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A Preliminary Study of the Nuclear Subterrene

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LOS ALAMOS, NEW MEXICO 87544

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M. C. Smith, Editor

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FOREWORD

This report is the product of a series of reviews, analyses, and discussions among a small group of Los Alamos Scientific Laboratory (LASL) staff members during the spring, summer, and fall of 1970. The group consisted of individuals from several Laboratory Divisions, and included a broad range of backgrounds, viewpoints, interests, and professional specialties. As the work of this group continued, a consensus appeared concerning the feasibility of developing a Nuclear Subterrene as a rapid, versatile, economical method of deep earth excavation, tunneling, and shaft-sinking. The concept offered the challenge of a major scientific development and the prospect of a significant technological breakthrough. The Nuclear Subterrene was seen to offer potential solutions to many of man's urgent ecological problems, the means of exploiting many of the earth's still untapped natural resources, and the exciting possibility of a practical solution to the emerging crisis in the world's energy supply. Drilling and tunneling by melting the rock was found to be the most promising method of accomplishing these things. It was concluded that the capabilities of high-temperature heat pipes and of small nuclear reactors put the development of a practical rock-melting system--in the form of the Nuclear Subterrene–within the grasp of present technology.

This report presents the outline of a proposed program for development of the Nuclear Subterrene, a summary of the technical background of such a program, several specific program goals, and some speculations concerning applications of the program's products. Several appendixes provide greater detail on some of these subjects.

The ad hoc committee which offers this report acknowledges with gratitude the assistance of several individuals who contributed to its preparation, particularly T. P. Cotter, LASL Group N-5, for technical information on heat pipes and other aspects of the proposed program; the members of LASL Group N-5 for discussions of conceptual designs of compact, fast, nuclear reactors of appropriate sizes compatible with heat pipes; Dr. A. Rosenzweig of the University of New Mexico, a consultant to LASL Group CMF-4 and to this group on rocks, minerals, geology, and geothermal energy reserviors; Dr. J. Weertman of Northwestern University, a consultant to LASL Group CMF-13 and to this group on geophysics in general and the mechanics of creep and fracture of rock in particular; and Richard C. Crook, Chief of the Utilities and Engineering Division of the Zia Company, for information on the geology of the Los Alamos area. Appendix G was prepared by Dr. Orson L. Anderson of Columbia University, a consultant to LASL Group GMX-6, whose enthusiasm and helpfulness are deeply appreciated. Like the committee members who authored this report, these individuals have contributed their time and special knowledge to this study in addition to performing their regular duties for the Laboratory.

A PRELIMINARY STUDY OF THE NUCLEAR SUBTERRENE

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ABSTRACT

The rock-melting drill was invented at Los Alamos Scientific Laboratory in 1960. Electrically heated, laboratory-scale drills were subsequently shown to penetrate igneous rocks at usefully high rates, with moderate power comsumptions. The development of compact nuclear reactors and of heat pipes now makes possible the extension of this technology to much larger melting penetrators, potentially capable of producing holes up to several meters in diameter and several tens of kilometers long or deep.

Development of a rapid, versatile, economical method of boring large, long shafts and tunnels offers solutions to many of man's most urgent ecological, scientific, raw-materials, and energy-supply problems. A melting method appears to be the most promising and flexible means of producing such holes. It is relatively insensitive to the composition, hardness, structure, and temperature of the rock, and offers the possibilities of producing self-supporting, glass-lined holes in almost any formation and (using a technique called lithofracturing) of eliminating the debris-removal problem by forcing molten rock into cracks created in the bore wall.

Large rock-melting penetrators, called Electric Subterrenes or Nuclear Subterrenes according to the energy source used, are discussed in this report, together with problems anticipated in their development. It is concluded that this development is within the grasp of present technology.

Introduction

In a few kilometers immediately beneath its surface, the earth contains most of the raw materials needed by man and offers solutions to many of his most urgent technological and ecological problems. These subterranean resources include natural minerals and hydrocarbons, fresh water, and clean geothermal energy; direct routes for tunnels to transport liquids, fluidized solids, gases, wastes, and man himself; armored and shielded sites for storage and disposal of liquids and gases and for high-temperature, high-pressure manufacturing operations; and rock structures whose experimental investigation will contribute directly to progress in the geological sciences and eventually to control of earthquakes and volcanoes.

Man's exploration and exploitation of these locations and resources have so far been limited principally by the technical and economic difficulties of producing large, long holes in the hard rocks of the earth's crust and mantle. The tools and techniques for drilling, boring, shaft-sinking, tunneling, and mining in rock are highly developed and, in the environments in which they have evolved, are quite efficient. However, their efficiencies decrease rapidly and their costs rise in proportion as they are extended to greater depths, harder rocks, and higher rock temperatures and pressures. Among conventional rock-penetration systems, only the rotary drill appears to be capable of penetrating the earth to depths greater than 4 to 5 km at an economically useful rate, and at such depths it produces holes no larger than about 50 cm in diameter. Even with substantial improvements in materials and techniques, it is unlikely that existing methods can be used to explore or excavate the earth to depths greater than about 12 to 15 km. A new, economical, rapid method of producing larger holes to greater depths is needed.

At the Los Alamos Scientific Laboratory, a device has been developed that bores holes in rocks by progressively melting them instead of chipping, abrading, or spalling them away. The energy requirement for melting rock is relatively high, but it is not prohibitive. (Common igneous rocks melt at about 1200°C and, in being heated from 20°C to just above their melting ranges, they absorb about 4300 joules of energy per cubic centimeter. In comparison, the corresponding figures for metallic aluminum are about 660°C and 2720 J/cm^3, and for steel they are about 1500°C and 8000 J/cm^3. The energy requirement for rotary drilling in most igneous rocks is about 2000 to 3000 J/cm^3.) Even for a penetrator of very large diameter advancing at a high rate, the melting energy can easily be provided by a compact, high-temperature, nuclear reactor, and LASL has pioneered in the development of such reactors. Energy transfer from the reactor to a melting tool at the rates and densities required would probably be impossible except by means of heat pipes, which have also been highly developed at LASL. Combining the three major components--a refractory rock-melting tool, a nuclear reactor, and a system of heat pipes--into a large, rock-melting penetrator called a Nuclear Subterrene would be a natural extension of existing LASL technologies, talents, and scientific interests.

The LASL rock-melting drill has so far been developed only to the stage of a small, functional, electrically heated prototype. Tested in this form, it has been shown to penetrate basalt and other igneous rocks at usefully high rates and with moderate power consumptions. As it advances, the penetrator forces molten rock laterally into voids in the unmelted rock around the bore, and backward around the periphery of the penetrator. The molten rock freezes in these locations, producing an obsidian-like glass lining on the wall of the hole which helps to seal and support it. The lining also forms a seal around the penetrator, tight enough to permit high pressures to be developed in molten rock ahead of it. A technique similar to hydrofracturing may therefore be possible with more rugged designs of the drill. High lithostatic pressure in the melt, developed by the penetrator acting as a piston, would create fissures in the solid rock around the hole and force the molten rock into these fissures. Freezing there, the waste rock would be removed from the hole without being brought to the surface, and one of the major problems of tunneling and deep-hole drilling–debris removal–would be eliminated.

Further development of the rock-melting drill into an operational Nuclear Subterrene, and the necessary research in rock mechanics, creep, and control and guidance systems, will require a large investment of time, manpower, facilities, and money. However, the list of existing and potential applications for rapidly produced, relatively inexpensive, large holes, tunnels, and underground excavations is very long. The immediate rewards alone, particularly from the widespread exploitation of geothermal energy which it would make possible, appear to justify such a development program, and LASL is uniquely competent to undertake it.

Applications

Large-diameter holes in the earth's crust are useful at almost any depth. Near ground level they are used for highway and railroad tunnels and as conduits for fresh water, drainage, and irrigation. At depths of a few meters they are needed for subways, pipelines, and channels for the collection and transportation of wastes. At greater depth they serve as wells for petroleum and water, mine entries and ventilation ducts, and silos for missiles and their control systems. In most cases, such bores and excavations are produced with reasonable efficiency by existing rock-penetration systems. The conventional methods, however, become inefficient when extremely hard rocks, rocks that vary widely in hardness, or high rock temperatures or pressures are encountered. There exists, therefore, a class of boreholes that current drilling and tunneling techniques are not designed to produce. A few of the applications of such holes are considered briefly below and in Appendixes F, G, and H.

Geothermal Energy. Neglecting variations in the chemical and mineralogical compositions of the rocks encountered, the principal changes that occur as a borehole is extended downward from the earth's surface are progressive increases in temperature and pressure of the rocks being penetrated. The geothermal gradient varies widely from place to place, but averages about 20°C/km. From the average density of known igneous rocks, it is assumed that the lithostatic pressure increases with depth at the rate of about 0.3 kbar/km. (One kilobar is a pressure of 1000 bars, or 14,504 psi.)

In many regions of recent volcanic or intrusive activity in the earth's crust, geothermal gradients are as great as 150 to 180°C/km; rock temperatures high enough to produce high-grade steam exist within 2 or 3 km of the surface, where rock pressures are still relatively low. In a few fortunate places, the hot rock is sufficiently fragmented to be accessible to naturally circulating ground water, is overlain by impermeable strata which have prevented rapid cooling by free escape of steam, and is connected to the surface by a small number of natural steam vents. Where this occurs (for example, in Italy, New Zealand, and northern California), conventional power plants have been built to use the steam in generating commercial electricity. Elsewhere, in spite of the fact that these energy reservoirs are sometimes closer to the surface than are the bottom levels of a deep mine, the exploitation of geothermal energy has not so far been undertaken. This is principally because the connected porosity of the igneous rock is low, so that there is no ground-water circulation, and no natural steam is produced. To create a system of holes and cracks in which the required circulation could be established would involve drilling large-diameter holes into the hot, igneous rock and then creating large heat-transfer surfaces at the bottoms of the holes. With existing rock-penetration and fragmentation techniques, each of these steps would involve difficulties so great that no serious attempt has yet been made to develop geothermal energy reserviors of this type. However, as is discussed in Appendix F, these regions are potential sources of vast amounts of energy. If suitable holes could be drilled to enter them, and a sufficiently large heat-transfer surface created within them, their energy could be extracted without contaminating the surface environment except for an amount of waste heat normal for any power plant.

The rate of advance of a rock-melting penetrator should increase with increasing rock temperature, because each increment of thermal energy initially present in the rock would reduce by that same amount the quantity of heat the penetrator would be required to provide. In principle, the maximum ambient temperature at which a Nuclear Subterrene could operate is that at which creep of the rock would close the hole around or behind the penetrator at a significant rate. (Presumably, by cooling the hole, it should be possible to postpone this closure to still higher ambient temperatures.) In practice, with good engineering design and carefully selected component materials, it should eventually be possible to approach this temperature limit quite closely.

Because the normal geothermal gradient is 20°C/km, rocks at temperatures of at least 300°C could be reached by holes about 15 km deep drilled almost anywhere. Although the relatively shallow thermal reserviors considered above will, of course, be the first ones to be exploited, this deeper source of energy is so vast that it is impossible to foresee an energy requirement by man great enough ever to reduce it significantly. When large-diameter holes can be drilled in hot rocks to such depths, and large heat-transfer surfaces can be extended from them, then geothermal energy plants--producing no atmospheric pollution and creating no unusual hazards--can be built wherever energy is required, including sites near the centers of densely populated metropolitan areas. However, at a depth of 15 km, the natural lithostatic pressure is of the order of 5 kbar (75,000 psi). Temperatures there are no higher than in a shallow geothermal reservoir, but pressure and distance from the surface create major new problems. To survive and operate efficiently in this environment, a self-contained Subterrene would require very rugged, highly refractory armor, and would possibly be controlled and guided by telemetry from the surface. Development of such a device is a formidable task, but it does not appear to be beyond the grasp of present technology. It is, in fact, an appropriate goal for the developers of a Nuclear Subterrene.

Transportation. Underground transportation of gases, liquids, fluidized solids, cargo, and passengers is an obvious application of large, long, relatively shallow holes in the earth's crust. Thousands of kilometers of bores and tunnels are produced for these purposes each year in the United States, at a cost of billions of dollars. They are made by conventional boring, tunneling, and trenching methods that are slow, expensive, and normally require that the hole be lined with concrete or steel. Larger, longer, and more numerous holes would certainly be produced and used if they could be made more rapidly and cheaply.

For example, several serious proposals have been made for diversion of fresh water from the great rivers of northern North America to large metropolitan areas and to arid regions of the southwestern United States for domestic and industrial use and for irrigation. Hundreds of kilometers of tunnels would be required for conduits through mountains and for siphons under intersecting drainage systems. A major deterrent to such projects is simply the cost of making and lining these large holes.

Subsea tunnels for railway and vehicular traffic already connect some of the islands of Japan, and others are in the planning and construction stages. Highway and airport congestion, as well as natural topographic and urban obstacles, make it inevitable that more such underground transportation systems will be developed--with large effects on population distribution and city planning. One possibility discussed by Edwards (1965) is that of transporting passengers, mail, and freight through long, horizontal tunnels in vehicles propelled at high velocity by an air stream. Another possibility is the use of curved paths through the earth along which vehicles would travel under gravitational acceleration like pendulum bobs. Such systems could be fast, comfortable, efficient, and economical. They would avoid atmospheric pollution, surface traffic, and right-of-way problems, and preserve the surface landscape from further encroachment by highways and airstrips and their related service establishments. They would, however, require boring of complex systems of large inclined and horizontal or curved tunnels, which cannot yet be produced economically.

Five of the principal problems of producing large, long tunnels by conventional methods are (1) low rates of advance, (2) the difficulty of removing waste rock from the hole, (3) limitations on hole size and shape, (4) the necessity of lining or casing the bore, and (5) damage to the surface landscape and ecology--which is considered objectionable even on the Arctic slope of Alaska. The Nuclear Subterrene is potentially capable of producing large-diameter holes at relatively high rates in any type of rock. With successful application of the lithostatic fracturing technique discussed in Appendix D, the major problem of waste-rock disposal will be eliminated and the surface environment can remain essentially undisturbed. A nuclear reactor can provide the energy required by even an extremely large penetrator and, since the melting tool would not rotate, the penetrator and the hole produced by it could have almost any desired cross-sectional shape.

Finally, if the glass lining produced by the melting penetrator seals and supports the wall of the bore to the degree indicated by early tests, then casings or other linings will not be required even in porous and poorly consolidated formations, thus eliminating a major item of cost and a common cause of delay.

The Nuclear Subterrene may, then, be competitive with existing systems for producing large, long, relatively shallow holes for underground transportation. This might, in fact, be its most widespread application.

Waste Collection and Disposal. The problem of collecting and disposing of the great volumes of domestic and industrial wastes produced by modern civilization is being attacked in a variety of ways, but so far only on a local basis and with limited success. Proposals have been made for elaborate systems of conduits to collect liquid and fluidized-solid wastes from a large region and transport them to a single processing or disposal plant (Thompson and Wasp, 1970). The disposal system might be as simple as the natural filter represented by a porous sandstone overlain by an impervious limestone or shale, with clean water pumped from deep wells a few kilometers downstream for irrigation or other reuse. Alternatively, the underground waste-collection system might discharge to evaporators heated by geothermal energy, whose products would be clean water and a compact, solid residue to be used as fertilizer, land fill, or as a source of fuels, chemicals, and secondary metals.

If indeed a Nuclear Subterrene can produce long, large-diameter, glass-lined holes at high rates, reasonable costs, and under cities as well as in remote regions, then such waste-disposal systems will become possible and a great advance in reducing environmental pollution will have been made. The subsurface geology in large regions of the United States is ideal for filtering and purifying water.

Storage. Preservation as well as disposal is possible in large underground openings, which are naturally shielded and armored by the rock around them. In dense rock or with an impervious lining (which might be simply a glass), such cavities are excellent for large-volume storage. Natural caverns are now used for storage of compressed gases, liquids, and hazardous solids of all kinds, and artificial ones are used for missile sites and control centers. Such uses would multiply if the holes could be produced rapidly and at moderate cost wherever and whenever they were needed.

Nuclear and Thermonuclear Reactors. Development of nuclear reactors as commercial power sources has been handicapped by concern about the possibilities of criticality accidents and the spread of radioactive contamination. Fusion reactors, when they become possible, may be viewed with equal alarm. A solution is to install such energy sources in underground chambers at sufficient depths so that the surface population is fully protected by the intervening rock. The simple act of concealing these power plants would make their public acceptance easier, and this, of course, is also true of installations of many other kinds.

High-Temperature, High-Pressure Processing. Many chemical and physical manufacturing and processing operations involve high temperature, high pressure, and the hazards of overpressure, explosion, toxicity, or radioactivity. Underground bores, or chambers excavated from them, are ideal reaction vessels for such operations.

Desalination. Evaporative processes for producing pure water from brackish wells and from saline inland seas or the oceans themselves are, in general, prohibitively expensive because of their large power requirements. Tunnels such as might be produced by a Nuclear Subterrene could bring impure water in large volume to a shallow geothermal energy reservoir where it would be evaporated and the steam condensed elsewhere, perhaps in cooler tunnels at a higher elevation. In many cases, the dissolved salts extracted from the feed water would have sufficient value so that their recovery would pay a large fraction of the cost of such an operation.

A development that would combine desalination with recovery of geothermal energy has been proposed for the Imperial Valley of California (University Bulletin, 1970). At shallow to moderate depths under this valley exist an estimated one billion acre-feet (about $1.2 \times 10^{12} m^3$) of concentrated brine at temperatures of 600 to 800°F (315 to 425°C). If means can be found to extract the hot brine economically, steam from it could be used to generate electricity and the condensed water could be used for irrigation.

Prospecting, Exploration, and Mining. Every hole in the ground is a prospect hole, and systems of underground bores such as those considered above will inevitably discover new reserves of water, natural gas, petroleum, coal, and ore minerals of every kind. Any liquids or gases encountered could be extracted through the bore hole, which might also be used to introduce and recover the solutions required to leach some types of underground ore bodies in place.

As is discussed in Appendix C, it is not necessary that the Subterrene melt all of the rock through which it passes, or that it force a major fraction of what it melts into cracks in the wall of the hole. Instead, the penetrator can be perforated so that it leaves behind one or a multitude of cores which can be transported to a mill for fine-grinding and recovery of their mineral content. The Subterrene could, then, be used for mining as well as for prospecting and exploration. Since the Subterrene advances by melting the rock, it is conceivable that it might be modified to serve as a concentrating and smelting device as well as a mining machine. If a quiet pool of molten rock were maintained, a separation of immiscible liquid phases would occur because of density differences, and the phase of value (normally the more dense one) could be recovered separately. Thus, separation of a sulfide phase from a silicate phase in the Subterrene would be equivalent to the matte-smelting operation now used to recover copper or nickel.

Underground mines, however developed, require many kilometers of holes of various diameters for entry, haulage, hoisting, drainage, ventilation, and for communications and electrical conduits. The Subterrene may also contribute to conventional mining by producing such holes more rapidly and more economically than is now possible, especially in the very hard rocks in which many deep ore bodies occur.

Scientific Applications. Wherever holes are drilled in previously unexplored rock, geological and geophysical information can be collected from rock samples and from measurements of temperature, gravitational and magnetic fields, sound velocities, radioactivity, etc. The deeper the hole the greater the scientific interest of these observations, and the Nuclear Subterrene has the potential of entering regions of the earth never before penetrated.

As is further discussed in Appendix G, a Subterrene might reach certain regions whose exploration would be of particular interest to the geological sciences. One of these is the Mohorovicic discontinuity, which is detected by seismic methods at depths ranging from about 7 km at some points under the ocean floor to as much as 70 km in some places under the continents. It is usually considered to represent the boundary between the earth's crust and mantle, but there is so far no general agreement concerning its physical nature. This can be determined only by direct investigation.

All current theories of major deformation processes of the earth's crust--including continental drift, mountain building, plate tectonics, and convection--involve large-scale motion of the mantle, and depend on estimates of the properties of the mantle rock. Geologists do not now agree even concerning the type of rock that constitutes the mantle, and only actual sampling of it can provide the information needed to answer this and many other questions. Of particular importance is knowledge of the chemical composition, density, water content, melting temperature, and grain size of mantle rock; the amount of radioactive heating that occurs in it; and such properties as its elastic constants, creep strength, specific heat, thermal conductivity, and electrical resistivity.

Direct measurements of temperature profiles in very deep holes would permit much better estimates to be made of rock temperatures at greater depths than are now possible from heat-flow studies at the surface.

The ability to predict, and perhaps eventually to control, earthquakes (Sylvester, 1970) will require knowledge of the changes with time of stress and strain in seismically active regions within the earth's crust. Such changes at depth cannot be estimated accurately from measurements made at the earth's surface. The depth of focus of a shallow earthquake is typically 10 to 15 km. To monitor the significant changes in stress and strain in a seismically active region will clearly require a net of holes extending to depths of this order. It is possible that extensions of these holes, or lubricating fluids injected from them, might be used to relieve locally the elastic strains which would otherwise accumulate to cause a major earthquake.

Deep tunnels and laboratories excavated from them are ideal sites for research in the geologic sciences, rock mechanics, and high-temperature, high-pressure chemistry and physics.

The list of existing and potential uses for large holes in the earth is almost endless. A multitude of important applications awaits the development of some new, rapid, low-cost means of producing the holes. Any one of these applications, for example, the exploitation of just one of the known, shallow, geothermal energy reservoirs, could justify the large investment of time, effort, and money required to develop a new rock-penetration system. However, except for the Nuclear Subterrene, no candidate system has so far been proposed whose potential appears to justify a development investment of this magnitude.

Existing Rock-Penetration Systems

It is easy to see from the above paragraphs that large holes in the earth's crust would have economic, ecologic, and scientific applications. It is much less easy to make the required holes.

Only two methods are now in common use for producing large underground shafts and tunnels. One is drilling and blasting, which is the traditional technique of mining, shaft-sinking, and tunneling. The other is rotary drilling, which has been highly developed for production of oil and water wells, and in recent years has been extended to "continuous" boring of relatively large shafts and tunnels.

Drilling and Blasting. Traditional mining methods require that men work at or very close to the rock face with drills, explosives, loaders, and conveyors. Both men and equipment must be protected against heat, dust, water, impure air, and falling rock, and must be provided with services, replacements, and transportation. Operations are cyclic, involving successively drilling, blasting, ventilating the hole, barring down loose rock, mucking out, supporting the walls and roof, extending such services as air, water, and power, and then drilling again. Advance rates are typically not more than a few meters a day and are reduced rapidly as rocks become harder, the environment more hazardous, and the working face farther from the portal. The cumulative effect of these increasing difficulties is that, even with very large investments of time and money, the general method of drilling and blasting probably cannot be used to produce holes more than about 5 km deep or about 10 km long. Where geothermal gradients are high, the maximum range is much less than this because elaborate life-support systems become necessary and high temperatures limit the use of conventional explosives and of the common types of mining machinery. However, drilling and blasting represent the only existing method of producing very large shafts and tunnels and of penetrating rock that is very hard or that changes significantly in character along the path of the excavation.

Rotary Drilling. Rotary drills were developed to produce larger, longer, or deeper holes than can be made efficiently by the percussion drills normally used in hard-rock mining, but are smaller than typical mine shafts and tunnels. The small, rotary, coring drill called a "diamond drill" is the standard tool for mineral exploration. Rotary drills equipped with larger bits faced with hardened steel, metal carbides, or diamonds are used to produce relatively deep wells for water, oil, and natural gas. In still larger sizes, rotary equipment is now used to bore mine shafts and ventilation ducts and, equipped with a propulsion system, it has recently become the "continuous" tunnel-boring machine.

In a report (Fenix and Scisson, 1969) prepared for ARPA and the AEC, it was concluded that, with certain significant developments in materials, equipment, and techniques, it would probably be possible to use what is essentially a large oil-field rotary drill rig to reach a depth of 50,000 ft (15.24 km). This is about twice the depth of the deepest hole so far drilled anywhere. It was estimated that the time required to drill the hole under "ideal" conditions would be 4.75 yr, and that the cost would be about $20 million. Most of the hole would be slightly less than 10 in. (25 cm) in diameter, which is representative of current deep-well drilling practice. Apparently, these conclusions represent reasonable extrapolations of the present state of the art of conventional rotary drilling. It is unlikely that much deeper holes than this, or much larger holes to depths approaching 50,000 ft, can be made by rotary drills in the foreseeable future.

Relatively large-diameter holes have been drilled by heavy rotary equipment, but only to limited depths. Probably the largest of these was a 16.5 ft (5 m) diameter mine shaft recently drilled in northwestern New Mexico to a final depth of 784 ft (239 m). This required almost six months to complete, so that the rate of advance averaged about 1.5 m/day (Albuquerque Journal, May 6, 1970). Depths below 1500 m have been reached with smaller-diameter holes. However, the potential of the rotary-drilling method with regard to both depth and diameter of the hole produced is limited by three principal factors:

(1) Power is transmitted to the drill bit by a rotating steel drill pipe extending downward from the surface. Since the weight that can be sustained by a drill bit is limited, most of the drill string must be supported from above. There are obvious limitations on the weight that can be supported in this way, the distance through which rotational energy can be transmitted efficiently, and the diameter and mass that can be rotated against the friction of the hole bottom and wall and of any drilling fluid used.

(2) The rotary bit cuts and chips away the rock at the bottom of the hole and, like any cutting tool, it dulls and must at intervals be removed for sharpening or replacement. The harder and more abrasive the rock and the higher its temperature, the shorter the life of the tool. In hard, hot rock, it is necessary to replace even a diamond bit after no more than a few meters of drilling. Improvements in drill bits are possible and are being actively sought, but no large improvements over existing carbide and diamond tools appear to be imminent.

(3) Bit replacement involves lifting the entire drill string from the hole, uncoupling the successive pipe sections as they reach the surface, changing the bit, and reassembling the pipe as it is lowered back into the hole. In deep holes in hard rock, more time may be devoted to this operation than to drilling between bit changes, and there are limitations on both the diameter and the mass of a drill string that can be handled in this way.

As is further discussed in Appendix A, there are at least two modified types of rotary drills in which the necessity of transmitting rotational energy through a long drill pipe has been avoided. In one of these, a down-hole turbine or electric motor is used to rotate a drill bit at the end of the pipe string. Unfortunately, this change in the rotational drive does not overcome the inherent limitations on hole depth and diameter, rock hardness and temperature, and bit life between changes, to which conventional rotary drills are subject. A second modification of the rotary drill is the "continuous" tunneling machine, which is self-propelled, electrically powered, and designed usually to bore tunnels from about 2 to 10 m diameter. Machines of this type are limited principally by their inability to penetrate very hard rocks, including many of the common igneous rocks (Jacobs and others, in Yardley, 1970).

Novel Drills. Particularly because of the high costs and low rates involved in drilling through very hard rocks with existing rotary drills, a variety of novel rock-penetration devices operating on several different principles have been proposed. Some of these are discussed in Appendix A. Among them, only the jet-piercing drill has so far been a commercial success. This is a spallatlon device in which fuel oil is burned with oxygen at the rock face, heating it and creating thermal stress gradients in the rock to spall successive thin layers from its surface. Unfortunately, most of the common igneous rocks do not spall easily, and the industrial usefulness of this type of drill is apparently limited to a few specific types of rock, such as some of the Minnesota taconites.

No existing rock-penetration system satisfies all the requirements implicit in the above discussions of possible applications to large holes. A method is needed that can produce holes having large cross-sectional areas, preferably of arbitrary shape, of great length or to great depth, in a wide variety of rocks under extreme conditions of temperature and pressure, and at high rates and moderate costs. A rock-melting penetrator is potentially capable of satisfying all these requirements, and in addition produces a melt that can be used to great advantage. The authors of this report are not aware of any other rock-penetration system that has either comparable flexibility or equal possibilities for widespread usefulness.

Development of a Nuclear Subterrene

It is evident that the design, construciton, and initial operation of a Nuclear Subterrene present a broad variety of difficult problems. These can, however, be attacked systematically, and to a large degree in the order of their increasing difficulty.

Laboratory Studies. The history, design, and present status of the LASL rock-melting drill are described in Appendix B. It has so far been demonstrated only as an electrically heated laboratory device that produced holes up to about 5 cm in diameter and 15 cm deep in basalt and concrete, at rates of the order of 1 m/h. In its operation, a hot, cylindrical, refractory metal penetrator was pressed against the bottom of the hole, melting the rock and forcing most of the melt to flow back through an axial opeining in the penetrator. A gas stream just behind the penetrator.was used to cool and fragment the resulting lava, and carry it out of the hole as the fine scoriae shown in Fig. 1. Some of the melted rock near the periphery of the penetrator was back-extruded and froze as an obsidian-like glass that lined the wall of the hole. Energy consumption of the device was not accurately measured, but was generally between two and three times that actually required to heat and melt the rock being penetrated. (Thermal efficiencies should be significantly higher than this in larger units equipped with more efficient heat-transfer systems and designed for reduced heat loss to cooling water and gas. However, direct power cost is actually a minor part of the total cost of any drilling or tunneling operation.)

