A FEASIBILITY STUDY OF
A HYBRID EROSION DRILLING CONCEPT

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SECTION 1

INTRODUCTION AND SUMMARY

This report presents the results of a system analysis of the ERODRILL concept. ERODRILL is an erosion drilling technique that uses a stream of propellant capsules carried in the drilling mud and ignited near the bottom of the drill hole to provide a fluid jet on the rock face. The concept evaluated in this study was a hybrid system using the erosion drill to cut a kerf for a conventional rotary drill to break to. Based upon previous data, it is reasonable to expect such a system to achieve drilling rates a factor of two greater than conventional rotary drills alone. The operating parameters used to evaluate this concept were:

Depth	10,000 feet
Mud temperature	350°F
Rock compressive strength (at hole bottom)	15,000 to 20,000 psi
Rock bit	8½-inch-diameter tricone
Weight on bit	30,000 pounds
Conventional drilling rate	20 ft/hr
Drilling rate with kerf cut	40 ft/hr
Bubble velocity in annulus	150 ft/min
Mud velocity in annulus (for chip lifting)	150 ft/min
Mud velocity in drill stem	13 ft/sec (780 ft/min)
Mud flow rate	320 g/min
Mud density	75 lb/ft ³ ($\rho = 1.2$)
Mud viscosity	10 centipoise
Drill pipe	4½ in. o.d.; 3 in. i.d.

Using these operating parameters, a preliminary design was made and a hypergolic propellant, Hercules HES 6573, was chosen. Economic analysis of this preliminary design indicates that it is particularly attractive for offshore drilling, where cost per foot is very high and improvements in drilling rates can result in significant savings. If the cost per propellant capsule (estimated to be \$4 in production quantities) can be reduced 40 percent or the achieved drilling rate increased by 32 percent, ERODRILL can also be economically attractive for deep (20,000 feet) land wells. Considerable improvements in cost or drilling rate would be required for the hybrid system to be competitive with conventional drilling methods for shallow land wells.

Section 2 of this report presents the background and rationale for this program. The system, from its initial conception to its current hybrid design, is described in Section 3. The propellant selection process is presented in Section 4. Section 5 is the hazard evaluation and reliability analysis and Section 6 the economic analysis. Conclusions and recommendations appear in Section 7.

SECTION 2

BACKGROUND

The present world-wide energy shortage requires economic improvements in the technology of extracting energy from underground sources. The major restriction in obtaining increased output of oil and gas is the time and cost of drilling holes. Other techniques, such as water-flooding, extraction of geothermal energy, and in situ retorting of oil shale or coal all require the drilling of holes. It would obviously improve the energy situation if more rapid and economical means of drilling holes in the earth media could be devised.

For any method of drilling, it is convenient to define a specific energy which identifies how much energy it takes (in joules) to remove 1 cubic centimeter of rock. If one knows the specific energy (E) for any drilling scheme and the power (P) that can be transmitted to the rock, then P/E is the rate at which rock is removed. Thus the criteria for a rapid drilling technique are a low specific energy and/or the transmittal of a large amount of power to the rock. Conventional rotary drills have reasonably low specific energy, but can transmit only a few tens of horsepower to the rock.

A major effort is being devoted to finding faster and cheaper ways of drilling rock. Maurer (Reference 1) summarized the state of the art in novel drilling techniques, given in Table 1, which is an estimate of potential rates for drilling 20-cm-diameter holes in medium-strength rock by the techniques evaluated. It can be seen that erosion (by high velocity water jets) gives one

TABLE 1
ESTIMATES OF MAXIMUM DRILLING RATES FOR 20-cm-DIAMETER
NOVEL DRILLS IN MEDIUM-STRENGTH ROCK*

Drill	Status	Rock Removal Mechanism	Spec. Energy (J/cc)	Max. Power To Rock (hp)	Max. Potential Drilling Rate (cm/min)
Rotary ^a	Field Drill	Mechanical	200-500	20-30	14-85
Spark ^a	Laboratory Drill	Mechanical	200-400	100-200	35-140
Erosion ^a	Laboratory Drill	Mechanical	2000-4000	1000-2000	34-140
Explosive ^a	Field Drill	Mechanical	200-400	75-100	26-70
Forced Flame	Field Drill	Spalling ^b	1500	300-600	28-56
Jet Piercing	Field Drill	Spalling ^b	1500	100-200	9-18
Electric Disintegration	Laboratory Drill	Spalling ^c	1500	100-150	9-14
Pellet ^a	Laboratory Drill	Mechanical ^a	200-400	10-20	4-14
Turbine ^a	Field Drill	Mechanical ^a	400-1300	30-40	3-14
Plasma	Laboratory Tests	Spalling ^b	1500	80-120	8-11
Electric Arc	Laboratory Tests	Spalling ^b	1500	45-90	4-8
High Frequency	Shatters Rock	Spalling ^b	1500	30-60	3-6
Plasma	Laboratory Tests	Fusion	5000	80-120	2-3
Electric Heater	Laboratory Drill	Fusion	5000	50-100	1-3
Electric Arc	Laboratory Tests	Fusion	5000	45-90	1-3
Nuclear	Conceptual	Fusion	5000	1250-2500 ^e	1-3
Laser	Small Holes	Spalling ^b	1500	12-24	1-2
Electron Beam	Small Holes	Spalling ^b	1500	10-20	1-2
Microwave	Shatters Rock	Spalling ^b	1500	10-20	1-2
Induction	Shatters Rock	Spalling ^d	1500	5-10	0.5-1.0
Laser	Small Holes	Fusion	5000	10-20	0.3-0.6
Electron Beam	Small Holes	Fusion	5000	10-20	0.3-0.6
Electron Beam	Small Holes	Vaporization	12,000	10-20	0.1-0.2
Laser	Small Holes	Vaporization	12,000	7-14	0.1-0.2
Ultrasonic ^a	Laboratory Drill	Mechanical	20,000	5-10	0.04-0.07

^aWater-filled borehole

^bLimited to highly spallable rock such as taconite

^cLimited to highly spallable rock with high electrical conductivity

^dLimited to highly spallable rock with high magnetic susceptibility

^eOne hundred-cm-diameter drill

* Reference 1

of the highest potential drilling rates. These high drilling rates are projected in spite of the fact that the specific energy of the erosion process is not as favorable as other techniques. The key to the rapid drilling of the erosion technique is its ability to concentrate large amounts of horsepower on the rock; Table 1 shows 1000 to 2000 horsepower. The attainment of these rates was said to await the development of large-capacity high-pressure mechanical pumps.

It is clear from the above information that a drilling scheme that maximized the horsepower applied and minimized the specific energy might have a high economic potential in commercial drilling. Such schemes have been evaluated by others. In each case, however, the source of energy (i.e., a hydraulic pump) has been on the surface at the top of the drill hole. To achieve very high horsepower at the bottom of a deep hole under these conditions becomes almost impossible due to the limitations of mechanical pumps and the large down-the-hole frictional losses.

A potential method of providing the sudden release of large amounts of energy at the bottom of a hole (i.e., high horsepower) is by the use of explosives or propellants. Ostrovski has used explosive capsules for drilling holes (Reference 2). The release of explosive energy, however, is difficult to control. Also the very high detonation pressures of explosives result in limitations to the size of a capsule and the rate they can be fired. Propellants were first tested as a source of drilling energy by Maurer (Reference 3). The tests were conducted by putting nozzles on the muzzle of a conventional cannon and filling a portion of the barrel with fluid. Conventional propellant was then ignited and drove the fluid through the nozzles at relatively high velocity. The tests showed quite interesting results. The cannon employed nozzles of 5-mm to 25-mm diameter and peak nozzle pressures up to 1.7 kbar (25,000 psi). The size of the

nozzles did not appear to affect the specific energy. At the higher pressures, the specific energy appears to be almost constant. These data check with the conclusions made above. Tests were also performed with a four-nozzle bit (each 5 mm in diameter). At 1.4-kbar (21,000 psi) peak pressure, all the rock between craters was removed. Maurer postulated that if the cannon had been rotated in the test, a smooth cylindrical hole would have been produced. The specific energy for the multiple nozzle tests was quite similar to that of the single nozzle tests. Maurer concluded that if such a cannon could be fired every second, it could drill large holes in reasonably strong rock at rates of 1 m/min. He further concluded, however, that the mechanics of producing these high pressure pulses down hole would be complicated and the equipment would be subjected to high shock loads. For these reasons, therefore, he felt that it was more feasible to pump continuously (from the surface) through hydraulic jet drills for oil well drilling.

There have been significant advances in the technology of jet drilling and the tailoring of propellant properties since Maurer wrote his paper in 1969. Moreover, the national motivation for developing economic ways to drill offshore wells or very deep land wells has become much stronger. These considerations justified the evaluation of a novel concept for jet drilling using propellant capsules. This concept, ERODRILL, is described in detail in the following section.

SECTION 3

SYSTEM DESCRIPTION

3.1 BASIC CONCEPT

A simplified schematic showing the basic initial concept of ERODRILL is shown in Figure 1. A single drill stem goes from the surface to the bottom of the hole. The drill stem would be rotated continuously to prevent it from sticking. Attached at the bottom is a high pressure chamber; lengths of 1 to 3 meters for this chamber were assumed. For pure erosion, the multiple nozzles can control the diameter of the hole better than a single nozzle. A check valve is shown at the top of the high pressure chamber. Some form of volume accumulator or reservoir may be required near the bottom to prevent a large pressure pulse from forming in the outer annulus during the fluid discharge phase.

As shown in Figure 1, the method of getting an energy source to the bottom is to use capsules of propellant introduced sequentially at the top of the drill collar. These capsules are 7 to 20 cm long and separated from each other by several meters of drilling fluid. The capsules have a diameter which is as large as the inner diameter of the drill stem will allow without their becoming stuck. These capsules will, therefore, maintain their spacing with a certain accuracy. The initial upward flow from the combusting capsule would close the check valve and force the drill fluid to flow out of the nozzles. Some of the exhaust gases would flow out the nozzle until the gas pressure dropped to that of the static head of fluid outside the nozzles.

