GL01298

HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PLAN

JUNE 1978

DIVISION OF GEOTHERMAL ENERGY

DRAFT

CONTENTS

HOT DRY ROCK GEOTHERMAL ENERGY
DEVELOPMENT PLAN

SUMMARY

A DOE/DGE plan is presented for investigating the industrial usefulness of the hot dry rock (HDR) geothermal energy resource of the United States. The overall objective of the Federal program is to determine the potential of HDR as a significant energy source and to provide a basis for its timely commercial development--if, in fact, that development is warranted.

Although DGE has established quantitative power-on-line goals for both hydrothermal and geopressured geothermal resources as a basis for program planning, this approach is premature for HDR. However, given reasonable success in research and development activities and commitment of the requisite capital by the private sector, a significant amount of commercial electrical generating capacity and an equal or greater amount of additional heat for direct use may be available from HDR reservoirs by the year 2000, with a rapidly increasing contribution to the Nation's energy needs thereafter. To provide a focus for the activities needed to make this possible, a major decision milestone has been targeted for the mid-1980's to determine the commercial viability of the HDR resource and the proper Federal role in its commercialization. This includes decisions as to Federal support for demonstration facilities as well as appropriate incentive measures to encourage industrial investment.

By any standard, the HDR resource base of the Country is extremely large. For purposes of this document, it is defined as that portion of the unmelted crustal rock underlying the United States at depths less than 10 km and at temperatures commercially useful either for electrical generation or for direct use as heat, but which does not spontaneously produce hot water or steam at a rate adequate for the economic extraction of its energy. No firm basis so far exists for evaluating quantitatively what fraction of the resource base can be recovered economically. If, however, the recovery factor were 2%, this resource would support the entire nontransportation needs of the United States for over 2000 years at the present rate of energy consumption. To provide for commercial HDR development in the late 1990's and

early 2000's, as herein discussed, a major effort in the national program--starting immediately and continuing through the next decade--must be directed toward determination of the resource potential and selection and characterization of specific sites for possible further development.

Similarly, although the extraction of geothermal heat from a man-made HDR system has now been demonstrated in preliminary experiments at one specific site,[1] much remains to be learned about creating such systems, about the engineering problems involved in operating them continuously, and about their reliability, productivity, lifetimes, and economics. A second major activity (in parallel with evaluation of the resource) must therefore be development of the technology required to extract and utilize it competitively in an environmentally sound manner. In addition to the development of needed special materials, equipment, instrumentation, and techniques, this will involve the construction and operation of a series of evaluative heat-extraction systems and perhaps of pilot plants and commercial-size demonstrations.

Hot dry rock systems will share many of the institutional problems of other types of geothermal system developments. However, since in this case only heat (and not indigenous hot water or steam) will be extracted from the earth, existing laws and attitudes pertaining to water or mineral rights and land usage may not apply. Continuing attention must be given to the unique legal, institutional, environmental, and socio-political questions which this peculiarity will raise.

In consonance with the program's overall objective, the major portion of the government-sponsored program will be accomplished through contracts and cooperative agreements with the private business sector. This approach will foster continuous transfer of technology and assure the most rapid development of the resource that its demonstrated potential justifies.

To implement and coordinate the group of interrelated activities comprising this program, a management organization and time and cost schedules are outlined in the pages that follow.

I. INTRODUCTION

One of the largest energy supplies available to the United States is the natural heat available from the accessible part of the earth's crust within its borders, as has recently been recognized in the Department of Energy's "Inexhaustible Energy Resources Planning Study." Thus far, however, energy from this source has been utilized beneficially only in a few places where heat has already been extracted from the rock by natural ground-water circulation and is brought to the surface by hot springs, geysers, steam vents, or through relatively shallow drilled holes. Elsewhere, where either the permeability of the rock or its water content are insufficient to support such natural hydrothermal systems, even the technologies required to extract energy efficiently from the hot dry rock have not yet been fully developed.

According to the United States Geological Survey (USGS),[2] usefully hot dry rock, at depths accessible to existing drilling technology, can be expected to occur in two principal geological environments:

- In areas of recent volcanism, where the rate of increase of rock temperature with depth (the "geothermal gradient") is significantly higher than the global average, for example, 40°C/km or more. This means that usefully high temperatures can be expected at relatively shallow depths. Here, in the "crystallized parts and hot margins" of igneous system, the USGS estimates a heat content of about 190 000 quads* above a reference temperature of 300°C, to a variable depth generally less than 10 km. Further calculation suggests that about 400 000 quads should be available from this resource at temperatures greater than 150°C.
- In "regional conductive environments," where heat flow has not been enhanced by the intrusion of molten rock into the earth's crust, so that geothermal gradients are generally lower than in volcanic regions and depths to usefully hot rock are correspondingly greater. Here, again at depths less than 10 km but at temperatures above 15°C, the USGS estimates a heat content of about 31 750 000 quads.

---

*1 quad = 10^{15} Btu = 334 megawatt-centuries.

1 milliquad (mQ) = 10^{-3} quad = 10^{12} Btu = 33.4 megawatt-years.

Present total U.S. energy consumption is about 75 quads per year.

The sum of both high- and low-gradient contributions, about 32 million quads, is the USGS estimate of the HDR geothermal "resource base." Much of this heat is, of course, at temperatures too low to be economically useful, and much more of it is at depths too great for it to be economically recoverable using existing or near-future drilling technology. However, at least 13 million quads (about 40%) is believed to exist at temperatures above 150°C (Fig. 1)--the minimum assumed by both the USGS and DOE to be potentially useful for generating electricity under present economic conditions. A much larger amount of energy is present at intermediate temperatures appropriate to such uses as residential or commercial space-heating and food, chemical, and agricultural processing. A principal objective of this Federal program is to determine what fraction of that heat exists at depths which are sufficiently shallow to be economically attractive, either currently or with improved technology and removal of any existing institutional barriers.

The high-grade component of the HDR resource base is analogous to the hydrothermal situations in that the reservoirs are within areas of high heat flow. These are sometimes in or contiguous to known geothermal resource areas (KGRA's). In a number of known cases, high-geothermal-gradient areas are located sufficiently close to energy load centers so that not only the production of electricity, but also process and residential space heating, may be economic. In many cases, however, their exploitation may be inhibited, particularly for nonelectric uses, because of remote location or environmental or aesthetic concerns. On the other hand, the much larger but generally lower-grade regional-conductive component of the HDR resource base is generally distributed across the country and largely avoids the site-specific difficulties of the high-grade resource. Two basic thermal regions have been defined in the U.S.: the Eastern and the Western Heat-Flow Provinces. Within both provinces, there are large areas of regionally higher heat flow associated with converging plate boundaries or general rifting, as well as other anomalously hot areas which are a result of radiogenic heat sources[3,4] superimposed on a normal gradient. Figure 2 is an incomplete geothermal-gradient map of the conterminous 48 states, with a large number of high-gradient areas identified. Regions characterized by near-normal gradients are widely, and

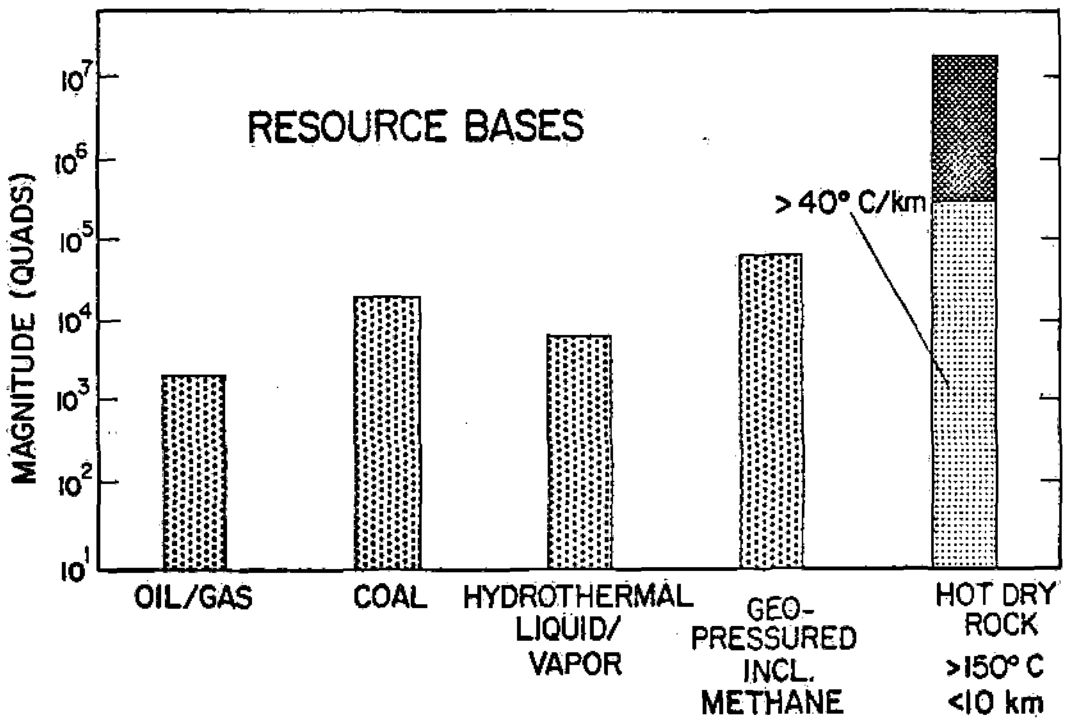


Fig. 1. Comparison of resource bases (note logarithmic scale).

Sources:

1. Oil/gas and coal, DOE estimates based on open-file data from the MOPPS study.

2. Hydrothermal and geopressured, recalculated from USGS Circular 726 (Ref. 2).

3. Hot dry rock, taken from HDR77-A01, "Hot Dry Rock Geothermal Energy Development Project: Annual Report for Fiscal Year 1977;" Los Alamos Scientific Laboratory (Mar. 1978).

   Recalculated in part from:

   (a) USGS Circular 726 (10-km-depth basis)

   (b) Hot Dry Rock Geothermal Energy: Status of Exploration and Assessment, Report No. 1 of the Hot Dry Rock Assessment Panel, Energy Research and Development Administration, ERDA 77-74 (June 1977) (geothermal temperature gradients).

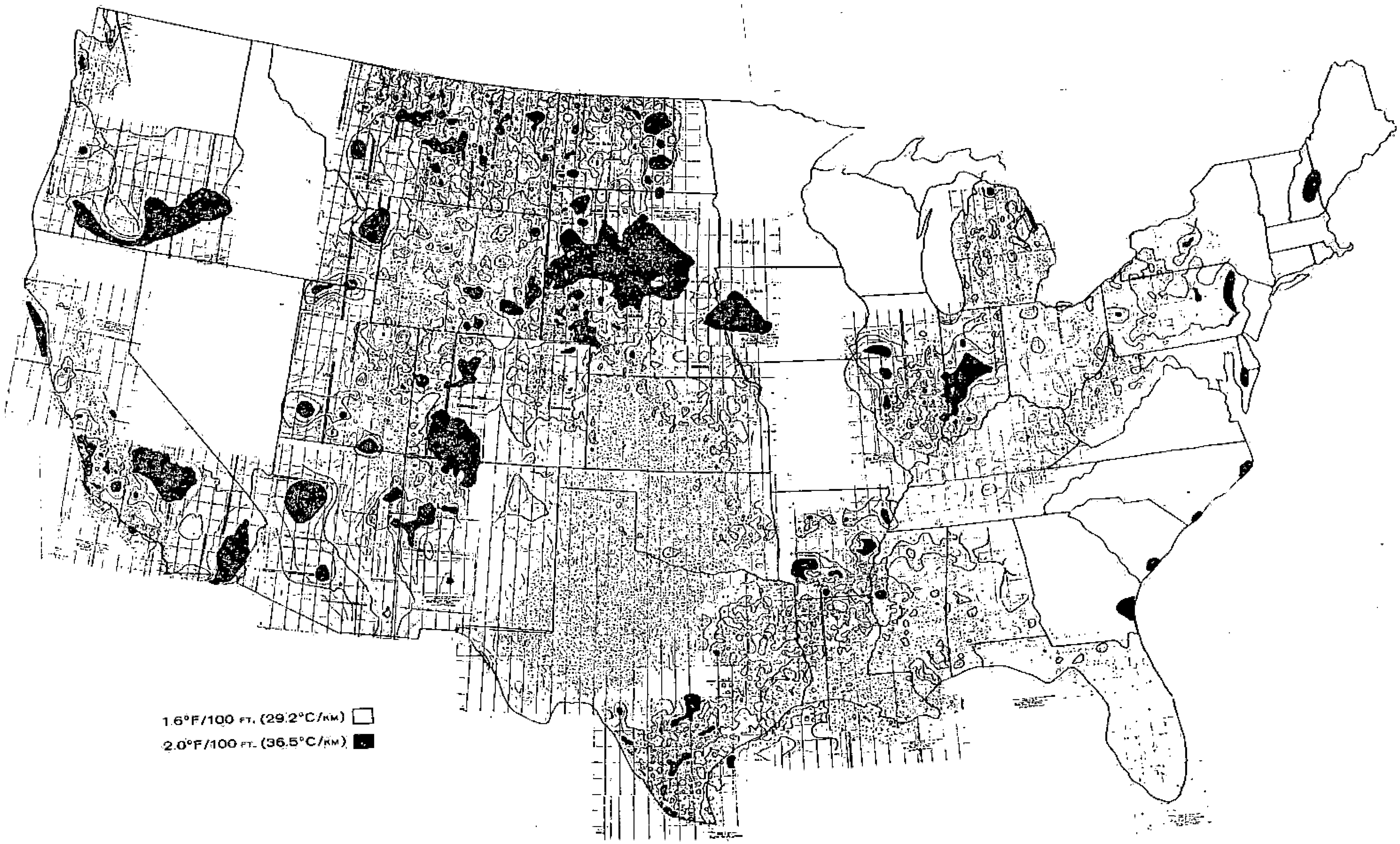


Fig. 2. Preliminary geothermal-gradient map. (Primary source, AAPG maps).

more-or-less uniformly, distributed to provide essentially unlimited flexibility in locating and sizing HDR systems near load centers (subject, of course, to economic and institutional constraints). This site-independence is a particularly attractive feature of HDR systems.

Until the extraction and distribution technologies and the institutional aspects of HDR systems are better understood, any estimate of the fraction of the resource base that might actually be economically recoverable is necessarily speculative. If, however, the recovery factor were ultimately as much as 2%, as was assumed for hot dry rock in the ERDA Definition Report,[5] then the energy recoverable from hot dry rock would be about 260 000 quads at temperatures above 150°C. This quantity of energy is approximately 10 times the amount estimated in report ERDA 76-1 (Ref. 6) to be potentially recoverable from the total U.S. depletable resources of natural gas, petroleum, oil shale, coal, uranium (used in light-water reactors), and natural hydrothermal systems combined. Simply because of the large size of the resource-base estimate, HDR qualifies as "essentially inexhaustible," together with fusion and solar-energy sources.

II. OBJECTIVES

The specific initial objectives of the Federal Hot Dry Rock Geothermal Energy Program are (1) to establish basic technical feasibility of the hydraulically fractured HDR system for impermeable rock by 1980, (2) to confirm technical feasibility and obtain economic data for HDR energy extraction systems in the commercial size-range by 1985, and (3) to support commercialization by the early 1990's. Beyond this, in view of the energy pressures upon the United States and an increasing awareness of the advantages of dispersed, relatively small energy systems, it is important that the HDR resource be investigated in geological situations in which the permeability of the rock is significant and developmental methods other than just hydraulic fracturing may be required.

Critical questions to be resolved in the development of HDR geothermal energy systems include the following:

- The magnitude, quality, distribution, depth, and geological environment of HDR geothermal reservoirs.
- The technical and economic feasibility of extracting energy from them in usable forms at usefully high rates for commercially attractive periods of time.
- Environmental acceptability of complete HDR energy systems.
- Institutional issues, including legal complexities such as definition of the resource, its ownership and tax status, jurisdictional responsibilities and land-use and leasing restraints on its development; the availability and cost of capital (for exploration, land-acquisition, reservoir development, and plant construction); and legislative means and policy actions which will encourage commercialization.
- Potential societal impacts.
- Appropriate information-dissemination mechanisms for technology transfer and for public-education and industrial-motivation programs.

III. SCOPE

The Hot Dry Rock Program is intended to embrace all of the activities necessary to create an industrial structure that can and will proceed expeditiously with commercialization of the HDR resource. Major Federal involvement in a successful HDR program would continue through FY1990, then diminish to a liaison, coordination, and technical-support role by FY2000.

The program will comprise two main, parallel streams of effort--one, a system-development sequence leading from field experiments through evaluative systems and any necessary pilot plants to perhaps commercial-scale demonstration systems; the second, a continuing group of supporting activities including laboratory work, reservoir modeling, instrument and equipment development, and environmental, legal, and institutional support.

Cost-sharing with industry is an integral part of the National HDR Program. Federal expenditure is expected to peak in the mid-1980's and, if the program is successful, to decline quickly thereafter as commercial interests provide a rapidly increasing part of the total funds required for continued development of HDR systems.

Execution of the program will be achieved through a management team consisting of a National Laboratory and an appropriate Department of Energy Operations Office. This team will report to a Program Director in the DOE's Division of Geothermal Energy. The proposed management structure is depicted in Figure 3 and discussed further in Sec. 5 and Appendix K.

IV. STRATEGY AND APPROACH

A. Motivation and Assumptions

The entire program strategy is motivated by the enormity of the resource base and paced jointly by budgetary constraints and by the requirement for a decision in the mid-1980's concerning the commercial viability of HDR systems and the appropriate Federal role in their commercialization.

To nurture an industry willing and able to attempt large-scale commercial development of HDR systems, the program strategy must include: (a) step-by-step unequivocal demonstration of economic soundness; (b) provision of risk-aversion mechanisms; and (c) timely removal/mitigation of existing and potential institutional barriers; as well as the obvious need to further several key reservoir-development technologies such as those discussed in Appendix D. Detailed planning and implementation of the HDR Program will be carefully integrated with the ongoing Hydrothermal and Geopressured Programs for maximum cost-effectiveness. A formal mechanism will be established for coordination of RD&D and siting efforts with other DOE Energy Programs. This is particularly important in the areas of: (a) low-temperature power conversion; (b) high-temperature drilling, logging and hole-completion; (c) site selection; and (d) reservoir-enhancement techniques.

To develop the credibility required for industrial support of HDR development, some number of prototype systems, pilot plants, and demonstrations will be required. A strategy for specifying their numbers, types, and locations has been formulated, with several major assumptions intended to:

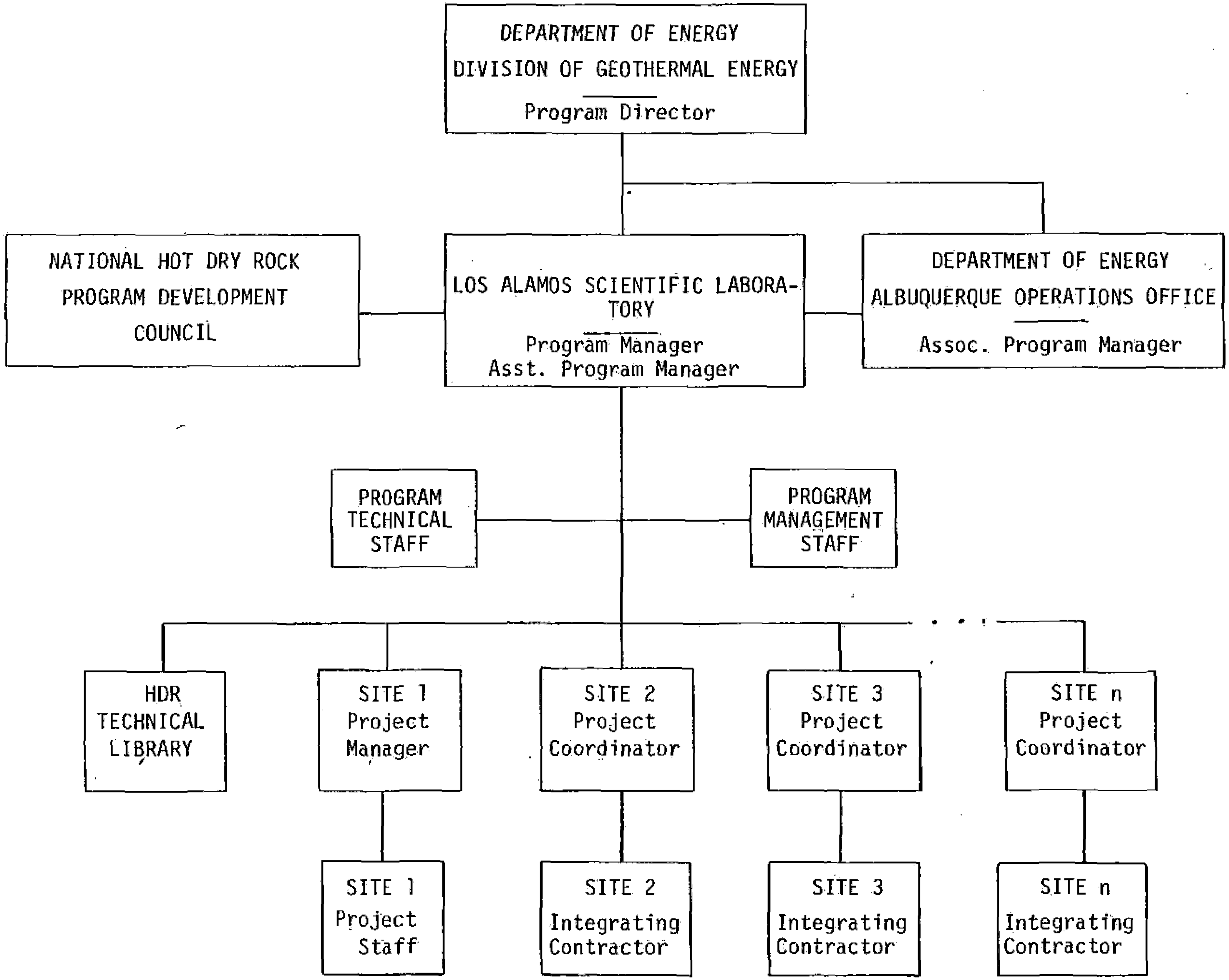


Fig. 3. Proposed management structure for Federal HDR Program (first level).

- establish confidence in the ability of HDR technology to produce useful heat economically and reliably in a variety of geological environments and geographic locations, as is discussed in Appendix E;
- implement parallel efforts, to reduce risk of failure;
- identify the plant type (electric/nonelectric/congeneration) appropriate to a given site, using economic criteria.

The applicability of various HDR reservoir concepts (Appendix D) to different geologies distributed across the country must be demonstrated if widespread industrial interest in HDR systems is to be aroused. Consequently, a number of evaluative energy extraction loops and probably of pilot and demonstration plants will be required in several different geologies in both volcanic and nonvolcanic regions. In addition, some redundancy will be necessary to increase credibility and reduce the impact of a failure at any single location. The methodology used consisted of a matrix approach to end uses and basic geologies anticipated. The type of plant considered for a particular geology was based on criteria associated with eventual economic viability. For example, high temperature-gradient, silicic/basaltic-volcanic or nonvolcanic areas may be ideally suited for electricity generation and lower gradient areas for district or process-heating applications. A larger number of site locations is suggested initially for nonvolcanic than for recently active volcanic regions, including unproductive hydrothermal reservoirs in sediments and deep crystalline or sedimentary formations with moderate gradients and low porosity and permeability. High priority will be placed on locating some of these facilities near population centers in both the Eastern and the Western U.S. One possible geographic distribution (necessarily speculative at this point) of HDR prototype, pilot-plant and demonstration systems is shown in Figure 4. It was developed principally on the basis of the considerations discussed above, temperature-gradient data of the type shown in Figure 2, and the available information on the natures and locations of HDR reservoir types--summarized in Appendix E.

