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ROCK MELTING TECHNOLOGY  
AND GEOTHERMAL DRILLING

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National awareness of the potential future shortages in energy resources has heightened interest in exploration and utilization of a variety of geothermal energy (GTE) reservoirs. The status of conventional drilling of GTE wells is reviewed briefly and problem areas which lead to higher drilling costs are identified and R&D directions toward solution are suggested. In the immediate future, an expanded program of drilling in GTE formations can benefit from improvements in drilling equipment and technology normally associated with oil or gas wells. Over a longer time period, the new rock-melting drill bits being developed as a part of the Los Alamos Scientific Laboratory's Subterrene Program offer new solutions to a number of problems which frequently hamper GTE drilling, including the most basic problem - high temperature. Two of the most favorable characteristics of rock-melting penetrators are their ability to operate effectively in hot rock and produce glass linings around the hole as an integral part of the drilling process. The technical advantages to be gained by use of rock-melting penetrators are discussed in relation to the basic needs for GTE wells.

The present status of the Subterrene Program in the development of rock-melting penetrators for hard, hot rock drilling is reviewed. Extruding penetrators which condition the melt into predictable debris forms, i. e., glass rods, pellets or rock wool, have been developed and utilized in a variety of igneous and metamorphic rocks. A field test system for shallow hole experiments is being developed and the preliminary results are reviewed.

I. INTRODUCTION

This brief summary report will first review the status of geothermal well technology, which includes drilling and operational problems especially related to geothermal wells, and cost comparisons are made. This survey is a result of an extensive review of the literature and the published data. It is also the result of many personal discussions with individuals in the

various elements of the drilling and geothermal energy (GTE) industries. This survey and the detailed results and conclusions reached are contained in a report (Ref. 1) recently issued by the Los Alamos Scientific Laboratory. It is concluded that short-term improvements in current drilling technology can solve some of the problems encountered in GTE wells, especially those associated with the higher temperatures, and potentially produce significant reduction in drilling costs.

To develop and greatly expand the use of GTE in the future, new drilling methods and equipment are needed to penetrate hard, abrasive, rock and to provide hole stabilization and support at the very high temperatures and other extreme conditions which are encountered in GTE wells. The second portion of this report reviews the concepts and status of one such new technique — rock melting, indicates the status of the program to develop a prototype rock melting GTE penetration system, and indicates how such a system may solve some of the GTE well drilling problems and result in further cost reductions.

## II. STATUS OF CURRENT DRILLING TECHNOLOGY

It is well established that drilling technology plays a major, often pacing, role in both the exploration (Ref. 2) and production (Ref. 3) phases of GTE reservoir development. For the purposes of this summary and to characterize the general situation, we will review the data from the two major GTE reservoirs where the majority of U. S. drilling has been conducted: The Geysers field and the Imperial Valley.

The Geysers field is characterized by:

- (1) Dry steam at 180–240°C (360–460°F) and 3400 kPa (500 psi).
- (2) Jointed, fractured, hard rock, ~50% of drilling time used to change bits.
- (3) Difficult terrain for site preparation.
- (4) Heavy duty rigs required.
- (5) Difficult well completions; use of air causes exceptional air-steam erosion.

And in the Imperial Valley:

- (1) Hot brines at 260–360°C (500–680°F) at high pressures.
- (2) Sedimentary formations.
- (3) Flat geography, accessible sites.
- (4) Smaller rigs.

The well depths are quite similar, 1.5 to 2.0 km (5000 to 6000 ft), with high temperature circulating muds (or air) required with surface heat exchangers, and elevated temperature cements used in the well casing programs. The detailed drilling conditions at these two areas are summarized in Tables 1 and 2.

The influence of these factors on costs is summarized in Fig. 1, where average total well costs in 1972 at depths of 1.5 km (~1 mile) for the two areas are compared to the average cost experience for oil and gas well drilling. We note that the cost of the Imperial Valley wells is approximately twice that of oil and gas wells, and for The Geysers field the factor is four to five. The enhanced costs in the Imperial Valley might be those associated primarily with higher temperatures and the additional increments at The Geysers are attributed to geological complications and more difficult completions. The causes of the additional cost factors for GTE drilling are therefore summarized as:

- (1) Higher temperatures.
- (2) Difficult, hard abrasive rock.
- (3) Equipment erosion from high velocity particles.
- (4) Higher rig siting costs.
- (5) Deep, longer diameter holes.