Because such a penetrator melts rock instead of cutting or chipping it, its working face is subjected primarily to corrosion and erosion rather than to abrasive wear and impact. A molybdenum penetrator operated satisfactorily in the laboratory tests described above, and tungsten or a metal carbide or boride might be more resistant to attack by the flowing lava. However, life tests have not been made, and among the first laboratory investigations required in development of a Subterrene would be those concerned with the service lives of penetrators made from a variety of refractory materials. The intent would be to develop a penetrator capable of continuous operation for weeks or months, so that the problems, delays, and expense of replacing bits or cutters could be eliminated. These experiments would necessarily consider such variables as the type and chemical nature of the rock being penetrated, the viscosity of the melt produced, the effects of variations in flow rate past the penetrator surface, and the importance of environmental pressure. Initially, these tests would be made with electrically heated, laboratory-scale devices on well-characterized rock samples at ambient temperature and pressure. As soon as possible, heat pipes would be incorporated into the test units, both to increase their capabilities and to accumulate experience in the design, fabrication, and operation of heat-pipe systems, and the tests would be extended to elevated rock temperatures and high hydrostatic pressures.

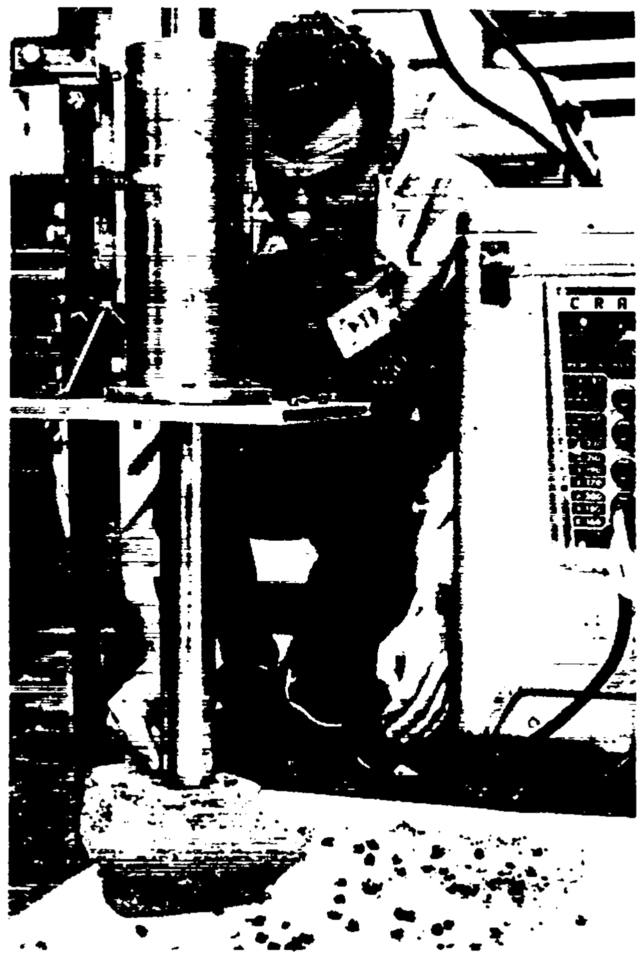


Fig. 1.
An assembled laboratory-scale rock-melting drill, and scoriae ejected from the hole.

In the small holes produced by the laboratory rock-melting drill, the glass that lined the completed hole appeared to be strong, continuous, and impermeable. As is illustrated Fig. 2, it filled the pores and graded into the structure of the surrounding unmelted rock, to which it adhered tightly. Its thickness could be varied by adjusting either the rate of advance of the penetrator or the proportion of heat transferred radially from the penetrator. Direct production of permanently self-supporting, uncased, glass-lined, sealed holes is an attractive possibility offered by the melting penetrator. Methods of controlling the thickness, structure, and continuity of the glass lining must be developed, the properties of glasses produced from a variety of rocks and sediments under realistic drilling conditions must be determined, the importance and effects of accelerated cooling must be investigated, and the degree of support and sealing provided by the glass must be determined experimentally.

Analogy with the freezing method of ground support and with the very successful new technique of *shotcreting* indicates that the glass-lined bore may indeed be pressure-tight and self-supporting even in gravel, weak and broken rock, and water-bearing formations. Roof and wall stabilization in weak, wet, flowing ground by freezing it in place is now common. In shotcreting, a quick-setting cement mixed with a coarse aggregate is sprayed on the wall of the hole to a thickness of a few centimeters as soon as possible after new surface is exposed by drilling or blasting. The peening action of the coarse aggregate particles drives the cement into the cracks and voids and produces a strong bond with the wall. Sufficient strength is developed by this continuous, supporting concrete membrane within a few hours to minimize relaxation and settling of the "protective zone" of rock around the new opening. Permanently self-supporting tunnels can be made even in initially unconsolidated materials. According to

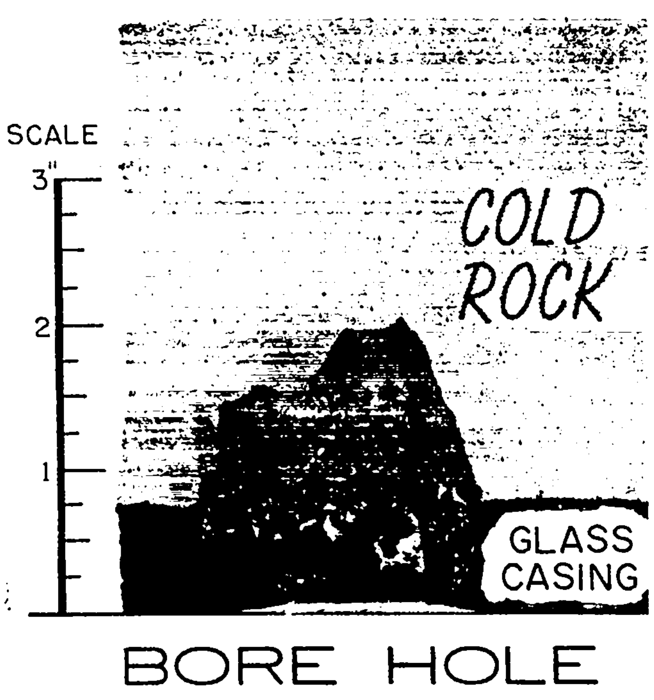


Fig. 2.
Fragment of a relatively thick glass layer produced by a laboratory scale rock-melting device.

Mason (in Yardley, 1970) and others, shotcreting permits sealed tunnels, otherwise unlined and unsupported, to be produced under virtually all conditions encountered in tunneling. Most glasses have compressive strengths at least 10 times that of concrete, and develop them as soon as they are cooled. With the rock-melting penetrator, the glass forms as part of the wall while the bore is being created and before any significant relaxation can occur. It therefore is probable that the glass liner will be even more effective than shotcrete in supporting the opening, and it is produced directly during boring rather than by a separate operation involving transportation of material from the surface to the working face. It is a permanent lining, and should never require maintenance. When drainage into or out of the hole is desired, the glass bore-lining can undoubtedly be perforated by conventional methods.

Hydrofracturing is a technique commonly used in petroleum production to create a crack system in rock adjacent to the bore-hole and so facilitate drainage of crude petroleum from the surrounding rock into the well. It is accomplished by inserting temporary seals in the well above and below the zone to be fractured and using a high-pressure pump to produce hydrostatic pressure in that zone of few tens to a few hundreds of bars above the ambient pressure. The crack system thus created normally extends for several meters in every direction from the wall, the resulting local volume increase being accommodated within a few crack-system diameters by porosity and the elastic distortion of uncracked rock. Carefully sized sand is often injected with the fracturing fluid to prop the cracks open after the hydrostatic pressure that created them has been released. Hydrofracturing has been used successfully in a wide variety of rocks, and in very deep wells. As is discussed in Appendix D, it is probable that a similar fracture system can be created by lithostatic pressure of molten rock compressed by the rock-melting penetrator, acting as a piston, in the cylinder represented by the glass-lined bore. Most of the melt ahead of the penetrator would be injected into these fissures, where it would freeze and remain. There it would hold the cracks open and contribute to both the thickness and the intimate attachment of the glass bore-lining. More importantly, this technique would make it unnecessary to remove waste rock to the surface through the bore previously created, eliminating one of the greatest problems, sources of delay, and expenses of conventional tunneling and deep-hole drilling. The *lithofracturing* technique obviously requires experimental development and demonstration, first in the laboratory and then in the field, under conditions of rock temperature and pressure representative of those existing in deep holes in the earth's crust. Its potential importance in drilling and tunneling is emphasized by the following quotation from Howard (1967): "A boring machine alone, however, will not be enough. Unless the other elements of the process [of tunneling] are improved commensurably, the full potential of this [or any] innovation cannot be realized. . . . currently available underground haulage technology is completely inadequate to provide for disposal of the tremendous amounts of broken rock that would be produced by a truly high speed tunneling machine." Lithofracturing would eliminate this problem.

An incidental advantage of the lithofracturing technique is that the high pressure maintained ahead of the penetrator would tend to suppress dehydration and calcination of the rocks being penetrated, either of which would increase their melting temperatures.

Penetrator life, melting rate, flow characteristics of the melt, integrity of the glass bore-liner, ease and effectiveness of lithofracturing, and resistance of the finished bore to closure by collapse or creep, all depend directly upon the properties and behavior of the rock being penetrated. Unfortunately, very little is known about rocks under the conditions of temperature and pressure that exist deep in the earth's crust. To accumulate the information needed for rational design of advanced versions of the Subterrene, and of the systems of holes they will produce, will require extensive and continuing investigations in the areas of rock characterization, rock properties under extreme conditions, and rock mechanics in general. Among characteristics of rocks to be investigated are their melting temperatures and energies, viscosities, creep and fracture behaviors, the types and degrees of activity induced in them by exposure to the radiation field of a nuclear reactor passing through them, and the degree to which this activity is contained in and retained by the glass bore-liner. (Weight is not a major factor in design of a Nuclear Subterrene, and heat pipes do not lose efficiency if they turn corners to eliminate direct radiation paths out of the reactor. Shielding of the nuclear energy source can therefore be very effective, and it is expected that any added activity induced in the rock will in general be small relative to the level of its natural radioactivity. However, this must be carefully verified.)

A rock-melting penetrator must supply heat to the rock into which it is advancing, transmit pressure to the melt that it creates, control the flow of the melt both radially and axially, maintain its own shape and integrity, and protect the Subterrene components within and behind it. Refractory materials and engineering designs to perform these functions must be investigated, developed, and tested in laboratory studies and in series of scaling-up experiments in the field. For collection of geological and geophysical information, it is important that either the Subterrene or some auxiliary device be capable not only of boring holes but also of producing and extracting cores representative of the rocks being penetrated. This could be done by leaving an opening in the penetrator face through which an unmelted core--protected by a fused coating--would be delivered to a core barrel that could be retrieved and replaced periodically. Coring experiments will be required to develop such a system, and to incorporate it into the appropriate penetrator designs. Investigations will be made of the core diameters and core-handling systems needed to ensure that the recovered core is representative in all respects of the rock being penetrated including moisture content and grain size.

Prototype rock-melting drills and full-scale Subterrenes up to perhaps 2 m in diameter will, in general, use electrical energy provided through trailing cables, which will facilitate maintenance, modification, retrieval, and reuse. However, when transmission of electricity to the unit becomes impractical--in very large, very long, very deep, or very hot holes, or in very remote locations--then a compact nuclear reactor is the obvious choice for an energy source. Design and testing of electrical heaters for Subterrenes of various sizes must begin when the development program is initiated, and work on nuclear heaters must be undertaken as soon as possible thereafter. Both will require intensive materials research as well as sophisticated engineering design.

With either type of heater, transfer of thermal energy from the heat source to the penetrator shell entirely by conduction is impractical because of the very high temperature gradient which would be required to maintain the necessary energy density. Fortunately, heat pipes, discussed in Appendix C, can transmit thermal energy at extremely high density over distances up to several meters and with temperature drops of only a few degrees. A system of heat pipes to perform this function appears to be essential for successful operation of any large rock-melting device. However, rugged versions of the heat pipe, capable of continuous operation at high temperatures and high external pressures for weeks or months, have not yet been built. Their design and testing must also be undertaken as soon as development of the Subterrene is begun.

It is evident that theoretical, laboratory, and field studies in several different areas should begin together as soon as development of a Nuclear Subterrene is seriously undertaken. Many of these investigations must be continued throughout the life of the program to accumulate the further information required to design and use more advanced Subterrenes.

Initial Field Tests. It has already been demonstrated that a melting penetrator can produce holes in rocks at usefully high rates and with moderate energy consumptions. A gasoline-driven, 300-hp generator can produce the electrical energy required to melt a hole 25 cm in diameter through igneous rock at 100 m/day.

It is proposed that, while the laboratory investigations described above are in progress, a truck- or trailer-mounted unit be designed capable of continuously providing the electrical energy required to produce a 25-cm-diam hole at 100 m/day, and also capable of handling several hundred meters of drill pipe and electrical cable into and out of the hole. The required information collected in the laboratory would be incorporated into the design of a penetrator capable of producing a shaft of this size. The penetrator would be assembled at the end of a rigid string of steel drill pipe, suitably instrumented, and tested initially in producing vertical holes in local tuffs and basalts. When it had operated successfully in these formations, it would be tested elsewhere in granites, andesites, sedimentary rocks, unconsolidated gravels, and other formations of interest.

This first Electric Subterrene would be used to investigate a wide variety of problems associated both with the penetrator system and with the formations being penetrated. In particular, it would be used to study penetrator life, penetration rates, force and energy requirements, control and integrity of the glass bore-liner, effectiveness of the lithofracturing technique, and applicability of the melting technique to production of holes through unconsolidated formations, shear zones, water-bearing regions, and other difficult geologic structures. It would also be used to investigate interesting regions in which larger and more advanced Subterrenes might subsequently be tested and used. It is possible that the Electric Subterrene will prove to be economically useful for commercial production of water and oil wells, ventilation shafts, conduits for electricity and gas, etc.

The Type 1 **Nuclear** Subterrene. The degrees to which an electrically heated Subterrene can be extended with regard to hole diameter, hole length and depth, and rock temperature and pressure are limited by its energy requirement and the difficulties of supplying the required amount of electrical energy to it through a trailing cable. A compact nuclear reactor could furnish the energy required by even a very large penetrator advancing at a high rate, and would permit conceptual design of a self-contained unit controlled by telemetry from the surface. However, new problems arise concerning shielding the reactor and possible activation both of other Subterrene components and of the wall of the bore. Because of the intense radioactivity of the fission products accumulated in the reactor section, it may not be desirable to bring a Nuclear Subterrene back to the surface to move it to a new location. If this is the case, it would be used to create only one very long or very deep shaft or tunnel, or one interconnected system of shafts or tunnels, and then be permanently buried at a safe depth by permitting rock collapse to occur around it.

A Type 1 Nuclear Subterrene is visualized as the next development step beyond the electrically heated Subterrene discussed above. It would consist of a nuclear reactor and heat pipes supplying energy to a penetrator 2 m or more in diameter; its detailed design and testing of its components would be in progress during field trials of the Electric Subterrene. Advanced development of the electrical unit would include design and testing of a propulsion system, studies of wall-cooling systems which may be required for continuous operation, and development of control and guidance systems operated by telemetry from the surface. When the capabilities and reliability of the Electric Subterrene had been fully demonstrated, the electrical heater would be replaced by a nuclear reactor, and the first Nuclear Subterrene would be ready for test.

Subterranean telemetry is a new development that has recently been demonstrated by the Sandia Corporation during underground nuclear tests in the Aleutians. Underground telemetry signals were transmitted through dolomite to a receiver 110 m away, from which they were conducted to the surface by cable. Sandia now plans to install an advanced version of a fixed, cylindrical-antenna, underground telemetry system at the Nevada Test Site, using low-frequency rf signals and relay stations. The Russians are also investigating underground radio communication, and they predict ranges of many kilometers under some conditions, with very high signal-to-noise ratios (Dolukhanov, 1970). It is reasonable to expect that subterranean telemetry may be developed sufficiently to control and guide a Nuclear Subterrene from the surface.

Presumably, the initial testing of the Type 1 Nuclear Subterrene would be in relatively cool rocks near the earth's surface, probably continuing a tunnel begun by the Electric Subterrene. The tunnel entry would be open and its interior would be filled with air. A suitably shielded Nuclear Subterrene would therefore be accessible for maintenance, repair, and modification. Air, cooling water, electrical energy, and direct control and guidance could be provided for it. It would be both a demonstration and a research unit to study cost, usefulness, service life, types and degree of radioactivity developed in the tunnel wall, and the extent to which this activity was retained by the glass bore-lining.

A general design concept for the Type 1 Nuclear Subterrene is developed in Appendix C.

The Type 2 **Nuclear** Subterrene. Perhaps the most important potential application of the Subterrene, both economically and ecologically, is in the exploitation of geothermal energy. Shallow geothermal energy reservoirs can probably be penetrated by vertical holes, produced by advanced versions of the Electric Subterrene cooled by fluid circulation from the surface. Deeper and hotter reservoirs and more elaborate development systems involving horizontal as well as vertical holes would require a Nuclear Subterrene capable of continuous, unattended operation for long periods at environmental temperatures of about 500°C. Sophisticated thermal protection would be required for all Subterrene components, and human access would be limited to short visits with elaborate life-support systems.

Development of the Type 2 Nuclear Subterrene from the Type 1 unit would involve principally evolution of control, guidance, and propulsion systems having increased temperature capabilities. The conceptual design of the Type 2 Subterrene is considered in Appendix C.

The Type 3 Nuclear Subterrene. The ultimate goal in development of the Nuclear Subterrene is the production of a device capable of penetrating the earth to depths of tens of kilometers to reach the geothermal reservoir wherever energy is required and to extend geological and geophysical exploration into the earth's mantle. In addition to the high ambient temperature faced by the Type 2 Subterrene, the Type 3 device would encounter extremely high ambient pressure. At 30 km depth, rock pressure is presumed to be about 10 kbar (145,000 psi), and a Subterrene to resist such a pressure without the benefit of coolant supplied from the surface would require sophisticated design and much materials research and development. However, to retard creep closure of the bore in such an environment may require cooling of the glass bore-liner by fluid circulated from the surface. If so, the fluid would also be available to cool certain Subterrene components. The flexibility of a melting penetrator with regard to hole shape, and the possibility of back-extruding a glass curtain to partition off separate channels in an appropriately shaped hole may make it feasible to provide and maintain this circulation without lowering pipe or other types of hole-dividers from the surface.

At least initially, the Type 3 Nuclear Subterrene would probably be designed for one-way vertical travel, and might be propelled downward either by gravity or–to provide the force required for lithofracturing--by hydrostatic pressure from above. It would differ from the Type 2 Subterrene principally in being much more heavily constructed, lacking an internal propulsion system, and requiring a different arrangement for guidance.

The concept of a Type 3 Nuclear Subterrene is also considered in Appendix C.

Summary

Many applications now await the development of some new device capable of producing large, long holes through difficult geological structures at high rates and moderate costs. These uses are of sufficient economic, social, ecologic, and scientific importance to justify establishment and continued support of a major development program such as that outlined above. The magnitude and scope of a program of this nature are such that the work will probably not be attempted by any industrial organization, but could be sponsored by a government agency such as the United States Atomic Energy Commission. Los Alamos Scientific Laboratory has the unique skills to carry out all phases of the program.

Only a rock-melting penetrator appears to have the inherent capability and flexibility required to produce the types of holes now needed and to produce them under the variety of difficult subsurface conditions which obtain when very long or very deep holes are created in the earth's crust. An economically useful rock-melting penetrator, in the form of an Electric Subterrene mounted on rigid drill pipe, can probably be built and demonstrated within about three years after the development program begins. Larger and more flexible Subterrenes, eventually powered by nuclear reactors, would evolve from this. It is believed that within 10 to 15 years a Nuclear Subterrene could be produced which would be capable of penetrating the earth's crust and entering its outer mantle.

In addition to boring devices and demonstration holes of many types, the proposed program would develop useful new knowledge in a wide variety of scientific and technical areas, particularly including the geologic sciences, rock mechanics, and the applications of heat pipes and nuclear reactors.

APPENDIX A

EXISTING AND PROPOSED ROCK-PENETRATION SYSTEMS

The common industrial techniques of drilling and blasting and of rotary drilling were considered at some length in the body of this report, where it was concluded that in many important situations neither can be used efficiently nor economically. The same conclusion has, of course, been stated frequently by others, and the evidence that it is correct is clear: many shafts and tunnels which obviously are urgently needed have not so far been dug or drilled.

In attempts to improve this situation, many proposals have been made for modifications of existing drilling devices and for development of new ones, and some of these proposed devices have been built and tested. An excellent review of the subject is given by Maurer (1968) and some of the same devices are discussed by Ostrovskii (1960); both sources have been drawn on freely in the discussions below.

Augmented Rotary Drills

A number of methods have been proposed for increasing the drilling rates of rotary drills. One of these is the turbine drill, mentioned in the body of this report. In the turbine drill, transmission of energy by rotating the drill pipe is avoided by pumping a fluid down the pipe to drive a turbine at its lower end, and the turbine rotates only the drill bit. This does not avoid the requirements that most of the mass of the drill string be supported from the surface, and that the entire drill string be withdrawn from the hole to change the bit. The turbine drill has not so far been commercially successful in the United States, although it has apparently been used extensively for deep-hole drilling in the USSR. Maurer reports drilling rates only about one-half those of conventional rotary drills, although Ostrovskii indicates that in hard rock the rates may be higher for the turbine drill. Submerged electric motors of special design have also been used by the Russians for down-hole bit rotation. With either device, the limitations on hole depth and diameter and on the temperature and hardness of rock that can be penetrated economically are apparently the same as for the conventional rotary drill. Problems in pumping, power conduction, and turbine and motor maintenance are also introduced.

Several ideas have been offered to improve the performance of conventional rotary drills. One is to build electrodes into the drill bit and maintain an electric arc between them during drilling to heat and degrade the rock so that it can be fragmented more easily by cutters on the bit. Lasers, plasmas, or electron beams could, of course, be used for the same purpose. Such a system is essentially a combination of the rotary drill with a spallation device of the type discussed below.

Small increases in drilling rate have been observed when acoustical waves were transmitted through the rotary bit to crack rocks ahead of it. Several mechanical methods of vibrating the bit have also been tried, including air- and solenoid-actuated pistons striking anvils on the bit, and rotating eccentric weights to give unbalanced vertical forces. These produce low-frequency vibrations that are relatively ineffective in weakening the rock. Higher frequencies in the sonic and supersonic range are more effective, although their action on the rock is primarily through cavitational effects in the drilling fluid rather than by direct mechanical action. Magnetostrictive or electrostrictive devices are used to produce vibration, which is amplified by designing the cutting tool so that it resonates at the frequency of the driver. The power output of a high-frequency device of this type is so small that it has little effect on drilling rate, and its effect would disappear entirely in deep holes where cavitation dies out as a result of high pressure on the drilling fluid.

A relatively recent development is the "continuous" tunneling machine, a large, self-propelled, rotary drill usually used to excavate tunnels for sewage systems, water supplies, subways, railroads, and highways. Such a machine is limited primarily by its inability to penetrate very hard rocks, including many of the common igneous rocks (Jacobs and others, in Yardley, 1970). In softer formations, different types of cutters are required for different types of rocks, and no tunneling machine so far developed has been versatile enough to operate successfully in the different rock types encountered in most very long or very deep holes. Instantaneous rate of advance of this type of machine is about 2 m/h in relatively hard rock to more than 20 m/h in soft rock but, owing to down-time for mucking out, extending services, machine repairs, etc., the average rates in "good ground" are about one-half of these instantaneous values. When rock having compressive strength greater than about 25,000 to 35,000 psi (1760 to 2460 kg/cm^2) is encountered, drilling and blasting are used instead of tunneling machines. Many granites, basalts, dolerites, etc., have compressive strengths in the range 40,000 to 70,000 psi (2810 to 4920 kg/cm^2), and cannot successfully be penetrated by existing machines of this type.

The continuous tunneling machine uses electric motors geared directly to the rotating cutting tool, and so avoids the difficulties of transmitting power through a long drill pipe. However, there are inherent limitations on the machine itself. Thus, the hole in which it operates must be large enough to accommodate electric motors, a massive drive system, and equipment for handling cuttings, and to permit human access for changing cutters. Holes under about 2.5 m diameter are inconvenient to make, and under about 1.7 m diameter they are essentially impossible. An upper limit of diameter has not yet been established for machines of this type, but is probably about 10 m. Since rotating cutters are used, hole sections are necessarily circular or some combination of circles.

Much of the technology of the continuous rotary tunneling machine is directly transferrable to a self-propelled Subterrene. It is possible that the first Subterrene for horizontal boring would be a commercial tunneling machine in which the rotary drilling head was replaced by a melting penetrator, with provision for additional cooling of machine components and of the tunnel wall. The laser systems developed for precise guidance of rotary machines will also be useful for the first Subterrenes, although they will probably be replaced eventually by subterranean telemetry or by self-contained, preprogrammed guidance systems.

For continuous tunneling in hard rock, drilling rates can be increased by shattering the rock ahead of the machine by explosive charges detonated in pilot holes. This combination of mining and boring techniques requires that pilot holes be produced by a separate drilling system, that conventional explosives be handled, with the usual delays for loading the holes, blasting, and ventilating, and that the tunneling machine be protected by heavy blast shields. It appears to be primarily an emergency method to be used when a tunneling machine encounters rock too hard for it to penetrate at a useful rate in its normal operating mode.

No technique so far proposed for increasing the capabilities of rotary drills appears to be generally useful for overcoming their inherent limitations with regard to hole size, hole length or depth, and the types, temperatures, and pressures of the formations in which they can operate efficiently.

Spallation Drills

Rocks generally are relatively poor conductors of heat, so that high temperature gradients are created in them when their surfaces are exposed to high-intensity heat sources. Differential thermal expansion creates high stresses just below the heated surfaces, and these are augmented by variations in thermal expansion among mineral species composing the rock, by vaporization of water, by phase changes in quartz grains, etc. In some rocks, the stresses cause successive thin layers to spall from the surface. However, many types of rock–including most of the common igneous rocks–are resistant to spalling.

The jet-piercing drill, a spallation device described in the body of this report, has been commercially successful in drilling certain taconites, which are very hard and thus difficult to penetrate with conventional drills. The jet-piercing drill uses an oxygen-fuel oil flame to heat the rock surfaces. Other heat sources have also been tried, including other types of flames, electric currents, superheated steam, high-frequency electric and magnetic fields, and microwaves.

Although the spallation drill is useful in rock that spalls easily, its usefulness is definitely limited to such rock, and therefore to a few rather special drilling situations.

Erosion Drills

High-pressure water jets can drill most rocks, including very hard ones, without the use of solid abrasives in the jet. Very high power outputs and correspondingly high drilling rates appear possible with them, and their performance can be improved by pulsing the jet. However, power requirements are high; large-capacity, high-pressure pumps must be developed for them; and nozzle erosion may limit the time that the drill can operate at the bottom of the hole. According to Ostrovskii, certain kinds of rock (such as some types of shale) cannot be cut with water jets. Wall and roof support will be major problems in poorly consolidated formations, and performance of such drills at high rock temperatures has not been investigated. In spite of these limitations, it appears that–at least for most kinds of coherent rock at relatively low temperatures–the water-jet drill is potentially useful. Its probable usefulness for producing shallow tunnels to contain underground utility services in urban areas is now being investigated at Oak Ridge National Laboratory. Preliminary results from laboratory tests at ORNL (McClain and Cristy, 1970) are very encouraging.

Low-speed abrasive jets in which sand or other abrasive particles are projected against the rock by a relatively low-velocity stream of water or air have also been investigated. A large-scale experimental device of this type, the "pellet drill," used steel balls as the abrasive. In such devices energy transfer to the abrasive particles is inefficient, drilling rates are low, and no known drill operating on this principle is being further developed.

Continuous Penetrators

A device has been proposed which consists of a massive conical penetrator that is forced through the rock, crushing material ahead of it and displacing this material into a zone of crushed rock surrounding the hole. Maurer concludes that the force required to drive the penetrator would be excessive, limiting its usefulness to weak, highly porous rock or unconsolidated material. A device of this type in the form of the "compacting auger," which looks and acts like a wood screw, is already in commercial use to produce holes for underground power lines through soil. The concept of such a device is related to that of a lithofracturing penetrator discussed in Appendix D. However, in the absence of a molten phase, the continuous penetrator will be effective only in poorly consolidated formations.

Explosive Drills

Several types of explosive drills have been developed and thoroughly tested in the USSR. In general, the liquid components of an explosive mixture are mixed either within a capsule as it passes through a nozzle just above the bottom of the hole or in the space just below such a nozzle, and are then detonated in that space. Small explosive charges are used, fired at intervals of from a few hundredths of a second to about 1 sec. Penetration rates are high except in soft or plastic rocks. However, costs are also high, and supplying the explosive from the surface and timing the explosions at the bottom of a deep hole are difficult. Flushing cuttings from the bottom of the hole is a major problem, and high rock temperatures would introduce new problems related both to stability of the explosive components and to increased plasticity of the rock being penetrated.

