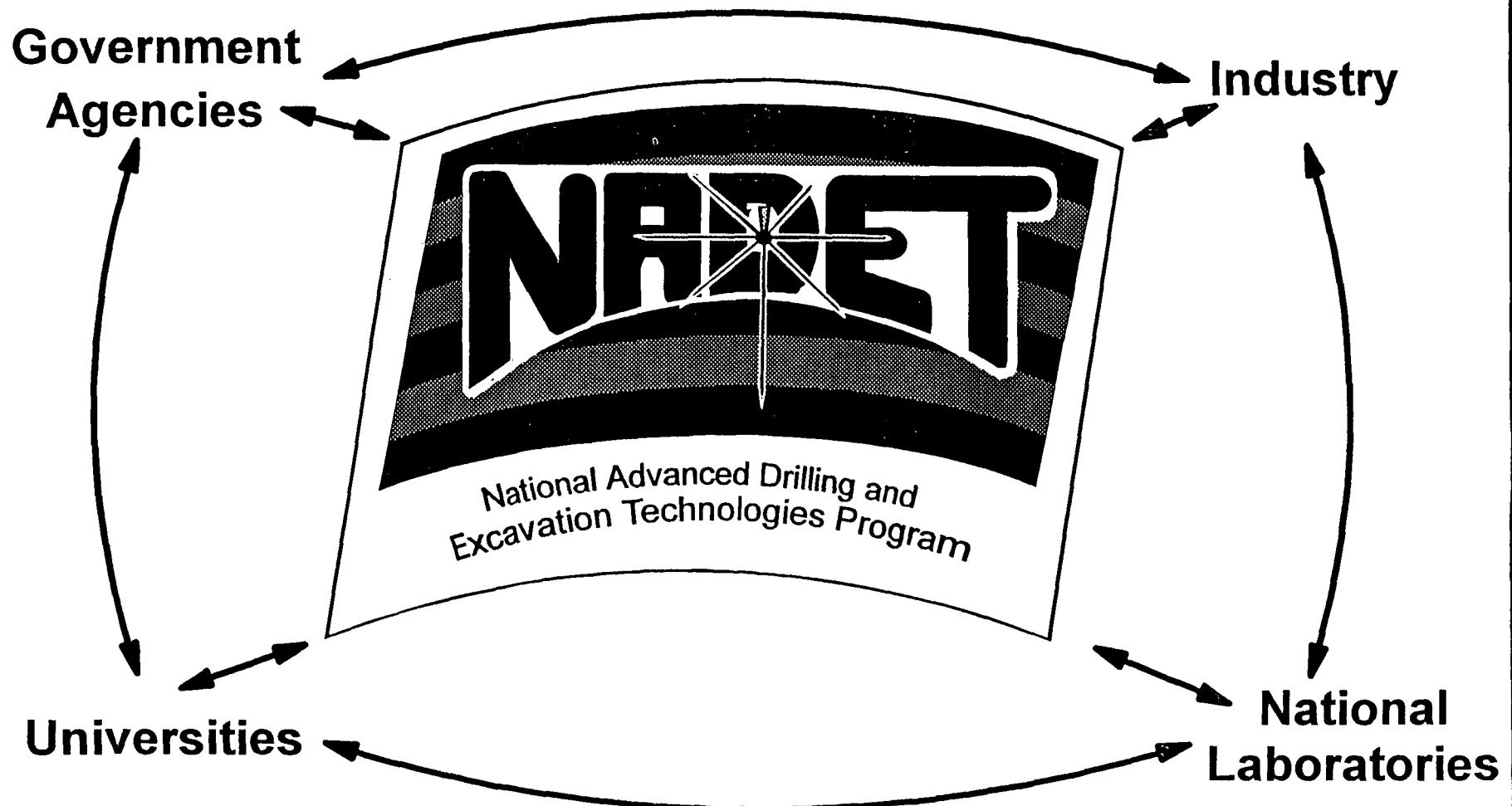
**Coal**      **\$120 Billion**

**Civil Tunnel and  
Underground  
Facilities**      **\$19.8 - 20.7 Billion**

**Mining, Drilling and  
Rock Excavation**  
(Total value of crude  
mineral production)      **\$1,584 Billion**



# NADET Program Stakeholders



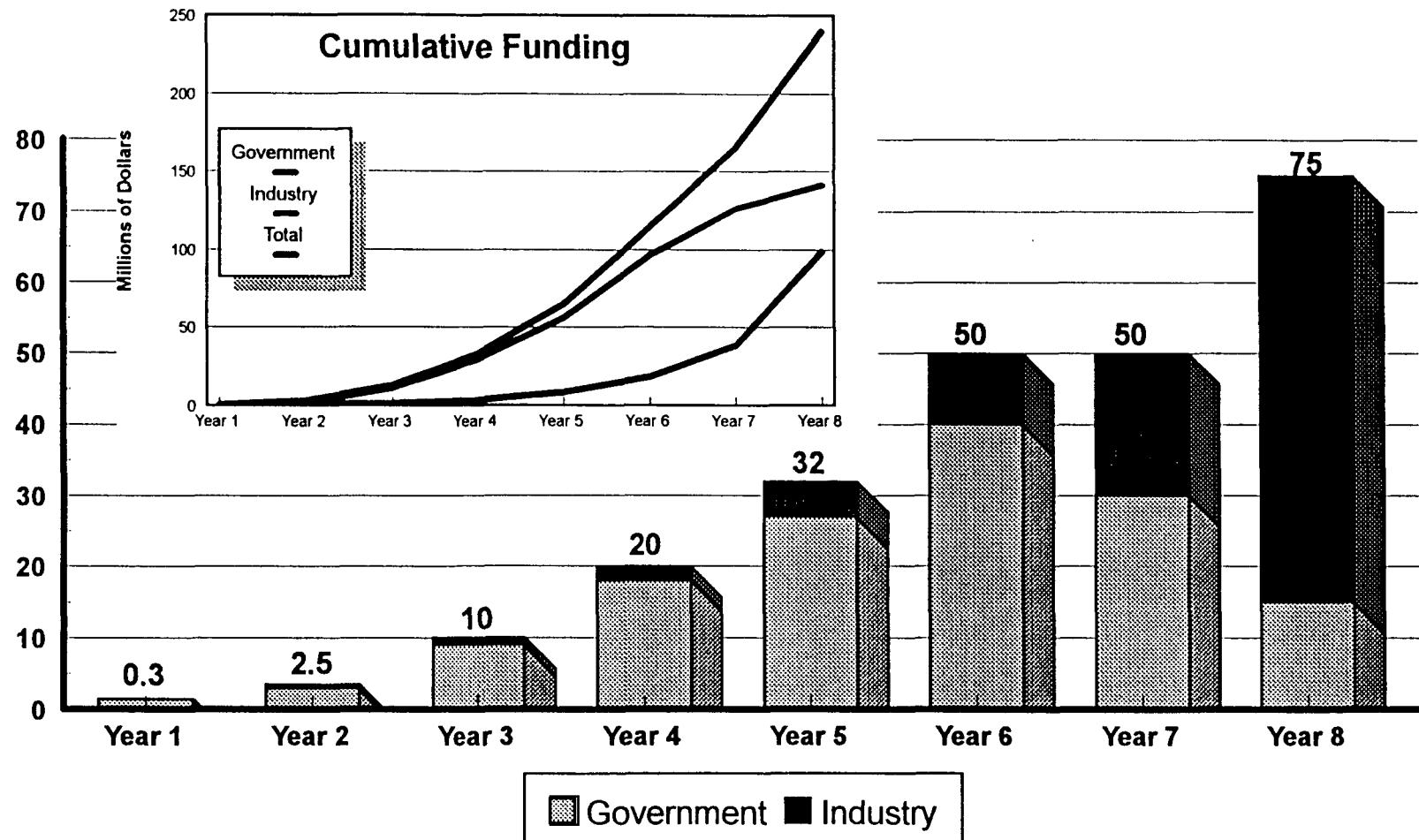
## NADET Program Phases

***Phase 1: Feasibility Analysis and Program Planning***

***Phase 2: Development of Advanced Technologies; Building and Field Testing of Prototype System***

***Phase 3: System Commercialization***

# Estimated NADET Funding

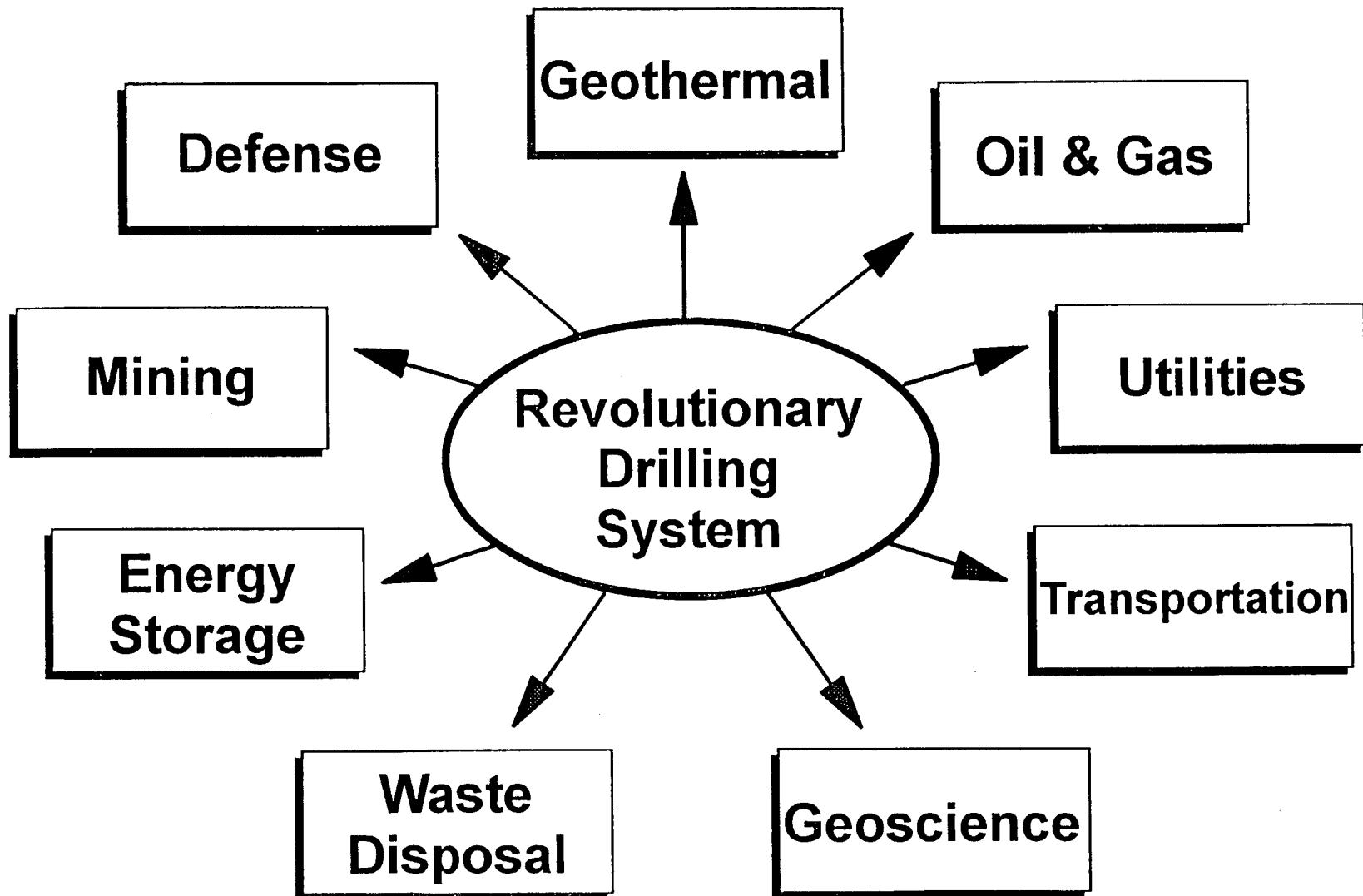


## **Spreading the Word about NADET**

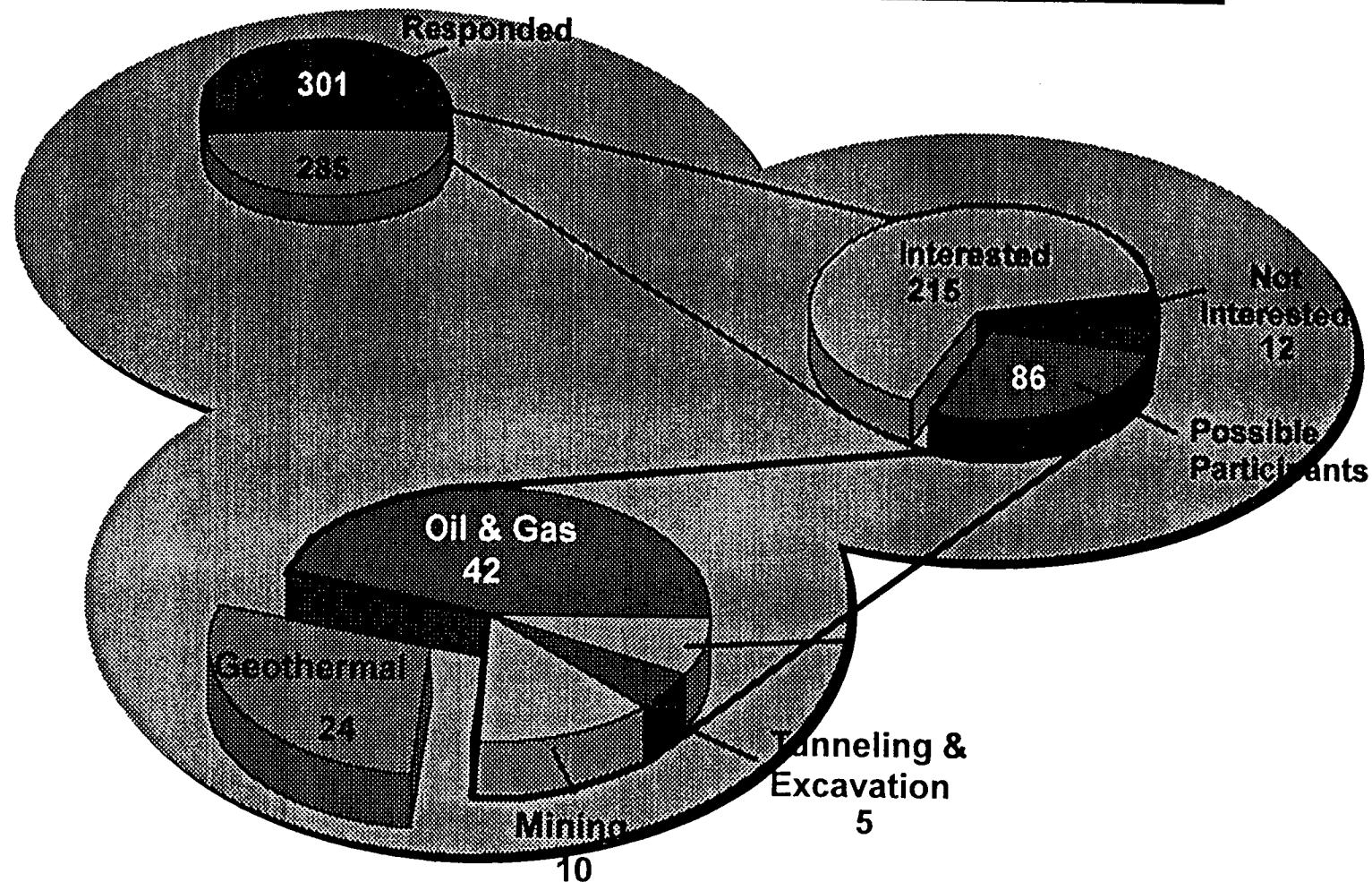
- ★ Newsletter**
- ★ Industry Meetings / Technical Papers**
- ★ Brochure**

## **Background Studies**

- ★ Review of Russian Literature**
- ★ Systems Analysis**



# Industry Survey



# NADET Funding

<b>Office</b>	<b>FY '94 Funding ( \$000)</b>	<b>FY '95 Funding ( \$000)</b>
Energy Efficiency and Renewable Energy	1,010	2,850
Fossil Energy	5,627	4,908
Environmental Management	2,271	1,975
Civilian Radioactive Waste Management	282	1,058
Energy Research	TBD	TBD
<b>Total*</b>	<b>[9190]</b>	<b>[10791]</b>

## **Review of Russian Literature**

- ★ Mechanical Techniques**
- ★ Hydraulic Techniques**
- ★ Thermal Techniques**
- ★ Electrophysical Techniques**
- ★ Combined Techniques**
- ★ Chemical Techniques**

## **Review of Russian Literature**

- ★ **Title:** Novel and Advanced Technologies for Rock Disintegration and Drilling Wells (Russian Technology)
- ★ **Objective:** Review past and current Russian work on advanced drilling technology and publish results including technology limitations and need for further R & D.
- ★ **Performer:** Team of 9 Russian Drilling Experts led by Dr. Moisey Eskin and directed (coordinated by) William C. Mauer
- ★ **Principal Investigator:** William C. Mauer
- ★ **Budget:** \$45,000 - DOE/GD  
\$25,000 - DOE/METC
- ★ **Expected Completion Date:** May, 1995

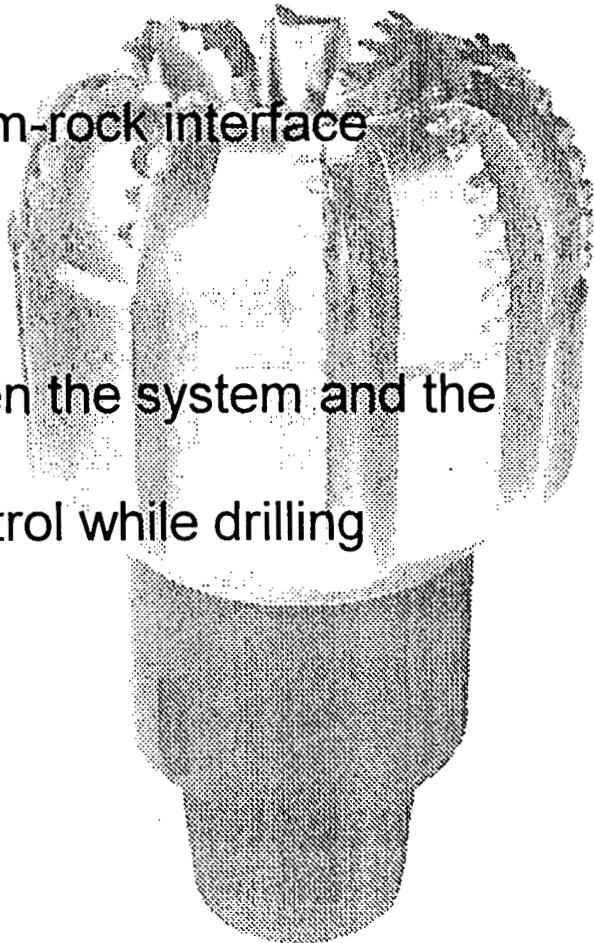
## **Advanced Drilling Systems Study**

- ★ **Title:** Advanced Drilling Systems Study
- ★ **Objective:** To identify advanced drilling concepts and evaluate these concepts from the perspective of the entire system required to drill, maintain, and complete a well.
- ★ **Performer:** Sandia National Laboratory
- ★ **Principal Investigator:** Kenneth Pierce
- ★ **Budget:** \$300k
- ★ **Expected Completion Date:** Spring, 1995

# Advanced Drilling Systems Study

## ★ Basic Drilling Functions:

- Transmission of energy to the system-rock interface
- Reduction of the rock
- Removal of the rock
- Directional drilling and control
- Sensing and communication between the system and the operator
- Borehole maintenance and well control while drilling
- Preservation of the borehole



## **Advanced Drilling Systems Study -- Expected Outcomes**

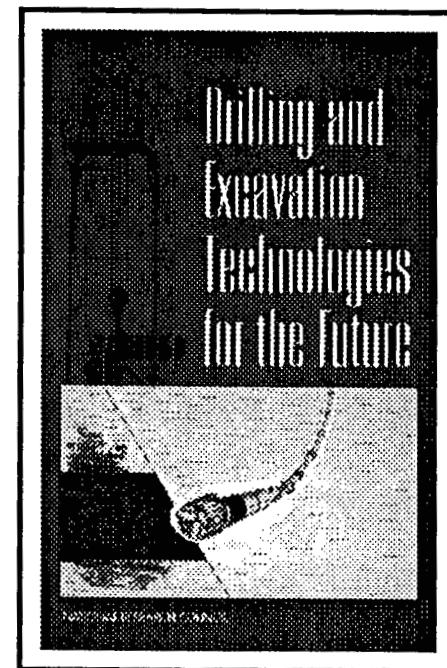
- ★ **Provide system descriptions:**
  - Basic and function descriptions
  - Environmental and safety concerns
  - Particular capabilities and advantages
  - System technical / financial limitations
- ★ **Estimate capital and operating costs**
- ★ **Assess performance:**
  - Relative to current technology
  - Variation with rock type and hardness
  - Rate of penetration (order-of-magnitude)
- ★ **Identify common problems**
- ★ **Outline possible development program:**
  - Technical problems and needs
  - Likelihood of success