The higher temperatures are especially significant in raising drilling costs, perhaps by a factor of two as indicated above. Table 3 records the influence of the cost-raising factors as distributed across the various elements of the drilling process. This broad distribution of the problems indicates that improvement of GTE drilling will require R&D effort in all elements of the drilling system.

The above discussion centered primarily on wells in conventional GTE reservoirs where maximum depths may not exceed 3 km (10,000 ft). For projected dry hot rock and perhaps future geopressurized reservoir developments, the depths, temperatures, and drilling costs could be considerably greater. Drilling costs increase very rapidly with depth, as illustrated in Fig. 2. The cost-per-unit-depth varies about as the square of depth and total cost as the cube of depth. The average oil- and gas-well costs are shown cross hatched; typical well costs at The Geysers and Imperial Valley are shown as 160 \$/m (50 \$/ft) and 80 \$/m (25 \$/ft), respectively; for depths of 10 km (30,000 ft), costs could be \$6,000,000 to \$10,000,000 per well, assuming high temperature problems are solved.

Table 4 attempts to scope the projected GTE well drilling demands and costs (in 1972 dollars) for several proposed national geothermal energy goals. Considering several of the current goals, this analysis indicates:

- (1) That The Geysers may have  $\sim \$25 \times 10^6$  invested in 92 production wells with an electrical power output of  $\sim 500$  MWe. (We neglect exploratory holes, dry holes, etc.)

- (2) The possible numbers of wells and cost for a 20,000-MWe power production goal in the year 1985 would be ~5000 and cost a few billion dollars.
- (3) If the dry hot rock technology proves feasible, and GTE development extends beyond the conventional hydrothermal reservoirs, then only ~2000 wells would be required but costs could be  $\$10 \times 10^9$ , since the wells will be deeper and in hard hot rock.

Another mix of future GTE resource development would require somewhat different numbers of wells, but the cost will still be several billion dollars.

It has been amply demonstrated that naturally occurring hot-water and vapor-dominated geothermal reservoirs can be penetrated by rotary drilling methods that have been developed principally for oil and gas wells. However, there are factors in geothermal fields such as high temperatures, corrosive fluid and gases, unfavorable siting situations, and often hard abrasive rocks, which combine to make the average rotary-drilled geothermal wells more expensive than average oil and gas wells of comparable depth. High well costs could significantly impede the expansion of geothermal energy sources to a level where they will contribute substantially to our national energy supply.

### III. ROCK MELTING TECHNOLOGY — POTENTIAL APPLICATIONS TO GTE WELLS

Rock-melting penetrators (Subterrenes) are under development at the Los Alamos Scientific Laboratory (Refs. 4 and 5). These devices can produce self-supporting glass-lined holes in rock and soil by progressively melting with a nonrotating, electrically heated bit, rather than by chipping, abrading, or spalling. Rocks and soils melt at temperatures that are relatively high, e. g., common igneous rock melts at ~1500 K, almost the melting temperature of steel (1500 to 1800 K). Thus, the melting penetrators utilize refractory metals such as molybdenum and tungsten in their construction.

Excavation by rock- and soil-melting offers potentially desirable and integrated solutions to the three major areas of the excavation process:

- (1) Forming the hole.
- (2) Providing stability and structural support.
- (3) Forming and removing or displacing the debris or cuttings.

The liquid form of the rock-melt produced by the hot penetrator introduces new solution approaches into the latter two areas especially:

- (1) The liquid melt can be formed and chilled into a glass lining to seal/support the borehole walls.

- (2) Excess liquid melt can be chilled and formed into glass rods, glass pellets or rock wool, as suited to an optimized debris removal system.
- (3) Glass cased cores can be formed and removed by wire line techniques.

The development program has already demonstrated a variety of melting configurations (Refs. 6 and 7) and debris handling options (see Fig. 3). Both laboratory experiments and a field test program have demonstrated the basic feasibility of the rock-melting approach.

