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ROCK MELTING
AS A DRILLING TECHNIQUE

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LOS ALAMOS SCIENTIFIC LABORATORY
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ROCK MELTING
AS A DRILLING TECHNIQUE

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ABSTRACT

Rocks melt rapidly in contact with tungsten or molybdenum heated electrically to incandescence. The metals exhibit excellent strength and resistance to corrosion. Drills applying these observations have been constructed and tested with continuous removal of the lava. The hydrodynamics of molten rock moving beneath a drill is presented. Appropriate lines for additional developmental work are suggested.

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I - INTRODUCTION

This report describes a method and some associated experimental studies for drilling holes in the earth. To drill holes conventionally, one breaks and grinds the solid rocks: Turn them into a liquid and the problems become those of hydrodynamics and heat transfer — motion is through a fluid.

The notion was conceived in 1960. As an initial test, tungsten foil was heated to incandescence electrically and was easily pushed through samples of igneous rock. Molten rock protected the hot metal surface from attack by the water vapor which boiled from the rock. This first indication that the common refractory metals are suitable for construction of drills for rock melting has been established by a variety of additional experiments.

Further experiments confirmed that the energy needed for melting rock is similar to the amount required (about one kcal/cm³) to break and pulverize it. The essential design problem was reduced quickly to development of techniques for removal of the lava. Design of several devices and their experimental test is described in Section II; some associated theory is presented in Section III; and our conclusions are presented briefly in Section IV. A picture of the type of drill to which these experiments led is shown in Fig. 1.

Fig. 1. A typical thermal drill. Rock, melted by the heated molybdenum foot, flows to the center of the drill. A high-velocity gas stream forms pellets of the melt and blows them to the surface.

II - EXPERIMENTAL SECTION

By way of introduction to the experiments we have carried out, it is useful to summarize the general features needed for a thermal drill for rock. The melting points of most common siliceous minerals fall in the range from 1100 - 1500°C. The highest lava temperature which has been reported is 1300°C. A drill capable of melting through minerals such as these must retain its strength at somewhat higher temperatures, preferably to about 1700°C. Although this is well above the melting point of steel, it is well within the range for practical use of the refractory metals molybdenum, tungsten, rhenium, and iridium.

The heats required for melting a variety of siliceous minerals have been measured at $\sim 1,000 \text{ cal/cm}^3$, including both the heat of fusion and the heat required to bring the mineral from room temperature to the melting point. The amount of power which must be supplied to each square centimeter of the drill face for various drilling rates is listed in Table 1 on the following page.

As the thermal diffusivity of rock is low ($< .01 \frac{\text{cm}^2}{\text{sec}}$) most of the heat spreading in front of the drill face will be overtaken for drilling rates of practical interest. On the other hand, the heat spreading from the hot sides of the

drill is essentially lost. Therefore, more efficient utilization of the available energy will be obtained with drills having higher ratios of frontal-to-side areas. To achieve high drilling rates, a large temperature gradient or a very small thermal impedance is necessary between the power source and the working face of the drill. For example, for delivery of $100 \text{ cal/cm}^2\text{-sec}$ from a power source at 1800°C to the drill face at 1300°C , the thermal impedance will correspond to only about 1.5 cm of Mo or 0.005 cm of helium gas. Even for slower drilling rates, this may be a critical design consideration.

TABLE 1 - POWER FOR VARIOUS DRILLING RATES

<u>Speed</u>		<u>Power Flux</u>	
<u>cm/sec</u>	<u>ft/day</u>	<u>cal/cm²sec</u>	<u>watts/cm²</u>
0.001	2.7	1	4.2
0.01	27	10	42
0.1	270	100	420
1.0	2700	1000	4200

Rocks melt at temperatures where the resulting fluid is typically highly viscous with properties like glass at glass-blowing temperatures. In the experiments of this study, viscosities of 10^2 to 10^4 poise were utilized. The reported viscosities of minerals seldom decrease below 10 poise even well above the melting temperatures, so that melts are never watery (10^{-2} poise).

This causes their containment of released gases and is related to their remarkable adhesion to hot metal surfaces. After the molten rock cools, a glass-like obsidian remains. These are the properties which must be utilized in handling the melt and removing it from the hole.