Figure 1 Schematic of ERODRILL concept.

The pressure on the fluid and propellant column would be greater than this and the check valve would open, allowing the chamber to be refilled. A small blocking capsule, which could be filled with drilling fluid or perhaps a very viscous fluid, is placed just above each propellant capsule to prevent the exhaust gases from bubbling up to the next capsule after the check valve has opened. This capsule and the capsule holding the propellant would be weak enough so that they would be ripped apart and ejected through the nozzles upon combustion and impact. The time for one cycle would be the time to eject the fluid from the nozzle plus the time to refill the chamber. The nozzle shown is a schematic of one which would drill by pure erosion.

At the outset of this program it was determined that the system to be evaluated in this study should be a hybrid, combining an erosion drill with a conventional rotary bit. This hybrid system would not represent a radical change from present drilling techniques and would therefore be more likely to be accepted readily by industry. Further, the propellant system, which represented the largest unknown, would be common to both hybrid and pure erosion drills. It was estimated that by combining the two techniques, an increase in drilling speed of a factor of two over conventional methods might be achieved.

The operating parameters that provide the design criteria for the system are specified in Section 1. In the design evolved to meet these criteria a propellant cartridge is used that burns at one end only, thus minimizing the energy lost to water vaporization. The unburned end of the propellant capsule acts as a piston in the combustion chamber, forcing drilling mud above it through "down comers" and thus into the jet stream. The drilling mud in the combustion chamber below the ignited propellant capsule is accelerated by the combustion products through half-inch diameter

holes, into a 3/8-inch port and through a tungsten carbide nozzle. The propellant is initiated by a stainless steel spike located concentrically within the combustion chamber.

The detailed design of the combustion chamber is shown in Figure 2. The chamber would be fabricated of 4340 steel, which has a yield stress of approximately 180,000 psi. The chamber is designed to contain an internal pressure of 60,000 psi. This pressure level is more than twice that generated by the simultaneous initiation of two propellant charges. Such an initiation could conceivably occur if for some reason one propellant charge did not ignite. The length of the initiation spike is sufficient that the first capsule would be completely pierced when the second was initiated; the second charge would then almost certainly light off the first as well. If this were to occur, the pressure within the chamber would approximately double, or about 35,000 psi.

The length of the combustion chamber depends upon the depth of the well, as sufficient length must be provided to expand the propellant cases isentropically to ambient hydrostatic pressure to prevent blowout of the well. Chamber length at a 1000 foot depth would be about 30 feet; at 10,000 feet only a 10 foot length would be required.

In the design of the combustion chamber, standard oil field equipment and joints were used wherever possible, for both compatibility and reliability in the field. For example, the check valve at the bottom of the combustion chamber is a TRW Mission check valve, which has been subjected to 15,000-psi loading for 10^4 cycles without failure. The chamber fits to a standard 3-inch-i.d., 4½-inch-o.d. drill pipe at one end and a tri-cone bit at the other.

Figure 2 ERODRILL combustion chamber.

Figure 3 shows the sequence of operation of the combustion chamber. In the first panel, both check valves are open and mud is flowing to the drill bit at 320 gallons per minute. A propellant capsule, traveling at 7 ft/sec, has entered the combustion chamber and is approaching the initiation spike. The propellant, which is hypergolic in water, is initiated when the skin of the capsule is pierced. Panel two shows the propellant capsules shortly after initiation. Both check valves are closed. The propellant is initiated on one end only; the unburned end of the capsule then acts as a piston, forcing the drilling mud above it through the $\frac{1}{2}$ -inch-diameter holes and into the down comers, where it joins the jet stream. The Mission check valve closes and the mud beneath the burning propellant capsule is accelerated into the jet nozzle. The erosive action of the mud jet cuts a kerf around the outside diameter of the hole. The third panel shows the condition of the combustion chamber after the propellant gases have been expanded to ambient pressure. Both check valves are again open; drilling mud is flowing to the rotary bit at 320 gallons per minute.

Consideration was given to providing a release mechanism downhole to prevent cartridges from bunching up. However, even at feed rates of four per minute the capsules are separated from one another by 190 feet of drilling mud. It was therefore felt that such a mechanism would not be required.

In addition to adding the combustion chamber to the drill stem, two items must be added to the above-ground equipment: a pressure control system on the returning mud and an automated propellant loading system.

Propellant cartridge entering combustion chamber.

1. Mud check valve opens.
2. Mud flow rate is 320 gallons/minute.

Propellant initiates and moves upward. Both check valves are closed. Kerf is being cut through 4 mm orifice. Pressure in chamber is 15,000 psi above ambient for $\frac{1}{4}$ second.

1. Gases expand to ambient pressure.
2. Both check valves open and mud flows at 320 gallons/minute.

Figure 3 Sequence of operation of combustion chamber.

A conceptual design of an automated propellant loading system is shown in Figures 4 and 5. In this system, a fairly simple propellant hopper or magazine which feeds propellant charges into the drilling mud at a pre-timed rate through a special ball valve is envisioned. As the capsules enter the stream they pass by a microswitch counter. The control system also senses and counts charge initiation downhole; a constant tally of unburned charges is thus available.

Figure 4 ERODRILL propellant loading system.

Figure 5 ERODRILL propellant loading system.

SECTION 4

PROPELLANT SELECTION

The following data summarize the results of the propellant analyses and preliminary design in relation to the ERODRILL concept. The most straightforward and promising approach to providing a chemical energy source (i.e., propellant) to the subsurface water expulsion chamber was a solid monopropellant system which could be initiated hypergolically. The initial analyses associated with this concept revealed that poor expulsion efficiencies were inherent with this concept, and these efficiencies were due to the severe heat loss of the combustion gases to the surrounding drilling fluid. In attempts to optimize this propellant system and minimize the amount of propellant required in each operational cycle, the idea of incorporating a slow burning propellant piston upstream of the main propellant charge was considered, and it was felt that this approach might have merit, but heat losses associated with this type of system are very difficult to analyze and must be established experimentally. In the following analyses, it was assumed that a combustible piston would be used to minimize losses, and the propellant grains were sized according to this assumption.

4.1 EXPULSION SYSTEM CONCEPT

To minimize the quantity of gas that must be vented after each water jet drilling cycle, the expulsion process should be completed in two distinct thermodynamic processes. During propellant combustion, the drilling fluid will be expelled at a nearly constant flow rate due to isobaric (constant pressure)

combustion of the propellant. After the propellant grain has been consumed, the combustion gases will then expand isentropically to the ambient hydrostatic pressure expelling additional working fluid in a regressive mode. After expansion to ambient pressure, the combustion gases will be at a temperature higher than ambient, and thermal equilibration with the surroundings will then reduce the volume of the spent gas bubble (i.e., ambient fluid will backflow into the chamber as the gas volume decays).

This process is shown graphically in Figure 6, and the total work done on the drilling mud during these two processes can be established as follows:

a. Isobaric expulsion work

$$W = \int P dV = (P_c - P_\infty) \frac{\Delta V}{J}$$

where P_c = combustion pressure
 P_∞ = ambient pressure
 ΔV = fluid volume expelled
 J = 778 ft-lb/Btu

b. Isentropic expulsion work

During this process the integral of PdV via an isentropic process yields the following relationships:

$$\int P dV = C_p (T_1 - T_2)$$

where

C_p = specific heat at constant pressure
 T_1 = initial gas temperature
 T_2 = final gas temperature

$$T_1/T_2 = (P_1/P_2)^{\gamma-1/\gamma}, \quad P_1/P_2 = (V_2/V_1)^\gamma$$

Figure 6 Drilling fluid expulsion characteristics.

This establishes the work done by the gases, but the work done on the surroundings must be subtracted to establish the net drilling fluid work. This work term can be expressed as:

$$W_{\infty} = P_{\infty} \Delta V/J$$

A summation of these three distinct work terms results in the net work done on the drilling fluid as:

$$W_{NET} = \frac{(P_c - P_{\infty})}{J} V_1 + W_g C_p (T_1 - T_2) - \frac{P_{\infty}}{J} (V_2 - V_1)$$

$$W_{NET} = (P_c - P_{\infty}) \frac{V_1}{J} + W_g T_1 \left\{ 1 - \left(\frac{P_{\infty}}{P_c} \right)^{\gamma-1/\gamma} \right\} - \frac{P_{\infty} V_1}{J}$$

$$\left\{ \left(\frac{P_c}{P_{\infty}} \right)^{1/\gamma} - 1 \right\}$$

At the end of the combustion process, the amount of propellant gases in the chamber can be approximated by perfect gas relationships as:

$$P_c V_1 = \frac{W_g R_u T_1}{M} \quad W_g = \frac{P_c V_1 M}{R_u T_1}$$

Combining this into the above work equation results in the following expression:

$$\frac{W_{NET}}{V_1} = \frac{P_c}{J} + \frac{P_c M C_p}{R_u} \left\{ 1 - \left(\frac{P_{\infty}}{P_c} \right)^{\gamma-1/\gamma} \right\} - \frac{P_{\infty}}{J} \left(\frac{P_c}{P_{\infty}} \right)^{1/\gamma}$$

$$\frac{W_{NET}}{P_c V_1} = \frac{1}{J} + \frac{M C_p}{R_u} \left\{ 1 - \left(\frac{P_{\infty}}{P_c} \right)^{\gamma-1/\gamma} \right\} - \left(\frac{P_{\infty}}{P_c} \right)^{\gamma-1/\gamma} - \frac{1}{J} \left(\frac{P_{\infty}}{P_c} \right)^{\gamma-1/\gamma}$$

$$= \left(\frac{1}{J} + \frac{M C_p}{R_u} \right) \left\{ 1 - \left(\frac{P_{\infty}}{P_c} \right)^{\gamma-1/\gamma} \right\}$$

Since

$$\frac{R_u}{M} = J (C_p - C_v),$$

thus

$$\frac{MC_p}{R_u} = \frac{C_p}{J(C_p - C_v)} = \frac{\gamma}{J(\gamma - 1)}$$

we have

$$\frac{W_{NET}}{V_1 P_c} = \frac{1}{J} \left\{ \frac{2\gamma - 1}{\gamma - 1} \right\} \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma - 1/\gamma} \right\} \quad (1)$$

This expression represents the total energy associated with the two step fluid expulsion process and is shown graphically in Figure 7 as a function of the specific heat ratio for a system operating at 20,000 psia in a 5000-psia environment. Although not a strong function of specific heat ratio, more fluid work can be achieved through the higher specific heat ratio combustion products.