Chemical Drills

Fluorine and other reactive chemicals, injected in a gas stream from a pressurized capsule lowered into the hole, have been used in the laboratory to drill holes in a variety of sedimentary and igneous rocks. Because of high costs and the difficulties of handling large volumes of very reactive chemicals, the technique appears to have little promise for large-scale drilling. However, the introduction of less active chemicals to soften rock in advance of a conventional drill may be useful in some cases, and very hot water under high pressure may be effective for this purpose, as is discussed in Appendix E.

Melting Drills

Both Maurer and Ostrovskii comment on the use of the rock-melting technique to produce holes in the earth. Maurer feels that the energy requirement of a melting device is so high that its drilling rate will necessarily be low. He notes that such a device is versatile in that it can create holes in any type of rock, and predicts that its first application will be in drilling strong rocks, in which conventional drill bits are dulled rapidly. Ostrovskii concludes that fusion and even vaporization of rocks may be expedient in penetrating deep-lying rocks, where high rock and hydrostatic pressures and plasticity of the rock make drilling extremely difficult by any known mechanical means. He notes that fusion and vaporization processes are independent of the physical and mechanical properties of the rock, which change markedly with depth, and indicates that the walls of the drilled hole can indeed be strengthened during drilling by melting the rock.

APPENDIX B

INITIAL DEVELOPMENT OF THE LASL ROCK-MELTING DRILL

The feasibility of rock melting as a drilling method was first explored at LASL in 1960-1962, culminating in a final report (Armstrong *et al.*, 1965) and issuance of U.S. Patent No. 3,357,505 covering the general method. This preliminary study was made by a few LASL staff members on a part-time basis, and used no specialized equipment. (For example, a small commercial welding transformer supplied the electrical current.) Experiments were performed on chance rocks found locally, and the largest holes made were about 5 cm diam and 15 cm deep. Feasibility of the technique was demonstrated and interest was aroused. During 1956-1966, after the final report of the work was published, about 150 letters of inquiry were received concerning the method, the Laboratory was visited by several industrial groups and by a military delegation, and serious consideration was given to use of the device as a lunar drill for the Apollo flight series. Because of other commitments of the group in which the rock-melting drill was invented, its further development was not pursued at LASL, and so far as is known it has not been undertaken elsewhere.

The crucial result of the initial LASL experiments was that the relatively simple devices built and tested bored holes at steady, usefully high rates through samples of local basalts and other igneous rocks, without serious corrosion or deformation of the drills. Power requirements were two to three times that theoretically required to melt basalt. (This is considered moderate in view of the small sizes of the drills, the relatively inefficient heat-transfer systems used in them, and the large volumes of cooling water and gas circulated through them.) One experimental difficulty was that the rock samples usually cracked during drilling, as is illustrated in Fig. B-1. To minimize cracking, the samples were embedded in concrete, which was banded with a corrugated steel shell. In development of the Subterrene, it is proposed instead to supplement the thermal stresses by mechanical means to create cracks in which most of the melt can be deposited. This is discussed in Appendix D.

Fig. B-1.
Cracks in a basalt boulder, produced by penetration with a rock-melting drill.

Two of the electrically heated devices tested are shown in Figs. B-2 and B-3, and some of the holes drilled are shown in Fig. B-4. In the device shown in Fig. B-5, subjected only to preliminary testing, the electric heater was encased in boron nitride, which, when properly oriented, is both a good conductor of heat and a good electrical insulator. This permitted solid, rugged construction.

The essential design problem with early versions of the rock-melting penetrator was soon reduced to development of techniques for removing the lava. In the 1-in.-diam drill shown in Fig. B-2, the melt was back-extruded through an axial tube in which its temperature was reduced about 100°C, so that it left the tube as a hot glass rod that could be handled mechanically. In later devices, a high-velocity gas stream was used to fragment and cool the back-extruded lava and propel it up a tube as small, irregular pellets. An "open bucket" device was also tested successfully, with periodic removal of the drill and of a reservoir built into it when the latter had been filled with molten rock. In the Subterrene, it is proposed to eliminate the problem of removing rock from the hole by using the lithofracturing technique discussed in Appendix D.

Unavoidably, in the operation of a melting device, some rock is melted at the edges of the penetrator and is extruded back around it or forced into voids in adjacent unmelted rock. As is suggested by the photograph of Fig.

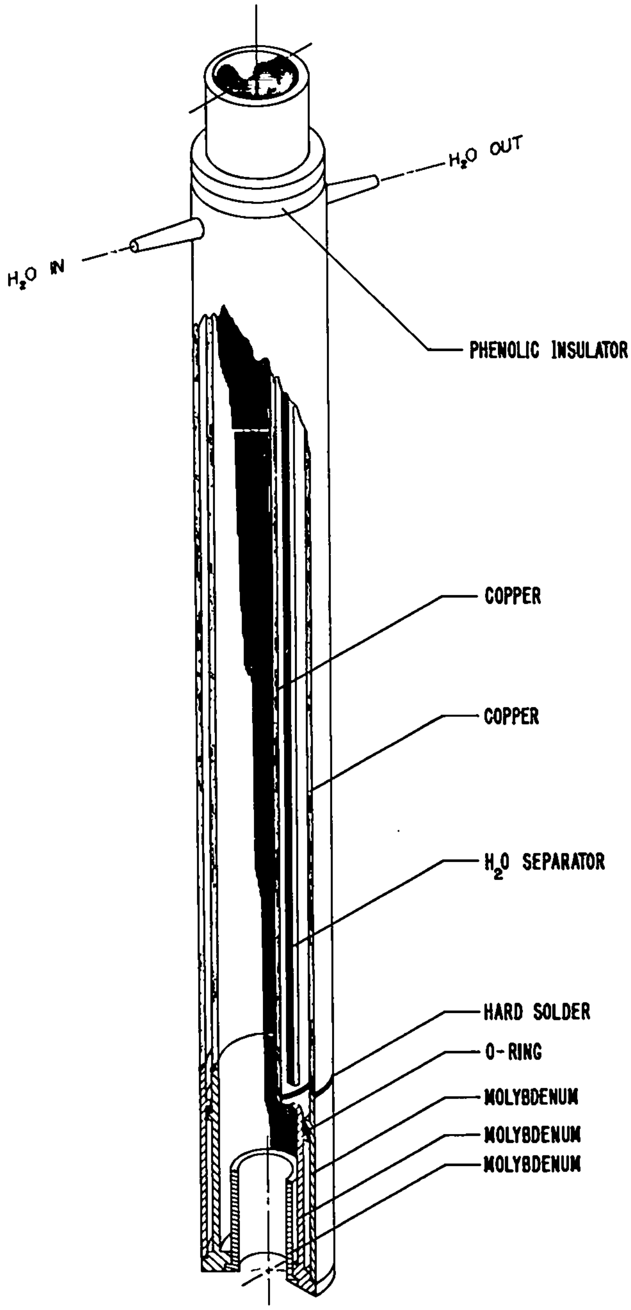


Fig. B-2.
An early drilling device, the 1-in.-diam drill. The water-cooled, double-walled copper stem conducts a large electrical current (100 A) to the reentrant molybdenum wall that serves as the heater. The 3/8-in.-diam extrusion tube is heated by conduction from the foot, and is designed to reduce the melt temperature approximately 100°C for extrusion as a glass-like rod. In operation, the drill penetrated to its full depth of about 8 in. (From Armstrong et al., 1965).

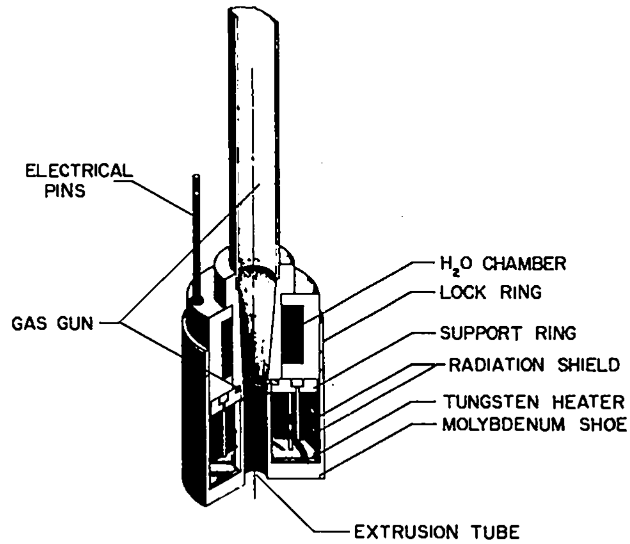


Fig. B-3.
The gas-gap drill. Heat is conducted from the tungsten-foil heater to the 2-in.-diam molybdenum melting-shoe across a narrow gap in the helium-filled chamber. The gas gun propels the melt to the surface. (From Armstrong et al., 1965.)

B-4, this fraction of the lava freezes as an obsidian-like glass liner on the wall of the bore. The lining grades into and is firmly attached to solid rock around the hole. It is expected to be effective in sealing and supporting the bore. Experience with laboratory-scale devices indicates that the thickness of the glass liner can be increased either by reducing the rate of advance of the penetrator or by increasing the proportion of heat that flows radially from it instead of axially into rock ahead of it. Lithofracturing is expected to increase both the thickness of the glass liner and the intimacy of its attachment to the surrounding rock.

Several concepts developed in this experimental work, concerned largely with the flow of molten rock ahead of the penetrator, can be applied to design and performance of a Subterrene. They were based on the following model.

It is convenient to consider that the penetrator stands still and the rock moves toward it, so that the problem becomes one of hydrodynamic flow around a hot barrier. Velocity of the rock far from the penetrator is v^*. Rock temperature decreases exponentially with distance, z, from the drill face, as $\exp(-c\rho v^* z/\lambda)$. For a typical basalt, $\lambda = 0.01$ cal/cm-sec-°C, $c = 0.3$ cal/g-°C, $\rho = 2.8$ g/cm^3, $v^* = 0.05$ cm/sec, and the characteristic decay distance of temperature, $\lambda/c\rho v^*$, is 0.3 cm. Rock viscosity varies with temperature as $\exp(E/RT)$ so that, for $E = 140$ kcal/mole and $T_1 = 1700$°K, the characteristic decay distance for viscosity, E/RT, is about 1/40 of that for temperature, or about 0.01 cm. Within 0.3 cm of

Fig. B-4.
Two laboratory-scale rock-melting drills, and samples of the holes, glass, and scoriae produced by them.

the penetrator face, then, rock viscosity increases by many orders of magnitude. Flow of the molten rock therefore occurs within a very thin, film-like channel along the face of the penetrator.

The hydrodynamic problem is well represented by regarding the viscosity to vary as

$$\eta = \eta_0 e^{\beta z} \quad ,$$

where η_0 is viscosity at the penetrator face ($z = 0$) and

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

The Navier-Stokes equation for incompressible materials is represented in cylindrical coordinates by

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

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

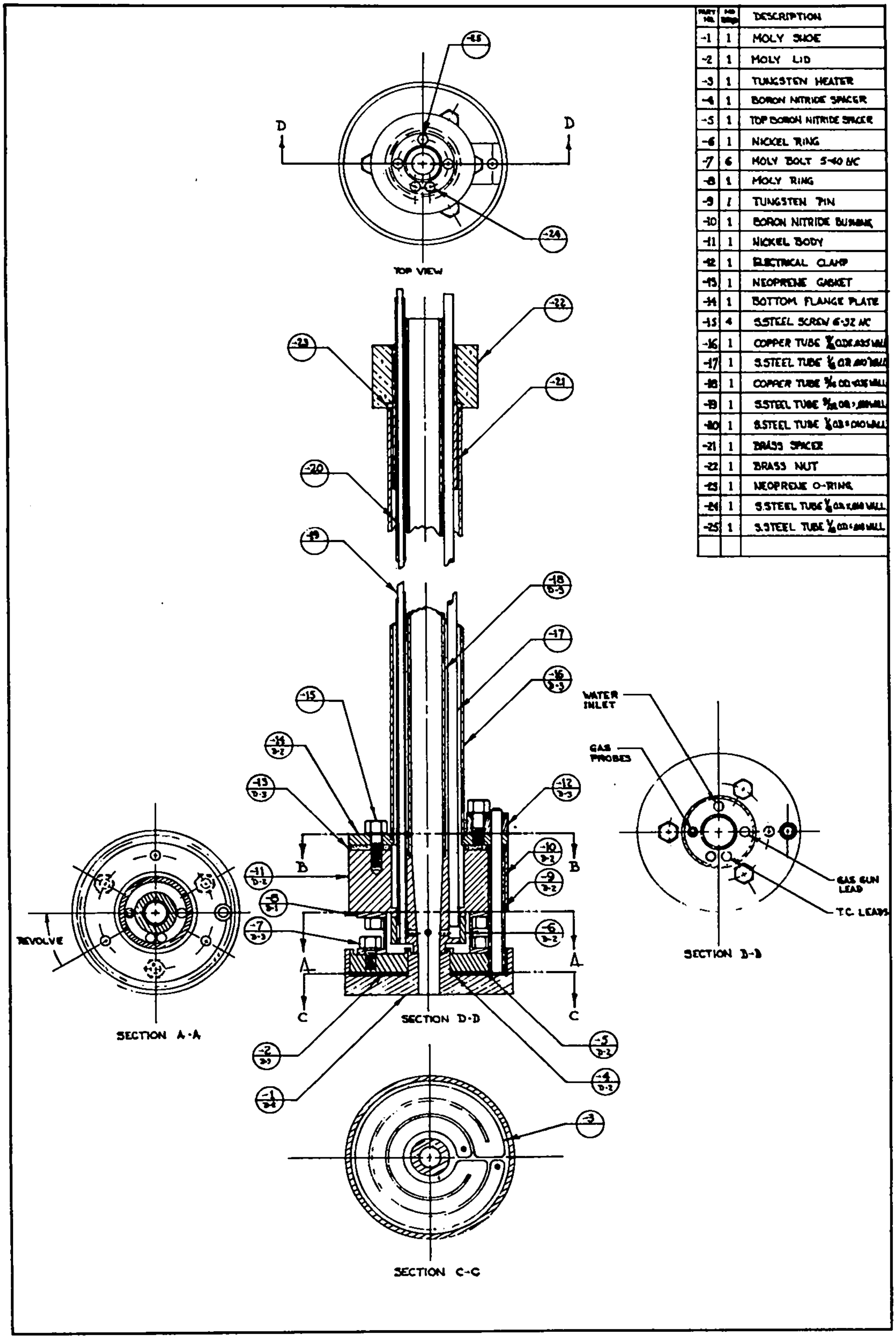
Together with the equation of continuity, $\nabla \cdot v = 0$, this system was solved exactly (in Armstrong *et al.*, 1965) with the assumption that $v = v(z)$, yielding the solution

$$v = -v^* \left[1 - e^{-\beta z}(\beta z + 1)\right] \quad , \qquad \text{(B-4)}$$

$$u = \beta^2 v^* z e^{-\beta z}\left(\frac{r^2 - a^2}{2r}\right) \quad , \qquad \text{(B-5)}$$

$$p = -\eta_0 v^* \beta^3 \left[\frac{z^2}{2} + \frac{z}{\beta} + \frac{r^2}{4} - \frac{a^2}{2}\ln r\right] + \text{const.} \qquad \text{(B-6)}$$

The horizontal component of the velocity, u, in Fig. B-6, is zero both at the penetrator face ($z = 0$), due to nonslippage, and in the solid rock ($z = \infty$), and reaches a maximum at $z = 1/\beta$. The "channel flow" properties of this thin layer are as though a fluid with uniform viscosity, η_0, were flowing through a channel of width $\sqrt[3]{12}(1/\beta) = 2.29\,(1/\beta)$.



PART NO.	NO. REQ.	DESCRIPTION
-1	1	MOLY SHOE
-2	1	MOLY LID
-3	1	TUNGSTEN HEATER
-4	1	BORON NITRIDE SPACER
-5	1	TOP BORON NITRIDE SPACER
-6	1	NICKEL RING
-7	6	MOLY BOLT 5-40 NC
-8	1	MOLY RING
-9	1	TUNGSTEN PIN
-10	1	BORON NITRIDE BUSHING
-11	1	NICKEL BODY
-12	1	ELECTRICAL CLAMP
-13	1	NEOPRENE GASKET
-14	1	BOTTOM FLANGE PLATE
-15	4	S.STEEL SCREW 6-32 NC
-16	1	COPPER TUBE [illegible]
-17	1	S.STEEL TUBE [illegible]
-18	1	COPPER TUBE [illegible]
-19	1	S.STEEL TUBE [illegible]
-20	1	S.STEEL TUBE [illegible]
-21	1	BRASS SPACER
-22	1	BRASS NUT
-23	1	NEOPRENE O-RING
-24	1	S.STEEL TUBE [illegible]
-25	1	S.STEEL TUBE [illegible]

Fig. B-5.
A 2-in.-diam encased heater using boron nitride insulation. (From Armstrong et al., 1965.)

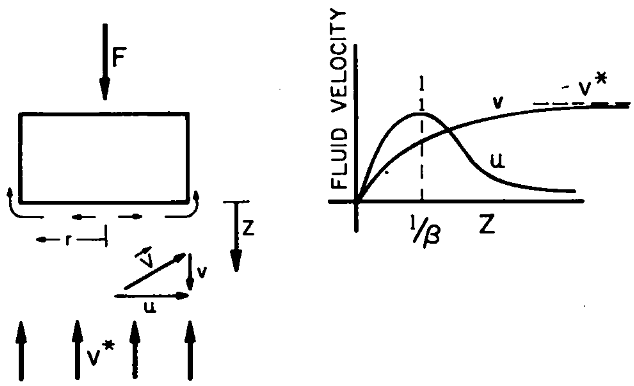


Fig. B-6.
The horizontal component, u, and the vertical component, v, of fluid-flow velocity as functions of distance, z, from the penetrator face.

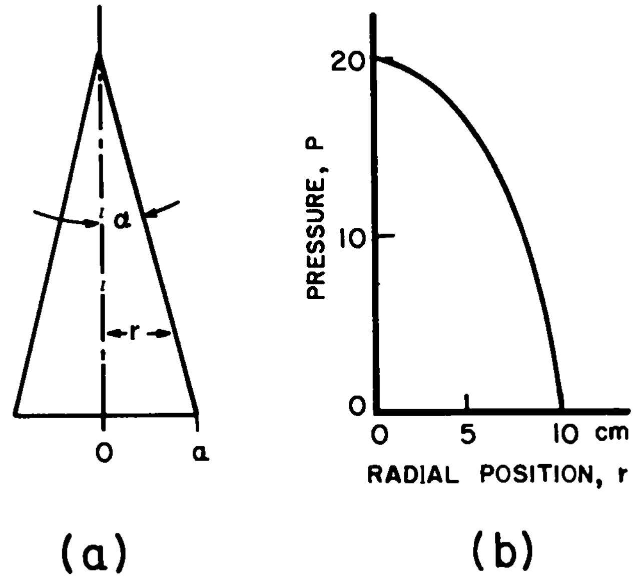


Fig. B-7.
(a) A simple conical penetrator. (b) The pressure distribution along the surface of the penetrating cone.

Another result of this development is an expression for the total applied force, in which $F \propto \eta_0 v^* \beta^3$ [as in Eq. (B-6)]. Since β is itself proportional to v*, F increases as the fourth power of the velocity, v*, unless the penetrator temperature is raised to decrease η_0. Hence, the final conclusion of the early theory was that, as higher penetration rates were sought, the device should be constructed to apply very large pressures to the rock, which requires strong, rugged construction.

Much of the above development can be adapted to the devices considered in this report, for example to a cone-shaped penetrator doing only melting of the rock (with no cracking), toward which the earth moves with velocity v*. In such a case, the temperature distribution projected onto a horizontal plane is the same as that for a cylindrical penetrator, but the heat flux from the surface is reduced by $\sin\alpha$, and the channel width, $1/\beta$, is increased, i.e., $\beta = \beta_0 \sin\alpha$, where β_0 is given by Eq. (B-1). The flow lines in rock far ahead of the penetrator are almost parallel to its path, and near the penetrator they represent fanning radial flow nearly parallel to its conical surface. The pressure gradient in lava flowing along the surface of the penetrator is reduced by the factor $\sin^3\alpha$. These factors become very significant for a sharp cone in which, for example, $\sin\alpha \sim 10^{-1}$.

For the pressure distribution along the surface of a conical penetrator, illustrated in Fig. B-7, the above development gives an expression of the form

$$P = p(a) + 1/4\ [\eta_0 \beta_0^{\,3} v^* \sin^2\alpha\,(\alpha^2 - r^2)]\ . \qquad \text{(B-7)}$$

This is the equation of a parabola whose apex coincides with that of the cone (r = 0). For a small drill with typical values

$a = 10$ cm,

$\eta_0 = 10^2$ g/cm-sec,

$v^* = 0.1$ cm/sec (~ 86 m/d),

$\beta_0 = 2000\ v^* = 200\ \text{cm}^{-1}$

$\sin\alpha = 0.1$,

it follows that the pressure drop along the surface of the penetrator is only 20 bar. If, however, the same values are applied to a Subterrene with radius of 1 m (a = 100), the pressure at the apex of the penetrator is 2 kbar above that at its shoulder. In this case the solid rock adjacent to the apex would certainly fracture, the flow of liquid melt would no longer be along the surface from point to shoulder, and the above analysis breaks down. This situation is considered in Appendix D.

APPENDIX C

NUCLEAR SUBTERRENE CONCEPTS, DESIGNS, AND PROBLEMS

To this time, only laboratory-scale rock-melting devices have been operated, and it is obviously hazardous to predict what directions development may take in leading to an operating Nuclear Subterrene and its eventual applications. However, data obtained in the original rock-melting experiments were sufficiently detailed and convincing that quite long extrapolations from them can be made confidently. To provide perspective concerning the nature, scope, magnitude, and difficulty of the development program here considered, these projections are attempted in the sections that follow, although necessarily in general terms. Major areas requiring development, environmental constraints, conceptual designs, and potential material problems are outlined, and probable program directions are indicated.

Heat Pipes

In the early rock-melting experiments described in Appendix B, a major limitation on performance of the devices tested was that of delivering a sufficiently large heat flux to the melting face of the penetrator. With the development of the heat pipe, this problem has been solved. Heat-pipe technology is now sufficiently advanced so that it is evident that heat pipes can indeed transport energy from a compact source to an extended melting surface at rates high enough for a melting device to penetrate rock at a usefully high rate.

The components and operating principles of a heat pipe have been discussed by Kemme (1969, A and B) and are illustrated in Fig. C-1. Essentially, a heat pipe is an elongated, gastight cavity that contains a suitable liquid and its vapor. In a Subterrene, the evaporator end of the heat pipe would be located within the heat source, whether electrical or nuclear, and the condenser section would be at or near the rock-melting surface. The heat-pipe cavity is lined with a "wick," which is a capillary structure commonly built up from multiple layers of woven-wire screen, and occupying perhaps one-third of the cross section of the cavity. The wick is constantly saturated with the working liquid, which, by capillary action, is continuously returned from the condenser section to the evaporator. There it is continuously evaporated, so that the interior space of the heat pipe is kept filled with vapor diffusing toward the slightly cooler condenser. At the condenser, it deposits its heat of vaporization and is returned as a liquid by the wick to be recycled.

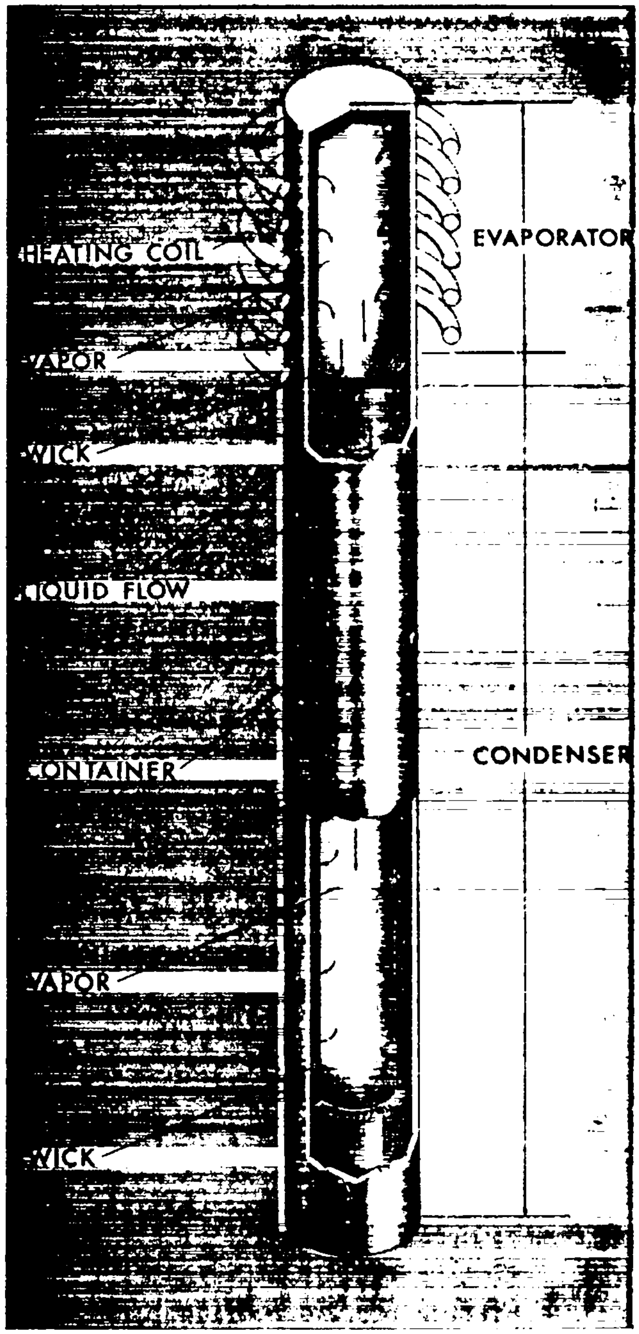


Fig. C-1.
Heat pipe invented by G. M. Grover at Los Alamos Scientific Laboratory.

The unique advantage of the heat pipe is its ability to maintain extremely large heat fluxes while only very small temperature differences exist between its hot and cold ends. This is to be contrasted with the large temperature gradients (hundreds of degrees per centimeter) required to transfer heat at similar rates through a thermal conductor. When the penetrator face must be maintained at, say, 1500°K (1227°C) for weeks or months, and the heat source is many centimeters from this face, it is apparent that a heat pipe is the only practical method of energy transfer that will avoid overheating of the reactor.

For an operating temperature in the range 1400 to 1800°K (1127 to 1527°C), the heat-pipe container would be a gastight refractory metal tube or shell. The appropriate working fluid would be lithium, which is apparently the best of all known heat-pipe fluids (Kemme, 1966; Busse *et al.*, 1968). Lithium heat pipes made of Nb-1% Zr alloys have been operated at temperatures up to 1600°K (1327°C) for several thousand hours; others made of TZM molybdenum alloy have been operated for similar periods up to 1700°K (1427°C); and still others made of Ta-10% W alloy have been operated for short periods up to 2100°K (1827°C). A heat-pipe lifetime of at least one year can apparently be anticipated at the temperature levels required for operation of a Subterrene.

At 1400 °K the vapor pressure of lithium is 0.2 bar, and at 1800°K it is 3 bar. The heat-pipe container will evidently receive little internal support from the working vapor, and so must itself be designed to support any large external pressure to which it is exposed. No working fluid is known whose vapor pressure at these temperatures is appreciable relative to an environmental pressure of, say, 10 kbar. If one were available, the opposite problem would exist--that of containing the fluid during the period when the external pressure was increasing from 1 bar to 10 kbar.

If the energy source is above the penetrator face, the working fluid must be transported up the wick, against gravity, by capillary action. This limits the vertical dimension of the heat pipe which, with lithium and a reasonable capillary pore size, cannot exceed about 1 m. However, as suggested by Fig. C-2, as many 1-m heat pipes can be used in series as may be required, so that this does not limit the vertical length of the heat-pipe system. The figure also indicates another peculiarity of heat-pipe design: the heat-pipe cavity must be so constructed that the vapor within it has an appreciable velocity parallel to the surface on which it is required to condense and deposit energy. This is because, in manufacture, such cavities cannot be purged completely of noncondensable gases. These gases are swept by the working vapor to the end of the condenser, where they form a blanket having very low thermal conductance. This, however, does not interfere with heat transfer to the sides of the condenser section.

A tunneling speed of 100 m/day would require a heat flux about of 500 W/cm^2 delivered to the melting surface of the penetrator. At 1400°K, a lithium heat pipe can readily transport 10 kW/cm^2 of vapor-passage cross-sectional area, and at 1800°K its capacity should increase by a factor of more than five. Thus, each square centimeter of vapor passage can supply heat to at least 20 cm^2 of penetrator surface, and the penetrator can easily accommodate the heat pipes required.

At heat fluxes above about 250 W/cm^2 across the liquid-vapor interface in the evaporator region, ebullition occurs in the wick and unacceptable hot spots are formed. However, since the side wall as well as the end of the cavity is available for heat transfer, a surface area 40 or more times the cross-sectional area of the vapor passage can easily be provided in the evaporator, even within a very compact heat source.