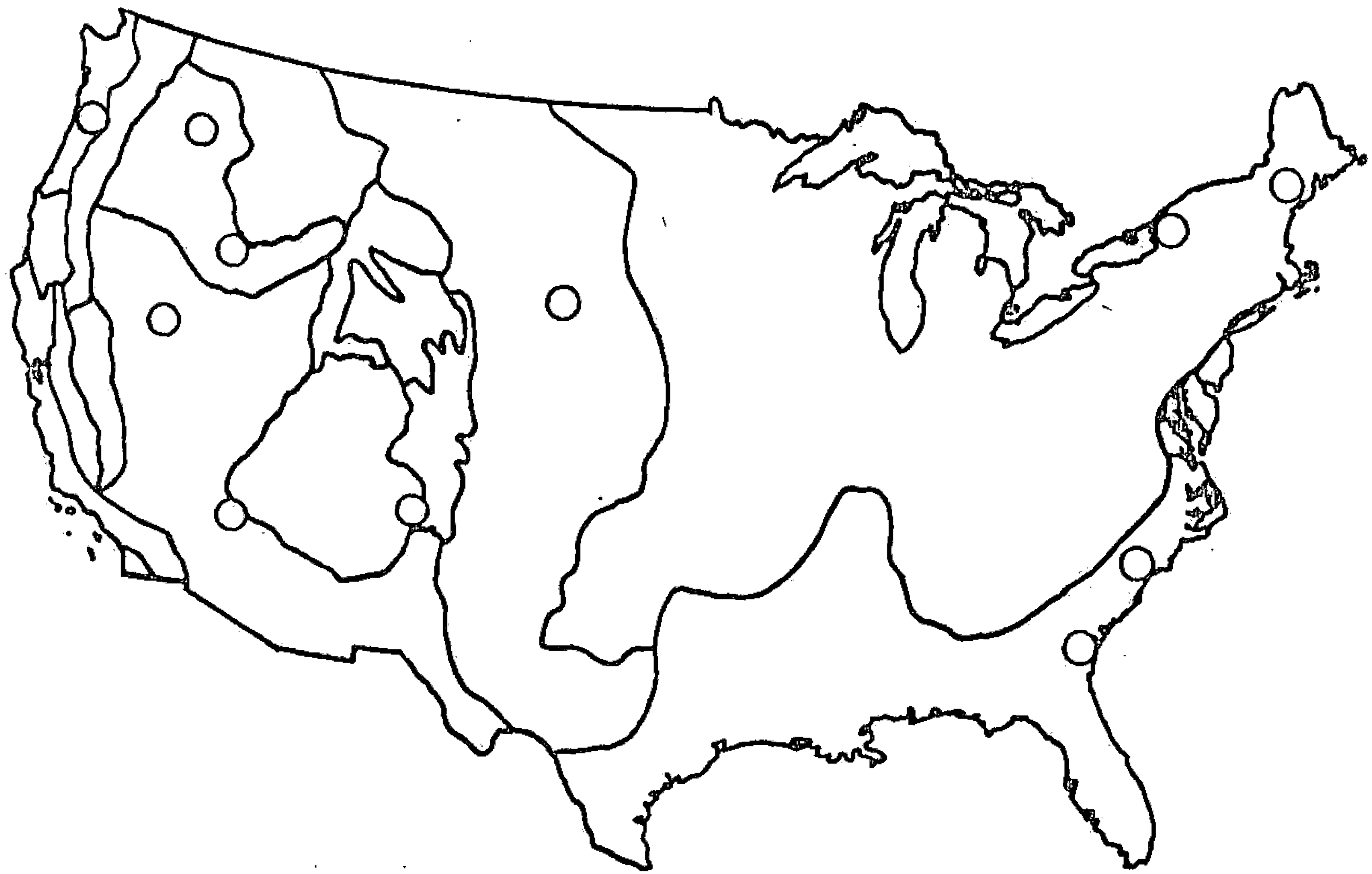


Fig. 4. Geographic distribution of initial HDR experimental prototype, pilot plant, and demonstration systems (preliminary).

For purposes of this early planning document, several important additional assumptions have been made:

(1) The power-conversion technology involved in producing electrical energy from the heat extracted by the geofluid is essentially the same as that required in the hydrothermal and solar programs, although there will be some effect on it of the slow, rather large-amplitude temperature swings expected in fluid produced from most HDR systems. Consequently, the HDR Program needs will be met in large part by assimilation of economically attractive developments from these related programs. However, some complete electric and/or cogeneration system demonstrations will probably be required to empirically assess the range of special interface and efficiency problems incurred by coupling to an HDR source. It is assumed that (a) virtually all of the reservoir-fluid-related data from nonelectric (space-or process-heat only) systems will be directly applicable to electric systems; (b) most of the required electric-conversion technology demonstrations can be accomplished at the pilot-plant ($\sim$10 MWe) stage; and (c) not more than two commercial-scale ($\sim$50 MWe) electric/cogeneration system demonstrations will be required to evince economic viability.

(2) Site selection will be based primarily on: (a) geological, geophysical, geochemical, heat-flow, and other evidence that an HDR reservoir of suitable temperature, size, permeability, depth, and formation characteristics is present; (b) absence of constraints on its use imposed by ownership, availability of water, environmental issues, topography, accessibility, or other factors; (c) proximity of a market for energy such as an electric-power transmission grid, a large industrial user of process heat, or a growing population center; (d) visibility to industry, governmental entities, environmental groups, news media, and the public; (e) potential for joint funding and cooperative development with industrial organizations and/or local governments. It is tentatively assumed that, with regard to energy extraction and reservoir performance, two out of three identified sites could eventually be developed successfully for a predicted end use.

(3) Drill-rig availability and capability will keep pace with the needs of the program, despite strong competition from other geothermal and fossil-fuel programs.

B. Major Program Elements and Milestones

The Federal Hot Dry Rock Program includes the following major elements:

1. A vigorous resource-evaluation effort--at national, regional, and local levels--will be initiated in FY79, brought to a high level for about 5 yr, with responsibility for its continuation transferred entirely to industry by 1990 (see Appendix F).

2. Identification and detailed characterization of specific sites for development of prototype energy extraction systems, pilot plants, and commercial-scale demonstrations, will be completed by the end of FY83 (see Appendix G).

3. A series of prototype systems, representing proposed combinations of geographic locations, geological situations, and heat-extraction methods, will be constructed and operated to investigate and develop in the field the technologies required to produce geothermal energy wherever it is needed and in sufficient quantity and quality to satisfy the specific needs of its potential users. Development of these systems will begin at the rate probably of one or two per year, with operations overlapping in time, and the last of them will either be abandoned or converted to a pilot-scale operation in about FY87. The number and scheduling of their development will depend jointly on the funding available and the priority assigned to demonstrating the flexibility with regard to location which is believed to be a major advantage of HDR systems.

4. Construction and operation of pilot plants will be based on information collected in the operation of evaluative systems and at locations found in those investigations to have special interest. The pilot plants will serve primarily for identification and solution of any technical problems that may appear or be predicted in relatively long-term operation of heat-extraction, distribution, or power-conversion subsystems. At least one of these pilot plants would be for electrical generation (including cogeneration if the local situation permitted) at a nominal 10-MWe generating capacity, and others would be solely for production of process heat. Design and construction of such plants would overlap the final phases of

experimentation with prototype energy extraction systems. Each pilot plant would be operated for a sufficient period to demonstrate reliability and longevity and might, if it filled a local need and were taken over by a commercial organization or local government, continue in operation for its full lifetime. Pilot plant activity would begin in FY82, peak in about FY88, and Federal involvement would terminate in about FY90.

5. Contingent upon both successful operation of pilot plants and a perceived need for larger-scale operations to demonstrate economic viability, demonstration systems would be constructed for electrical generation at the small commercial scale (about 50 MWe) and for direct use of heat (at a scale appropriate to the local situation). These would be intended primarily to provide convincing de facto confirmation of economic soundness and to establish the reliability of commercial-scale HDR systems. Major industrial participation and cost-sharing are anticipated in this activity, which would peak in about FY92 and be completed before FY2000.

6. Specialized equipment, materials, instruments, and techniques will be developed, as required to create and operate HDR systems. These activities are expected to continue through the lifetime of the Federal Program.

7. Development and operation, at appropriate levels, of laboratory and analytical capabilities required to design, fabricate, evaluate, operate, understand, and model HDR systems would also continue through the entire Program. The level of effort for these activities will be determined largely by the operating problems that appear in evaluative pilot plant, and demonstration systems.

8. A continuing aggressive effort will be required in the areas of environmental effects and institutional issues. Such problems as legal description of the resource, leasing and licensing procedures, proprietary rights, conflicting regulations, etc., must be confronted and resolved early in the Program. Technology transfer, both within the United States and in exchanges with other countries, represents another significant continuing effort.

A more detailed description of these Program elements is provided in the following section which, for convenience, is divided into two major parts: Sec. C, Hot Dry Rock Systems Development, and Sec. D, Hot Dry Rock Technology Development.

C. Hot Dry Rock Systems Development

The elements in this subset of the program constitute the major technical and economic HDR developments and demonstrations. The development sequence begins with exploration and resource evaluation--largely Government-funded activities--and continues through potential-site characterization, specific-site selection, construction and operation of prototype systems and small pilot plants and finally, if they are found to be necessary, of commercial-scale demonstrations operated by cooperative agreement with industry.

1. Exploration and Resource Evaluation. It is here assumed that, from separate funding, USGS studies of the geothermal resource base will continue on both regional and national scales and as case studies of one or more typical HDR areas. This information--together with reports of the Hot Dry Rock Assessment Panel (HDRAP), the LASL Hot Dry Rock Project, DOE-supported investigations of hydrothermal areas, and others--should provide a reasonable basis for identifying geothermal areas in which the potential probably exists for HDR development.

Two general classes of potential sites are anticipated:

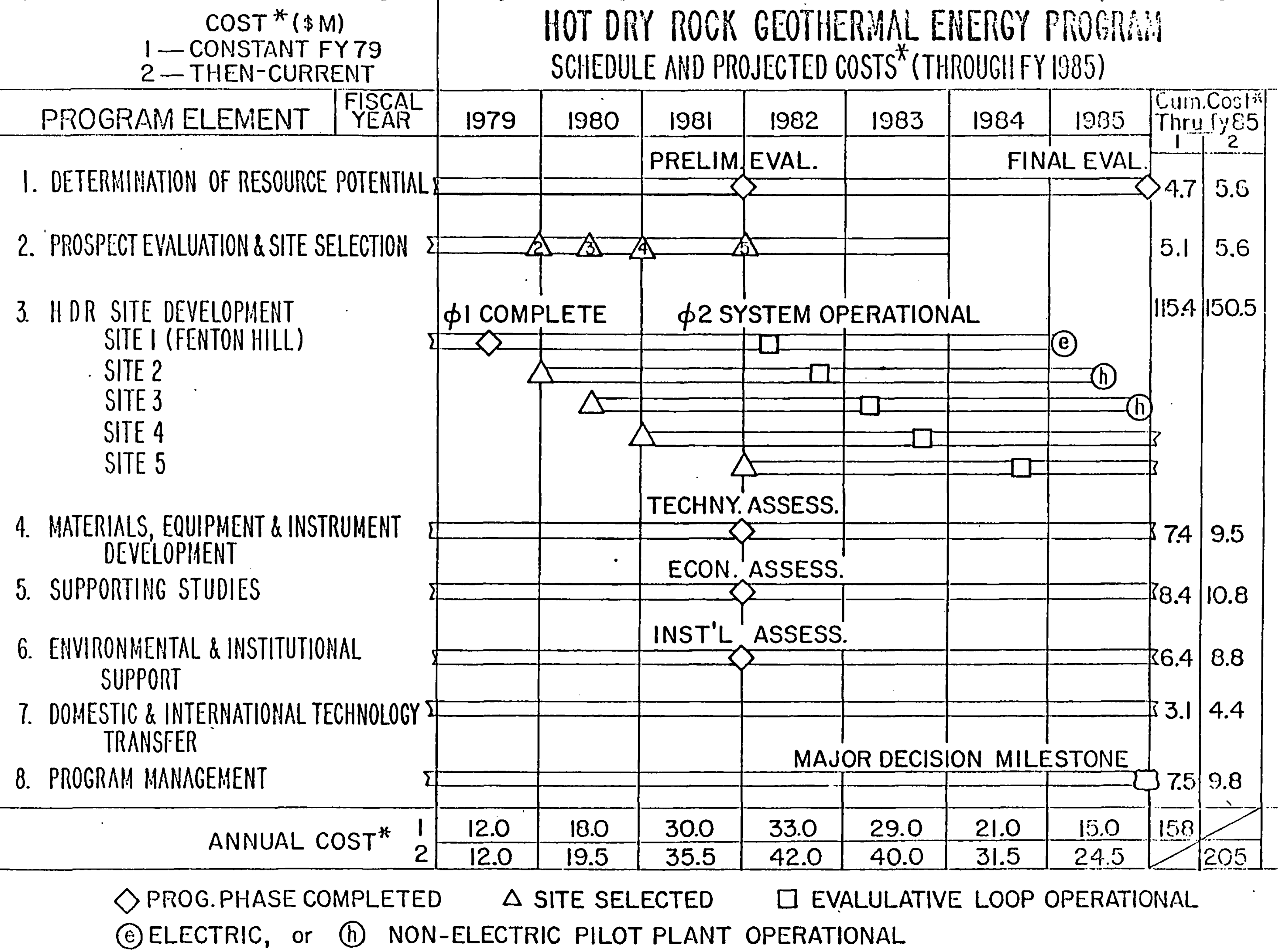
- Target-of-Opportunity Sites: "Dry" holes, resulting from hydrothermal or petroleum exploration, which, if they cannot be made productive by stimulation treatments, may be suitable for energy extraction by HDR techniques;
- Ad Hoc Sites: Areas selected specifically for their HDR promise.

Both types of sites will be incorporated into program planning from the beginning. Commonalities are such that exploration and evaluation--involving both geological and market appraisal--can in many cases be done jointly with the hydrothermal exploration effort. It will be necessary however to collect, organize, and evaluate the existing data concerning each area of interest. In general, it will be found that important gaps exist in the available geological or geophysical information, and/or in that concerned with local power demand, land-use, or environmental constraints on exploration and development. A field reconnaissance and survey program will be required to fill these gaps in order to permit identification of specific sites that merit, and are available for, more detailed investigation, and to establish priorities for this purpose. Much of the field work will be done by industrial and university subcontractors. The activity will be brought essentially to full strength in FY80, remain at that level for about 5 yr, and then taper off rapidly when enough sites have been identified to provide for future developmental needs of this program and to verify the general distribution of the HDR resource.

2. Site Characterization. With the exception of site 1 (the LASL Fenton Hill site), and such existing unproductive wells as may be made available by commercial energy companies or by other government activity, each identified experimental site is expected to require: detailed local investigation from the surface; the drilling of at least one exploratory hole to a sufficient depth to examine the subsurface geology, hydrology, and heat flow below the active ground-water circulation; and a few downhole experiments in this hole to establish particularly the initial permeability of the *in situ* hot rock as a function of pressure. A preliminary estimate is that at least five individual sites will have been evaluated by the end of FY81 in different geologic settings in the western U.S. and in areas of higher-than-normal geothermal gradient in the midwestern and eastern U S. These evaluations will take into account the local market for heat of the grade that might ultimately be produced there from hot dry rock at an economical drilling depth. It is roughly estimated (Appendix H) that 1 yr and an outlay of $0.6 million will be required for acquisition of access rights and permits and for surface studies, and that one additional year and an outlay varying between $3 million and $4 million will be needed for exploratory drilling and initial downhole studies. The laboratory core studies, reservoir analyses, and environmental and institutional investigations associated with this work are included in other activities listed in Fig. 5 and Appendix A.

3. Prototype Systems. To determine what modifications of the technology now being developed at site 1 (Fenton Hill) may be required in other geological environments, it will in general be necessary at each subsequent site to establish an evaluation air-rejection energy-extraction loop and to operate it for a period of from a few months to a year or more. The time and funding requirements for doing so can be expected to vary widely, depending principally upon hole depths required and the difficulties

Fig. 5.



HOT DRY ROCK GEOTHERMAL ENERGY PROGRAM
SCHEDULE AND PROJECTED COSTS* (THROUGH FY 1985)
COST* ($ M)
1 — CONSTANT FY 79
2 — THEN-CURRENT
PROGRAM ELEMENT
FISCAL YEAR
1979
1980
1981
1982
1983
1984
1985
Cum. Cost* Thru fy85
1
2
1. DETERMINATION OF RESOURCE POTENTIAL
PRELIM. EVAL.
FINAL EVAL.
4.7
5.6
2. PROSPECT EVALUATION & SITE SELECTION
2
3
4
5
5.1
5.6
3. HDR SITE DEVELOPMENT
SITE 1 (FENTON HILL)
SITE 2
SITE 3
SITE 4
SITE 5
φ1 COMPLETE
φ2 SYSTEM OPERATIONAL
e
h
h
115.4
150.5
4. MATERIALS, EQUIPMENT & INSTRUMENT DEVELOPMENT
TECHNY. ASSESS.
7.4
9.5
5. SUPPORTING STUDIES
ECON. ASSESS.
8.4
10.8
6. ENVIRONMENTAL & INSTITUTIONAL SUPPORT
INST'L ASSESS.
6.4
8.8
7. DOMESTIC & INTERNATIONAL TECHNOLOGY TRANSFER
3.1
4.4
8. PROGRAM MANAGEMENT
MAJOR DECISION MILESTONE
7.5
9.8
ANNUAL COST* 1
12.0
18.0
30.0
33.0
29.0
21.0
15.0
158
ANNUAL COST* 2
12.0
19.5
35.5
42.0
40.0
31.5
24.5
205
◇ PROG. PHASE COMPLETED
△ SITE SELECTED
□ EVALULATIVE LOOP OPERATIONAL
e ELECTRIC, or h NON-ELECTRIC PILOT PLANT OPERATIONAL

encountered in drilling and other operations. As a preliminary estimate (made with the benefit of the Fenton Hill experience and assuming that the site characterization described above has been completed), it is projected that about 1 yr and between $4 million and $5 million will be required to complete an underground circulation loop; another year and about $3 million will be needed for initial experiments with this loop and completion of the surface facilities required to circulate fluid continuously through it; $1 million per year will support its experimental operation; and, for sites not to be developed beyond this stage, $0.5 million will be spent on site restoration and abandonment. Again, this does not include associated laboratory and field studies of types listed in Appendix A, many of which will be done at a central laboratory or by specialized technical groups which will serve more than one field site.

4. Pilot Plants. To investigate system behavior and reliability and to develop and demonstrate the technology required to use the energy produced from HDR systems, it is tentatively assumed that a total of at least three pilot-scale plants will be required by FY85. Of these, one would be an electrical-generating plant with a capacity of the order of 10 MWe, and two of nominal 50-MWt capacity would produce 1.5 milliquad/yr of heat for direct use. The electrical-generating pilot plant might also be used for investigations of cogeneration, in which waste heat from generating electricity is made available for other uses. In each case, about 1 yr (contemporaneous with completion of a prototype system at the same site) and $0.2 million would be devoted to conceptual design of the pilot plant, and one additional year and $0.2 million to its final design. In the case of a generating plant, 3 yr and $15 million would be required for additional drilling, procurements, and plant construction, and $1.5 million per year for plant operation. For direct use, it is assumed that 2 yr and $10 million would support drilling and construction, including the fluid-distribution system, but that operating cost would be $1 million per year. In each case, $1 million is listed for disposal or restoration of those sites not to be developed to the demonstration stage.

5. Demonstration Plants. To demonstrate reliability and investigate economics at the small commercial scale, construction and operation of one or more demonstration plants may be necessary, to generate electrical energy at perhaps 50 MWe or to produce heat for direct use at perhaps 100 MWt (3 mQ/yr) ultimate capacity. Again, a demonstration electrical plant might

also be available for a demonstration of cogeneration. Conceptual and final design of demonstration systems is assumed to have approximately the same costs and time-frame as do pilot plants, considered above, and it is assumed that this expense would be supported entirely by the Department of Energy. Subsequent construction and operating costs are assumed to be shared equally with an industrial partner or partners. It is estamated that, for electrical demonstration plants, 3 yr and a total (government plus private funding) of $100 million would be required for drilling, procurement, and construction, and that operating costs thereafter would be about $2 million per year. For nonelectrical plants it is estimated that about 2 yr and $25 million would be required, including design and construction of the fluid distribution system, and that subsequent operation costs would be about $1 million per year. For both types of plants it is assumed that, except when the demonstration plant was built at a Federal Government installation, the Government interest would be disposed of in accord with PL 93-410 and DOE policy after an operating period of 2-5 yr. It is, however, suggested that at least the first of the demonstration systems might appropriately be located at a major Government installation such as a military base or a national laboratory--for example, at Los Alamos Scientific Laboratory, where conversion away from natural gas has been mandated by the Federal Government, and where development of an HDR district space-heating system appears possible. Such a demonstration system would serve as an encouraging model for many small communities in the United States.

D. Hot Dry Rock Technology Development.

The other activities listed in Appendix A have not been developed in detail. All are deemed essential to support a national Hot Dry Rock Program. The funding levels shown in Fig. 5 are preliminary estimates only, and the appropriate annual support levels actually remain to be established on the basis of those required to achieve the HDR commercialization goals. For example, as is discussed in Appendix I, to implement the evolutionary sequence of experimental and demonstration systems, certain high-temperature tools, equipment, and instrumentation, the need for which is peculiar to HDR systems, will have to be developed. Components of these technical service functions are described below.

As commercialization of hydrothermal resources continues, many aspects of ongoing hardware and software developments will be directly applicable to the HDR RD&D effort. Only if special needs are identified for HDR that are not addressed--or cannot be addressed in a timely manner--in other DOE/DGE programs, will separate HDR-sponsored projects be initiated.

1. Equipment and Materials Development. Prototype-phase experience at site 1 (LASL's Fenton Hill experiment, reviewed in Appendix B) has identified a number of areas in which currently available equipment and materials are marginal or inadequate for use in the high-temperature, hard-rock, downhole environment. Major examples of these are: directional-drilling and drill-guidance equipment; coring bits and sidewall-sampling apparatus; openhole packers; a system for testing and calibrating downhole equipment and instrumentation; improved temperature- and corrosion-resistant cements; high-temperature elastomers; and improved bearing materials and seals for use in hot, muddy water. Most of these needs are common to all geothermal programs and, in many cases, also to near-future fossil-fuel exploration and production requirements. Consequently, a relatively large, long-range DOE program in the equipment and materials area is indicated, particularly with regard to drilling and hole-completion technologies. The HDR Program's needs will be integrated into this effort, and certain parts thereof will be executed directly under the aegis and funding of the HDR Program.

2. Instrument Development. Specialized remote-sensing apparatus is needed for geological and geophysical studies made from the surface, together with a variety of small-diameter, temperature- and pressure-resistant downhole instruments and accessories. Essential to the creation of HDR reservoirs are the abilities to: (1) accurately determine and control the geometry of wellbores, and (2) ascertain the size, shape, location and orientation of fractures. Among specific needs engendered by these requirements are: hole-surveying, drill-guidance, and orienting devices; radar, sonar, acoustic, electromagnetic, visual, and photographic downhole observation systems; improved flowmeters, pressure sensors, inclinometers, pH meters, and impression packers; downhole recording, switching, and multiplexing systems; flexible, shielded, armored, waterproofed, multiconductor instrument cable with greater temperature and pressure resistance; improved cableheads; and possibly alternative signal-transmission systems. Several of these required developments will, individually, entail relatively large expenditures.

3. Technique Development. New techniques will be needed to deal with the novel types of problems already experienced and anticipated in the development and operation of manmade geothermal systems. Among these are directional drilling in harder rock and at higher temperatures than have previously been encountered, and with an accuracy that has not heretofore been required. Improved sidetracking methods are also needed for holes in very hard rock. Hydraulic- and explosive-fracturing methods require much additional investigation and development, together with other potential means of increasing formation permeability such as pressure cycling, selective chemical attack (leaching), and introduction of special proppants into existing fractures. Highly accurate techniques of borehole and fracture mapping are presently needed, and must be adapted for use in a single hole. Again, several of these developments will require relatively large efforts, which must likewise be carefully coordinated with the similar needs of other programs. It can be expected that new needs will continue to appear as additional sites are investigated.

4. Laboratory Investigations. Supporting work of several types is required in both field and central laboratories. Among major activities of this nature are the following:

a. Geochemical Engineering. Chemical interactions between the circulating water and the rock will be important in determining the time-variant flow behavior of the underground loop, the difficulties experienced with formation plugging and with corrosion and scaling of the well casing and surface plumbing, and the chemical nature of the hot fluid produced. These interactions will depend on the chemistry of the water injected into the system, the temperatures, pressures, and hydraulics throughout the system, and the chemical and mineralogical make-up of the rock. They will, therefore, be strongly site-dependent and, to the degree that the exposed reservoir rock varies from point to point, they will vary within a single system. Accordingly, a vigorous, continuing program of geochemical studies will be needed, which will include several types of observations and experiments that must be repeated for each new site which differs significantly from those previously investigated.

Field geochemistry. Continuous and detailed chemical monitoring of injected and recovered fluids will be required during all major flow experiments and extended system operations, both to understand and control system behavior and as a component of environmental monitoring programs. Downhole sidewall samples of rock exposed to the circulating fluid should be taken at intervals for laboratory investigation of chemical, mineralogical, and structural alterations with time. Coordinated laboratory and field studies will be made of the effects of specific chemical and particulate additions to the injected fluid on the chemical and flow behavior of the system. The possibilities of by-product production and of thermochemical mining operations will also be investigated to the degree that funding and manpower permit.

Laboratory geochemistry. Laboratory circulation loops permit detailed investigations of dissolution and precipitation reactions and rock alterations, as functions of temperature, pressure, fluid composition, and time. Samples tested will be taken from cores recovered during drilling operations and by sidewall sampling, from essentially all prototype field systems. Laboratory loops will range in size from quite small--for quick, flexible experiments and more detailed investigations--to bench-scale chemical-engineering loops that accept samples large enough to reproduce accurately the in situ rock structure and flow conditions. Small loops of several types already exist, and a number of them can be usefully employed in HDR investigations. Depending on the problems encountered in the field, these may be adequate, but more are likely to be needed.

Although the major commitment of the geochemical studies is to solving problems associated with reservoir mechanics and surface-plant performance, by-product recovery should also be carefully examined. Solution mining of strategic elements is an important possible serendipitous benefit of HDR energy systems.