Potential applications of Subterrene drilling systems for making geothermal wells are summarized in Table 5. The four major types of geothermal reservoirs are listed and the two basic well functions, exploratory and production, are indicated. In exploration and currently urgent resource assessments, rock melting devices could make small diameter, shallow, self-cased holes for thermal gradient measurements. Subterrenes could also be useful for economical exploration of deep hot water or steam reservoirs where very high formation temperatures prevail. For production wells there are two specialized backup or auxiliary devices that could be used in conjunction with rotary drilling systems: first, a hole-stabilization tool for use in caving formations, hydrating or swelling clays, or lost-circulation zones. This tool would be a thermal device producing either a rock-glass lining or injecting structural stabilizing materials into borehole walls. Second, a tool that would be used for completing holes into production zones where high formation temperatures and hot fluids are encountered and where reservoir contamination is undesirable. In certain deep, very hot water or steam reservoirs, or in magmas and lavas that are extremely difficult or impossible to penetrate with rotary drills, Subterrene systems could be developed for the formation of entire production wells.

The present technical activities of the Los Alamos rock-melting project that are directed toward the development of a GTE drilling system are:

- (1) Demonstrate the ability to penetrate hard dense rock, reliably in the field.
- (2) Improve advance rates of extruding penetrators.
- (3) Develop system models of deep, rock-melting drilling systems for analysis and optimization.

The first objective is being pursued through a field test operation (see Fig. 4). Testing has concentrated on an extruding penetration design of 84-mm (3-1/4 in.) diameter (see Fig. 5). A hole ~20-m (65-ft) deep has been produced in a dense, basalt layer. The tests to date have yielded data on bit life (erosion and corrosion of the penetrator), evolved improved methods for hot debris (pellets and rock wool) handling, improved glass lining-forming techniques, and developed reliable, semiautomatic rig operating methods.

A major development project to perfect a prototype GTE rock-melting well drilling system has been initiated. Larger diameter, higher advance rate, extruding penetrators have been designed and laboratory tests indicate a three-fold improvement can be achieved. A new electrical heating concept, in which a portion of the power is deposited in the melt layer, is under development.

Theoretical models for the thermal design and the fluid mechanics, electrical, structural, mechanical and economic aspects of a deep drilling system are being developed. A proof-of-concept R&D project which includes melting into a lava lake, tests of prototype hole forming and debris handling components in a high pressure, a high temperature laboratory simulator, and final system field tests in hard rock have been initiated.

#### IV. CONCLUSIONS

The current demands for the drilling of geothermal energy wells can be met with current oil and gas drilling technology. However, the combinations of GTE conditions of temperature, pressure, hard fractured rock, and corrosion raise the cost of average geothermal wells two to five times above the equally deep oil and gas wells. An expanded and accelerated GTE development effort can benefit from improvements in drilling technology which will lower costs.

Short-term improvements in current drilling equipment should include:

- (1) Establishment of a drilling system R&D facility and institute.
- (2) Development of a standardized line of rigs dedicated to GTE well drilling and especially designed to solve the problems particular to such drilling.
- (3) Longer lifetimes for bit cutting edges and bearings.
- (4) Stem and casing materials that can stand up to GTE well temperatures and corrosive conditions.
- (5) Muds and cements able to withstand high temperatures.
- (6) Better methods to measure downhole temperature, pressure, porosity, permeability, fracture orientation, and general formation lithology; means of obtaining undisturbed fluid samples; and measurement/sampling techniques that do not delay the drilling operations.

Longer term R&D on new drilling methods and advanced drilling technologies can potentially pay off in a greatly expanded national GTE development program. Future exploration and extraction efforts for other minerals and fuels will also benefit from successful development of advanced drilling systems. Rock melting technology may provide one such significant advancement, especially in affording penetration into deeper, very hot GTE formations and reservoirs.