4.2 CHEMICAL ENERGY AVAILABILITY

With a given amount of high pressure/high temperature gases produced by the combustion of a solid propellant, the maximum amount of work that could be accomplished would be represented by the expression

$$Q_{MAX} = C_p (T_c - T_\infty) \text{ Btu/lbm}$$

This assumes that the gases can be expanded over a wide pressure ratio (or volumetric ratio) in extracting chemical energy. In an isentropic (ideal) process,

Figure 7 Effect of specific heat ratio on drilling fluid energy.

$$\frac{T}{T_c} = \left(\frac{P_c}{P_\infty} \right)^{\gamma-1/\gamma}$$

Within a fixed pressure environment

$$Q_{MAX} = C_p T_c (1 - T_\infty/T_c) = C_p T_c \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\}$$

and for a propellant charge of 1.0 lbm

$$PV = \frac{WR_{uc}T}{M} \quad W = 1.0 \quad T_c = \frac{PVM}{R_u}$$

$$Q_{MAX} = \frac{C_p PVM}{R_u} \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\}$$

$$\frac{R_u}{M} = J(C_p - C_v)$$

$$Q_{MAX} = \frac{P_v}{J(\gamma-1)} \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\}$$

or

$$\frac{Q_{MAX}}{V_1 P_c} = \frac{1}{J(\gamma-1)} \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\} \quad (2)$$

Combining this with equation (1) yields an "efficiency" term relating the fluid work achieved to that ideally available as

$$\eta_{MAX} = \frac{W_{NET}}{Q_{MAX}} = 2\gamma - 1$$

(This expression is larger than 1.0 due to the initial isobaric work-producing process, but further indicates the desirability of high specific heat into gases.)

To provide a realistic baseline efficiency term that can be utilized to investigate different propellant systems, especially where heat losses must be considered, it has been elected to establish system expulsion efficiencies in terms of the total chemical energy available from a propellant in a given final temperature (i.e., 350°F) environment. This then defines the energy available from the propellant as

$$Q_{MAX} = C_p (T_c - T_\infty) \text{ Btu/lbm}$$

From Equation (1), the fluid mass involved can be expressed as follows

$$P_c V_1 = \frac{W_g R_u T_1}{M}$$

where T_1 is the combustion chamber temperature at propellant burnout (less than combustion temperature due to heat loss)

$$\frac{W_{NET}^M}{g R_u T_1} = \frac{1}{J} \left\{ \frac{2\gamma-1}{\gamma-1} \right\} \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\}$$

$$W_{NET} = \frac{W_g R_u T_1}{MJ} \left(\frac{2\gamma-1}{\gamma-1} \right) \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\} \text{ Btu}$$

the total energy available from the propellant is

$$Q_{TOTAL} = W_g C_p (T_c - T_\infty) \text{ Btu}$$

hence the system efficiency can be expressed as

$$\eta = \frac{W_{NET}}{Q_{TOTAL}}$$

$$\begin{aligned}
\eta &= \frac{\frac{W_g R_u T_i}{MJ} \left(\frac{2\gamma-1}{\gamma-1} \right) \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\}}{W_g C_p (T_c - T_\infty)} \\
&= \frac{\frac{R}{J} T_1 \left(\frac{2\gamma-1}{\gamma-1} \right) \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\}}{C_p (T_c - T_\infty)} \\
&= \left(\frac{2\gamma-1}{\gamma} \right) \left(\frac{T_1}{T_c - T_\infty} \right) \left\{ 1 - \left(\frac{P_\infty}{P_c} \right)^{\gamma-1/\gamma} \right\} \quad (3)
\end{aligned}$$

One of the most promising propellant candidates (from a cost consideration) is Hercules formulation HES 6573, which has the following pertinent properties

$$\gamma = 1.180 \quad T_c = 4550^\circ \text{R}$$

The efficiency of this propellant is shown in Figure 8 as a function of the chamber temperature at the end of combustion when operated in an ambient environment of 350°F (810°R). If the heat-loss characteristics were negligible and the final chamber temperature were the combustion temperature of the propellant, only 27 percent of the chemical energy could be utilized. If the heat loss were so high that the gases cooled to the ambient temperature of 350°F , the efficiency would be less than 5 percent.

The original calculations (see Appendix B) were based on the propellant gases losing energy to the drilling fluid, and these analyses indicated a chamber temperature of 1890°R , resulting in an efficiency of 11 percent. The approach of isolating the propellant from the drilling fluid can result in less heat loss and thus higher chamber temperatures. An efficiency goal of 22 percent has been established. This means that the chamber temperature will need to be at 3740°R (using a 4550°R propellant)

Figure 8 Expulsion efficiencies.

which may be achieved with unique design features such as combustible pistons. The remainder of the analyses associated with this concept will assume that this type of efficiency is available from the propellant system and will use the Hercules HES 6573 propellant as a baseline for the analyses.

This allows the assumption to be made that the heat loss is proportional to the difference between combustion temperature and ambient temperature, i.e.,

$$Q_{\text{LOSS}} = k(T_c - T_\infty) = C_p (T_c - T_1)$$

$$k = \frac{C_p (T_c - T_1)}{(T_c - T_\infty)} = 0.2869 \frac{(4550 - 3750)}{(4550 - 810)}$$

$$k = 0.0614$$

Propellants other than this baseline will then result in chamber temperatures according to the following expression:

$$T_1 = T_c - 0.0614 \left(\frac{T_c - T}{C_p} \right) \quad (4)$$

(This expression will be utilized later to establish the expulsion efficiencies of various propellant candidates.)

4.3 SOLID MONOPROPELLANT EVALUATION

Table 2 lists eight propellant formulations that have the potential for predictable and controllable operation at temperatures of 350°F and pressures to 25,000 psia. Since cycle cost is of considerable concern in this application, the propellants must be evaluated to establish the lowest cost (not necessarily the most efficient) propellant system for the ERODRILL concept. As

a design point for evaluation of the propellants, the following environmental and pressure requirements have been established.

Ambient pressure	= 500 psia
Ambient temperature	= 350°F
Combustion pressure	= 20,000 psia
Nozzle ΔP	= 15,000 psig

With these requirements, the heat loss characteristics of the propellant are established from Equation (4), which result in the combustion chamber temperatures shown in Table 2.

The next step in the evaluation is to establish the expulsion efficiencies from Equation (3), the net fluid work term from Equation (1), and the chamber volume at burn-out (V_1) from the perfect gas law. The fluid chamber volume V_2 can be calculated from the isentropic expansion characteristics, which allows the expulsion costs to be established. As shown on line 15 of Table 2, the Hercules 6573 propellant represents the lowest cost approach (for the price information available) in considering just the chemicals associated with manufacturing the propellant and is recommended as the baseline propellant approach.

Ignition of the propellant will be accomplished by the use of a lithium aluminum hydride (LiAlH_4) material which is hypergolic with water, and it is estimated that 0.10 lbm of this ignition material will be needed to produce an ignition flash to ignite the propellant booster coating. To assure ignition and water retention of the caseless propellant grains, it is recommended that the raw grains be dip coated with a BKNO_3 slurry to produce a coating approximately 0.030 inch thick. When cured, this coated grain should then be dip coated with a waterproof epoxy approximately 0.030 inch thick. When the LiAlH_4 ignition

TABLE 2

PROPELLANT EVALUATION

Physical and Ballistic Characteristics	HI TEMP	8028	6573	5808	6616	RRC1	RRC2	RRC3
Combustion Temperature, $^{\circ}\text{R}$	5656	3831	4547	5131	3696	3258	3135	3034
Combustion Molecular Weight, lbm/mol	24.35	20.80	45.38	28.19	20.67	48.22	48.63	49.25
Specific Heat Ratio, $\gamma = c_p/c_v$	1.231	1.266	1.180	1.199	1.268	1.1431	1.1307	1.1273
Specific Heat at $Q_p=C(c_p)$, Btu/lb/ $^{\circ}\text{R}$	0.435	0.4544	0.2869	0.4244	0.4545	0.3672	0.4682	0.4560
Propellant Density, lbm/ft ³	111.07	105.46	129.79	112.32	102.34	121.80	119.36	116.99
$H_{\text{available}}(T_{\text{comb}} - T_{\text{amb}})(c_p)@700=810^{\circ}\text{R}$, btu/lbm	2108	1373	1072	1834	1312	899	1089	1014
Propellant Raw Material Cost, \$/lbm		3.52	0.58			3.71	3.71	3.71
Final Chamber Temperature (T_1), $^{\circ}\text{R}$ (Equation 4)	4972	3423	3747	4506	3306	2849	2830	2735
Expulsion Efficiency, % (Equation 3)	27.91	34.65	22.00	25.03	35.24	20.87	20.11	19.83
Expulsion Work Per Pound of Propellant (Btu)	588.3	475.7	235.8	459.1	462.3	187.6	219.0	201.1
Fluid Work Term $W_{\text{net}}/V_1 P_c$ (Equation 1)	1.4497	1.455	1.440	1.444	1.456	1.432	1.429	1.428
Chamber Volume at Burnout (V_1), Ft ³	.10954	.8829	.04430	.08575	.08581	.03170	.03122	.02979
Final Chamber Volume (V_2), Ft ³	.3378	.2639	.1434	.2725	.2561	.1066	.1064	.1019
Fluid Expelled/Propellant Cost, Ft ³ /	--	.0749	.2472	--	--	.0287	.0287	.0275

canister is pierced, the reaction with the water in the drilling fluid will produce a very hot flash and a significant amount of hot metal particles. This will burn the epoxy coating near the ignition canister allowing the BKNO_3 surface coating to flash and ignite the propellant. Estimated costs of this ignition approach for a 1.0-lbm propellant grain are calculated as follows:

LiAlH_4	10 lb at \$3.00 = \$0.30/lb
BKNO_3	(5% by weight at \$30.00 lb) = \$1.50
Epoxy	(5% by weight at \$3.00 lb) = \$0.15
Aluminum canister for LiAlH_4 at \$0.05 each	
(It is felt that a hermetically sealed aluminum canister can be used to house the ignition material, and over-oxidation of the propellant can be accomplished to combust this canister and assure a residue free breech.)	

