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Lunar Drilling

The association of the Bureau of Mines with lunar-drill programs since 1964 includes: (1) advising and consulting with NASA and with contractors making prototype drills, and (2) conducting laboratory investigations of problems related to drilling in ultrahigh vacuum, at lunar temperature extremes, and in reduced gravity. This paper reviews problems related to lunar drilling, data from Bureau drilling tests for lunar applications, and possible methods for predicting drillability of lunar materials from their engineering properties.

INTRODUCTION AND BACKGROUND

In his quest for knowledge of the Moon, man will need to examine lunar-subsurface phenomena. In order to obtain data on these phenomena, he will require adequate drilling systems. NASA has been conducting two lunar-drill programs to complement the manned spaceflight program. The Apollo Lunar Surface Drill (ALSD) Program is developing a lightweight, hand-held, rotary-percussive drill capable of boring a 1-inch-diameter hole to a depth of 10 feet in the Moon's surface. The other program is developing a moderate-depth drill for post-Apollo applications and includes two different models, each designed to bore a 2-inch-diameter hole to a depth of 100 feet.

Developing a lunar drill is a necessary first step in the exploration of the Moon because it provides the key to the subsurface geology. All drills being developed for this purpose are core drills; that is, they cut a solid cylindrical core which can be transported back to Earth for subsequent analysis. The extraction of this core sample, however, is not the sole objective of the lunar drills, for after the core is taken the hole will be available for the emplacement of geophysical instruments such as heat probes, radiation detectors, and seismic devices.

Drilling a hole on the Moon does not, at first glance, appear extraordinarily difficult. We have, after all, mechanically drilled rock on Earth for more than a century, although the greatest advances did not occur until the last 20 years (tungsten-carbide insert bits for percussive drilling and the wire-line system for diamond drilling). When all factors of lunar drilling are considered, however, they combine into an intricate and complex problem involving the environmental effects of high vacuum, reduced gravity, and temperature extremes not encountered on Earth (ref. 1).

To drill a hole on Earth to a predetermined depth within a rigid time schedule, while collecting good samples, requires a certain amount of skill. The Earth driller uses a machine which has been thoroughly tested, and, in addition, he probably has access to an unlimited supply of replacement parts. Although the components of the lunar drills will have been rigorously tested, it is extremely difficult to test-run the complete drilling system in the temperature-vacuum-gravity environment to be encountered on the Moon.

The lunar environment, the most hostile yet encountered by man, will have a significant effect on the design and operation of a drill. Systems for drilling deep holes on Earth depend on water or air as the flushing medium to remove cuttings and cool the bit. Normally the flushing medium flows down through the hollow drill rods, across the face of the bit, and then out of the hole in the annular space between the drill rod and hole wall. A liquid flushing medium probably accounts for some lubricating action at the bit-rock interface; soap or glycerine additives are sometimes used to enhance this action (ref. 2).

Lack of water and the ultrahigh vacuum necessitate that drilling on the Moon must be accomplished dry; that is, without any flushing medium. Although liquids could be used in lunar drilling, spacecraft weight limitations prohibit transport of the required quantity from Earth. The possibility that Earth-produced media used on the Moon may contaminate lunar samples also bars their use. Consequently, all lunar-drill systems under development use an augering action to remove cuttings from the bottom of the hole mechanically.

Cooling the drill bit without a flushing medium is a significant problem, especially in rotary systems which convert a high percent of the available energy into heat at the bit. One approach to the problem is an internally cooled diamond bit that uses a closed-loop cooling system and a highly conductive matrix material that will conduct bit heat through the drill string rapidly. Removal of heat through the cuttings which serve as a heat sink is another possibility.

Another possible difficulty in lunar drilling is that lunar vacuum may cause rock cuttings to adhere to each other or to the drill steel (ref. 3). Drilling tests have been conducted in vacuum chambers in the range of 10^{-6} to 10^{-7} torr and, at these pressures, there do not appear to be any adhesion problems with the proposed cutting-removal systems. No drilling under simulated lunar vacuum conditions has been performed. Bottom-hole pressures caused by outgassing of rock as it is being drilled may also inhibit particle adhesion or welding in these tests. Whether outgassing will occur in lunar rocks is not known, although information on the outgassing characteristics of simulated lunar rocks being developed by the Bureau of Mines may help to answer this question (ref. 4).

The other difficulties that lunar temperature and gravity impose on drilling systems and techniques can probably be overcome by our present technology. Suitable design criteria should be adequate to cope with the temperature range of −250° to +250° F to be encountered on the Moon. Thrust, an important parameter in drilling, will be affected by lunar gravity, which is approximately one-sixth that of Earth. For example, the ALSD, which will be hand-held by the astronaut, must operate under an axial thrust of somewhat less than 20 pounds. This thrust will be adequate for unconsolidated material or soft rock, but will be insufficient for drilling harder rocks. The moderate-depth lunar drill attached to the lunar module (LM) should provide adequate thrust for drilling hard rock.

Other constraints that are placed on lunar-drill systems are total weight and available power. Since the volume of rock removed is directly proportional to power input, the energy source powering the drill becomes a critical factor in its performance. The Bureau of Mines is studying the ability of both drilling systems to operate effectively within existing power and weight limitations.

DESCRIPTION OF SYSTEMS

Apollo Lunar-Surface Drill (ALSD)

Figure 1 shows the development model of the ALSD. This drill is being developed by the Martin Co. under a contract awarded by NASA's Manned Spacecraft Center, Houston, Tex., in November 1966.