Chemical modeling. The development of models which couple hydrodynamics with chemical kinetics throughout the entire hot dry rock energy system will become important in predicting system performance, and will thus require long-range support.

b. Rock Mechanics, Fluid Mechanics, and Heat Transfer. It is inherent in the HDR concept that controlled modifications are made in a subterranean fluid-circulation system, usually involving mechanical operations to increase permeability locally and always requiring detailed understanding of fluid flow and heat transfer between the rock and the fluid. Extensive rock-mechanics studies are needed, at each site, to determine the *in situ* physical and mechanical properties of the reservoir formation, and its fracturing, crack-extension, stress-relaxation, thermal-stress-cracking, and creep behavior. Fluid-mechanics investigations of several types are also needed, including physical modeling of flow through regions where mathematical modeling is unsatisfactory (for example, the fracture-borehole connection). Physical as well as chemical interactions of the rock and the fluid must be studied, with regard particularly to heat transfer, boundary layers, and pore-pressure effects on mechanical behavior.

c. Mineralogic, Petrographic, and Geochronological Studies. Detailed studies of outcrop, core, cuttings, and sidewall rock samples will be required throughout the history of each site investigated to understand the geological and the thermal environment of the underground system and as a basis both for designing it and for monitoring its changes with time.

5. Analytical Modeling Studies. The correlation and interpretation of much of the data collected in the activities outlined above will require sophisticated mathematical and computer analyses, and development of predictive capabilities will require the assimilation and extension of entirely new bodies of knowledge. Strong capabilities in these areas must be developed and maintained in complementary efforts associated with several parts of the overall HDR program. As the need becomes apparent, complete analyses will be conducted of HDR systems in specific geographic and socio-political settings. The development and evaluation of new design concepts for both underground and surface parts of the complete energy system will also be an important part of this activity, which, among other things, will involve extensions of present knowledge in the areas of reservoir engineering and low-temperature conversion cycles.

E. Commercialization Issues

1. Economics of HDR. The economic factors surrounding the development of hot dry rock as a commercially viable source of power must be fully and objectively presented and reviewed at all stages of the program. If it is assumed that the hydrothermal and geopressured programs will have provided the necessary development work for low-temperature surface-conversion plants for electric and process heat, the capital investment and operating costs associated with such equipment should be well characterized and documented in operating demonstration- and commercial-size systems. Because HDR systems can use these conversion systems with minimum modification, the main concern rests on reservoir-development costs. These include site development, drilling and completion, and fluid gathering and transportation system costs. Work done so far[7,8] has been concerned with sensitivity studies of the important parameters, including reservoir capacity (mass flow rate per pair of wells), reservoir lifetime or drawdown (change in wellhead fluid enthalpy with time), well-drilling, fracturing and casing costs, reservoir temperature (100-300°C), and geothermal temperature gradient (∇T, 20-200°C/km). Tentative conclusions derived therefrom are that:

- electricity generated from high-grade HDR sources can be competitive in the anticipated time frame of its availability, and
- process heat--either as a cogeneration product from a high-grade HDR system, or directly from a low-grade source--is competitive even now, if the source is in reasonable proximity to the user.

Future work on economics will particularly require more accurate estimates of escalating drilling costs and of uncertainties in those costs, and of the additional benefits that can be derived from cogeneration.

It is expected that other DGE programs will provide valuable information in this area. However, data on conventional and directional drilling in hot, hard crystalline rock are limited, so that additional field data may be required. At the inception of the Federal HDR program, an extensive industrial analysis of HDR economics (expanding the system studies being conducted in the LASL Project during FY78-79) will commence, and it will continue throughout the federally-funded period. This effort will be directed by the Program Management Office with the assistance of a consortium of organizations involved with exploration, drilling and completion, powerplant design and construction, institutional matters and investment strategies, power and heat distribution, and transportation and environmental effects.

2. Environmental Investigations. All major field activities must be carefully monitored to document fully the spectrum of environmental effects that might be produced by widespread development of HDR energy systems, including all residuals over the predevelopment condition of each site. Among the potential environmental hazards usually considered, special attention should be directed to water consumption, ground-water contamination, subsidence, and earthquake risk. A large part of this effort will involve preparation of Environmental Assessments (EA's) and Environmental Impact Statements (EIS's) as required for site dedication (Appendix J). It is expected that a considerable fraction of the ongoing environmental assessment and characterization work of the hydrothermal-resource development effort will be applicable to the HDR case. For example, for those HDR sites to be located within or near an existing high-grade hydrothermal field, it is anticipated that one Environmental Impact Statement could be written to cover both HDR- and hydrothermal-related development activities.

3. Institutional Issues. Commercial development of the hydrothermal resources of the United States has suffered from inadequate and inconsistent definitions of the resource, positive deterrents to exploration on public lands, delays and acreage limitations on leasing, land-use and water-use conflicts, overlapping governmental jurisdictions, uncertainties in tax status, and the resulting unavailability of risk capital for exploration, development, and exploitation. These same issues will be faced by hot dry rock development, complicated by the fact that a new type of resource must be legally defined. Their clarification will require a group of activities focused on legal, institutional, and financial impediments to development, and the means and consequences of eliminating them. These are discussed in Appendix J.

F. Domestic and International Technology Transfer

Domestic and international cooperation will be actively pursued in the development of this worldwide energy supply, and prompt dissemination of the information and technologies will be a major thrust of the program.

1. Technology Transfer. One principal objective of this program is to establish a base of new technology which will be extended and exploited by industrial organizations, and by other governmental bodies from small

communities to large Federal agencies. To this end, non-DOE support, cooperation, and participation will be sought and encouraged in all parts of the program. Among other things this will include exchanges of geologic, geophysical, and hydrologic information; cooperation in the development of equipment, instruments, techniques, and analyses; and field experiments in existing hot, dry holes drilled by energy companies. It must also include implementation of an efficient and imaginative plan for promptly disseminating information developed in the program to those who can benefit from it.

2. International Programs. Both at the direction of the Congress and in fulfilling its commitments under a group of bilateral and multinational agreements, DOE is responsible for transfer of nonnuclear energy technology outside, as well as within, the boundaries of the United States. Sufficient funding and effort must be committed to these international programs to provide adequate flexibility in implementing them as opportunities to cooperate and assist are discovered in other countries and in acquiring and utilizing the information developed elsewhere in the world.

V. IMPLEMENTATION

The program elements described above are listed in outline form in Appendix A, and timelines and estimated costs for them are shown in Figure 5. Because of large uncertainties in many of these initial cost estimates, management expense and contingency allowances (which must be generous for typical drilling programs and downhole experiments) have not been separately identified. Not included are such activities as the development of low-temperature energy-conversion equipment, which it is assumed will be accomplished in other programs, and not indicated are the contributions that many of the activities listed here will make to other energy programs, including "wet" geothermal systems and borehole (*in situ*) technology in general. While the costs shown are not trivial, they are in fact small compared with those of many other energy activities—for example, the installation of scrubbers on coal-fired power plants.

In the proposed management structure outlined in Fig. 3, ultimate responsibility for the program rests with the DGE Program Director at DOE Headquarters. Responsibility for day-to-day execution of the program is vested in a field management team, comprising the Los Alamos Scientific Laboratory (LASL) and the DOE Albuquerque Operations Office (ALO). Reporting to the Program Director, a Program Management function will be established as a discrete entity within LASL. Headed by the Program Manager, this office will have the staff and the expertise--either within its own walls or those of its Operations Office affiliate--to respond quickly and positively to contingencies as they arise. The field management team will be given the technical authority and fiscal control required for effective program management. This team will be strictly accountable to the Program Director's Office, and will submit plans and recommendations thereto on fiscal and policy matters as the program unfolds.

A "National Hot Dry Rock Program Development Council", largely industrial in make-up, will be organized to assist in the planning and to periodically review the progress of the Federal Program. The structure and functions of this Council are outlined in Appendix C.

A "Hot Dry Rock Library" that will serve as a comprehensive central repository and national distribution center for HDR-related literature will be established at LASL. Pertinent books, reports, patents, etc., will be acquired, filed, and systematically made available on a need basis.

REFERENCES

1. LASL HDR Project Staff, "Hot Dry Rock Geothermal Energy Development Project, Annual Report Fiscal Year 1977," Los Alamos Scientific Laboratory report LA-7109-PR (February 1978).

2. D. E. White and D. L. Williams, Eds., "Assessment of Geothermal Resources of the United States - 1975," Geological Survey Circular 726 (1975).

3. Hot Dry Rock Geothermal Energy: Status of Exploration and Assessment: Report No. 1 of the Hot Dry Rock Assessment Panel," Energy Research and Development Administration report ERDA 77-74 (June 1977).

4. J. K. Costain, L. Glover III, A. K. Sinha, "Evaluation and Targeting of Geothermal Energy Resources in the South Eastern United States," Virginia Polytechnic Institute report VPI-SU-5103-3 (1977).

5. "Definition Report: Geothermal Energy Research, Development and Demonstration Program," Energy Research and Development Administration, Division of Geothermal Energy report ERDA-86 (October 1975).

6. "National Plan for Energy Research, Development, and Demonstration: Creating Energy Choices for the Future," Energy Research and Development Administration report ERDA 76-1 (1976).

7. S. L. Milora and J. W. Tester, Geothermal Energy as a Source of Electric Power (MIT press, Cambridge, MA, 1976).

8. R. L. Bivins, R. G. Cummings, G. E. Morris, and J. W. Tester, "Economics of HDR Systems," in "Hot Dry Rock Geothermal Energy Development Project, Annual Report Fiscal Year 1977," Los Alamos Scientific Laboratory report LA-7109-PR (February 1978, pp. 222-236).

APPENDIX A

MAJOR ELEMENTS CONSTITUTING A NATIONAL HOT DRY ROCK PROGRAM

1. DETERMINATION OF RESOURCE POTENTIAL

   a. USGS regional and national studies (not included in cost estimates)
   b. Reconnaissance studies at the surface: geological, geochemical, geophysical, hydrologic, shallow heat-flow

2. PROSPECT EVALUATION AND SITE SELECTION

   a. Identification of prospects for experimental sites
   b. Detailed local studies at the surface
   c. Exploratory drilling
   d. Subsurface studies: geology, hydrology, temperature gradients, heat flow
   e. Analysis of local energy market
   f. Assessment of local environmental and institutional barriers to development
   g. Synthesis and selection of sites for development

3. HDR SITE DEVELOPMENT

   a. Drilling and completion of connected underground heat-extraction system
   b. Construction of surface heat-dissipation system and completion of loop
   c. Energy extraction and reservoir quality/life assessment
   d. Evaluation of suitability for pilot plant
   e. Engineering design and construction of pilot plant
   f. Pilot plant activation and checkout
   g. Seismic, hydrologic, microclimatological, and biological monitoring
   h. Effluent fluids control
   i. Abandonment and restoration of unsuitable sites

4. MATERIALS, EQUIPMENT, AND INSTRUMENT DEVELOPMENT

   a. Straight- and directional-drilling tools and materials
   b. Hole-completion equipment and materials
   c. Coring and sidewall-sampling apparatus
   d. Downhole pumps
   e. Test and calibration facilities for equipment and instruments
   f. Small-diameter, temperature- and pressure-resistant instruments for hole-surveying, drill guidance, logging, visual and photographic observation, fracture mapping, sampling, and monitoring of temperature, pressure, flow rate, microseismic signals, rock properties, and fluid characteristics

Appendix A (Continued)

g. Data-transmission systems

5. SUPPORTING ANALYTIC AND EXPERIMENTAL STUDIES

a. Remote sensing from the surface and downhole for formation identification and characterization, detailed hydrologic studies, hole mapping, and mapping of natural and created fracture systems
b. Hole-sidetracking, directional drilling, and drill guidance technique development
c. Cementing technique development
d. Hydraulic and explosive fracturing technique development
e. Fracture propping technique development
f. Selective leaching technique development
g. Chemical and mineralogical analyses
h. Rock ages and thermal and geochemical histories
i. Physical, thermophysical, mechanical, and thermomechanical properties, as functions of temperature, pressure, stress condition, chemical environment, and time
j. Stress-relaxation and creep behavior of rock
k. Geochemical, including dissolution, precipitation, and rock-alteration reactions, effects of additives, and deterioration and corrosion of system components
l. Physical modeling of underground flow systems and their components
m. Data analysis and interpretation
n. Mathematical modeling of fluid flow, heat flow, chemical interactions, fracturing and crack-extension processes, and system changes with time
o. Systems analyses
p. Drilling costs
q. Fracturing and completion costs
r. Surface plant costs
   - electric
   - nonelectric
s. Site development costs
t. Cost-benefit analyses
u. Reservoir management strategies
   - with power drawdown
   - variable loads

6. ENVIRONMENTAL AND INSTITUTIONAL SUPPORT

a. Environmental data-base compilation
b. Water consumption studies
c. Environmentalist group interaction
d. Environmental legislation
e. Preparation of Environmental Assessments/Impact Statements
f. Permits and leases
g. Definitions, jurisdiction, rights, and other legal considerations
h. Policy analysis
i. Cost and availability of capital
j. Loan programs
k. Socioeconomic impact assessment

Appendix A (Continued)

7. DOMESTIC AND INTERNATIONAL TECHNOLOGY TRANSFER

   a. Public information and education
   b. Subcontracted developments and supporting activities
   c. Cooperative and funded projects
   d. Bilateral international programs
   e. Multinational programs
   f. Informal cooperative international arrangements

APPENDIX B

STATUS OF THE LASL HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROJECT

APPENDIX B

2. STATUS OF SITE 1 (FENTON HILL)

I. INTRODUCTION

On May 28, 1977, as the production well at Fenton Hill was being redrilled along a planned trajectory, it intersected a low-impedance hydraulic fracture in direct communication with the injection well, EE-1. Thus, a necessary prerequisite for a full-scale test of the LASL Hot Dry Rock Concept, that of establishing a high flow rate between wells at low wellhead differential pressures, was satisfied. Previously, communication with EE-1 had been through high-impedance fractures, and flow was insufficient to evaluate the heat-extraction concept.

In September, with much of the work on the surface plant of the energy-extraction loop nearly complete, we conducted a preliminary test of the entire system—surface plant and downhole flow paths. During 96 h of closed-loop circulation, fluid salinity remained low (<400 ppm), water losses continually decreased, and no induced seismic activity occurred. The operating power level was 3.2 MW (thermal) and fluid temperature reached 130°C at the surface. This test demonstrated for the first time that heat could be extracted at a usefully high rate from hot dry rock at depth and transported to the surface by a manmade system. The test further indicated a high probability that no significant problem would be encountered during sustained operation of the system.

Full-scale operation of the loop occurred from January 27 to April 12. During this Phase I test the thermal drawdown, impedance to flow, water losses, and fluid geochemistry of the system were studied in detail. In addition the experimental area was closely monitored for induced seismic activity. Results of these studies are briefly discussed in this Appendix.

II. LOOP OPERATION

During the Phase I operation, 20 channels of information about the loop were recorded: 7 flow rates, 8 pressures, and 5 temperatures. In addition to the loop instrumentation, 80 channels of thermocouple data were recorded. The thermocouples were strategically located on the heat exchanger to study possible corrosion and scaling problems.

Control functions for the Phase I loop were minimal. The CDA (Control and Data Acquisition) operator could manually start and stop four fans on the heat exchanger and manually stop the make-up pumps and main circulating pumps. A Hewlett Packard 9830 calculator was programmed to check all measurements against predetermined minimum and maximum values. If these parameters were exceeded the calculator would sound an alarm and define the problem with a printed statement. If the problem could result in damage to the pumps the calculator would also turn off all pumps immediately.

The numeric displays were updated every 15 s. All data channels were recorded on magnetic tape and on the line printer at 15-min intervals. If any of the predetermined parameters mentioned in the preceding paragraph was exceeded the recording interval changed to 1 min.

On January 27 the system was started by the make-up pump drawing water from the EE-1 fluid-reservoir pit. An output pressure of 175 psi was reached within a few minutes. At that time the main circulating pumps were turned on. The flow was into the EE-1 borehole, through the fracture system and out of GT-2, where the flow was vented to the GT-2 pond. After several hundred thousand gallons of water had been pumped, the flow was diverted to the heat exchangers and back to the main pumps. The system was then "closed-loop." The inlet pressure to the main pumps was controlled by the make-up pump pressure, which in turn was controlled by a back-pressure valve. This valve was set at 175 psi and automatically diverted the make-up flow back to the EE-1 reserve pit when that pressure was exceeded. As the return flow from the heat exchanger gradually increased, the make-up flow was proportionally reduced. The EE-1 borehole pressure had been "red-lined" at 1300 psi for technical reasons. As the pressure approached that value, the flow was throttled at the control valve. After a few days the pressure and flow stabilized at $\sim$1300 psi and 125 gpm.

After 3 wk of operation in this mode, the impedance of the fracture system started to drop. The result was a demand for more flow to maintain the wellhead pressure. The control valve was therefore adjusted to allow for more flow. Finally the control valve was wide open, the flow exceeded 270 gpm, and the desired inlet pressure of 1300 psi could not be maintained. At that time we decided to control on flow, and a constant rate of 230 gpm was established.

The loop was operated under these conditions until it was "shut in" on April 13, 1978. "Shut in" was maintained for 10 days and then the system was vented.

The operation of the system for the 75 days of the test was an almost unqualified success. The system was "down" about 2% of the time. Equipment failures, largely a result of the use of new components and operation under winter conditions along with abrupt changes in flow rates through the downhole fracture system and interruptions in utility-supplied electrical power, necessitated only an occasional temporary cessation in circulation.

III. THE DOWNHOLE SYSTEM

Figure B-1 summarizes the current knowledge of the distribution of the flow between wells. About 90% of the water pumped into EE-1 is injected into a single fracture at 9030 ft, where the temperature of undisturbed rock is 185°C. The fracture at that depth is believed to be a member of a series of ancient northwesterly striking vertical fractures separated horizontally by distances of 15 to 20 ft, which have been hydraulically reopened. Flow into any fractures intersected above the main injection point is blocked by casing cement. Below this point fractures have high intrinsic impedances at current operating pressures. Flow through the 9030-ft fracture enters the producing well through four fractures intersecting GT-2B, but two fractures (one at 8755 and the other at 8860 ft) account for most of the flow. The fractures intersecting GT-2B must be considered distinct from the main fracture in EE-1. Not part of the northwesterly striking set, they intersect the main fracture and provide for the lateral flow which is necessary to complete the connection between wells.

IV. THERMAL POWER AND DRAWDOWN

Injection and production flow rates were measured with venturi meters and differential-pressure transducers. Surface injection and production temperatures were measured with thermocouples inserted into the wellheads. In addition, a temperature-surveying tool employing a thermistor was positioned downhole in the production well, designated as GT-2B, for almost the entire duration of the test. A total of 58 surveys was run during Phase I heat production. Between surveys the tool was stationed at 2.6 km (8600 ft),

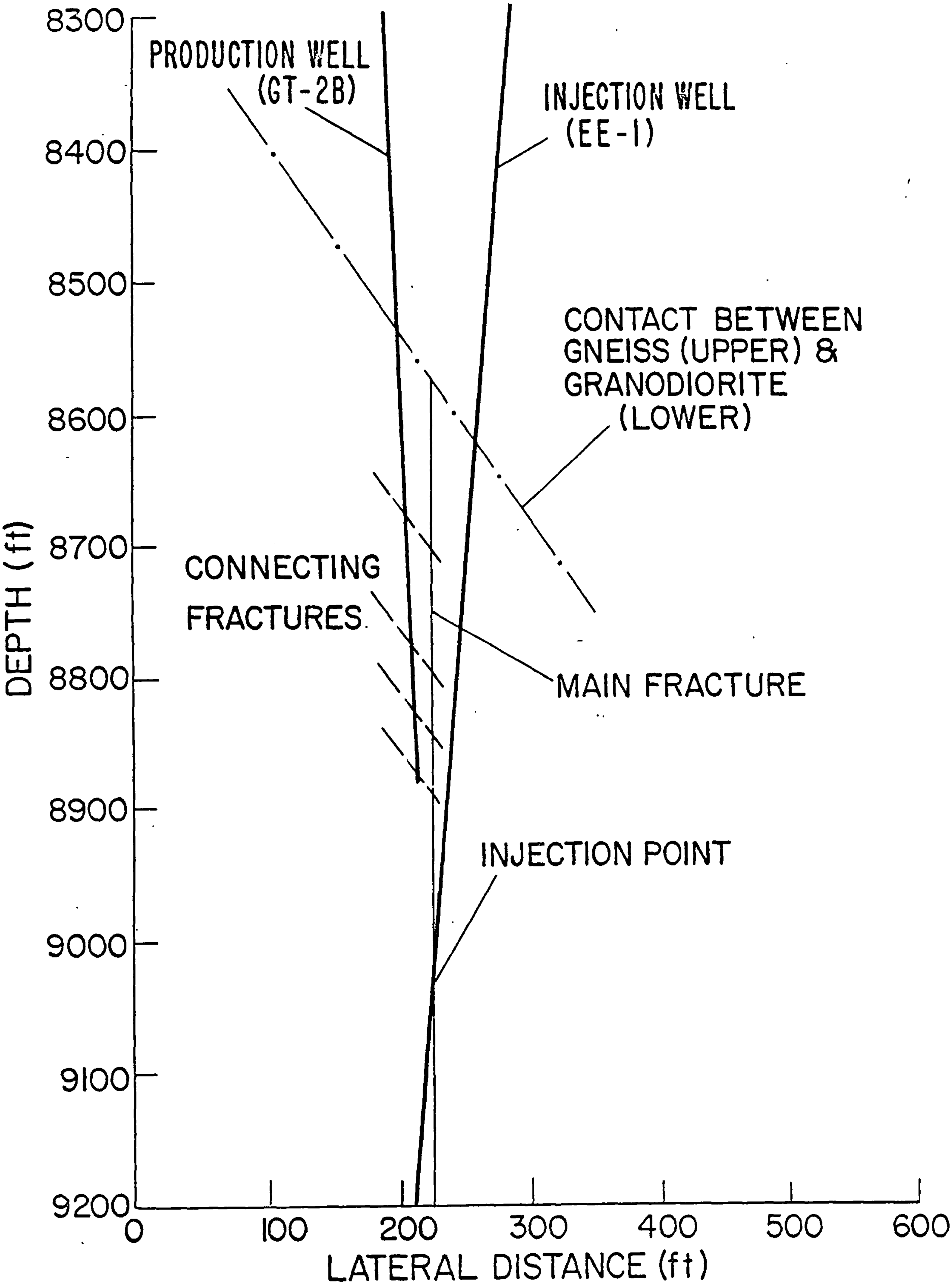


Fig. B-1. The inferred fracture system in relation to Fenton Hill injection and production wells (NE-SW) section.

just downstream (that is, uphole) of all the known flow connections between the reservoir and the production well. In this fashion the mixed-mean temperature of all the water flows converging on GT-2B was almost continuously monitored. Typical surveys are presented in Fig. B-2. The uppermost survey was obtained on February 4, 1978, 7 days after the start of power production, while the middle and lower surveys were obtained after 12 and 16 days, respectively. Even a cursory look at these surveys indicates a reservoir-to-well connection of fascinating complexity. The major temperature changes at the depths indicated are associated with flow connections that had been identified in earlier testing. (The uppermost connection was actually identified upon re-examining the earlier data.) We found in earlier testing that 20% and 80% of the flow entered the production well through the deepest and next-deepest of these four connections, respectively, while the flow rates in the upper two were too small to be measured. Both major connections 1 and 2 actually consist of two connections each. At connection 2, a definitely colder flow entered at the bottom while 2 m up, water at least 5° hotter entered the well. The February 9 survey, and even more pronouncedly the February 13 survey, show the development of new flow connections between the previously determined major connections 1 and 2; and, in fact, the magnitude of the temperature change at 2.68 km (8800 ft) suggests that a major new connection has also developed there. Unlike the injection well, which operates at high pressure, the pressure in the production well is close to normal hydrostatic, so we conclude that this new connection was caused by thermal or chemical-dissolution effects rather than by pressurization.

Figure B-3 presents the variation of temperature at 2.6 km (8500 ft) with time. This represents the best indication of the overall thermal drawdown of the reservoir. Also shown are theoretical results for a reservoir with a surface area (one side only) of 8000 m^2 (8.6×10^4 ft^2). In the computation, the fracture aperture was assumed to be constant, 0.2 mm; the assumed inlet temperature was 50°C; the inlet was located 30 m above the fracture bottom; and the outlet was located at the top. We assumed that in addition to the GT-2 outflow, one-half of the make-up flow was effectively extracting heat. The temporal variation of this combined flow rate was represented as a curve with three linear segments. The "scallop" in the predicted and measured temperatures at 25 days is due to a rapid flow-rate increase.