Because of the relatively high cost of the ignition system, larger propellant grains would tend to be cheaper on a per pound basis. Cartridge price (which does not include any labor, assembly, inspection, processing, etc.) as a function of propellant load for small quantities is shown in Figure 9.

4.4 PROPELLANT BALLISTICS

As the mechanical drill stem rotates at approximately 120 rpm, the ideal burn time for the propellant grain would be 0.50 seconds (one revolution) which would allow the constant pressure expulsion process to occur during one revolution and the isentropic expulsion process to occur in the next few revolutions. Whatever the burn time selected, the operating characteristics of the propellant grain and expulsion system will be ambient-pressure dependent, and this must be considered in the design. To provide an indication as to this characteristic, a combustion time of 0.50 seconds has been assumed for the 20,000 psia to 5,000 psia ambient design case, and the ballistics established as a function

Figure 9 Cartridge material cost.

of ambient pressure as shown in Figures 10 and 11. As shown in Figure 10, the propellant grain burns longer at the shallower depths (because of the lower combustion pressures) but the nozzle ΔP increases with decreasing depth.

Figure 11 indicates that the amount of fluid expelled during the isobaric portion of the process is relatively insensitive to depth, but the isentropic blowdown is very depth dependent (i.e., at the shallower depths, a considerably larger chamber is required to achieve gas expansion to ambient pressure). The chamber must be sufficient in volume to hold enough fluid for shallow (1000 psia ambient) operation to fully expand the gases, and when operated at deeper depths, the system will not expel as much fluid. For example, a system using a 1.0lbm grain would be capable of expelling 32.0 lbm of water at 1000 psia ambient during both processes. This would require a fluid chamber volume of 0.576 ft³. When this same chamber was operated at 5000-psia back pressure, only 8 pounds of the total 32 pounds would be expelled and the remaining 24 pounds would remain in the chamber.

A failure mode that was considered in the design of the ERODRILL system is the situation where two cartridges are fired within a single chamber. Figure 12 shows the effect on system pressures with two cartridges firing. Maximum chamber pressure reaches 40,000 psia at 5000 psia ambient pressure. The combustion chamber has been designed to contain 60,000 psia internal pressure.

4.5 GAS GENERATOR CARTRIDGE DESIGN

The design of the propellant grain and ignition system for this concept requires that a fixed design point be established to define the ballistic requirements, and then the behavior of this

Figure 10 Ballistic characteristics.

Figure 11 Expulsion characteristics (drilling fluid assumed to be water at 350°F).

Figure 12 Effect of operating pressures with multiple cartridge firing.

cartridge design be analyzed at other operating conditions (as was previously presented). As a baseline design condition, the following conditions are elected:

Ambient pressure	5,000 psia
Combustion pressure	20,000 psia
Ambient temperature	350°F
Burn time	0.50 seconds
Propellant weight	TBD
Maximum cartridge diam.	2.75 inches

(Ballistic and physical characteristics of the selected HES 6573 propellant are presented in Table 2, and the combustion characteristics are shown in Table 3).

It is estimated that the constant pressure temperature coefficient of this propellant will be approximately $0.25\%/^{\circ}\text{F} = \pi_k$ (typical for this family of Hercules propellants); hence the burn rate at a pressure of 1000 psia and 350°F can be established as

$$\frac{r_2}{r_1} = e^{\pi_k \Delta T} = e^{0.0025(280)} = 2.014$$

Measured (1000 psia, 70°F) burn rate for the propellant is 0.64 in./sec; hence the burn rate at 1000 psi and 350°F will be 1.290 in./sec. Hercules data indicates a rather high pressure exponent (i.e., $\eta = 0.81$), which will result in a burn rate at 20,000 psi, 350°F as

$$r = 1.290 \left(\frac{20000}{1000} \right)^{0.81} = 14.60 \text{ in./sec}$$

TABLE 3
COMBUSTION CHARACTERISTICS OF HES 6573

Designation: Name Super Hi-Temp #1
H.E.S.# 6573
Date 4/22/65

CALCULATED DATA (1000 psia)

T_v , °K 3180
 T_p , °K 2672
 n_g , moles/g 0.0230
 n_t , moles/g 0.0230
Vol. gas/g, cc 74.11
Residue, % 0
F, (ft.lb/lb) 203,400
Density, g/cc 2.09
Hex, cal/g 1.19
 I_{sp} (PE = 14.7)* 180
 I_{sp} (PE = VAC)* 194

EXPERIMENTAL DATA

Density, g/cc 2.0
Bulk Dens., g/cc 0.78
Exptl. Hex, cal/g 1,091
Relative Force
(Wt.) To: HES 5808.7C 54
(Vol.) To: HES 5808.7C 63
Relative Quickness
(Wt.) To: HES 5808.7C 92
(Vol) To: HES 5808.7C 102
Burning Rate, in./sec.
Temp., °F Press. Rate, in./sec
70 1000 0.64

Pressure Exp., n 0.81
C in ($r = CP^n$) = 0.0024

MISCELLANEOUS DATA

*c = 8.81
 C_d = 0.008874

STABILITY DATA

Thermal Stability

Temp. (°F)	Expos. Time (Hrs.)	Wt. Loss (%)
400	4	1.74
300	96	0.4
500	4	11.8
500	24	14.5
500	96	16.8

Gas Composition (Chamber) (Mole %)

Prod.	%	Prod.	%
N ₂	0.31	O ₂	10.63
CO ₂	33.42	O	0.13
CO	1.05	OH	1.22
H ₂ O	27.41	NO	0.13
H ₂	0.13	Cl	0.09
Ave. M.W. of Gas	43.48		
HCl	0.65		
K	0.17		
KO	0.13		
KOM	0.13		
KCl	23.22		
K2C12	1.39		

Impact (Bruceton Method)
(cm)

Friction (10 Failures)
(psi)

FSD
(joules)

Finished Grain

13.9 0%
20.3 50%

170

6.25

FORMULATION

%	Ingrid. & Grade
84	KP 100 Mesh
15	Hycar 4021
1	Trimmene Base

10 parts solvent added
MEK or acetone
0.0-0.3% graphite glazing
depending on granulation

Surface Deterrent

Surface deterrents have not been used on this propellant, however, they may be added.

Granulations Avail.

o.d. - 0.53-0.250

Length - 0.01-7.0

*1-see below

Custom Made to Size

Yes: X No: X

Manufacturing Method

Solvent Extr. X

Solventless Extr.

Cast Pelleted

*1-This granulation has been made.

Others are available, but a web thickness greater than 1 inch is not recommended.

Figure 13 ERODRILL propellant grain design (conceptual design).

To avoid excessive heat loss to the drilling fluid, the design shown in Figure 13 has been established. By providing an outside inhibitor (i.e., a slow burning propellant) the grain can be combusted as an end burner, with a total propellant length of 10.5 inches (which produces a $\frac{1}{2}$ -second burn time). As further assurance against heat losses, the propellant grain should fit as tightly as possible in the breech, i.e., 3.00-inch breech i.d. with a 2.75-inch grain o.d., and the center bore should be sufficiently large to assure the mechanism for piercing the hypergolic ignition fluid canister can extend freely down the bore--a "reasonable" bore diameter is assumed to be 1.0 inch. These diameter constraints and the required propellant length of 10.5 inches now define the propellant grain as 2.69 inch o.d. x 1.06 inch i.d. x 10.5 inches long, which represents a propellant mass of 3.63 lbm/cartridge. Since the grain is combusting as an end burner, the reaction of gases coming off the end should cause the propellant grain to serve as a "piston" and follow the water surface during combustion.

4.6 SPECIFIC CHAMBER DESIGN CHARACTERISTICS

For the previously established propellant grain weight of 3.63 lbm, Figure 13 indicates that the chamber should be designed to house 84.16 lbm of 350°F water (1.51 ft³) if the system is to be capable of expanding the gases to ambient pressure when operated at the shallow depths (1000 psia). This results in a fluid chamber 3 inches in diameter x 30 feet long, which does not appear to be an unrealistic requirement. This size chamber would be used at all operating depths, since the deeper depths will only use a portion of the total drilling fluid load.

4.7 BUBBLE EVALUATION

The release of high-pressure permanent combustion product gases into the outer annulus during the isentropic expansion phase could fracture the rock formation and cause lost circulation problems. To avoid this phenomenon, the combustion chamber must be lengthened to allow the gases to expand inside the chamber to the hydrostatic bottom-hole pressure before entering into the annulus. As the gaseous bubble enters the wellbore fluid, the bubble expands as it flows up the wellbore, thereby displacing mud out of the well. This reduces the bottom-hole pressure, which may allow formation fluid or gas to flow into the well causing "kicks" or blowout. Thus, an open circulation system is inadequate for the ERODRILL system. To prevent blowout and to control the bubble size, a choked circulating system must be considered. The choke pressure must be set so that no excessive bottom-hole pressure results and what can be handled safely. A factor of concern is that, as the gaseous bubbles rise, they can appear to be a kick from the formation. They would have, of course, a chemical composition quite different from those of a kick. An automatic gas analyzer, therefore, could determine continuously whether the bubbles were the exhaust gases or a kick.