## **Advanced Drilling Systems Study -- Systems Investigated**

- ★ Standard "conventional" technology
- ★ Advanced "conventional" technology
- ★ Water Jet/Rotary Hybrid
- ★ Explosive/Rotary Hybrid
- ★ Spark/Rotary Hybrid
- ★ Microwave/Rotary Hybrid
- ★ Hydraulic Hammer
- ★ Thermal Spallation Jet
- ★ High-Pressure Jet
- ★ Spark Drill
- ★ Explosive Drill
- ★ Pulsed-Laser Water Jet
- ★ Plasma Arc

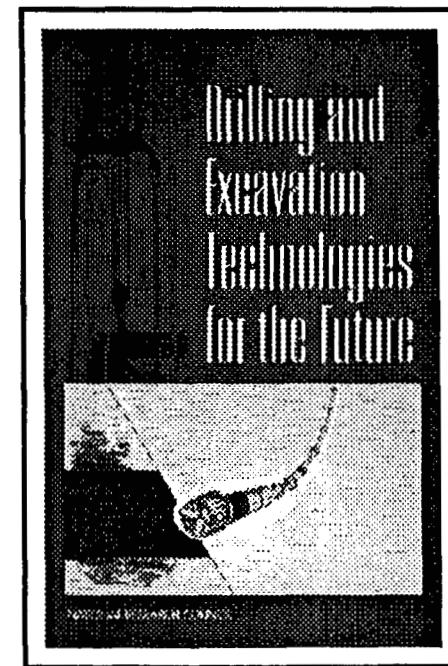
## National Research Council Study -- Recommendations

- ★ R & D needed in Advanced Drilling technology to improve the drilling system (both long-term/short-term)
- ★ Principal R & D thrust in smart drilling system
  - Rock properties
  - Sensors
  - Control systems
  - Steering methods
  - Telemetry
  - Support of borehole



## National Research Council Study -- Recommendations

- ★ Incremental improvements of present drilling technology
  - Cutting materials, bearings and bits
  - Environmentally benign fluids
  - Downhole motors
  - Novel drilling technology
- ★ R & D program a national effort



# Participants Response Form

	<p>Please indicate whether you wish to become a participant in the National Advanced Drilling and Excavation Technologies (NADET) Program of the Department of Energy by completing this form.</p>
<p><input checked="" type="checkbox"/> Yes, I would like to participate actively in the NADET Program. The area(s) I wish to be considered as a participant include(s):</p> <p><input type="checkbox"/> Planning: One or more planning committees will advise Program Officers about appropriate research activities that should be undertaken within the overall context of the Program. The committees will lay out projected research projects, along with estimated budgets and schedules.</p> <p><input type="checkbox"/> Peer Review: Panels of experts will review and recommend proposals for funding under NADET. The panels will also periodically review the progress of sponsored research projects and recommend changes in content and scope.</p> <p><input type="checkbox"/> Research: Individuals, universities, private companies, or any eligible organization will receive contracts, grants, and cooperative agreements to perform research as identified in Requests for Proposals (RFP) issued by Program Officers.</p> <p><input type="checkbox"/> Financing: A sponsor's committee, composed of funding organizations (i.e., Federal agencies, private companies, industrial consortia), will provide oversight, review and policy guidance to the Program.</p> <p><input checked="" type="checkbox"/> No, I do not wish to participate in NADET at this time. However, continue to send me information about the Program.</p> <p><input checked="" type="checkbox"/> I am no longer interested in NADET. Please remove my name from your mailing list.</p>	
<p>Please indicate your views on the idea of holding regional workshops on NADET by answering the following:</p> <p><input type="checkbox"/> Yes, I would attend a regional workshop to discuss research priorities for NADET. Locations I would find convenient for such a workshop include:</p> <hr/> <hr/> <hr/> <p><input type="checkbox"/> Other approaches I would suggest for sharing information about research needs for NADET include:</p> <hr/> <hr/> <hr/> <hr/>	

## Phase 2 Activities

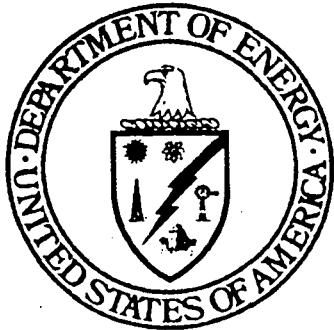
### **Small Business Innovation Research (SBIR) Program Solicitation**

#### **Advanced Drilling Technologies**

- Drill bit sensing and evaluation
- Formation properties sensing and evaluation
- Drill bit positioning and steering
- Borehole stabilization

**Closing date: March 1, 1995**

## **Appendix D**

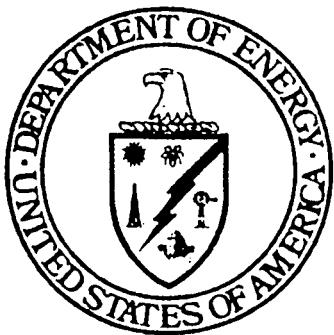


# YMP DEVELOPMENT INTERESTS

- TUNNEL BORING MACHINE TECHNOLOGY
- DRY, HARD-ROCK DRILLING & WIRELINE CORING
- DUAL-WALL DRILLING TECHNOLOGY  
(LOW FORMATION DAMAGE)
- PDC/TSP BIT TECHNOLOGY  
(INCREASED PENETRATION IN HARD ROCK)
- TUBULAR TECHNOLOGY  
(COMPOSITES - FATIGUE RESISTANCE)
- CUTTINGS CONTAINMENT / SAMPLING TECHNOLOGY
- DIRECTIONAL AND ANGLE DRILLING TECHNOLOGY

YUCCA  
MOUNTAIN  
PROJECT

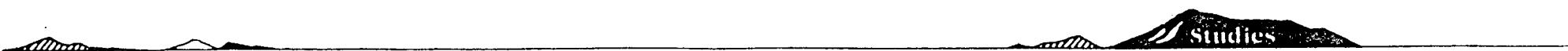




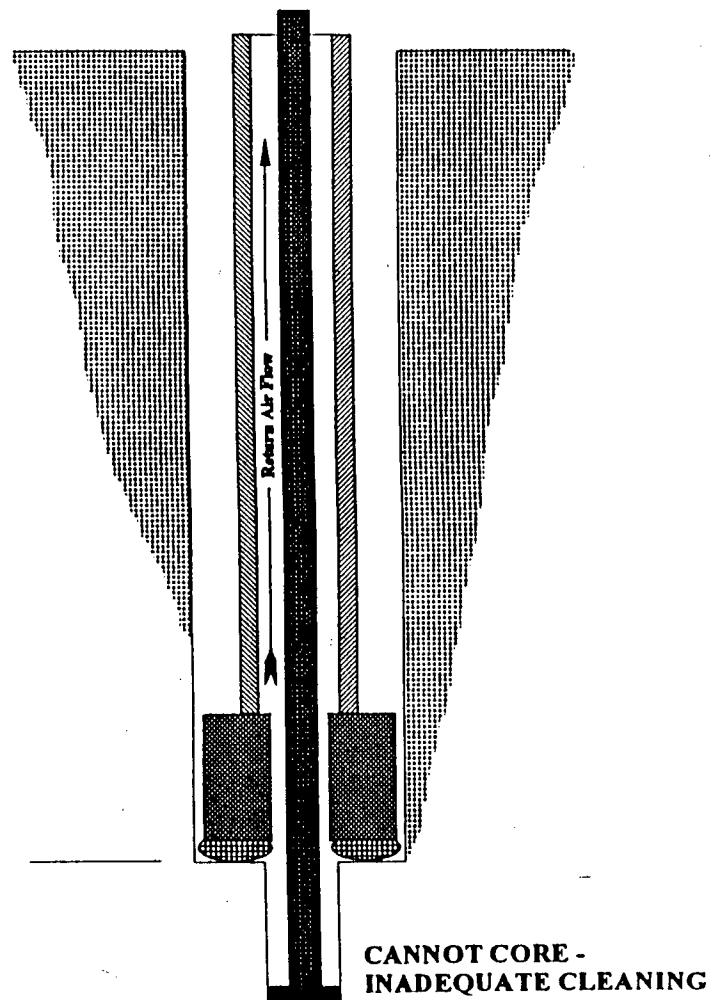
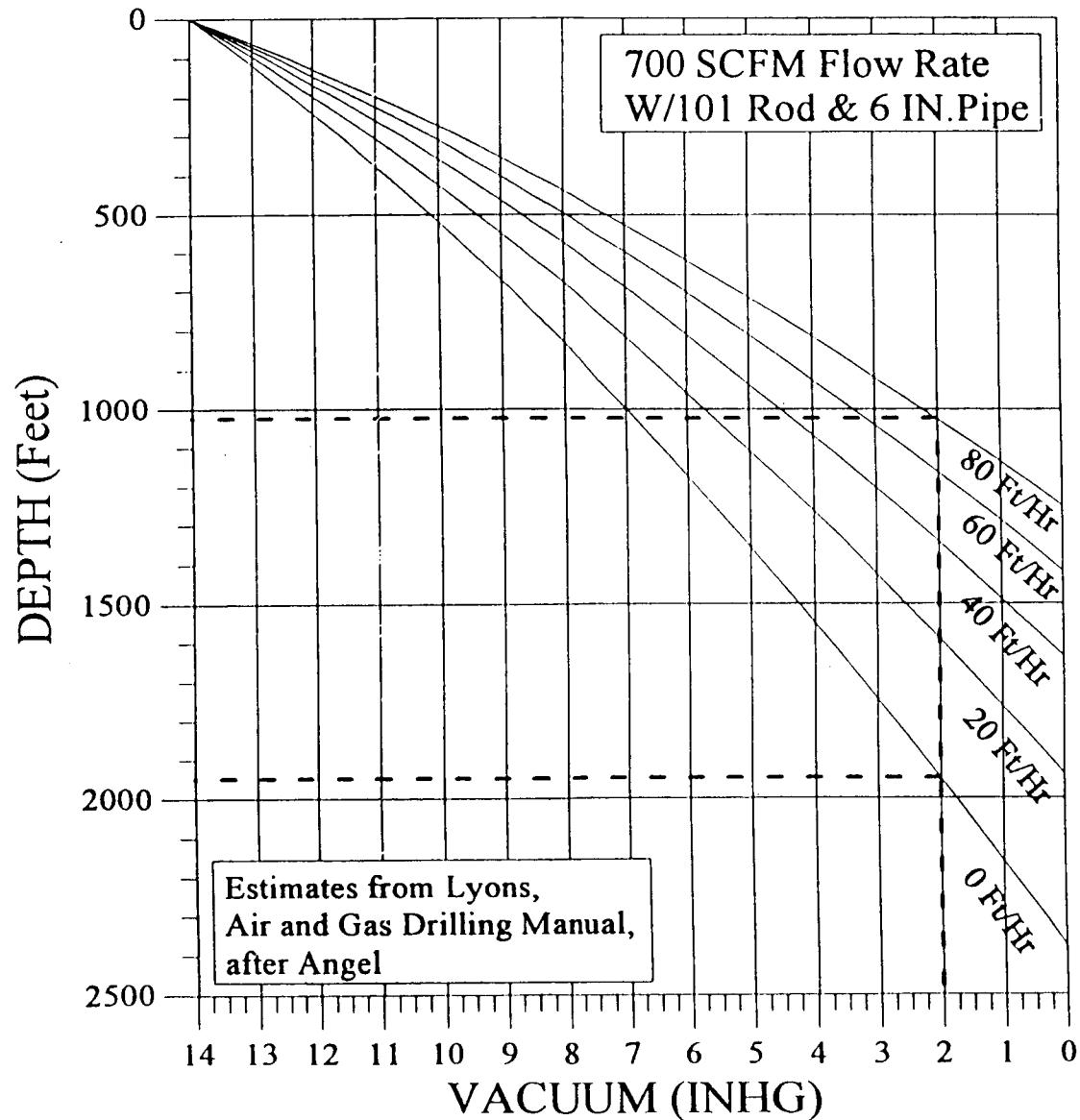
# YMP DEVELOPMENT PROGRAMS

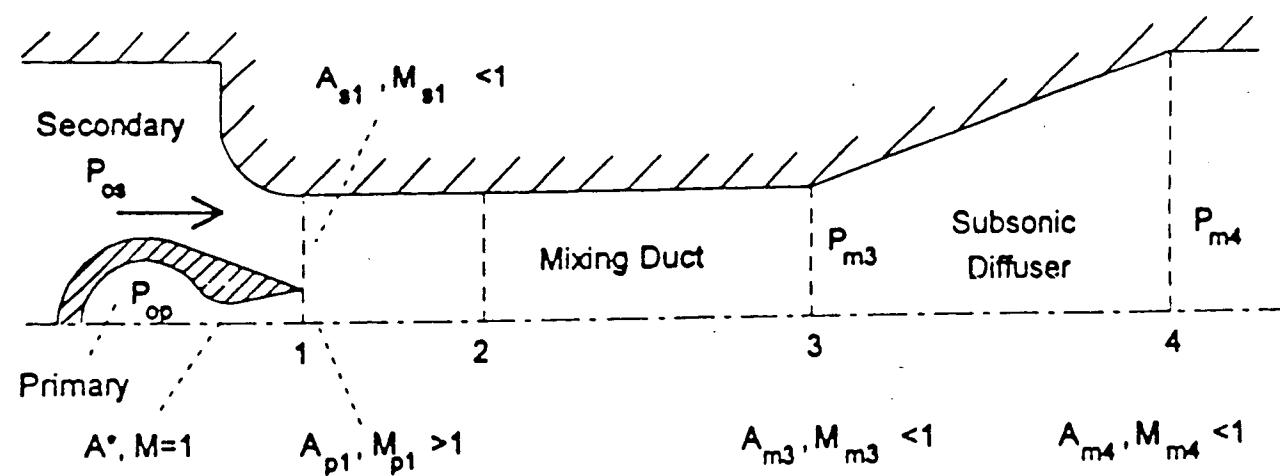
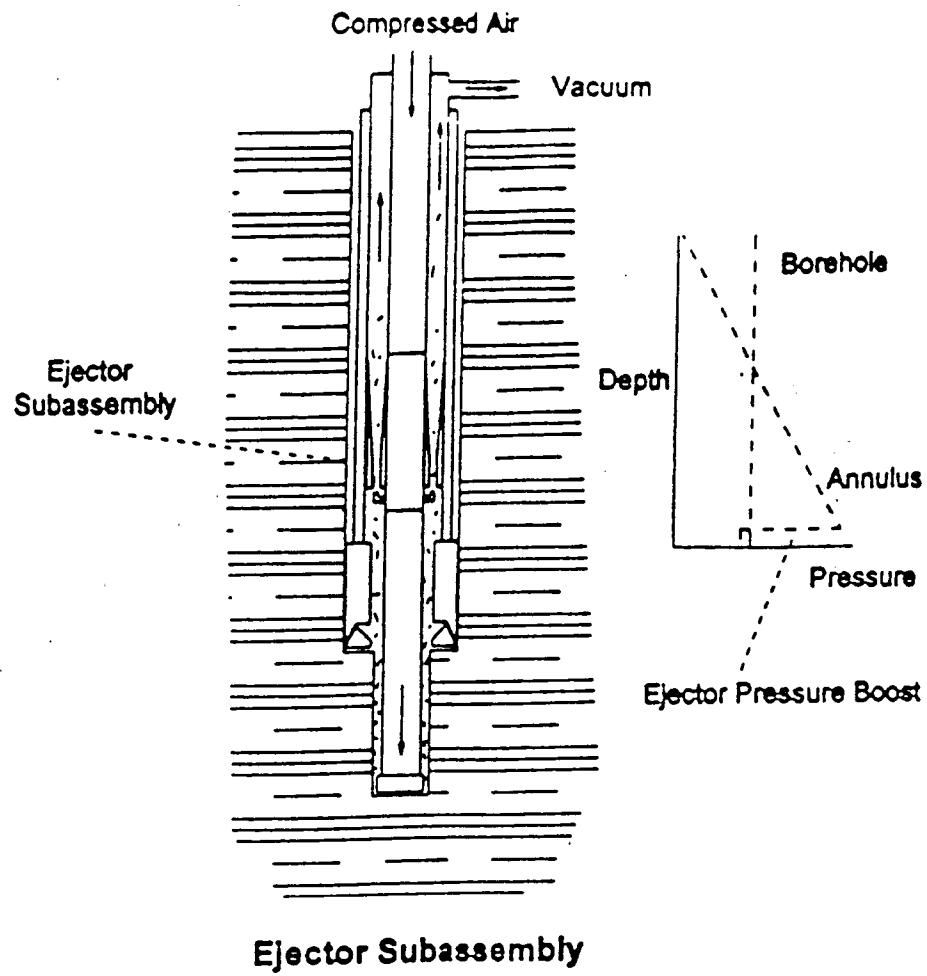
ACTIVITIES	PARTICIPANTS	FY94 FUNDING (\$000)	FY95 FUNDING (\$000)
Prototype testing of minidisk cutter for use in construction of ESF alcoves	Colorado School of Mines Earth Mechanics Institute	200	400
Construction of open center Dual-Wall drill bit with retrievable center cone	Rock Bit Industries	0	100
Air flow simulator for "balanced air" circulation analysis during coring	Colorado School of Mines	0	220
Core Rod ejector sub construction and testing	Quest Integrated, Inc.	0	288
Electrocoring Tool development	Ruhle & Associates	0	50
Core Rod ejector sub feasibility analysis	Quest Integrated, Inc.	26	0
Analysis and Computer Model of Core Rod Vibration with PDC core bits	Colorado School of Mines	56	0
<b>TOTAL</b>		<b>282</b>	<b>1058</b>

YUCCA  
MOUNTAIN  
PROJECT



# BALANCED AIR CORING CAPABILITY (14 INHG Vacuum At Rotary Head)





Ejector Geometry and Definitions

# Field Experience with Wireline Coring through a Dual Wall Drilling System

**R. Long**

Department of Energy

Yucca Mountain Site Characterization Project

Las Vegas, Nevada

**E. Wright**

Raytheon Services Nevada

Las Vegas, Nevada

**U. Clanton, retired.**

Department of Energy

Yucca Mountain Site Characterization Project

Las Vegas, Nevada

**D. Wonderly**

Reynolds Electrical and Engineering Company

Yucca Mountain Site Characterization Project

Las Vegas, Nevada

## Introduction

Dual Wall drilling systems have been used for many years in the mining industry to obtain relatively uncontaminated samples of potential ore bodies from deep boreholes. The Department of Energy's Yucca Mountain Site Characterization Project Office (YMP) is presently utilizing an extension of this technology (Long *et al.*, 1992) to acquire subsurface samples for study of the unsaturated zone overlaying a horizon of volcanic rock which will potentially host the nation's first underground repository for high level nuclear waste. A thorough understanding of the "undisturbed" nature of the unsaturated zone is essential for determining the suitability of the site to comply with licensing requirements which presently require consideration of conditions over a period of 10,000 years. As a result of this need for detailed scientific information, the sampling system for the site vertical borehole program at Yucca Mountain must be able to acquire continuous core and leave the borehole as close to in situ conditions as possible. The dual wall sampling system developed through YMP's Prototype Drilling Program has proven successful in acquiring geologic samples suitable for site characterization studies.

The YMP initiated field drilling operations on its first deep unsaturated zone exploratory borehole at Yucca Mountain, Nevada, in the Spring of 1992. This present 12-1/4 inch diameter borehole, UZ-16, is planned to a depth of approximately 1700 feet (40 feet below the water table). Drilling has been limited to daylight only operations, 5 days per week, because of the startup of several segments of the field program. Though little recognized, the dual wall sampling method actually increases overall efficiency for single shift operations because it allows for the dual wall pipe to be left in the hole during periods of inactivity without fear of hole conditions deteriorating to a point that operations are affected.

Experience to date indicates that difficulties associated with drilling and coring in a dry, abrasive environment to the planned depths of approximately 2600 feet appear manageable. Program initiatives are now focused in the following areas: 1) Reduction of the time required to accomplish the intensive sampling; 2) Improving overall system resistance to fatigue, and; 3) increasing capability for successful uncontaminated sampling (both core and borehole) at maximum planned depths.