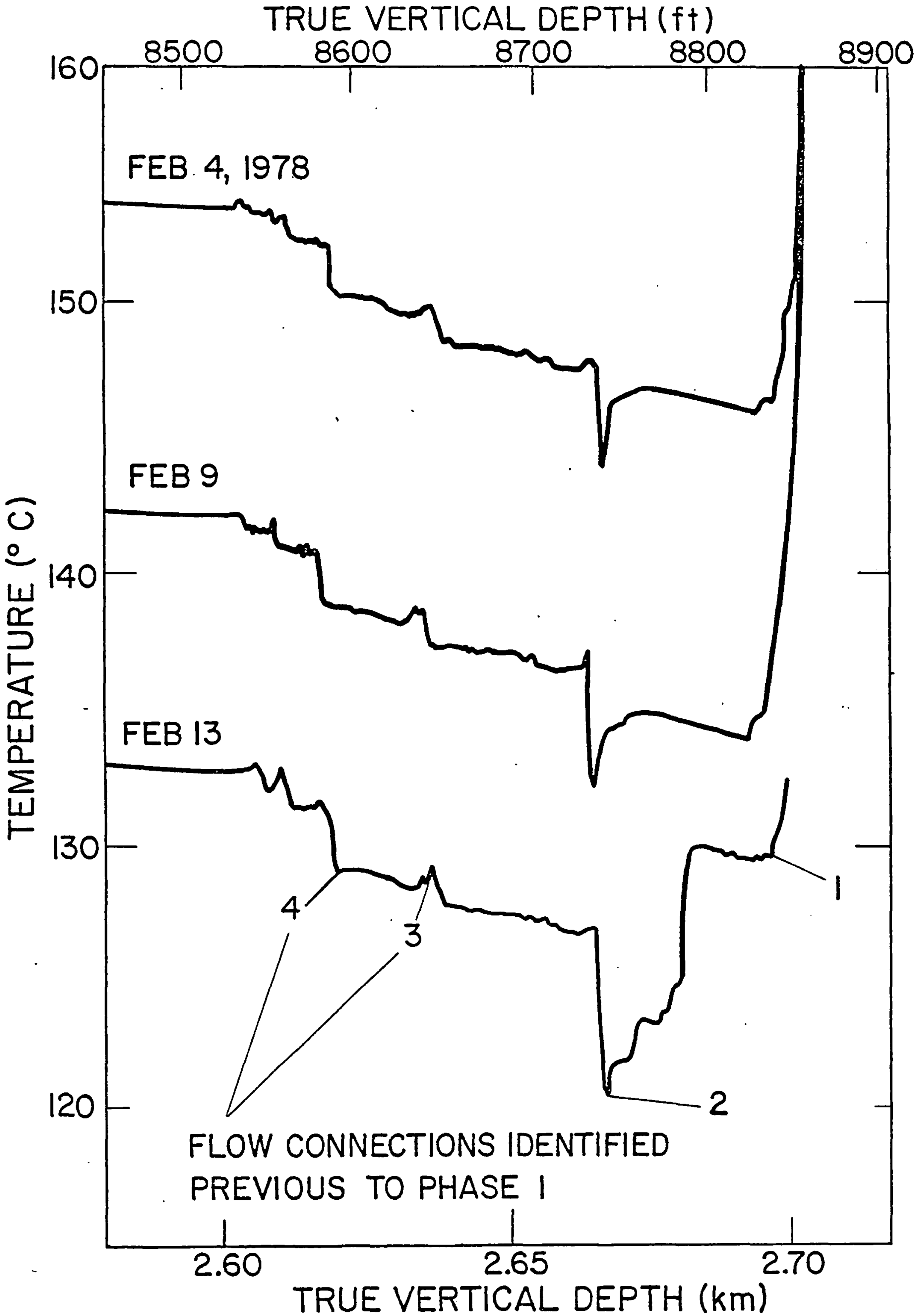


Fig. B-2. Temperature surveys in production well GT-2B.

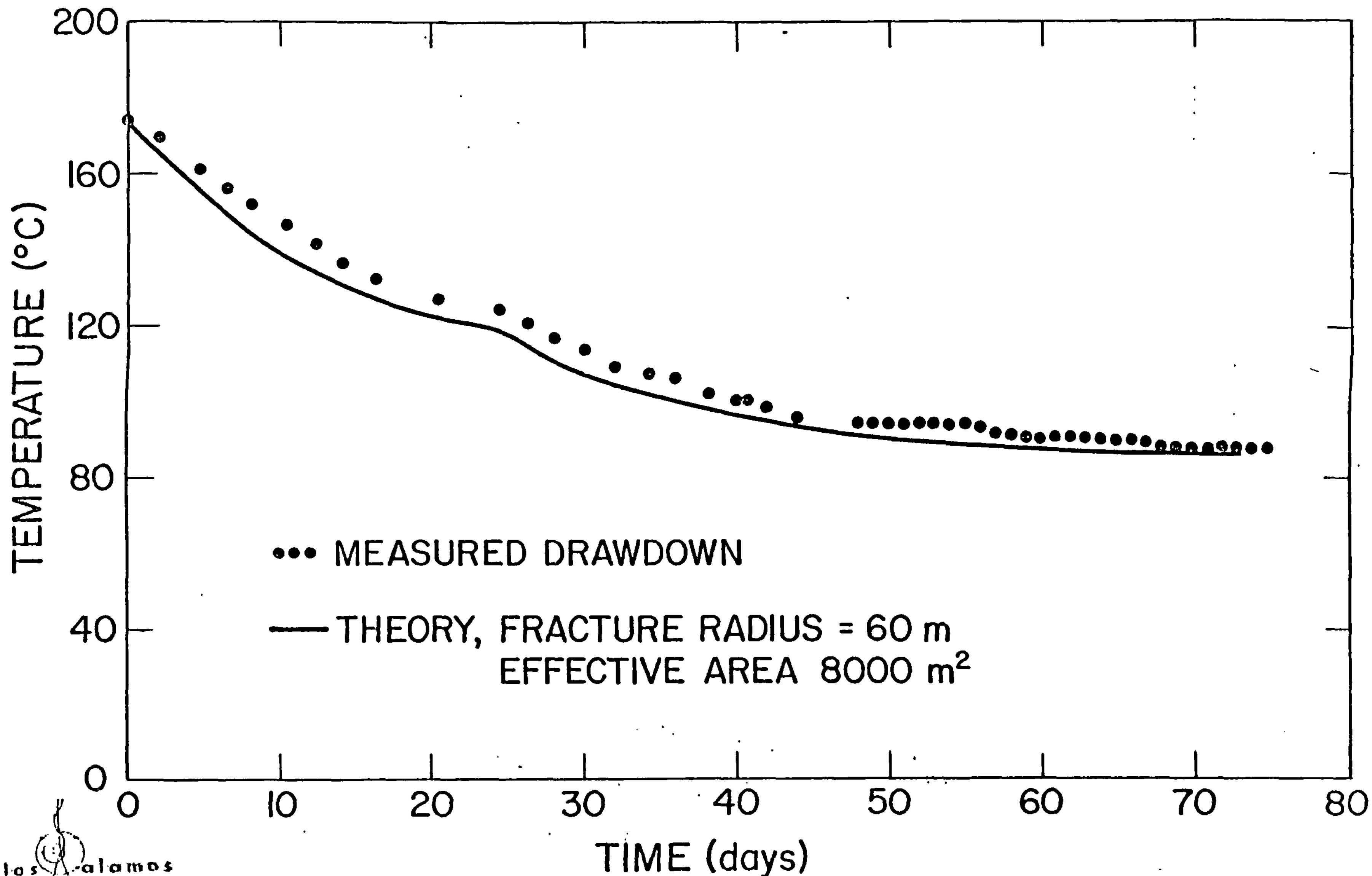


Fig. B-3. Reservoir production temperature.

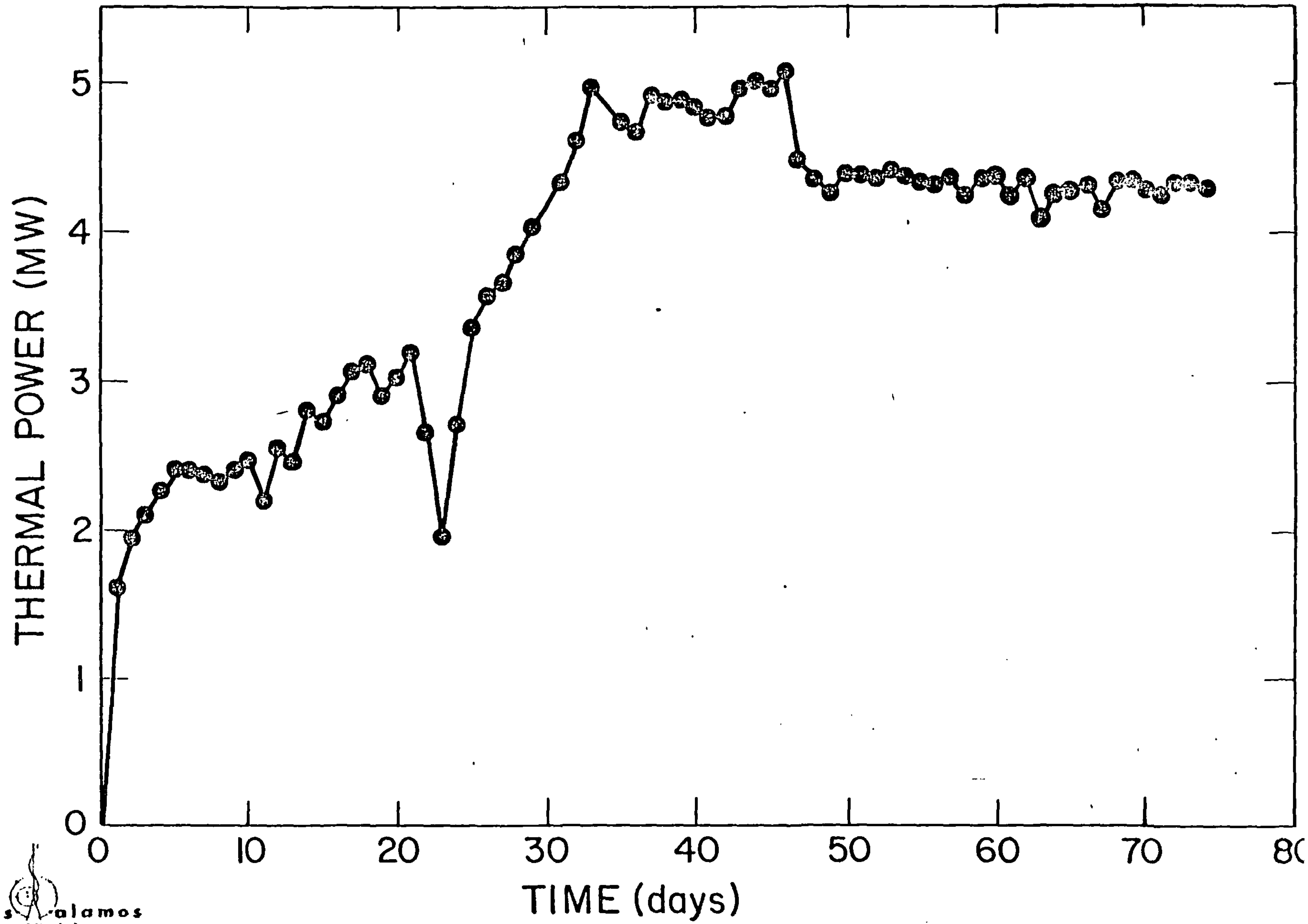
The theoretical curve indicates that the downhole temperature always decreases, but at a slower and slower rate; in contrast, the data on several occasions have shown absolutely no decrease for periods as long as several days. Thermal-stress cracking, if it did occur, occurred so late in this phase of the test that it has not so far contributed much to thermal performance. In fact, even if the temperature were to remain perfectly steady for 20 days (a rather unlikely event), the actual temperature would still be only a few degrees higher than that predicted. Given the relatively short time scale for the test, the only reasonable way to convincingly demonstrate thermal-stress cracking would have been to increase the flow rate considerably so as to drive the predicted curve downward, and then to see if the actual temperature followed the prediction.

Because of the decreasing impedance, the flow rate could not be maintained at constant pressure for long periods at more than $\sim$230 gpm. Consequently, the energy extraction rate increased gradually to $\sim$5 MW (t) as flow rate increased to $\sim$270 gpm, and thereafter remained nearly constant at $\sim$4.3 MW (t) while flow rate was reduced for safety considerations to 230 gpm (Fig. B-4). The effects of temperature drawdown on energy extraction rate were obscured by these changes in flow rate.

V. FLOW IMPEDANCE

Flow impedance is the pressure drop through the fracture system connecting the two wellbores divided by the flow rate. There is some ambiguity in this definition because the inlet flow differs from the outlet flow by the rate at which water diffuses into the rock surrounding the fracture. Conservatively, one may use the outlet flow rate in calculating impedance. Because there were no downhole pressure gauges, the downhole pressure drop through the fracture system was obtained from the pressure difference between EE-1 and GT-2 measured at the surface and corrected for the difference in density of water in the two wellbores.

In the course of this test, the impedance began to fall after 1 wk of flow. Figure B-5 is an idealized (averaged) graph of the flow and pressure history in EE-1. After attaining a roughly constant value of 15 psi/gpm in the first few hours of operation the flow rate into EE-1 was limited by surface plumbing and, as the impedance dropped and it became impossible to hold constant



los alamos
scientific laboratory
of the University of California

Fig. B-4. Thermal power variation.

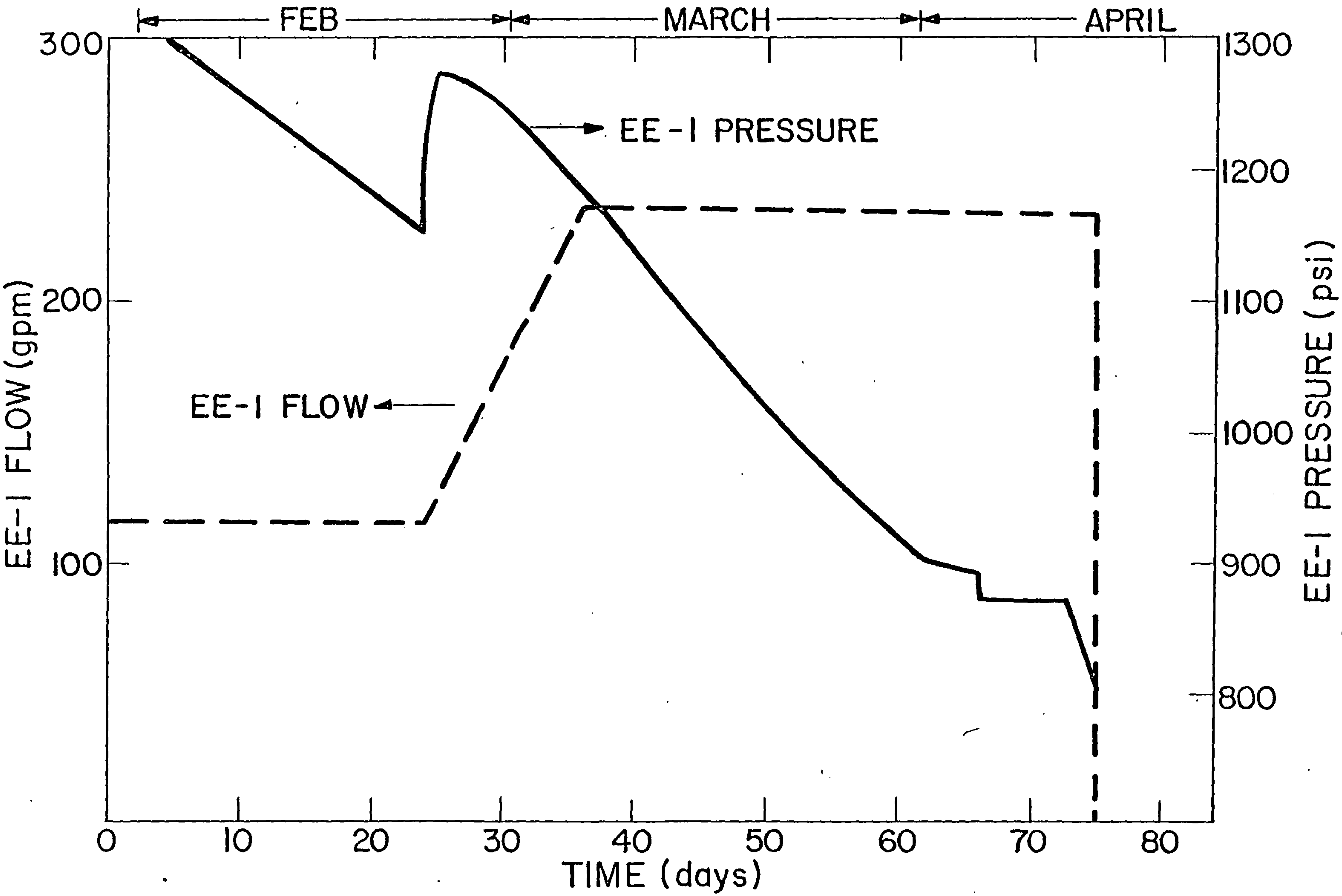


Fig. B-5. Idealized pressure and flow history in EE-1.

pressure, it was decided to maintain constant flow rate. This was done during the second half of the test, as seen in Fig. B-5.

The impedance decreased to less than 1/3 of the original value in the first 40 days, but decreased only 25% more from day 40 to the end of the run at day 75. This is shown in Fig. B-6. Throughout the 75-day period, numerous discontinuous decreases in impedance occurred, contributing to the overall decrease. None was associated with seismic effects observable at the surface.*

Continuous changes in impedance may have been the result of the shrinkage of fracture faces away from each other, caused by cooling and pressurization. Abrupt changes in impedance may have resulted from changes in the compressive stresses within the reservoir, caused by cooling or pressurization of the entire region. When the stresses in the rock decrease together, so that the stress differences do not change, the normal stresses across many of the fractures will decrease while the shear stress remains constant, and one fracture face may slip across the other. Because the pre-existing fractures were not truly planar, this slippage may result in a partially open crack, supported by small irregularities along the faces. Such an event would represent an abrupt change in flow impedance.

The real reservoir must be much more complex than any of these models, with both irregular regions of cooling and irregular regions of pressurization (not necessarily the same regions). Stresses will be relieved in some regions and concentrated in others, possibly leading to extensive breaking up of the rock.

VI. WATER LOSSES

During the test a total of 18 million gallons of water flowed between the wells through the fracture system. Of this, 1.3 million gallons were lost to the surroundings. Since the termination of closed-circuit flow, 300 000 gal or roughly 1/4 of this has returned through GT-2B. Figure B-7 shows the water losses expressed in terms of flow rate. Water-loss rate decreased from

---

*Many small impedance decreases must have been missed, but those which were observed were sufficient to account for over half of the flow increase observed during the run. Thus, many of the events which gave rise to impedance changes took place within a short time span, possibly only fractions of a second.

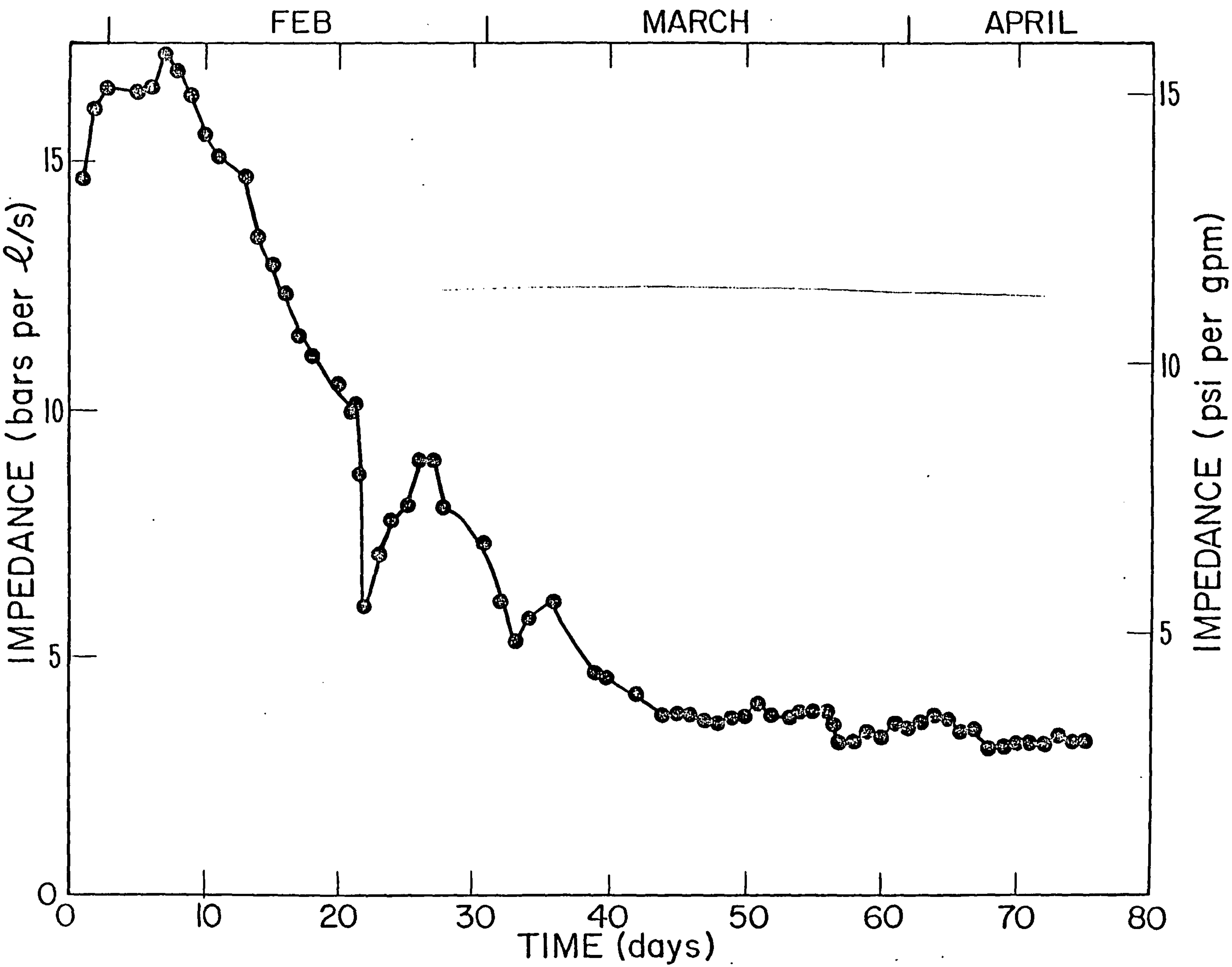


Fig. B-6. Flow impedance.

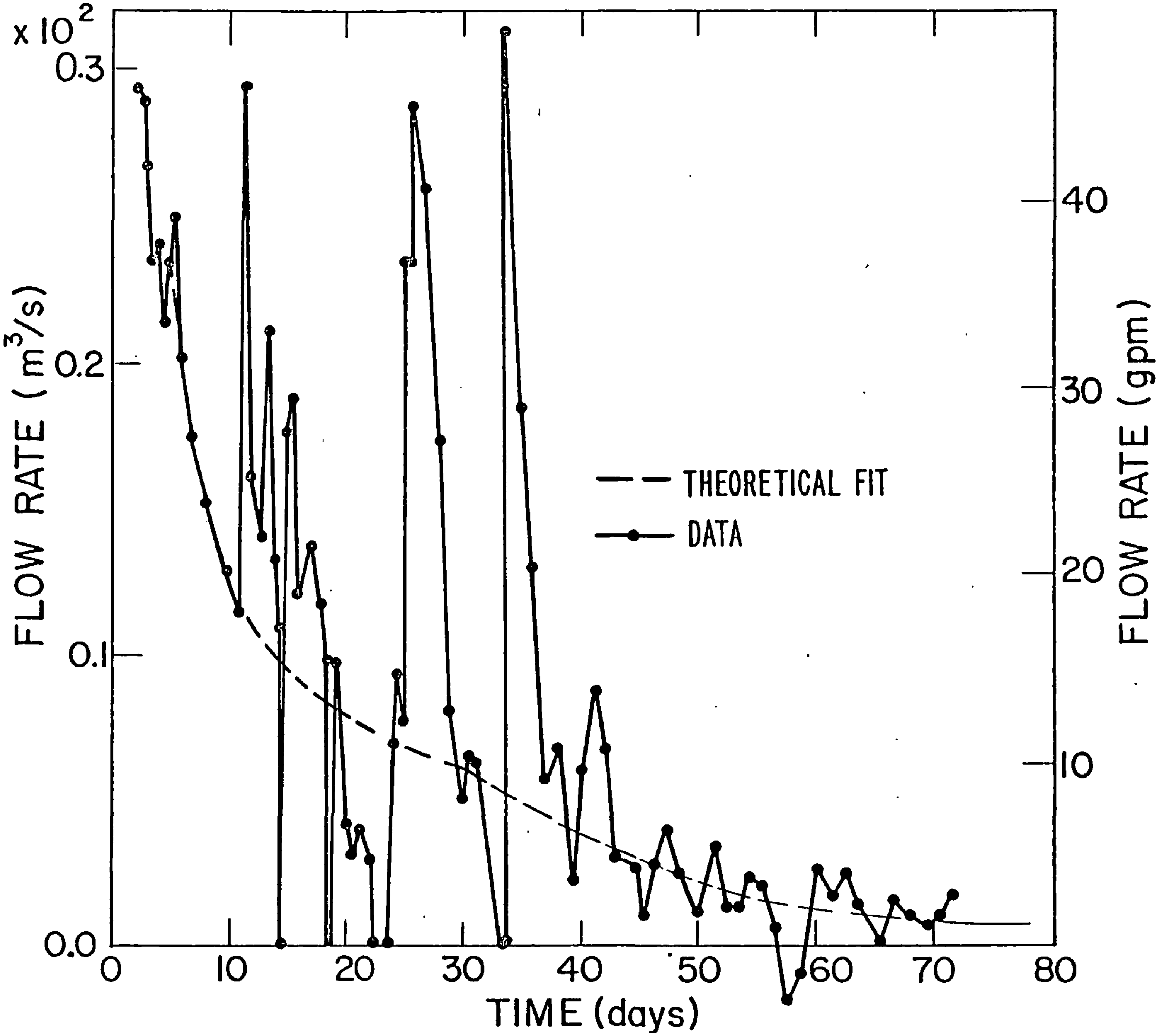


Fig. B-7. Water loss.

a high in excess of 2.5 ℓ/s (40 gpm) to 0.6 ℓ/s (10 gpm) after 25 days of flow at a system throughput flow rate of 7.5 ℓ/s (120 gpm). Subsequently, as the flow rate was increased to the peak sustained flow of 14.5 ℓ/s (230 gpm), water losses dropped to less than 0.3 ℓ/s (5 gpm), or 1-1/2% of throughput flow.