The complete drill system will weigh about 25 Earth-pounds and will be operated by one astronaut. The drill is battery powered, with the power pack located above the drill motor. This electric rotary-percussive system is designed to drill a 1-inch-diameter hole 10 feet deep and to take a core sample approximately three-fourths inch in diameter. Helical auger flights (flutes) on the drill steel remove the cuttings.

Figure 2 shows three test bits of different configurations for the ALSD; the bits illustrated have, respectively, three, four, and five tungsten-carbide inserts as cutting elements. Comparative laboratory tests of the bits in several simulated lunar rocks at the Twin Cities Mining Research Center have determined the optimum bit configuration to be the one with five inserts. Scientists at the NASA Marshall

FIGURE 1.—Development model of Apollo lunar surface drill.

Space Flight Center have recently completed tests in which the ALSD drilled two holes in vesicular basalt in a vacuum chamber at a pressure of 10^{-6} to 10^{-7} torr. These test results are presently being analyzed.

Moderate-Depth Lunar Drill

Two parallel contracts were awarded in mid-1965 by the NASA Marshall Space Flight Center for developing a drill capable of drilling a 2-inch-diameter hole to a depth of 100 feet while taking a solid core sample. Specifications for the drills included a system weight of 200 Earth-pounds (exclusive of power supply), a power draw of 5 kilowatts from the spacecraft, and the capability of removing cuttings mechanically.

Under one contract, a gas-operated, down-hole percussive drill (figs. 3 and 4) was developed by Northrop Space Laboratories. In this system, nitrogen gas is compressed in the surface unit located inside the revolving drum. A flexible concentric steel hose wrapped on the drum advances and retracts the down-hole drill and conveys the operating and exhaust gases to the down-hole hammer. The down-hole portion consists of a core-type tungsten-carbide button bit; a reciprocating piston to provide the necessary blow intensity; a hollow, teflon-coated core barrel; and a cuttings container or chip basket.

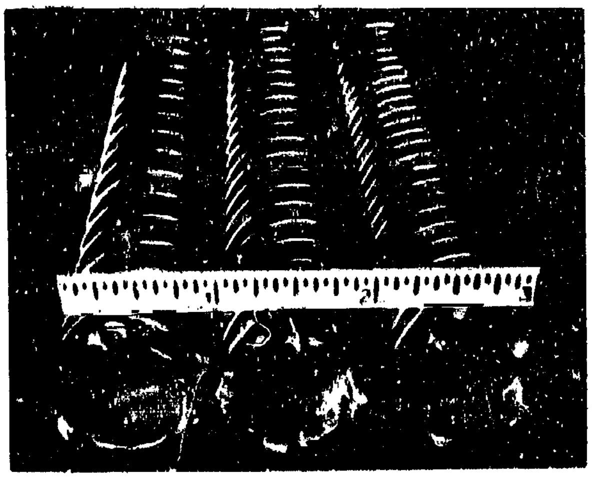

FIGURE 2.—Apollo lunar surface drill test bits.

Spiral flutes on the outside of the down-hole section auger the cuttings from the bit face, up past the core barrel, and into the top of the chip basket. After each 3¼-foot drill advance, the drill is retracted from the hole by the flexible drill string. The core barrel and chip basket are then emptied, and the cycle is repeated.

The other moderate-depth lunar-drill system was developed by the Westinghouse Defense and Space Center. This system (figs. 5 and 6) is like conventional wire-line diamond drills except for the cuttings-removal mechanism. The down-hole portion consists of a surface-set diamond coring bit, a core barrel, and a chip basket. As with the percussive moderate-depth drill, spiral flutes on the outside of the down-hole portion transport the rock cuttings to the chip basket. The rotary mechanism is housed

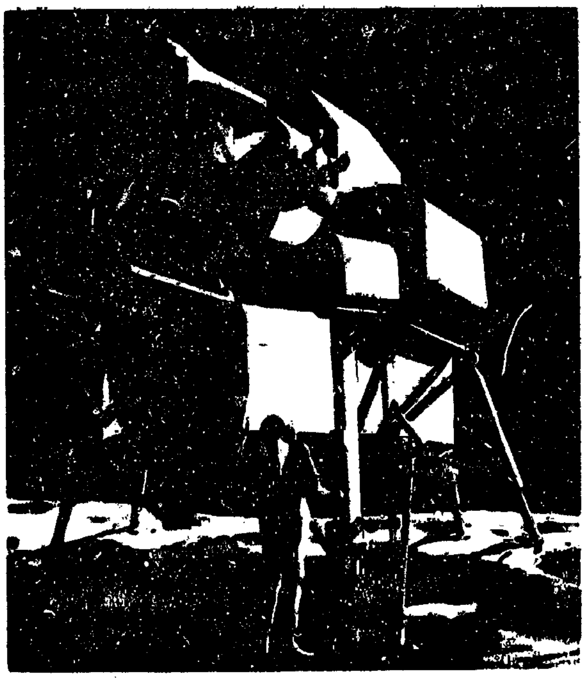

FIGURE 3.—Moderate-depth lunar drill, percussive type.