## System Description

Figures 1 through 6 are added to facilitate discussion of the various downhole and surface components of the dual wall sampling system. The first two figures are taken from Long *et al.*, 1992, and depict the basic downhole coring and reaming components. As shown in figure 1, core is taken with a CHD-101 (3.7 inch OD rod) coring assembly through 9-5/8 inch OD, by 6 inch ID, dual wall drill pipe. A 2.4 inch diameter core is retrieved in this manner leaving a 4-3/8 inch core track and a 12-1/4 inch finished borehole. Air is circulated in a conventional manner during coring, down the inside of the core rod and back to surface between the core rod and inner tube of the dual wall pipe. A vacuum is used to insure that a preferential path is maintained at the reaming bit for the cuttings and air to be pulled into the dual wall pipe instead of being blown around the reaming bit and contaminating the borehole. Some risk of formation damage is accepted in the core track in order to acquire core; however, the worst of the damage should be removed during the reaming cycle.

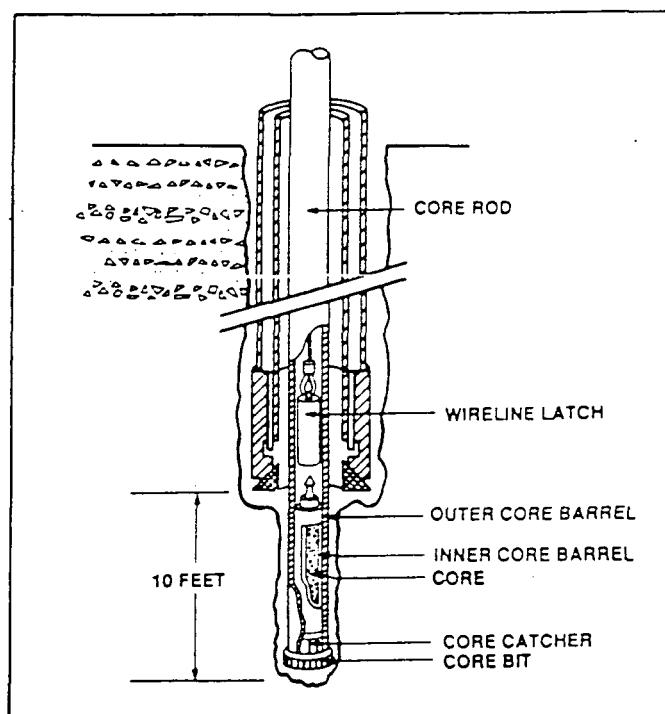


Figure 1. Wireline coring with the dual wall system.

Core samples are taken as much as 40 feet ahead of the dual wall reaming assembly in typical wireline increments of 10 feet each. The maximum core-ahead interval of 40 feet, established during the Prototype Drilling Program, appears to also be a present functional limit for operations at Yucca Mountain. The limber core rod usually begins to deviate excessively beyond 40 feet causing difficulties during the ream down cycle.

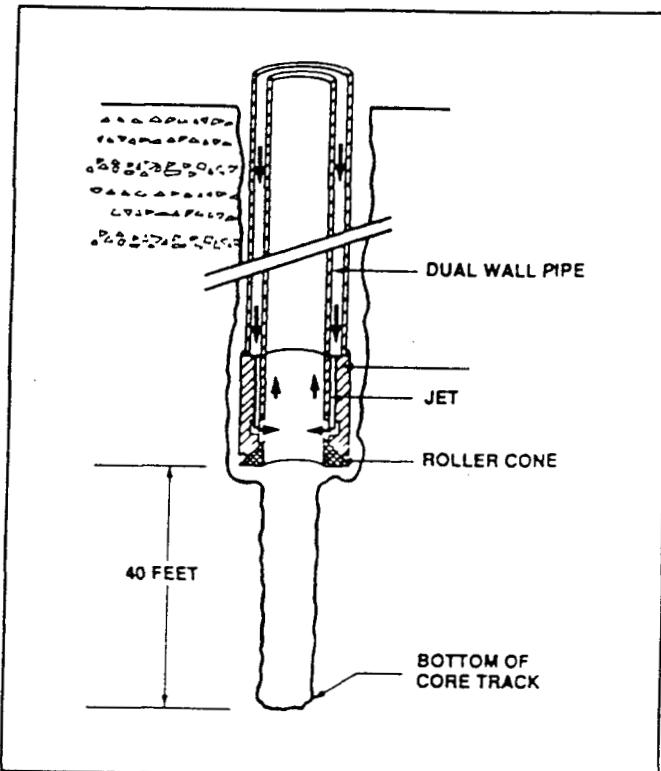


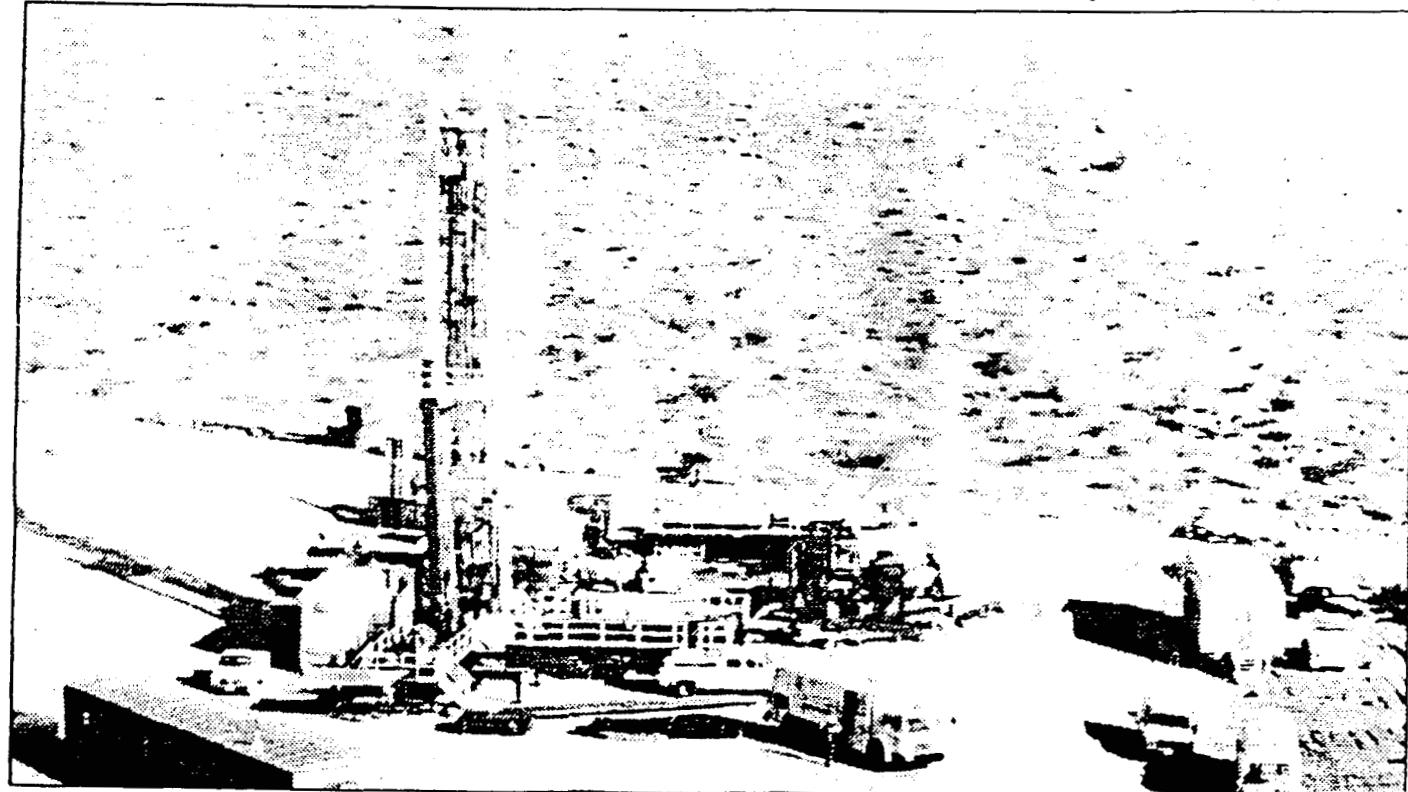
Figure 2. Reaming with the dual wall system.

Figure 2 shows the ream down cycle. Again, a vacuum is utilized to insure that a preferential return path for the cuttings remains inside the dual wall pipe. Locally high pressure air is used to clean the cutters on the reaming bit. However, net injection into the formation is avoided by insuring that more air is withdrawn than is injected. This control also applies during coring, at least at the top of the core track at the reaming bit. This process of dual wall reaming is also referred to as balanced air drilling and results in minimum contamination of the borehole wall.

Recent reaming bit designs have incorporated a modification in the throat of the bit, an ID reduction to 4-1/2 inches. This modification centralizes the CHD-101 coring system inside the 6 inch line pipe used as the inner tube of the dual wall pipe. This size of dual wall pipe was initially intended for a larger coring assembly (CHD-134). The CHD-101 assembly was used to reduce friction losses and insure a vacuum is maintained at the reaming bit at all times during coring. This results in the core rod being operated in an environment it was not designed for, a small pipe in a "large" hole. Problems caused by this environment and solutions are discussed in subsequent sections.

Figure 3 shows the layout of the rig and surface equipment. The main component of the system is the one-of-a-kind LM-300 drill rig, discussed in Long *et al* (1992). The other major components are laid out in a somewhat quadrangular fashion. The pipe rack is in the foreground and to the right of the rig mast. It is perpendicular to the rig and parallel to the air compressor package at the far end of the drill site. To the immediate right of the pipe rack are the sampling cyclone, vacuum truck and meter run which, more or less, form a line parallel to the drill rig. Air passes counterclockwise around the quadrangle from the compressors until it finally is filtered and exhausted at the meter run.

Figure 3. Layout of the drill rig and surface equipment.



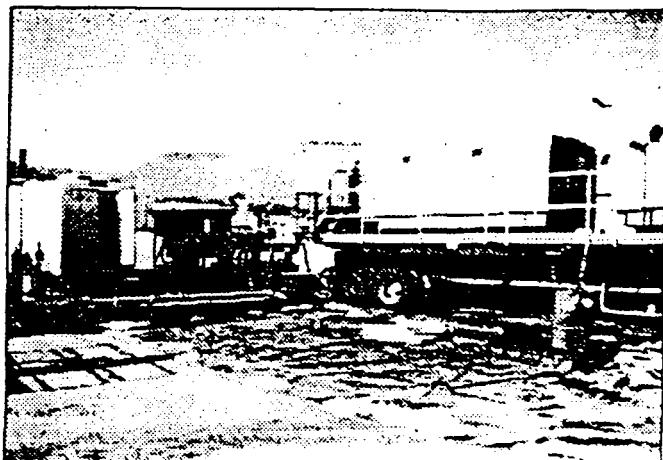


Figure 4. Inlet side of air circulation system.

Figure 4 shows the detail of the inlet side of the air circulation system. Air passes from the compressors, on the right, to the air processing and metering system, center, and down the manifold where equipment in the white truck, on the left, injects Sulfur Hexafluoride ( $SF_6$ ) tracer at a concentration of 0.75 to 2.5 parts per million. Two Atlas Copco, 1200 CFM, oil-less compressors are used to supply the air, although there is no requirement for oil free air from the compressors. The air processing and metering system drops out any system oil. However, it was primarily designed to drop out free water formed when the air temperature in its cooling section is brought to within 10 degrees (Fahrenheit) of ambient conditions. Relatively cool air without free water is required to insure that in situ geochemistry is not compromised during the coring process.

The flexible, braided steel covered air line is shown connected to the side of the rig mast in figure 5 (right center). Hard line carries the air up the mast to hoses connected to the tophead drive and connector subs. The larger line to the right of the air line is the discharge line to the sampling cyclone. Also visible in this figure is the pipe handling system (lower center) which is used to lift the 20 foot long sections of dual wall pipe into

position for running in and out of the hole. Each section of dual wall rod weighs approximately 1200 pounds. The pipe handling system was added primarily for safety. However, significant savings in dual wall pipe trip time were also realized.



Figure 5. Inlet air line, discharge air line, and pipe handling arm.

The discharge and sampling side of the surface layout is shown in figure 6. Cuttings laden air enters the cyclone on the right. The majority of the cuttings are dropped out in the cyclone for either sampling or subsequent disposal onto the conveyor belt when the air is turned off. An earlier study investigated the possibility of installing a rotary gate valve on the bottom of the cyclone to allow continuous removal of cuttings during drilling. However, no rotary gates were found to be presently available which could handle both the vacuum on the discharge line and the large abrasive cuttings produced during reaming. Allowing the cuttings to buildup in the bottom of the cyclone during a single reaming cycle has not been a problem to date. Any reduction in efficiency caused by operating the cyclone in this manner, does not appear to cause significant additional carryover of dust into the bag filters.

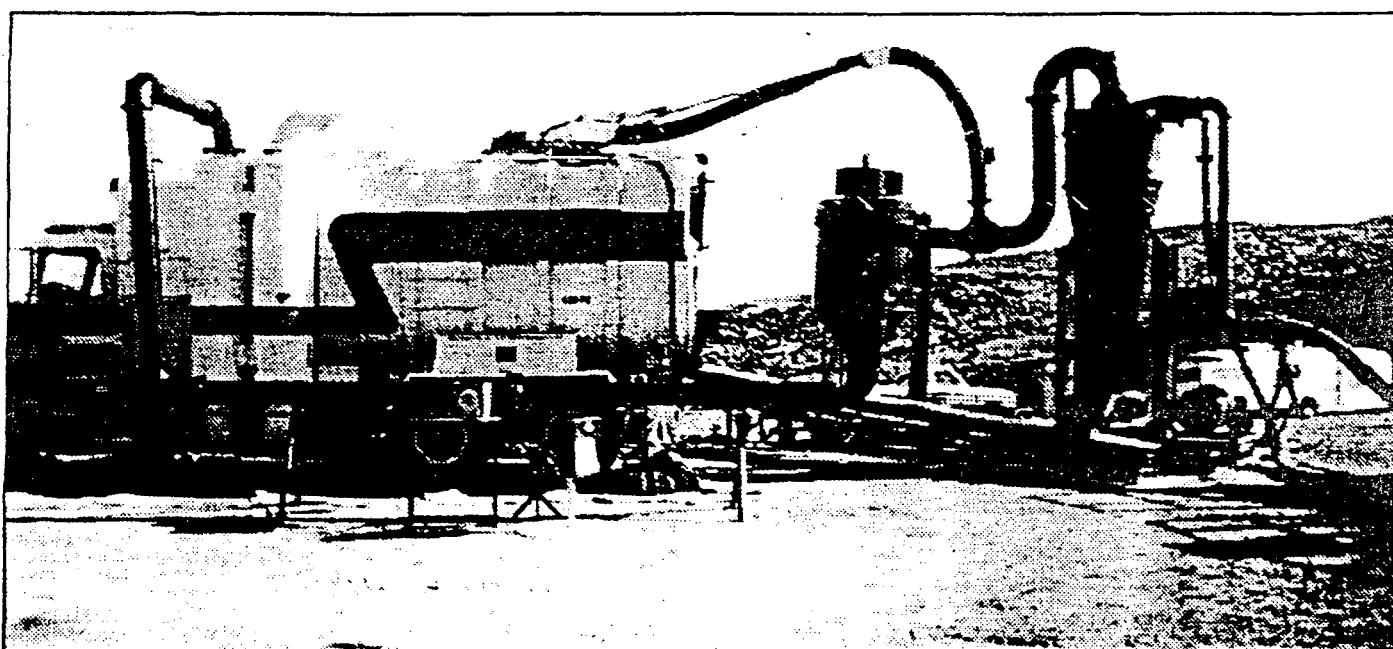


Figure 6. Cuttings removal equipment on discharge air line.

As mentioned previously, the truck in figure 6 houses both the baghouse filters and settling tank (aft section) in addition to the blower (mid section behind cab) which generates the vacuum for the discharge line. Air discharges from the truck blower through the meter run (visible in foreground) and is then discharged vertically. The truck will be replaced in early 1993 with a separate baghouse and a more powerful blower. While the truck is adequate for drilling this first relatively shallow borehole, a more powerful system will be required for drilling deeper. As depth increases, the success of the balanced air system will depend on closer control of air in and out of the borehole. The self cleaning bag type filter system has proven to be an operationally sound method for cleaning the air for metering and for satisfying environmental requirements.

### Program Initiatives

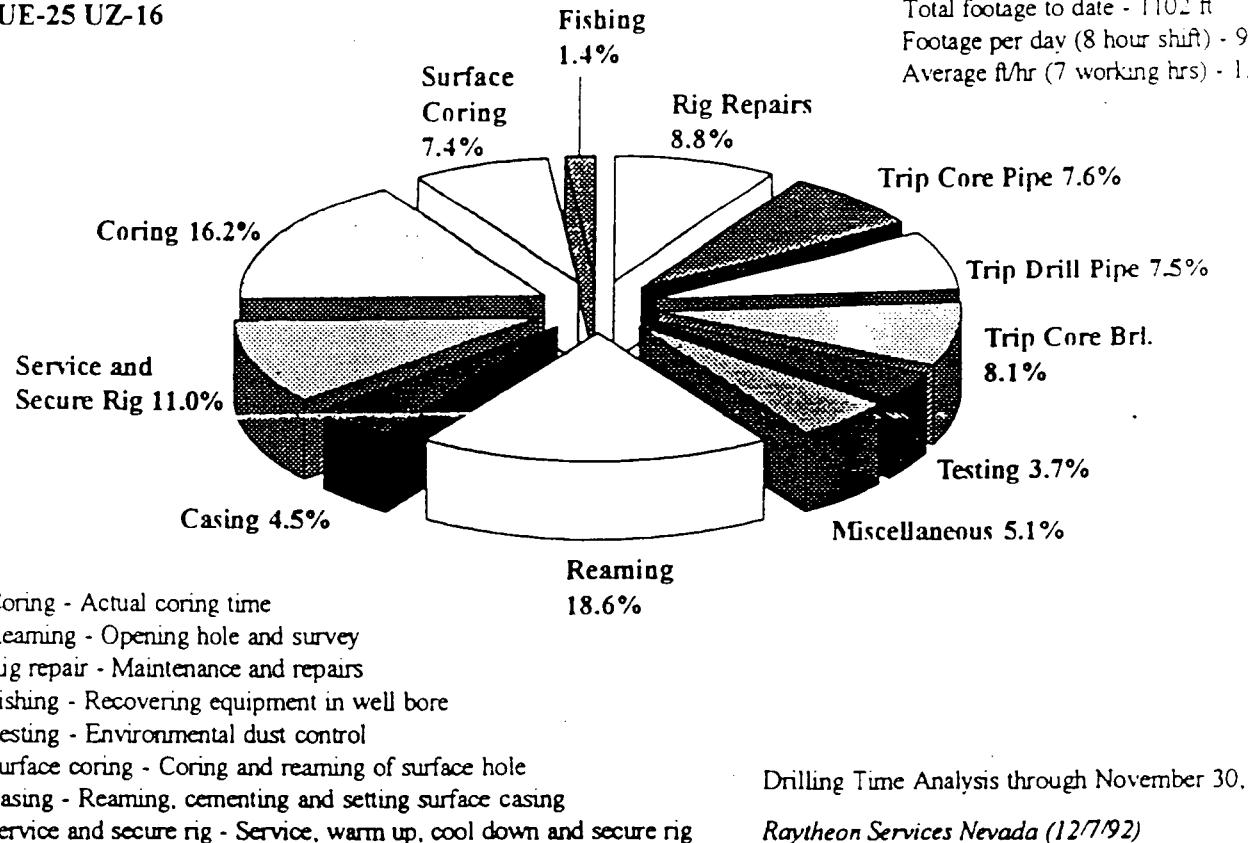
Planned improvements in the YMP's ability to acquire geologic samples can be summarized in three major headings: 1) Improving sampling efficiency; 2) Improving durability of equipment, and; 3) Improving capability of the system for uncontaminated sampling at greater depths. Improvements in all three areas will be required to insure cost and schedule of the site vertical borehole program are minimized and scientific objectives are achieved.

**Improving Efficiency.** Regardless of what drilling system or specialized equipment is used to acquire core, all managers involved in scientific drilling need to fully appreciate the time requirements for an intensive, core based, sampling program.

Simply stated, any continuous coring program is going to take time and increase the risk of delays caused by difficult drilling conditions. When the requirement to construct a 12 to 14 inch diameter, uncontaminated borehole is added to the coring requirement it is not reasonable to expect overall penetration rate records to be achieved on the first borehole in the drilling program. The YMP is presently pursuing the more practical approach of first concentrating on the basics and making certain that the scientific objectives are being met. The second phase of that approach is to continually evaluate the process and make improvements along the way to reduce the time required to complete the program. The minimum core requirement for a characterization program like that at Yucca Mountain is difficult to ascertain at the beginning of the program. The investigation is similar to wildcat drilling in the oil industry. If unexpected features in the rock are discovered, additional drilling (or coring in this case) are required to assure an understanding of the geology. In order to mitigate the effect of any potential increase in the requirement for core at Yucca Mountain (in addition to the need to reduce present planned schedule), the YMP is continuing to consider and evaluate methods to acquire suitable core more quickly.