## ACKNOWLEDGMENT

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\*Copies of these reports are available from: National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22151

Table 1. Geothermal drilling at the Geysers

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Resource:	Dry steam at 180 to 240°C and 3400 kPa.
Geology:	Igneous, badly jointed and fractured.
Surface:	Mountainous terrain.
Rig sizes and power:	Extra heavy duty and power.
Hole sizes and casings:	500-mm (20-in.) conductor pipe, 445-mm (17-1/2-in.) surface hole, 311-mm (12-1/4-in.) to steam, 216-mm (8-1/2-in.) open to T. D. Buttress connections. 200- to 3000-m depths. High temperature cement required.
Circulation:	High temperature mud in upper hole, air to T. D. Exceptional air/steam erosion of equipment. Excessive lost circulation.
Drillability:	Initial: 15 m/h. Depth: 5 m/h. Temperature, fatigue, and corrosion leads to bearing failures. Average bit life extends from 45- to 75-m lengths. Approximately 50% time used to change bits.
Logging:	Up to ~temperature limits of ~260°C.
Completion:	Heavy equipment needed because of erosion.

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Table 2. Geothermal drilling in Imperial Valley

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Resources:	Hot brines at 260–360°C and high pressures.
Geology:	Sedimentary to 2.4- to 6.0-km depths.
Surface:	Accessible, flat.
Rig sizes and power:	Smaller, portable rigs are satisfactory.
Hole sizes and casings:	500-mm (20-in.) conductor pipe, 445-mm (17-1/2-in.) surface hole, 270-mm (10-5/7-in.) to T.D. 300- to 2100-m depths. High temperature cement required.
Circulation:	High temperature mud required. Some lost circulation but not a significant problem. 90°C mud cooled 20°C in cooling tower.
Drillability:	High rates, e.g., 15 m/h. Low bit costs.
Logging:	Up to equipment limits of 260°C.
Completion:	Simple: log, install valve, wash.

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Table 3. Summary of current geothermal drilling problems

Item	Type of GTE field		Symbols and problem descriptions
	Sedimentary hot water	Hard, igneous vapor dominated	
Surface locations	—	G	G: Difficult geological conditions typical of many GTE fields, including sites, hard rocks, caving formations, etc.
Drilling-rig design	R, X	R, G, X	R: Rigs of high mobility are needed, adequately equipped to handle rapid changes in hole conditions.
Other surface equipment	T, C, X	T, C, E, X	X: Dependence on oil- and gas-industry materials and equipment, competition for supplies.
Bits and drillability	T, C, D, X	G, T, C, D, X	T: Temperatures up to ~660 K cause rubber, elastomer, metallurgical, mud, cement, and electronic problems.
Mud-circulation systems	T, G, F, X	T, G, F, X	C: Corrosion problems caused by ground fluids and gases.
Hole support and control	G, T, F	G, T, F	E: High stem, casing, and surface-equipment erosion by air + steam + rock cuttings.
Cements	T, X	T, X	D: Directional drilling equipment not available for hard rock at high temperatures.
Downhole measurements	T, X	T, X	F: Hot saline waters contaminate drilling muds. Also, muds can reduce or kill well productivity or may hydrate clays.

Table 3. Summary of current geothermal drilling problems (contd)

Item	Type of GTE field		Symbols and problem descriptions
	Sedimentary hot water	Hard, igneous vapor Dominated	
Tubular goods	T, C, X	T, C, X	0: Lack of organized GTE well drilling-data bank and ways to use such data to optimize drilling programs.
Optimized drilling	0	0	

Table 4. Projected GTE drilling costs for electric power development in U. S.

Total power goal, MW(e)	Conventional steam systems		Dry hot rock systems	
	Number of holes	Cost, \$ × 10 <sup>-9</sup>	Number of holes	Cost, \$ × 10 <sup>-9</sup>
412	92	0.023	—	—
20,000 <sup>a</sup>	4,460	1.1	1,600	10.3
200,000 <sup>b</sup>	44,600	11.0	16,000	103.0
400,000 <sup>c</sup>	85,200	22.0	32,000	206.0

<sup>a</sup>AEC goal for 1985.

<sup>b</sup>AEC goal for 2000.

<sup>c</sup>Hickel, 1972.