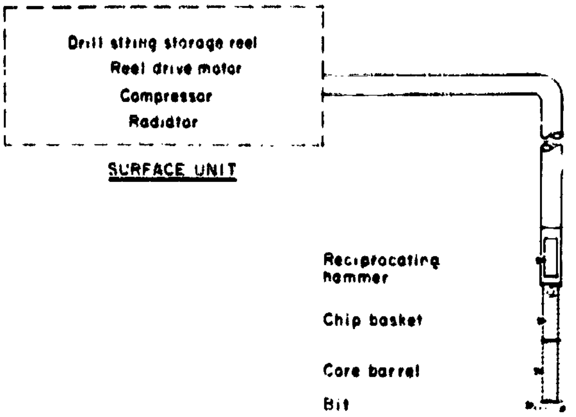

FIGURE 4.—Schematic of percussive drill.

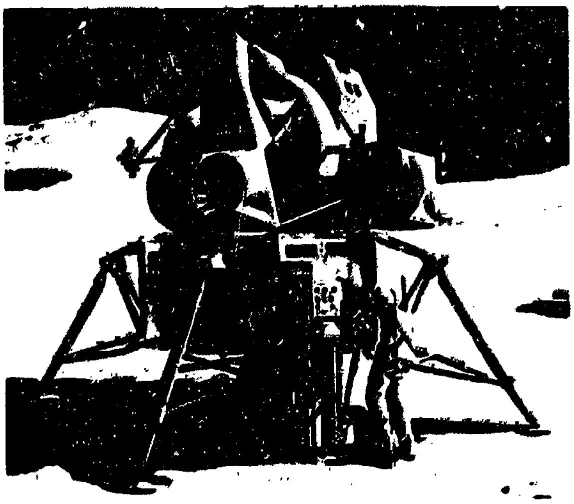

FIGURE 5.—Moderate-depth lunar drill, diamond rotary type.

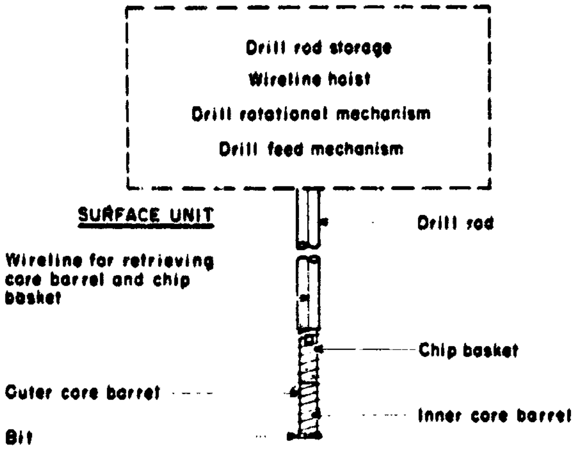

FIGURE 6.—Schematic of diamond rotary drill.

in the surface unit attached to the lunar module.

The down-hole portion contains a rotating outer barrel, to which the bit is attached, and a stationary inner tube containing the core barrel and the chip basket. After drilling has progressed 5 feet, an "overshot" assembly is lowered on the end of a line inside the drill pipe and attached to the inner tube assembly; the core barrel and chip basket are then pulled to the surface, while the bit and drill string remain in the hole. After the inner tube assembly has been replaced, another 5-foot section of drill pipe is added and the cycle is repeated. If the bit life is adequate, the entire 100 feet can thus be drilled without removing the drill string from the hole. The diamond bit is one of the most critical components of this system.

BUREAU OF MINES PARTICIPATION

Testing Lunar-Drill Hardware

The Bureau of Mines has provided both consulting services and laboratory support ever since the moderate-depth lunar-drill development program was initiated in 1964. Laboratory drilling tests with the down-hole assembly of the percussive-type drill have been started at the Bureau's Twin Cities Mining Research Center laboratories. The apparatus being tested includes a core barrel and bit from the Northrop system attached to a percussive drill that provides the same blow intensity as does the engineering model (fig. 7). A range of simulated lunar materials has been drilled to study penetration rates and cuttings-removal characteristics.

Bureau support for the diamond rotary lunar drill has included dry drilling tests of bits to study cuttings removal, bit life, and bit heat generation (fig. 8). The studies show that, if the cuttings are not removed rapidly enough, drilling efficiency falls off because the energy lost in attrition of the cuttings creates sufficient heat to damage both the drill bit and the core sample.

In a series of tests with the diamond-drill bit, we were able to drill more than 10 feet into Dresser basalt without a flushing medium (fig. 9). A similar bit has been tested by Westinghouse in a vacuum chamber at pressures of 10^{-6} to 10^{-7} torr. When the drilling was done in vacuum, the cuttings appeared to be ejected from the hole at a much greater velocity than that which occurred when the drilling was done in atmosphere; this is probably a result of outgassing of the rock at the bit-rock interface. This, the first of the vacuum drilling tests, indicated that a vacuum of this magnitude had no adverse effect on drill performance (ref. 5).

Other Laboratory Experiments

In addition to testing lunar-drill hardware, the Bureau has been studying the fundamental problems associated with drilling in a lunar environment. Since drilling without a flushing medium represents a critical problem, a series of experiments has been conducted to investigate the effects of flushing media on drilling efficiency and penetration rate. In these experiments a laboratory diamond drill and a rotary-percussive drill were tested on several simulated lunar rocks selected to represent a wide range of physical properties. The rocks included flow (tholeiitic) basalt, fresh rhyolite, vesicular basalt, and dacite. Dresser basalt, a hard, dense, intrusive basalt, was also included.