In principle, there is no reason why a heat flux of at least 500 W/cm^2 should not be attainable in the condenser section of a heat pipe. Experimentally, the largest condensation heat flux so far verified is about 30 W/cm^2, more than an order of magnitude less than is required at the melting face to achieve a desirable penetration velocity. Undoubtedly this can be improved, but experiments with large cooling fluxes have not yet been performed.

Electrical and Nuclear Heaters

Much of the early development of rock-melting devices will be done using electrical heaters. The design and construction of such heaters, whether resistive or inductive, is straightforward, and no major problems are expected in making them compatible with the heat-pipe system. However, fast nuclear reactors will be required for the more ambitious types of Subterrenes, and conceptual design studies and materials research for such reactors should begin very early in the development program.

The basic technology of a heavily armored, shielded, insulated, fast reactor of the type required for a Nuclear Subterrene appears to have been established. The necessary high-temperature fuels have been studied extensively in the SNAP-50 program, where a similar reactor technology is required. Criticality studies for reactors whose cores are about 40 vol% heat pipes have indicated that for 100 kW to 10 MW thermal power outputs the required core sizes would be roughly from 18 cm diam and 25 cm long to 1 m diam and 1 m long. (To these dimensions must be added the requirements for nuclear shielding, thermal insulation, and protective armor.) A schematic cross section of a typical reactor core of this type is shown in Fig. C-3. This core concept was devised for a heat supply for use in space (Salmi and Grover, 1970). It appears that conventional reactor-poison control systems can be used with such designs. However, in Subterrene applications, particular attention must be given to provisions for inserting large amounts of shutdown poison. Since neither size nor mass is a stringent restraint, the problems of radiation shielding appear to be minimal.

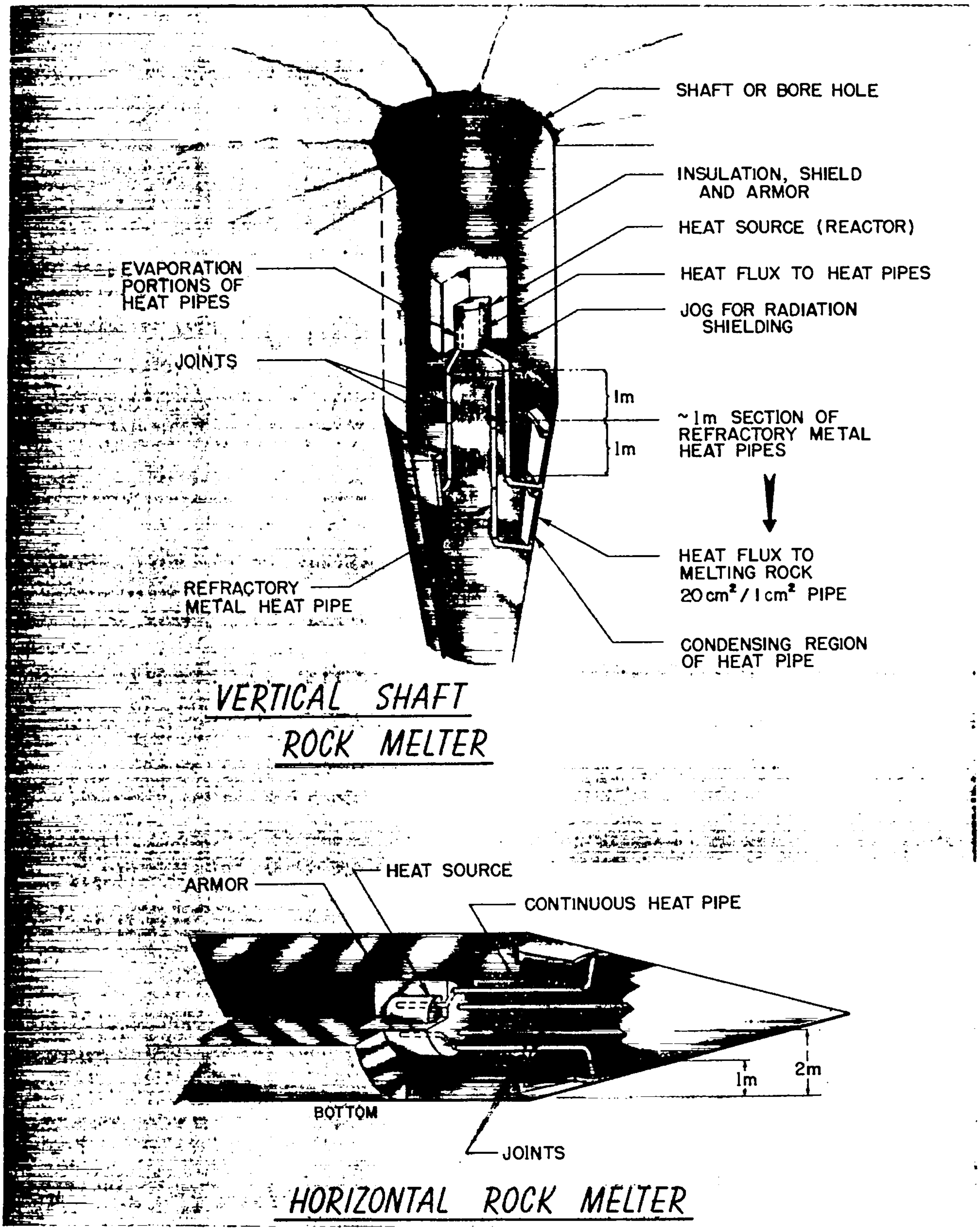


Fig. C-2.
Schematic diagrams of heat-pipe systems installed in two types of rock-melting penetrators.

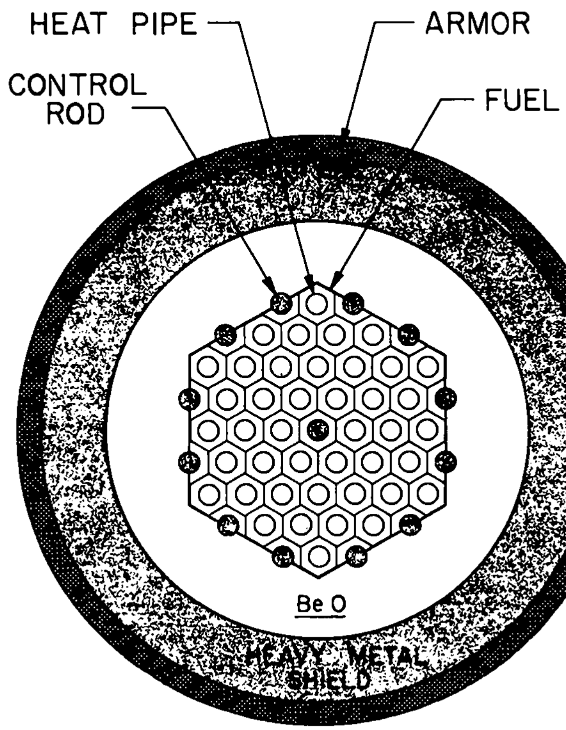


Fig. C-3.
Schematic cross section of a typical reactor core for use in a Nuclear Subterrene.

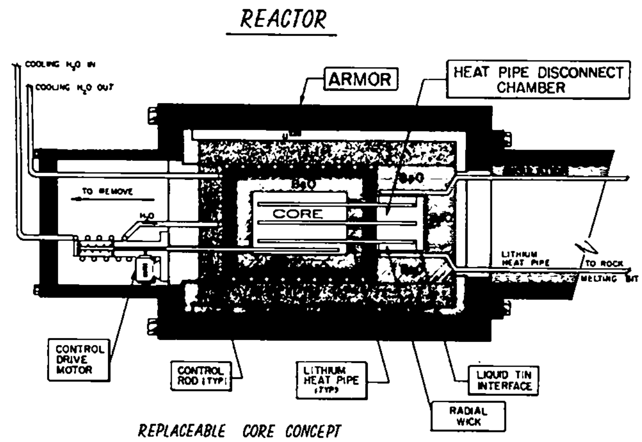


Fig. C-4.
Schematic diagram of a heat-pipe reactor incorporating the concept of a replaceable core.

A reactor installation concept for a Nuclear Subterrene is sketched in Fig. C-4, which also illustrates a scheme that could allow reactor replacement.

Initial Field-Test Unit

Concurrently with the laboratory experiments discussed in the body of this report, design and construction of a relatively ambitious mobile shaft-melter should be undertaken. Such a unit is sketched in Fig. C-5. It might well be based on a commercial truck-mounted drill rig large enough to handle several hundred meters of drill pipe into and out of the hole. The commercial unit would be modified by omitting the drill-rotation system, adding a generator to supply electrical energy to the melting penetrator, providing a mechanical- or fluid-pressure system to exert a controlled downward force on the drill stem, and providing circulating water and compressed air to cool vulnerable parts of the down-hole equipment and bore wall and, if necessary, to eject scoriae from the hole. As design information was collected in the laboratory it would be incorporated into the design of an electrically heated penetrator to be mounted at the end of the rigid drill string. When the mobile unit had been completed and fully instrumented, it would be used in the field to produce vertical holes in a variety of *in situ* rock formations and sediments. It would be used for hardware

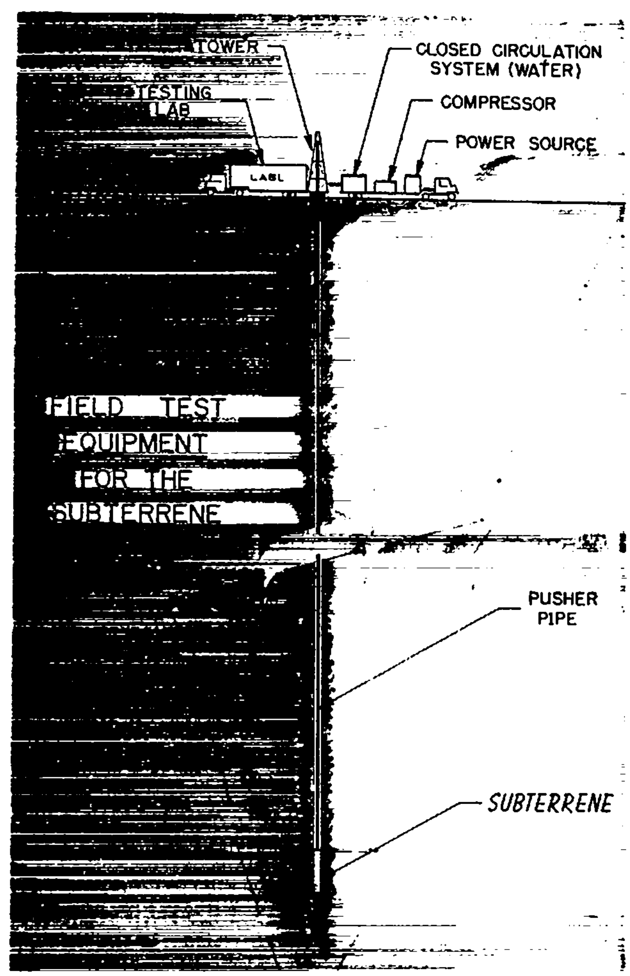


Fig. C-5.
The initial electrically heated field-test unit.

development and demonstration and for determinations of pressure and power requirements, penetration rates, the feasibility of the lithofracturing technique, the production of uncased holes in unconsolidated ground, the difficulties experienced in wet or porous ground, etc.

There are reasons to believe that an Electric Subterrene of this general type may eventually be useful commercially for producing vertical holes for such applications as recovery of oil, gas, water, or steam, and inclined or horizontal holes for ventilation, sewage disposal, and conduits for utilities. Whether such applications materialize or not, the information collected from this first field-test unit will be essential for rational design of the more ambitious Subterrenes discussed below.

Subterrene Development

The development of Subterrene technology beyond its initial stages may take any of several directions, depending largely on the results of laboratory tests and experience with the field-test unit discussed above. However, based on the function and environment of the tunnel or shaft to be bored, it is possible to divide the program into three successive phases. These represent increasing degrees of difficulty in design, material selection, construction, and control, and of temperature and pressure of the rock to be penetrated. Although each will evolve into the next, three specific types of Subterrenes can be identified corresponding to these phases, and representing successive stages in developing a self-contained Nuclear Subterrene finally capable of producing large holes in and beneath the earth's crust. These three types are:

Type 1. A tunneling Subterrene for production of open tunnels in rock at low temperatures and pressures. Initially this would be electrically powered, and subsequently powered by a nuclear reactor. It would produce large, long tunnels in rocks at temperatures no greater than about 200°C, depths no greater than about 3 km, and pressures no greater than about 1 kbar.

Type 2. A hot-tunnel Subterrene. This would be a nuclear-powered unit designed to bore large, long tunnels at depths and pressures similar to those encountered by the Type 1 Subterrene, but at rock temperatures up to about 500°C.

Type 3. The deep-probe Nuclear Subterrene. This is visualized as a nuclear-powered device, ultimately self-contained, that could operate at very high rock temperatures and pressures. It would be designed to bore to depths greater than 3 km, and eventually of 30 km or more.

These three types of Subterrenes are discussed individually in the sections that follow. Many variations of them are possible, for example, a Type 1 Subterrene to bore large-diameter vertical shafts to limited depths.

Type 1 Subterrene

Tunnels intended for such applications as transportation, water supply, and sewage disposal will deliberately avoid the higher-temperature regions of the earth's crust. The Type 1 Subterrene is intended to produce such tunnels as well as to provide the basis for developing the design features required for more difficult rock-melting tasks and environments.

If the temperature of the rock to be entered is 200°C or less and the geothermal gradient is normal (20°C/km), the Type 1 Subterrene will operate at depths no greater than about 10 km and therefore at rock pressures no greater than about 3 kbar. The relatively shallow and cool tunnels produced will be filled with air. With ventilation systems of the kind usually provided for tunneling operations, they can be entered by men unencumbered by special life-support systems, so that the Subterrene will be accessible for maintenance, repair, modification, and direct control and guidance. Auxiliary electrical power, cooling water, and compressed air can be brought directly to it.

The major components of the Type 1 Subterrene will be:

1. The rock-melting penetrator, operating at a surface temperature of perhaps 1150°C.

2. An electrical heat source, subsequently replaced by a nuclear reactor, operating at about 1500°C.

3. Heat pipes to transport thermal energy from the heat source to the penetrator.

4. A prime mover and thruster to advance the Subterrene against the rock face.

5. A control, guidance, and service module.

6. At least initially, a materials-handling system to remove rock debris. Feasibility of the lithofracturing technique, demonstrated early in the campaign of the mobile field-test unit, would allow this feature of the Type 1 Subterrene to be eliminated.

A design concept for a Subterrene intended to produce a tunnel about 7 m in diameter is shown in Fig. C-6. (No attempt has been made to show detailed component designs, and the configurations shown are intended primarily to indicate problem areas and to suggest general design solutions.) In this case, the unit is not intended to accomplish lithofracturing, but rather is designed for minimum energy consumption and maximum recovery of the rock being penetrated. To maintain

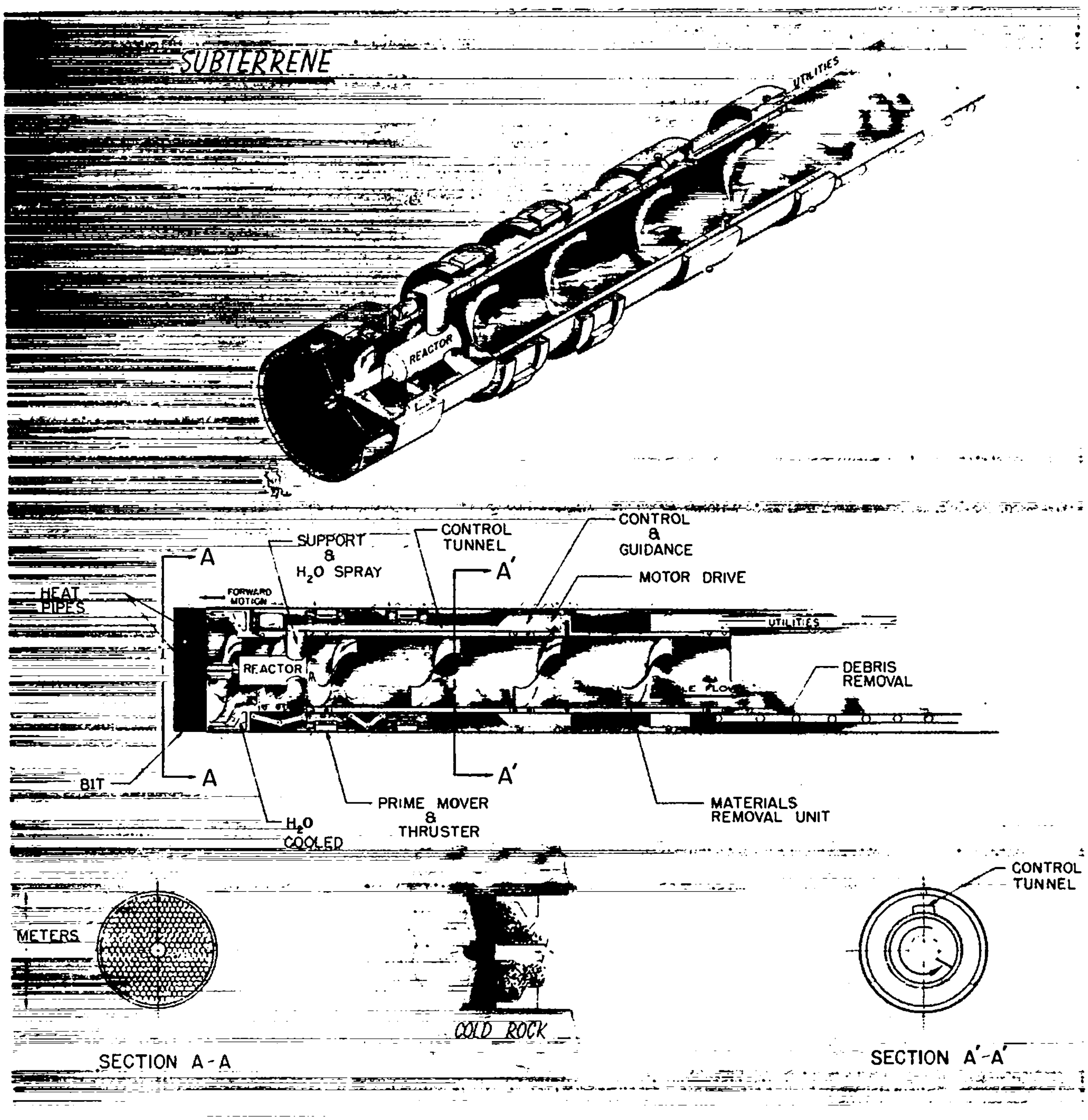


Fig. C-6.
Design concept of a Type 1 Nuclear Subterrene equipped for continuous debris removal.

the rigidity required of the penetrator, its honeycomb structure must occupy about 20 to 25% of the cross-sectional area of the tunnel, so that about this fraction of the rock must be melted. Some of the melt will be back-extruded around the periphery of the penetrator and will glass-line the tunnel. However, most of it will flow backward through openings in the penetrator structure as glass coatings on unmelted cores that would represent about 75 to 80% of the rock. To facilitate handling, these cores must be broken into short lengths which, in the figure, is accomplished by a core-breaker constituting the forward end of a helical conveyor. (A simpler solution may be to design kinks or bends into the pass-through channels of the penetrator.)

The nuclear heat source for such a reactor would be required to produce about 50 MW of power and to operate continuously at about 1500°C. It would be constructed of a refractory metal (perhaps tungsten or Nb-1% Zr alloy), heavily armored, shielded with thick reflectors-insulators (perhaps of BeO), and cooled by refractory metal heat pipes with lithium as the working fluid. To reduce radiation-streaming, the heat pipes would be brought through the shield and armor in optically blocked paths, and the external radiation level should be very low.

The thruster sketched in Fig. C-6 is similar to some used in existing rotary boring devices. It incorporates a double-compression lock-on to the tunnel walls and a hydraulic forward thruster required in this case to provide controllable force of about 7×10^6 kg (15.4×10^6 lb). A sequential lock-unlock action produces continuous forward motion with essentially uninterrupted thrust. (It may be possible to purchase a commercial tunneling machine, without the boring head and rotary drive, to serve as a body for this type of Subterrene.)

Debris removal in the Subterrene of Fig. C-6 is accomplished by a breaker-pickup at the penetrator end, feeding a helix inside a tube (an internal stoker). A relatively slow rotation of the helix can move broken rock at a high rate relative to the velocity of the Subterrene. The tube containing the helix can therefore be small relative to the Subterrene diameter to sweep the debris past the reactor and other structures. With a materials handling system of this type, it may be necessary to provide a water spray to cool the mixed rock. Thus, if 25% of the rock is melted at 1200°C and this is mixed with the other 75% at 200°C, the mean temperature of the mixed rock will still be above 500°C. To cool the mass of rock removed from a 7-m-diam tunnel to 200°C will require a water flow of about 400 liters/min (120 gal/min). An ingenious idea is needed to recapture the waste thermal energy of the melted rock and make it usable in the Subterrene.

The least well-defined component of this unit is the service module, which must provide control, guidance, services, surveillance, power, etc. Conceivably, the module could be occupied by a human operator if a modest life-support system were provided.

Table C-I lists some significant parameters for this Type 1 Subterrene. Obviously, it is a very ambitious tunneling machine, and it is both larger and more complex than would be attempted early in the program. Once perfected, however, it would have broad usefulness and would be an ideal test vehicle for solving the problems associated with the Type 2 Subterrenes.

Type 2 Subterrene

The most exciting possibility of a rock-melting penetrator is its potential ability to bore into rocks at temperatures of the order of 500°C. Indeed, the melting operation itself will become easier as the rocks being penetrated become hotter, because their initial temperatures will be closer to their melting ranges. High temperature, however, introduces difficulties that affect the configuration and design details of the Nuclear Subterrene. In particular, (1) access to the Subterrene will be strictly limited, and either robots or complex, insulated, life-support systems will be required; (2) only minimal communication to the surface and service umbilicals from it will be possible; and (3) all rock removed from the working face will be very hot, and its handling and removal will be exceedingly difficult.

Conceptually, at least, lithofracturing--discussed in Appendix D--offers an attractive solution to the materials handling problem. This technique will probably require a pointed or wedge-shaped bit, with very high pressures imposed on its sloping surfaces by a thruster. The pressure levels required are of the order of the rock overburden pressures which, for tunneling situations of the type anticipated for the Type 2 Subterrene, are up to about 700 bar (10,000 psi). The structural problems of such a penetrator are formidable, but they appear to be solvable. If the rate of forward advance, cone angle of the penetrator, and crack-propagation and fracture characteristics of the rock are favorable, it appears probable that all rock melted in making the tunnel can be forced into the fractured rock surrounding the tunnel. If so, the problem of debris removal will have been solved, and a significant breakthrough in tunneling and boring will have been accomplished.

Design details of a Type 2 Subterrene are necessarily more speculative than are those presented above for a Type 1 unit. Figure C-7 presents a conceptual design of a Type 2 Subterrene equipped for lithofracturing. No debris-handling machinery is required, but the prime mover, thruster, and penetrator must be substantial structures, and much of the hardware must operate uncooled at temperatures of about 500°C. Control and guidance systems must be self-contained and remotely controlled, and telemetered communications will be essential.

Data are given in Table C-II for a Type 2 Nuclear Subterrene of this general design capable of producing a tunnel 2 m in diameter in hot rock at an advance rate of

TABLE C-I

SUMMARY OF DATA FOR A TYPE 1 SUBTERRENE EXCAVATING A TUNNEL OF ~ 7 m DIAMETER AND PROGRESSING AT A RATE OF 100 m/day

Quantity	Approximate Magnitude
Maximum Depth	< 3 km
Maximum Rock Temperature	< 200°C
Total Rock Mass Flow	~ 10×10^6 kg/day (4.0×10^3 m^3/day) ≡ 10,000 tons/day
Power Required to Melt 25% of Rock	~ 50 MW
Velocity of Subterrene	100 m/day ≡ 12 ft/hr
Force Required on Melting Bit	~ 7×10^6 kg ≡ 15.4×10^6 lb ≡ 8000 tons
Heat Flux Required at Bit Surface	~ 500 W/cm^2
Rock-Cooling Water Flow Required to Cool Rock Mass to ~ 200°C	2 gal/sec ≡ 14 lb/sec ≡ 7 kg/sec

100 m/day. Its application might be in continuing an access tunnel produced by a Type 1 Subterrene to the periphery of a shallow geothermal energy reservoir. After the Type 1 device had been withdrawn, or had followed a circular path back to the original tunnel, the self-contained Type 2 device would be advanced to the rock face and, on command, would extend the tunnel into the high-temperature region. After the hot tunnel had been completed and the Type 2 Subterrene withdrawn, it might be necessary to increase the heat-transfer surface by hydrofracturing, using high-pressure water. If so, hydrofracturing would be greatly facilitiated by the presence of fracture zones already created by lithofracturing.

Type 3 Subterrene

Ultimately, a rock-melting Subterrene should be possible that can probe very deeply into, and perhaps beneath, the earth's crust to develop geothermal energy in regions where geothermal gradients are normal, and to extend direct geologic and geophysical exploration to the upper mantle under the continents. Beneath the Colorado Plateau, the Mohorovicic discontinuity is at the anomalously shallow depth of about 30 km, which is a natural goal for penetration by the Type 3 Nuclear Subterrene.

At a depth of 30 km, the normal geothermal gradient (20°C/km) would result in rock temperatures of about 600°C, and the overburden pressure would be nearly 10 kbar (about 145,000 psi). Design details of a Subterrene to operate under such extreme conditions are necessarily even less definite than are those for Type 1 and Type 2 Subterrenes. It may be necessary to abandon the concept of a mechanical thruster as the prime mover and to provide the thrust required for lithofracturing either by fluid pressure controlled from the surface or by the weight of a drill stem above the penetrator. A fluid circulation system may be needed to cool the glass lining the hole so that, even at great depth, it can resist closure by creep of the surrounding rock. A fluid-flow system for recovering rock samples may therefore be needed.

Figure C-8 is a schematic of a Type 3 Subterrene, design and guidance for which would be based on data from the truck-mounted field-test unit and the Type 2 Subterrene. Mechanical structures, control, and guidance will all be major engineering problems. The unit illustrated has a sharp taper of about 10 to 1 to facilitate lithofracturing. Thrust is provided by a nonrotating pipe string combined with a fluid-pressure scheme. A down-hole pump is used to provide coolant out-flow through a porous metal wall on the cylindrical section behind the penetrator to chill the glass lining of the shaft. Provision for continuous geophysical sampling could probably be made by leaving a flow-through opening in the penetrator and adding a core extractor. However, to allow access for experiments, it may be desirable to design the Type 3 unit so that the heater system can be withdrawn from the penetrator shell, while fluid pressure is maintained to support the wall of the hole.

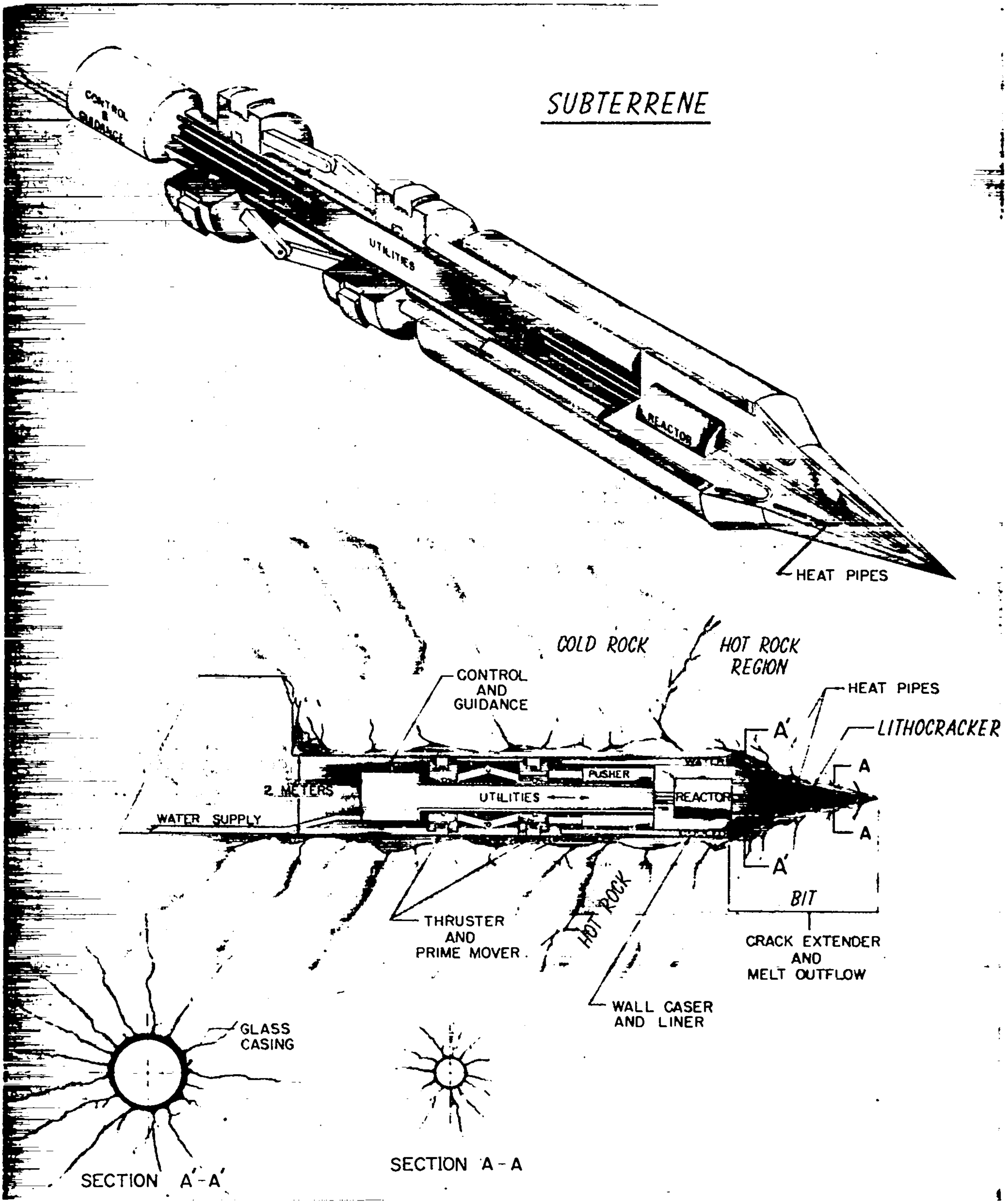


Fig. C-7.
Design concept of a Type 2 Nuclear Subterrene intended for tunneling in hot rock and equipped for lithofracturing.