II A - EARLY EXPERIMENTS

Our first experiments were designed to test whether the common refractory metals were attacked by molten rock. The encouraging results led us to examine the behavior of a number of simple cutting and piercing devices fabricated for the most part of molybdenum foil or small tungsten or molybdenum rod and heated by passing large currents through the pieces in contact with the rock (see Fig. 2, the one-inch drill). A number of properties of the rock samples were checked out (density change on melting, viscosity, electrical conductivity and melting points). These experiments demonstrated that a variety of basaltic rocks could be pierced by hot tungsten or molybdenum drills, that the lava could be induced to flow into small tubes near the drill face, and that it could be extruded as rod.

Fig. 2 An early drilling device, the one-inch drill. The water-cooled, double-walled stem serves to conduct a large current (1000 amp) through the reentrant molybdenum walls that serve as the heater. The 3/8-inch extrusion tube is heated by conduction from the foot and is designed to reduce the melt temperature approximately 100° for extrusion as a glass-like rod. In practice, the drill penetrated to its full depth, about 8 in.

II B - GAS GAP DRILL

The device which we have tested most thoroughly is shown in Figs. 3 and 4. Power of ~ 15 v and 150 amp supplied from a small commercial welding transformer is dissipated in a flat heater fabricated from 0.038 cm tungsten sheet. The heater is suspended 0.05 cm above the inside surface of the shoe by insulated tungsten pins. Heat is conducted to the shoe through a thin, helium-filled gap. The heated cylindrical molybdenum shoe is pressed into the rock, the melted rock being forced through its central orifice and extrusion tube. The drill is attached to a length of steel pipe through which extruded rock is blown by high-velocity helium (2000 cm/sec) and around which are clustered the appropriate gas, water, and electrical leads. The pipe also transmits the force to the drill from several gas-actuated pistons.

Rock samples crack when subjected to local internal heating, allowing the lava to flow through the resulting fissures instead of being extruded by the drill. To avoid this difficulty, specimens are encased in concrete which, in turn, is banded by steel.

At very slow drilling rates the molten rock was extruded as a smooth rod similar to manufactured glass rod, as shown in Fig. 5. When the speed was increased, small irregular pellets, still hot and plastic, also shown in Fig. 5, were carried up the gas gun tube. This operation was nevertheless consistent and well controlled.

Fig. 3 The gas-gap drill. Power is conducted from the tungsten foil heater to the two-inch molybdenum shoe across a thin gap in the helium-filled chamber. The gas gun carries the melt to the surface.

Fig. 4 The gas-gap drill - exploded view.

Fig. 5 Photograph of extrudate. Rod is produced at low drillings rates; pellets, at higher rates in which the lava has failed to congeal.

The depth of the penetration, temperature, and downward force for a run with a device of this type are shown in Fig. 6. The temperature was measured by a thermocouple bearing against the top of the extrusion tube which was 50 - 100 degrees cooler than the foot. The small rapid temperature fluctuations evident in Fig. 6 occurred when the successive pellets were formed and ejected. The large dips in temperature occurred when the smooth downward movement of the drill was momentarily interrupted and flow of the molten rock through the extrusion tube was slowed or stopped. This effect results from adhesion of the outside of the shoe to the side of the hole. When the downward force was increased, the temperature exhibited a small but clearly established decrease. This effect is discussed in later sections.

II C - DESIGNS WITH ENCASED HEATER

A cut-away view of another design is shown in Fig. 7. A tungsten foil heater is embedded between two 0.020-in. plates of boron nitride. The methods provided for removal of the molten rock are those used successfully with the gas gap device. This heater may be operated up to approximately 1850°C, at which point an irreversible change in the heater resistance occurs. X-ray examination has established that W_2B and WB are formed on the heater

Fig. 6. An experiment with the gas-gap drill, February 2, 1961. Note the smooth drilling rate through the basalt sample, corresponding to 18 feet per day.

Fig. 7 Drawing of a two-inch encased heater, using boron nitride insulation.

surface. Figure 8 shows a similar heater with 0.020-in. tungsten wire embedded in spiral grooves. This arrangement allows lower currents to be used for heating.