FIGURE 7.—Laboratory simulation of moderate-depth percussive drill.

The bench-mounted diamond drill was instrumented to record penetration rate, power consumption, bit rotational speed, and bit temperature while drilling in a block of rock. These tests were run: (*a*) with water flush, (*b*) with air flush, and (*c*) with no flushing medium. When there was no flushing medium, the drill hole was alined on the edge of a square block with a segment of the hole exposed to allow cuttings to spin out.

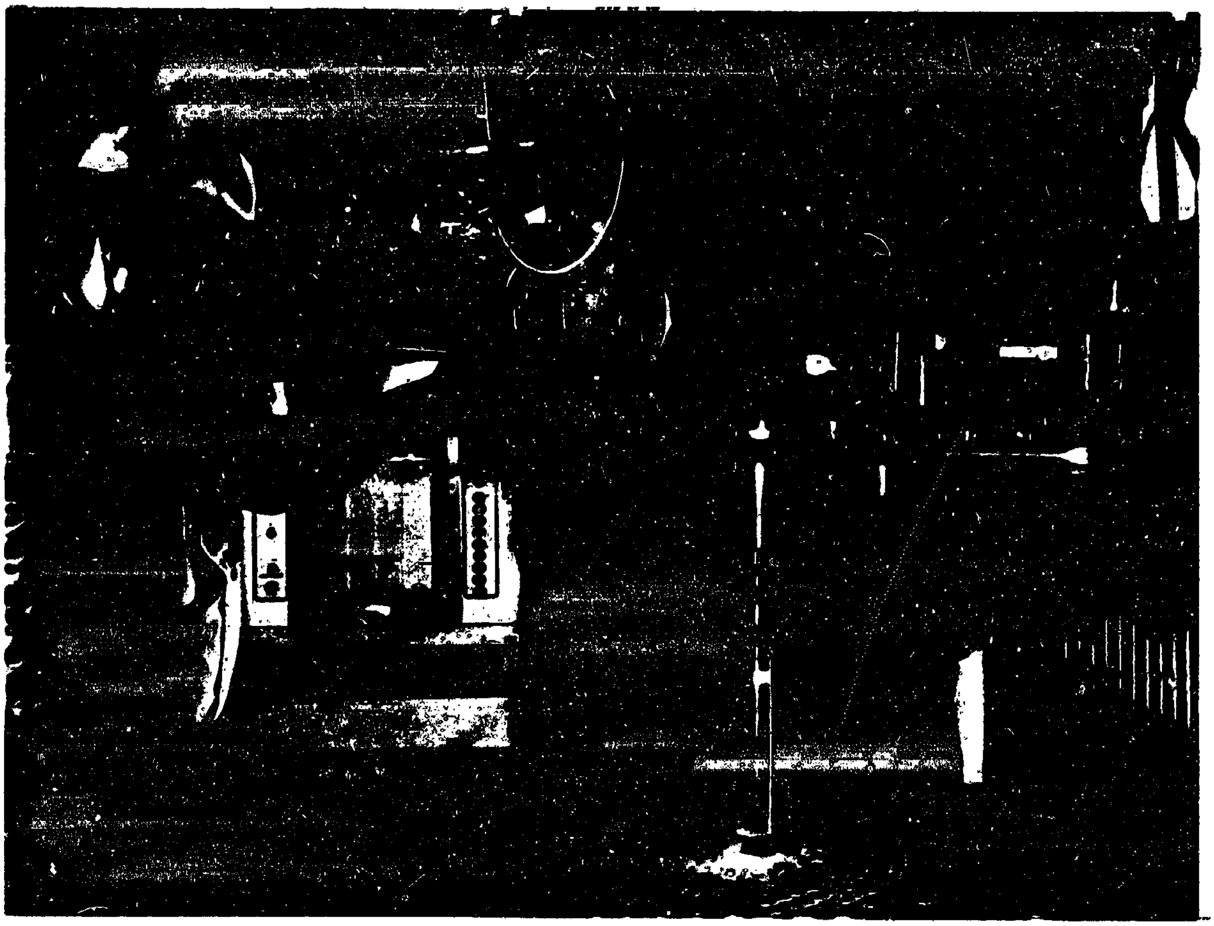

FIGURE 8.—Dry drilling in basalt with lunar test bit.

Figures 10 to 14 show relative penetration rates with diamond bits in five rock types using water flush, air flush, and no flushing medium. In general, highest penetration rates were obtained with water flush, followed by air flush and no flushing medium in that order. However, for vesicular basalt and dacite (figs. 13 and 14), drilling without any flushing medium produced higher rates than did air flush.

In addition to the effects of the flushing medium on diamond drilling, other factors such as bit crown design, diamond count, and diamond size influence bit performance. Figure 15 compares the performance of three ⅞-inch-diameter diamond bits in a soft and a hard rock with water flush. The highest penetration rate in hard rock (basalt) was obtained with the small diamonds, while the highest rate in soft rock (rhyolite) was with the largest diamonds.

Experiments were then conducted on the same rock samples with a bench-mounted electric rotary-percussive drill with the same parameters recorded. Figure 16 compares penetration rates for the laboratory rotary-percussive drill in the five rocks drilled. Since the penetration rate-thrust curve "tops out" at a different thrust level for each rock drilled, each rock has its own point of optimum thrust with a specific drill.