The dashed line of the figure is the result from a two-dimensional computer model. This is a nonlinear diffusion model describing the permeation of the water into the pores and fractures in the surrounding rock. For this calculation the input was the measured pressure that drives the water into the surrounding rock, that is, the pressure in the EE-1 wellbore corrected to the bottomhole value. The many short-term transients are caused by operational shut downs and are included in the calculations. The general trends, however, are as expected for this type of water-loss phenomenon. For a nearly constant pressure from the first to the 25th day the loss rate decreased as the porosity near the main fracture was filled with water and pressurized. After 25 days the decrease continued, but at a faster rate in response to a decreasing pressure in the EE-1 wellbore. The data of Fig. B-8 are the integral of the water loss as recorded independently on a totalizing flow meter, and are corrected for the major vent that occurred on the 23rd day. The solid curve of this figure is the result of the same calculations that are plotted on the previous figure. Because the short-term transients are not obvious in the integral data, the general agreement with the diffusion calculations can be seen. The general trends in the data and the diffusion model indicate that the water-loss rate would have decreased to even lower values if the experiment had continued.

VII. WATER CHEMISTRY

Analyses were made throughout the test for the following dissolved species: Ca, Na, K, Si, F, SiO_2, Cl, and SO_4. In addition, the conductivity and pH of the water were measured. Representative curves of concentration versus time are given in Figs. B-9 and -10. The variation in conductivity is given in Fig. B-11. There are several features common to all of the graphs. First, the very early samples had high concentrations of each of the species measured, and due to dilution with make-up water, these high concentrations dropped very rapidly. These early samples reflect the nature of the water, which had been

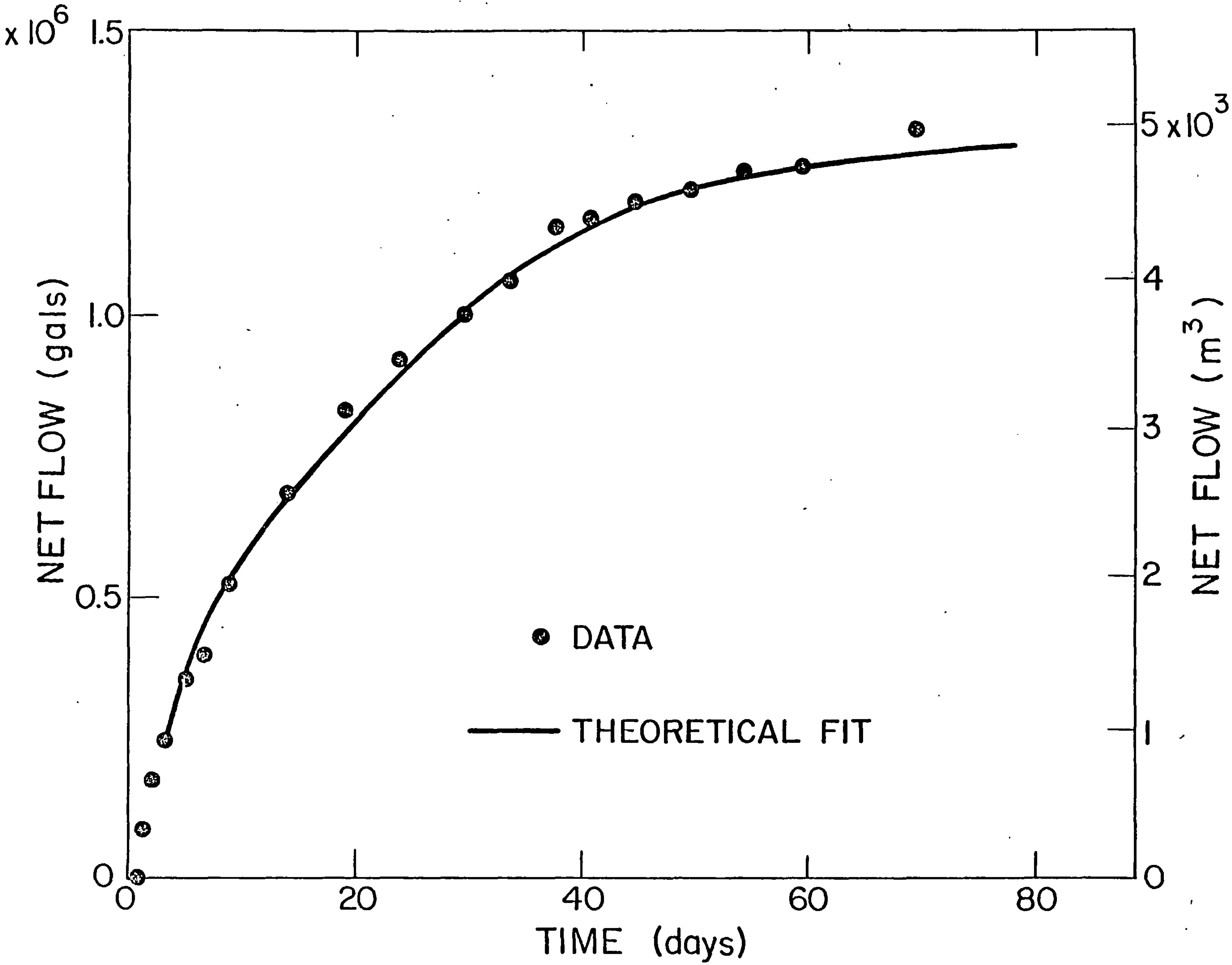


Fig. B-8. Net water loss.

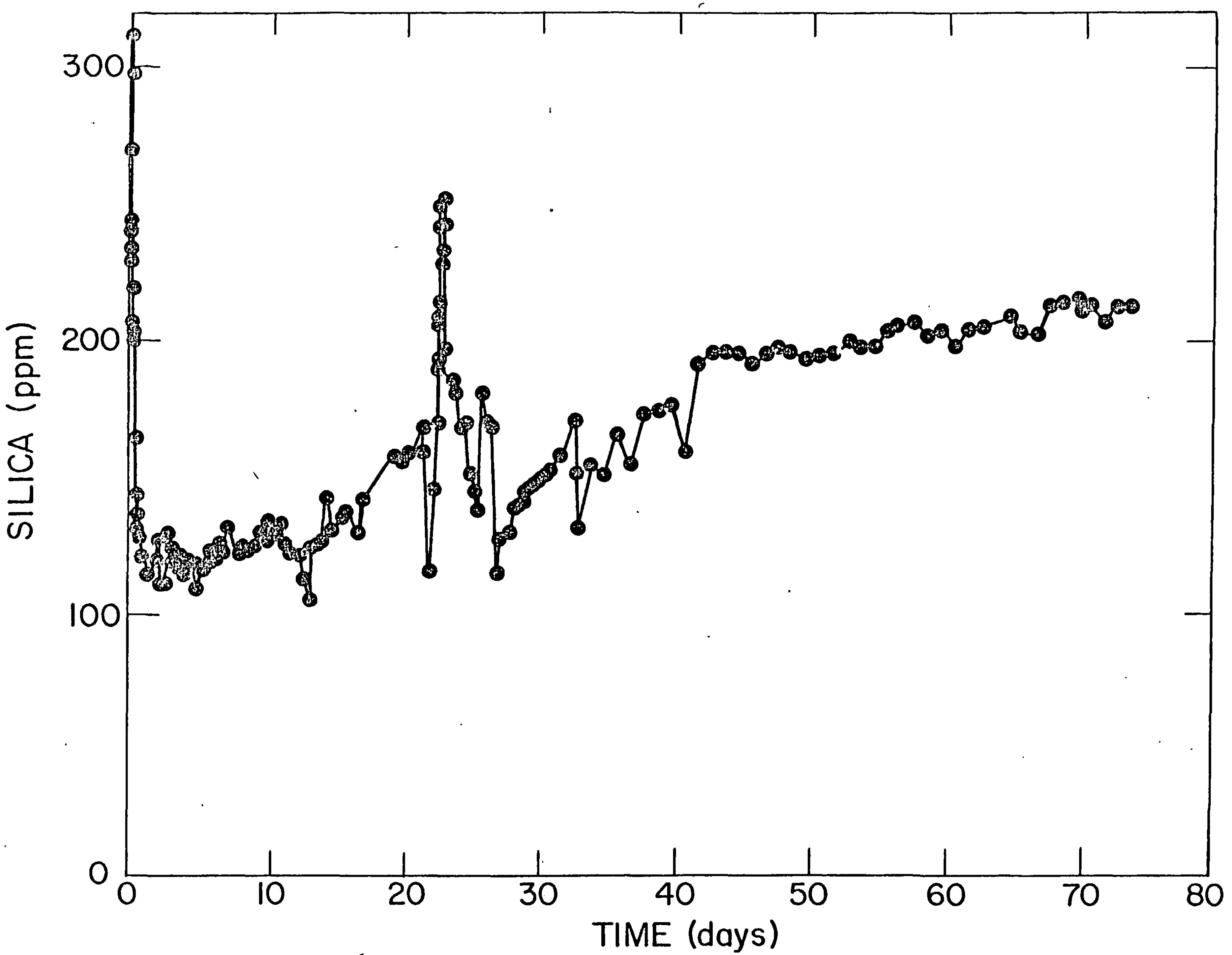


Fig. B-9. Silica concentration versus time.

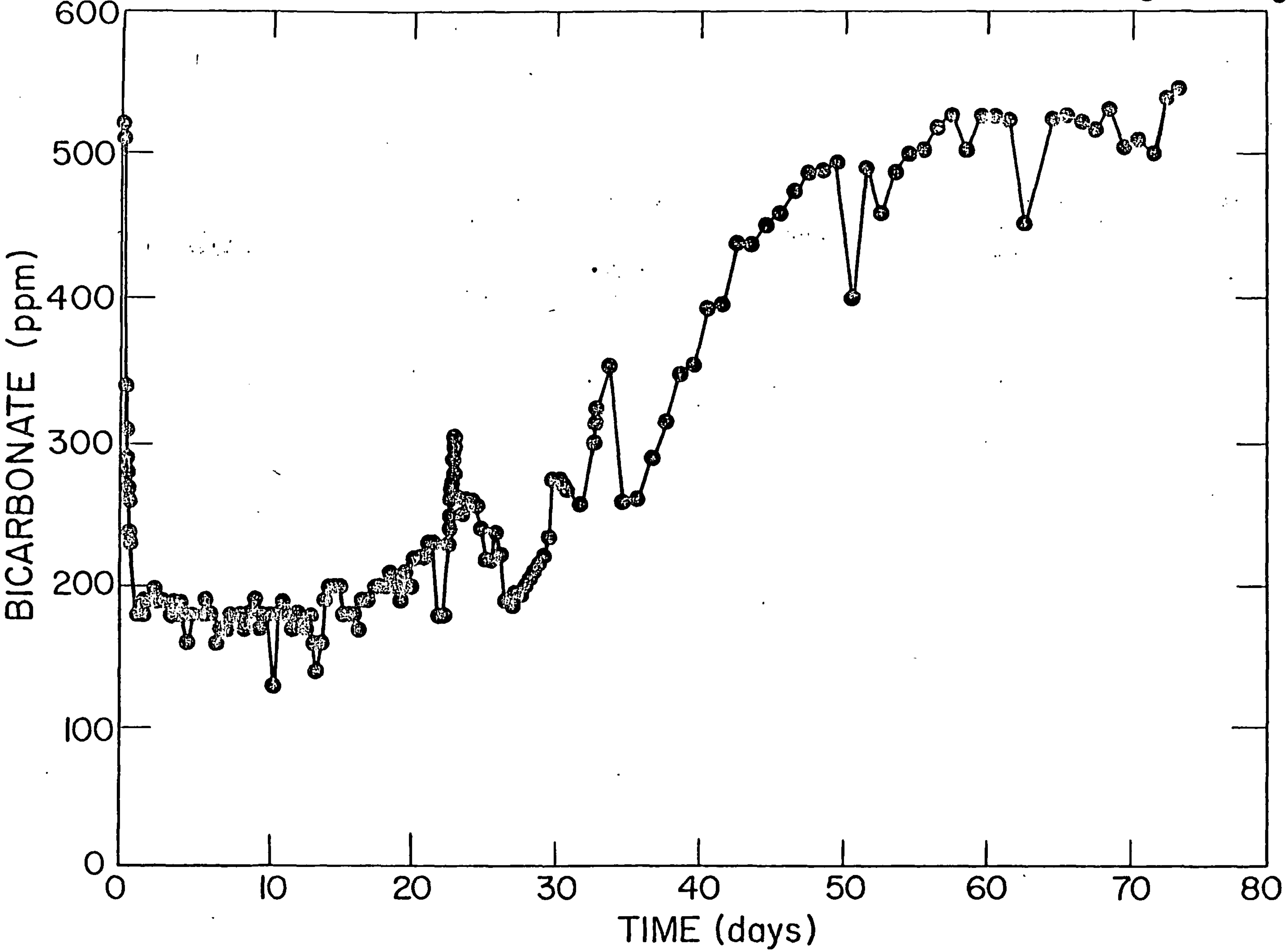


Fig. B-10. Bicarbonate concentration versus time.

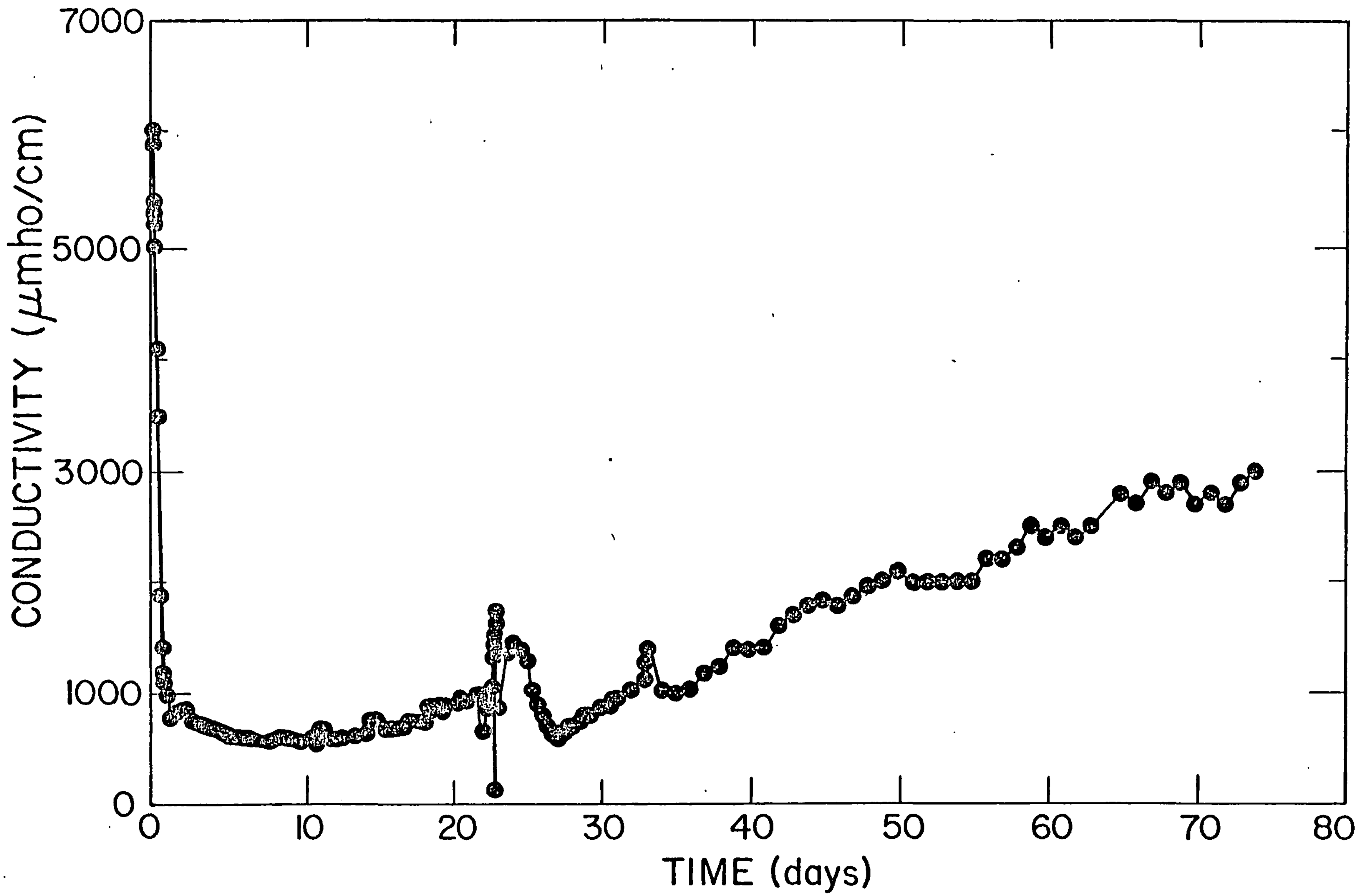


Fig. B-11. Fluid electrical conductivity.

stagnant in the reservoir for more than 3 months. After an initial flushing of the reservoir (∿60 000 gal) in which the water recovered at GT-2 was discarded, the system was operated as a closed loop and the make-up flow rate equalled the water losses to permeability storage in the reservoir. As the make-up requirements dropped, the dilution effect was lessened and the concentrations of dissolved material began to rise toward "saturation" values. On several occasions, the system had to be shut down for various lengths of time. The effects of shut-downs are apparent in the chemistry of the fluids. As the pressure in the system dropped, water which had been stored in the rock returned to the reservoir and then to the surface, carrying more dissolved material because of longer periods of contact with the rock and higher rock temperatures. The spike on each graph at day 23 is an example. As the system was restored to operating temperatures and pressures, make-up losses were again high to replace fluid which had returned from the permeability storage. This high make-up had a strong dilution effect as is seen in the "low" just after the 23rd day.

Dissolution of minerals continued until the end of the run. Several curves show an apparent leveling off starting at days 40 - 50. Notwithstanding the general increase in the salinity of the water, in absolute terms the concentration of dissolved solids remained low. Visual inspection of the interior of the major flow line indicated no apparent deposition or corrosion. Some deposition of calcite did occur at sample ports and at points along the lines where leaks had occurred. Silica concentrations exceeded the quartz saturation value at the measured temperature of the fluid leaving the reservoir.

VIII. SEISMIC MONITORING

Seismic monitoring was done to detect local seismic sources and to discriminate among several possible source types -- manmade disturbances, earthquakes, and faulting induced by the pressurized fluid injection into the inlet well of the HDR system.

The monitoring array consisted of seven surface stations at distances up to 750 m from the wells, two shallow borehole stations (∿125-m deep) at about 1 and 3 km, and stations of the LASL regional seismic network -- the nearest of which is about 10 km away. The two borehole stations were positioned a few meters below the Permian sandstone -- Quaternary tuff interface.

The only local earthquakes identified during the loop operation were located by the array near a fault 15 km west of the HDR geothermal site. These microquakes had local magnitudes (M_L) of -0.8, 0.0, and 0.5 as determined by signal duration. Many blasts and earthquakes were observed with more distant epicenters, and many sonic booms. Some of the smaller of these acoustic signals required the seismograms of the regional network for positive identification.

The background noise at the Fenton Hill site was generally high during the day, beginning with sunrise when thermal expansion of the metal sheds took place, and the amplitudes of noise bursts frequently exceeded levels expected for $M_L = 1.0$ earthquakes. At night, however, the background noise was nearly always below signal levels for $M_L = -1.0$ earthquakes.

Although it is likely that $M_L < 0.0$ earthquakes would not have been identified during the daytime, the absence of detected induced earthquakes with $M_L > -1.0$ at night is reasonable evidence that none with $M_L > 0.0$ occurred during the loop operation.

IX. SUMMARY

- The surface facilities and data acquisition systems proved sufficient for a short-term test (75 days) of the first artificially produced geothermal reservoir.
- Thermal drawdown for the first small experimental system followed closely the theoretical curve for an 8000-m^2 system.
- Reservoir flow impedance decreased from an initial 1625 KPa-s/ℓ (15 psi/gpm) to about 325 KPa-s/ℓ (3 psi/gpm) by both continuous and discontinuous drops in impedance.
- Permeation water-loss rate quickly decreased to less than 3 gpm (<1-1/2% of circulation rate).
- Geofluid chemistry is most acceptable, with 1500 - 2000 ppm total dissolved solids and no evidence of scaling in main flow passages.
- There is no evidence of any measurable seismicity induced at the site.

APPENDIX B

3. PLANS FOR FURTHER DEVELOPMENT OF FENTON HILL SITE

I. SPECIAL ASPECTS OF THE SITE

HDR Test Site No. 1 at Fenton Hill, New Mexico, is unusual, vis-à-vis future sites, in several respects. First, it has been the only hot dry rock energy extraction experiment in the United States, carried as a project initially by the AEC, then ERDA, and currently by DOE. As such, its role has gradually evolved. Second, it has been and will continue to be a multiple-function site, serving not only as an HDR concept demonstration, but also as a research arena for reservoir technique development and for the development and test of materials, drilling-related equipment, and downhole instrumentation. Finally, it is staffed and operated directly by LASL personnel and therefore partakes of the characteristics of a Laboratory Technical Area.

With the expansion in FY79 of the Hot Dry Rock effort to a federal program of national scope, Fenton Hill will eventually become one among several projects (sites) within that program. However, by virtue of the foregoing unusual aspects, the Fenton Hill site presents some unique opportunities to the Program, which will be exploited in its future development.

II. FENTON HILL AS AN ELECTRIC GENERATION SITE

Fenton Hill is an excellent candidate site, and because of time constraints (see Appendix H) can probably be the only candidate HDR site, for the construction and operation of an electric generation pilot plant by the mid-1980's (by which time the commercial viability of the HDR energy source must be judged). It may be asked whether an electric generation pilot plant should be built anywhere under full or partial government funding. The answer appears to be unequivocally "yes, at least once" for several reasons:

(1) There are some technical interface issues involved in the conversion of HDR to electricity that are sufficiently different from their parallels with other types of geothermal sources to merit evaluation in a pilot-plant scale: optimum *modus operandi* under characteristic HDR reservoir drawdown; effects of a primary fluid chemistry

intermediate between hydroelectric purity and hydrothermal brines; accommodation of stop/start transients; system implementation in regions with harsh winters; etc.

(2) Historically hyperconservative public utilities will not risk capital investment in such a venture until it "has been done somewhere before", irrespective of how attractive it may appear on paper.

(3) The promotional value of electricity production cannot be estimated. Although demonstration of the reservoir through simple heat rejection is adequate from the technical standpoint to prove that part of the system deemed "risky", the psychological impact of completing the energy conversion must be weighed. The customer (voter and taxpayer), the legislator, the environmentalist — indeed most of the parties of interest — have a "feeling" for electric kilowatts produced that they will never have for Btu/hour rejected.

Given, then, sufficient motivation for the government to fund at least one electric pilot plant (which could be cost-shared by industry, even retroactively once the system was on-line), the logical site is Fenton Hill:

(a) present status of Fenton Hill is such that it enjoys about a 2-yr "leg-up" over other sites for an electric pilot plant scenario;

(b) at the point where commitment to pilot-plant construction is appropriate, Fenton Hill will be probably the best characterized (that is, lowest technical risk) HDR site;

(c) continuous environmental surveillance over many years should facilitate meeting NEPA requirements;

(d) the site is on federal (USFS) land which should render institutional problems tractable; and

(e) there are a number of small load centers in the area which could effectively utilize a 7-10 MWe production.

It is therefore appropriate to plan for an electric pilot plant at Fenton Hill. At this time, we leave open the question of whether such plant will be DOE-funded, industry-funded, or cost-shared (either initially or retroactively).