4.7.1 Downhole Bubble Size. Based on the propellant ballistic analysis in Section 3.3, it can be shown that the bubble size during the isobaric portion of the process is relatively insensitive to depth, but the isentropic blow-down is very depth dependent. As shown in Figure 10, the propellant grain burns longer at shallower depths (because of lower combustion pressure) but the nozzle Δp increases linearly with decreasing depth. Thus, at the end of the isentropic expansion, the bubble size is given by

$$\bar{V} = \left(\frac{\bar{W}_p}{\rho_p} + A \sqrt{\frac{2(\alpha + \beta H)}{\rho}} \tau \right) \left(\frac{\alpha + \beta H}{H} \right)^{1/\gamma}$$

where

- $\bar{W}_p$ = weight of propellant in pounds
- ρ_p = density of propellant in pounds/cuft.
- A = total nozzle area in feet²
- ρ = drill mud density in pounds/cuft.
- τ = propellant burn time in seconds
- H = well depth in feet
- γ = specific heat ratio
- α, β = constants

For the ERODRILL system, bubble size versus depth is shown in Figure 14.

As indicated in the propellant gas composition analysis, approximately 30 percent of the gas products are condensible water vapor; thus the gas bubble size can be further reduced.

4.7.2 Steady-State Bubble Train. Gas also rises in the semi-closed-in circulating system, because gas density is less than mud. However, gas cannot expand arbitrarily under this condition. Due to high viscosity of the drill mud, for a given circulating rate, the bubble rising speed may be approximated by drill mud speed in the annulus. In the annulus, the temperature of the gas bubble should be lowered to the fluid temperature. Thus, gas expansion as pressure changes is predictable by using isothermal law.

Figure 14 Bottomhole gas bubble size in annulus.

Consider the following system:

- Let N_u = number of bubbles in upper annulus
 L_u = upper annulus length, feet
 A_u = upper annulus cross-section area, feet²
 Q = mud flow rate, ft³/minute
 s = gas bubble condensation percentage
 t = cutting cycle time, minutes
 ρ = mud density lb/ft³
 P = bottom hole pressure, psia
 P_c = choke pressure, psia
 V = bottom hole gas bubble size, ft³

then the mud column between bubbles in the upper annulus is

$$h_u = \frac{Qt}{A_u}$$

and the maximum bubble length in upper annulus is

$$\ell_u = (1-s) \left(\frac{P}{P_c} \right) \left(\frac{V}{A_u} \right)$$

For a given P , P_c , and t , the number of bubbles in the upper annulus may be found from the following relationship:

$$N_u h_u + \ell_u \sum_{j=0}^{N_u-1} \left[\frac{1}{1 + \left(\frac{h_u \rho}{144 P_c} \right)^j} \right] = L_u \quad (5)$$

The pressure at the interface of the upper annulus and the lower annulus is

$$P'_c = P_c + \frac{(N_u-1) h_u \rho}{144}$$

Total drill fluid in length replaced by the gaseous bubble in the upper annulus is

$$H_u = \ell_u \sum_{j=0}^{N_u-1} \left[\frac{1}{1 + \left(\frac{h_u \rho}{144 P_c} \right)^j} \right] \quad (6)$$

The number of bubbles in the lower annulus can be obtained similarly by defining

$$h_\ell = \frac{Qt}{A_\ell}$$

$$\ell_\ell = (1-s) \left(\frac{P}{P'_c} \right) \left(\frac{V}{A_\ell} \right)$$

Then,

$$N_\ell h_\ell + \ell_\ell \sum_{j=0}^{N_\ell-1} \left[\frac{1}{1 + \left(\frac{h_\ell \rho}{144 P'_c} \right)^j} \right] = L_\ell \quad (7)$$

Let ℓ be the bottom-hole gas bubble length. For large P'_c , the above equation may be approximated by

$$N_\ell \approx \frac{2L}{2h_\ell + \ell_\ell + \ell} \quad (8)$$

Total drill fluid in length replaced by gaseous bubbles in the lower annulus is

$$H_\ell = \ell_\ell \sum_{j=0}^{N_u-1} \left[\frac{1}{1 + \left(\frac{h_\ell \rho}{144 P'_c} \right)^j} \right] \quad (9)$$

The total number of bubbles in the annulus is given by

$$N_T = N_u + N_\ell$$

and the total drill fluid in length replaced in the annulus by gaseous bubbles is

$$H_T = H_u + H_\ell$$

For the ERODRILL system, the total number of bubbles in the annulus versus well depth is plotted in Figure 15 for different drill cycles and choke pressures. The total drill fluid replaced by gaseous bubble versus well depth is also plotted in Figure 16.

The choke pressure should be limited to 500 psig to avoid annular pressure exceeding either the casing burst rating or the formation breakdown pressure. Attention must be given to the well while removing the pipe, changing bits, logging, etc. All gaseous bubbles must be circulated out to ensure control of the well.

Figure 15 Steady-state bubble train.

Figure 16 Steady-state bubble train.

SECTION 5

HAZARD EVALUATION AND RELIABILITY

5.1 HAZARD EVALUATION

The baseline design of a propellant cartridge for the ERODRILL program consists of a composite rocket propellant with a boron/potassium nitrate igniter and a water-reactive lithium aluminum hydride initiator. The following discussion centers around the transportation, storage, and handling hazard of the completely assembled cartridge.

1. Composite Propellant

A composite propellant of the HES 6573 type consists of potassium perchlorate oxidizer and a polybutadiene acrylic nitrile (PBAN) organic binder. This combination is thermally very stable and is very difficult to ignite by spark (ESD), friction, or shock. The propellant has been characterized to be nondetonable when fired with a No. 8 blasting cap. Drop weight impact, friction sensitivity, and ESD discharge sensitivity have been measured and are all well above the sensitivity thresholds commonly accepted for ordnance items.

If an assembled cartridge were inadvertently dropped from 100 feet, the impact would not cause it to ignite unless the initiator can bursts open and some of the spilled lithium aluminum hydride reacts with ambient moisture.

Even if a cartridge should inadvertently ignite, the ventral thrust feature of the open-ended grain will make it

a localized hazard and the grain will not ignite adjacent areas in a rocket projectile fashion. The fact that individual grains are not encased in metal must be considered an additional safety feature in that overpressure cannot cause fragmentation of the casing as in a rocket motor or gas generator. However, storage of numerous bare grains in one shipping container will make it likely that fire spreads from one grain to the other quite rapidly if one of the grains in one box should catch on fire. The waterproof coating is not expected to offer much protection in this situation.

2. Boron/Potassium Nitrate

Boron/potassium nitrate is commonly used as an igniting material and is expected to be compatible with the composite grain on the one side and the aluminum can and the epoxy coating on the other side. Boron/potassium nitrate is much less sensitive to friction and ESD initiation than zirconium compositions, which are sometimes used in similar applications. The friction and drop-weight sensitivity will depend on the amount and type of binder used. The binder will be soft and pliable and will reduce the already low sensitivity of the dry B/KNO_3 material further.

3. Lithium Aluminum Hydride

Lithium aluminum hydride ($LiAlH_4$) is a water-reactive, nonpyrophoric white powder. Paragraph 172.5 of 49 CFR of the Department of Transportation classifies $LiAlH_4$ as a flammable solid and it must be shipped with a yellow label. The quantity in a single unit must not exceed 25 pounds.

If the aluminum can should burst open accidentally in dry air, no fire would result. However, if it were raining during

the accident or the material was spilled on wet ground, a fire would result. Lithium aluminum hydride fires can be extinguished with dry sand. The double seal (the aluminum can and the epoxy sealant) makes a leakage of the initiator very unlikely.

4. Shipping Classification

The shipping classification of the assembled grain will most likely be "Explosive Class B." As such, the grains can be shipped and stored in larger quantities and with less precautions than other explosive devices commonly used in oil well operations such as perforating shaped charges classified as "Explosive Class A." If the HES 6573 propellant is used as is, a copy of the classification obtained by Hercules for this propellant from the Bureau of Explosives of the Association of American Railroads will be requested. If a new propellant is developed specifically for the ERODRILL application, RRC will have the propellant and grains manufactured therefrom and then tested and classified by the Bureau of Explosives.

5. Disposal of Outdated or Damaged Grains

Handling instructions to be shipped with the grains will include instructions on safe disposal of unwanted grains. Disposal could be achieved by burning the grain in a wire mesh cage or in an old barrel into which numerous holes have been punched with a pick such that at least 50 percent of the surface area is open. Ignition could be achieved by a quart of oil poured over the grain and an old rag on which it rests.

5.2 RELIABILITY

All of the down hole system with the exception of the propellant cartridge and combustion chamber consists of standard drilling hardware. Since the combustion chamber design is similar to military gun tubes, the reliability of the mechanical parts of the system should be equivalent to existing drilling equipment.

The propellant being considered is a commercially available formulation, and the method of ignition is certainly simple, requiring only the piercing of a container in the presence of water. One would expect this system to be highly reliable; however, testing and verification of this would be most important during a follow-on program.

SECTION 6

ERODRILL ECONOMIC EVALUATION

6.1 EXPECTED DRILLING RATE

Let us now consider drilling an 8½-inch-diameter hole in Darley Dale Sandstone. We will assume the specific energy to be about 1000 J/cc as obtained from the Farmer-Atwell data (see Appendix A). In this analysis, rather than calculating pressure time histories of the combustion chamber, we will use a reasonable system efficiency in determining the required propellant weight and the drilling rates. Propellants evaluated for the ERODRILL application ranged from 20 to 35 percent in calculated expulsion efficiency at a chamber temperature of 3300°R, with the baseline propellant having an efficiency of 22 percent. For this analysis we will use the more conservative assumption of 18 percent efficiency.

The following calculation is presented for a typical drilling cycle utilizing the ERODRILL propellant charge to cut a kerf. The numbers used are approximations.

Assume:

- (1) Three nozzles are used to cut the kerf: nozzle diameter = 0.357 cm; the total nozzle area = 0.3 cm².
- (2) Based on the study of parameters for minimum specific energy, the width of the kerf will be approximately equal to three times the nozzle diameter, i.e., = 1.07 cm.
- (3) Propellant has 1070 Btu/lb = 2.53×10^6 J/kg.
- (4) System efficiency, η = 18 percent in ejecting the drill fluid.
- (5) Pressure across nozzle = 15,000 psig (1000 bar).
- (6) Density of the fluid = 1.2 g/cc.
- (7) Effective cutting time = 0.6 sec.