Since optimum thrust is important in lunar drilling, where thrust is severely limited by the low lunar gravity, a separate study was made of this phenomenon. Figure 17 shows a direct relationship between optimum thrust and coefficient of rock strength. This strength

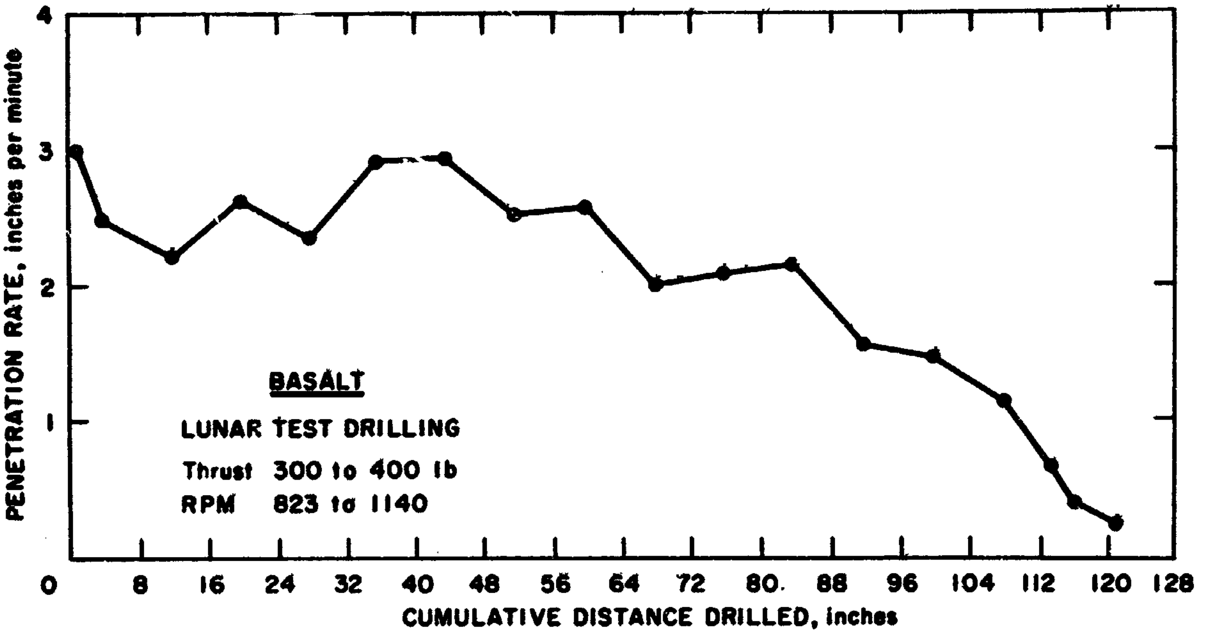

FIGURE 9.—Penetration rate against distance drilled with a prototype lunar diamond bit. Material drilled, basalt; thrust, 300 to 400 pounds; speed, 823 to 1140 rpm.

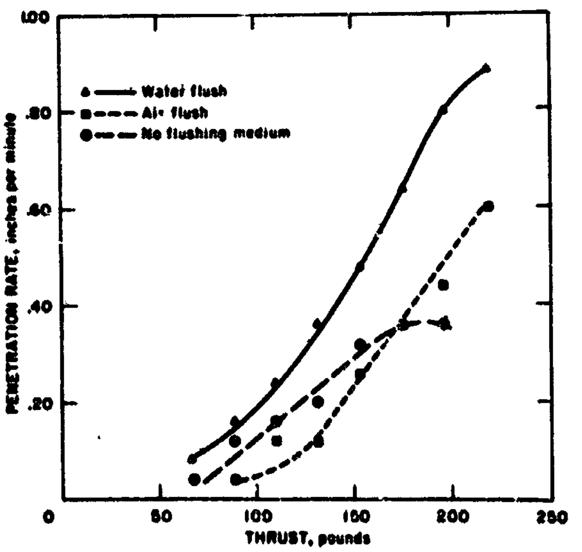

FIGURE 10.—Effects of flushing methods on penetration rate in Dresser basalt with ¾-inch diamond rotary bit.

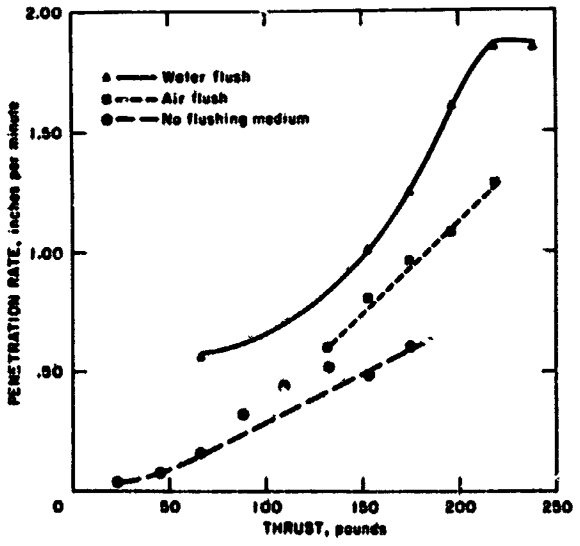

FIGURE 11.—Effects of flushing methods on penetration rate in flow basalt with ¾-inch diamond rotary bit.

measurement is a simple test of the energy involved in breaking a unit volume of rock to a given size. It is performed by placing a rock sample in a tube, dropping a standard weight from a standard height, and measuring the volume of minus 35-mesh material produced.