Table 5. Potential subterrene geothermal well applications

Well function	General requirements	Types of Geothermal field			
		Water or vapor-dominated reservoir	Dry-hot-rock systems	Magmas and lavas	Geopressurized reservoirs
E X P L O R A T I O N	Small and economical.	Thermal-gradient holes.	Thermal-gradient holes.	Thermal-gradient holes.	
	Directionally controllable.	Heat anomaly probes.		Heat anomaly probes.	
	Formation evaluation capability.	Discovery wells.			
	Holes enlarge-able to production size, if desired.				
P R O D U C T I O N	Large enough to achieve optimum production flow rates.	Special hole-stabilization tool, backup to rotary drills.	Special hole-stabilization tool, backup to rotary drills.	Special hole-stabilization tool, backup to rotary drills.	Special hole-stabilization tool, backup to rotary drills.
	Directionally controllable.	Production wells.	Hole-completion tool in very hot rocks.	Production wells in very hot rocks.	Hole-completion tool in very hot rocks.
	Hole made can be reworked and maintained.	Reinjection disposal holes.		Production wells in molten rocks.	
		Production-augmentation holes.			

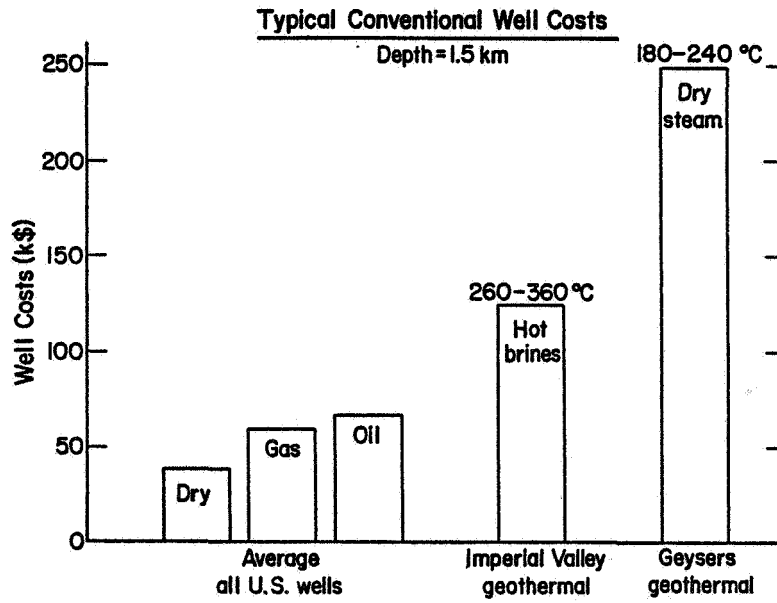


Fig. 1. Cost comparison of typical average GTE well drilling to comparable oil and gas well drilling (1972 dollars)