III. DEVELOPMENTAL SEQUENCE

The planned sequence for the continued development of the Fenton Hill site is shown in Fig. B-12. The Phase 1 (5 MWt nominal) reservoir was established, in its present configuration, in FY77 and the associated experimental program is presently ongoing. This small system was created to: (a) demonstrate initial technical feasibility (100-h Segment I test); (b) provide short-term information on predictability of drawdown, time-variation of impedance, water loss rate, geofluid chemistry, and stop/start transients (1700-h Segment II test); (c) serve as a test bed for evaluation of reservoir enhancement techniques, such as operation under high back pressure and accelerated thermal-stress cracking, and of alternative operating modes, such as "modified huff-puff" (planned 2200-h Segment III test); and finally, provide an expendable system for evaluating high-risk/high-payoff reservoir-extension workover techniques and for conducting a small preliminary electric generation experiment (planned Segment IV test, up to 5000 h). All of this Phase 1 work will be completed by the end of the third quarter of FY79.

In parallel with the completion of the Phase 1 effort, planning and initiation of the Phase 2 system will proceed. The primary objective of this effort is to demonstrate reservoir longevity by creating a pilot-plant-sized system [30-50 MW(t)] with a projected life in excess of 10 yr. A third well, EE-2, will be drilled at the site to a bottom-hole temperature of 250-275°C and will serve as the production well for the Phase 2 system. Drilling of EE-2 will begin in the second quarter of FY79 while the Segment IV test of the Phase 1 system is in progress. Before the rig is released, it will be skidded over the existing GT-2 well to deepen that well for the DWETS (see Sec. IV) facility. After an extensive series of diagnostic and fracture experiments in the EE-2 wellbore, existing well EE-1 will be worked over to an EE-1A configuration to serve as the Phase 2 injection well. It is anticipated that the EE-1A workover operation will begin in the third quarter of FY80. A half-year period, devoted to completion of the subterranean system and a comprehensive set of communication tests, will follow the redrilling of EE-1A. A comparison of the Phase 1 and Phase 2 systems is shown schematically in Fig. B-13.

Planning of the Phase 2 surface system will parallel establishment of the reservoir. Some long-lead procurements will have to be initiated early including: high-pressure, remote-operated valves; additional air-cooled heat-exchanger units; and appropriate additional/larger circulation pumps, if required. Construction of the surface system will begin in the last quarter of FY80, partially

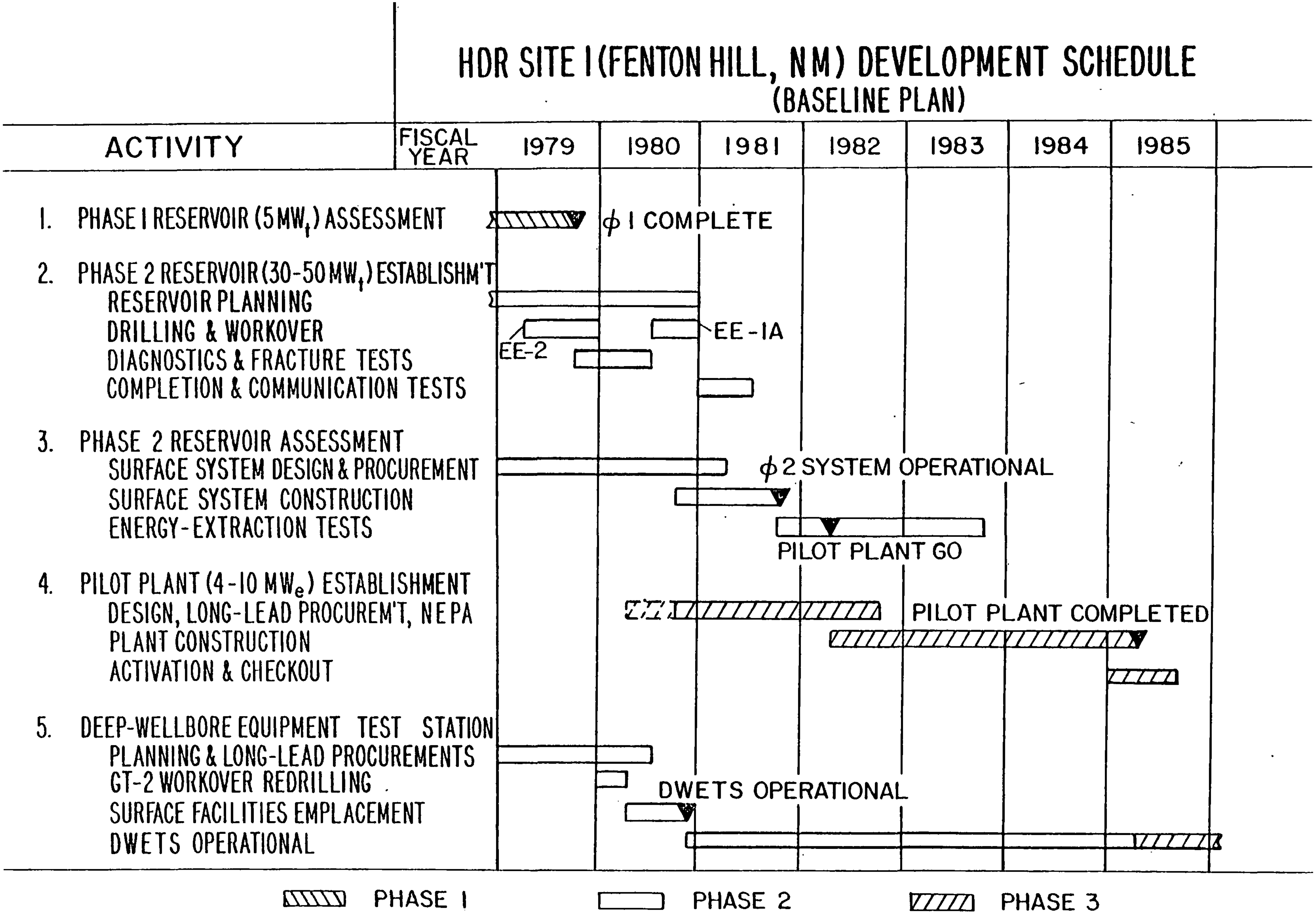
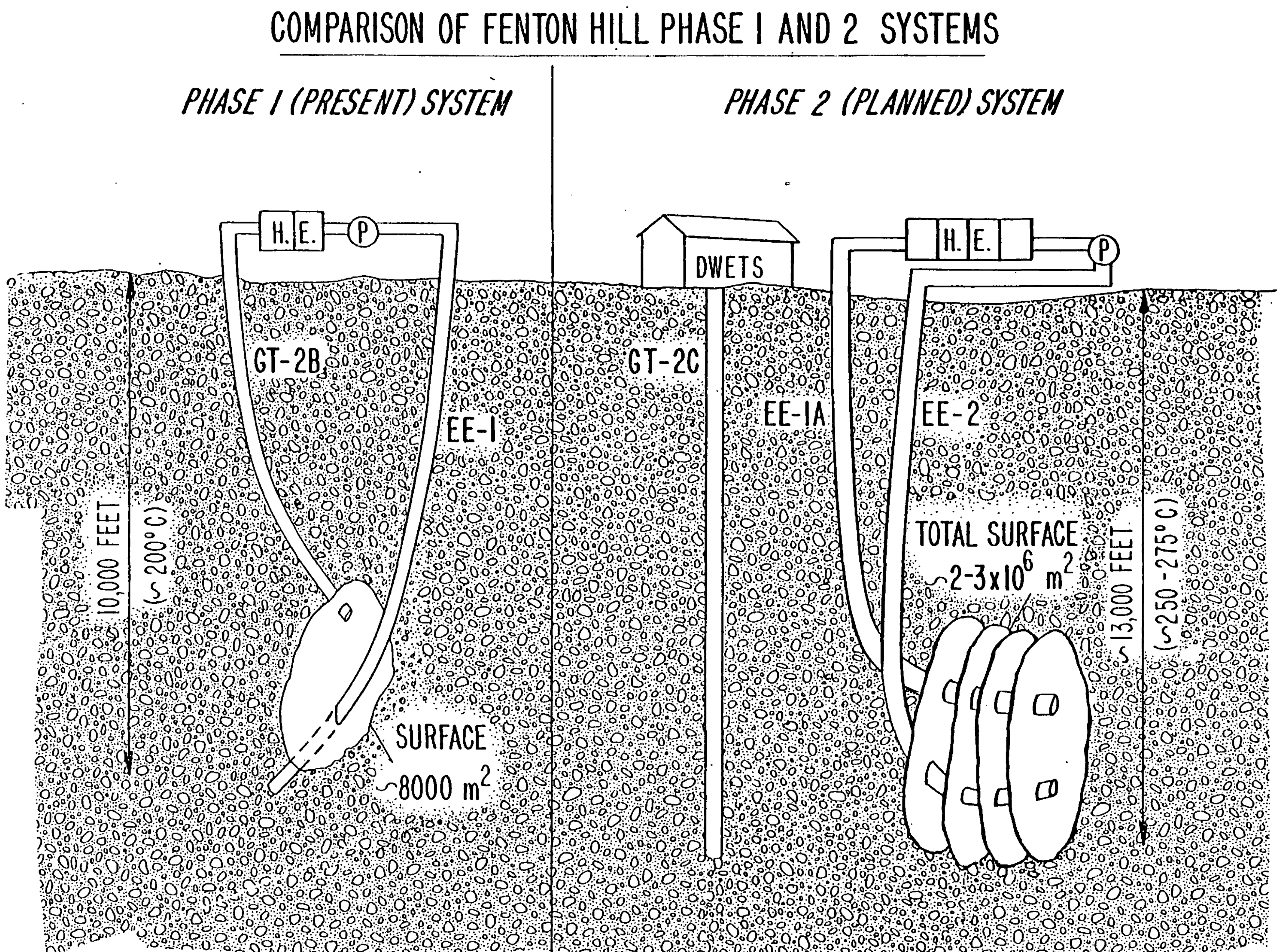


Fig. B-12 HDR Site 1 (Fenton Hill, NM) Development Schedule (Baseline Plan).

Fig. B-13



COMPARISON OF FENTON HILL PHASE I AND 2 SYSTEMS
PHASE I (PRESENT) SYSTEM
PHASE 2 (PLANNED) SYSTEM
H.E.
P
GT-2B
EE-I
10,000 FEET
(∽ 200°C)
SURFACE
∽8000 m²
DWETS
GT-2C
EE-IA
EE-2
TOTAL SURFACE
∽2-3x10⁶ m²
∽13,000 FEET
(∽250 - 275° C)

overlapping the EE-1A workover, and be completed late in FY81. The installation will be designed such that most of it, other than the air-rejection heat exchangers, will be usable by the possible follow-on electric pilot plant. (The heat exchangers will be reusable in reservoir evaluation tests at subsequent HDR sites.) Upon completion of construction, the Phase 2 loop will be activated for a protracted energy-extraction test. It is estimated that after 6 months of continuous operation, it will be possible to define the minimum reservoir lifetime with adequate confidence to permit a go-ahead decision on pilot plant construction. This would occur at about the end of the first quarter of FY82. Figure B-14 presents an artist's conception of the site layout at that time.

As early as the end of FY80 or the beginning of FY81, during the Phase 2 reservoir assessment, serious negotiations would begin with the local utilities concerning establishment of a 4-10 MWe electric generation pilot plant at Fenton Hill. As more and more positive data are obtained on the reservoir, these negotiations will become more intensive and plant design, long-lead procurements (for example, turboalternator, pumps, condenser) and permit acquisition will proceed. Plant construction is expected to begin in the second quarter of FY82 and be completed by the end of the first quarter of FY85. The plant will then be checked out and on-line in mid-FY85. Given the successful establishment of this plant, it is assumed that the electricity produced will be marketed to New Mexico consumers by the participating utility, and the government's role in this aspect of the Fenton Hill operation will terminate at this point.

IV. DWETS FACILITY

In addition to demonstrating the HDR utilization scheme, Fenton Hill is also a research site, as was noted in Sec. I. One major research area is development of downhole instruments and equipment for geothermal wells, specifically those either peculiar to HDR needs or for which the need arises earliest in the HDR program. These developments are, of course, coordinated with developments and needs in the other DOE geothermal programs to produce hardware of greatest transprogrammatic utility and obviate duplication.

A long-recognized need in the instrument and equipment development area is for a captive and dedicated wellbore with suitable data acquisition and surface handling equipment wherein controlled _in situ_ tests of such prototypical hardware can be conducted. It is therefore planned, in the course of creating the Phase 2 reservoir, to deepen and straighten wellbore GT-2 as indicated in Fig. B-12, to a GT-2C configuration with a bottom-hole temperature of 275-300°C. This wellbore will then become the heart of a dedicated national test facility. With the addition of a cable-handling rig, and a structure to contain high-pressure pumping equipment, data acquisition and processing equipment, and a tool preparation area, this small complex becomes the Deep-Wellbore Equipment Test Station (DWETS), shown conceptually in Figs. B-13, B-14, and B-15.

It is anticipated that the DWETS facility will be operational in the last quarter of FY80. In addition to LASL's utilization thereof, LASL will maintain this facility for use by other DOE Laboratories and their contractors on a scheduled basis. The _in situ_ test capability provided by this facility will complement the simulated wellbore test capabilities of LASL's Instrument Sonde Test Facility, which will be operational early in FY79 and will also be available to other DOE Laboratories and their contractors. Operation by LASL of the DWETS facility at Fenton Hill is expected to continue beyond FY85 for as long as it proves useful to the DOE.

V. SUPPORTING ACTIVITIES

Not shown in Fig. B-12, but of paramount importance to the development of the Fenton Hill site, are a group of ongoing support activities. Among these are:

- theoretical analysis, data processing, and modeling;
- laboratory studies, including rock properties measurements, chemical analyses, and simulations;
- HDR-specific instrument and equipment development (as noted in Sec. IV and discussed in Appendix I); and
- environmental surveillance at the site with special attention to possible seismic, hydrologic, and microclimatological effects.

These supporting activities continue through FY85.

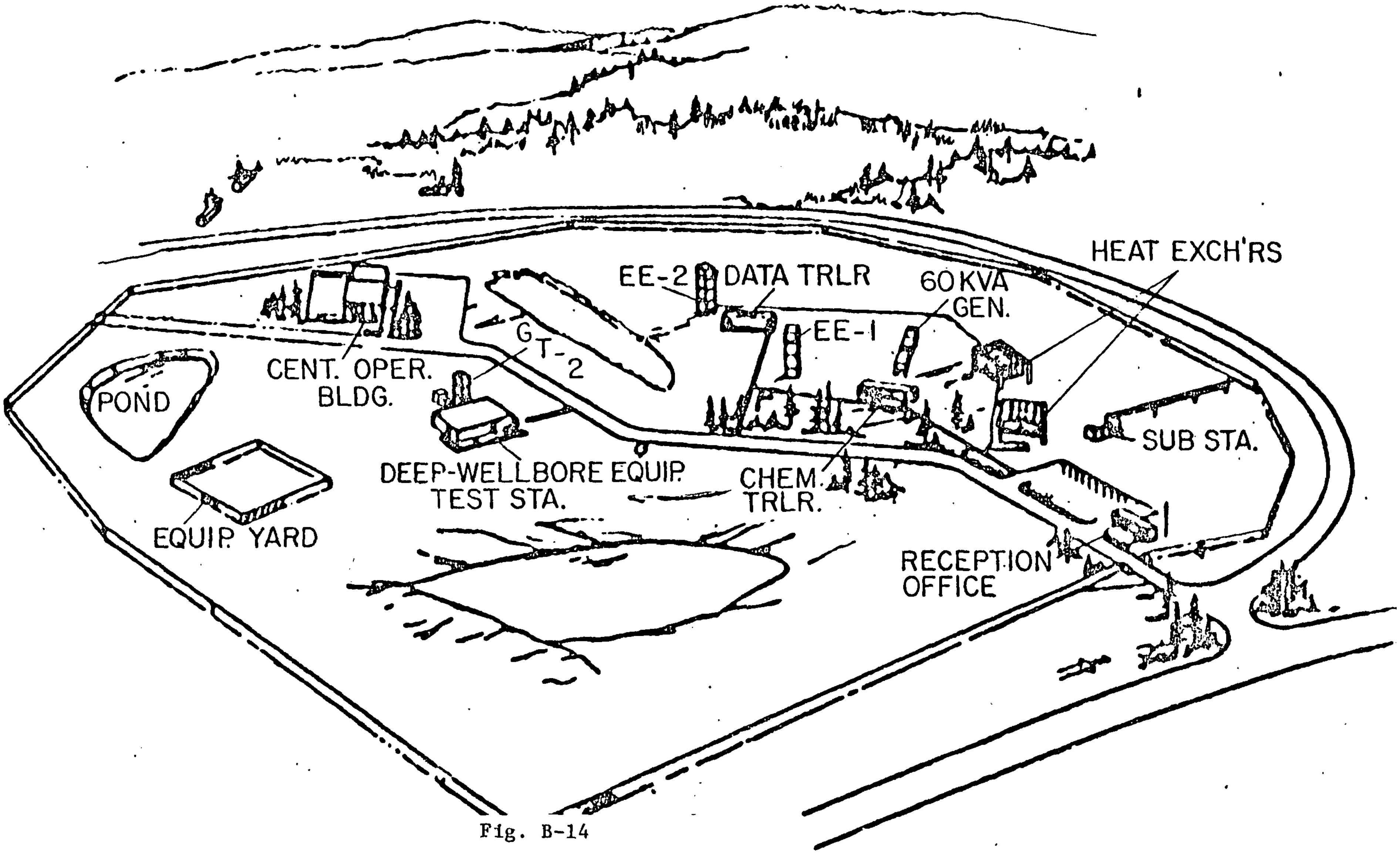
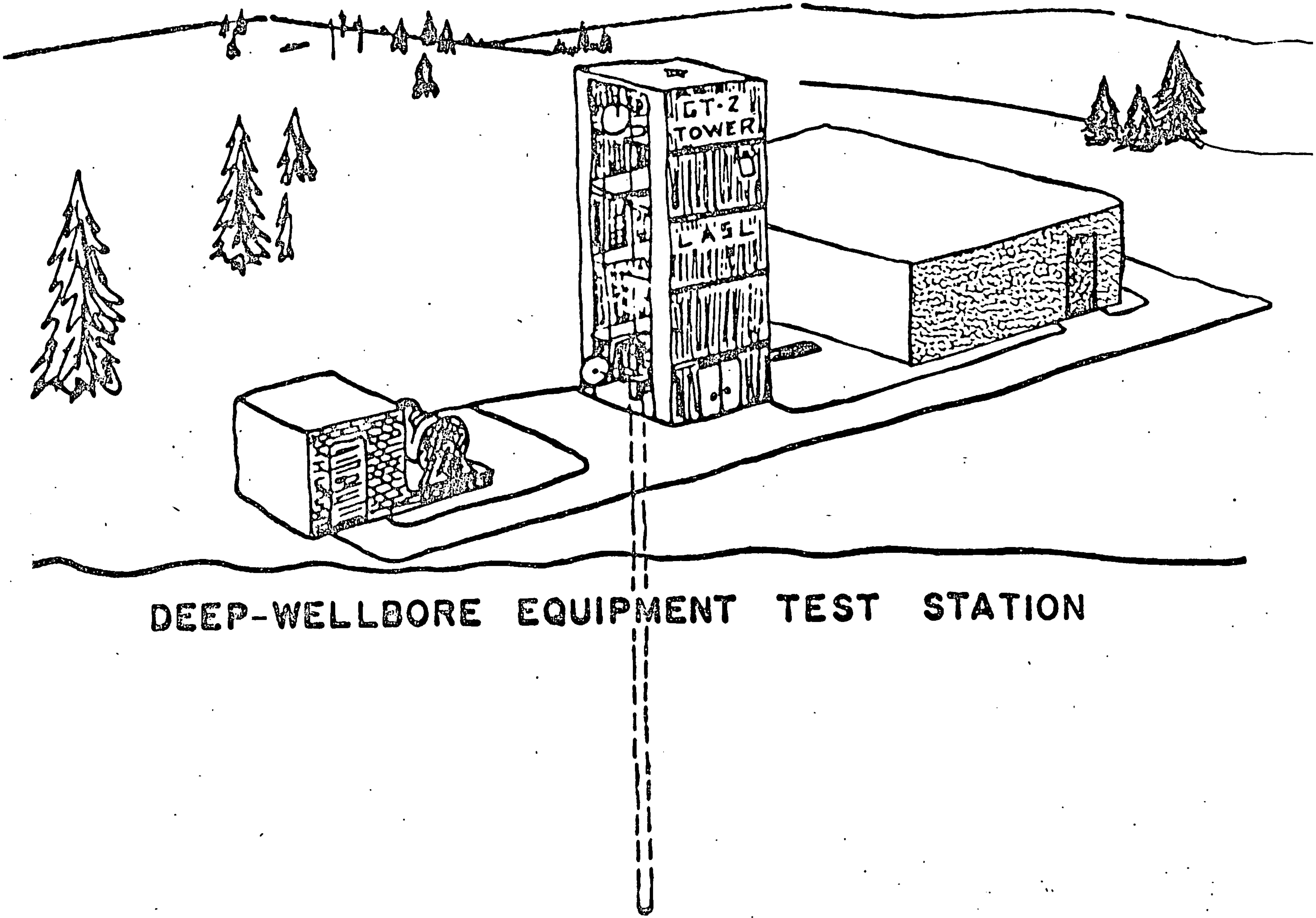


Fig. B-14

HOT DRY ROCK GEOTHERMAL ENERGY SITE I (FENTON HILL, N. M.)
AS IT WILL APPEAR CIRCA EARLY 1982



DEEP-WELLBORE EQUIPMENT TEST STATION

APPENDIX B

4. SELECTED RECENT PUBLICATIONS CONCERNING THE STATUS OF THE LOS ALAMOS SCIENTIFIC LABORATORY HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROJECT

1. LASL HDR Project Staff, "Hot Dry Rock Geothermal Energy Development Project," Los Alamos Scientific Laboratory report LA-7109-PR (February 1978).

2. K. H. Rea, "Environmental Investigations Associated with the LASL Hot Dry Rock Geothermal Energy Development Project," Los Alamos Scientific Laboratory report LA-6972 (December 1977).

3. J. N. Albright and R. J. Hanold, "Seismic Mapping of Hydraulic Fractures Made in Basement Rocks," Proc. ERDA Symp. on Enhanced Oil & Gas Recovery, Tulsa, 1976 (ERDA, Washington, DC, 1976) Vol. 1 - Gas, pp. C-8/1-13.

4. R. D. McFarland and H. D. Murphy, "Extracting Energy from Hydraulically Fractured Geothermal Reservoirs," Proc. 11th Intersociety Energy Conversion Engineering Conf., State Line, Nevada, September 12-17, 1976, Vol. 1, pp. 828-835.

5. R. A. Pettitt, "Planning, Drilling, Logging, and Testing of Energy Extraction Hole EE-1, Phases I and II," Los Alamos Scientific Laboratory report LA-6906-MS (August 1977).

6. A. W. Laughlin and A. Eddy, "Petrography and Geochemistry of Precambrian Rocks from GT-1 and EE-1," Los Alamos Scientific Laboratory report LA-6930-MS (August 1977).

7. H. D. Murphy, R. G. Lawton, J. W. Tester, R. M. Potter, D. W. Brown, and R. L. Aamodt, "Preliminary Assessment of a Geothermal Energy Reservoir Formed by Hydraulic Fracturing," Soc. Pet. Eng. 17, 317-326 (August 1977).

8. J. W. Tester and M. C. Smith, "Energy Extraction Characteristics of Hot Dry Rock Geothermal Systems," Proc. 12th Intersociety Energy Conversion Engineering Conference, Washington, DC, August 28 - September 1, 1977 (Americal Nuclear Society, La Grange Park, Illinois, 1977), Vol. 1, pp. 816-823.

9. W. C. Maurer, J. D. Nixon, L. W. Matson, and J. C. Rowley, "New Turbo-drill for Geothermal Drilling," Proc. 12th Intersociety Energy Conversion Engineering Conference, Washington, DC, August 28 - September 2, 1977 (American Nuclear Society, La Grange Park, Illinois, 1977) Vol. 1, pp. 904-911.

10. J. N. Albright, R. L. Aamodt, and R. M. Potter, "Definition of Fluid-Filled Fractures in Basement Rocks," Proc. 3rd ERDA Symp. on Enhanced Oil and Gas Recovery and Improved Drilling Procedures, Tulsa, 1977 (ERDA, Washington, DC, 1977), Vol. 2 - Gas and Drilling, pp. E-2/1-2/8.

11. J. W. Tester; C. E. Holley, Jr.; and L. A. Blatz, "Solution Chemistry and Scaling in Hot Dry Rock Geothermal Systems," Proc. 83rd National Meeting AIChE, Houston, March 21-25, 1977.

12. P. R. Kintzinger, F. G. West, and R. L. Aamodt, "Downhole Electrical Detection of Hydraulic Fractures in GT-2 and EE-1," Los Alamos Scientific Laboratory report LA-6890-MS (July 1977).

13. H. N. Fisher, "An Interpretation of the Pressure and Flow Data for the Two Fractures of the Los Alamos Hot Dry Rock (HDR) Geothermal System," Proc. of the 18th US Symposium on Rock Mechanics, Keystone, Colorado, June 22, 1977.

14. "Hot Dry Rock Geothermal Energy: Status of Exploration and Assessment: Report No. 1 of the Hot Dry Rock Assessment Panel," Energy Research and Development Administration Division of Geothermal Energy report ERDA 77-74 (June 1977).