Another important drilling problem that was investigated in the Bureau laboratories

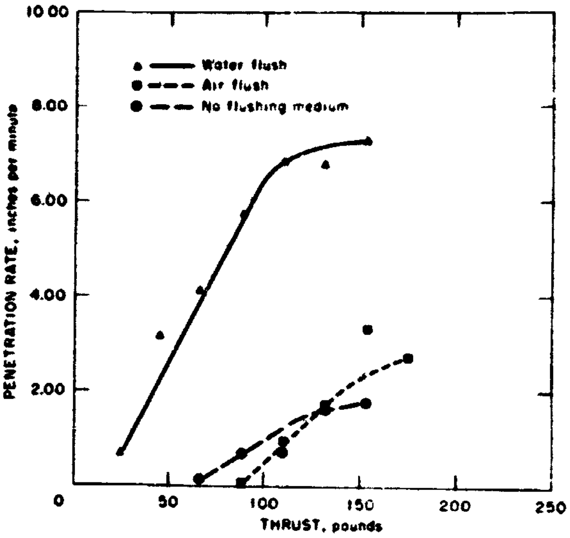

FIGURE 12.—Effects of flushing methods on penetration rate in rhyolite with ½-inch diamond rotary bit.

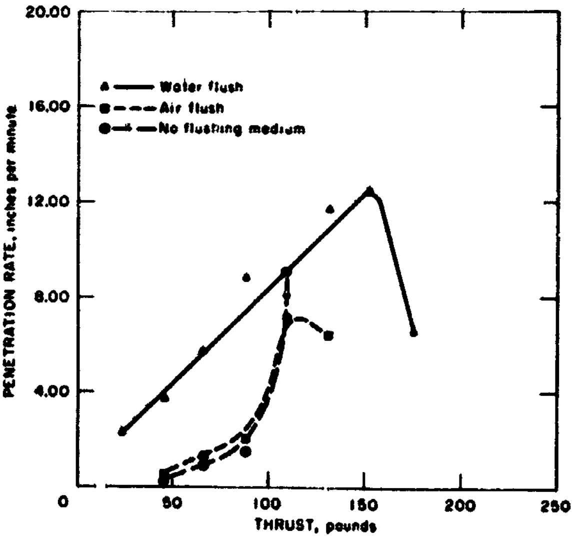

FIGURE 13.—Effects of flushing methods on penetration rate in vesicular basalt with ½-inch diamond rotary bit.

was bit heat generated by a drill with no flushing medium. Figures 18 and 19 show the effects of thrust and drilling time on the bit temperature of a laboratory rotary-percussive drill. Increased thrust and increased drilling time do not increase bit temperature significantly as long as cuttings are removed promptly.

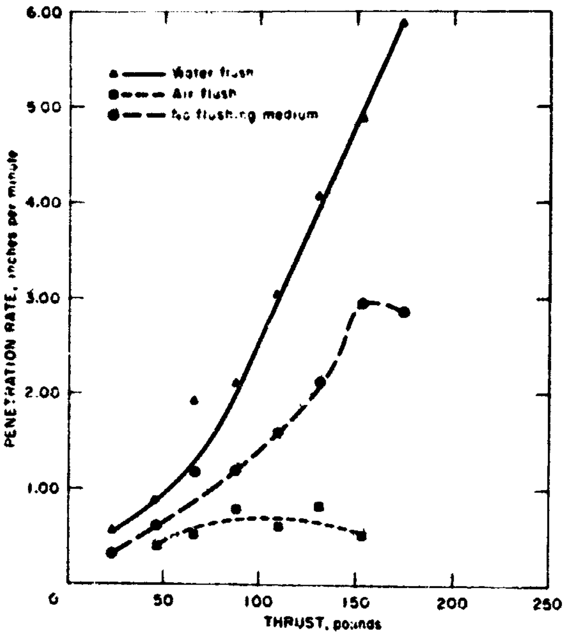

FIGURE 14.—Effects of flushing methods on penetration rate in dacite with ½-inch diamond rotary bit.

In an effort to find a substitute for liquid and gaseous flushing media for the lunar diamond drill, the Bureau experimented with solid lubricants introduced to the bit-rock interface. Preliminary experiments show that these lubricants improved the efficiency of a bench-mounted diamond rotary drill. It appears that a solid lubricant, if properly used, can reduce side-hole and matrix friction without impairing the cutting capability of the diamonds. Further drilling tests with dry lubricants are underway at the Twin Cities Mining Research Center, along with efforts to design a reliable system to introduce these lubricants to the bit-rock interface.

Studies of cuttings removal by mechanical means are also underway; the down-hole assembly of the percussive-type lunar drill and a transparent tube to simulate the drill hole are being used in these studies.