Figure 7 shows the time analysis for operations at UZ-16 through November, 30, 1992. The efficiency discussion will be centered around considerations for reducing time shown in the categories noted in the figure. The major categories can be discussed under the general headings: LM-300 Drill Rig, Core Bits, and Reaming Bits.

Figure 7. Time Analysis  
UE-25 UZ-16



*LM-300 Drill Rig.* The above mentioned requirement for speed during coring was incorporated into the construction of the LM-300. The size of the rig dwarfs most mining industry rigs, even Lang Exploratory Drilling's new LM-300E which has even greater pullback capability. The size was required to be able to stand back a minimum of 40 feet of core rod in the derrick. This capability allows the core rod to be pulled out of the hole quickly, thereby mitigating the impact of the continuous coring/reaming cycles on schedule. A higher mast is being considered for subsequent rigs in order that 60 feet, or more, of core rod can be racked in the derrick.

Rig maintenance and repair represents approximately 20% of the time. The majority of the repair time was associated with a changeout of transmissions. This is considered an unusual occurrence; repair time is expected to be much lower on subsequent boreholes. Some reductions have already been made to the time required for startup and shutdown; however, most of the remaining time is caused by routine servicing and is not considered feasible to reduce. Some increase in maintenance and operation efficiency (~5%) is expected to result when operations are able to be conducted on a 24 hour per day basis. Additionally, some proposals for all electric rigs are being considered which are expected to require less servicing time.

The pipe handling system for the Dual Wall pipe will likely be a requirement for all subsequent rigs. Because of the weight of the pipe (1200 pounds per 20 foot length), an efficient laydown system is the best and safest way to manage it. An efficient laydown system will especially be needed if, as expected, a requirement for a 3000 foot depth capability for the dual wall system is realized.

*Core Bits.* As shown in figure 7, the time categories associated with coring, tripping the wireline core barrel, and tripping the core rod represent approximately 32% of the total operations

time; and coring alone represents approximately 16% of total time. Much of this time is simply caused by the continuous coring operation. However, much of the coring time and wireline barrel tripping time has been associated with short core runs caused by jamming in the inner barrel. Significant vertical fracturing in the hard volcanic rock at Yucca Mountain makes it one of the most difficult areas to acquire core quickly. UZ-16 is being drilled in an area referred to as the imbricate fault zone. This area is more highly fractured than the rest of Yucca Mountain and is characterized by both parallel, high angle fractures and intervals where the rock is so broken that only short pieces of core (6 inches or less) can be recovered for as much as 20-30 feet at a time. Anti-jam barrels have been attempted in these intervals with no success.

The highly fractured intervals also result in short run life on the PDC (Polycrystalline Diamond Cutter) core bits. Interestingly, all PDC failures to date have occurred because of impact damage as opposed to excessive heating. The cool air (usually less than 100 degrees Fahrenheit), at 200-700 CFM, appears to provide adequate cooling and/or bottomhole cleaning to prevent significant heat checking of the core bits in conditions of even the hardest rock. Figure 8 shows the types of core bits predominantly run to date at UZ-16. Aggressive cutting structures are desired because of the low rotary speed limitations (around 60 RPM) associated with coring in totally dry conditions. Drawbacks associated with the use of these aggressive cutting structures, such as vibration and core barrel stability, will be discussed later under improving durability.

A loose correlation between bit usage and degree of fracturing can be made from the left to right ordering of the bits in figure 8. The PDC bits of the type on the right are used in intervals where there is little fracturing or the volcanic tuff is poorly welded (soft and/or friable), allowing for maximum penetration rates. As fracturing increases (usually noted by increased

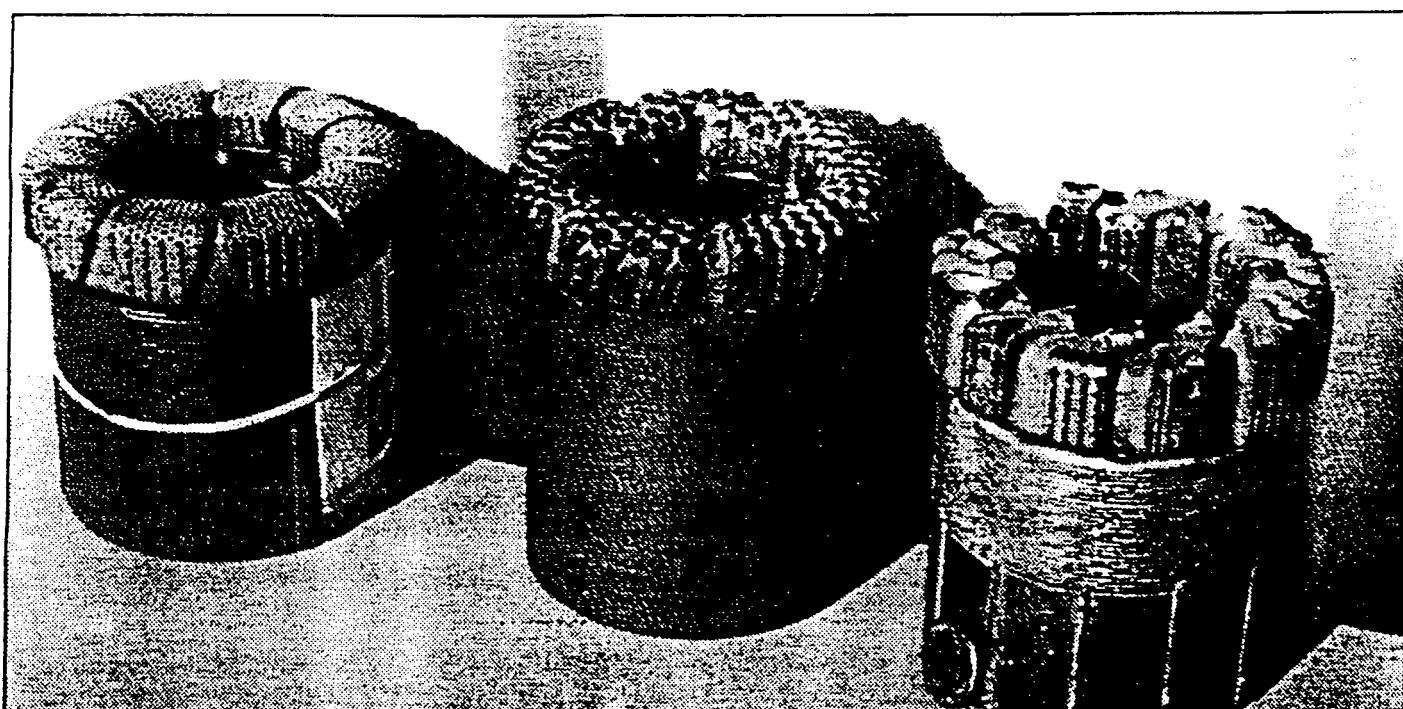


Figure 8. Small stone (20/40) surface set bit, large stone (3/6) surface set bit, PDC bit

and early breakage of the PDC cutters) a 3-6 stone per carat Carbonado core bit is run. This bit provides an aggressive surface set cutting structure relatively resistant to impact breakage because of the amorphous structure of the diamonds. The 20-40 stones per carat Carbonado surface set bit on the left is normally run in intervals of high fracturing. Some premium diamonds were tried in approximately this same cutting structure but wore significantly more quickly than the Carbonados.

The YMP will continue to push for improvements in cutting efficiency and durability of the PDC cutting structures for dry hard rock coring because of their potential to provide core more quickly. Acquiring core quickly provides the following benefits considered essential to the success of the site characterization program: 1) Increased probability that in-situ conditions are not significantly affected by the coring process, and; 2) Increased probability of achieving essential site characterization goals within present budget and schedule. The relatively small cutters (~3/8 inch diameter) on the PDC bit in figure 8 have been recessed into the matrix of the core bit face (especially on the gauge cutters) to increase cutting efficiency and durability. This reduces early fracture failure of the cutters while still maintaining an aggressive cutting structure. Similar designs from various manufacturers are presently being evaluated at the Colorado School of Mines, Earth Mechanics Research Institute, prior to being field tested at Yucca Mountain. This program will continue as a focus for development of PDC core bits for dry coring at Yucca Mountain. In the near future, PDC's with larger (~1/2 inch) cutters and antiwhirl characteristics are expected to appear on the scene. The increase in the aggressiveness of the cutting structure should significantly affect penetration rate; however, as will be discussed in the durability section, the vibration caused by the more aggressive cutting structure will have to be adequately minimized by the antiwhirl design. It is recognized that if a durable PDC bit can be developed which will provide acceptable penetration rates at low bit weights (2000 pounds or less), core runs could potentially be longer than 40 feet. Thus, there is significant interest in these more aggressive structures because of their potential to reduce the number of core/ream cycles. This would have the greatest impact on reducing schedule.

**Reaming Bits.** In addition to the core bits, reaming bit cutting structures have also been studied at the Earth Mechanics Research Institute. The most promising structure to date is made from a six cone design with the cones alternating such that every other heel pack is cutting both inner and outer gauge. Cutters are still based on design criteria similar to standard tricone rotary bit designs. The most successful cutting structure to date has been similar to a Hughes Tool Company J-22 bit which represents an IADC bit classification of 5-1-7 or 5-2-7. Performance optimization for the reaming bits in the immediate future will continue to be based on optimization of tungsten carbide inserts (TCI's) on roller cone cutting structures.

Figure 9 shows the potential basis for improving reaming bit efficiency in hard rock drilling well beyond that presently available in roller cone structures. It is a cutting structure based on tunnel boring machine (TBM) designs except that it is much smaller. This size reduction was made possible because of recent improvements in bearing technology. The Earth Mechanics Research Institute is presently conducting tests on the

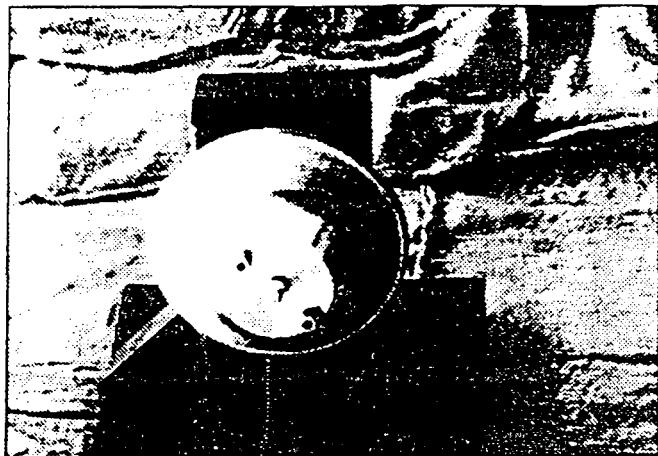


Figure 9. Experimental disc cutter.

new cutter and hopes to have a 13-14 inch diameter prototype bit available for testing by the latter part of 1993.

**Improving Durability.** The term, improving durability, will be used in the context for this paper to mean decreasing the probability of fatigue failure or increasing service life of presently available drilling equipment. Three areas presently being considered for improvements in durability are: 1) Drill Rig; 2) Core Rod, and; 3) Dual Wall Pipe. These areas are chosen because they have the greatest potential for causing unexpected delays in the present drilling environment at Yucca Mountain.

**Drill Rig.** Despite the unexpected difficulties experienced with the transmission, the LM-300 has performed exceptionally well to date. It has been large enough to handle the reaming and yet light enough to provide an excellent coring capability. The only area for potential improvement in durability will be on design of future drill rigs. On subsequent rigs, electric motors will likely replace hydraulic motors. Environmental considerations are as much a factor in this decision as improvements in required service and service life.

**Core Rod.** The core rod (including core barrel) is arguably the weakest link in the downhole system. The two primary reasons for this are: 1) The rod is not being used in the environment it was designed for, and; 2) The rod is undergoing cyclic stresses which it was not designed for and which are maximized by the aggressive cutting structures on the PDC core bits. The core rod of the dimensions used has a vibratory tendency which is driven by the "stick-slip" motion of the more aggressive core bits. Although antiwhirl core bit designs hold some promise for mitigating this downhole phenomenon it is relatively certain that other measures will have to be taken to achieve a reliable system.

As mentioned previously, the CHD-101 core rod is being used inside a 6 inch diameter dual wall pipe. In normal mining industry coring, this rod is used inside a borehole between 4 and 4-3/8 inches. In effect, "small pipe" is being used to drill in a "large borehole" in the present balanced air, dual wall sampling process. Because there are no standards for this type of operation in the mining industry, an analysis of the connections was performed by one of the YMP's contractors, Science

Applications International Corporation (SAIC). This study is interesting in that it is believed to be the first time that API recommendations have been applied to mining industry tubulars and the study will be the subject of a future paper. Two conclusions from the study pertinent to this paper are: 1) The bending strength ratio of the present CHD-101 rod is on the order of 1.25, and; 2) API recommends a bending strength ratio between 2.25 and 2.85 for rotary shouldered connections on small pipe in a large hole. The present bending strength ratio of the CHD-101 core rod connections indicates that it is prone to fatigue failure in the last engaged thread of the pin if vibrations typical of those on which the API recommendation is based are encountered. A relatively simple solution has already been enacted to improve conditions. Core rod stock of ASTM A 519-4130 steel was available from Longyear which, when machined, would provide a connection with a bending strength ratio of 2.4. The OD of the new rod was increased from 3.701 inches to 3.875 inches and the tensile strength of the pin connection was decreased by approximately 2 percent (slight reduction in pin area). Core rod weight was increased from approximately 8.8 to 14.2 pounds per foot.

In summary, the new rod should be stiffer, more resistant to fatigue, and, therefore, better able to handle the vibration and torque variations created by the more aggressive cutting structures of the core bits. It is hoped that the new rod will also help reduce the deviation tendency previously experienced during coring such that core/ream cycles in excess of 40 feet can be achieved.

Another characteristic of core rod with dimensions similar to the CHD-101 rod is a natural harmonic frequency of vibration in the system with a peak occurring at approximately 1200 feet and 60-90 RPM. A separate paper is being presented in this symposium on the specifics of the vibrational characteristics of the CHD-101 rod. This vibrational tendency is not damped because of the dry drilling conditions and significantly increases the cyclic stresses on the tubulars. This resonant condition is considered contributory to the recent failure of the pin connection of the top reaming shell stabilizer of the core barrel at a depth of 1196 feet. A reaming shell in the same position failed in basically the same manner during prototype drilling at 1283 feet. Figures 10 and 11 show the failed reaming shell. Figure 10 shows the fatigue failure in detail while figure 11 shows the inner machining of the reaming shell. The internal upset noted at the base of the shadow line inside the

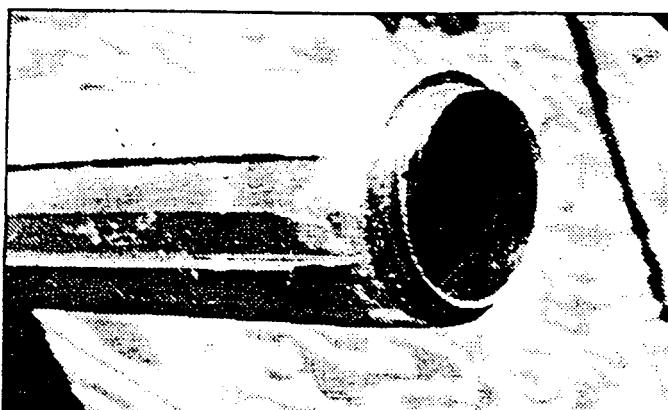


Figure 10. Reaming shell fatigue failure.

reaming shell in figure 11 is the upset machined in the shell to allow for the latches on the inner barrel to engage and hold it in place during coring. After discussion with Longyear, it was discovered that an additional 30,000 pounds of tensile strength could be obtained by reducing the available ID of the pin area 1/16 inch. This modification will be added to future reaming shells.

**Dual Wall Pipe.** The outer tube of the dual-wall pipe is made of 9-5/8" diameter, 47 pound/foot, K-55 casing stock. This provides a tube of adequate strength and relatively high fatigue resistance for the relatively shallow depths anticipated in YMP's drilling program. The only anticipated change in this design will be a modification of the connection threads. In order to make the connection more fatigue resistant the YMP will be requiring compliance with recently published guidelines for reduction of root thread height on these connections (Tsukano, 1990).

**Improving Capability.** As mentioned previously, YMP's first concern in the Site Vertical Borehole Program is to verify that the scientific objectives are being achieved. For uncontaminated sampling, this translates to developing confidence that the balanced air system will function to the maximum anticipated depth of 2600 feet. Estimates indicate that the present system should be effective at 2600 feet as long as adequate monitoring and control of injection and withdrawal air is maintained. Some system changes are in the process of being made and others are being planned to better maintain control of downhole drilling conditions.

**Surface Equipment.** Modifications are being made to both monitor and control functions of the surface equipment to better control downhole conditions at greater depths. The requirement to monitor air rate in and out of the borehole will be satisfied by a system from Fisher Controls which will provide a digital readout on the driller's console of air rate in and out of the borehole. This rate will also be digitally recorded in order that air volume can be integrated with time. The system is anticipated to be installed by the end of January.

As mentioned previously, the present vacuum system will be replaced with a more powerful one capable of delivering 18 inches of mercury vacuum to the tophead drive while drawing up to 700 SCFM of air out of the borehole. With proper usage, this system should be more than adequate for all drilling conditions.

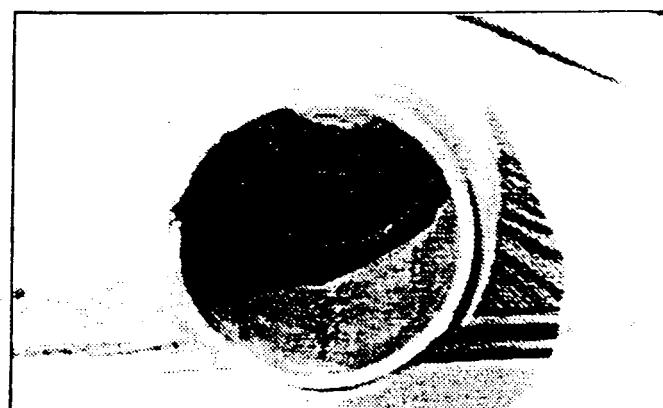


Figure 11. Machined upset for latch.

**Downhole Equipment.** The ultimate improvement in capability would be a reaming bit which both cores and reams at the same time. As noted in the time breakdown in figure 7, if coring was accomplished during reaming, eliminating core rod tripping altogether, a potential for a 24% reduction of overall sampling time might be realized. Such a bit is being considered and will eventually be designed and tested after potential difficulties with downhole circulation are proven to be eliminated. An effective, balanced circulation system is essential to uncontaminated sampling.

The first step toward improving downhole capability will be to augment existing configurations to minimize the risk of problems occurring downhole. Two modifications being considered at this time are: 1) A wireline retrievable center section for the open center reaming bits, and; 2) A venturi system located in the reaming bit to augment the vacuum system during deep reaming and coring.

The need for a wireline retrievable center section for the reaming bit was observed while drilling the highly fractured intervals of the imbricate fault zone, as previously discussed. If a center section could be developed which could be run quickly on wireline, problems with plugging of the dual wall pipe during reaming would be eliminated. In addition, this feature would allow coring further ahead of the dual wall than is presently possible.

A venturi system was tested during prototype drilling and initially appeared both feasible and very effective. The system operates from a portion of the drilling air which is bled off and used to develop a pressure wave inside the dual wall pipe to form/augment the vacuum at the bottom of the hole. The phenomenon is similar to the operation of an ejector; however, the center of the pipe must be open and, therefore, the air has to be injected from the circumference of the inner tube of the dual wall. Testing is planned in 1993 to investigate if the diffuser profile developed between the 4-1/2 inch ID throat of the new reaming bits to the 6 inch ID of the dual wall will provide enough mechanical expansion to stabilize the pressure wave. If this system is feasible, it would likely be used during reaming and might eliminate the need for developing a wireline retrievable center section for the reaming bits.

### **Summary and Applications Discussion**

Experience to date indicates that mining industry dual wall and wireline coring systems can be utilized for acquiring geologic samples in the unsaturated zone very close to in situ conditions. The concept of using a heavy walled drilling string to protect a lighter coring string from difficult drilling conditions, or to protect the formation from the effects of contamination caused by normal circulation of cuttings past the formation face, appears sound. Problems associated with utilizing mining industry coring strings both inside dual wall pipe and in difficult, dry coring conditions appear solvable with attention to application detail and use of appropriate API recommendations.

Perhaps this demonstrated feasibility of extension of application of mining industry technology using oil industry guidelines and recommendations is the most significant demonstration in this paper. It would appear that API recommendations and design criteria could be used to extend the operational limits of the dual wall pipe as long as the additional weight of the inner

string was accounted for. Such a system might find application in harsh environments such as deep geothermal drilling or in highly overpressured gas drilling. For the gas drilling, if the primary cuttings carrying fluid was circulated inside the dual wall, a weighted kill and/or hole conditioning mud could be very slowly pumped down the outside of the drill pipe. Such a system would have the potential of making drilling in hazardous conditions routine.