15. J. R. Archuleta, C. F. Fink, and J. Kurtenbach, "Equipment Development Report: Downhole Fluid Injector," Los Alamos Scientific Laboratory report LA-7151-MS (February 1978).

16. J. R. Archuleta, C. F. Fink, and J. Kurtenbach, "Equipment Development Report: Borehole Fluid Sampling Tool," Los Alamos Scientific Laboratory report LA-7152-MS (February 1978).

17. H. D. Murphy, "Thermal Stress Cracking and the Enhancement of Heat Extraction from Fractured Geothermal Reservoirs," Los Alamos Scientific Laboratory report LA-7235-MS (April 1978).

18. R. Wunder, "Thermal Drawdown and Recovery of Singly and Multiply Fractured Hot Dry Rock Reservoirs," Los Alamos Scientific Laboratory report LA-7219-MS (April 1978).

19. C. W. Aiken, A. W. Laughlin, and F. G. West, "Residual Bouguer Gravity Anomaly Map of Northern New Mexico," Los Alamos Scientific Laboratory publication LA-6737-MAP (March 1977).

APPENDIX C

THE NATIONAL HOT DRY ROCK PROGRAM DEVELOPMENT COUNCIL

To assist in the planning and to review periodically the progress of the Federal Hot Dry Rock Development Program, a "National Hot Dry Rock Program Development Council" shall be organized, whose chairman shall be the chairman of its Executive Committee and shall be elected by that committee from among its appointed members. The Executive Committee shall consist of five appointed and three nonvoting ex officio members, as follows:

Appointed Members

- The Geological Survey, U.S. Department of the Interior (1 member).
- U.S. colleges, universities, and their research institutes (1 member).
- U.S. energy companies directly involved with geothermal energy development and production (2 members, one of whom shall have special expertise in the area of the legal and institutional problems faced by the geothermal industry).
- U.S. electrical power companies (1 member).

Ex Officio Members

- Federal Program Director or his official representative.
- One representative of the DOE National Laboratory managing the Federal Program, appointed by its Program Manager.
- One representative of the DOE Operations Office participating in this program, appointed by the Associate Program Manager.

Initial appointments to the Executive Committee shall be for a term of 1 yr only and shall be made by the DOE National Laboratory managing the program. Subsequent appointments shall be for 1-, 2-, and 3-yr terms, to provide finally for a standard 3-yr term with either one or two reappointments or new appointments each year, these to be made by consensus of the Executive Committee. The chairman of the Executive Committee (and thus also of the Council) shall be elected to that position for a term of approximately 1 yr, the election to be held at the first meeting after appointment of committee members for the ensuing year becomes effective, with the newly elected chairman to take office at the next subsequent meeting of the Committee.

Additional members of the Council shall be appointed and, if desirable, reappointed by consensus of the Executive Committee, initially for 1-yr terms but subsequently for 2- or 3-yr terms to provide finally for a standard 3-yr term with approximately one-third of the appointments expiring each year. The Council shall be organized into Standing Committees of three to five members each, dealing at least initially with the following areas:

Resource Potential

Site Selection

Drilling and Hole Completions

Equipment and Instrumentation

Reservoir Engineering

Utilization Systems and Economics

Legal, Institutional, and Environmental Concerns

Additional Standing Committees may be organized and existing Standing Committees dissolved by action of the Executive Committee. The chairman of each Standing Committee shall be appointed by the Executive Committee and may be from among the membership of the Executive Committee.

The Secretary to the Council shall be provided by the DOE National Laboratory and shall not be a voting member of the Council.

Reimbursement for services on and to the Council shall cover the costs of travel and subsistence plus (to those who can accept it) a standard honorarium, in accordance with the policies and regulations concerning consultants and visiting scientists of the DOE National Laboratory managing the Federal Program.

APPENDIX D

POSSIBLE HDR ENERGY EXTRACTION SYSTEMS

I. INTRODUCTION

Where a natural ground-water circulation system does not exist to form and maintain a hydrothermal reservoir, the obvious method of extracting heat from the earth's crust is to imitate nature by creating one. This will involve introducing a heat-extraction fluid into the hot rock, somehow insuring that it flows over a sufficient surface area to extract heat from the rock at a useful rate for a usefully long time, recovering the heated fluid, and finally extracting the useful heat from the fluid and either using the heat directly or converting it so some other form of energy. Many variations are possible in systems of this general type, whose individual utilities will depend jointly upon the characteristics of the local subsurface geology and of the local market for energy. However, nearly all such systems will share several common characteristics.

A. The Fluid Used. Principally because of the large volume of fluid needed to transport heat at commercially useful rates and the fact that a significant fraction of this fluid will be lost from the system into rock even of extremely low permeability, a very inexpensive heat-extraction fluid is required. The obvious choice is water, whose physical and thermodynamic properties fortunately are favorable for this use. However, the remarkable solvent power and interactive chemical nature of water make it probable that its use will also result in systems problems associated with mineral dissolution and alteration, scaling, and corrosion.

B. Fluid Conservation. In most places even water is expensive, and in arid regions it is often essentially unobtainable in large quantity. To conserve both water and the heat that it may already have extracted from the reservoir, it will usually be important that the rate of fluid loss from the heat-extraction system be minimized. At least in the upper parts of the system, this may also be necessary to avoid aquifer contamination and to conform to National Environmental Protection Agency (NEPA) and other water-quality regulations.

C. Drilling. To have remained hot through geologic time, a geothermal reservoir must in most cases have been covered by a relatively thick insulating layer of rocks or sediments. Therefore, except in areas of active or recent volcanism, the openings required to introduce and recover the heat-transport fluid must normally be deep--commonly at least a kilometer or two. To excavate them by any means other than drilling would be prohibitively expensive, and for the forseeable future the drilling equipment and techniques will undoubtedly be generally similar to those now used to exploit petroleum, natural-gas, and hydrothermal reservoirs. Further, to accommodate the rates of fluid flow required of a commercial energy system, the drilled holes must have relatively large diameters--probably of the order of 15 - 50 cm. Finally, to conserve water and heat and to avoid dilution by and contamination of aquifers above the reservoir, these holes will in general require casing, at least in their upper sections.

D. Heat-Transfer Surface. Because rocks and sediments are poor thermal conductors, to maintain an economically high rate of heat extraction from the geothermal reservoir will require that a large surface area of the hot rock be in contact with the heat-transport fluid. As is further discussed below, creation of the necessary heat-transfer surface by drilling more, larger, or deeper holes, or by locally enlarging those of normal size, is in general so expensive that it cannot be justified by the value of the increased rate of energy extraction. Therefore, provision must usually be made to circulate water outside of the borehole, through either natural or manmade flow passages, where it will contact a surface area much larger than that of the wall of the hole itself.

E. Permeability and Void Volume. To extract heat at a high rate requires not only that a large volume of water move through the rock per unit of time but that it remain in the reservoir long enough to be heated to a usefully high temperature. To provide for the required flow rates and residence times, it is necessary that--locally--the permeability of the hot rock be high and the total volume of connected voids be large.

The general image of a hot dry rock energy system that emerges is, then, one or more deep, large-diameter, drilled and cased holes, through which cool water is introduced into a natural thermal reservoir and hot water or steam is recovered from it. Around the lower, hotter section of each hole, and connecting the holes if there are more than one, is an extended permeable region with large void volume and surface area and low flow-impedance, through which water injected at one location will circulate and from which most of it can be recovered through the same or another hole or holes.

II. HEAT-EXTRACTION CONCEPTS

There are many ways in which the general requirements outlined above can be met. Which of these may be appropriate to any given local situation depends upon a number of variables, several of which are discussed in Appendix E. One of these, of course, is the technology that is available to satisfy an existing energy need in any of a wide variety of geographic and geological environments. In this connection it is important to examine the concepts, designs, advantages, and limitations of some of the many underground systems that have been or can be proposed for recovery of energy from hot dry rock geothermal reservoirs of several possible types.

More than anything else, it is the magnitude and distribution of permeability in the reservoir rock that controls the design of any heat-extraction system that might be expected to operate effectively in the reservoir. Accordingly, systems concepts will be discussed here in that frame of reference, and typical geologic situations in which such systems might be useful will be considered in Appendix E.

A. Very Low Permeability. When the initial permeability of the hot reservoir rock is of the order of a millidarcy or less, the fluid circulation required to create and maintain a productive hydrothermal reservoir does not occur naturally; heat transport is primarily by conduction; and the possibility exists of producing a relatively simple heat-extraction system from which the rate of fluid will be low.

1. Downhole Heat Exchangers. Most of the early and many of the recent proposals for extracting energy from hot dry rock have been based upon pumped or buoyant circulation of a heat-transport fluid through a heat-exchanger inserted into a water-filled borehole.[1] In fact, the value of the heat conducted into a hole through the limited surface area of its own wall is in

general insufficient to amortize the cost of drilling the hole, and the situation cannot ordinarily be corrected simply by additional drilling to enlarge or extend the hole. This may not be true if thermal conduction is supplemented by the circulation of steam or hot water through the borehole wall, as evidently occurs, for example, at Klamath Falls, Oregon.[2] In that special case, the very simple heat exchanger sketched in Fig. D-1 works very effectively and economically, at least in large part because the well casing is perforated at the levels of two vertically separated aquifers, so that buoyant circulation of hot water through the well is made possible. However, in a formation of very low natural permeability, this type of circulation cannot occur at a usefully high rate unless the permeability around the wellbore has been increased artificially, by some means such as those discussed below.

To correct this deficiency in surface area, it is often proposed that the wellbore be enlarged locally, preferably to a degree sufficient to permit buoyant circulation of water within the cavity so that heat is transferred rapidly from the hole wall to the heat exchanger. One suggested method is to underream the hole mechanically (Fig. D-2), which is expensive (primarily because of the drilling rig required), quite limited in the degree of hole enlargement that is possible, and introduces some danger of junking the hole. Another is to spring the hole by detonating explosives in it (Fig. D-3), which is relatively inexpensive and leaves very little junk in the hole, but again is quite limited in the degree of hole enlargement that is possible. As is discussed below, this offers the additional attractive possibility of opening fractures outside of the enlarged borehole through which the heat-transport fluid can also circulate, but with the accompanying danger that--unless the properties of the explosive are well matched to those of the rock--a compacted zone of extremely low porosity may be created around the wellbore, which can prevent fluid circulation instead of enhancing it.[3]

Principally because neither underreaming nor explosive springing can enlarge a borehole by more than a few hole diameters, it seems unlikely that either will normally be useful for creating cavities which are large enough to be used economically as heat-transfer pools for a downhole heat exchanger. However, at least in some types of formations, it may be possible to create openings that are large enough, by either solution-mining or water-jet drilling. The outstanding possibility appears to be in salt domes or thick, bedded salt deposits (Fig. D-4).

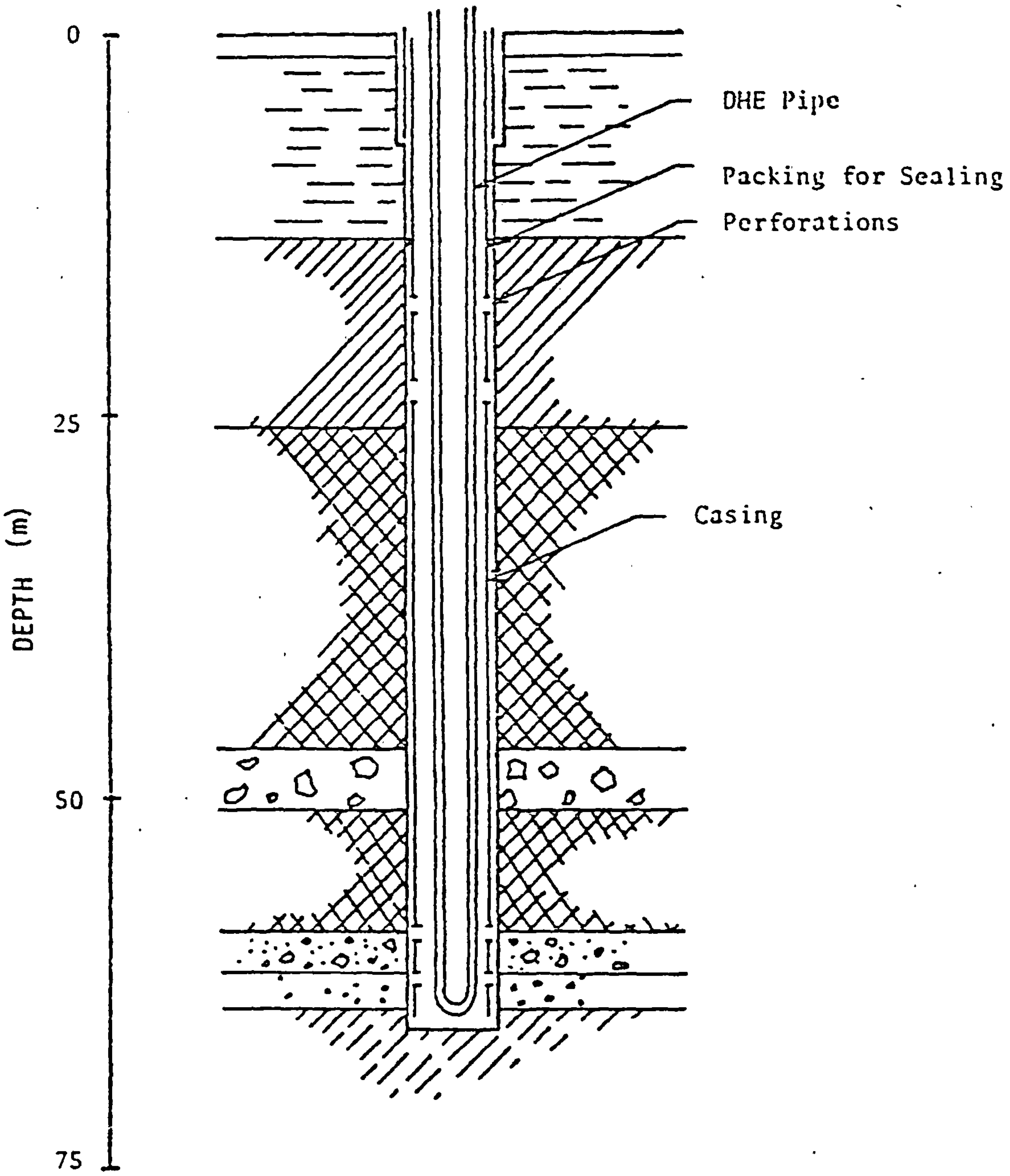


Fig. D-1. Typical downhole heat exchanger of a type used at Klamath Falls, Oregon (Ref. 4).

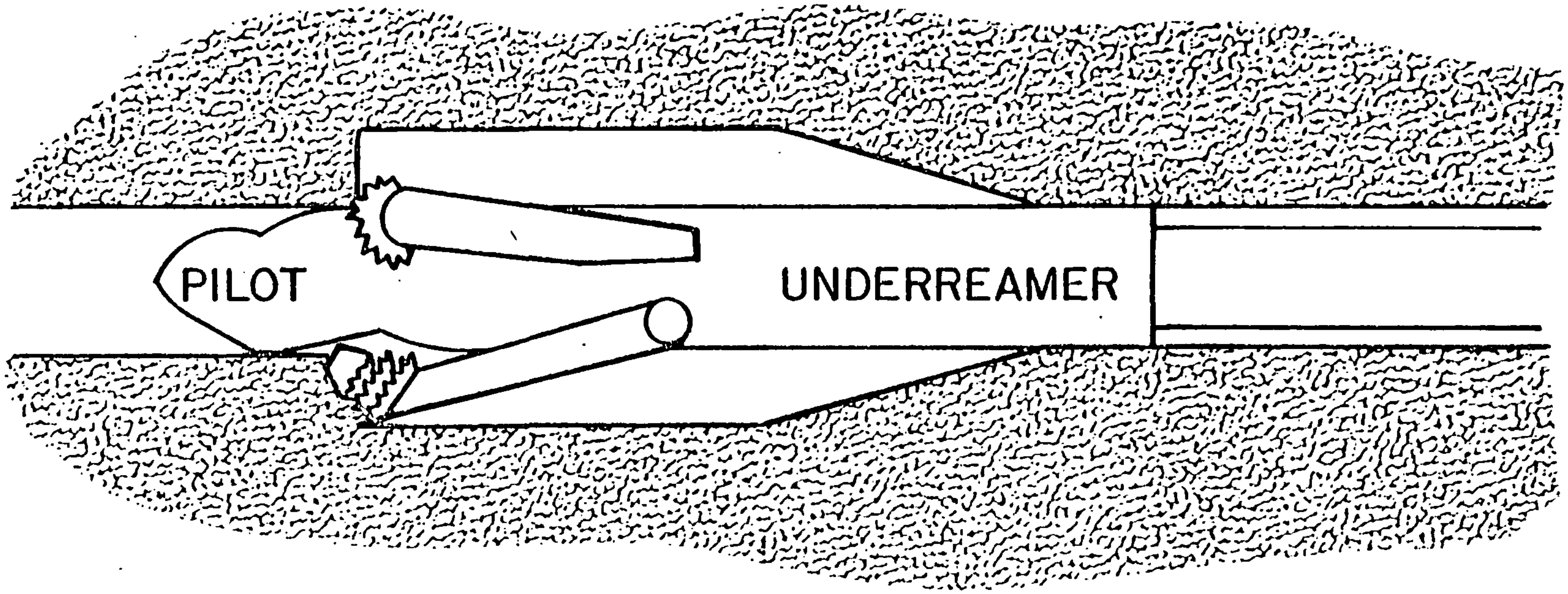


Fig. D-2. Mechanical borehole enlargement by underreaming.

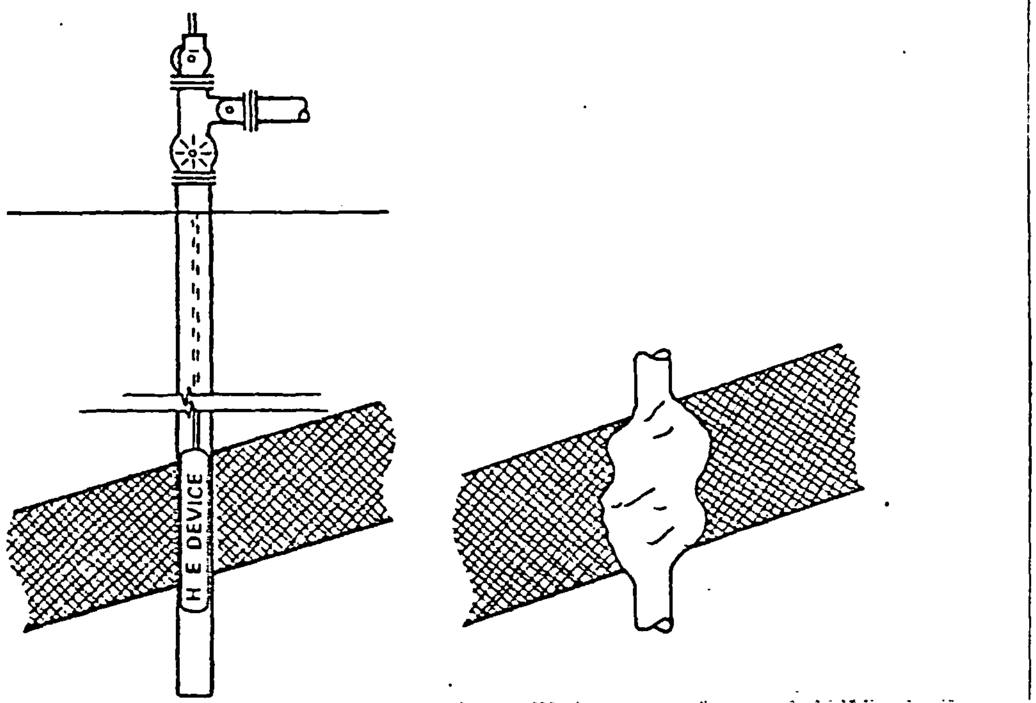


Fig. D-3. Borehole enlarged locally by springing it with chemical explosives (Ref. 3).

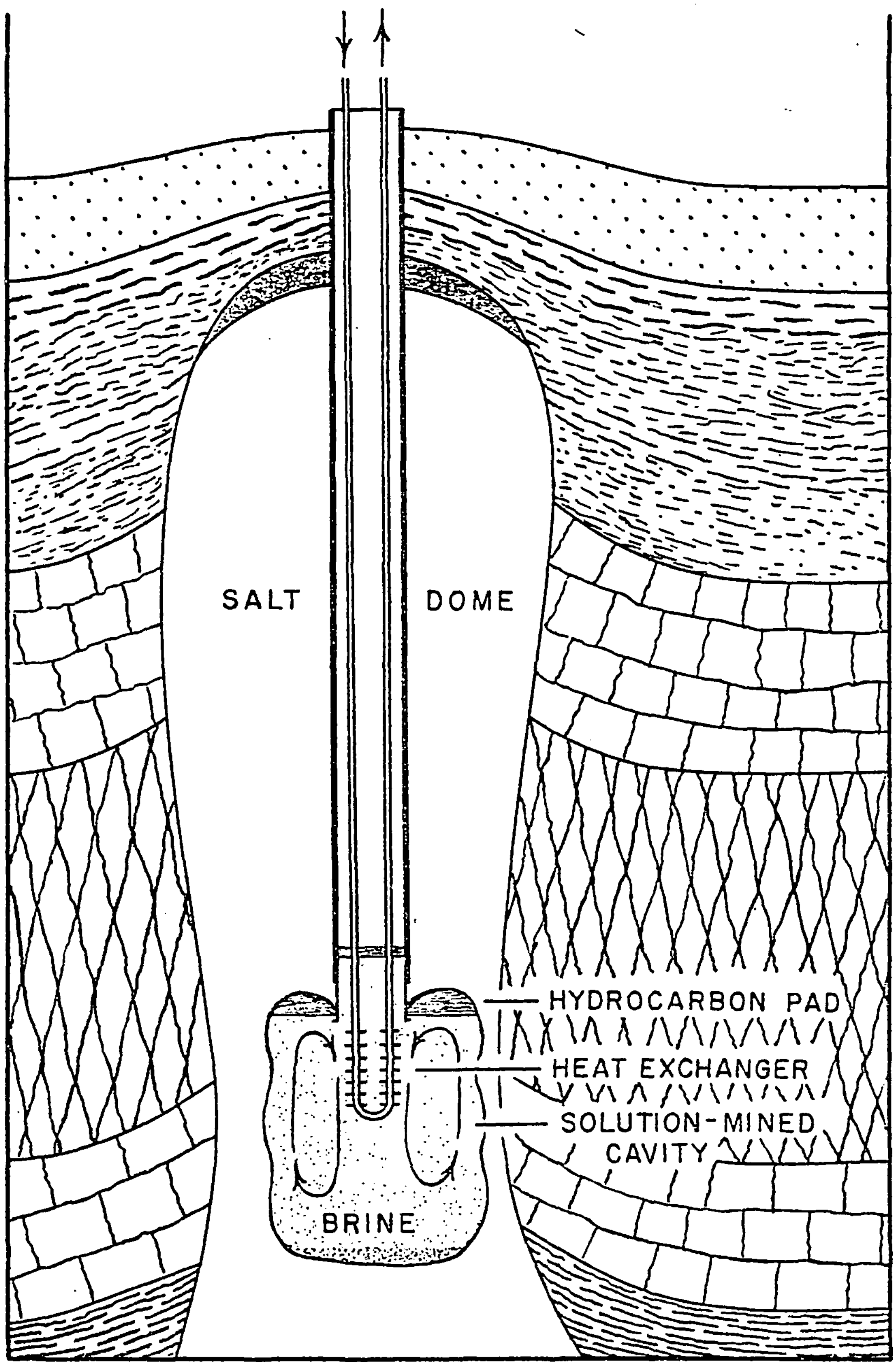


Fig. D-4. Heat exchanger immersed in a solution-mined cavity in a salt dome.

Because of the low permeability of salt, large cavities in natural salt deposits are now used to store petroleum products, natural gas, and compressed air. Except where an old salt mine can be tightly sealed for this purpose, the usual method of creating the cavity is by dissolving the salt in water.[5] Because solid salt is a relatively good thermal conductor, convective circulation of brine should be capable of transferring heat at a relatively high rate from the wall of such a cavity to the surface of the heat exchanger. Circulation of pure water or some other liquid through the heat exchanger would then transport heat to the surface without the corosion and salt-deposition problems that would be expected in the well casing and surface plumbing if the brine itself were circulated.

At least in principle, solution-mining of large cavities should be possible in other types of rock, for example in massive limestones, but--because solvents other than water would normally be required--it is unlikely that this would be economical. It is possible that a device such as the water-jet drill[6] might be used to produce a usefully large cavity by mechanically removing material from around the borehole. Again, however, it is doubtful that enlargement beyond a few hole-diameters would be practical even with water jets, except perhaps in very weakly cemented formations--where the possibility of subsequent caving may make the creation of a large cavity undesirable.