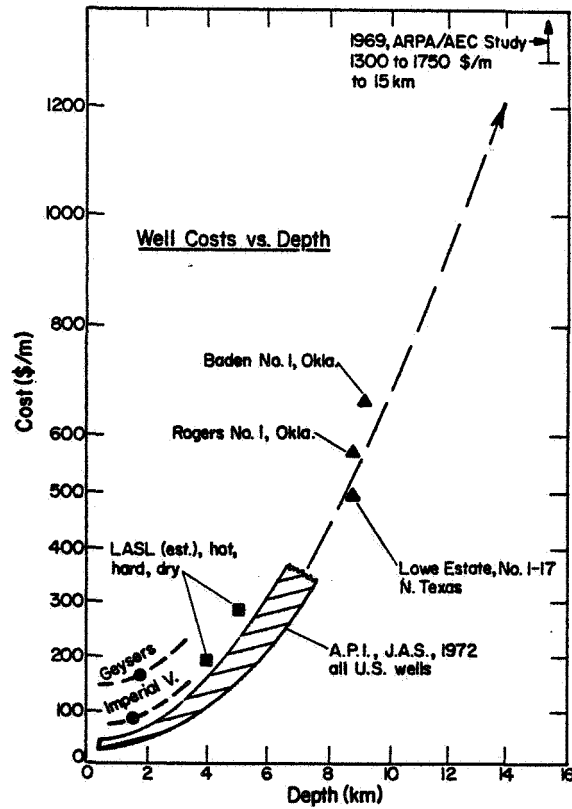
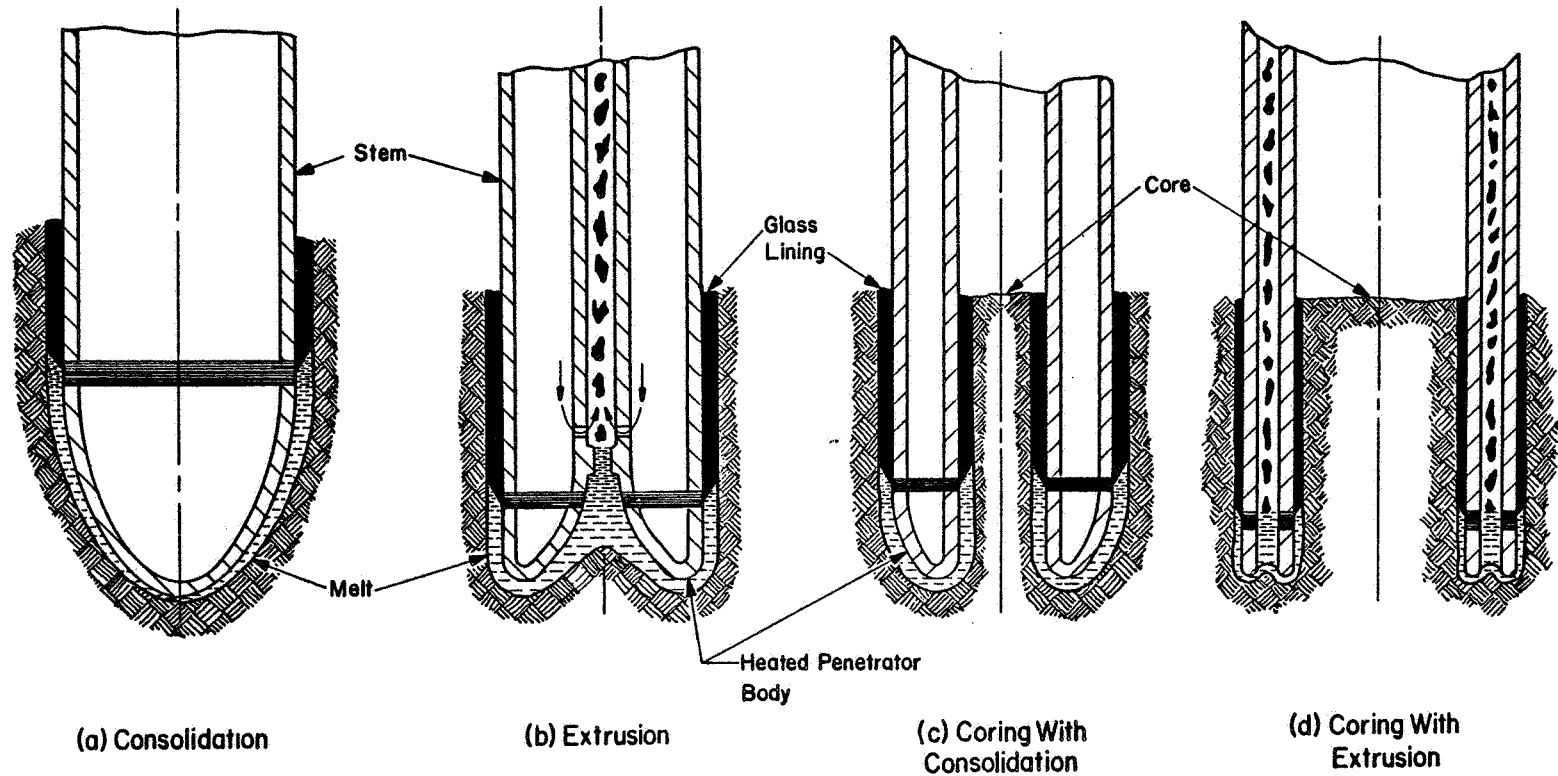