### **Acknowledgment**

A special thanks is extended to Margaret Westcamp and Karl Moore of SAIC for the graphics layout of this manuscript, and Greg Fehr for information provided on the core rod connections and for his excellent analysis of the CHD-101 core rod connections as compared to API guidelines. Additional appreciation is extended to Dr. Bill Mitchell and Bill Eustes of the Colorado School of Mines, Petroleum Department for their information regarding the vibratory nature of the CHD-101 core rod. And sincere thanks is further extended to Dr. Levent Ozdemir, Jim Friant, and Richard and Leslie Gertsch of the Colorado School of Mines Earth Mechanics Research Institute for information on the disc cutter bit and their continuing work in the YMP bit testing program.

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## **Appendix E**

# Natural Gas Products

## Drilling, Completion, and Stimulation

### Mission

- To develop and promote DCS systems which are economically viable, reliable, highly efficient, environmentally acceptable and beneficial to the domestic natural gas industry. A balance of market pull/technology push will be incorporated into product planning to ensure that the needs of the market are met while the contributions of latest scientific breakthroughs are exploited.

MISSION.DCS

**MECC**

FUELS PRODUCTS

# Natural Gas Products

## Drilling, Completion, and Stimulation

### Goals

- To develop DCS product systems that efficiently extract natural gas through more cost-effective and environmentally compatible technology

### Objectives

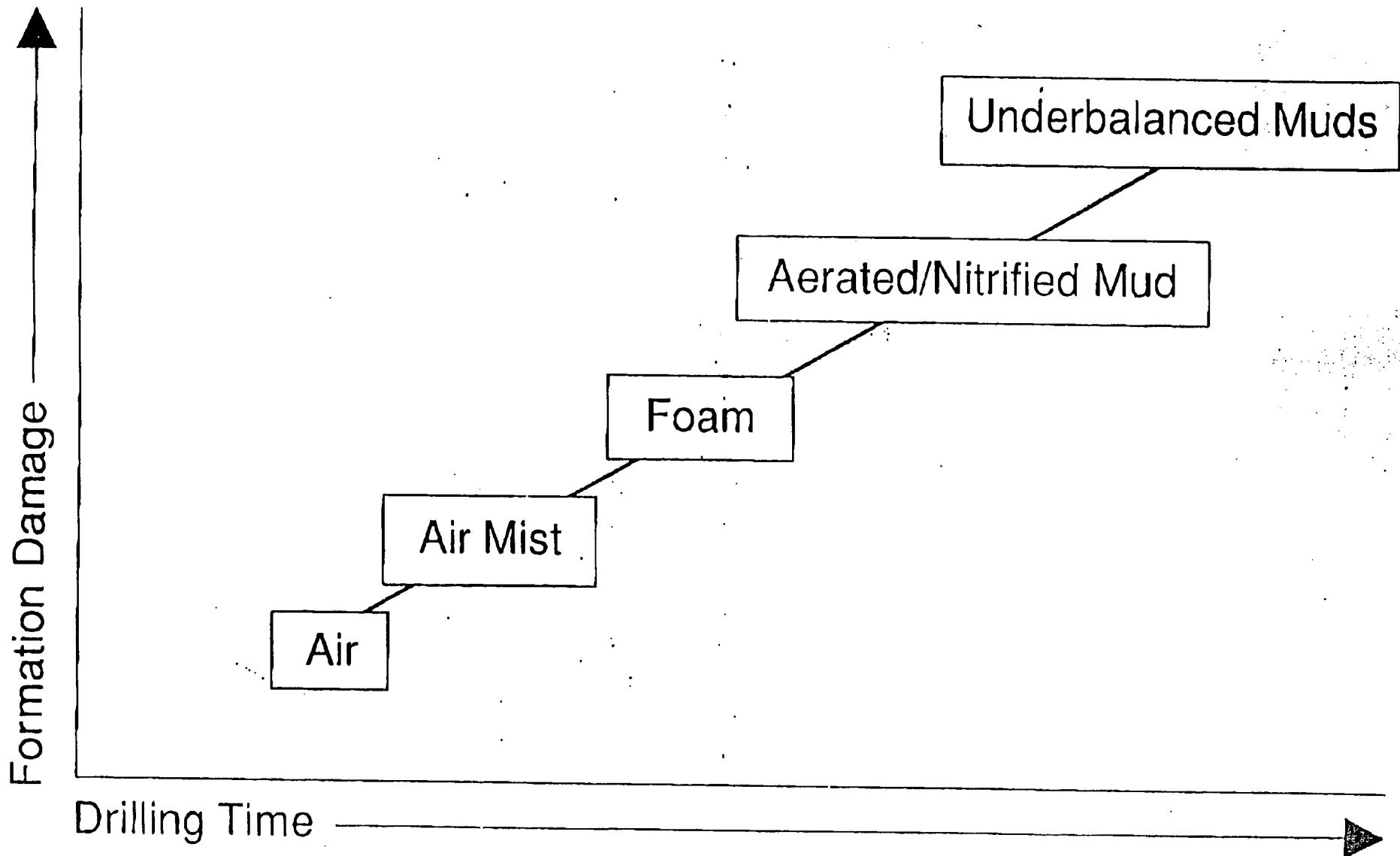
- Improve near-term economics/develop DCS products for underbalanced/conv. drilling and non-damaging stimulation
- Develop mid-term advanced DCS systems that reduce cost or improve recovery of natural gas in the US.

GOALS.DCS

**MECC**

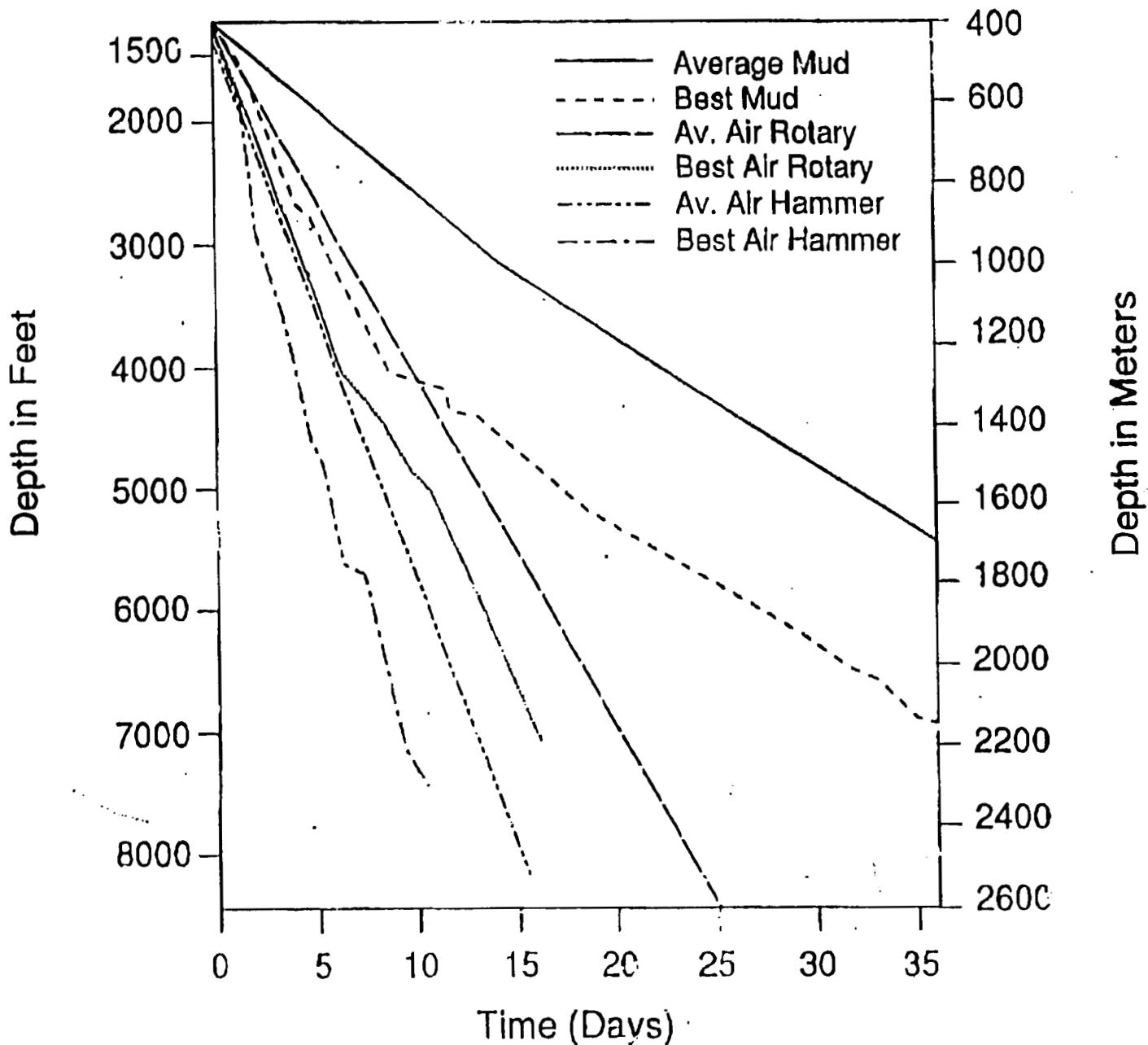
FUELS PRODUCTS

# Strategy for Reduced Damage Drilling

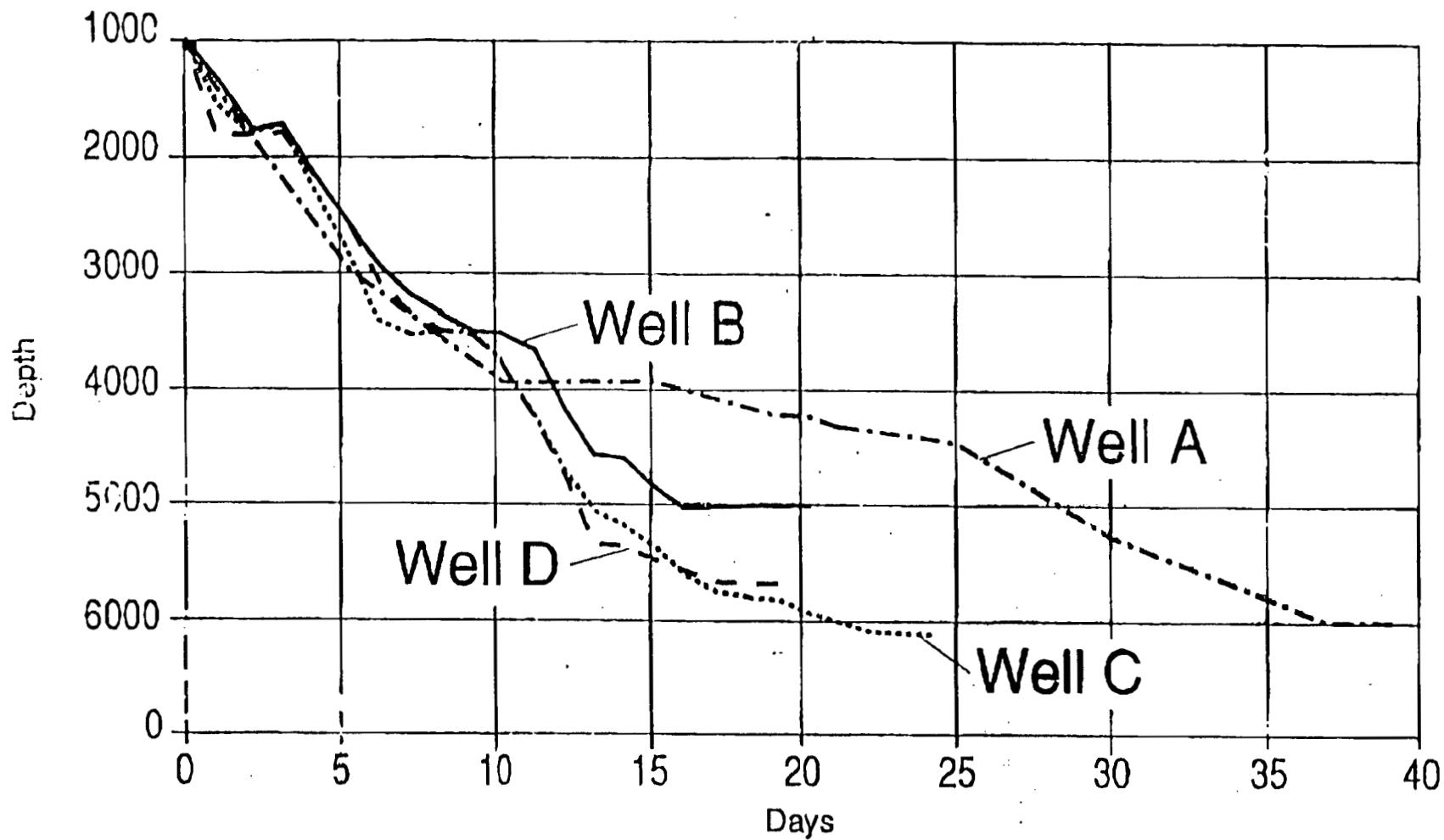


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# Drilling Time Curve - Jumping Pound Area of Alberta



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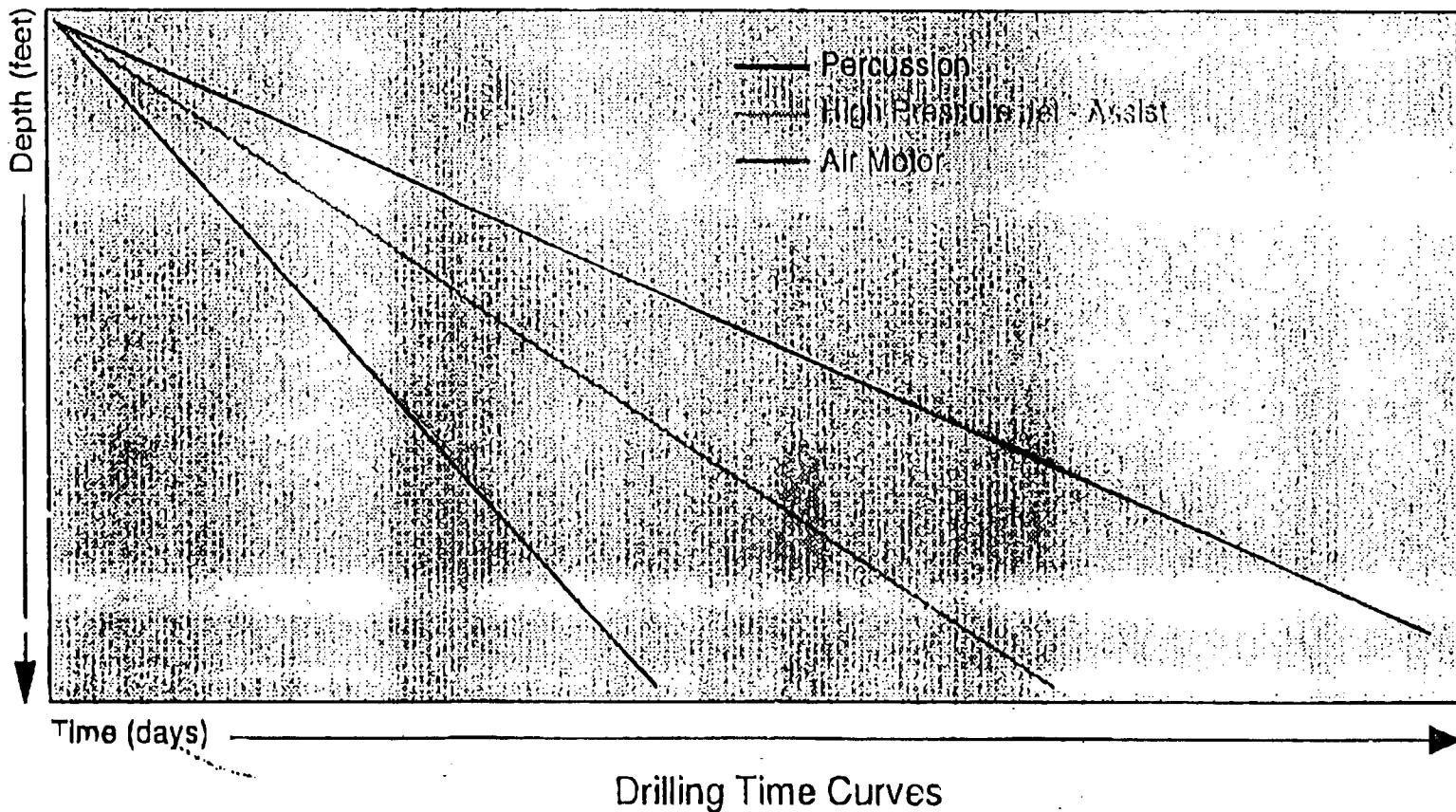


Interval	Well A	Well B	Well C	Well D
Surface Hole	0-774' mud	0-725' mud	0-770' mud	0-805' mud
Intermediate Hole	744-2578' mud	725-2510 mud	770-2525' mud	805-1427' air 1427-2507'mud
Production Hole	2578-5008' mud	2510-4000' air	2525-4144'air 4144-5100' mud	2507-4319' air 4319-4650' mud
% Air Drilled	0%	37%	32%	52%

Example of drilling fluid impact on drilling rates in a Southern Oklahoma Province

# Directional/Horizontal Drilling Systems

## Target Basin and Field



- Optimum drilling system defined for a geologic setting or basin

## Appendix F

Department of Energy  
Geothermal Program

***Geothermal Drilling R&D***

Stan Calvert  
January 17, 1995

# Overview

## ■ Past Accomplishments

## ■ Current Projects

*Advanced PDC/TSP Bit Development*

*Lost Circulation Control*

*Acoustic Telemetry*

*Borehole Instrumentation*

*Slim Hole Drilling*

*Geothermal Drilling Organization*

## ■ Future Plans

# Background

## DOE Geothermal Drilling R&D

■ **Performer:** Sandia National Laboratories

■ **Budget:** FY 95 - \$3.5M, historically  
approx. \$2-4M

■ **Past Accomplishments:**

*PDC Bit Development*

*Lost Circulation: Materials, Borehole Televiewer,  
Rolling Float Meter*

*High Temperature Muds, Cements, Elastomers*

# Advanced PDC/TSP Bits

- *Objective: Increase bit life and penetration rate in hard formation*
- **Participants and Partnerships:**
  - Smith International and Megadiamond
  - Dennis Tool Company and DBS
  - Security Diamond Products
  - Hughes Christiansen Company
  - Maurer Engineering and Slimdrill International
  - Amoco Production Research
- **Expected Outcomes**
  - Advanced PDC cutter materials
  - Optimized PDC daw cutter and Track-Set bit design
  - Advanced TSP bit
  - Advanced impregnated diamond bits

# Advanced PDC/TSP Bits

## Highlights to Date

- **Benchmarking**
- **PDC Single Cutter Wear Testing - Wear Rate Correlations**
- **PDC Bit Design - Field Testing at Catoosa**
- **Claw Cutter - Stress Analysis and Wear Testing**
- **TSP Bits - Good abrasion resistance in wear tests; disappointing field test**
- **Impregnated Diamond Bits - Wear Testing, Mechanistic Modeling**

# Lost Circulation Control

## ■ Loss Zone Characterization

- *Further field testing of Rolling Float Meter*
- *Doppler Flowmeter evaluation*
- *Refine and demonstrate use of inflow/outflow information*

## ■ Treating Loss Zones

- *Drillable Straddle Packer*
- *Porous Packer*
- *Cementitious Muds*

# Acoustic Telemetry

- **Objective:** *Develop faster data link for downhole measurements - for both drilling and production monitoring*
- **Industry Partner:** Baker Oil Tools
- **Highlights**
  - *Surface simulation facility*
  - *Mobile test laboratory*
  - *Production tubing field test*
  - *Promising correlation between testing and models*
- **Near Term Plans**
  - *Field test system with rotating drillstring - November 1995*

# Borehole Instrumentation

- **Objective:** *Develop low cost, portable, reliable, high temperature borehole logging tools*
- **Industry field testing participants**
  - *Uhocal*
  - *California Energy*
  - *CalPine*
  - *The Geysers Sulfur Banks Consortium*
- **Memory Logging Tools - Slickline and slim-hole**  
deployable, on-board data recording
  - *Pressure/Temperature*
  - *Spectral gamma*
- **Fluid/Gas Sampler**

# **Slim Hole Drilling**

- **Objective:** *Demonstrate viability of lower-cost slim holes for geothermal exploration*
- **Project Activities**
  - *Evaluate applicability of wellbore simulator codes*
  - *Formulate model for applying Steamboat Hills field test results*
  - *Analyze Japanese slim-hole data*
  - *Conduct new slim-hole exploration projects*