Discussion of Laboratory Results

Analysis of the data in figures 10 to 14 shows that water flush yields a higher penetration rate in diamond drilling than does either air

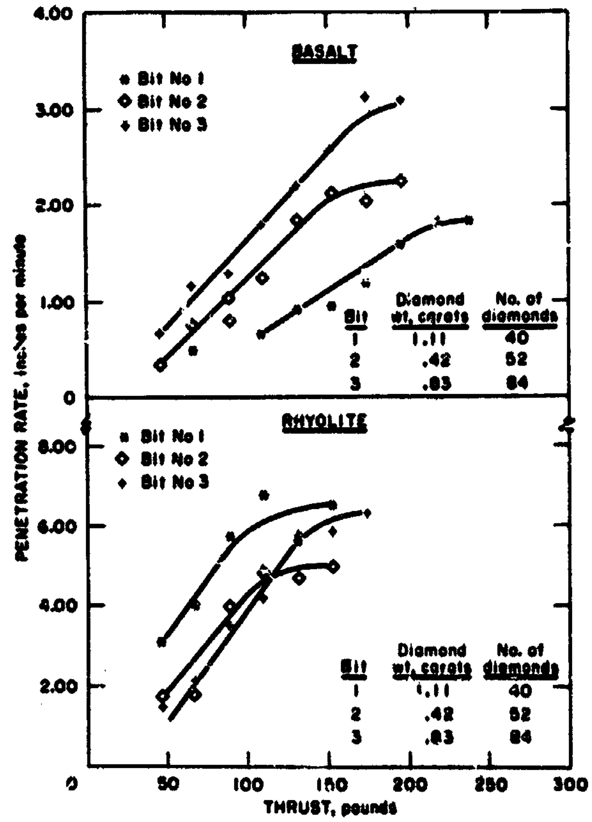

FIGURE 15.—Comparison of three different ¼-inch rotary diamond bits in basalt and rhyolite with water flush.

	Bit no. 1	Bit no. 2	Bit no. 3
Kerf area, sq. in.	0.178	0.187	0.181
Matrix hardness, RC	30-40	35-40	30-35
Diamond weight, kt.	1.11	0.48	0.83
Diamond count	40	52	84
Diamond grade	AAA	A	AAA

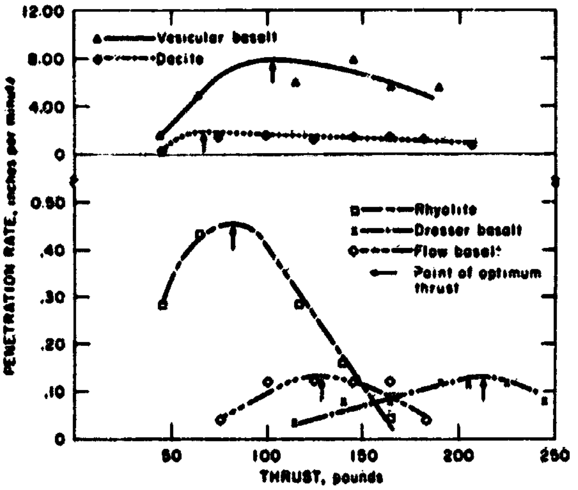

FIGURE 16.—Penetration rate against thrust in simulated lunar rocks for laboratory rotary-percussive drill with 1-inch core bit.

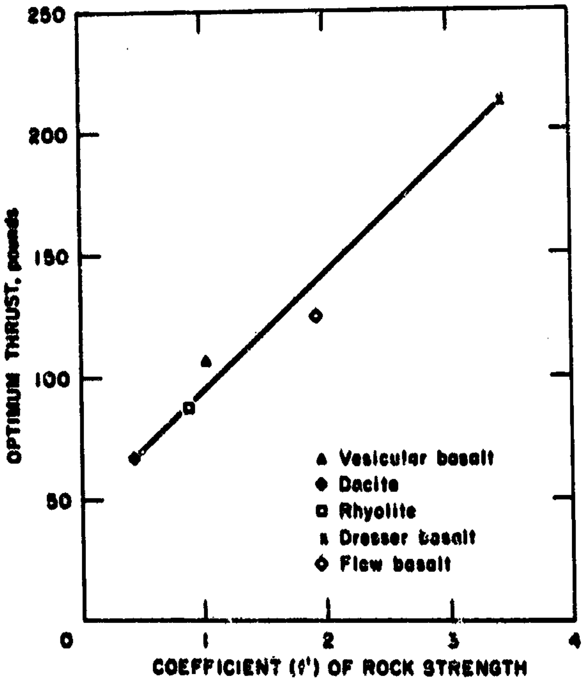

FIGURE 17.—Optimum thrust for each rock type against coefficient of rock strength for laboratory rotary-percussive drill with 1-inch core bit.

flush or no flushing. Therefore, in diamond drilling on the Moon when mechanical means are used for removing cuttings, lower penetration rates would be expected than those obtainable on the same rocks when a liquid flush is used.

Comparative studies of different bits show that matching diamond bit crown design to rock type is an important consideration in lunar drilling. A hard rock, such as basalt, is best drilled with a bit consisting of a large number of small, close-set stones, and a soft rock is more vulnerable to a bit with fewer,