The velocity of flow through orifice is

$$v = \sqrt{\frac{2 \times 1000 \text{ bars} \times 10^6 \text{ dynes/cm}^2 \text{ bar}}{1.2 \text{ g/cc}}}$$
$$= 40,800 \text{ cm/sec}$$

The flow rate is

$$Q = 40,800 \text{ cm/sec} \times 0.3 \text{ cm}^2 = 12.2 \text{ liters/sec}$$

Power applied to the rock is

$$P = 0.3 \text{ cm}^2 \times 40800 \text{ cm/sec} \times 1000 \text{ bars} \times 10^{-4}$$
$$= 1220 \text{ kW} = 1620 \text{ hp}$$

The work done is

$$W = 1,220,000 \text{ watts} \times 0.6 \text{ sec} = 7.32 \times 10^5 \text{ joules}$$

Since we assume the specific energy of the rock to be 1000 J/cc then the volume of the rock excavated is

$$\bar{V} = \frac{7.32 \times 10^5 \text{ joules}}{1000 \text{ joules/cc}} = 732 \text{ cc}$$

The area of the circular slot

$$a = \pi (10.8^2 - 9.73^2) = 69.0 \text{ cm}^2$$

The depth of the kerf is

$$h = \frac{732 \text{ cc}}{69.0 \text{ cm}^2} = 10.6 \text{ cm} = 4.2 \text{ inches}$$

In the calculations given above, the fluid jets were assumed to drill 10.6 cm deep in a fraction of a second. The width of the slot was 1.07 cm, which means that the hole aspect ratio (HAR) at the bottom of such a hole would be approximately 10:1. Although these jets would be continuously moving instead of remaining stationary, it is probable that the kerf depth would be less than 10.6 cm. However, after the propellant has been consumed, the combustion gases will expand continuously for some time, expelling additional work fluid. If this additional cutting is considered, the 10.6 cm may be possible.

The amount of propellant required is

$$\begin{aligned} W_p &= \frac{7.32 \times 10^5 \text{ joules}}{2.53 \times 10^6 \text{ J/kg} \times 0.18} \\ &= 1.60 \text{ kg} \\ &= 3.54 \text{ pounds} \end{aligned}$$

From this calculation, each propellant charge will cut a kerf about 4.2 inches deep and about 0.42 inch wide. The assumption is made that for this type of rock conventional rotary drilling will penetrate at a rate of 20 ft/hr or 4 in./min and that with a free surface to break to (i.e., the kerf) the rotary drill will penetrate at a rate of 40 ft/hr or 8 in./min. Therefore, one would double the drilling rate if charges were deployed every half minute.

6.2 CASE WELLS

The economic assumptions for the four drilling cases are presented in Table 4.

TABLE 4
ECONOMIC ASSUMPTIONS

Case	Rig Cost (\$/day)	Depth (ft)	Conventional Bit Cost (\$)	ERODRILL Bit Cost (\$)	Conventional Rate (ft/hr)	ERODRILL Rate (ft/hr)	Trip Time (hr)	Bit Life (hr)	Capsule Cost (\$)	Capsule Firing Rate (shot/min)
Shallow Land	3600	10,000	2000	4000	10	20	7.5	100	4	2
Deep Land	6000	20,000	2000	4000	10	20	15.0	100	4	2
Offshore Platform	15000	10,000	2000	4000	20	40	7.5	100	4	2
Offshore Floater	75000	10,000	2000	4000	20	40	7.5	100	4	2

In all of these wells, the assumption is made that firing one charge every 30 seconds will double the drilling rate. This is consistent with the Exxon high-pressure drilling tests provided the capsules are sufficiently large.

It is also assumed that charges can be manufactured in production quantities for \$4 each. This cost is consistent with costs of other large quantity explosive or propellant devices such as shaped charges, gas generators, etc., which are considerably more complex. This assumption is based on the fact that the raw propellant cost is \$2.05. Currently, the majority of the cost is in the ignition. To obtain \$4/cartridge, the ignitor costs must be reduced. There are a number of potential low-cost ignition systems that need to be further evaluated.

6.3 DRILLING COSTS

The cost per foot of hole drilled with conventional or ERODRILL bits equals:

$$C = \frac{B + R (D + T) + 60 D \cdot c \cdot r}{F} \quad (10)$$

where

- C = Footage Cost (\$/ft)
- B = Bit Cost (\$)
- R = Hourly Rig Cost (\$/hr)
- T = Trip Time (hr)
- D = Drilling Time (hr)
- P = Penetration Rate (ft/hr)
- F = Bit Footage (feet) PXD
- c = Capsule Cost (\$)
- r = Capsule Firing Rate (shots/min)

In the use of conventional bits, the last term (60 D·c·r) equals zero.

6.3.1 Shallow Land Well. The footage drilling cost for drilling shallow land wells equals (from Equation 10):

$$\text{Conventional Cost} = \frac{\$2000 + 150 (7.5 + 100)}{10 \times 100} = \$18.13/\text{foot}$$

$$\text{ERODRILL Cost} = \frac{\$4000 + 150 (107.5) + 60 \times 100 \times 4 \times 2}{20 \times 100} = \$34.06/\text{foot}$$

(Based on \$4 per charge, two shots per minute, and doubling drilling rate.)

This shows that the cost of drilling the shallow land with the ERODRILL system is \$34.06 per foot compared to \$18.13 per foot for the conventional bits. Figure 17 shows that in shallow land wells the propellant cost would have to be less than \$1.34/capsule charge in order for the ERODRILL to compete with conventional bits. Conversely, if the charges cost \$4 each, the ERODRILL would have to drill 3.8 times as fast as conventional bits on shallow land wells to save money.

Figure 17 ERODRILL costs--shallow land well.

Figure 18 ERODRILL costs-- deep land wells.

6.3.2 Deep Land Wells. The footage drilling cost for drilling deep land wells equals (from Equation 10):

Conventional Cost = \$30.75/hr

ERODRILL Cost = \$40.38/hr

(based on firing \$4 charges every 30 seconds)

The propellant charge cost will have to be less than \$2.40 per charge for ERODRILL to be economical on these deep land rigs as shown in Figure 18. Conversely, if the capsules cost \$4 each, on deep land wells the ERODRILL would have to drill 2.63 times as fast as conventional bits in order to save money.

Figure 19 ERODRILL costs--offshore platform.

6.3.3 Offshore Platform. The footage costs for drilling from an offshore platform equals (from Equation 10):

Conventional Cost = \$34.59/foot

ERODRILL Cost = \$29.80/foot

This corresponds to a 14-percent savings with ERODRILL based on doubling drilling rate by firing \$4 charges every 30 seconds. The ERODRILL system would save money as long as the capsule cost remains below \$5.60/charge as shown in Figure 19. If the capsules cost \$4, the ERODRILL would only have to drill 1.72 times as fast as conventional bits to save money on offshore platform wells.

Figure 20 ERODRILL costs--offshore floater.

6.3.4 Offshore Floater. The cost for drilling at a depth of 10,000 feet from an offshore floater equals (from Equation 10):

Conventional Cost = \$168.97/foot

ERODRILL Cost = \$ 96.98/foot

This corresponds to a 43 percent savings for the \$4 charges fired every 30 seconds. The ERODRILL would produce a savings as long as the capsules cost less than \$28.00 each as shown in Figure 20 (i.e., \$3,360/hour capsule cost).

Figure 21 ERODRILL costs--offshore rig.

The costs in Figures 17 through 20 are based on the ERODRILL drilling twice as fast as conventional bits. Figure 21 shows that on the floating rig, the ERODRILL would produce savings as long as it drills more than 15 percent faster than conventional bits. Based on Exxon's experience of doubling and tripling drilling rates, it should be possible to drill much more than 15 percent faster, which indicates that ERODRILL has high potential for being economic on offshore floating drilling vessels. Over 250 floaters are being used worldwide so ERODRILL in this application could result in savings of hundreds of millions of dollars.

6.4 CONCLUSIONS

The following conclusions have been reached from this preliminary economics study:

1. On shallow land wells (10,000 feet), the ERODRILL system will have to drill 3 to 4 times faster than conventional bits to save money (based on \$4 per capsule).
2. On deep land wells (20,000 feet) ERODRILL has potential for saving money if the capsules can be built for less than \$2.60 each or if the ERODRILL drilling rate is 2.63 times that of conventional bits.
3. On offshore platform wells, ERODRILL will reduce costs if the capsules can be built for less than \$5.60 each (assuming doubling the drilling rate).
4. On offshore floating drilling rigs, the ERODRILL will reduce costs if the capsules cost less than \$28 each (double drilling rate) or if the drilling rate is increased by at least 15 percent (\$4 capsules).
5. ERODRILLS have the greatest potential application for offshore drilling because of the high costs involved.

See Table 5 for data on the ERODRILL curves.

TABLE 5
DATA FOR ERODRILL CURVES
(Figures 17 to 21)

<u>Case</u>	<u>\$/Charge</u>	<u>\$/foot</u>
Shallow Land		
ERODRILL	0	10.06
ERODRILL	4	34.06
Conventional	--	18.13
Deep Land		
ERODRILL	0	16.38
ERODRILL	4	40.38
Conventional	--	30.75
Offshore Platform		
ERODRILL	0	17.80
ERODRILL	10	47.80
Conventional	--	34.59
Offshore Floater		
ERODRILL	0	84.98
ERODRILL	30	174.98
Conventional	--	168.97
Offshore Floater	Drilling Rate Increase	
ERODRILL	0	193.97
ERODRILL	10	176.34
ERODRILL	20	161.34
ERODRILL	30	149.21
ERODRILL	40	138.55
ERODRILL	50	129.31
ERODRILL	60	121.23
ERODRILL	70	114.10
ERODRILL	80	107.76
ERODRILL	90	102.09
ERODRILL	100	96.98
Conventional	--	168.97

SECTION 7

CONCLUSIONS AND RECOMMENDATIONS

Analysis of a preliminary design for a hybrid ERODRILL system indicates that the system is practicable for both fabrication and operation in the field. The system as designed is compatible with standard 3-inch i.d., 4½-inch o.d. drilling pipe and rotary drill bits. Very little additional wellhead equipment will be required in field use. Dynamic loading on the downhole system with this concept is negligible; the upward thrust on the drill stem is only about 6,000 pounds per pulse while the downward force on the drill stem during drilling is 30,000 pounds.