TABLE C-II

SUMMARY OF DATA FOR A TYPE 2 SUBTERRENE MELTING A TUNNEL
2 m DIAMETER AT THE RATE OF 100 m/day
AND USING THE LITHOFRACTURING TECHNIQUE OF MELTED-ROCK DISPOSAL

Quantity	Approximate Magnitude
Maximum Depth	< 3 km
Maximum Rock Temperature	$< 600°$C
Rock Mass-Melting Rate	8×10^5 kg/day (314 m^3/day) = 800 tons/day
Power Requirement*	~ 15 MW
Force on Penetrator	$\sim 18 \times 10^6$ lb $\equiv$ 9000 ton $\cong 8.2 \times 10^6$ kg
Lithocracking Pressure at Cone Tip	~ 1 kbar $\equiv$ 15,000 lb/in^2
Heat Flux at Penetrator Surface	~ 50 W/cm^2

*Assuming that all of the rock is melted.

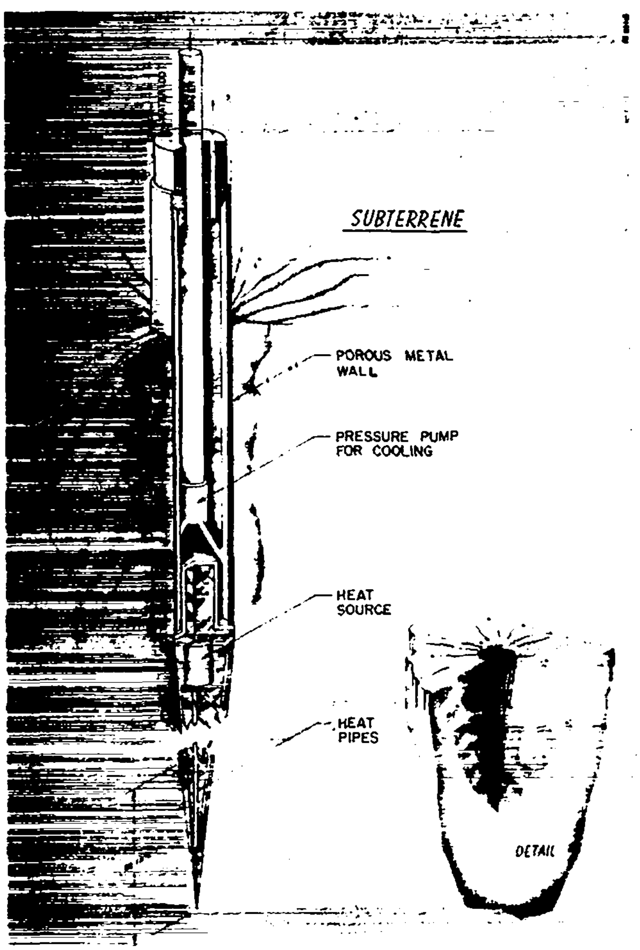


Fig. C-8.
Schematic of a Type 3 Nuclear Subterrene.

It is apparent that some very difficult scientific and engineering problems will be involved in the development of the Nuclear Subterrene. In particular:

- The high heat fluxes at the melting face of the penetrator can be provided only by heat pipes. High-temperature, refractory-metal heat pipes must be adapted to this purpose.
- Small, high-temperature, high-energy-density nuclear reactors are required, having fast neutron spectra and provision for cooling by heat pipes. Such reactors are now being developed for other purposes, but new designs will be needed for Subterrenes.
- Very rugged refractory structures and components will be required to operate for long periods at very high temperatures. Their design and fabrication will extend existing technology to its limits.
- Control, guidance, and communications systems for self-contained Subterrenes present extremely difficult problems.
- For Subterrenes that do not utilize lithofracturing, a scheme is needed to reclaim as much as possible of the energy deposited in the melted portion of the rock debris. Even when lithofracturing is used, some cooling of the glass bore lining will be required and, again, recovery and utilization of this waste heat would produce a desirable increase in efficiency of the boring operation.

Fortunately, a sequence of logical development steps can be defined to accomplish these design objectives, and a program of laboratory investigations and field tests can be outlined to collect the data required to build and operate progressively more advanced Subterrenes.

APPENDIX D

LITHOFRACTURING AND ROCK MECHANICS

In all drilling, tunneling, and shaft-sinking, a major source of delay, difficulty, and expense is the very troublesome operation of removing the rock fragments broken away from the working face. One of the most promising features of a rock-melting system is that it offers the possibility of completely eliminating debris removal. It would accomplish this by *lithofracturing*, the technique of producing and extending cracks in solid rock around the bore by means of lithostatic pressure developed in molten rock ahead of the advancing Subterrene. All molten rock not used in glass-lining the bore would be forced into these cracks, where it would freeze and remain. Only solid cores saved for geologic and geophysical investigations would be transported back to the surface.

This appendix reviews some basic aspects of rock stresses and rock mechanics, and provides background information on the lithofracturing concept. The actual conditions under which cracks form and extend in solid rock and the mechanisms and parameters of the flow of molten rock can, of course, be established only by laboratory experiments and field tests. However, an elementary analysis of the lithofracturing process is possible, and the results of this analysis support the feasibility of the technique.

Stresses in Rocks Distant from the Excavation

Lithostatic Conditions. The nominal stress field in rock relatively deep in the earth's crust is represented by the compressive state produced by the mass of rock above the particular region of interest. This overburden, or lithostatic, stress field will exist undisturbed only in areas that are tectonically relaxed and are unperturbed by such local inhomogeneities as gas or liquid bubbles, faults, intrusions, and high thermal gradients. In such non-nominal situations, the local structure and stress state must be examined individually.

To illustrate the magnitudes of overburden stresses at depth, it is convenient to refer to the coordinate system shown in Fig. D-1, where the XY plane is horizontal and the Z-axis is vertical. The compressive stresses at a point deep in the rock are directly proportional to the mass of the overlying rock, and increase linearly with depth. Mathematically, the axial (vertical) component of the overburden stress, σ_Z, is given by

$$\sigma_Z = -\bar{\gamma} h \quad , \qquad \text{(D-1)}$$

where $\bar{\gamma}$ is the average density of the overlying rock and h is the vertical distance from the earth's surface to the point being considered. (In this notation, compressive stress is considered negative.)

The horizontal components of stress, σ_H, are less than the vertical stress, to which they are related by either

$$\sigma_H = \sigma_X = \sigma_Y = \nu\sigma_Z/(1-\nu), \text{ the Elastic Law,} \qquad \text{(D-2)}$$

or

$$\sigma_H = \sigma_X = \sigma_Y = \sigma_Z/(f + \sqrt{1+f^2})^2 \quad , \text{ the Inelastic Law,} \qquad \text{(D-3)}$$

where ν is Poisson's ratio for rock and f is the internal friction coefficient for rock (0.3 to 0.7). At least in a preliminary analysis, the rock may be assumed to behave elastically, and Eq. (D-2) can be used. Like most other brittle materials, rocks have properties such that $0.1 < \nu < 0.25$, so that (from the elastic law) σ_H will range between about 0.11 σ_Z and about 0.33 σ_Z. Since rock densities are of the order of 2.5 g/cm^3, the vertical stress gradient due to the overburden will be approximately -2.5 g/cm^2 per centimeter of depth, or -0.25 bar/m,

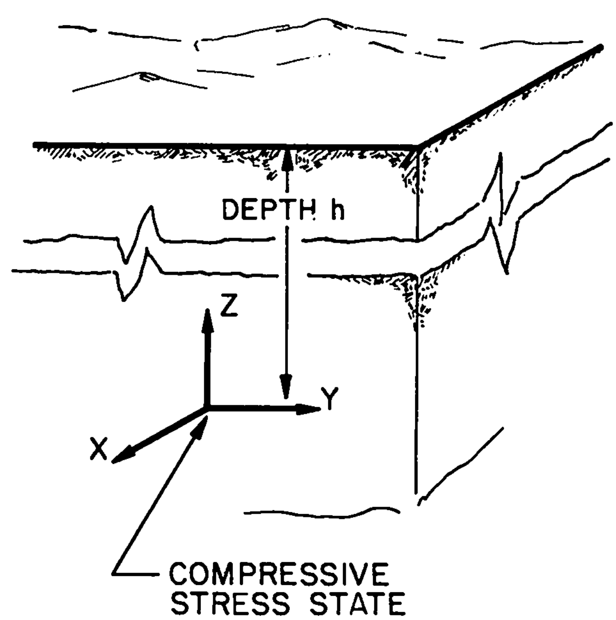


Fig. D-1.
The nominal stress field in rock at depth h beneath the earth's surface.

and the gradient of horizontal stress will be between about −0.028 and −0.083 bar/m. For example, at a depth of 3 km in rock whose mean density is 2.5 g/cm^3 and whose Poisson's ratio is 0.2, the components of the lithostatic stress field are

$$\sigma_Z = -750 \text{ bar} = -0.75 \text{ kbar } (-10{,}900 \text{ psi}),$$

$$\sigma_H = -190 \text{ bar} = -0.19 \text{ kbar } (-2700 \text{ psi}).$$

Pressurized Borehole. The relatively simple state of compressive stress in deep rocks will be perturbed locally by any discontinuity, such as a shaft or tunnel melted by a Subterrene. One of the simpler and more illuminating situations is the local stress condition produced by a vertical borehole. Neglecting for the present the glass liner, any cracks or fractures around the hole, and any residual stresses or temperature gradients left by the Subterrene, the elastic stress state is that illustrated by Fig. D-2. Here a deep cylindrical hole of diameter 2a has been introduced into the lithostatic stress field, and the hole has been filled with a gas or liquid to produce an internal fluid pressure P_0. At the wall of the hole this internal pressure directly opposes that horizontal component of lithostatic pressure [(σ_H, Eq. (D-2)] exerted radially, and this opposing pressure is transmitted elastically through the solid rock around the hole. However, the stress perturbation in the rock falls off rapidly with radial distance r from the center of the hole, and the radial stress in the wall rock is given by

$$\sigma_r = \sigma_H - (P_o + \sigma_H)(a/r)^2 \ . \qquad \text{(D-4)}$$

The tangential stress produced at the surface of the hole by the internal pressure is additive to that produced by the horizontal component of lithostatic pressure, but again the effect decays as $(a/r)^2$ with increasing distance into the rock, and the tangential stress in the wall rock is given by

$$\sigma_\theta = \sigma_H + (P_o + \sigma_H)(a/r)^2 \ . \qquad \text{(D-5)}$$

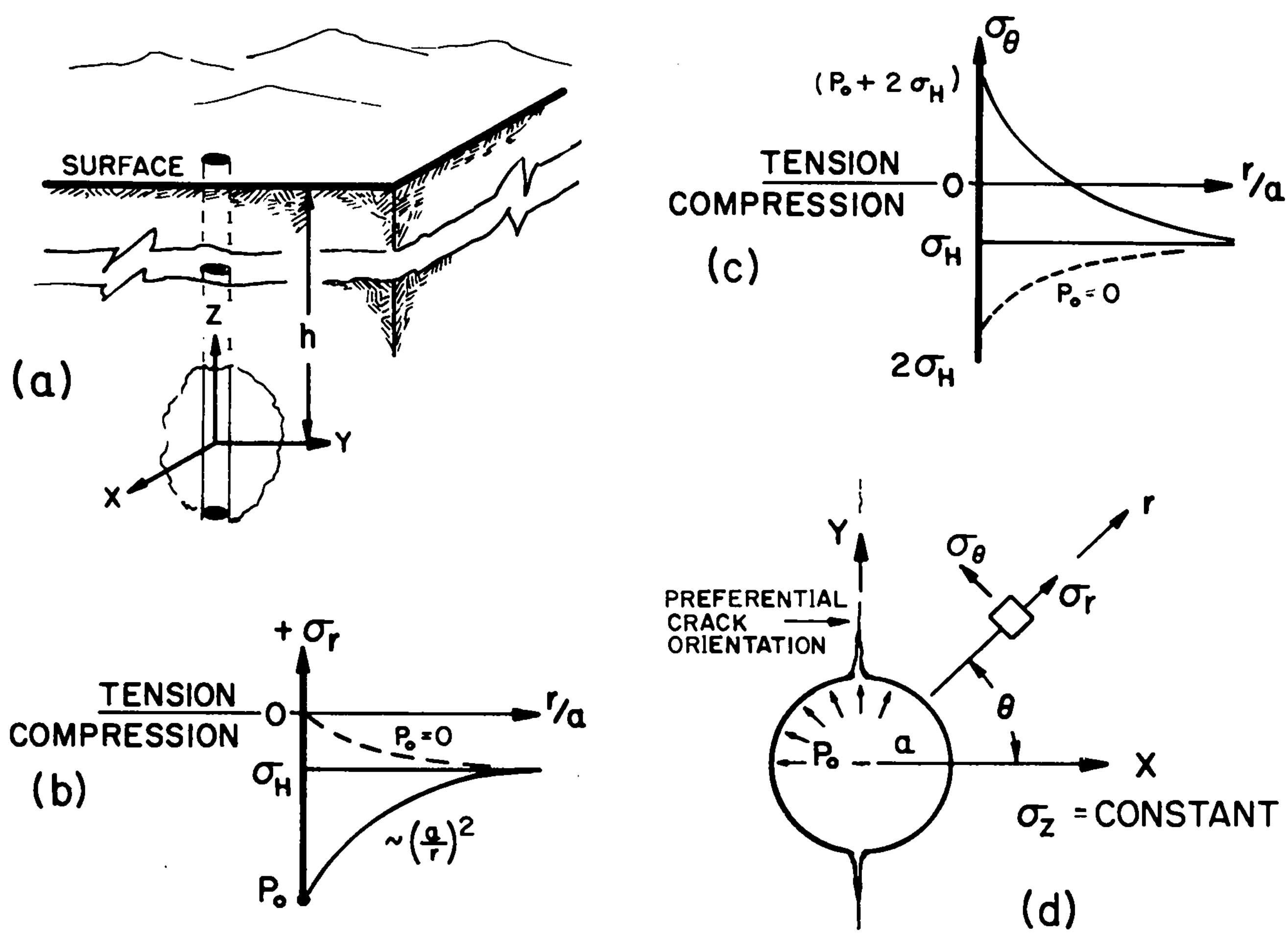


Fig. D-2.
(a) The stress situation around a pressurized deep hole in the earth's crust; (b) the radial stress state in rock around the hole; (c) the tangential stress state; (d) vertical cracks formed by the internal pressure.

These stress distributions are indicated in Fig. D-2(b) and (c). At distances of the order of 10 hole radii, the stress perturbations have essentially died out, and the stress situation has again become that represented by Eqs. (D-1) and (D-2).

The tangential stress in the wall created by internal pressure is tensile, and so is opposite in sign to the compressive stress represented by σ_H. Equation (D-5) therefore indicates that if sufficient internal pressure ($P_o > 2\sigma_H$) is developed in the hole, for example, by the use of high-pressure pumps at the earth's surface, the net tangential stress in the wall will be positive, i.e., tensile. Thus, from Eqs. (D-5), (D-2), and (D-1):

$$\sigma_\theta\Big|_{r=a} = P_o + 2\sigma_H = P_o + 2\nu\,\sigma_Z/(1-\nu)$$
$$= P_o - 2\nu\bar{\gamma}h/(1-\nu) \qquad \text{(D-6)}$$

If $\nu \cong 0.2$, then the tangential stress at the hole surface is

$$\sigma_\theta\Big|_{r=a} \cong P_o - 0.5\,\bar{\gamma}h = P_o + 0.5\,\sigma_Z \quad .$$

Thus, the stress in the wall will just become tensile when internal pressure in the hole is approximately one-half the overburden pressure. Since this tensile stress is tangential, a sufficient increase in internal pressure would be expected to cause vertical cracks to appear in the wall, as is illustrated by Fig. D-2(d). The tensile strengths of rocks are low, of the order of only 40 to 100 bar (500 to 1500 psi). The pressure required in a deep hole to form cracks in its wall is therefore generally less than the overburden pressure. This conclusion is substantiated by extensive oil field experience in hydrofracturing. The hydrofracturing data of Fig. D-3 demonstrate that, at least down to about 3.6 km in sedimentary rocks, the rock breakdown (fracture) pressure is from about 0.44 to about 0.75 times the overburden pressure (Harrison *et al.*, 1954). It is interesting that a water-filled hole would have an internal pressure at depth of approximately 0.4 of the overburden pressure.

The situation for a horizontal tunnel is qualitatively the same as for a vertical shaft or borehole. The stress state around the tunnel is more complex, but as internal pressure at the tunnel wall is increased one would expect cracks to form predominantly in vertical planes extending parallel to the tunnel axis.

Fracture Criteria for Rocks. As yet, little research has been directed toward determining the fracture criterion for rocks under the conditions of high hydrostatic pressure and high temperature at depth. One notable recent attempt has, however, been made by Cherry *et al.* (1968) to determine the strengths (onset of cracking) of rocks subjected to complex stress states, and in particular to high hydrostatic fields. This work indicated that the onset of fracture could be described by a quantity Y, which was found to increase with mean local hydrostatic stress. The results for dolomite are shown in Fig. D-4, where the fracture parameter Y is plotted against magnitude of the mean stress at fracture.

The current state of knowledge concerning the fracture of rock at depth has been reviewed by Fairhurst (1969). Clearly, more study of rock fracture is needed for better than order-of-magnitude predictions of the stresses required to initiate fracture at depth.

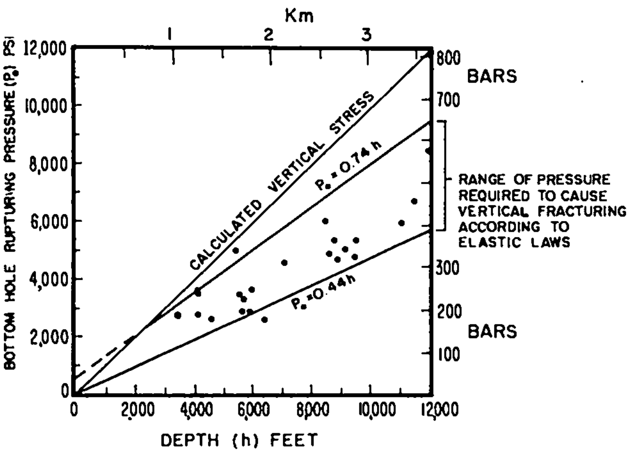


Fig. D-3.
The hydrostatic pressure required to produce hydrofracturing as a function of the overburden pressure at the level at which fracture occurred. (Adapted from Harrison et al., 1954).

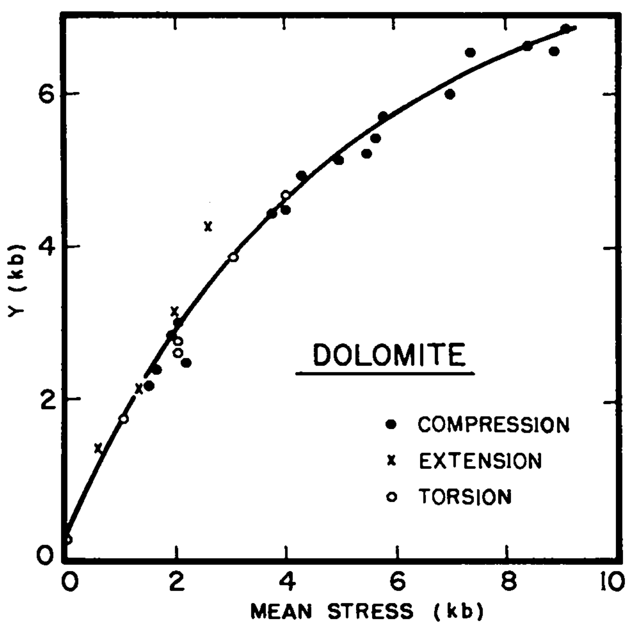


Fig. D-4.
The fracture parameter Y for dolomite as a function of mean stress at fracture. (Adapted from Cherry et al., 1968).

Near-Field Stresses--Crack Extension

The discussion above indicates that stresses applied to a borehole or tunnel are local, and that their influence would be expected to be significant only within a region whose diameter was of the order of 10 times that of the hole. Now it is instructive to review the near-field stress states, to consider the thermal field and the thermal-stress field around a hole being produced by melting, and to discuss what is known about the extension of cracks in rocks.

Thermal Boundary Layers and Thermal Stresses. Most rocks are good thermal insulators. The effects of an abrupt change in surface temperature or of a heat flux suddenly applied to a rock surface will in general not penetrate either very rapidly or, unless the time scale is long, very deeply.

For example, suppose that a cylindrical hole 2 m in diameter exists in a semi-infinite body of granite having the following typical properties (Ingersoll *et al.*, 1954):

Thermal conductivity = λ = 0.0065 cal/cm-sec-°C

Specific Heat = C_p = 0.19 cal/g-°C

Density = ρ = 2.7 g/cm^3

Thermal Diffusivity = D = 0.0127 cm^2/sec.

Suppose that the surface temperature of the hole, T_s is suddenly raised from 100 to 1100°C, which is approximately the melting temperature of granite. To determine the temperature of the surrounding rock as a function of time and of dimensionless radial distance, r/a, from the hole, the parameter of interest is the nondimensional Fourier number (Schneider, 1963)

$$F_o = (D/a^2)t \quad , \qquad \text{(D-7)}$$

where time, t, is in seconds. For the rock properties assumed,

$$F_o = 1.26 \times 10^{-6}\, t \ .$$

Roughly, this is the scale factor of time for a "thermal wave" to move out into the granite. Progress of the thermal wave is illustrated in Fig. D-5. In 1 h it has penetrated only about one hole radius from the hole surface, and for the temperature wave to reach 10 hole radii would require something like 40 days. Alternatively, the results of this calculation can be expressed in terms of the time required for rock at a specified distance from the hole to rise in temperature by a given amount, as has been done in Fig. D-6. To raise the rock temperature 20°C at a distance of one hole radius from the heated surface will require about 20 h, and at 5 hole radii this will require several hundred hours. Such results indicate that the thermal perturbation in the earth caused by passage of a rock-melting penetrator is extremely local.

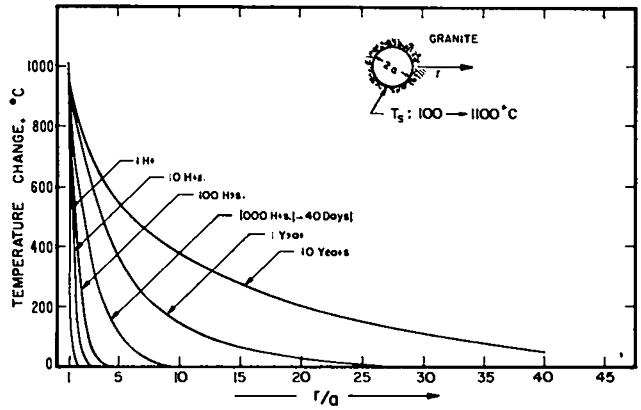


Fig. D-5.
Penetration into granite of the temperature wave from a bore surface whose temperature has been raised abruptly by 1000°C.

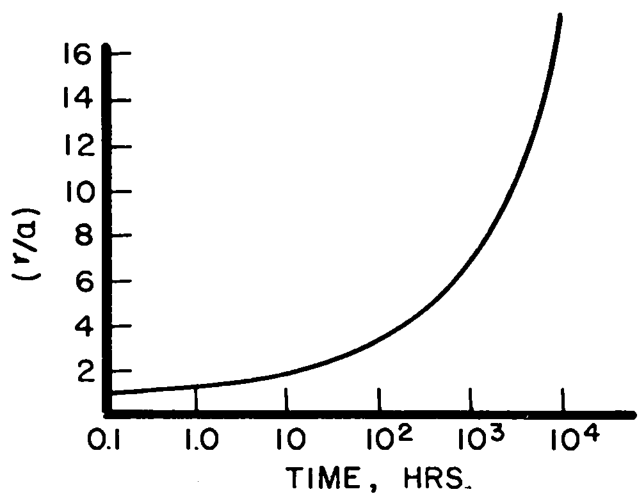


Fig. D-6.
Time required for a 20°C temperature rise to occur in granite at various radial distances from a bore surface whose temperature has been raised abruptly by 1000°C.

The insulating properties of rock illustrated above are of great importance to the rock-melting concept. Unmelted rock in the immediate vicinity of the penetrator forms a thermal blanket that minimizes the energy loss by unnecessary heating of rock farther from the hole. It is necessary to heat only a thin layer of rock, and not the whole earth.

An estimate of the heat loss above that required to melt rock adjacent to the penetrator face can be made by considering the rate at which heat must be transferred laterally from the moving heat source to raise the surface of the unmelted rock to its melting temperature. This is approximately the heat flux required to flow through the layer of melted rock, and so is an estimate of the rate of heat loss to unmelted rock beyond it. Using the example of the Type 2 Subterrene described in Appendix C, together with the thermophysical properties of granite, the analysis shows that this heat flux is only about 2 W/cm^2, or about 4% of the 50 W/cm^2 required to melt the rock. Heat transferred to solid rock ahead of the Subterrene will subsequently be utilized as the Subterrene advances, and only that conducted laterally will be lost. Much of the lateral heat loss will be derived from molten rock back-extruded from ahead of the Subterrene, so that melting efficiency may in fact be considerably higher than this calculation indicates.

Since the thermal perturbations are restricted to very thin layers adjacent to rock surfaces, the thermal stresses generated in rock near the heated (or chilled) surface are easily estimated. For this situation, the magnitude of the thermal stress can be estimated from the simple relation

$$\sigma_{th} \cong \frac{\bar{\alpha} E}{(1-\nu)} (T_o - T_s) \quad , \qquad \text{(D-8)}$$

where σ_{th} = thermal stress, kg/cm^2,

$\bar{\alpha}$ = mean coefficient of thermal expansion, $°C^{-1}$,

E = elastic modulus, kg/cm^2,

ν = Poisson's ratio,

T_o = temperature of undisturbed rock mass, °C,

and

T_s temperature of the rock surface, °C.

The temperature gradients that cause thermal stresses are illustrated in Fig. D-7. If the surface is heated to above the mean temperature of the surrounding rock, the stress state is biaxial compression; if the surface is cooled, it is biaxial tension. The magnitude of such stresses can be indicated by substituting into Eq. (D-8) the following typical rock properties:

$\bar{\alpha} = 8 \times 10^{-6}\ °C^{-1}$,

$E = 10^6\ kg/cm^2$,

$\nu = 0.2$.

With these substitutions,

$$\sigma_{th} \cong 10(T_o - T_s) = \pm\, 10\Delta T.$$

Since the tensile strengths of rocks are of the order of 40 to 100 kg/cm^2, a ΔT of only 4 to 10°C may create

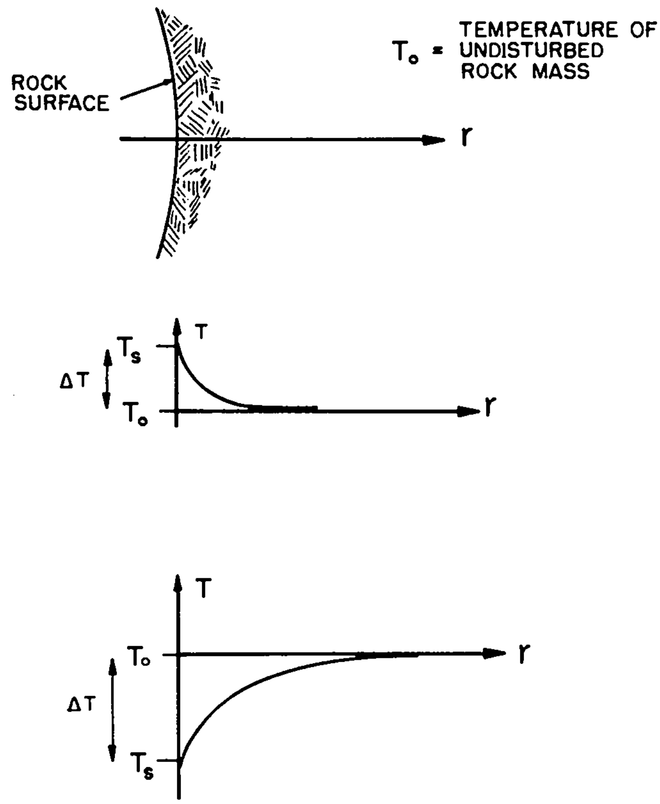


Fig. D-7.
(a) A borehole surface which is abruptly heated or cooled; (b) biaxial compression developed at a heated surface, which can cause spalling; (c) biaxial tension developed at a chilled surface, which can cause cracking.

thermal stress sufficient to cause tensile cracking. Spalling appears to require a temperature difference about 10 times this great, reflecting the fact that the compressive strengths of rocks (800 to 2500 kg/cm^2) are much higher than their tensile strengths.