A different method for removal of the molten rock, extremely simple in concept, was used in the "open bucket" device pictured in Fig. 9. As soon as the drill had penetrated far enough to fill the bucket, it was raised out of the hole, tilted through use of a special hinge which transmitted the required power and cooling water; and the molten rock was emptied into a container beside the hole. This sort of intermittent operation was successfully used for drilling holes in several rock samples (cast, as in other tests, in concrete billets). These experiments confirmed the feasibility of this general approach and provided a rigorous test of the use of boron nitride for electrical insulation at operating temperature and power levels.

Fig. 8 An encased heater of tungsten wire.

Fig. 9 Drawing of an "open bucket" drill.

III. THEORY OF MOLTEN ROCK FLOWING UNDER A HOT FOOT

Fig. 10 The Hydrodynamic Problem

Let a disc of radius a , punched with a hole of radius b , maintained at a high temperature T_1 , be pushed into a rock with a force F with the flows so constrained that the melt flows through the center hole. What is the velocity downward? What are the flow patterns of the melt? What is the pressure distribution in the melt?

It is appropriate to consider the foot to stand still and the rock to move upward toward it with a velocity v^* far from the foot, so that the problem becomes a hydrodynamic one of flow around a hot barrier. The temperature distribution itself tends to die off in the upstream z -direction exponentially as $\exp\left(-\frac{c\rho v^*}{\lambda} z\right)$, with the characteristic decay distance $\frac{\lambda}{c\rho v^*}$ being, say, 0.3 cm for $\lambda = 0.01$ cal/cm-sec deg, $c = 0.3$ cal/gm-deg, $\rho = 2.8$ gm/cm³, $v^* = 0.05$ cm/sec. But the viscosity is so sensitive to the temperature, being of the form $\eta = Ae^{E/RT}$, that within this 0.3 cm it undergoes a change of many orders of magnitude; and its characteristic decay distance in the z direction is reduced by a factor of $\frac{E}{RT_1}$, or about $\frac{1}{40}$ of 0.3 cm, to only 10^{-2} cm, taking $E = 140,000$ cal/mol, and $T_1 = 1700^\circ\text{K}$. Hence the flow occurs within a very thin film-like channel along the foot.

III A - HYDRODYNAMIC THEORY

Accordingly, the hydrodynamic problem is well represented by allowing the viscosity to vary as $\eta = \eta_0 e^{\beta z}$ with η_0 being the viscosity at the foot ($z = 0$) and β being evaluated by

$$\beta = \frac{E}{RT_1} \left(\frac{T_1 - T_0}{T_1} \right) \frac{c\rho v^*}{\lambda} \quad (1)$$

The Navier-Stokes equation for a cylindrical system with varying viscosity, in the presence of only viscous drag and pressure gradients, is given by

$$\frac{2}{r} \frac{\partial}{\partial r} r \eta \frac{\partial u}{\partial r} - 2 \eta \frac{u}{r^2} + \frac{\partial}{\partial z} \eta \left(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} \right) = \frac{\partial p}{\partial r} \quad (2)$$

$$\frac{1}{r} \frac{\partial}{\partial r} r \eta \left(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} \right) + 2 \frac{\partial}{\partial z} \eta \frac{\partial v}{\partial z} = \frac{\partial p}{\partial z} \quad (3)$$

where $v = v_z$, $u = v_r$.

The equation of continuity, $\nabla \cdot \vec{v} = 0$, with the assumption $v = v(z)$ yields $u = -v'(z) \frac{r^2 - a^2}{2r}$ (letting $u(a) = 0$), where primes indicate differentiation.