# Geothermal Drilling Organization

- **Objective:** *Identify and complete short-term cost-shared projects that result in a new drilling product or service that reduce costs for the geothermal industry*
- **Current Projects:**
  - *Improved high temperature positive displacement air motors - Baker Hughes Inteq*
  - *Advanced casing cement formulations - Halliburton and Unocal*
  - *Retrievable whipstock for geothermal - A-Z Grant*
  - *Rotating head rubber seals - A-Z Grant*
  - *Testing of cementitious muds for lost circulation control - Halliburton and California Energy*

## **Appendix G**



**DRILLING AND EXCAVATING TECHNOLOGY NEEDS  
FOR SOLAR SYSTEM EXPLORATION**

**A NASA-DOE DIALOGUE  
STAGE ONE: MISSION PERSPECTIVES**

FOR DISCUSSION AT THE  
**NATIONAL ADVANCED DRILLING  
AND EXCAVATION TECHNOLOGY (NADET) MEETING**

**JANUARY 17, 1995**

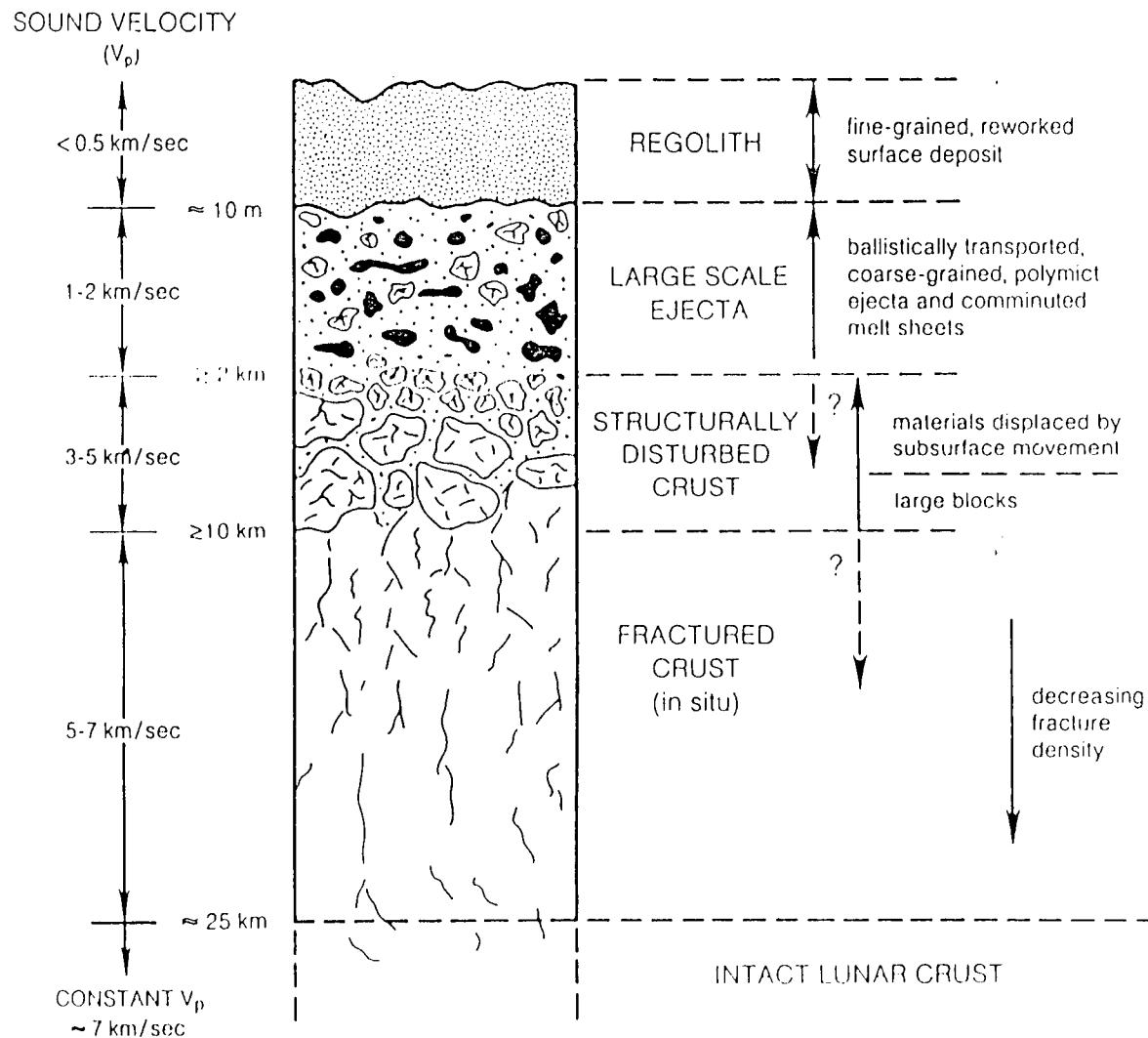
## CONTRIBUTORS TO MISSION PERSPECTIVE

STEVE BRODY	Hq NASA/SX	OVERSIGHT
ALAN WILLOUGHBY	NASA LEWIS RC/ANALEX CORP.	MISSIONS SYNTHESIS, ASTEROIDS
DAVE LAVERY	Hq NASA/XS	PLANETARY ROVER PROGRAM
DAVE MCKAY	NASA JOHNSON SFC	LUNAR RESOURCES
MIKE MEYERS	Hq NASA/SLC	EXOBIOLOGY
JOHN LEWIS	U. OF ARIZONA	ASTEROIDS, COMETS
JOHN MANKINS	Hq NASA/X	ADVANCED CONCEPTS
CHUCK WEISBIN	JET PROPULSION LABORATORY	MICRODRILLS, ROSETTA

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- \* ASTEROIDS II, EDITED BY RICHARD P. BINZEL, TOM GEHRELS, AND MILDRED SHAPELY MATTHEWS, THE UNIVERSITY OF ARIZONA PRESS, TUCSON, AZ, 1989.
- \* LUNAR SOURCEBOOK A USER'S GUIDE TO THE MOON, EDITED BY GRANT H. HEIKEN, DAVID T. VANIMAN, AND BEVAN M. FRENCH, CAMBRIDGE UNIVERSITY PRESS, CAMBRIDGE, UK, 1991.
- \* MARS, EDITED BY HUGH H. KIEFFER, BRUCE M. JAKOSKY, CONWAY W. SNYDER, AND MILDRED S. MATTHEWS, THE UNIVERSITY OF ARIZONA PRESS, TUCSON, AZ, 1992.
- \* MARS POLAR PATHFINDER, DAVID A. PAIGE, PRINCIPAL INVESTIGATOR, UNIVERSITY OF CALIFORNIA AT LOS ANGELES, 1994.
- \* RESOURCES OF NEAR EARTH SPACE, EDITED BY JOHN S. LEWIS, MILDRED S. MATTHEWS, AND MARY L. GUERRIERI, THE UNIVERSITY OF ARIZONA PRESS, TUCSON, AZ, 1993.

# CROSS SECTION OF LUNAR CRUST

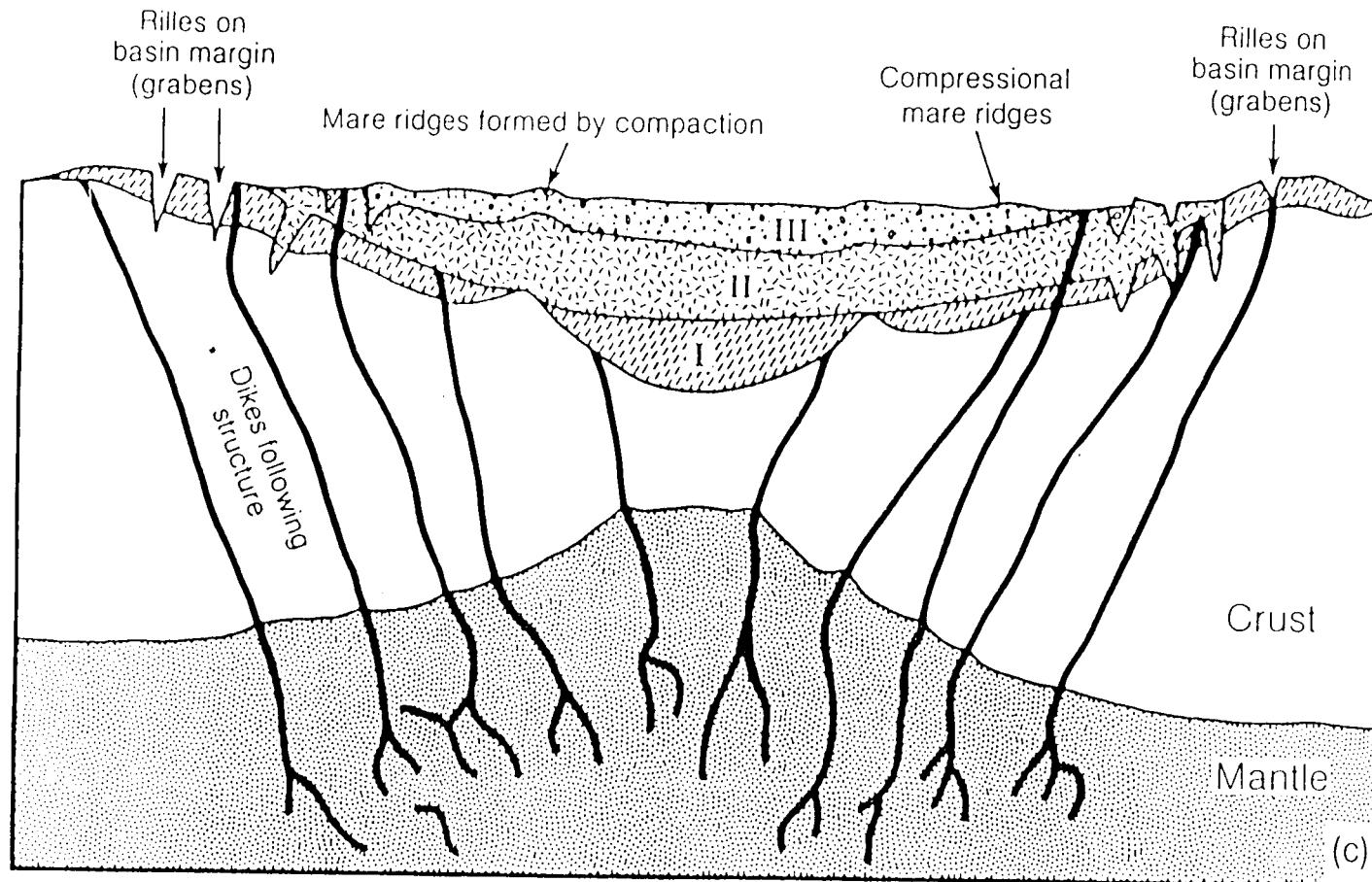


Highly schematic cross-section illustrating the idealized effects of large-scale cratering on the structure of the upper lunar crust; see discussion of megaregolith in the text. A structurally disturbed lunar crust is also inferred from seismic measurements, e.g., from sound velocity ( $V_p$ ) (Toksoz *et al.*, 1973). The depth scale in the figure is highly uncertain, because the total number of large craters and basins remains unknown. Highly variable depth effects must exist in different regions, depending on the degree to which an area has been affected by basin-sized impacts.

# DRILLING, CORING AND EXCAVATING NEEDS - MOON

<u>PHASE</u>	<u>MISSION DRIVER</u>	<u>NEED</u>
"CHEAP" PRELIMINARY EXPLORATION	<ul style="list-style-type: none"> <li>* LUNAR ORIGIN &amp; EVOLUTION</li> <li>* BELOW REGOLITH</li> </ul>	<ul style="list-style-type: none"> <li>* CORING</li> <li>&gt;5 M (MARE)</li> <li>&gt;10 M (HIGHLANDS)</li> </ul>
SERIOUS IN-DEPTH EXPLORATION	<ul style="list-style-type: none"> <li>* LUNAR ORIGIN</li> <li>* INTO CRUST</li> <li>* FIND ORES</li> </ul>	<ul style="list-style-type: none"> <li>* CORING</li> <li>&gt;2 KM</li> <li>* ? [ "Rich Dirt" ]</li> </ul>
INDUSTRIALIZATION AND HABITATION	<ul style="list-style-type: none"> <li>* LOX PRODUCTION</li> <li>* UNDERGROUND HABITATS AND MINES</li> <li>* HELIUM-3 RECOVERY</li> </ul>	<ul style="list-style-type: none"> <li>* SURFACE EXCAVATION</li> <li>* LARGE VOLUME UNDERGROUND EXCAVATION</li> <li>* CLEAN OUT LAVA TUBES</li> <li>* VERY LARGE VOLUME SURFACE MINES</li> </ul> <p style="text-align: right; margin-top: 20px;"> <i>To avoid radiation for living space.</i> </p>

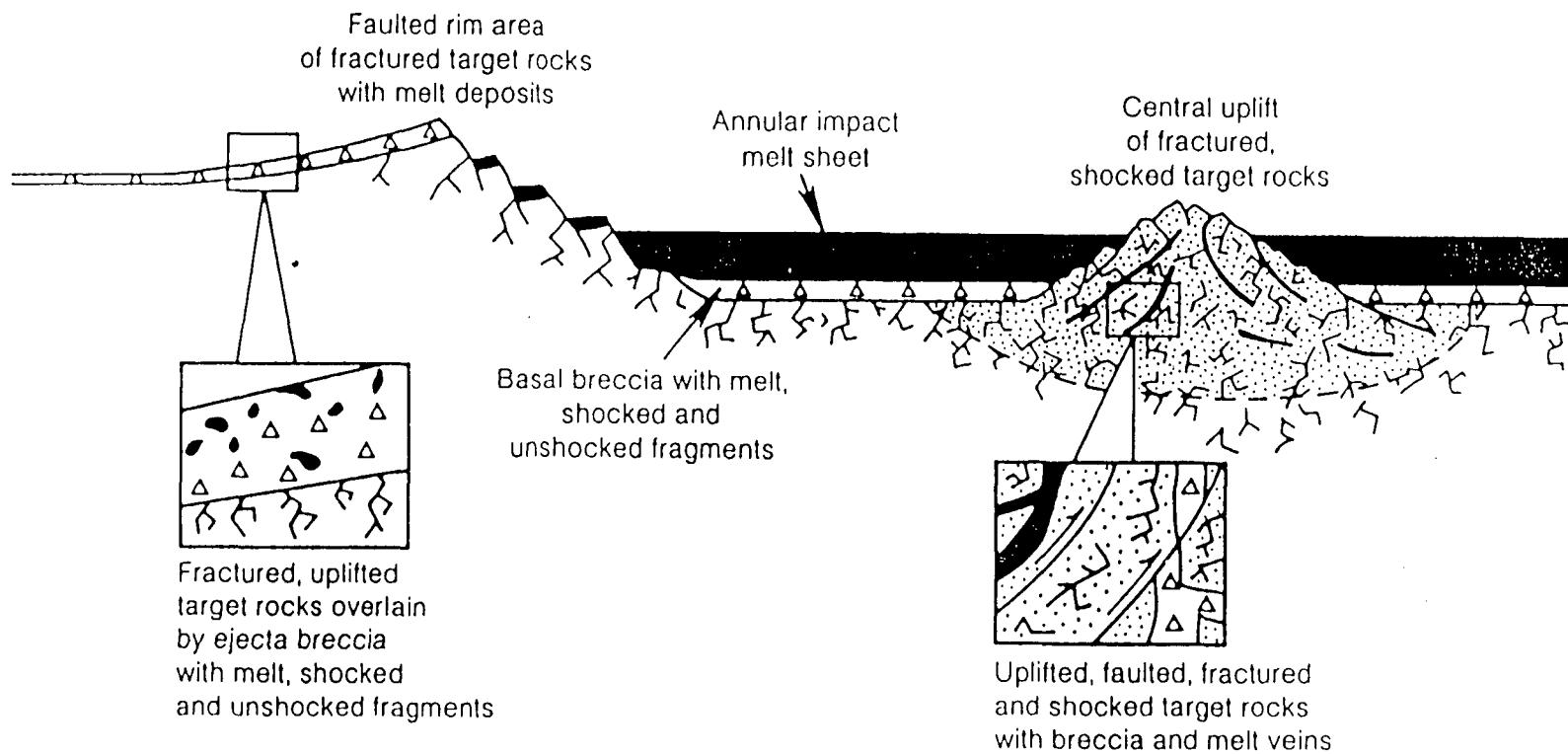
# CROSS SECTION OF LUNAR MARE



These maps indicate basalt thicknesses of 0.5-1 km in the shelf areas, increasing to a few kilometers in the basin interiors (Fig. 4.25). The total volume of lunar basalt erupted is thus estimated at  $\sim 6.5 \times 10^6 \text{ km}^3$ , i.e., <1% of the lunar mantle volume.

REFERENCE: LUNAR SOURCEBOOK, PAGE 106.

# CROSS SECTION OF A COMPLEX LUNAR CRATER



## LUNAR TEMPERATURE VERSUS DEPTH

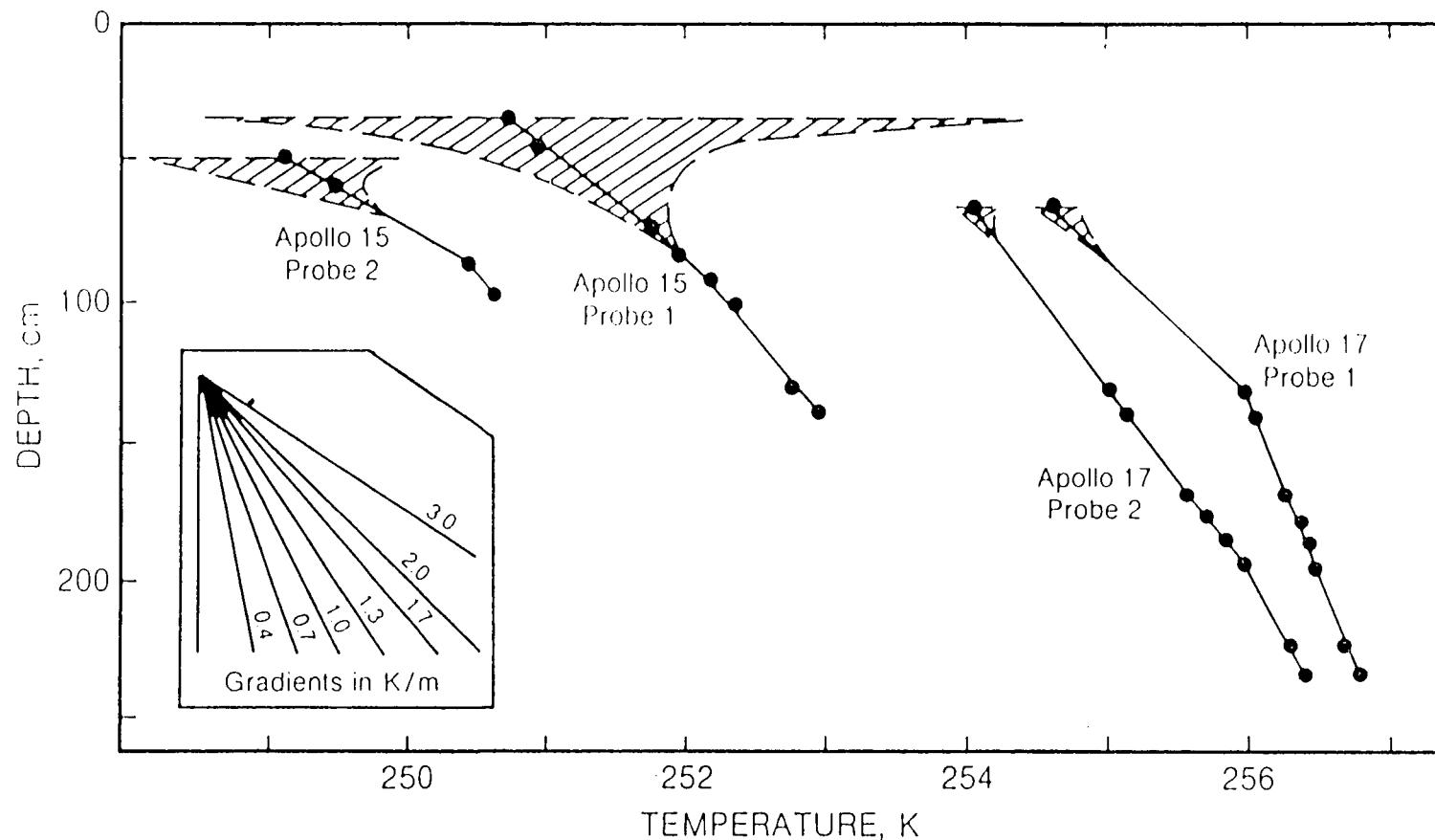


Fig. 3.9. Temperature fluctuations in the lunar regolith as a function of depth (after Langseth and Keihm, 1977). Note that the small temperature scale at the bottom of the diagram does not permit plotting of the extreme temperature fluctuations at depths less than  $\sim 30$  cm; this region is left blank. Hatched areas show day-night temperature fluctuations below  $\sim 30$  to 70 cm. Below  $\sim 50$  cm there is essentially no temperature fluctuation due to the lunar day-night temperature cycles, and the steady temperature gradients recorded are due to internal lunar heat flow.