Maurer (1968) has reviewed the general situation of both spalling and tension cracking as methods of breaking rocks.

Crack Extension in Rock. Of particular interest to the probable success of the rock-melting penetrator is the lithofracturing concept, which requires that the high interface pressures produced by the thrust of the penetrator form, open, and extend cracks in the solid rock adjacent to the hole, and squeeze most of the pressurized melt into these cracks.

The basic facts of fracturing (Hubbert *et al.*, 1957) and crack extension (Harrison *et al.*, 1954) in rock by hydraulic pressurization of a hole in the rock have been well established. The available evidence indicates that, once a crack is opened in rock at depth, the crack will extend over a large area and open wide enough to produce a large fracture volume. Harrison *et al.* (1954) conclude: ". . .a large majority of pressure-induced well bore fractures are vertical, particularly in deeper wells; and variations in the pressures necessary to create and extend fractures can be explained largely on the basis of established rock properties. It is also shown that variations due to tectonic forces should usually be expected to be slight. Other results indicate that during the extension of fractures rather large fracture volumes are. . .created by the parting of the formation."

Verification of the crack-extension behavior of rocks pressurized hydraulically and of the fracture volumes produced have been obtained in wells at Oak Ridge National Laboratory. The ORNL data have been analyzed by Sun (1969) of the U. S. Geological Survey, who found reasonable quantitative agreement between these experimental results and theoretical models of crack-extension radii, crack widths, and crack volumes. Specifically, it was demonstrated that the cracks formed from a borehole 10 cm in diameter extended outwards to distances of 50 to 60 m, i.e., crack depths were 500 to 600 times the hole diameter. Crack widths were small, of the order of 1 cm. These dimensions were in good agreement with those calculated from theoretical analyses of the extension of pressurized, liquid-filled cracks.

The physical situation of such a crack is illustrated in Fig. D-8. Here a circular crack* of radius L_c is shown extending outward from a borehole or tunnel of radius a

*The elastic fracture-mechanics solutions indicate that the crack shape will actually be an oblate disk of elliptical cross section.

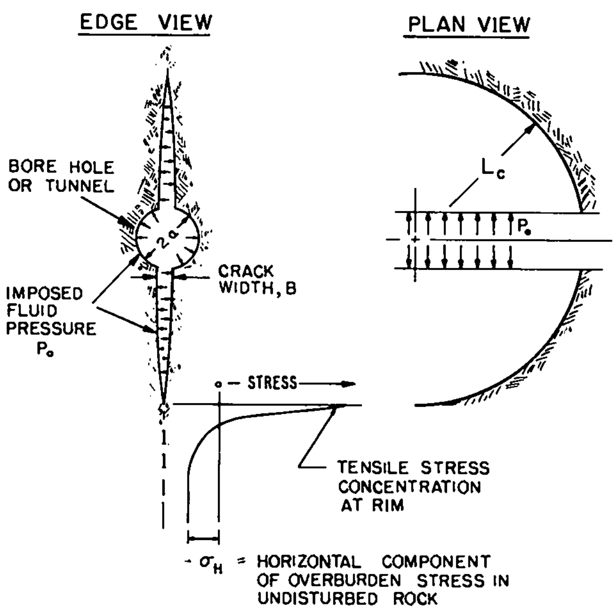


Fig. D-8.
The extension of a circular crack from a pressurized hole.

under the action of pressure P_o imposed by a liquid that extends into the crack. Available solutions for the liquid-filled crack (Sneddon and Lowengrub, 1969) indicate that estimates of crack volume U, width B, and stress-intensity factor at the crack rim, s, will be given by

$$U = \frac{16}{3}\,\frac{(1-\nu^2)}{E}\,\left(P_o - \frac{\nu}{(1-\nu)}\bar{\gamma}h\right) L_c^3 \quad , \qquad \text{(D-9)}$$

$$B = \frac{8}{\pi E}\,(1-\nu^2)\left(P_o - \frac{\nu}{(1-\nu)}\bar{\gamma}h\right) L_c \quad , \qquad \text{(D-10)}$$

$$s \simeq 3 + 2.115\,(1 + L_c/a)^{1/2} \quad . \qquad \text{(D-11)}$$

Here $\Delta P = P_o - \nu\bar{\gamma}h/(1-\nu)$ is the net pressure in excess of the horizontal lithostatic compression, σ_H, and the crack dimensions are noted to be linearly related to ΔP.

An indication of the net pressure required to extend a crack is obtained from a quantity C, the module of cohesion of a material, defined by

$$C = \pi\left(P_o - \frac{\nu\bar{\gamma}h}{1-\nu}\right)\left(\frac{L_c}{2}\right)^{1/2} \quad . \qquad \text{(D-12)}$$

C has apparently not been determined for rocks. If it is truly a constant, then Eq. (D-12) indicates that the longer a crack, the lower the net pressure required to extend it.

The volumes of cracks of several different geometries, formed in granite having the properties listed above, are indicated in Table D-I. These results show that lower pressures are required to form very long, thin cracks than to form short, wide ones, and that the long, thin cracks have unexpectedly large volumes. For comparison, a 1-m length of a hole 2 m in diameter has a volume of only 3.14 m^3.

Lithofracture Mechanics

The preceding discussions have established the bases required to develop the lithofracturing concept. Briefly, it is postulated that a rock-melting penetrator of proper shape can be provided with sufficient thrust to crack the rock immediately surrounding it; that the interface pressure will force the melted rock into these cracks; that the pressurized melt flowing into them will further extend the cracks; and that continuation of these processes will produce a crack volume sufficient to accommodate the melt, so that a glass-lined hole is produced containing no rock debris. In support of this concept, the following information is available.

1. It is known that, under the action of a heated penetrator, rock melts into a viscous, glass-like liquid whose density is slightly less than that of the crystalline rock being melted. Under modest pressure, this melt flows

TABLE D-I

CALCULATED DIMENSIONS AND VOLUMES OF CRACKS FORMED IN GRANITE

Crack Radius, L_c, m	Crack Width, B, cm	Crack Volume, U, m^3	Net Pressure, ΔP kg/cm²	(lb/in²)
5	0.2	0.11	165	(2,300)
10	0.5	1.05	200	(2,800)
20	1.0	8.0	200	(2,800)
50	1.0	52.0	80	(1,150)
100	2.0	420	80	(1,150)

radially to openings in the penetrator and to its periphery, and backward through such openings and into any clearance existing around the periphery. Upon cooling it forms a glass that can be handled as a solid, and produces a continuous and adherent lining on the wall of the hole.

2. Molten rock flows without slipping as a viscous fluid in the vicinity of a hot surface. Near a cold surface the melt cannot adhere, and frictional slipping occurs. At intermediate temperatures, a bond can form between the penetrator and the glass. However, with proper design the transition region in which this occurs can be made very narrow so that the bond can be broken by relatively weak shearing forces.

3. The general effects of pressure on viscosity are known. It is also known that water vapor lowers the melting temperatures of rocks, and that pressurization sufficient to prevent escape of carbon dioxide permits a carbonate rock, such as a limestone, to be melted at the relatively low melting temperature of the carbonate instead of the much higher one of the oxide. Under even moderate pressure, fluid melts can probably be produced from essentially all types of natural rocks at temperatures within the operating capability of a melting penetrator.

4. Rocks, solid or molten, are excellent thermal insulators. Very little of the heat introduced by the penetrator will be lost except as sensible heat in the melted rock. Temperature gradients will be high in rock adjacent to a hole which is heated or cooled, thermal stresses will also be high, and spalling and cracking are likely to occur in rocks of low thermal-stress resistance.

5. The tensile strengths of rocks are low. As a result, moderate hydraulic pressure in a hole or tunnel can cause tensile cracking in the adjacent rock. Pressurized fluid entering the cracks produces large lateral forces that tend to open them, and high stress-concentrations at their rims which tend to extend them. In general, the cracks remain thin, seldom exceeding 1 to 2 cm in width, but if sufficient pressurized fluid is provided they will extend over large distances, which may be hundreds of hole diameters. Therefore, the volume of such a crack system can be very large.

6. Rock-melting drills, which melt rock but do not develop the pressures needed for fracturing, have been built and successfully operated. The principles of such devices are understood, several functional designs have been tested, and the bases for new and improved designs exist.

Within this framework, and in advance of actual operating experience, what can be expected to happen when a high-temperature, high-thrust, rock-melting penetrator is forced into solid rock?

At least in its more advanced versions, the melting-penetrator itself is visualized as a conical or wedge-shaped body (Appendix C, Figs. C-7 and C-8). As the penetrator is forced into the rock, a thin film of glass-like melt forms over its hot surface. This fluid serves as a viscous pressure-transmitting medium to convert the axial thrust of the penetrator into uniformly distributed hydrostatic pressure on the wall of the hole, represented by P_0 in Fig. D-9. Stresses will be very high in rock at the tip of the penetrator, as was discussed in Appendix B, and cracking of the rock should start there. In general, the cracks would be expected to develop in diametrically opposed pairs, as indicated in Fig. D-10. Molten rock forced into the crack would lose heat to the crack surfaces, freeze as a glass at some distance from the penetrator, and prop the crack open. If the flow of molten rock were stopped by such plugs, then the walls of the borehole would again be subjected to large lateral hydrostatic forces. Either the original cracks would continue to enlarge in length and width, permitting the melt to flow past the previous plug, or new pairs of cracks would develop and start to fill with melt.

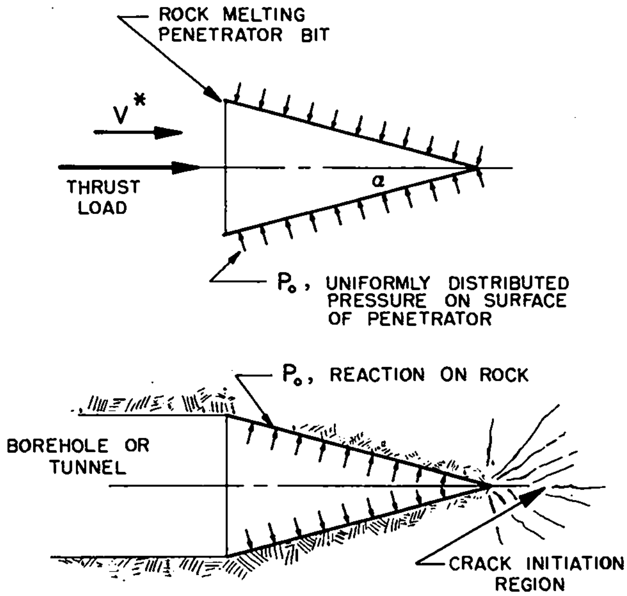


Fig. D-9.
Lithostatic pressure developed by a rock-melting penetrator, and crack initiation in the region of its tip.

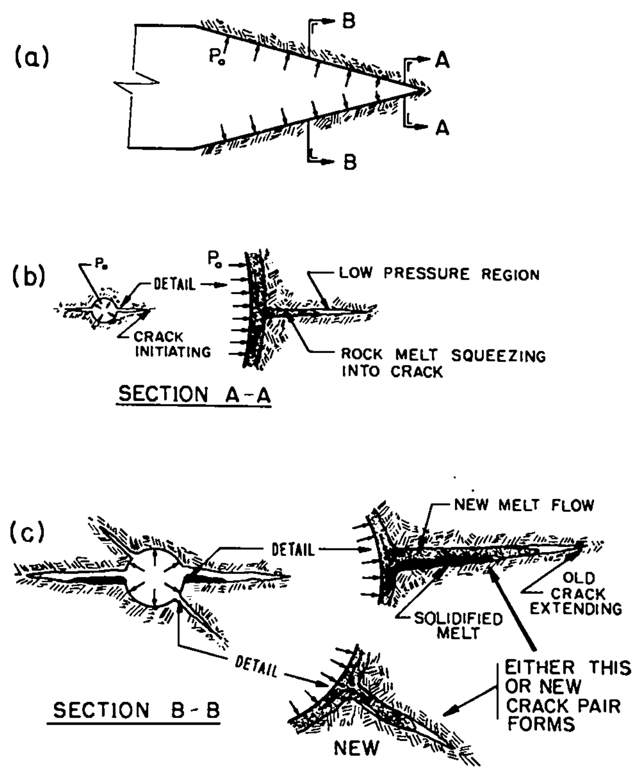


Fig. D-10.
(a) The advancing rock-melting penetrator; (b) a section through rock near the penetrator tip; (c) a section in the region of hole enlargement.

The processes of crack initiation, crack enlargement, and crack filling may be either continuous or intermittent. In the latter case, these processes might either be locally intermittent or might occur during a crack-enlargement period alternating with a flowing and freezing phase. An intermittent behavior, particularly if accompanied by temporary bonding of glass to the intermediate-temperature region of the penetrator surface, might result in a jerky forward motion of the advancing penetrator.

If the cracks become sufficiently numerous to interact thermally, there will be a general rise in temperature of the unmelted rock between the cracks. Heat deposited in this way in the region ahead of the penetrator will reduce the energy later required to melt the rock in that region, and so will eventually be used as the penetrator advances. In the meantime, the temperature gradients will create stress gradients that may result in additional cracking and fragmentation, facilitating subsequent lithofracturing and reducing the thrust required to produce it.

With such a variety of concepts and possibilities, it seems unlikely that any one solution will apply or any single pattern of behavior will appear in all rock formations a melting penetrator may encounter. In particular, variations are expected with depth and with the thrust imposed by the penetrator, and natural zones of weakness in the rock, such as bedding planes, blocky cleavages, and faults, will have effects that can be predicted only if the local structure is known. Despite the difficulty of predicting rock behavior in detail, it seems probable--if not, in fact, necessary--that yielding and fracturing of the rock will somehow occur to accommodate the volume of melt produced by the penetrator.

Grossly, the mechanical problem is simply that of creating tensile forces sufficient to crack the rock by producing corresponding compressive stresses on the penetrator surface. The tensile strengths of rocks are relatively low, and many refractory materials are available for penetrator construction which have strength properties at rock-melting temperatures sufficient to sustain the required compressive stresses. This problem can therefore undoubtedly be solved. The quantitative details of the solution, involving the time-dependent processes of rock melting, crack formation, squeezing outflow of melt, crack extension, freezing of the melt, old-crack reopening, new-crack formation, and progress of the penetrator, must await experimental results and complete thermal and mechanical analyses. However, some qualitative estimates of the probable penetrator action are possible.

The rate of advance of a rock-melting penetrator is obviously governed by the rate at which the rock is melted, and this is controlled by the power delivered to the penetrator surface. Cracking of the rock and outflow of the melt depend upon the thrust applied to the penetrator. Preceding the tip of the penetrator will be a region of cracked and fractured rock. As the penetrator enters this region, it will start to squeeze molten rock from the melted layer adjacent to the penetrator surface into these cracks. Since molten rock is relatively viscous and the melt moves as a thin film along the penetrator surface, the circumferential pressure gradient will be high. It is therefore probable that a number of cracks will be extended by liquid filling and pressurization instead of just one crack or one pair of cracks. The actual number will be governed by the nature of the original fracture zone produced by the penetrator tip, the viscosity of the melt, and the velocity of the Subterrene, which represents the rate at which melt is produced. Figure D-11 illustrates this probable sequence of events.

The extent of the cracked and glass-filled region around the hole will be determined by the number of cracks generated and the volume of melted rock intruded into them. This is illustrated in Table D-II, which lists the calculated average crack lengths and spacings for various numbers of cracks produced by a Subterrene 2 m in diameter. Melt volume was assumed to be approximately 3 m^3 per meter of hole length, and net interface pressure of 100 kg/cm^2 was assumed to act on the penetrator surface.

Intuitively, it seems that the 6-cm spacing produced when 100 cracks are formed represents a reasonable distance for circumferential flow of a rather viscous melt. Probably, then, the usual case will be extension and filling of a rather large number of relatively short cracks rather than a few very long ones, as would occur if the viscosity of the pressurizing fluid were low.

An obvious question concerning this general concept is: What is the net effect on the earth of creating this volume of cracks and squeezing out this quantity of glass into a previously solid rock formation? Essentially, a "tube" of volumetric strain (dilatation) is created around the hole, extending outward approximately as far as the cracks themselves extend. The increased bulk volume of material in this tube tends to increase its diameter, but

TABLE D-II

CRACK LENGTHS FOR A PENETRATOR MELTING A HOLE 2 METERS IN DIAMETER

Number of Cracks	Average Crack Length, m	Average Circumferential Crack Spacing, cm
2	100	300
10	20	60
50	4	12
100	2	6

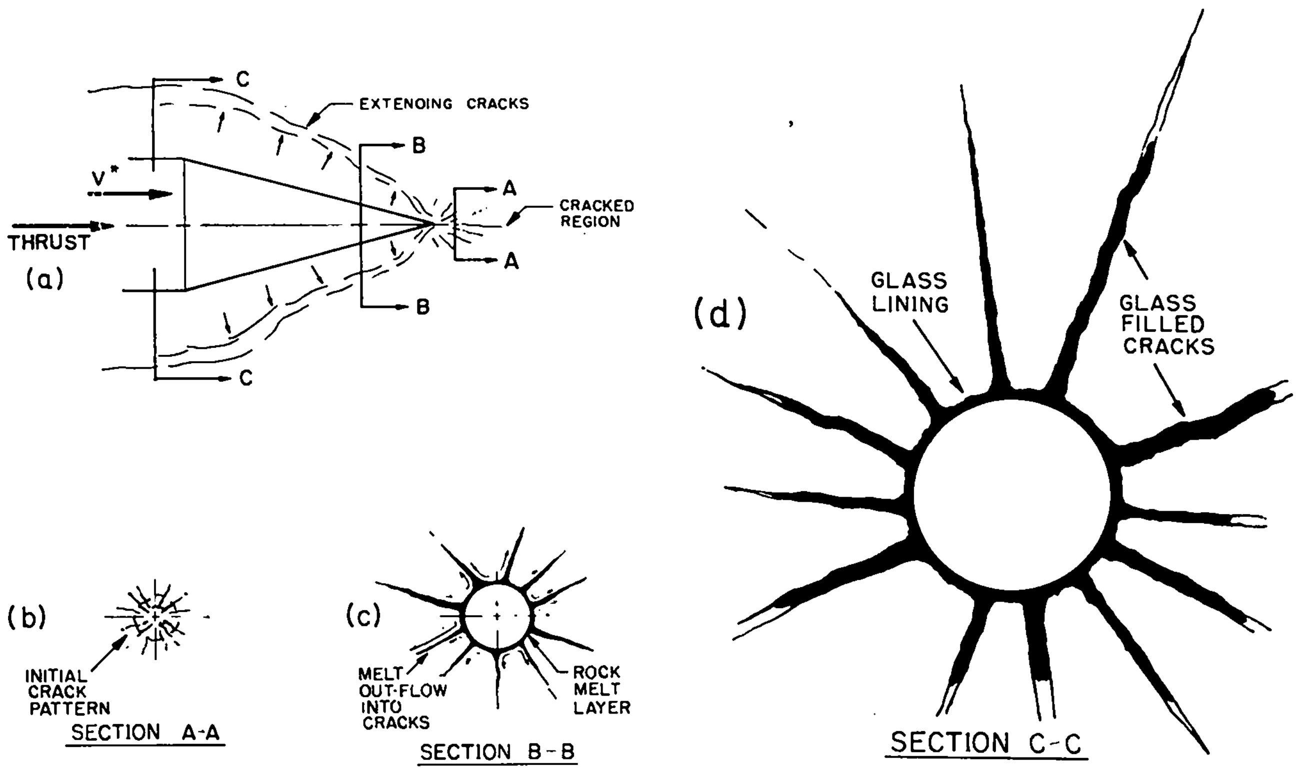


Fig. D-11.
(a) Lithocracking by an advancing Subterrene; (b) initial crack pattern in the region ahead of the penetrator tip; (c) the extending crack array; (d) the final crack configuration.

the increase is resisted by the solid rock around it. A region of enhanced compressive stress, above the nominal compression produced by the overburden pressure, will be created within another tube of rock somewhat larger than that in which dilatation has occurred. Only during the first few meters of penetration will there be a detectable effect at the earth's surface, and this will be a local bulge at most a few millimeters high. At depth, the passage of the Subterrene will leave behind a glass-lined hole surrounded by a limited region of enhanced compressive stress in which a volume increase has been accommodated by elastic strain of the rock and by collapse of any pre-existing voids.

This brief description of the extension of liquid-filled cracks is based upon several known but distinct phenomena: initiation of cracking in rock at depth by a lubricated penetrator; crack extension and opening by a pressurized fluid (hydrofracturing); and the flow and freezing of molten rock, as demonstrated in early experiments with the LASL rock-melting drill. Only extensive laboratory investigation and field testing will reveal the details of these processes as they occur in a full-scale boring operation. Together, however, they offer the potential of a revolutionary advance in excavation technique--borehole excavation without debris removal. This can be considered a direct response to the plea in a recent report of the National Research Council (1968):

> "The existing private mechanism for technological change is well developed, but it is largely directed toward the ingenious incremental changes in technique that are typical of competitive firms and suppliers engaged in winning a larger share of a relatively fixed market. However, continued ingenious incremental improvements in technology cannot so improve underground excavation that it will become a realistic alternative to surface excavation for construction activities by the end of this century. A radical change in the scope of thinking about underground excavation is needed to achieve that desirable goal."

APPENDIX E

THE SOLUBILITIES OF NATURAL MINERALS IN HOT WATER

Most natural minerals have significant solubilities in hot water, which offers both possibilities and problems when underground circulation systems are considered. On one hand, most commercial ore bodies have been formed by mineral deposition from hot, aqueous solutions, and the process can be reversed to extract and recover these minerals. If a leaching operation is sufficiently selective or is applied to a sufficiently concentrated ore body, then a geothermal energy development may also represent a profitable mining venture. On the other hand, the presence of significant concentrations of dissolved minerals in the feed water to a power plant may require preliminary processing of the water before steam flashed from it can be allowed to go to the turbines. Unless the material recovered from the water-treatment step has enough value to offset the additional processing cost, then the overall cost of power generation will be correspondingly increased.

The magnitude of this general problem is indicated by the work of Kennedy (1944, 1950), Morey *et al.* (1951, 1962), Wasserburg (1958), and Weill and Fyfe (1964). These researchers have studied the solubilities of quartz and other minerals in water at temperatures to 600°C and pressures to 4 kbar. The conclusion to be drawn from their work is that, if the specific volume of water is kept constant as it is heated to above the critical temperature (374°C), then there is no sharp change in trend of the solubility vs temperature relations for minerals such as quartz, albite, microcline, and enstatite. Thus high-density supercritical steam seems to be as good a solvent for minerals as is liquid water, and solubilities may continue to increase during heating at constant volume to temperatures distinctly above that of the critical phenomenon.

Quartz appears to be typical. The mechanism of its solution in water is described by the equation (Mosebach, 1957):

$$SiO_2 + 2H_2O \rightleftharpoons Si(OH)_4 \quad .$$

Solubility-vs-temperature curves for quartz in water at a series of pressures are plotted in Fig. E-1, and demonstrate that at pressures above about 750 bar solubility increases smoothly with temperature to well above the critical temperature. At very high temperatures and pressures, the solubility of quartz in water is surprisingly large, and this is also true of the solubilities of most other natural minerals.

A geothermal energy system such as that described in Appendix F, in which water at 250°C and 400 kg/cm² pressure is circulated through fractured granite at the rate of 80 kg/sec, would be expected to dissolve and bring to the surface about 3600 kg of minerals per day. Dissolution of these minerals would be expected to weaken the granite and increase its permeability to the circulating fluid, perhaps facilitating the extraction of its thermal energy. Some enlargement of water-circulation channels would result both from solution and from loosening of particles which would be carried away in suspension in the water. (Some of the early work on the solubility of minerals was incorrect because it was not recognized that many minerals, or components of minerals, can form colloidal suspensions and be transported by a fluid in much larger proportions than could be accounted for by true dissolution.) The general deterioration of the rock structure resulting from this type of attack should make further excavation easier when it is desirable to extend tunnels or enlarge chambers.

Since one ton of average granite contains uranium and thorium equivalent in energy content to 50 tons of coal (White, 1965), the recovery of these metals at the surface could represent a valuable by-product operation. (It is interesting that a geothermal energy plant intended to produce 10 MW of electricity, which could instead have been designed to burn 100 tons of coal per day, has the potential of recovering uranium and thorium at a rate

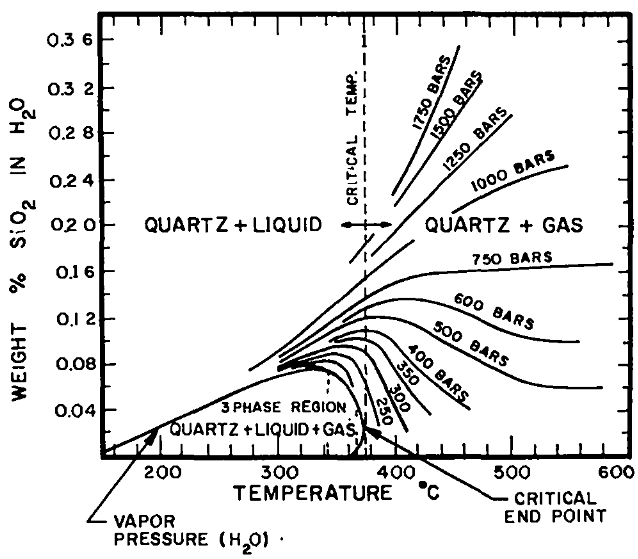


Fig. E-1.
Isobaric solubilities of quartz in water. (Adapted from Kennedy, 1950).

equivalent in energy to 200 tons of coal per day.) It is, however, unlikely that the minerals composing a granite would be dissolved nonselectively, and so it is not clear that the uranium and thorium would, in fact, be extracted by a simple hot-water system. Nevertheless, the possibility of leaching in place either as a direct mining operation or as an adjunct to a geothermal energy development is evident, and the selectivity of the operation could undoubtedly be increased by additions to the circulating fluid of chelating or complexing agents, etc.

It is also evident that--whether the mineral recovery is profitable or not--it will be necessary to treat water from underground circulation systems to demineralize it before it can be used directly for power generation, domestic heating, and many other purposes. However, as is suggested in Appendix F, the alternative exists of extracting most of the thermal energy from the water in a heat exchanger and then returning the water itself to the underground system.

APPENDIX F

GEOTHERMAL ENERGY

Geothermal energy (GTE), as the term is generally understood, represents that part of the earth's thermal energy that can economically be converted into electricity or other directly useful forms of energy. The requirements of economics now limit exploitation of the earth's natural heat to accessible regions in which large quantities of naturally occurring, high-quality steam have been discovered. A detailed description of known sources of this type, and of how they are being utilized, appears in the "Proceedings of the United Nations Conference on New Sources of Energy" (United Nations, 1964). The combination of geologic events needed to produce such a natural source of steam is unusual, and the number of known sources is correspondingly small. This has sometimes led to the conclusion that geothermal energy has little chance of contributing significantly to the future energy demands of the world (National Research Council, 1969; Chem. & Eng. News, August 17, 1970). This appendix challenges that conclusion, on the basis that the existence of an operating Subterrene would make possible the economical exploitation of many underground thermal-energy reservoirs not now considered to be useful geothermal energy sources.

Energy Requirements and Sources

According to Science News (August 1, 1970), the installed electrical generating capacity in the United States at the end of 1969 was 315 gigawatts (1 gigawatt = 10^6 kilowatts). If the forecast of the Federal Power Commission is correct, the electrical power industry of the United States will be required to increase its generating capacity by a factor of almost 10 during the next 30 years. There are, of course, also many requirements for energy in forms other than electricity, and these are increasing at similar rates.

According to Gambs (1970), the Federal Power Commission considers that the only commercial fuels available to thermal power plants are coal, oil, natural gas, and uranium. His projection of the roles played by these fuels is that by 1990 over 70% of the electrical energy of the United States will be produced from uranium, about 20% from oil and natural gas, and only about 10% from coal, which is now the major power-plant fuel.