Fig. 2. Well drilling costs vs depth



**Fig. 3. Schematic cross sections of rock-melting penetrators indicating different melting modes and debris handling techniques**

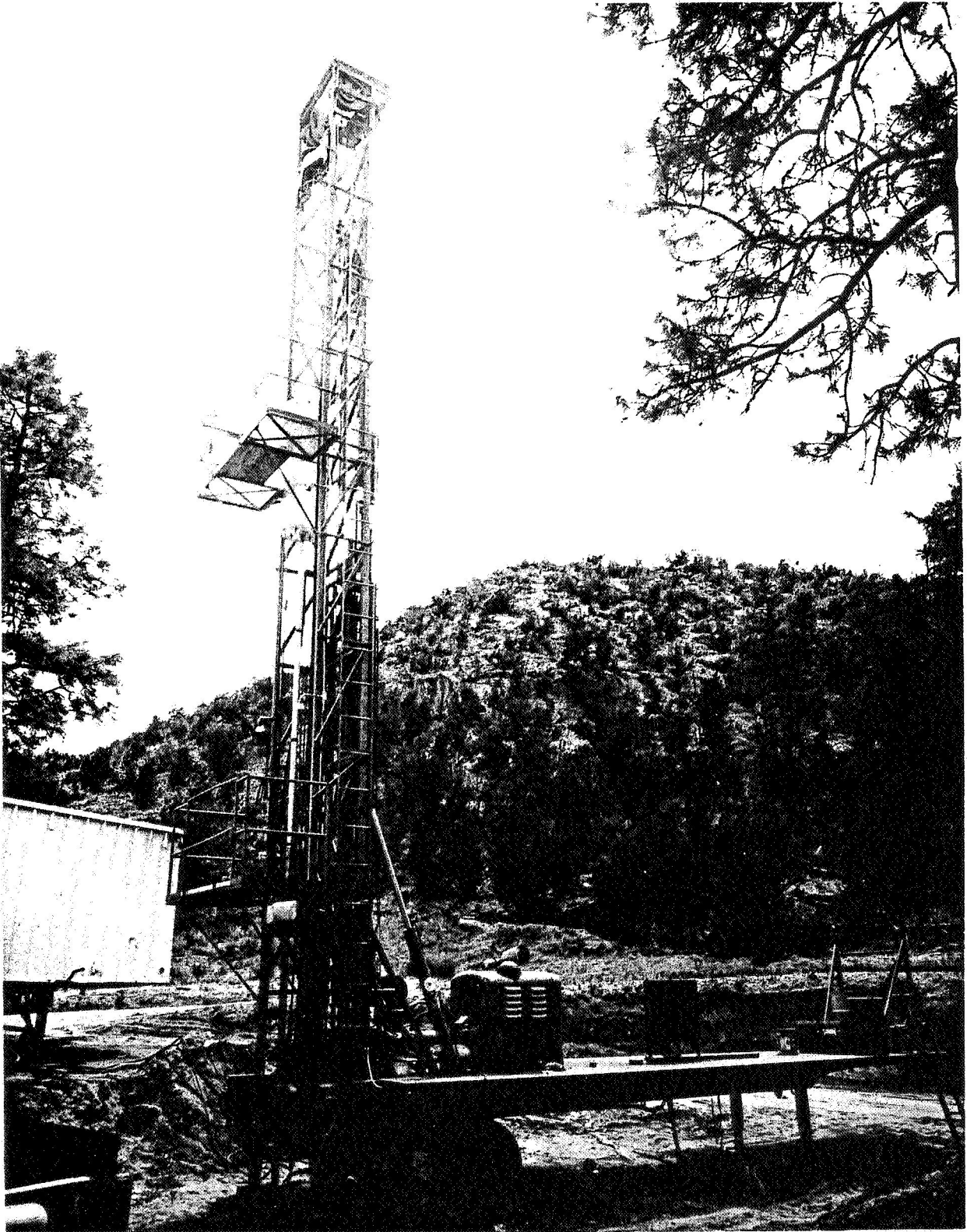


Fig. 4. Photograph of experimental field unit for test of prototype GTE rock melting penetrators, depth capability to ~300 m (1000 ft)