Both safety and reliability analyses have been performed which show the hybrid ERODRILL concept to be at least equivalently safe and reliable as standard drilling methods.

Preliminary economic analysis shows that with current assumptions, ERODRILL is extremely attractive for offshore drilling operations, and possibly within competitive reach for deep (20,000 feet) land wells. The hybrid concept does not at first blush appear economical for shallow (10,000 feet) land wells.

These conclusions are based upon assumptions about system performance, which, while they were based on the best available evidence, may be incorrect by as much as $\pm$ a factor of 2. The most logical next step for the program, then, is to obtain

experimental data on propellant burn efficiency, depth of kerf cut by the erosion jet, increases in drilling speed achieved, and the effects of charge size and feed rate. Low cost ignition systems need to be further evaluated and experimentally verified to assure a low-cost propellant cartridge. This data would allow design and fabrication of a full-scale prototype for field testing.

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APPENDIX A

PARAMETERS FOR MINIMUM SPECIFIC ENERGY

The hydraulic power (P) of a fluid ejected through a nozzle is given by

$$P = avp \quad (A-1)$$

where a is the cross-section area of the nozzle, v is the velocity of the fluid through the nozzle, and p is the static pressure difference across the nozzle. The velocity of the fluid in turn can be given by

$$v = \sqrt{\frac{2p}{\rho_j}} \quad (A-2)$$

where ρ_j is the fluid density. Combining Eqs. (A-1) and (A-2),

$$P = \sqrt{2} a \frac{p^{1.5}}{\rho_j^{0.5}} \quad (A-3)$$

It can be seen that the power applied to the rock for a given pressure and fluid density is controlled by the cross-sectional area of the nozzle, while the velocity of flow will be constant.

The first analysis of a fluid jet penetrating into a target was made by Birkhoff (Reference A-1) and independently by Pack and Evans (Reference A-2). Assuming incompressible steady-state flow and a strength of the target negligible with respect to the stagnation pressure of the jet, the rate of penetration (u) can be derived from Bernoulli's theorem:

$$u = \frac{v}{1 - \sqrt{\frac{\rho_t}{\rho_j}}} \quad (A-4)$$

where ρ_t is the density of the target. Thus for a water jet ($\rho_j = 1$) impacting a rock ($\rho_t = 2.4$)

$$u = \frac{v}{1 + \sqrt{2.4}} = \frac{v}{2.55} \quad (A-5)$$

This relationship should give a maximum penetration rate. ERO-DRILL will use jet velocities of approximately 420 m/sec. This value of v gives an upper limit of the penetration rate from Eq. (A-5) of ~ 165 m/sec if rock were to act as an inviscid fluid. The fact that actual penetration rates are almost two orders of magnitude lower than this indicates that the strength of the medium plays a dominant role in controlling the penetration rate at these jet velocities.

Most erosion experiments with water jets have used jets with diameters in the order of 1 mm (References A-3 through A-6). Farmer and Attewell (Reference A-7), however, conducted a series of these experiments with nozzles having diameters ranging from 1 to 4.8 mm. It is important to know the scaling laws which apply to jet penetration of rock. These are necessary in order to extrapolate from experimental test data to other input conditions. The following analysis of existing data draws conclusions which are somewhat different than those made by Farmer and Attewell (Reference A-7) and Maurer (Reference A-1). Because of these differences, the analysis will be presented in detail.

Farmer and Attewell plotted penetration rate (u) versus rate of fluid flow (Q) and, on the strength of these data, suggested that, for a given rock and for a given jet velocity,

u was proportional to Q. Figure A-1 is a plot of their data on five different rocks for a jet velocity of 500 m/sec. Since the experimental rate desired was for penetration in an existing hole rather than on a flat surface, data are not shown for holes whose final depth was less than the hole diameter. As will be shown later, such data tend to confuse the analysis. They further postulated that for jet velocities greater than some threshold, the diameter of the hole was a linear function of the diameter of the nozzle. Figure A-2 shows the supporting data. For reference, the compressive strength and acoustic P-wave velocity for these rocks is given in Table A-1.

TABLE A-1 PROPERTIES OF VARIOUS ROCKS*

<u>Rock</u>	<u>Approximate Static Compressive Strength (kgm/cm²)</u>	<u>Wave Velocity (m/sec)</u>
Ferruginous sandstone	270	2400
Darley Dale sandstone	580	2400
Oolitic limestone	540	3900
Carrara marble	1090	4900
Anhydrite	1200	4600

*Reference A-7

Assuming these data can be extrapolated (using the same jet velocity) to larger nozzle diameters, we can predict the penetration rate to be expected for a high horsepower jet drill. Let us use Darley Dale sandstone as an example and enlarge the nozzle diameter to 3 cm. Extrapolating Figure A-2, we find that the hole diameter would be 15.3 cm. Extrapolating Figure A-1, we find a drilling rate of approximately 200 m/sec. This value, although very attractive, poses one question as to whether the

Figure A-1 Penetration rate versus nozzle flow rate (data from Reference A-8). Water jet velocity approximately 500 m/sec; figures in parentheses are nozzle diameter.

Figure A-2 Nozzle diameter versus crater hole diameter (data from Reference A-8.) Water jet velocity approximately 500 m/sec.

drilling rates shown in Figure A-1 continue to be proportional to Q as Q increases. The data for Ferruginous sandstone, in fact, shows a tendency to level off.

The penetration rates in Reference A-7 are obtained by dividing the final penetration by the time of flow. The actual penetration rate was not determined as a function of time. Water jets are known to expand and break up as their distance from the nozzle increases. This breakup is manifested in reduced penetration rates as the ratio of standoff distance to diameter of the nozzle increases (Reference A-8). The spreading of the jet, combined with the flow of water and cuttings out of the hole, reduces the penetration efficiency of the jet. Leach and Walker (Reference A-7), using 1-mm-diameter jets, measured the effective pressure at the bottom of holes in various depths; their data are shown in Figure A-3. It can be seen that the bottom hole pressure is greatly reduced when the depth of the hole becomes much larger than its diameter. Superimposed on this plot are the ratios of penetration to hole diameter (hereafter referred to as the hole aspect ratio or HAR) for the Ferruginous sandstone data shown in Figures A-1 and A-2.

Since the parameter HAR is considered to be an important factor in erosion drilling, a definition will be given. Assuming the nozzle is relatively close to the surface being drilled, the HAR is defined as the ratio of hole depth to hole diameter. If the nozzle has been lowered into the hole, however, the HAR is defined as the ratio of the standoff distance (from the tip of the nozzle to the bottom of the hole) to the hole diameter.

Brook and Summers (Reference A-8) also recognized the importance of this phenomenon. They measured the penetration for various length jets of constant jet velocity and from these

data were able to plot penetration as a function of time. Data for Farley sandstone, using 0.84-mm-diameter jets of velocity 326 m/sec, are shown in Figure A-4. The slope of this curve can be taken as an average penetration rate. The penetration rate falls rapidly to roughly one-tenth of its initial value at a depth where the HAR is roughly 6.0.

The reduction in penetration efficiency with increasing hole depth is undoubtedly responsible for the anomalous high drilling rates projected by Farmer and Attewell's relation. The highest penetration rate observed for Ferruginous sandstone in Figure A-1 was obtained for an HAR of 2.0. Figure A-3 shows that the bottom hole pressure is degraded only about 10 percent for this ratio. It is probable, therefore, that the penetration rate curve in Figure A-1 is leveling off and will not become much greater than the 400 cm/sec observed. The same reasoning will probably apply to the data for other rocks shown in Figure A-1.

One other doubtful conclusion has been drawn from the Farmer and Attewell data. Maurer (Reference A-1) observes that for Darley Dale sandstone the specific energy went through a minimum as the jet velocity was raised. This minimum occurred at a flow velocity of 300 m/sec. This has been interpreted by some to mean that the highest velocity jets were not necessarily the most efficient. The data used to illustrate this point are shown in Table A-2. The specific energy does appear to reach a minimum at a fluid velocity of 300 m/sec. Although the data given in Reference A-7 are not directly usable, the Darley Dale data were converted to make a plot (Figure A-5) of specific energy versus HAR for the various fluid velocities employed. The data are also connected in a way that shows the dependence on the diameter of the nozzle. The data listed in Table A-2 are shown as a plot of specific energy versus HAR for the 1.59-mm-diameter nozzle. It is clear that the HAR plays a vital role in

For 1 mm diameter jets at nozzle pressure of 600 bars (data from Reference A-7). Arrows indicate HAR for ferruginous sandstone data shown in Figures A-2 and A-3. Numbers in parentheses are nozzle diameters.

Figure A-3 Ratio of bottom hole pressure to nozzle pressure versus hole aspect ratio (HAR).

Figure A-4 Penetration versus time for a 0.84-mm diameter jet at 326 m/sec in Farley sandstone.

Figure A-5 Specific energy vs HAR for Darley Dale sandstone.

TABLE A-2 EFFECT OF FLUID VELOCITY ON EROSION DRILLING RATE*
(Darley Dale sandstone; 1.59-mm-diameter nozzle;
0.50-cm hole.)

Velocity (m/sec)	Flow Rate (l/sec)	Drilling Rate (cm/sec)	Power Output (kW)	Specific Energy (J/cm ³)	HAR
210	0.42	3	9.3	15,800	1.3
255	0.51	7	16.6	12,100	2.5
300	0.59	14	27.0	9,900	4.3
340	0.68	18	39.3	11,200	5.0
390	0.77	24	59.3	12,600	6.2
435	0.87	30	82.3	14,000	7.0
500	0.99	38	125.0	16,800	7.8

* Farmer and Attewell (Reference A-7)

the drilling process. It is also clear why a minimum occurs in the data of Table A-2. The specific energy for the highest flow rate was obtained from a hole with a much larger HAR than that of the 300 m/sec flow rate. As the flow rate decreases, however, the specific energy must ultimately rise to a high value. So even at an HAR of 1 to 2, the specific energy for a flow rate of 210 m/sec is very high. A minimum must occur between these two high specific energy limits.