Equations 2 and 3 then become

$$\frac{\partial p}{\partial r} = -\eta_0 \frac{r^2 - a^2}{2r} \frac{d}{dz} e^{\beta z} v'' \quad (4)$$

$$\frac{\partial p}{\partial z} = 2\eta_0 \beta e^{\beta z} v' + \eta_0 e^{\beta z} v'' \quad (5)$$

Formation of $\frac{\partial^2 p}{\partial r \partial z}$ from these two expressions and equating the results yields a differential equation in $v(z)$

$$\frac{d^2}{dz^2} e^{\beta z} v'' = 0 \quad (6)$$

Integration yields the final results:

$$v = -v^* [1 - e^{-\beta z} (\beta z + 1)] \quad (7)$$

$$u = \beta^2 v^* z e^{-\beta z} \frac{r^2 - a^2}{2r} \quad (8)$$

$$p = -\eta_0 v^* \beta^3 \left[\frac{z^2}{2} + \frac{z}{\beta} + \frac{r^2}{4} - \frac{a^2}{2} \ln r \right] + \text{const} \quad (9)$$

The total force acting upward on the foot is

$$F = \int_b^a p \cdot 2\pi r dr = \frac{\pi}{8} \eta_o v^* \beta^3 [4a^4 \ln \frac{a}{b} - (3a^2 - b^2)(a^2 - b^2)] \quad (10)$$

Dividing this force by the total foot area, $\pi(a^2 - b^2)$, yields an average pressure $\bar{p}$ given by

$$\bar{p} = \eta_o \frac{v^* \beta^3 (a - b)^2}{3} f\left(\frac{a}{b}\right) \quad (11)$$

where

$$f(\xi) = \frac{3}{(\xi - 1)^2} \left[\frac{\xi^4}{2(\xi^2 - 1)} \ln \xi - \frac{1}{8}(3\xi^2 - 1) \right] \quad (12)$$

and

$$\xi = a/b \quad (12A)$$

The function $f(\xi)$ approaches 1 as $b \rightarrow a$, so that a thin ring of width $(a - b)$ is the Cartesian limit. The terms of Eq. 11 which form the coefficient of $f\left(\frac{a}{b}\right)$ are then the result for a uniform one-dimensional Cartesian-strip-type foot. The function $f(\xi)$ is rather slowly varying, containing therein all effects of cylindricity and converging flow. The other terms of Eq. 11 show the required downward pressure, $\bar{p}$, to be proportional to η_o , the viscosity at the foot (which is so highly sensitive to temperature), and to be proportional to v^{*4} (because of the form given in Eq. 1 for β).

The horizontal component of the velocity, u , (Eq. 8) is zero at the foot ($z = 0$) due to non-slippage, and in the solid rock ($z = \infty$); and is maximized

along the line $\beta z = 1$. The radial factors of Eq. 8 express the increase in inward flow as the melt is added to this inward flowing, converging stream.

The magnitude of the vertical component, v , (Eq. 7), monotonically increases from zero at the impenetrable foot, to v^* in the solid rock ($z = \infty$), and is 98% of v^* at $\beta z = 6$.

III B - PRESSURES AND FORCES

For some purposes it is of value to compare the pressure at $z = 0$, $r = a$, to the average pressure $\bar{p}$. This pressure is similar in form to that for $\bar{p}$, namely

$$p(a, 0) = \eta_0 \frac{v^* \beta^3 (a - b)^2}{2} g\left(\frac{a}{b}\right) \quad (13)$$

where

$$g(\xi) = \frac{1}{(\xi - 1)^2} \left[\xi^2 \ln \xi - \frac{\xi^2 - 1}{2} \right] \quad (14)$$

The ratio of $p(a, 0)$ to $\bar{p}$ is thus $\frac{3 g(\xi)}{2 f(\xi)}$. It varies slowly as a function of a/b from 1.5 to 1.0 with increasing ξ .

At this point it is probably appropriate to explain the meaning of these pressures. The terms involving p in the hydrodynamic equations all occur as derivatives of p so that the "zero" of pressure may be arbitrarily chosen.

The preceding expressions have involved the choice $p(b, 0) = 0$; i.e. pressures have been assigned with respect to the extrusion hole in the disc. In practice, the pressure of the melt will drop still lower in passing through the extrusion tube to a pressure p_1 . If a flowing gas or liquid is used for lifting the lava there will be changes in its pressure due to dynamic and viscous effects, and due to its hydrostatic head. Thus, questions pertaining to the meaning of the pressure zero are not trivial.