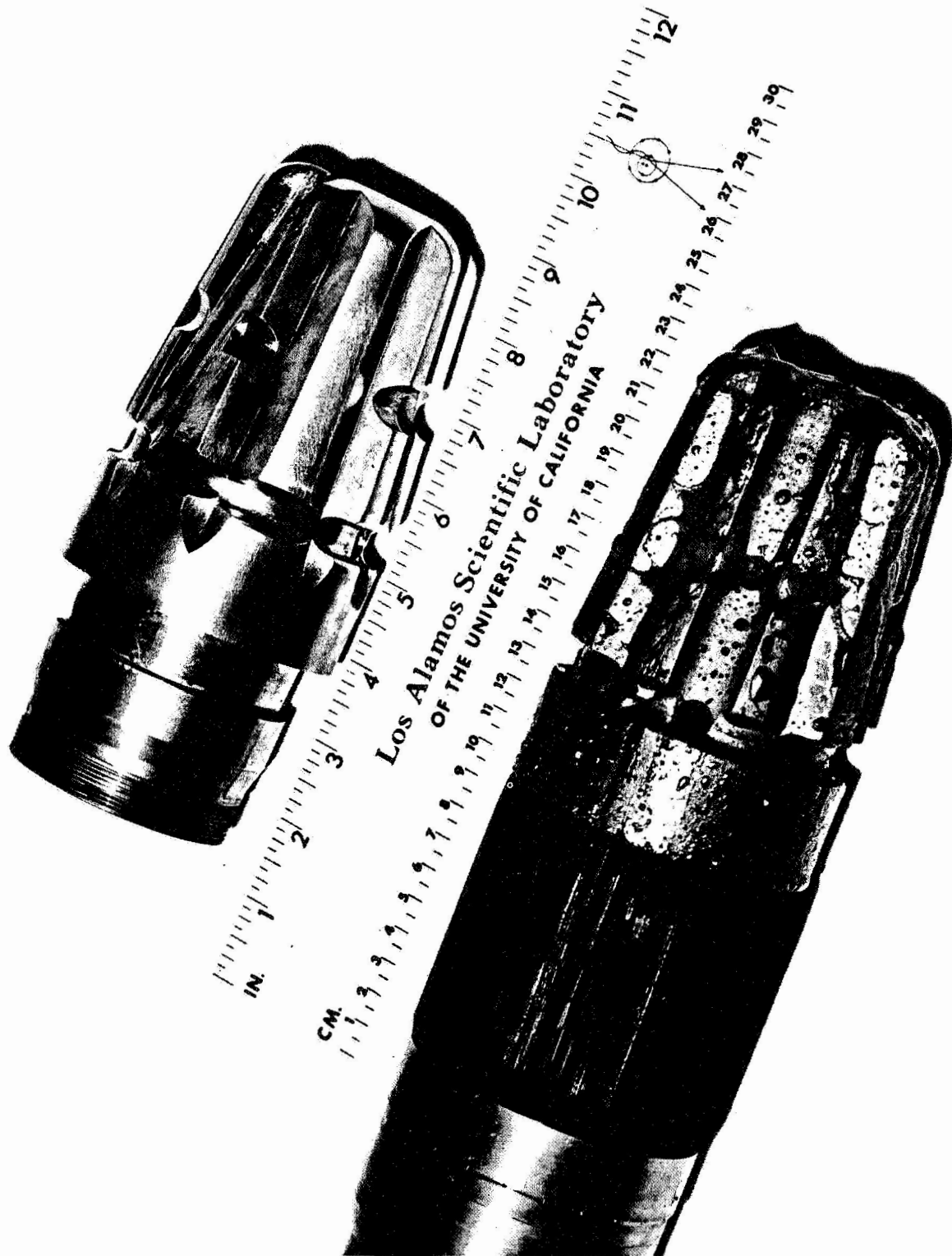


Fig. 5. Prototype GTE rock melting, extruding penetrator system, 84-mm (3-1/4-in.) diameter, currently undergoing field tests in basalt to ~30 m (100 ft)