Similar plots were made from the Farmer and Attewell data on three other rocks. They are shown in Figures A-6, A-7, and A-8. There is also some limited data on Indiana limestone at even larger nozzle diameters. These latter data were obtained from a water cannon (by Maurer, Reference A-9). Although the number of data points are insufficient to construct a family of curves as shown in Figures A-5 through A-8, the probable implications of the data are indicated by dashed lines in Figure A-9.

Figure A-6 Specific energy vs HAR for ferruginous sandstone.

Figure A-7 Specific energy vs HAR for oolitic limestone.

Figure A-8 Specific energy vs HAR for carrara marble.

Figure A-9 Specific energy vs HAR for Indiana limestone.

A study of these plots results in the following conclusions. The fact that the specific energy seems to rise as the HAR goes from 1 to zero implies that the initial formation of a hole in an infinite half plane is not as efficient as drilling in a hole having an HAR greater than 1. Once the hole has been started, however, and the jet nozzle is lowered into the hole, the specific energy probably does not rise as this number goes from 1 to zero. It may even decrease somewhat. The other conclusion related to the parameter HAR is that the minimum specific energy occurs at an HAR of roughly one to two. This emphasizes the importance of standoff distance in jet drilling. In particular, it would be desirable to maintain a distance of less than 1 or 2 diameters from the tip of the nozzle to the base of the hole during the course of the drilling.

As the nozzle diameter decreases below about 3 mm, the specific energy begins to increase radically. For diameters greater than approximately 4 mm, the specific energy drops very slowly. It is not clear why this diameter effect occurs. It may be related to the size of the debris particles which are removed by the erosion process and must move out of the hole without interfering with the jet. The hole diameter for a 4 mm-diameter jet is roughly 12 mm. Therefore, a radial space of roughly 4 mm would exist between the outside of the jet and the inside of the hole. It is hard to imagine that the debris particles would approach this size. A rebound effect, however, may occur near the bottom of the hole, which creates an inward velocity for this debris. Such an effect might then make the threshold debris size somewhat smaller for interference with the jet. The jet properties, depending on viscosity and surface tension, also may have some influence on this diameter effect.

Figure A-10 Minimum specific energy (for a given specific pressure) vs specific pressure.

Another possibility is as follows: as a jet impinges on the bottom of the hole, it is stagnant in only one hypothetical spot of zero radius. Everywhere else there are pressure gradients and resultant flow gradients. The combination of stress gradients and flow removes grains from the bottom of the hole. The mechanism involved is obviously quite complex. The size of the grain, its strength, its projection into the flow field, its geometrical interlocking with its neighbors, etc., all make the mechanism almost impossible to quantify for each grain. When a "weak" grain is displaced, the gap created undoubtedly weakens the support of its neighbors and makes them more susceptible to erosion. A "weak" grain is defined as one which, for whatever reasons, is easy for the jet to remove. The resulting erosion takes on a statistical aspect. If the jet is large enough to project its high stress field over a large number of grains, then the erosion rate will be dominated by the presence of the "weak" ones. If the jet projects its stress field over a statistically few numbers of grains, the chance of there being a "weak" grain is much reduced. Assuming an average grain diameter of approximately 0.15 mm (typical of sandstone), the ratio of the cross sectional area of a 3-mm-diameter jet and the cross sectional area of the grain is about 50 to 1. Any jet larger than this would appear to have a good statistical chance of having enough "weak" grains so that they would dominate the erosion process. As the jet diameter was reduced, however, the probability of having even one "weak" grain would become small.

Although the observed jet diameter effect is not clearly understood, one would expect that the knee of the curve of minimum specific energy versus jet diameter would occur at different jet diameters for different rock media and different flow velocities. For the five rocks plotted, however, and for the range of flow velocities employed, this knee appears to occur for jet diameters between 3 mm and 4 mm.

The final parameter whose effect is demonstrated in the above plots is that of flow velocity. The above data indicate that each particular rock has some threshold flow velocity which is required to give a reasonably low specific energy. Attempts have been made by other authors to find a correlation between specific energy and some property of the rock. One which appears to be relevant to the above discussion is a relation between specific energy and specific pressure, where specific pressure is the ratio of the dynamic impact pressure of the jet to the static compressive strength of the rock. Cooley (Reference A-11) concludes that the optimum jet pressure for minimum specific energy is approximately equal to the rock compressive strength, i.e., a specific pressure of one. Correlation of the data presented herein appears to bear this out. Figure A-10 shows the minimum specific energy for each specific pressure employed versus specific pressure for the four rocks plotted in Figures A-5, A-6, A-7, and A-8. It is clear that a break in the minimum specific energy curve is reached at a specific pressure near one. The data indicates that the specific energy then remains roughly constant as the specific pressure further increases. The data points, however, are coarsely spaced, and true minimum points (in Figures A-5 through A-8) are not necessarily obtained. It is much more probable that these curves drop rapidly to some value as the specific pressure approaches one, and then drop at a much lower rate as the specific energy becomes substantially greater than one.

It should be noted here that the value of specific energy which is addressed in this paper is that of water jet erosion within a hole. This is a relevant number for the drilling of holes. It does not include surface spallation which is caused by the initial impact of a very high velocity jet upon a relatively flat surface. The large transient stresses induced by the

latter are elucidated by the analysis made by Prichett and Riney (Reference A-11). The experimental results presented by Lucke and Cooley (Reference A-12) show a substantial decrease (more than an order of magnitude) in specific energy as the specific pressure increases from 1 to 30. In Barre granite, for example, specific energies ranging from 83 to ~ 400 J/cc were obtained for several shots at specific pressures over 10. These data, however, included the surface spallation of the medium. This undoubtedly accounts for the low numbers obtained and the wide spread in data although the inclusion of spallation is a realistic assumption for tunneling operations. This paper is addressed more to the problem of hole drilling. It is doubtful that rock would spall when subjected to surface pressures of the static fluid head at the bottom of a drill hole. The spallation process, therefore, is not included.

One can now make a general formula for optimum jet drilling. (1) The nozzle diameter for most rocks should be 4 mm or greater. There may, however, be rocks with grain structures which would raise or lower this number. (2) The nozzle should remain several hole diameters (or less) from the bottom of the hole. (3) The flow velocity should be such that the impact pressure is equal to or greater than the static compressive strength of the rock.

The test data employed above were all obtained from water jets eroding rocks in 1 atmosphere of air. These data would be quite appropriate, therefore, for drilling a dry hole. Most practical applications, however, would employ a hole filled with drilling fluid. For a deep hole, therefore, a substantial static head would exist in the fluid surrounding the exterior of the nozzle. Voitsekhovsky, et al., (Reference A-13) performed tests to determine the degradation of the jet dynamic pressures when the rocks and nozzle were submerged in fluids that were under static

pressures up to 100 bars. It was found that, for a jet of 2.2-mm diameter, there was very little effect if the nozzle was within 15 mm of the bottom of the hole. When this distance was increased to 50 mm, however, there was a severe degradation in the dynamic pressure. For a 2.2-mm-diameter jet, the hole diameter would be approximately 9 mm. A depth of 15 mm would represent an HAR of 1.7. It can be assumed, therefore, that, even in a fluid-filled hole, the maintenance of an HAR of the order of two or less will still result in a minimum specific energy for the jet erosion process.

The above arguments all relate to a stationary jet. If the jet is made to traverse along the rock surface, the above rules are no longer applicable. It is unlikely that the minimum specific energy at any given flow velocity can be reduced substantially from the minimum shown in Figure A-10. The optimum specific energy, for example, for a traversing cut on Darley Dale sandstone with a nozzle having a flow velocity of 500 m/sec has been measured to be approximately 2000 J/cc (Reference A-14), as compared to the value of 900 J/cc shown in Figure A-5.

The discrepancy between these two numbers probably comes from the fact that a 1-mm nozzle, even under optimum traversing conditions, still cannot obtain a specific energy as low as a 4-mm nozzle. In the following discussion, since nozzles equal to or greater than 4 mm will be assumed, the lower value of specific energy will be postulated.

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APPENDIX B

PROPELLANT SIZING PARAMETERS FOR ERODRILL

It has been proposed that a solid propellant be burned in a cavity at the end of the hollow drill shaft to pressurize water from 5,000 psia to 20,000 psia, expelling water in the cavity at a high rate through an orifice. The purpose of the jet of water is to dislodge any solid impediments at the drill bit.

Turbulence will undoubtedly be very high in the cavity near the burning propellant, and much of the thermal energy released by the burning propellant will heat the water in intimate contact with the gases. A parametric analysis was accomplished which assumed that a fraction of the water in the cavity would be heated to the same temperature as the evolving gases. Two steps are considered in the propellant combustion as follows:

1. A constant volume pressurization of the cavity from 5,000 psi to 20,000 psi
2. An increase in the specific volume of the gas and heated water at constant pressure

It was assumed that the volume increase was equal to the water expelled through the orifice at a density corresponding to a pressure of 20,000 psia and the local ambient temperature of 350°F (57.14 lbm/ft³). Figure B-1 shows that as the mass of water heated by each pound of propellant increases, cooling the gas and reducing its specific volume, the amount of water expelled per pound of propellant decreases. The effect is less pronounced at higher heated water-to-propellant mass ratios because a greater amount of the water is heated to a higher specific volume. Figure B-1 shows these results for two different solid propellant characteristics, varying mainly in the

Figure B-1 ERODRILL propellant sizing parameters (fraction of water in cavity heated by propellant).

molecular weight of the evolved gases. The propellant requirements of propellant B (MW = 48.6) compared to propellant A (MW = 18.0) are approximately doubled to expel the same amount of water. As the amount of water heated per pound of propellant increases, the amount of water expelled per pound of propellant decreases to asymptotic values of 2.30 and 1.25 lbm/lbm, for propellants A and B, respectively. These values are for a ratio of 10 lbm of water to 1.0 lbm of propellant in the drill tube cavity at the initiation of burning.