# LUNAR DENSITY VERSUS DEPTH

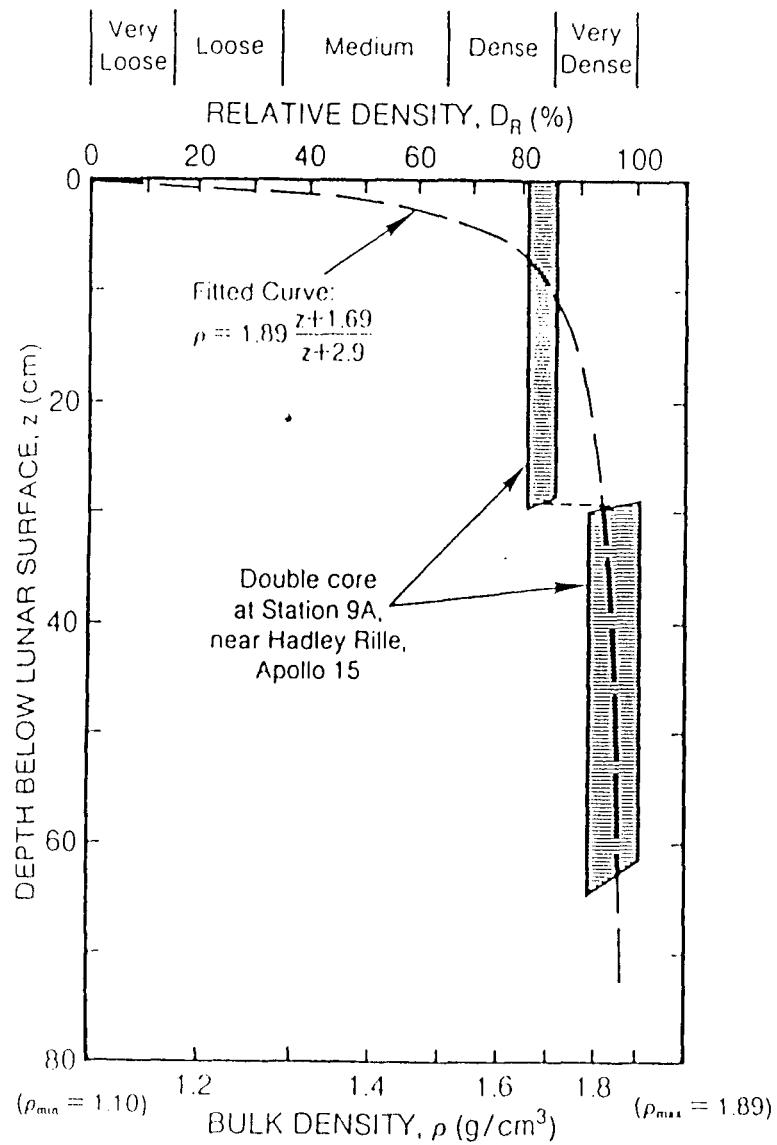
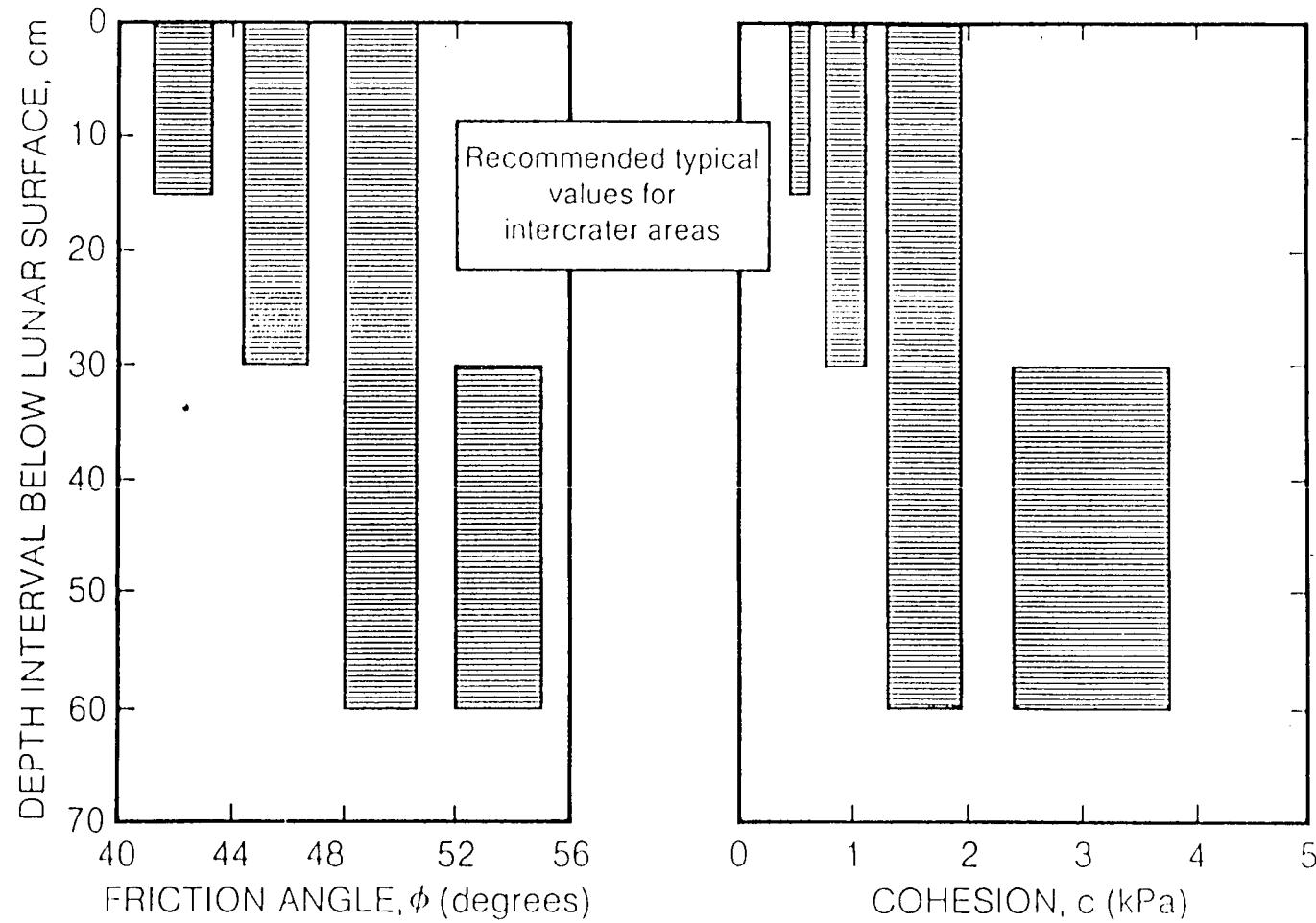


Fig. 9.19. Plots of *in situ* bulk density (bottom horizontal axis) and relative density (top horizontal axis) as a function of depth in the lunar soil layer at the Apollo 15 landing site (Hadley Rille), based on data from core tube samples (Fig. 9.11) and detailed studies of soil sample 15601,82 (Table 9.7) (after Carrier *et al.*, 1973a,b). The soil, although less dense near the surface (<10 cm deep), quickly becomes "dense" to "very dense" with depth (>20 cm).

REFERENCE: LUNAR SOURCEBOOK.

# SHEAR STRENGTH PARAMETERS FOR LUNAR SURFACE MATERIAL



Calculated average ("recommended") values of shear strength parameters (friction angle and cohesion) in the lunar surface material as a function of depth below the surface (vertical axis). Both parameters, particularly the cohesion, increase with depth.

REFERENCE: LUNAR SOURCEBOOK, PAGE 515.

# POSSIBLE LOCATIONS OF MARTIAN GROUND ICE AND WATER

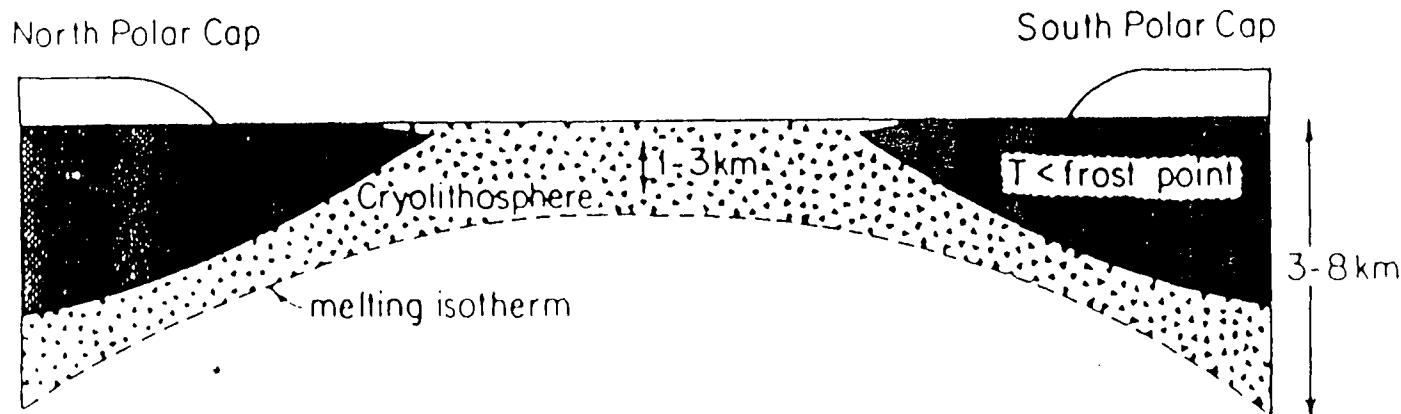


Fig. 3. A pole-to-pole cross section of the Martian crust illustrating the theoretical latitudinal variation in depth of the 273 K isotherm. Ground ice can exist in equilibrium with the atmosphere only at those latitudes and depths where crustal temperatures are below the frost point of atmospheric water vapor ( $\sim 198$  K; Farmer and Doms 1979). Outside these locations, ground ice can only survive if it is diffusively isolated from the atmosphere by a regolith of low gaseous permeability (see, e.g., Smoluchowski 1968; Clifford and Hillel 1983; Fanale et al. 1986) (Figure adapted from Fanale 1976 and Rossbacher and Judson 1981.)

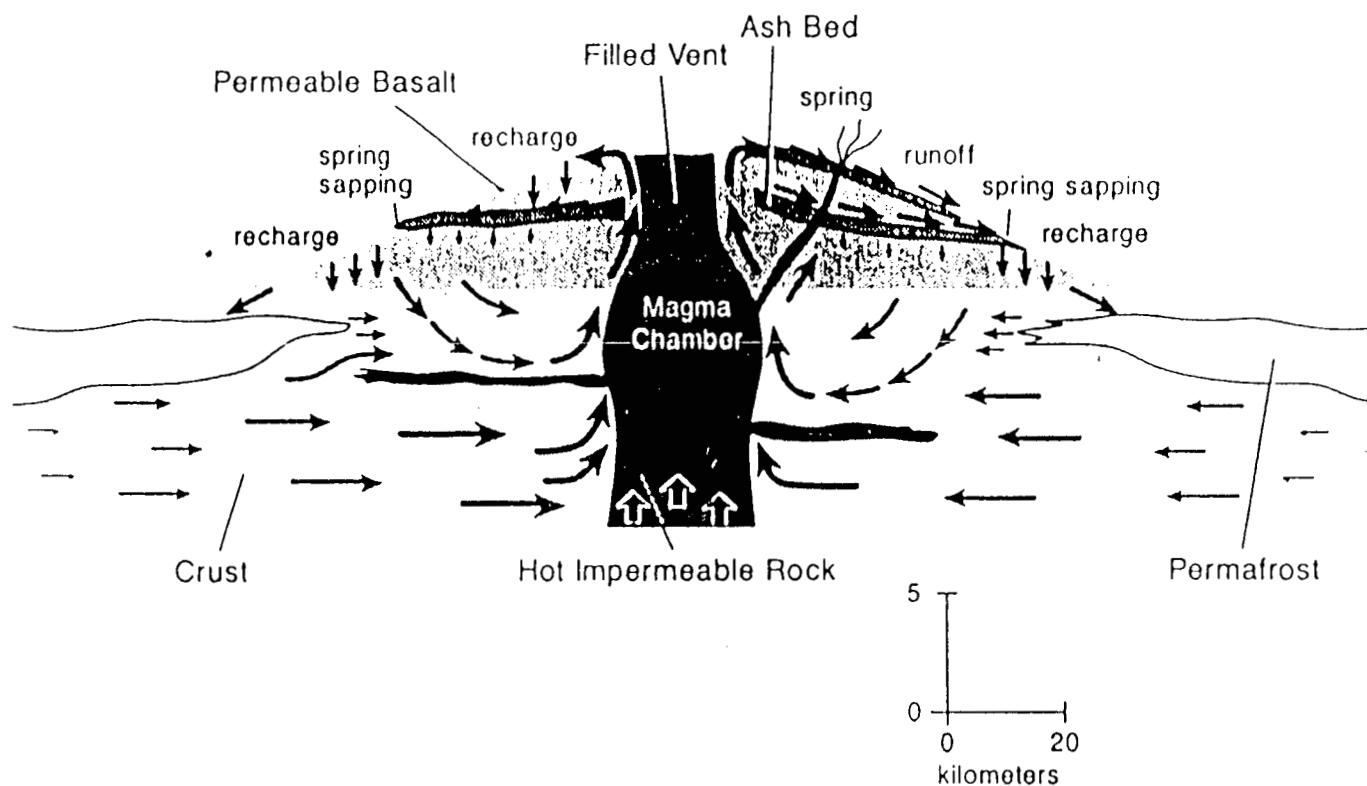
The general picture expected, then, is that ground ice will be found fairly close to the surface at high latitudes, but only hundreds of meters beneath the surface near the equator.

# DRILLING, CORING AND EXCAVATING NEEDS - MARS

<u>PHASE</u>	<u>MISSION DRIVER</u>	<u>NEED</u>
"CHEAP" PRELIMINARY EXPLORATION	<ul style="list-style-type: none"> <li>* COMPOSITION (THROUGH WEATHERING SURFACES)</li> <li>* CLIMATIC HISTORY</li> <li>* DRILL POLAR ICE</li> </ul>	<ul style="list-style-type: none"> <li>* MICRODRILLS (CM CLASS)</li> <li>* 0.5 M ROTARY-PERCUSSIVE DRILLS</li> </ul>
SERIOUS IN-DEPTH EXPLORATION	<ul style="list-style-type: none"> <li>* CLIMATIC HISTORY</li> <li>* DEEP DRILL POLAR ICE</li> <li>* FIND ORES</li> <li>* EXOBIOLOGY <ul style="list-style-type: none"> <li>* INTO SEDIMENTS</li> <li>* INTO PERMAFROST</li> <li>* BELOW PERMAFROST</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>* UP TO 6 KM CORES</li> <li>* ?</li> <li>* NONCONTAMINATING!</li> <li>* M'S - <math>\times 10^1</math> M</li> <li>* &gt; 10 M</li> <li>* 3-8 KM (FCN. LAT.)</li> </ul>
INDUSTRIALIZATION AND HABITATION	<ul style="list-style-type: none"> <li>* WATER PRODUCTS</li> <li>* UNDERGROUND HABITATS</li> <li>* AREOTHERMAL ENERGY?</li> </ul>	<ul style="list-style-type: none"> <li>* WELLS(?) &gt;10 M DEEP</li> <li>* 10 M (?) DEEP CAVES</li> <li>* ? X KM WELLS(?)</li> </ul>

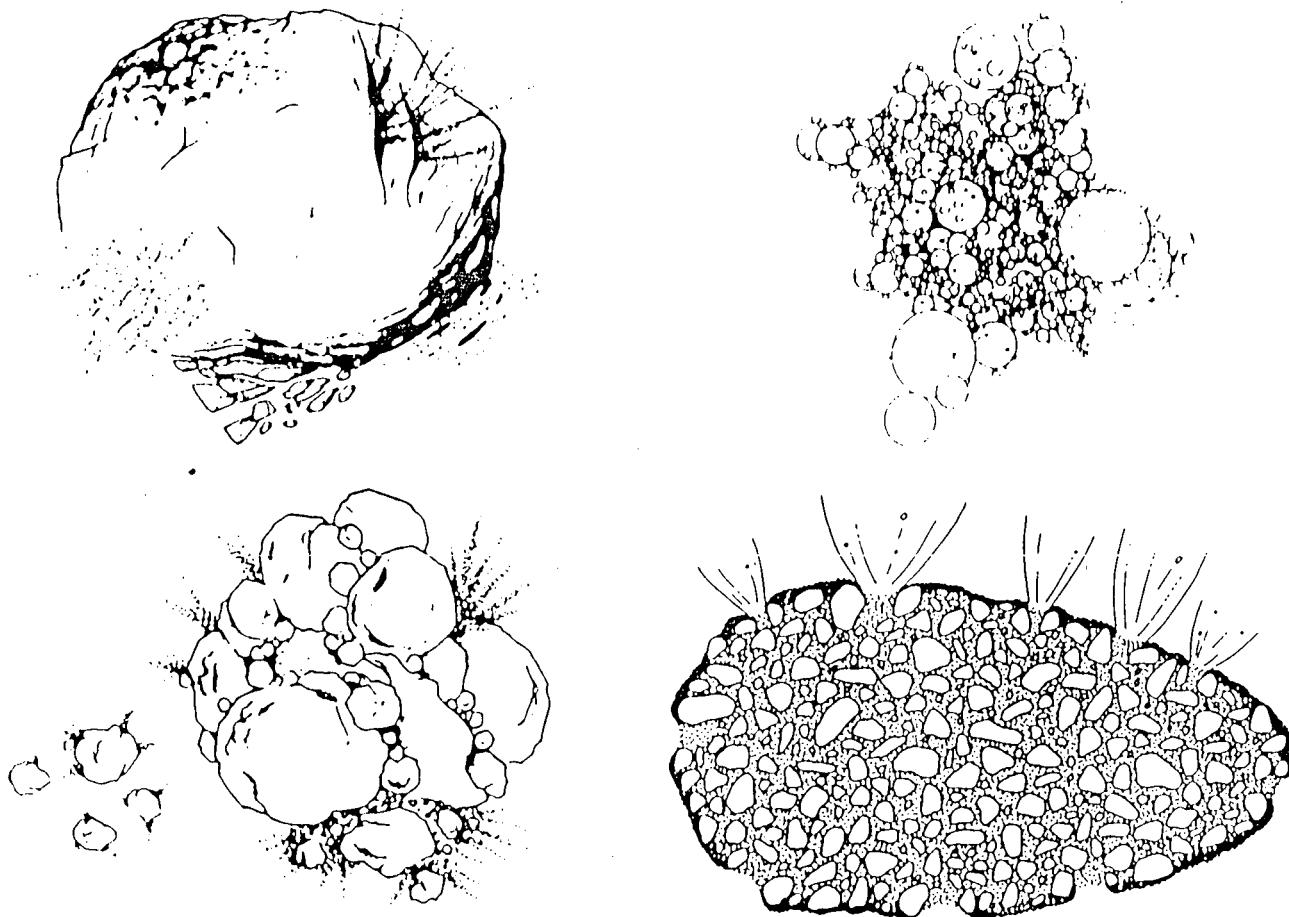
*See more permanent  
do fine polar  
Non-corp'*

# POSSIBLE HYDROTHERMAL SYSTEM ON MARS



REFERENCE: RESOURCES OF NEAR-EARTH SPACE, CHAPTER BY V. R. BAKER, ET AL.

## MODELS OF COMETARY NUCLEI



Four suggested models for the structure of cometary nuclei: (a) the icy conglomerate model (Whipple 1950; drawing from Weissman and Kieffer 1981); (b) the fractal model (Donn et al. 1985); (c) the primordial rubble pile (Weissman 1986a); and (d) the icy-glue model (Gombosi and Houpis 1986). All but (d) were suggested prior to the Halley spacecraft encounters in 1986.