There are many reasons for concern over the economic and environmental problems created by using these fuels, which will evidently be multiplied many times if the above projections are correct (Boffey, 1970; Lapp, 1970; Gambs, 1970). Some of the problems are:

1. The long-term availability of these fuels at reasonable cost.

2. Air pollution produced by almost any combustion process.

3. Radiation hazards associated with nuclear reactors.

4. Thermal pollution of surface waters, by almost any type of power plant.

5. Disposal of solid wastes, including coal ash and contaminated reactor products.

Public concern may eventually lead to controls so restrictive that some or all of these fuels (e.g., coal) will no longer be economical. This possibility and the rates at which known reserves (e.g., of natural gas) are being depleted make it uncertain that any one of these fuels can qualify as the major energy source in 1990.

The Advantages of Geothermal Energy

The question now to be considered is: Will geothermal energy, if more widely developed, reduce these problems and not introduce new ones that are equally serious? In this connection, it is known that:

1. Steam now being obtained from geothermal sources is an economical source of thermal energy (Paper GR/3 [G] in United Nations, 1964; Lessing, 1969).

2. The experience of geothermal energy plants in Italy, where noxious gases are present in the natural steam, indicates that significant air pollution can be avoided in an operation of commercial scale (Paper G/50 in United Nations, 1964).

3. A GTE plant presents no radiation hazard.

4. Thermal pollution by waste heat is common to all thermal energy plants, and must somehow be minimized in each case. However, there are ways in which much of this heat can either be used or stored in the heat sink represented by the cool upper region of the earth's crust.

5. In conventional GTE plants using natural steam,

there has been concern that streams and rivers would be contaminated by material brought to the surface by the steam and retained in the water condensed from it. Engineered GTE systems of the type discussed below will require an inventory of water which increases with time, so that no dumping of excess water will occur and this problem can be avoided. Alternatively, as is discussed in Appendix E, the dissolved material can sometimes be recovered as a useful by-product.

It is apparent that even widespread use of geothermal energy would introduce no peculiar hazards and would accomplish a major and timely reduction in environmental pollution. The questions that remain are concerned with the magnitude and availability of GTE reserves, and the probability that they can be exploited economically.

Geothermal Energy Sources

White (1965) classifies geothermal energy sources into four categories, based on the geothermal gradient and the presence or absence of circulating ground water.

Type I sources are regions in which the geothermal gradient is normal (about 20°C/km). Temperatures great enough to produce high-grade steam exist only at depths of about 10 km or more, where there is probably no free water. This situation exists under most of the earth's surface.

Type II sources are local areas of higher than normal geothermal gradient, which cannot at present be exploited economically because the temperature and hardness of the rock make the source difficult to penetrate and its low permeability prevents the ground-water circulation required to produce natural steam. These are usually regions in which there has been either volcanic activity or intrusive flow in recent geologic time. In the United States, such sources are common in the West, and there are several in New Mexico.

Type III sources are hot-springs areas, characterized by shallow ground water and convective heat transfer. In general, water temperatures are too low to be of interest for power generation.

Type IV sources are regions in which impermeable rock near the surface covers underlying formations that are permeable to circulating ground water. At depth, heat transfer is convective, but near the surface it occurs only by conduction through the rock. All present power production from geothermal energy originates in Type IV sources. The major ones are Larderello in Italy, Wairakei in New Zealand, and The Geysers and Salton Sea areas in California.

Table F-I lists our estimates of the total and realizable energy from each type of source in the continental United States. It is apparent that a pessimistic forecast of the role of geothermal energy would be made if--as has normally been done--only the energy of Type III and Type IV sources were considered to be economically available. Type II sources are much more interesting; they could supply the total electrical requirements of the United States for thousands of years. They become useful energy sources at depths of about 3 km, which, in cool sedimentary rocks, could certainly be reached by conventional drilling methods. However, these sources actually exist in hot, hard, igneous rocks, which no conventional drill of usefully large diameter is capable of penetrating at a reasonable rate. The existence of these enormous energy reservoirs is well known; it is the difficulty of penetrating them and the probable absence of useful amounts of steam that has so far prevented their exploitation.

The urgent need of the United States for new energy sources that will not aggravate the existing environmental pollution crisis indicates that research on and development of artificial hydrothermal energy systems based on Type II geothermal sources should be concomitant with Subterrene development. The following examples are intended to demonstrate that, in addition to affording possible solutions to the existing electrical power and pollution crises, a GTE system offers useful energy in other forms, and that its comprehensive exploitation could have a profound effect on future urban development.

The Jemez Caldera

The town of Los Alamos, New Mexico, is situated at an elevation of about 7000 ft on a plateau east of the extinct Jemez volcano. The geologic history of this volcanic mass has been studied extensively, both for its inherent geologic significance and for the existence of potential underground water supplies for the town (Ross *et al.*, 1961; Conover *et al.*, 1963; Griggs, 1964). Briefly, its history is this:

Volcanism in the Jemez region probably began during the Miocene period, about 10 million years ago. At that time, eruption of a series of massive andesite and latite lavas built up a typical volcanic cone, probably similar to Mt. Hood, which reached a final height of about 14,000 ft and a base diameter of about 30 miles. A quiet period followed, during which erosion formed canyons radiating from the summit. (These are still visible in details of the present caldera rim.) Then, during the late Pliocene or early Pleistocene period, about one million years ago, there occurred a succession of massive radial ash flows which built up the Pajarito Plateau on which Los Alamos is located. Expulsion of this material from within the volcanic mass permitted collapse of the remaining surface of the cone to form a large caldera that

TABLE F-I

GEOTHERMAL ENERGY RESOURCES OF THE CONTINENTAL UNITED STATES

Type of Source	Depth range in km for useful power	Geothermal gradient, °C/km	Temperature range at useful depth, °C	Total thermal energy, gigawatt-years	Available electrical energy, gigawatt-years	Number of years operation at 3000 gigawatts[(a)]
I	15 - 30	20	300 - 600	5×10^9	10^9	3×10^5
II	3 - 10	100	300 - 1000	10^8	2×10^7	7×10^3
III	0 - 3	--	100 - 200	2×10^4	10^3	0.3
IV	0.5 - 3	--	200 - 500	2×10^4	4×10^3	1.3

[(a)]The projected electrical requirement of the United States for the year 2000.

eventually reached a maximum diameter of about 16 miles. The final major volcanic event was the formation of about 15 extrusive domes of a very viscous rhyolite lava. These domes fill much of the caldera floor, and at depth may grade into a single mass.

A straightforward heat-flow estimate shows that the heat from the early volcanic activity in the Jemez region, including both the initial cone-building and the subsequent ash flows, has been dissipated almost completely. However, the relative youth of the rhyolite extrusions (less than one million years) and their close spacing within the large caldera suggest that rock temperatures at depths of 3 to 5 km may be as high as 700 to 800°C. Exploratory wells drilled through sediments in the caldera have encountered temperatures as high as 250°C at depths of about 1 mile (1.6 km), where the drill holes had just entered the rhyolite (Summers, 1965; U. S. Senate, 1964). What may represent the discovery of commercial-quality steam has recently been announced (Los Alamos Monitor, October 22, 1970). After four unsuccessful wells had been drilled, the fifth, in the western part of the caldera, encountered steam at a depth of 5000 ft (1.5 km). Since loose sand was encountered in the same hole at 4800 ft, it appears that the steam is probably generated from circulating ground water entering through the permeable sand. This, then, at least locally, is a Type IV geothermal energy source. Its rate of energy production and probable life as an energy source are unknown, and will be determined by such factors as rock temperature, water supply, and the heat-transfer area available at depth.

Figure F-1 is adapted from a map prepared by the U. S. Geological Survey (Smith *et al.*, 1970), to show a potential Type II geothermal energy source underlying the town of Los Alamos at a modest depth, and a possible location for a geothermal energy plant designed to exploit it. A method for developing a source of this type is outlined in the next section.

Development of the Los Alamos Geothermal Energy Source

On the basis of the regional geology, drilling experience in the Jemez caldera, and approximate heat-flow calculations, the rock temperature at a depth of about 3 km under the Los Alamos townsite is assumed to be 300°C. At this depth, the rock is Precambrian granite, assumed to have the properties listed in Appendix D.

After preliminary testing, perhaps by diamond core drilling to the maximum depth possible, a hole 40 cm (about 16 in.) in diameter would be produced with an Electric Subterrene to a depth of approximately 5 km. This hole would be cased with steel pipe, which would be plugged and perforated at a depth of about 4 km to allow hydrofracturing to occur from that point. Water at a pressure of about 100 kg/cm^2 (1500 psi) would then be injected from the surface to form and extend a thin, circular, vertical crack centered at the 4-km depth. The work required to produce the crack is approximately the product PV, where P is the pressure (100 kg/cm^2) and V is the crack volume. For a crack having a radius of 1 km (3300 ft), the volume is about 5.3×10^5 m^3, and the work is 5.3×10^{12} joules. A 700-hp pump would require about 3 months and 1.3×10^8 gal of water to form such a crack. A technique developed by the petroleum industry is hydrofracturing with a sand slurry, so that when the pressure in the cavity is released the sand will act as a permeable prop to keep the crack open. In the present case, a water slurry containing about 20% of carefully sized silica sand would probably be used for this purpose.

Another hole of the same (40 cm) diameter would be produced to intersect the upper region of the crack, at a depth of about 3 km. (This hole represents the hot-water exit of the geothermal system.) The hydrofracturing port at the 4-km depth would then be sealed and a new opening would be formed at the bottom of the original hole, at the 5-km depth. The system, illustrated in

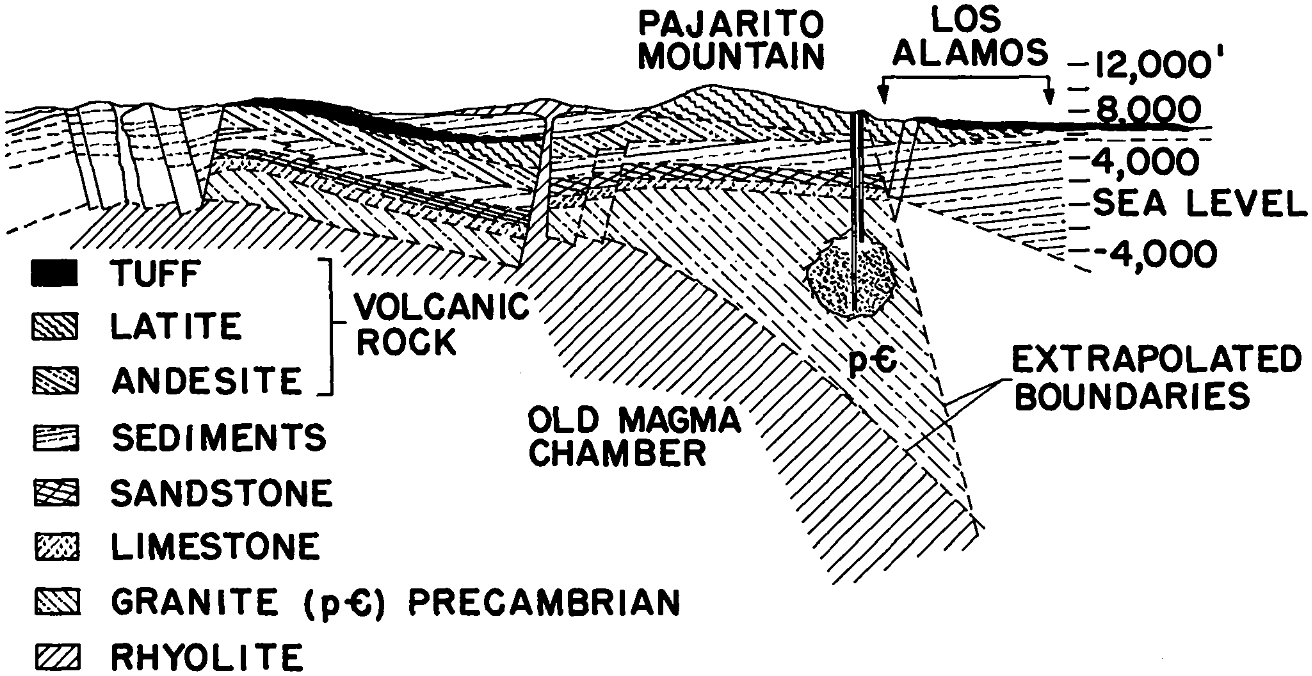


Fig. F-1.
A geologic section through the Jemez caldera and the surrounding area, indicating a possible site for a geothermal energy development near the town of Los Alamos, New Mexico. (Adapted from R. L. Smith et al., 1970).

Fig. F-2, would then be ready for the extraction of energy.

The heat-flow properties of this system (Carslaw and Jaeger, 1959) are such that temperature, T, of rock at a distance x (in centimeters) from the crack after time t (in seconds) is given by

$$T(x) = (T_o - T_c)\,\mathrm{erf}\,(x/2\sqrt{Dt})\ ,$$

where D is the thermal diffusivity of the rock. The gradient of temperature at the crack surface is

$$dT/dx\,\big|_{x=0} = (T_o - T_c)/\sqrt{\pi D t}\ ,$$

where T_o is the original temperature of the undisturbed rock and T_c is the temperature of the crack surface. Assuming that heat is removed so that the temperature of the water leaving the system is always the same, then $\overline{T}$, the average value of $T_o - T_c$, is

$$\overline{T} = \tfrac{1}{2}(T_o - T_{in} + T_o - T_{out}).$$

If $T_o = 300°C$, $T_{in} = 50°C$, and $T_{out} = 250°C$, then $\overline{T} = 150°C$.

Heat flow at any given time is given by

$$q = \lambda A \overline{T}/\sqrt{\pi D t}\ ,$$

where A is the total surface area of the circular crack and λ is the thermal conductivity of the rock. The total amount of heat withdrawn after time t is

$$H = \int_0^t \frac{\lambda A \overline{T}}{\sqrt{\pi D t'}}\,dt' = \frac{2\lambda A \overline{T}}{\sqrt{\pi D}}\sqrt{t}\ .$$

With a radius of 1 km, the crack area is about 6×10^{10} cm^2. For $\overline{T}$ of 150°C, the amount of heat withdrawn after 20 years is about 650,000 MW-days (1.3×10^{16} cal), giving an average rate of 89 MW.

Removal of heat from a body of rock results in a volume contraction, ΔV, given by $-\Delta V \cong 3 H \overline{\alpha}/c\rho$, where $\overline{\alpha}$ is the linear coefficient of thermal expansion in °C^{-1}, c is the heat capacity of the rock in cal/g-°C, and ρ is the rock density in g/cm^3. This thermal contraction will result in fracturing of rock adjacent to the primary crack (Appendix D). An extensive treatment of an analogous system, the cooling of a solidified lava bed, is given by Lachenbruch (1961). His work indicates that contraction cracks extend far beyond the thermally stressed zone. The thermal contraction resulting from extraction of heat equivalent to 4000 MW-days (8×10^{13} cal) will produce an additional crack volume of 2.4×10^9 cm^3, or about 0.5% of the volume of the original crack. If this new volume is represented by cracks with an average thickness of 0.5 cm, then the increment of heat-transfer surface created is 10^{10} cm^2, or about 20% of the surface area of the original crack. Thus, removing less than 1% of the immediately accessible thermal energy of the hot rock makes available a much greater amount of energy, whose

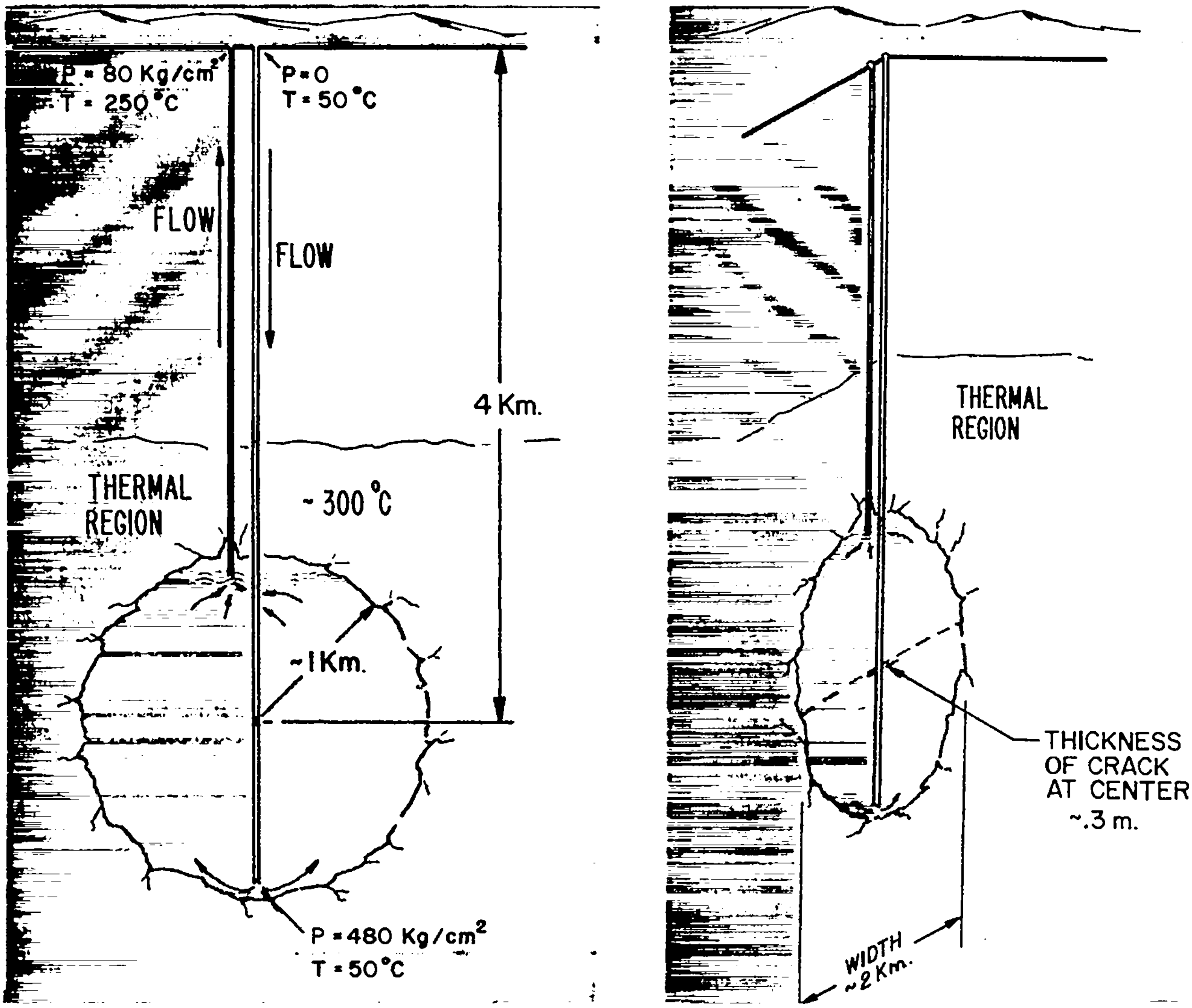


Fig. F-2.
Proposed system for developing the Los Alamos geothermal energy source.

removal will further increase the proportion of the heat reservoir that can eventually be exploited. The general nature of the crack system created is suggested by Fig. F-3.

This simple analysis indicates that a heat-extraction system consisting of two large holes penetrating a Type II geothermal energy source, plus a large initial crack produced by hydrofracturing, will be self-perpetuating in the sense that removal of heat from it will make even more heat available to it. Thermal-stress cracking will be concentrated in regions where the thermal gradient due to heat removal is greatest. This will probably be where initial rock temperatures are highest. The spontaneously generated crack system should therefore extend preferentially into regions of increasing temperature, so that the quality of the steam produced may actually improve with time until nearly all of the energy reservoir has been made available to the heat-transfer fluid. If, as seems possible, the downward extension of the geothermal reservoir is a column of rock of continuously increasing temperature extending as far as the earth's mantle, then the useful life of the energy extraction system may be practically unlimited.

Circulation of the amount of water (2×10^6 gal/day) required to extract energy at the rate of 89 MW will be produced by the pressure head (about 100 kg/cm^2) that results from the density difference (about 0.2 g/cm^3) between cold water entering the thermal reservoir and hot water leaving it. The flow of this volume of water through the 40-cm-diam supply and return pipes will be turbulent, resulting in a pressure drop of about 30 kg/cm^2 in the piping. Its flow through the circular bed

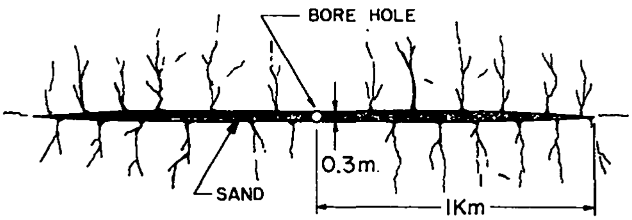


Fig. F-3.
Section through a sand-filled vertical crack produced by hydrofracturing, showing probable trends of additional cracks created by thermal stresses resulting from heat removal.

filled with fine gravel will involve an additional pressure drop of about 0.5 kg/cm^2, calculated from Darcy's law (Todd, 1959) and an assumed permeability of 160 kg/cm^2-day under unit hydraulic gradient . Thus, once circulation has been established by pumping cold water down the supply pipe, hot water at, say, 250°C will be brought to the surface spontaneously by the return line at a pressure of about 70 kg/cm^2. This is well in excess of the vapor pressure of water at 250°C (about 40 kg/cm^2), so that a liquid system will be maintained throughout. (This is considered an advantage because water--unlike steam--decreases in viscosity as its temperature increases, so that the mode of heat removal in the reservoir should be uniform, and because the thermal properties of water do not change markedly with pressure.) The excess pressure of about 30 kg/cm^2 above that required to maintain a condensed phase would permit the flow to be approximately doubled during periods of peak energy demand.

Banwell (1964) discusses the amount of electrical energy that can be produced from steam and hot water by an ideal heat engine. Using his figures and assuming 50% plant efficiency, a 10-MW electrical generating capacity would require a flow of 80 kg/sec (2 x 10^6 gal/day) of water at 250°C. The thermal energy available from this water, measured above 50°C, is about 65 MW. Hansen (Paper G/41 in United Nations, 1964) describes a multiple flashing cycle for production of electrical energy from water at 200°C. A similar cycle for water at 250°C is presented in Fig. F-4. With a flow rate of 80 kg/sec of water at 250°C and 40 kg/cm^2 pressure, which are reasonable for the underground system described above, an electrical output of 9.74 MW is predicted. To avoid the difficulty with dissolved minerals discussed in Appendix E, the thermal energy of the geothermal water is extracted in a primary heat exchanger and the mineral-bearing water is returned to underground circulation. Alternatively, a demineralizer could be used, and the demineralized geothermal water could be piped directly to the flash tanks. If desired, 55.9 kg/sec of water at 89°C could be withdrawn from the third flash tank for domestic heating or other uses.

The average per capita consumption of electrical energy in the United States for household and commercial purposes is about 0.8 kW (Singer, 1970). Thus, the power plant described above would supply the needs of a residential community of about 12,500 people. This development, with its original crack area of 6 x 10^{10} cm^2, could provide 89 MW (thermal) for 20 years to produce that amount of power continuously. However, it is believed that the increase of heat-transfer surface which results from heat removal would, in fact, prolong the useful life of the system far beyond 20 years.

A Geothermal-Energized Community

The geothermal energy system described above appears to be relatively inefficient, since it generates only about 10 MW of electricity from 65 MW of thermal energy. Apparently it can be justified economically only if the thermal-energy cost is low or if a premium can be paid for some special advantage of the system. In fact, a geothermal system can be justified either on the basis of low energy cost or because it minimizes environmental pollution. Further, it offers the possibility of a multiple-use system that would both improve its economic position and benefit society in other ways.

The heating of homes by hot water obtained from geothermal sources has been used with increasing success in Iceland since 1930, and is described by Bodvarsson (Paper GR/5 [G] in United Nations, 1964). Experience there shows that the optimum temperature of the domestic source is about 90°C, and that the maximum heating rate needed per capita is about 400 cal/sec. The hot water can be piped economically to many thousands of homes at distances up to 100 km from the geothermal well. Using these figures, it is calculated that the water at 89°C discharged from the final flash tank of the electrical power system outlined in Fig. F-4 could provide domestic heating for a town of 10,000 people under the most severe winter conditions. It could also supply all other domestic needs for hot water–for bathing, washing clothes and dishes, etc. Distribution of the primary hot water, at 250°C, would permit higher-temperature uses, such as cooking and clothes-drying.

The dual problem of obtaining adequate amounts of potable water and of purifying this water after it has been used is a major concern of modern society. The problem is compounded by the thermal pollution caused by energy wasted into rivers, by heavy rains that overwhelm waste-treatment plants, by industrial wastes that are not treated at all, and by other accidents and harmful practices. Its solution may lie in another application of geothermal energy.

A typical American community of 10,000 people

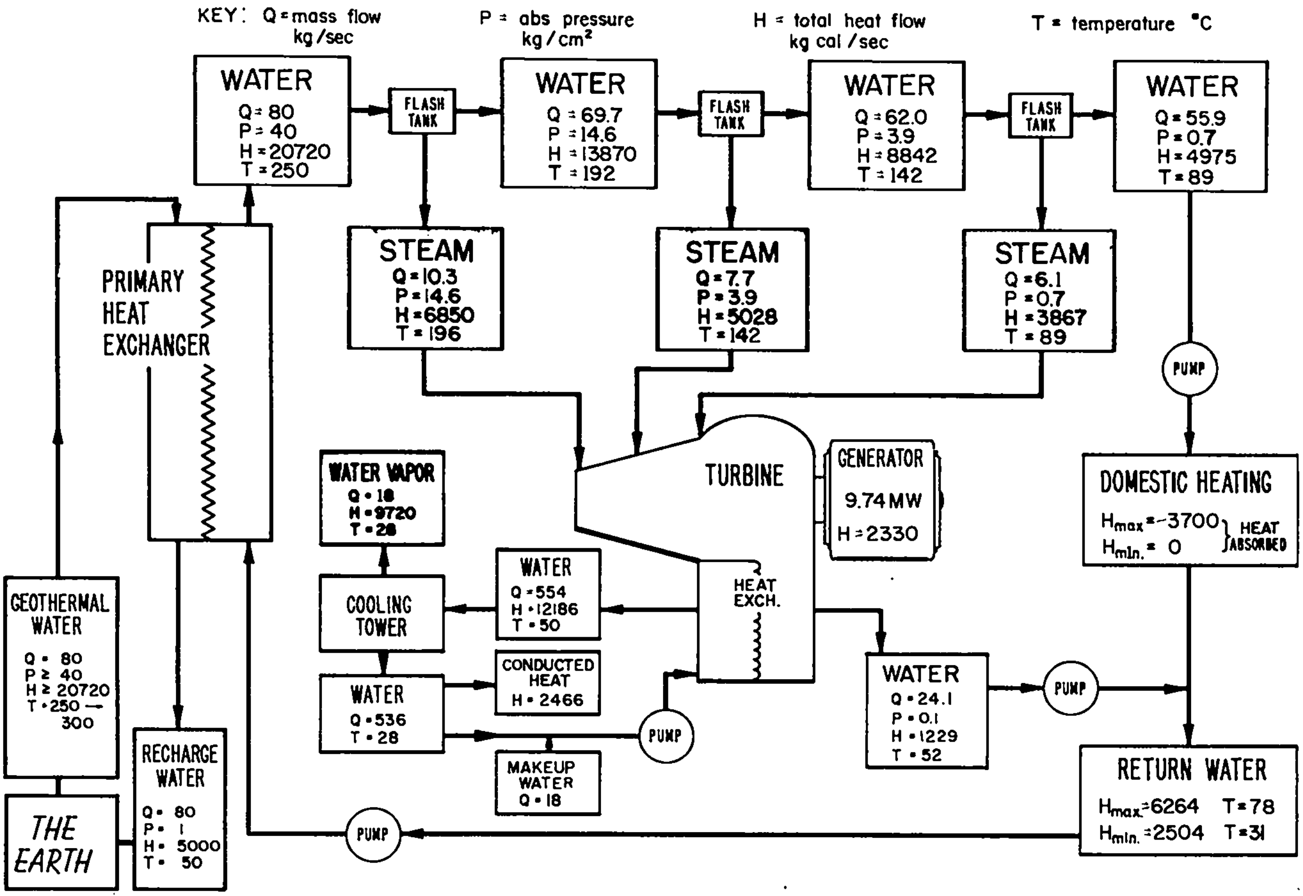


Fig. F-4.
A multiple-flashing cycle for electrical-power generation from geothermally heated water at 250 to 300°C.

uses over two million gallons of water per day. In general, this water is carefully processed to render it potable. However, even the best present systems will not remove certain chemical compounds (such as DDT) when they are present, and the chlorination required to destroy bacteria and viruses often leaves an offensive taste. A large fraction of the water is subsequently delivered to and processed by a waste-treatment plant and is finally discharged into rivers where, it is hoped, natural processes will again produce potable water. However, the next community downstream must, in fact, process it again, and the section of river between the two communities is often unattractive for recreational activities and is hostile to fish and plant life.