As an example of the interaction of the forces on the foot, the gas gap heater may be analyzed. For this device the downward forces are the externally applied force, F , and that due to the pressure p_1 operating over the circle of radius a . Opposing these are three upward forces:

- 1) The force due to the integrated pressure of the lava on the sole of the foot, given by $\bar{p} \cdot \pi (a^2 - b^2)$ where $\bar{p}$ is given by Eq. 11, but with p_b added thereto.
- 2) The shearing force along the walls of the extrusion tube, which may be evaluated by the well-known result that such forces are equal in magnitude to the pressure drop across the tube times its cross-sectional area.
- 3) The grabbing force, G , on the outside of the shoe.

If the melt passing through the extrusion tube may be assigned an average viscosity $\bar{\eta}$, then for Poiseuillian flow its pressure drop may be evaluated as

$$p_b - p_1 = 8 \bar{\eta} v^* \ell a^2 / b^4 \quad (14A)$$

The balance of forces may be written as

$$F + p_1 \cdot \pi a^2 = \frac{\eta_o v^* \beta^3 (a - b)^2}{3} f\left(\frac{a}{b}\right) \cdot \pi (a^2 - b^2) + p_b \cdot \pi (a^2 - b^2) + p_b \cdot \pi b^2 + G \quad (14B)$$

which, combined with Eq. 14A, becomes

$$F = G + \frac{\eta_o v^* \beta^3 (a - b)^2}{3} f\left(\frac{a}{b}\right) \cdot \pi (a^2 - b^2) + 8 \bar{\eta} v^* \ell \frac{a^2}{b^4} \cdot \pi a^2 \quad (15)$$

The relation (15) between the downward force F and the viscosities η_o and $\bar{\eta}$ is the mathematical expression that temperature may be squeezed out. An increased F requires an increased η_o and therefore a lowered T_1 (contained in β).

III C - SECOND APPROXIMATIONS AND DISCUSSION

A recapitulation of the analysis thus far is:

- 1) A discussion of the temperature profiles and the resulting viscosity profiles which thereby occur, culminating with the assumed form $\eta = \eta_o e^{\beta z}$ with an equation for β (Eq. 1).
- 2) A rigorous solution of the hydrodynamical problem of flows around the disc-type barrier in such a viscosity field (given by Eqs. 7 - 12A). This solution is new and its simplicity is remarkable.

The assumptions regarding the temperature field may be reexamined at this time for consistency with the hydrodynamical results. The first such assumption is that the temperature is independent of r . The heat flow, $\vec{I}$, due to the convection and conduction processes is given by

$$\vec{I} = c\rho\vec{v}T - \lambda \nabla T ; \quad \nabla \cdot \vec{I} = 0 \quad (16)$$

or

$$c\rho v \frac{\partial T}{\partial z} + c\rho u \frac{\partial T}{\partial r} - \lambda \frac{\partial^2 T}{\partial z^2} - \frac{\lambda}{r} \frac{\partial}{\partial r} r \frac{\partial T}{\partial r} = 0 \quad (17)$$

Of the possible solutions $T(r, z)$ there is a class which is independent of r , satisfying the relation

$$c\rho v \frac{dT}{dz} - \lambda \frac{d^2 T}{dz^2} = 0 \quad (18)$$

TABLE 2 - APPROXIMATE COMPUTATIONS
OF TEMPERATURE DISTRIBUTION

<u>x</u>	<u>Second Approximation</u>	<u>First Approximation</u>
0	1400°C	1400°C
1	1367	1365
2	1334	1332
3	1301	1299
4	1269	1267
5	1238	1236
6	1207	1205
7	1177	1175
8	1148	1146
9	1120	1118
10	1092	1090
> 10	1403e ^{-0.025x}	1400e ^{-0.025x}

Since the hydrodynamic assumption was that $v = v(z)$, the temperature assumption that $T = T(z)$ is indeed consistent.

If the form Eq. 7 for v is inserted into Eq. 18, an integration may be performed to yield the derivative, $T'(z)$, as

$$T'(z) = T'(0) \exp \left\{ - \frac{c\rho v^*}{\lambda\beta} \left[\beta z + e^{-\beta z} (\beta z + 2) - 2 \right] \right\} \quad (19)$$

This expression has been integrated numerically for the values

$$\frac{c\rho v^*}{\lambda\beta} = 0.025 \quad T(0) - T(\infty) = 1400 \text{ degrees}$$

with the results of this second approximation compared with the first approximation, namely

$$T(x) - T(\infty) = 1400 e^{-0.025x}$$

where x is used for βz . It is seen from Table II that the agreement is satisfying.