## DRILLING, CORING AND EXCAVATING NEEDS - COMETS

<u>PHASE</u>	<u>MISSION DRIVER</u>	<u>NEED</u>
"CHEAP" PRELIMINARY EXPLORATION	* SOLAR SYSTEM ORIGINS * ROSETTA - SAMPLE COMET NUCLEUS	* 1-2 CM CORE, UP TO 1 M DEEP, IN ICE- SILICATE @ 120 K.
SERIOUS IN-DEPTH EXPLORATION	* SOLAR SYSTEM ORIGINS * VOLATILES PROSPECTING	* DEEP DRILLING IN HARD ICE WITH FROZEN SILICATES & ORGANICS
INDUSTRIALIZATION AND HABITATION	* PRODUCTION OF PROPELLANT LIFE SUPPORT PRODUCTS * EARTH PROTECTION	* MILLIGRAVITY, LARGE SCALE MINING TECHNIQUES * BENEFICIATION OR MELTING OF ICE CHUNKS

# DRILLING, CORING AND EXCAVATING NEEDS ASTEROIDS, PHOBOS & DEIMOS

<u>PHASE</u>	<u>MISSION DRIVER</u>	<u>NEED</u>
"CHEAP" PRELIMINARY EXPLORATION	* VOLATILES ASSESSMENT * CARBONACEOUS OBJ. * HYDRATED SILICATES	* "BULKY CORES" OF SOFT MATERIAL
SERIOUS IN-DEPTH EXPLORATION	* PLANETARY ORIGINS * NEAR EARTH OBJECTS * MAIN BELT ASTEROIDS  * PROSPECTING FOR PRECIOUS METALS	* ABILITY TO CORE DIVERSE OR VERY NONHOMOGENEOUS OBJ. - CLAY - ROCK - METAL * MILLIGRAVITY OPERATIONS
INDUSTRIALIZATION AND HABITATION	* PRODUCTION OF PROPELLANT & LIFE SUPPORT PRODUCTS  * METALLIC CONSTRUCTION  * EARTH PROTECTION	* MILLIGRAVITY, LARGE SCALE MINING TECHNIQUES

# POSSIBLE GEOLOGY OF A DIFFERENTIATED MAIN BELT ASTEROID

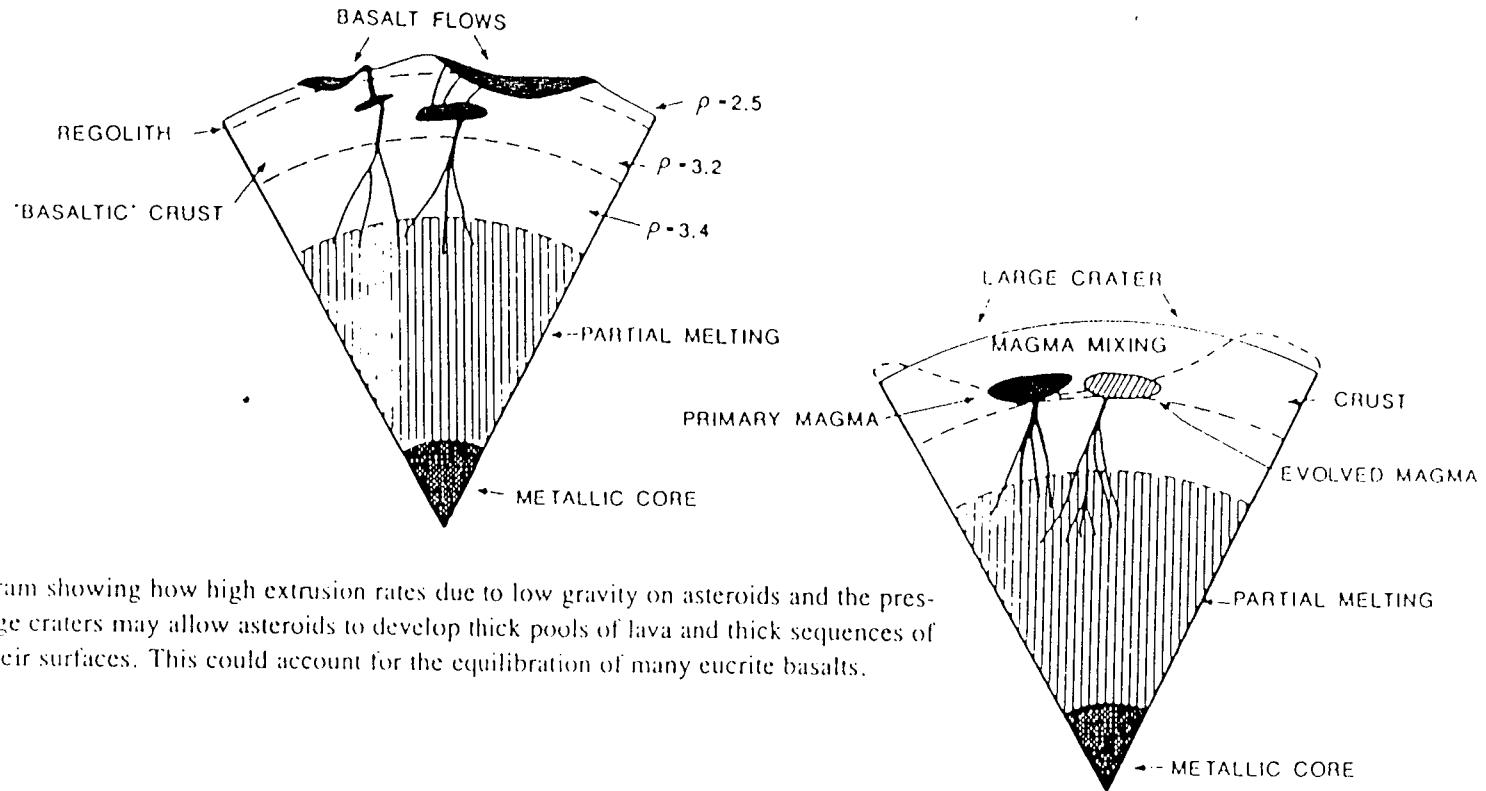


Diagram showing how high extrusion rates due to low gravity on asteroids and the presence of large craters may allow asteroids to develop thick pools of lava and thick sequences of flows on their surfaces. This could account for the equilibration of many eucrite basalts.

**SIZE: 10-500 KM DIAMETER.**  
**NEAR EARTH ASTEROIDS ARE**  
**JUST SMALL FRAGMENTS OFF**  
**MAIN BELT ASTEROIDS.**

Diagram showing how impacts on an asteroid undergoing magmatic activity can add twists to the course of petrologic events. A large crater could excavate magma chambers, thereby quenching them, or mix magmas of different composition. Extremely large craters could excavate down to the zone of partial melting, thus quenching in their high-temperature characteristics and possibly producing rocks that mimic igneous cumulates.

# COMPARING CARBONACEOUS ASTEROIDS TO COAL AND OIL

Elemental Composition of Ash-free Organic Phases<sup>a</sup>

	C	H	O	N	S	Tot.	C/H	Reference
C1 meteorite	73.6	4.6	10.3	1.66	7.23	97.4	15.9	Hayes 1967
C2 meteorite	78.	3.1	13.	1.7	4.2	100.	25..	Zinner 1988
Oil Shale, KY	82.0	7.4	6.3	2.3	2.0	100.	11.1	Smith and Jensen 1987
Oil Shale, UT	80.5	10.3	5.8	2.4	1.0	100.	7.8	Smith and Jensen 1987
Bituminous, PA	82.4	5.6	9.0	1.6	1.3	100.	14.6	Smoot 1979
Anthracite	89.4	3.8	4.6	1.1	1.1	100.	23.6	Smoot 1979
Heavy Petroleum	85.3	11.0	0.5	0.4	2.8	100.	7.7	
Light Petroleum	85.7	12.7	0.3	0.2	1.1	100.	6.8	

<sup>a</sup> All compositions are weight percent. C1 is Orgueil, water- and solvent-insoluble fraction only. (Content includes 1.28% Cl, 1.31% F; may be contamination.) C2 is Murchison. C1 and C2 organic phases are obtained by HCl/HF digestion of inorganic phases. Some insoluble mineral matter remains, so the above data have been recalculated on an ash-free basis. For a discussion on the nature and origins of the organic matter in carbonaceous meteorites, see Cronin et al. (1988). Petroleum data are for comparison only; derived by author from data in Perry and Chilton (1973) and Grayson and Eckroth (1982).

# ENVIRONMENTAL CONSTRAINTS FOR EXTRATERRESTRIAL DRILLING AND EXCAVATING

<u>LUNAR</u>	<u>MARTIAN</u>	<u>SMALL BODY</u>
* HARD VACUUM	* LOW PRESSURE	* HARD VACUUM
* 1/6 GRAVITY	* 1/3 GRAVITY	* MILLIGRAVITY
* TENACIOUS DUST * VERY ABRASIVE	* MAJOR DUST STORMS	* OCCASIONAL DUST
* ELECTROSTATIC CHARGE	* ELECTROSTATIC CHARGE * OXIDIZING ATMOSPHERE	* ELECTROSTATIC CHARGE * GASEOUS EMISSIONS
* TEMPERATURE EXTREMES	* LOW TEMPERATURES	* VERY LOW TEMPERATURES
* INTENSE RADIATION	* INTENSE RADIATION * BIOLOGICAL ISOLATION ISSUES	* INTENSE RADIATION
	* LONG COMM DELAYS	* POSSIBLE COMM DELAYS

## VALUABLE NEAR TERM CHALLENGES

- \* DRILLING & CORING TECHNIQUES FOR COMETARY ICES, AND MARTIAN POLAR CAPS.
- \* LOW DISTURBANCE "SOFT BODY BULKY CORING" TECHNIQUES FOR CARBONACEOUS, OTHER SOFT ASTEROIDS, OR COMETARY CRUSTS.
- \* TECHNIQUES FOR SEPARATING IRREGULAR ICE CHUNKS OFF COMET NUCLEI, ALONG NATURAL FRACTURE BOUNDARIES.
- \* BIOLOGICALLY NONCONTAMINATING MARS DRILLS.
- \* GASLESS, OR CLOSED GAS, LUNAR DRILLS.

## **Appendix H**

## Drilling Research in the Fossil Energy's Oil Program

New program in 1994 - reviewed research needs and developed a five-year implementation plan. (\$450K in FY94)

Participation in the Drilling Engineering Association and Completion Engineering Association projects on a limited basis.

Supported an ongoing project by Maurer Engineering on Horizontal Well drilling

Support Industry selected projects at the National Laboratories through the Oil Partnership Program. In 1994 and 1995 we supported a project on research for synthetic diamond drill bits and top drive rig failures.

A congressional mandate was included in the FY95 budget to work with the University of Tulsa in the areas of production and drilling. The Statements of Work for that money are being developed.

Support for a base program of research at the NIPER Laboratory. (\$475K in FY95) The details of the base program are presented in the following material.

Rhonda Lindsey Program Manager at Bartlesville Project Office (918) 337-4407

# **DRILLING PROGRAM @ NIPER**

**Funding (FY95):** \$1,575,000.

**Research Projects (\$475,000.):**

- Wellbore Stability
- Underbalanced Drilling
- Univ. of Tulsa - "Adv. Horiz. Coiled Tubing Drilling"

**RFP (Univ. of Tulsa):**

- Drilling, Paraffin Control (\$1,100,000.)

**Cooperative Research (CRADA):**

- Amoco & ARCO - Wellbore Stability & Underbalanced Drilling

**Reports:**

- A Review of Slimhole Drilling (9/94)
- Report on State-of-the-Art in Wellbore Stability (6/95)
- Status Report on Modeling of Wellbore Stability (9/95)
- Status Report on Advancements in Underbalanced Drilling (9/95)

**Contact:**

- Rhonda Lindsey - DOE Project Manager (918-337-4407)
- Herb Carroll - Contract Project Mgr., BDM-Oklahoma (918-337-4558)

## **Appendix I**

## Military Technology Applied to Advanced Drilling and Excavation

George A. Gazonas  
U.S. Army Research Laboratory  
Weapons Technology Directorate  
Aberdeen Proving Ground, MD 21005

The U.S. Army is interested in technology transfer of defense-related research to civilian applications such as those sponsored by the Department of Energy's National Advanced Drilling and Excavation Technologies (NADET) program. The NADET consortium consists of partners from industry, academia, and government collaborating to develop advanced drilling systems for penetrating/excavating hard rock. This article briefly outlines areas where the Army's research efforts may overlap with advanced drilling/excavation system requirements as outlined in the National Research Council's (NRC) recent report: Drilling and Excavation Technologies for the Future (1994). The report concludes that R&D efforts should be focused on: 1) development of "smart" drilling systems capable of sensing the subsurface formation and responding in real-time to the variable subsurface drilling environment, and 2) development of advanced drilling systems that will increase the cost effectiveness of drilling by increasing the efficiency of rock removal, increasing the wearability of bits, cutter materials, and bearings, and by developing environmentally benign drilling fluids and reliable, low-cost downhole motors.

The idea that military technology can be successfully used to enhance existing or develop advanced drilling systems is not new. The Soviets have experimented with novel (revolutionary) explosive drilling systems since the late 1950s where special explosive capsules were used to drill to depths of 2.8 km (Ostrovskii, 1960). Drilling concepts using shaped charges have also been proposed; Robinson (1962) suggested detonating a gauging charge within a cavity initially produced by a shaped charge in order to widen the borehole to accommodate the descending drill string. Godfrey (1970) described a method for excavating rock using massive concrete projectiles fired at hypervelocity ( $> 4$  km/s) from a gun, and capable of excavating an 8-ft-diameter hole a distance of 400 to 2,000 ft/day. In 1976, Sandia National Laboratories, in collaboration with Tround International, Inc. proposed the development of a hybrid (evolutionary) "Terra-Drill" system that essentially consisted of a downhole 'machine gun'

combined with a conventional rotary drill bit (Newsom et al, 1976). A prototype system was built capable of delivering 50-caliber rounds to the bottom of a borehole at 6 rounds/min; penetration rates into Madera limestone were doubled using this hybrid drilling system as compared to those obtained with a conventional rotary bit drilling system. As these examples show, military technology has been effectively used in the past to excavate and drill into rock; however, there is little current commercial use of the technology, possibly because of the perceived low reliability and hazards associated with using propellant- or explosive-based projectile propulsion systems (Maurer et al, 1990).

Thus, more than three decades have passed since it was shown that military technology could be effectively used to drill through rock. There have been many military advances since then that have enabled our military forces to maintain technological battlefield advantages in the areas of: 1) *Interior Ballistics*; 2) *Terminal Ballistics*; and 3) *Exterior Ballistics*. Several aspects of these three areas relevant to advanced drilling systems are outlined in the next section.

### *Interior Ballistics*

Recent advances in the development of insensitive munitions, high energy low vulnerability (HELOVA) solid propellants, and liquid gun propellants show great promise for increasing the battlefield survivability of combat vehicles. In insensitive munitions research is focused on reducing the response level of our ammunition to enemy threats; the hazard mitigation thus achieved with respect to the rigors of the battlefield is immediately transferable to the more benign oil field drilling environment. We could thus greatly reduce the hazard potential of advanced drilling systems that use high energy kinetic energy (KE) projectiles to fracture or penetrate rock.

The fundamental contact mechanisms which lead to friction and wear underlie both the erosion of gun barrels and wear of drill bits. The interior surfaces of gun barrels are subjected to high rate deformations induced by frictional interaction with the projectile which induces mechanical wear of the gun barrel. Mechanical wear is exacerbated by the chemical corrosion effects of propellant combustion products. In drilling operations, similar wear processes are operative at the bit-rock interface as the rapidly rotating bit penetrates through hot geothermal rock

formations which are inhabited by highly corrosive fluids. Since drill bit life is the controlling factor governing penetration rates in geothermal wells, ways of improving bit life might be found based on collaborative R&D efforts involving "lessons learned" from our gun erosion research.

Although interesting in concept, it is unlikely that the conventional gun barrel/borehole analogy is extendable to the degree that someday, surface launched projectiles will be used to drill deep wells. Many conventionally drilled wells are highly deviated as a result of drilling in anisotropic rock. The wells contain doglegs and ledges, and are often fluid-filled; these features would impede the motion of high KE projectiles during their flight down the wellbore. However, a hybrid drilling system that uses high KE surface-launched projectiles together with a conventional rotary grinding tool that uses compressed air, rather than drilling fluids to remove rock debris, could lead to an advanced drilling system that produces relatively straight vertical boreholes. The Army's emerging hybrid in-bore ram (HIRAM) propulsion technology uses a low pressure (750 psi) combustible methane/oxygen/nitrogen mixture to propel a projectile down a gun barrel using propulsion physics similar to that found in ramjet engines. The combustible gas mixture could be used to both propel the projectile down the well, and then remove the rock debris resulting from the impact. Boreholes drilled by hypervelocity projectiles should be straighter than boreholes drilled by conventional means, since the penetration behavior of solids deformed at high rates is governed by hydrodynamics, whereas the penetration mechanics of conventional drilling is dependent upon rock strength and anisotropy.

#### Terminal Ballistics

Although of strictly military origins, shaped charge jet technology is currently widely used by oil field service companies to laterally perforate well casings prior to hydraulic fracture treatments; Smith and Keating (1993) report cratering velocities of nearly 2.0 km/s in Berea sandstone using GOEX, Inc. shaped charges. New shaped charge jet warhead or explosively-formed penetrator designs exist which could be used to improve upon the continuous explosive drilling systems developed by the Soviets in the late 1950s. Since the mid 1970s, the use in Army applications of large-scale wave propagation computer codes ('hydrocodes') have enabled Army researchers to develop prototype KE projectiles and

shaped charges at reduced developmental costs. A similar approach might be taken in developing a hybrid rotary bit/explosive drilling system. Optimization of charge geometry, reduction of damage to the drill bit, and increased reliability could be achieved by shrewd application of hydrocodes. For example, a Lagrangian hydrocode simulation conducted by the author, shows that a linear shaped cutting charge, consisting of a mild steel liner and having an initial jet tip velocity of about 5 km/s, easily cuts through a 1-in thick concrete slab in only 10  $\mu$ s (Figure 1). The model predicts an average penetration velocity of about 2.5 km/s in the concrete. Moreover, a standard M3A1 demolition charge can produce a 3.5-in diameter hole, 5-ft deep in reinforced concrete (Table 1, pg. 42, Walters and Zukas, 1989). It is not difficult to imagine how such devices might be exploited to drill through hard rock.

Improvements in the Tround system (Newsom et al, 1976) could be made by using modeling techniques to optimize KE projectile geometry, material composition, and boundary conditions such as velocity. For example, hydrocodes might be used to simulate the impact and penetration of composite or ceramic projectiles into hard rock. Hydrocode computations, coupled with statistical experimental design, could be exploited to maximize projectile penetration depth as well as minimize projectile fragment size so as to eliminate deleterious effects on subsequent drilling operations.

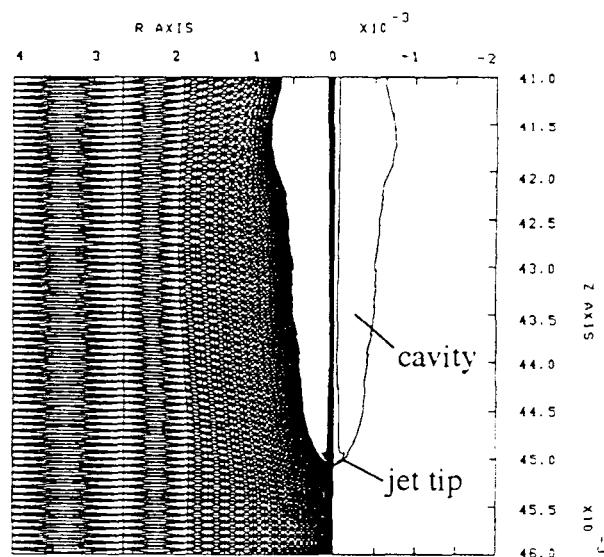


Figure 1. EPIC92 Hydrocode Simulation Showing Features of the Concrete Cavity in the Vicinity of the Jet Tip After 1.2  $\mu$ s (dimensions in meters).

## *Exterior Ballistics*

Conventional exterior ballistics research in the Army aims to improve the aerodynamic stability of projectiles in free flight, increase range, improve target accuracy and precision, etc. For example, current Army advanced artillery programs are directed at, among other things, improving projectile target accuracy based on making real-time comparisons of predicted and actual projectile trajectories using data from the Global Positioning System (GPS). Also under development is a system whereby sensors mounted on-board a projectile transmit via GPS near real-time video images of the terrain over which the projectile flies, to a ground-based station. These are examples of what in current Army parlance is known as "digitizing the battlefield", and emphasize the importance of the need to be able to conduct real-time communications in modern day warfare. This motivates the notion that the GPS might also be used in developing advanced drilling/excavation systems. For example, in remote areas or in areas of extreme topographic relief, the GPS could be used in lieu of tedious, costly geodetic surveying. The development of such "smart" drilling systems would also require real-time data acquisition from geophysical sensors whose coordinate locations could be optimally determined with the aid of the GPS. Information from multiple geophysical sensors could be collected and analyzed in near real-time to provide continuous feedback to either remotely control or to provide information for autonomous control of the drill bit.

The DOE's NADET program provides a unique opportunity to transfer defense-related technologies to civilian applications such as those found in the drilling and excavation industry. We have briefly outlined a few areas where modern military technology could benefit the development of advanced drilling or excavation systems. We are interested in conducting collaborative R&D, and welcome questions and comments on the ideas presented in this article. Additional information can be obtained by mail: George A. Gazonas, U.S. Army Research Laboratory, attn: AMSRL-WT-PD, Weapons Technology Directorate, Aberdeen Proving Ground, MD, 21005-5066, phone: (410) 278-6194, E-Mail: gazonas@arl.army.mil.

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