The only system that will guarantee a truly pure water supply is distillation. If geothermal energy is available, the community can draw on it to operate a multiple-effect distillation system which, because of the low impurity concentration in the feed stream, would require the minimum of distillation work. Such a system is outlined in Fig. F-5, where 37 kg/sec of water at 250°C from the geothermal source are used to distill 80 kg/sec (2×10^6 gal/day) of impure water. The system consists of optimized heat exchangers. Using heat-transfer coefficients from Perry (1950), and the temperature differences indicated in Fig. F-5, a total heat-transfer area of 4000 m^2 (44,000 ft^2) is calculated.

The best treatment for a flow-through water system would be to distill the incoming water for health and esthetic reasons, and the sewage effluent for the same and also for ecological reasons. If the public, through education, could be assured of the complete purification that heat sterilization-distillation affords, then a closed-loop system could be used, eliminating one distillation step and greatly reducing the demand on the natural water supply. The two types of systems are compared in Fig. F-6.

The remaining large energy requirement of the typical American community is transportation, primarily in the form of the private automobile. In an analysis of total energy use in the United States, Singer (1970) assigns a per capita use of 2 thermal kW (500 cal/sec) for transportation. This can be translated into a per capita distance traveled per day: If all transport is by automobile, energy use is 0.5 gal/mile, and if 1 gallon of

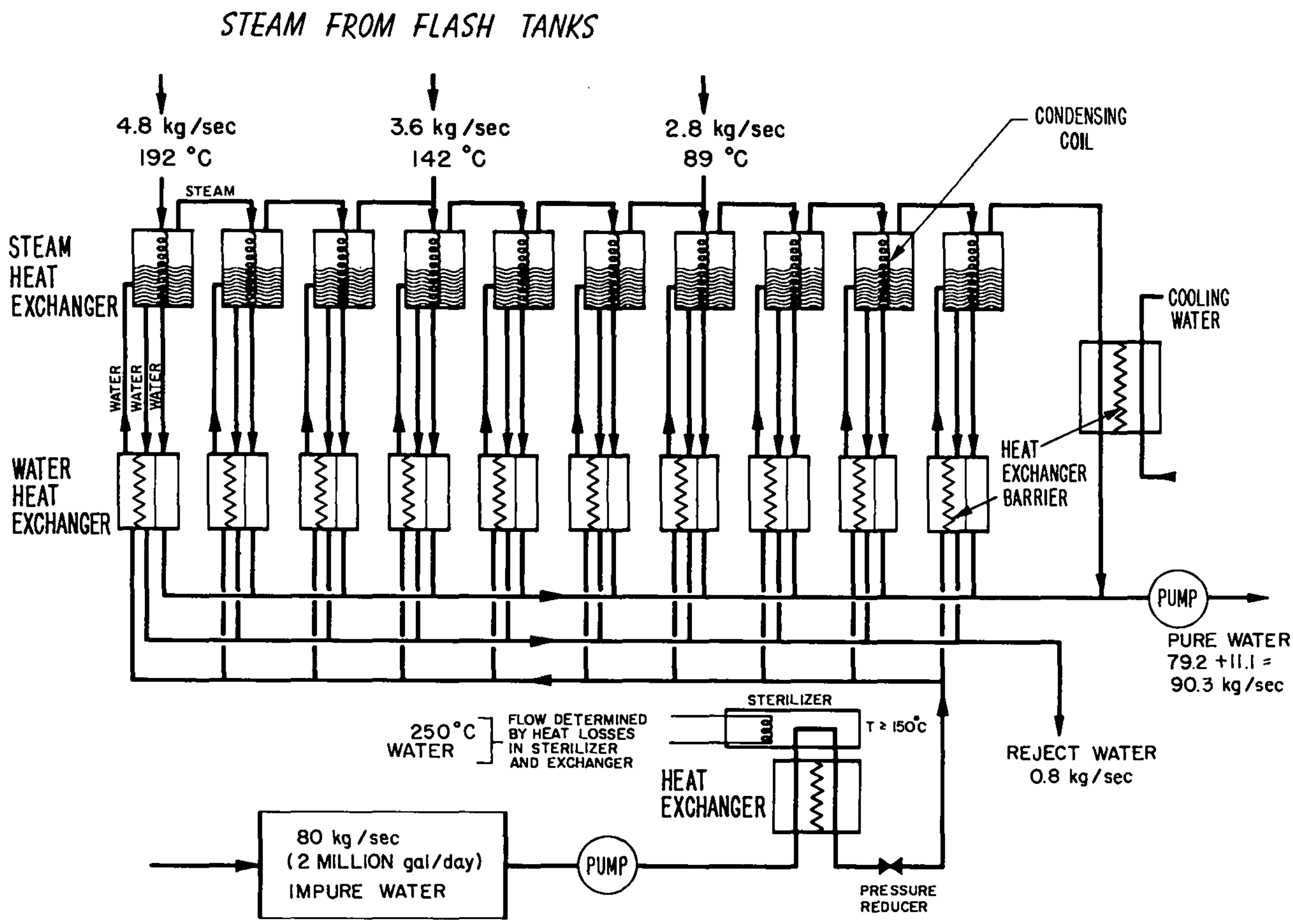


Fig. F-5.
A multiple-effect distillation system using steam from the flash tanks of a geothermal power plant.

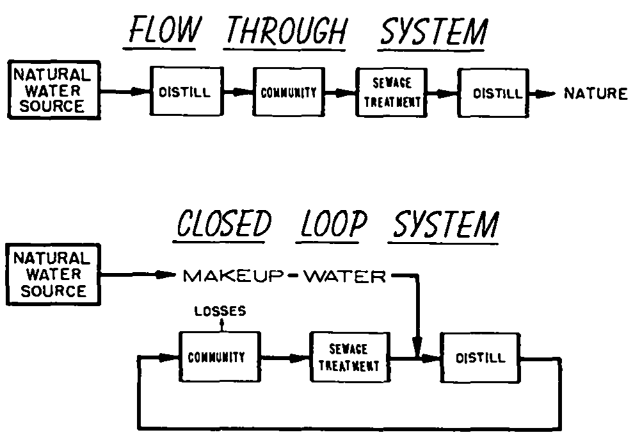


Fig. F-6.
Flow-through and closed-loop systems for water purification.

gasoline contains 32 x 10^6 cal of energy, then the equivalent distance traveled is 27 miles/day per person.

The unique feature of the geothermal system here being considered is its capability of delivering large amounts of water at 250°C. The question that now arises is whether or not this represents an energy density high enough to power vehicles economically. Hoffman (1966) presented a case for electric automobiles fueled by the more interesting types of storage batteries, such as the zinc-air type. He lists predicted performances (range vs speed under various driving conditions) for cars one-half of whose weight is batteries. A turboelectric system driven by flash steam from 250°C water would provide an available energy density of 6300 cal/kg of water carried. In Fig. F-7, the range of a vehicle powered by such a system is compared with that of one powered by lead-acid batteries, with one-third of the vehicle weight representing the energy source in each case. Evidently, the hot-water unit is competitive in this regard. A community whose main energy source was geothermal energy could provide a net of outlets at which refueling with hot water could be done rapidly and automatically. The 27 mile/day

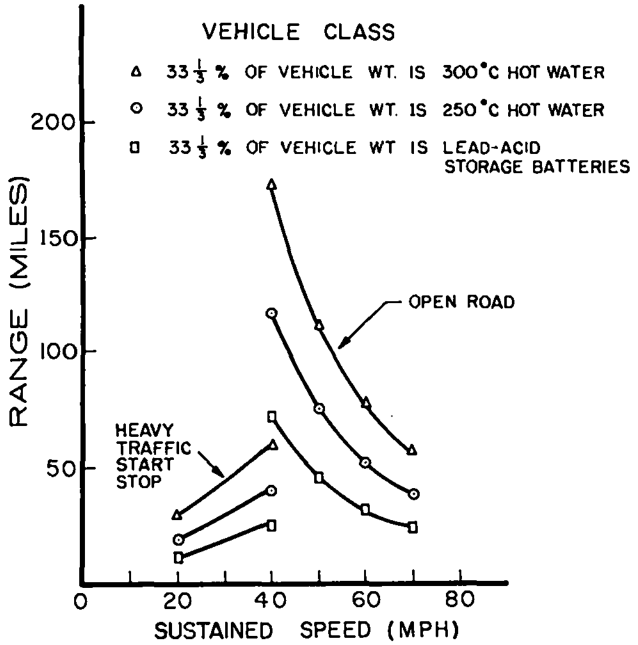


Fig. F-7.
Ranges of hot-water and storage-battery powered automobiles under various driving conditions.

per capita rate could be attained with 8 kg/sec of hot water, or less than 10% of the total geothermal flow contemplated for the community. It would, of course, be natural to extend such a system to widespread public transportation and commercial traffic.

If other methods of energy storage, such as very high-speed flywheels (Armagnac, 1970) and advanced types of storage batteries (Hoffman, 1966), prove successful in automotive applications, the contribution of geothermal energy will be in the primary energy-transfer system. The use of an emission-free electrical automobile, for example, merely shifts the source of pollution from the vehicle itself to the fossil-fueled power plant that generates electricity for it. An increase in capacity of a geothermal power plant would provide the electrical energy required by such a transportation system without adding pollutants to the atmosphere.

Figure F-8 outlines a complete utility system for a community of about 10,000 people supplied with geothermal energy. Aside from the transport system, which would require engineering development, all of the material and equipment required is currently available commercially. The system is complex, and it would not be easy to introduce all aspects of it into an existing town; thus, the proportion of homes designed for hot-water heating is now usually small. However, where entire new

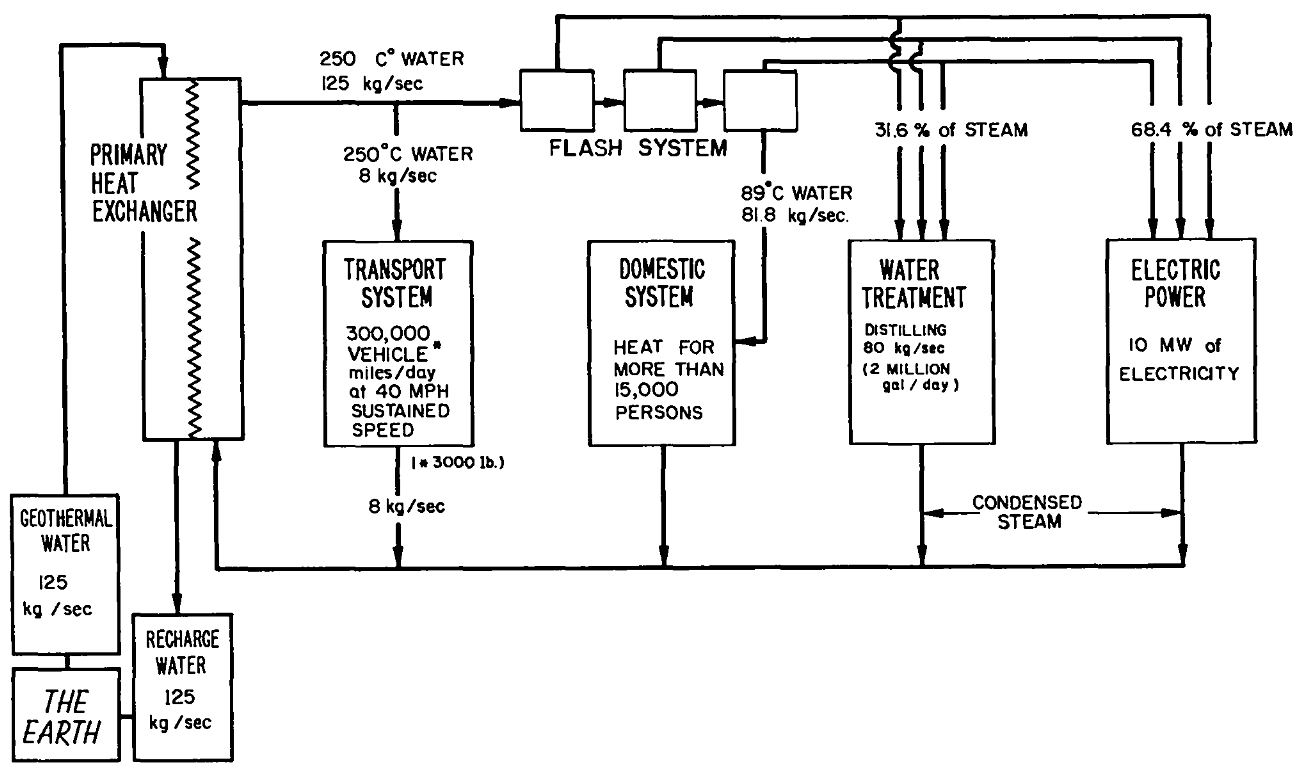


Fig. F-8.
A complete utility system based on geothermal energy.

communities are to be built, a complete utility system based on geothermal energy might be ideal. For example, there are plans to develop at least seven entirely new communities in New Mexico within the next 20 years. The expected total population of these communities is 500,000 (Albuquerque Journal, August 23, 1970) and important questions are being raised about their water supplies, sanitation facilities, and power requirements. It happens that most of these future towns will be located within 10 to 80 km of the Jemez geothermal energy source.

The reasoning applied above to towns applies as well to the needs of an industrial plant (for example, a pulp mill) for electricity, water, heat, and waste treatment. The ability to treat selectively and completely the wastes from each different manufacturing process could eliminate the industrial pollution of waterways.

A relatively simple development of a zone of modest temperature in a Type II geothermal energy source can supply a remarkably large amount of energy for a very long period of time. The energy is in such a form that it can be used to satisfy most of the energy requirements of a modern American community, producing minimum environmental pollution and helping to correct that which already exists. While shallow Type II sources are common only in the western United States, development of the Subterrene would permit probing for them at greater depths elsewhere, and should eventually permit similar development of Type I sources. These are essentially unlimited in extent and energy content, and are potentially available anywhere on the earth.

APPENDIX G

RESEARCH IN THE GEOLOGICAL SCIENCES

by

Orson L. Anderson

One of the most important insights of recent years is the recognition that tectonic activity on a global scale is concentrated in relatively narrow zones, forming a network that surrounds large areas of quiescence. The earth's surface structure is now considered to resemble an eggshell containing a network of cracks that form the boundaries of several large curved plates and a dozen or so small ones. The earth's tectonic zones--the cracks in the eggshell--are the sites of natural events that limit human habitation. Much of the world's earthquake and volcanic activity, and important portions of its mineral resources, are concentrated in these active zones. They must be studied carefully if man is to stabilize the quality of his environment. For example, it is not simply an accident that the Santa Barbara oil spill occurred in an area that was visited by a major earthquake less than 40 years ago.

Geological science has just passed through the stage of developing the time-and-motion relations (i.e., the kinematics) of the large plates comprising the outer shell of the earth. Plates move as individual units, and in discussing them an old nomenclature has been revived: We say that the plates comprise the *lithosphere* of the planet. On the plate boundaries, the forces that modify the exterior of the earth are actively expressing themselves by movements and deformations that can be observed and whose intensities can be measured. These forces create major problems for the populations of the active zones, and the results of the tectonic activity frequently yield extensive mineralizations of economic interest. A deeper understanding of the forces acting on the lithosphere is of critical importance, not only for understanding the dynamics of the planet but also for significant social and economic reasons. Geological sciences are therefore entering an era in which great attention is being given to the geodynamic (as contrasted to the kinematic) processes of the earth.

On the plate boundaries, three types of interactions occur: (1) Divergence occurs at rift zones such as the mid-Atlantic ridge, where upwelling from the underlying zone, called the *asthenosphere*, creates the lithosphere. (2) Collision creates underthrusting of the lithosphere deep into the asthenosphere, where the lithosphere is consumed by chemical processes. Collision also creates trenches, such as the Tonga Trench, and island areas such as the Aleutians. (3) Strike-slip movement, such as the relative motion of adjacent parts of southern California along the San Andreas Fault. This consists primarily of shearing displacements, involving only minor convergence and divergence of plates.

The lithosphere includes the earth's crust and also a portion of the mantle. It is distinguished from the underlying asthenosphere primarily on the basis of its physical properties, particularly its rigidity as determined by seismological techniques. It is not uniform, and is marked by major discontinuities both vertically and, along the tectonically active belts, horizontally. Its lower surface is known only in a general way, but is ordinarily defined through mapping of earthquake foci in the areas of underthrusting.

Between the rift zones lie the stable plates of the lithosphere. The boundaries between plates are not often the same as the boundaries between oceans and continents, and the idea of a continent has lost much of its uniqueness. A stable plate is relatively tranquil but not absolutely so; movements, mainly vertical, take place. Volcanism occurs, and the plate thickens and hardens. Significant vertical displacements, called uplifts, occur over large areas, with extensive deformation on all sides. Two such puzzling uplifts are the Colorado Plateau and the Himalayan Plateau. Such major vertical motions of large regions in the plate interiors are, at present, anomalies in the general scheme of plate kinematics.

Vertical movements, both within plates and at their boundaries, control the occurrence and distribution of many of our important mineral resources. Certainly, the fact that oil and gas are present only in sedimentary rocks restricts their occurrence to areas which at some time have subsided enough to accumulate sediments. Many mineral deposits of metamorphic origin require a history of significant subsidence and subsequent uplift. Many of the traditional theories of economic geology have been discredited as the evidence for plate tectonics has accumulated, and new theories must be sought in their place.

This is the general situation of the new theory of global tectonics, which is now revolutionizing the geological sciences. How can the drilling of a deep, wide hole affect tectonic theory?

By analogy, one might consider the results of drilling series of relatively shallow holes (no more than 1 km deep) across the ocean basins, as has been done in the JOIDES (Joint Oceanographic Institutions Deep Earth Sampling Group) drilling program. The results of this program, still in progress, are considered by many to remove all doubts about the motion of plates from a diverging source. It has been found that the age of the basalt basement of the ocean basin increases linearly with distance from the ridge which represents the source, and that the increase is symmetrical on opposite sides of the ridge. In this drilling program, cores have been taken which will provide a sedimentary history of the earth's crust over a succession of precisely known, interlocking intervals. Thus, we are beginning to acquire a library of the history of the crustal formation of our planet. The dramatic effect of this information from sea-floor drilling upon the revolution in the geological sciences is comparable to the impact of the evidence that Darwan brought to bear upon the biological sciences.

The parts of the plates that comprise continents are much thicker than are those in ocean basins. We need exploration holes drilled in the continents, but this task is even more formidable than that of the JOIDES program because the continental holes must be very much deeper. The ocean basins are recent additions to the plates, generated by upwelling since the time of the dinosaurs, whereas the continents are older, going back to the billion-year epoch in age. A core only 1 km deep, at most, gives much of the history of the crust in ocean basins; a depth of 20 to 40 km will be required to obtain comparable information in the continental interior.

Suppose that it became possible to drill a hole 20 to 30 km deep, the hole lining being hardened and having a diameter large enough so that instruments for physical measurements could be lowered into it. Where should such a hole be drilled?

One obvious place for deep-exploration drilling is the Colorado Plateau. Insofar as plate tectonics is concerned, this region is a mystery. In terms of the general global concept, the lithosphere of the Colorado Plateau is too high, too thin, and too young. It is hard to explain why a structure this thin has undergone so little deformation relative to that which has occurred in the highly deformed Rocky Mountains on the east and the greatly faulted Basin and Range Province of Nevada on the west. Being thin, however, the total crust of the Colorado Plateau can be sampled by cores from a hole no more than about 30 km deep. Another obvious place for drilling is the Midwest, perhaps around Missouri, where the granite basement is deep. This would give a section through a stable, old, and typical aspect of the continental part of a plate. A third place would be the Pacific coastal margin, where one plate is in collision with another. One result is certain: The rocks obtained from these three holes would be different, and all would add immensely to our library of the history of the crust of the earth.

If such holes were drilled, what specific information could be collected from experiments performed within them?

First, at least in the Colorado Plateau, it would be possible to sample the mantle material *in situ*. Information on the composition and properties of mantle material is vital to all geophysical and geochemical theories of planet interiors. It represents the integrating constant (which, when it has not been measured, must be assumed) in the density profile of the earth arrived at by integrating sound-velocity profiles. Further, the mantle rock is the mother material which, upon differentiation through melting and other phase changes, ultimately produces the great variety of materials we see in the crust. It is too much to expect that one sample of the mantle would be typical and would end all disputes. It is not too much to expect, however, that even one such sample would have a profound effect upon the geological sciences. It is easy to construct reasonable arguments that the worth of recovered mantle samples of our own planet is comparable to the worth of the returned lunar samples.

Second, it would be possible to make precise temperature measurements at depths much greater than those so far reached. Information on the thermal gradient down to 20 to 30 km would provide a striking insight into the thermal history of the planet. At the earth's surface, the gradient is about 20°C/km; at 200 km depth, it is evidently down to something like 4°C/km. However, our knowledge in this area is limited by the fact that we can now make measurements only at or very near the earth's surface. A more precisely determined thermal gradient is essential to geodynamical theories of the motion of the earth's interior, because such theories must account for heat transfer.

Third, the possession in the laboratory of a stratigraphic column descending to formations deposited billions of years ago would elucidate the history of the early formation of the crust.

Fourth, the recovery of samples of material adjacent to the rim of the hole at various depths might extend the magnetic calendar of our earth by an order of magnitude in time. The magnetic calendar, which is essentially a record of the reversals of the earth's magnetic poles, is known largely from investigations in the earth's ocean basins, and extends back only 50 to 100 million years.

Fifth, the actual determination of the density profile down to the crust-mantle boundary would provide a very careful check on two geophysical disciplines: seismology and gravity. In both of these disciplines, the interpretation of measurements depends on the trade-off of density against depth assumed in the particular model chosen.

Sixth, the use of metrology in the hole could provide a careful determination of relative motion around the hole. We speak of the motion of rigid plates, but it may turn out that a plate moves like a glacier–in which case the hole would be deformed by the motion of rock around it. Thus, a check could be made on one of the fundamental notions of plate tectonics.

APPENDIX H

OTHER APPLICATIONS OF LARGE SHAFTS AND TUNNELS

The list of existing and potential uses for large-diameter holes penetrating the earth to significant depths is nearly endless. A few of these uses were considered briefly in the body of this report, and some were further discussed in Appendixes E, F, and G. Several additional applications of large holes are reviewed in the paragraphs that follow.

Hydrogen Storage

Hydrogen exists in almost unlimited quantities in the biosphere, and the technology already exists for separating, liquefying, transporting, and storing it in very large quantities. Liquid and gaseous hydrogen could eventually replace fossil fuels in every application in which fuel is now burned for thermal energy, and this substitution could be made almost immediately with only minor modifications to existing distribution systems and consumer appliances. Internal-combustion engines and turbines can operate on hydrogen burned with air at temperatures low enough so that nitrogen oxides are not formed, or with oxygen so that nitrogen and other gases do not enter the combustion system. Hydrogen-oxygen fuel cells are becoming common as portable generators of electricity. In all of these cases, the only combustion product is water vapor, which can safely be released to the atmosphere. This use of hydrogen would produce no contamination of the environment, and would save the limited supply of fossil fuels for more important uses in chemical synthesis.

Generation of electrical power from steam or other energy sources is most efficient if it is done at a constant rate near that for which the particular power plant was designed. However, in most areas, power demand varies drastically with the time of day and season of the year. Means of utilizing the excess generating capacity that exists during slack periods are now being sought, since electrical energy itself is difficult to store. It should, however, be possible to "mine" geothermal energy or to operate a conventional power plant at a constant rate and use the relatively inexpensive excess energy available during low-demand periods to electrolyze water. The hydrogen and oxygen produced could then be stored separately underground either as liquids or as compressed gases, to be withdrawn and used when they were needed for heat, propulsion, or generation of additional electricity during peak-demand periods.

Other Means of Storing Energy

It is reported (Business Week, August 1, 1970) that engineers in several European countries are now developing another method of storing energy underground in the form of compressed air. During low-demand periods, excess power would be used to compress air and pump it into underground caverns. During peak periods this air would be released through turbines to drive electric generators. A cavity suitable for storing the air must be tightly sealed to prevent leakage, and must be large enough to contain a useful volume of air and still small enough so that relatively high pressure (e.g., 600 psi) can be developed in it during a pumping period of a few hours. A Swedish firm, Stal-Laval, has proposed a system which would require a shaft 1400 ft deep and 20 ft in diameter, leading into a 4.8-million ft^3 cavern. For a 220,000 kW plant of this type, they estimate a construction cost of about $43/kW, of which about one-third would be for excavating the shaft and storage chamber. This is less than their estimated cost of a pumped hydroelectric storage plant, such as that proposed by Consolidated Edison for Storm King Mountain, New York (which has been violently opposed by conservationists), and it could be constructed with much less scarring of the surface landscape.

Chemical Processing

The high-temperature, high-pressure environment that exists beneath the earth's surface is ideal for many chemical processes. Ore bodies discovered by drilling and, if necessary, made permeable to liquids by hydrofracturing or the use of explosives could in many cases be exploited by introducing leaching solutions at the surface or through a set of holes above the mineralized zone, permitting the solutions to percolate through that zone, and recovering them in horizontal tunnels in the barren rock below the ore body. Fossil fuels could be pyrolyzed, hydrogenated, or partially oxidized in place, and the carbonaceous gases could be recovered in similar systems of tunnels for use as fuel gases or for production of petrochemicals. Most of the waste products from such an operation would be left in place underground, and the rest could be returned to the cavities created when the valuable minerals were extracted.

Scientists working for the U. S. Department of the Interior have produced useful fuel oil from domestic garbage and other wastes (Industrial Research, June 1970). One ton of wet urban refuse treated with carbon monoxide and steam at 250°C and 1500 psi (105 kg/cm^2) pressure yields more than a barrel of low-sulfur oil. According to the National Research Council (*ibid.*), if antipollution standards on sulfur dioxide were rigidly enforced nationwide, there would not be enough low-sulfur fuel available to meet the present demand just for generating electric power. The pressures and temperatures in deep holes are well suited for converting garbage and other wastes into such an oil, which would contribute both to garbage disposal and to a reduction in air pollution by oil-fueled power plants. (Wood by-products and sewage sludge can also be processed into oil. However, the sulfur content of the oil produced from these materials is about 0.5%.)

High-Pressure Treatment

In estimating the relation between pressure and depth in the earth, the usual approximation is to consider that the earth is made up of a heavy hydrostatic liquid. At depths greater than about 20 km, this "lithostatic" approximation is fairly accurate, because the pressure is comparable to the strengths of the rocks. At the Mohorovicic discontinuity under the continents, the calculated rock pressure is about 9 kbar. A large hole extending to this depth would make available a relatively inert environment in which high-pressure experiments, and perhaps industrial processing, could be carried out on a scale now unattainable on the earth's surface.

In one of his last papers, Bridgman (1963) pointed out that the cascading method of supporting vessels, by nesting them in outer vessels, offered the most promising solution for extending the available range of hydrostatic pressures. An obvious difficulty is that each successive containing chamber is much larger and more complex. Bridgman was able to construct only a two-stage apparatus, in which he measured the compressibilities of materials up to 100 kbar. However, he visualized equipment the size of a cyclotron, which, with normal design and construction, would be enormously expensive. The high lithostatic pressures in the wall rock around a deep hole might be used to provide cascading support for experimental vessels within the hole, and so permit a considerable extension of the range of hydrostatic pressures now available to the experimentalist.

Heat Sinks

Thermal pollution produced by hot water discharged into streams and lakes by factories and power plants is now a serious problem in many parts of the world. Where geothermal gradients are at or below normal, rocks at shallow and moderate depths can be used to dissipate or store excess heat from such sources. Thus T. Lindbo, an engineer of the State Power Board of Sweden, has proposed (Design International, May 28, 1970) that radiator-like arrays of elliptical tubing be housed in rock formations, and that hot water from a nuclear power station be circulated through them. Excess heat would be deposited in the rocks, and the water would be returned to the reactor at near-ambient temperature for reuse as a coolant. A second circulation system might be used to recover the excess heat from the rocks and use it for domestic heating in about 10,000 nearby family units.

Heat-exchange systems of this type are potentially useful for a wide variety of industrial operations, and appear promising for combating a type of environmental pollution that has become common. They would, of course, be especially convenient for power plants or manufacturing facilities which were themselves built underground.

Cities

In addition to underground power plants, water supplies, sewage systems, transportation, factories, and warehouses, it is evident that cities of the future must eventually be built downward as well as upward and outward. The advantages of doing so have already been realized in several school systems in the United States, including that of Artesia, New Mexico. The underground temperature is nearly constant throughout the year, minimizing heating and air-conditioning requirements. There are no distractions from outside lights, traffic noise, and aircraft. No maintenance is required of a building exterior, and off-hours vandalism is nearly impossible. Lighting costs are insignificant, and with skillful interior decorating the underground environment can be very pleasant. Expensive surface land is preserved for athletic and recreational facilities and green areas. As pollution, noise, and congestion increase on the surface, the concept of a subterranean city in a "temperate zone" beneath the surface becomes more and more attractive.

Agriculture

Not only mushrooms, but also flowers, vegetables, and even grasses are grown commercially underground. Hydroponic systems are normally used, with ultraviolet lighting, and in some cases (e.g., in growing barley for cattle feed) the operations have become highly mechanized. The environmental advantages are apparent, and the growing season is unlimited. With increasing land costs and pollution problems on the earth's surface, underground farming and gardening are certain to expand.

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