The solutions given here must be qualified, however. Although the behavior in the region $z \geq 0$ and $b \leq r \leq a$ satisfies the governing equations and the desired boundary conditions, the behavior in other regions is not realistic. In truth, the solution is that for an infinite plane moving down into rock with a sink at its origin and with pressures applied such that the incoming flow splits along the boundary of the cylinder $r = a$ as well as along the plane $z = 0$. The devices which we describe in this paper are accurately

pictured by these solutions only as to the manner of flow of the lava along the sole of the shoe. Other theory must be brought to bear for flow along the outside surface of the shoe, or flow up the extrusion tube.

III D - NUMERICAL DESIGNS

The preceding theory is applied to two examples with the following assumed parameters:

$$\sigma = 2.8 \text{ gm/cm}^3$$

$$c = 0.3 \text{ cal/gm-deg}$$

$$\lambda = 0.005 \text{ cal/cm-sec-deg}$$

$$E \text{ (in the viscosity relationship)} = 140,000 \text{ cal/mol-deg}$$

$$T_1 = 1300^\circ\text{C} = 1573^\circ\text{K}$$

$$T_o = 27^\circ\text{C} = 300^\circ\text{K}$$

$$\eta_o = 100 \text{ poise}$$

$$\beta = 6,050 \text{ v}^* \text{ cm}^{-1} \text{ (Eq. 1)}$$

Equation 10 is used to evaluate the applied force necessary to move the lava along the foot for various velocities v^* . Power is calculated for melting the entire frontal area of the drill face, assuming 1000 cal/cm^3 to be used for this process. As an index of the heat conduction problem within the shoe, the

interior temperature of a 1 cm wall of tungsten with $T_1 = 1300^\circ\text{C}$ and a thermal conductivity of 0.25 cal/cm-sec-deg is also calculated. Compressive stresses are also presented. Roughly, a 5,000-psi stress should be regarded as an upper limit for safe performance.

Example 1: A two-inch drill with a 3/8-in. extrusion hole. These dimensions are those of the gas-gap drill.

$$a = 2.54 \text{ cm}$$

$$b = 0.476 \text{ cm}$$

From Eq. 10

$$F = 1.388 \times 10^{15} v^{*4} \text{ dynes}$$

$$= 13.88 (10^2 v^*)^4 \text{ kg}$$

$$A = 20.27 \text{ cm}^2$$

$$W = 84.73 v^* \text{ kw}$$

$$T_{\text{inside}} = 1300 + 4 \times 10^3 v^*$$

Results are shown in Table 3, page 35.

In the performance of the gas gap drill shown in Fig. 5, the smooth 20-min. operation shows a drilling rate of 0.0067 cm/sec = 18 ft/day. These calculations predict only 6.2-lb. force, about forty times less than observed. However, the shoe temperature of $\sim 1180^\circ\text{C}$ (assuming $100^\circ \Delta T$ along the tube) is seen from Fig. 11 to correspond to as much as 4×10^3 poise viscosity (forty times that assumed) so that the disparity can be so explained. The

Fig. 11 Viscosity of some basalts at different temperatures. From Handbook of Physical Constants, Geol. Soc. of Am., Special Paper No. 36, 1942.

extrusion pressures do not contribute appreciably at the measured temperatures of Fig. 5: The grabbing forces appear to make and break intermittently, and it is not plausible that their contribution would account for the observations.

TABLE 3 - NUMERICAL DESIGN - EXAMPLE I

v^* (cm/sec)	0.005	0.01	0.02	0.03	0.04	0.05
(m/day)	4.1	8.2	16.5	24.7	33.0	41.2
(ft/day)	14	27	54	81	108	135
F (kg)	.9	14	222	1130	3500	8700
(lb)	2	31	490	2500	7900	19100
Stress (psi)	1	10	160	820	2600	6400
Inside temp. (°C)	1320	1340	1380	1420	1460	1500
Power (kw)	0.42	0.85	1.69	2.54	3.39	4.24

It is seen that velocities exceeding 135 ft/day require excessive resulting stresses. Since these forces serve only to transport the lava from the outer regions of the sole to the extrusion hole through a small channel of melt, we may modify this design to that of Example 2:

Example 2: A two-inch drill with a large extrusion hole (1-3/4 in.)