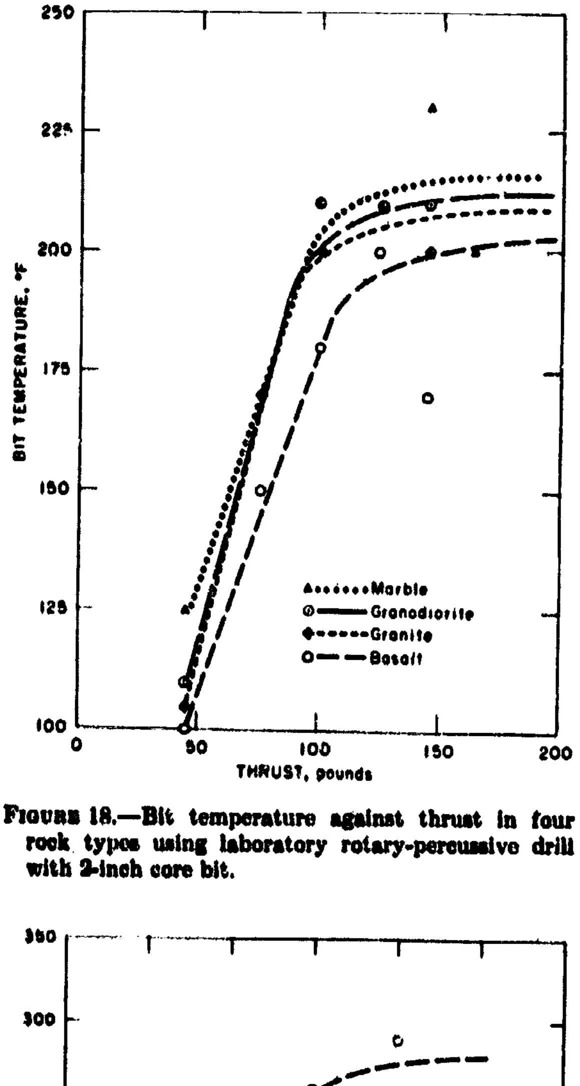

FIGURE 18.—Bit temperature against thrust in four rock types using laboratory rotary-percussive drill with 2-inch core bit.

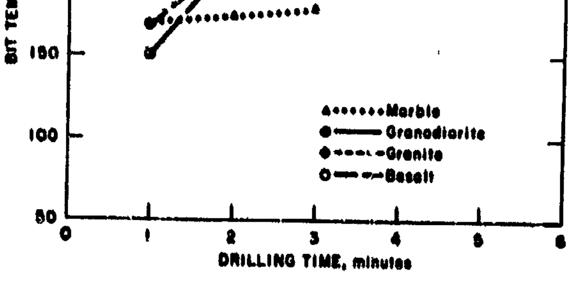

FIGURE 19.—Bit temperature against drilling time in four rock types using laboratory rotary-percussive drill with 2-inch core bit.

larger stones. Carat weight alone does not appear to be an important criterion, except possibly to increase the reliability of the bit. As more information is obtained about the stratigraphy of the Moon, we will be better able to specify bit-design criteria for lunar drills.

The optimum thrust for a rotary-percussive drill shows a linear relationship with the coefficient of rock strength. The results of similar studies in a range of simulated lunar rocks should predict optimum thrust values for any percussive or rotary-percussive drill in any specific rock expected to be encountered on the Moon. This comparison shows the value of physical properties of materials as an engineering tool used to predict drillability.

Bit-temperature studies of an uncooled rotary-percussive drill bit show that temperatures tend to stabilize after a sharp rise with increased thrust or drilling time as long as cuttings are removed promptly. Further tests of longer drilling times and in deeper holes will be necessary. As mentioned earlier, vacuum drilling tests conducted to date have been in the pressure range of 10^{-6} to 10^{-7} torr. Further drill tests in higher vacuum should be conducted.

SUMMARY

Drilling on the Moon, according to studies performed to date, will be affected by lack of atmosphere which necessitates drilling dry, by reduced gravity which means drills will have to be carefully designed to take advantage of available thrust, and, possibly, by temperature extremes when bit cooling may be a problem.

Experimental work conducted by the Bureau of Mines, by NASA, and by contractors has demonstrated that rock can be drilled dry, that is, without the use of flushing media, with adequate mechanical cuttings-removal systems. With further work, it should be possible, within the framework of our present technology, to raise the efficiency of dry drilling to a point where it approaches that of drilling with a flushing medium.

Thrust, or force required to hold the bit on the bottom of the hole, is usually obtained through use of the weight of the drill system.

Optimum drilling rates in specific rocks require an optimum thrust with a particular drill system; therefore, appropriate design features should be incorporated in a lunar-drill system to offset the effects of the reduced lunar gravity.

Initial studies and experiments were made to predict drilling rates with a specific drill in some simulated lunar rocks on the basis of their physical properties. Further work on drillability of a range of materials with prototype lunar drills would eliminate uncertainty about the performance of the drills.

A full understanding of the effects of vacuum on bit temperature and material adhesion in a lunar environment will require further tests in ultrahigh vacuum with particular attention given to drill instrumentation and sample preparation. The solutions to these problems will contribute to terrestrial drilling problems, just as our present drill technology has provided a foundation for the lunar drill.

REFERENCES

1. Faier, W. H.; and Campbell, J. A.: Lunar Drilling Study. Proc. 5th Symp. on Rock Mechanics, Univ. of Minn., May 1962, pp. 205–228.
2. Joris, A. C. T.; and McLaren, G.: Additives to Coolants Used in Diamond Drilling and Sawing in Australia. Min. Miner. Eng., vol. 3, no. 5, May 1967, p. 190.
3. Penn, S. H.: Wildcatting on the Moon. AIME preprint, Proc. 7th Symp. on Rock Mechanics, Pa. State Univ., June 1965, pp. 491–517.
4. Roepke, W. W.; and Schultz, C. W.: Mass Spectrometer Studies of Outgassing From Simulated Lunar Materials in Ultrahigh Vacuum. 14th Nat. Symp. Am. Vacuum Soc., Kansas City, Mo., Oct. 1967.
5. Woo, W. George: A Lunar Drill. Res./Develop., vol. 18, no. 12, Dec. 1967, pp. 44–45.