In this case

$$a = 2.54 \text{ cm}$$

$$b = 2.22 \text{ cm}$$

$$F = 3.83 \times 10^{12} v^{*4} \text{ dynes}$$

$$= 0.0383 (10^2 v^*)^4 \text{ kg}$$

Results are shown in Table 4.

TABLE 4 - NUMERICAL DESIGN - EXAMPLE II

v^* (cm/sec)	0.06	0.07	0.08	0.09	0.10	0.12	0.14	0.16
(m/day)	49	58	66	74	82	100	115	132
(ft/day)	162	189	216	243	270	324	378	432
F (lb)	110	200	350	550	840	1740	3200	5500
Stress (psi)	148	270	470	740	1140	2370	4400	7500

IV - DISCUSSION

The principal results of our experiments may be summarized as follows: The common refractory metals exhibit excellent strength and resistance to corrosion at the temperatures needed for rock melting. Molybdenum was used in most of our experiments; tungsten has greater strength and corrosion resistance at these temperatures (see Table 5). Drilling of rocks was demonstrated at a power consumption of 1 kcal/cm^3 and at rates up to 0.02 cm/sec (50 ft/day). The lava was removed in continuous fashion by constraining it to flow into a central orifice and carrying it away in a high-velocity gas stream. The flow of the lava is well described by the theory presented in this report.

Developmental work continuing along these lines should produce a useful and workable drill that is especially adaptable to hard, low melting rocks which present special difficulties with conventional methods. The following experiments are suggested:

Problems of straightforward linear melting without grabbing forces or extrusion can be studied by drilling into a sample upside down, with the melt

simply funneled into a central hole and dripping out. Thereby, very high-power, high-velocity drills could be studied as to their heater interactions and their force-temperature interactions.

Visual study of the flow patterns with some analogy as to temperature distribution, etc., can be obtained by drilling large blocks of clear glass.

Problems of extrusion, cooling of the lava, and its removal may be studied by melting a pot of rock which can be pressurized and which has a tube dipping into it, the upper end of which is the extrusion orifice.

Heater development also seems straightforward. Not only are wires and foil shapes of various materials among the possibilities, but the use of ceramic conductors, such as ZrB_2 , imbedded in ceramic insulators, such as BN, seems interesting.

TABLE 5 - PROPERTIES OF REFRACTORY METALS*

<u>Metal</u>	<u>M. P.</u> <u>°C</u>	<u>Creep</u> <u>Rate</u> ⁽¹⁾ <u>sec⁻¹</u>	<u>Creep</u> <u>Time</u> ⁽²⁾ <u>yrs</u>	<u>Air Corro-</u> <u>sion</u> ⁽³⁾ <u>cm/day</u>	<u>Rock Corro-</u> <u>sion</u> ⁽⁴⁾ <u>cm/day</u>	<u>Time</u> ⁽⁵⁾ <u>days</u>	<u>Hard-</u> <u>ness</u> ⁽⁶⁾ <u>kg/mm²</u>
Mo	2610	1.5×10^{-11}	2.2	10	0.2	0.17	160
W	3410	8.9×10^{-18}	3×10^6	0.7	0.01	2	470
Ir	2442	-	-	0.01	0.0002	150	380
Cr	1875	-	-	0.007	0.0001	200	-
Hf	1975	-	-	0.002	0.00003	500	-
Rh	1960	-	-	0.0001	0.000002	15000	100
Re	3180	-	-	2.4	0.04	0.5	310

(1) At 1300°C, stress = 1000 psi.

(2) Time for 0.1% deformation.

(3) At 1300°C.

(4) Taken as 1/60 of air corrosion rate.

(5) Time for 0.025 cm surface corrosion.

(6) At 1300°C.

* Ref: High Temperature Technology - Stanford Research Institute, 1960
McGraw Hill, Inc., New York