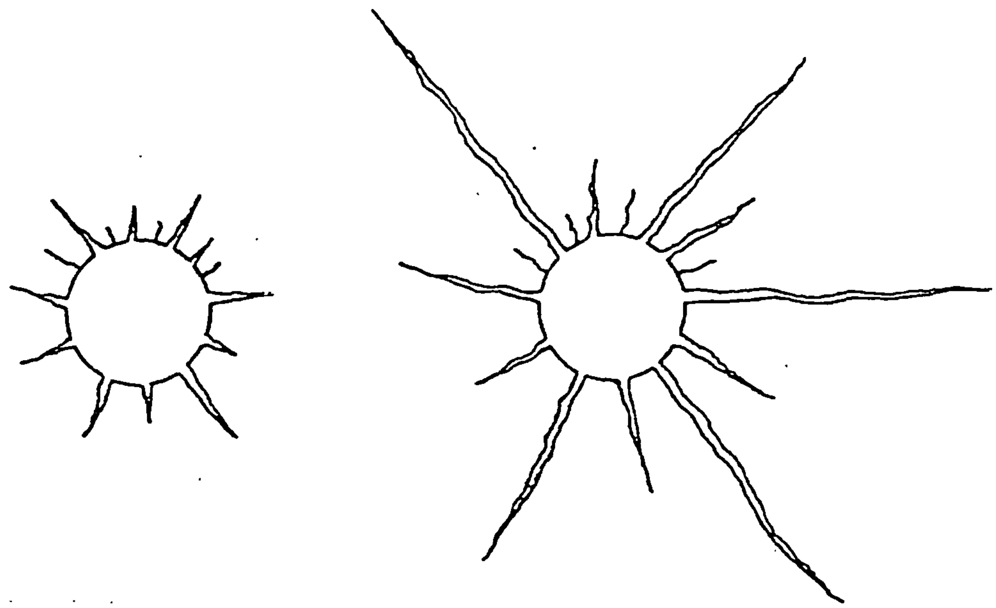
With the possible exception of solution-mined cavities in salt deposits, the insertion of downhole heat exchangers to recover energy from low-permeability formations appears unlikely to be economical.

2. Creation of Local Permeability. An alternative to increasing the heat-transfer area by enlarging a borehole is to create a region of high permeability around the hole, through which a heat-transport fluid can be circulated. There are a number of ways in which this might be done.

One possible method is to introduce through the borehole some chemical agent which will selectively attack one or more of the minerals present in the rock--for example, an acid to attack calcite fillings in ancient fracture systems. It is evident that, to create the connected void system required to increase permeability, the mineral that is to be removed must itself exist as a well-connected phase in the rock. In gneissic and other layered structures, and in the cases of veins, fracture fillings, and grain-boundary segregates, this may be true at relatively low overall concentrations of the reactive mineral. However, when that mineral exists as nearly equiazed, more uniformly distributed grains, a high degree of interconnectedness cannot be expected unless its concentration is of the order of 40% or more by volume--which would represent an unreasonably large fraction of the rock to be attacked and removed chemically. The distribution as well as the composition of the minerals present must, then, be taken into account when a leaching process is considered for creating permeability--although this may be less important if the object of the chemical treatment is simply to reduce flow-impedance through a pre-existing system of fine cracks or poorly connectee voids.

More commonly, the methods proposed for creating permeability around a borehole involve fracturing the rock mechanically rather than attacking it chemically. Of these methods, the detonation of chemical explosives in the borehole is the one most frequently suggested. This is a familiar and frequently successful technique for stimulating production from petroleum and natural-gas wells, and its use for that purpose in geothermal wells is now being investigated in Italy and the United States. Because the explosive can be inserted and detonated on a wire line, equipment requirements and fracturing costs are relatively low, and little junk is left in the hole.

When the shape of the stress pulse from an explosion is well matched to the properties and structure of the rock, the detonation is expected to produce a set of essentially radial fractures extending outward from the borehole (Fig. D-5). Because the volume of explosive that can be inserted is limited by the dimensions of the borehole, the radial extent of these fractures is also limited--and fracture density in general decreases exponentially with radial distance from the hole. In most types of rock, however, the original cracks can be subsequently extended either by repeated explosions[3] or by the use of fluid pressure.[8] Unfortunately, if the pulse shape does not match the rock properties, rock close to the borehole may be crushed and compacted, actually reducing its permeability by collapsing any voids that were initially present in it.[3] Further, any anisotropy or inhomogeneity in the wall rock



(a) (b)

Fig. D-5. (a) Radical fracture pattern produced by detonation of a chemical explosive in a borehole. (b) Extension of inital fractures by hydraulic pressurization (Ref. 11).

may be reflected in pronounced asymmetry of the fracture pattern produced, and in large local variations in permeability.[3] Fortunately, a wide variety of explosives and techniques for using them has been and is being developed to deal with such problems, including the use of slurries, liquids, gas mixtures, propellants, shaped charges, and gun-fired projectiles. However, problems remain with regard to the stabilities of most explosives in the higher temperature geothermal environments, and to matching the properties of the explosive to the characteristics of the in situ rock--which are not often known in detail before the fracturing attempt.

The extreme in explosive fracturing is represented by the downhole use of nuclear explosives, with which there is some published U.S. experience from the Plowshare gas-stimulation program. The possible application of such explosives to the development of geothermal energy systems has been discussed by Burnham and Steward,[9] Ramey et al.[10] and others. Their principal advantage is that very large amounts of explosive energy can be generated by a relatively small nuclear device, creating cavities large enough so that caving of the roof subsequently occurs to produce rubble-filled "chimneys" of considerable volume (Fig. D-6). By circulating water through the rubble--or introducing water and recovering steam--extraction both of natural geothermal heat and of heat deposited by the explosion can evidently be quite efficient.[12] From the engineering and the economic points of view, hot dry rock systems of this type appear feasible. However, environmental concerns arising from the earth shocks produced by large explosions and from the necessity of completely containing radioactive debris,[13] together with a widespread emotional reaction against use of nuclear explosives for any purpose, make it unlikely that this method of creating geothermal energy systems will be attempted in the United States in the foreseeable future. That may not always be true everywhere,[14] and it is possible that it may yet be tried in other countries or somewhere under the oceans.

At least three methods have been suggested for fracturing rock around a borehole by pressure pulses produced mechanically or hydraulically rather than by an explosion. Armstead[11] has proposed use of a device resembling a pile-driver, which would strike the upper surface of a weighted piston mounted in a sleeve at the top of a water-filled well casing (Fig. D-7). This would produce a shock wave that would travel down the water column to interact with

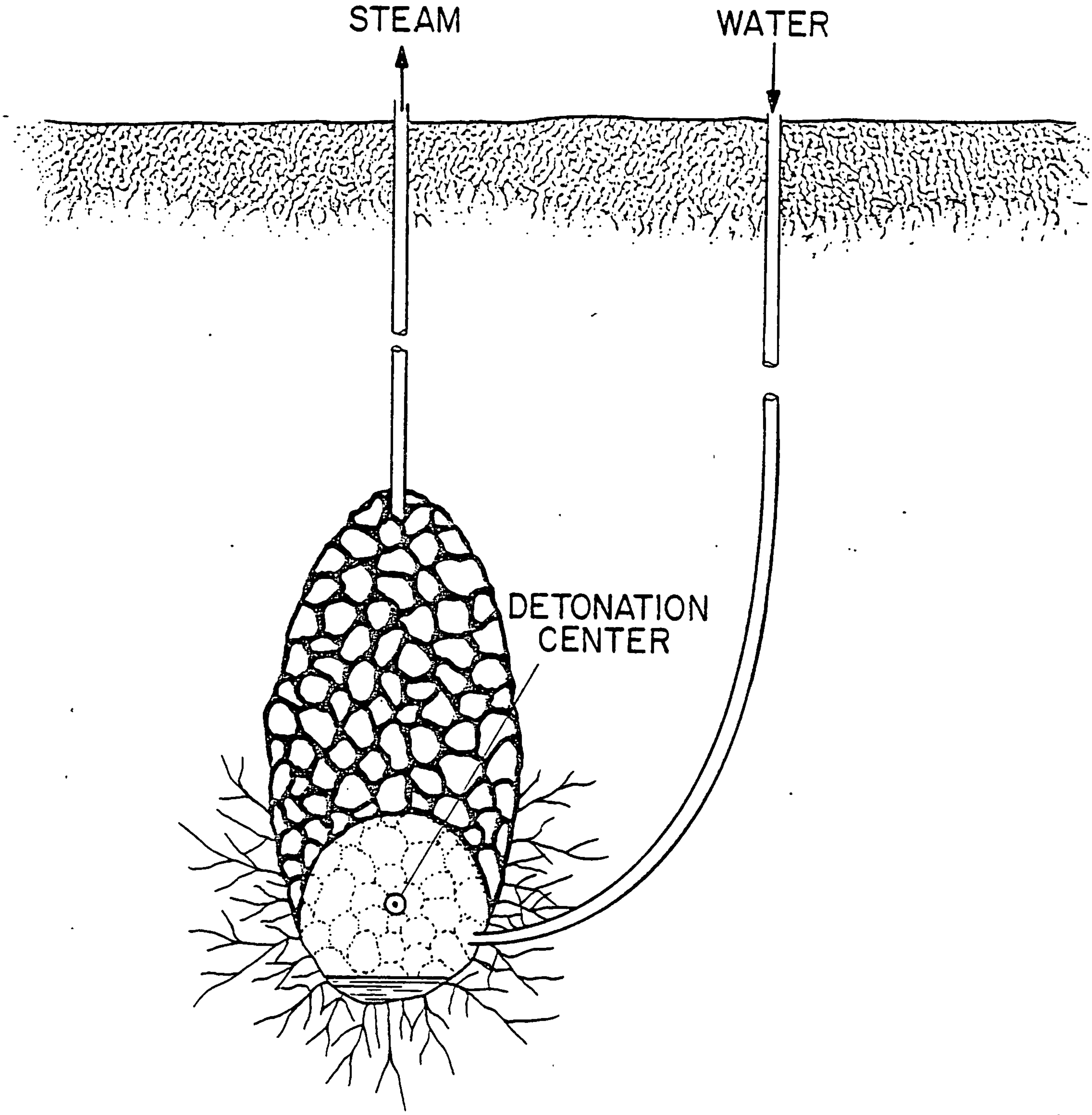


Fig. D-6. Rubble-filled chimney produced by caving of the roof into a cavity produced by a nuclear explosive.

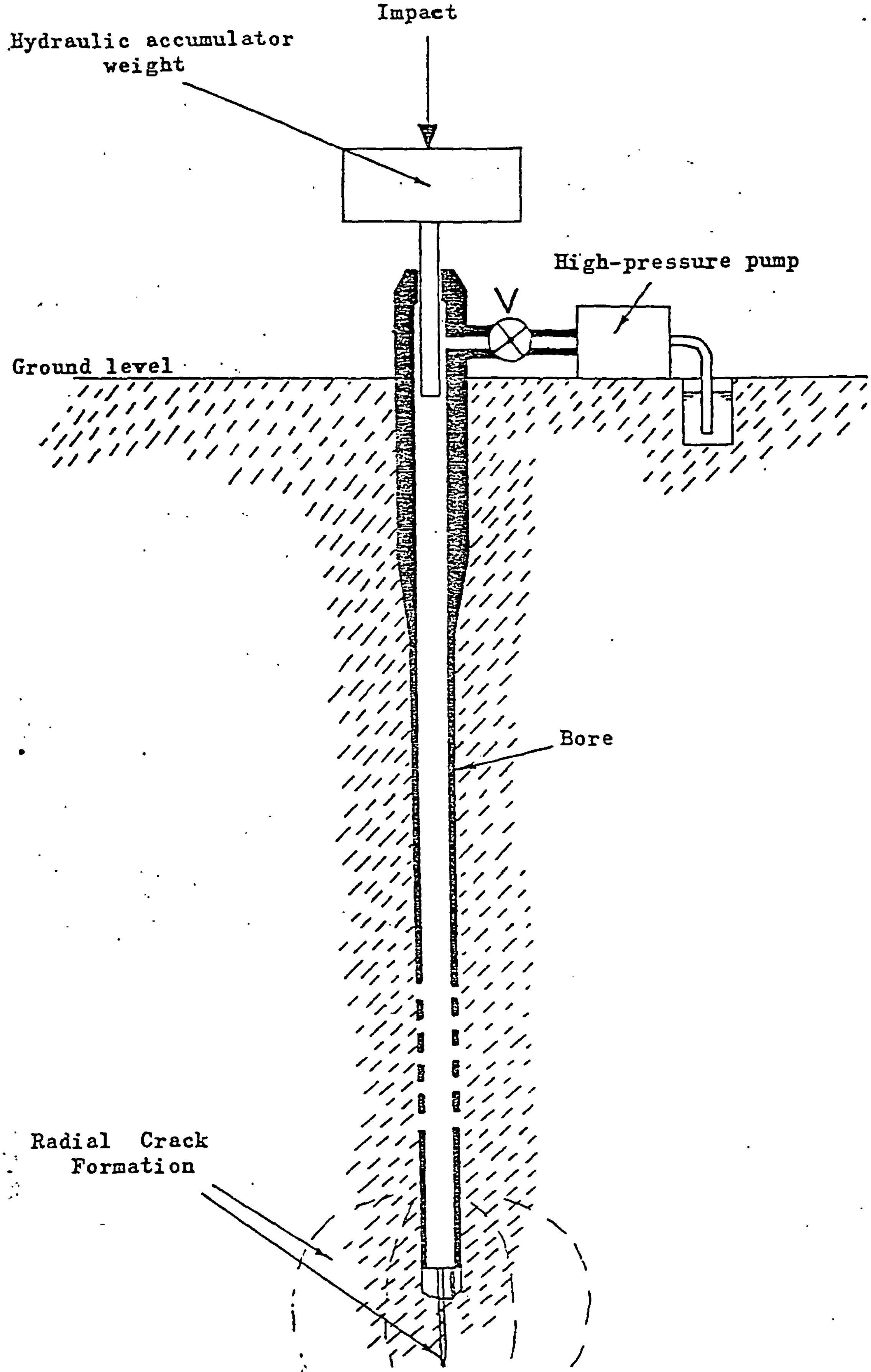


Fig. D-7. The use of mechanical impact to produce a pressure wave that fractures rock around an uncased section of a borehole (Ref. 16).

exposed rock surfaces below the bottom of the casing. By use of a high-pressure pump, water would be injected at the wellhead to raise the piston back into the striking position, and this could be repeated any number of times to form additional fractures or to extend those already present. A somewhat similar idea was at one time discussed at Los Alamos Scientific Laboratory (LASL), and the necessary equipment for it was actually assembled (but never used). This involved creation of a pressure pulse by the sudden release into the wellbore of a controlled volume of pressurized water through either a quick-opening valve or a blowout diaphragm. Neither this nor Armstead's impact system has yet been tried experimentally, and questions remain as to whether a usefully large pressure pulse could be developed without damaging the wellhead, the casing, or the cement around the casing, and whether the attenuated pulse reaching the bottom of the hole could create and extend fractures. In the meantime the ENEL Geothermal Research Center in Italy* has undertaken to investigate the less violent technique of using ordinary pumps to produce pressure cycles in the borehole, taking advantage of the low-cycle fatigue behavior of rocks discussed by Haimson _et al_.[15]

Other suggested methods of pressurizing the borehole wall either quasi-statically or dynamically include the use of downhole mechanical or hydraulic jacks and of repeated spark discharges in the water-filled borehole.

At LASL, the use of a pumped fluid to create permeability around the borehole is being investigated.[17] This technique, "hydraulic fracturing," is familiar and widely used for stimulating production of petroleum, natural-gas, and water wells. It involves isolating a section of the borehole by the use of temporary seals called "packers," then pressurizing it--usually by pumping water down a tubing string that penetrates the upper packer--until sufficient circumferential tension is developed to split the wall of the hole. The result is a thin crack, normal to the least principal earth stress (and therefore, at the depth of a geothermal system, expected to be planar, vertical, and with a specific azimuthal orientation controlled by the local tectonic stress field, as is suggested by Fig. D-8). Once formed, because of the stress concentration at its edges, such a crack can be extended over very large

---

*Centro di Ricerca Geothermica, Ente Nazional per l' Energia Elettrica.

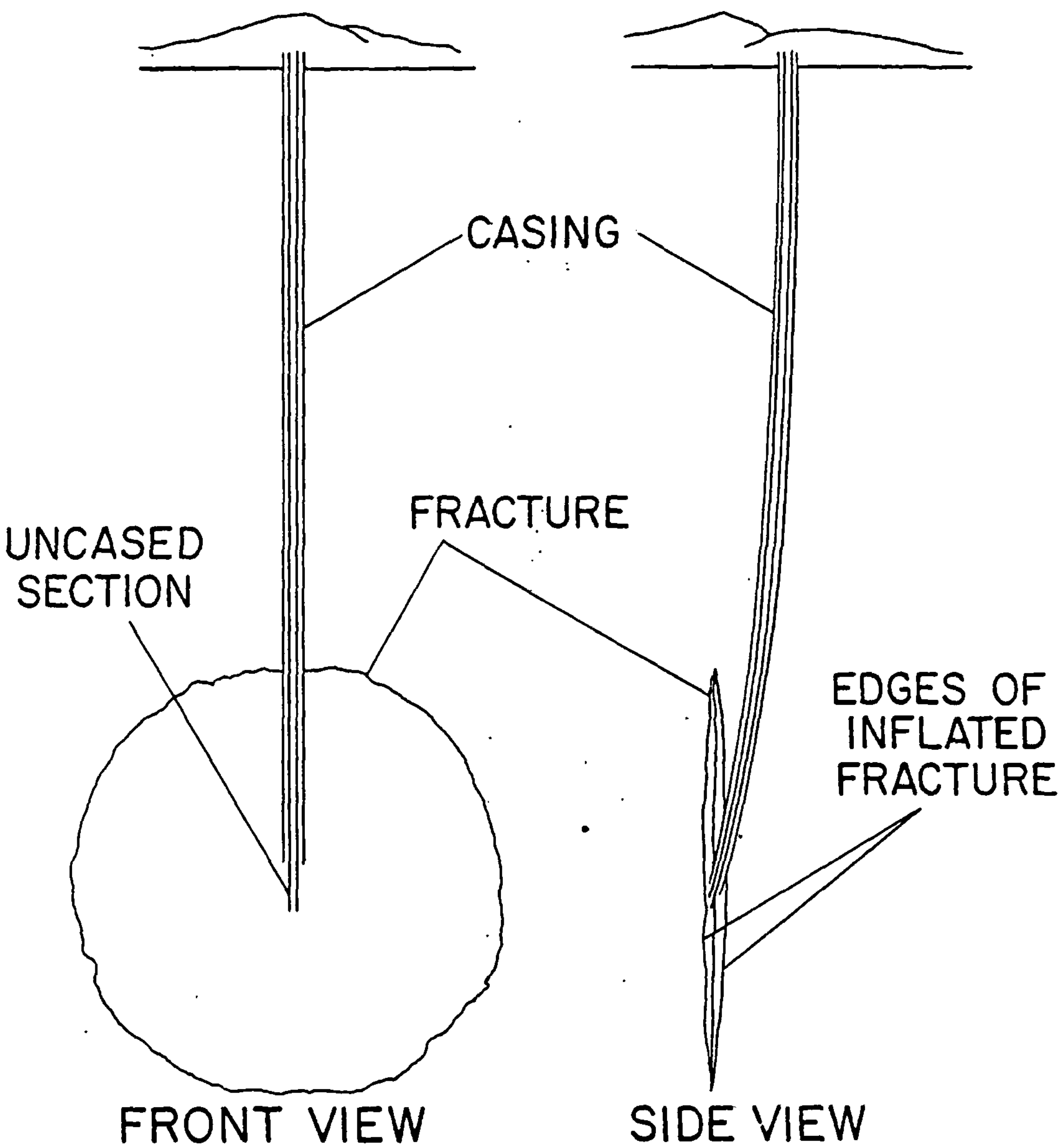


Fig. D-8. "Penny-shaped" hydraulic fracture.

distances simply by continuing to pump fluid into it, and (in gas-stimulation experiments) there is evidence that hydraulic fractures with radii of the order of 2 or 3 km have been produced.[18] This represents a very large heat-transfer surface which, however, will be useful for heat exchange only if fluid flow can be maintained through the fracture at reasonable rates and pumping pressures. Recent LASL experiments are encouraging in this regard in indicating that, in the granitic rocks being investigated there, the fractures are held open--"self-propped"--by a natural mismatch of their opposite surfaces.[19] Further, probably because of thermal-contraction effects, the resistance to fluid flow through them has decreased spontaneously as heat was extracted from their surfaces. If these effects are finally insufficient to permit the required rate of fluid flow, the possibilities remain of holding the cracks open with fluid pressure, of of injecting proppant particles into them, or of increasing their permeability either by chemical attack or by fragmentation with explosives. It is also possible, as has been suggested independently by R. M. Potter of LASL and by C. B. Raleigh of the U. S. Geological Survey, to produce a set of parallel fractures by repeated hydraulic fracturing from a single inclined borehole (Fig. D-9). This would increase the available heat-transfer surface and reduce overall flow-impedance of the fracture system, by distributing the total flow among a number of parallel paths.

Once fluid flow through and heat extraction from the permeable zone around a borehole have begun, thermal contraction is expected to produce additional cracks normal to the rock surfaces initially exposed to the fluid.[20] With continued cooling, these may open widely enough--to widths of the order of 0.5 mm or more[21]--so that water will also circulate through them. If this occurs, the creation of new flow channels and heat-transfer surfaces should progressively reduce flow impedance, increase temperature of the recovered fluid, and extend the useful life of the system.[22,23] In principle, this mechanism alone could be used to "grow" a permeable zone around a borehole. However, until a large increment of heat-transfer surface had been produced, the total rate of heat extraction would remain low, so that the initial growth of the crack system would be very slow. If it does operate beneficially, thermal-stress cracking will probably be useful primarily to extend the dimensions and prolong the useful life of fracture systems formed initially by some other method.

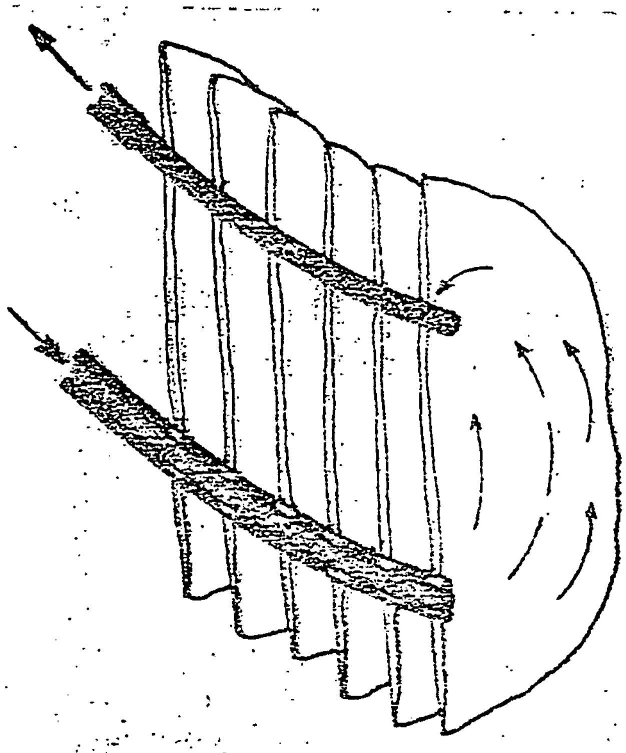


Fig. D-9. Series of parallel, vertical, hydraulic fractures, made from a single inclines borehole.

There is, then, a wide variety of methods for creating local permeability around a borehole drilled into hot rock of low initial permeability, so that water can be circulated through the rock and heat extracted from it. Of these, fracturing by the detonation of chemical explosives is being investigated intensively in the U.S.S.R.[24,7] and in the United Kingdom,[8] and both hydraulic fracturing and thermal-stress cracking are being investigated in the United States.[17]

3. Heat Extraction. When a region with adequate permeability and heat-transfer surface has been developed around a borehole, it is necessary to provide for fluid circulation within that region to extract heat from it, and then either to bring the heated fluid to the surface at a usefully high temperature or somehow to use the heat from it beneficially in a second underground system. Again, a number of engineering possibilities exist both for creating fluid circulation and for recovering thermal energy from the heated fluid.

Among other possibilities, Aladiev et al.[24] suggest the use of a downhole heat exchanger somehow inserted into the circulation path of the hot water, with which heat would be transferred to a relatively benign second fluid and only the latter would be brought to the surface. As was discussed above, even a simple U-tube heat exchanger (Fig. D-1) can sometimes be used very economically for this purpose if conductive heat transfer through the borehole wall is supplemented by the buoyant circulation of geothermal water through the hole. Creation of a large region of high permeability might permit convective cells to form around the wellbore, allowing heat to be extracted from dry hot rock with a system much like that now in use in some hydrothermal reservoirs. When a large cavity can be created, as in the case of a salt deposit (Fig. D-4), free buoyant circulation could certainly occur within it, increasing the probability that a usefully high rate of heat extraction could be maintained with an underground heat exchanger.

However, most current heat-extraction concepts envision bringing the primary fluid to the surface for energy recovery there rather than in a downhole heat exchanger. For example, Smith et al.[25] describe a concentric-pipe system (Fig. D-10) in which cool water flowing down the central pipe would be forced by the presence of a packer to flow out into the permeable region

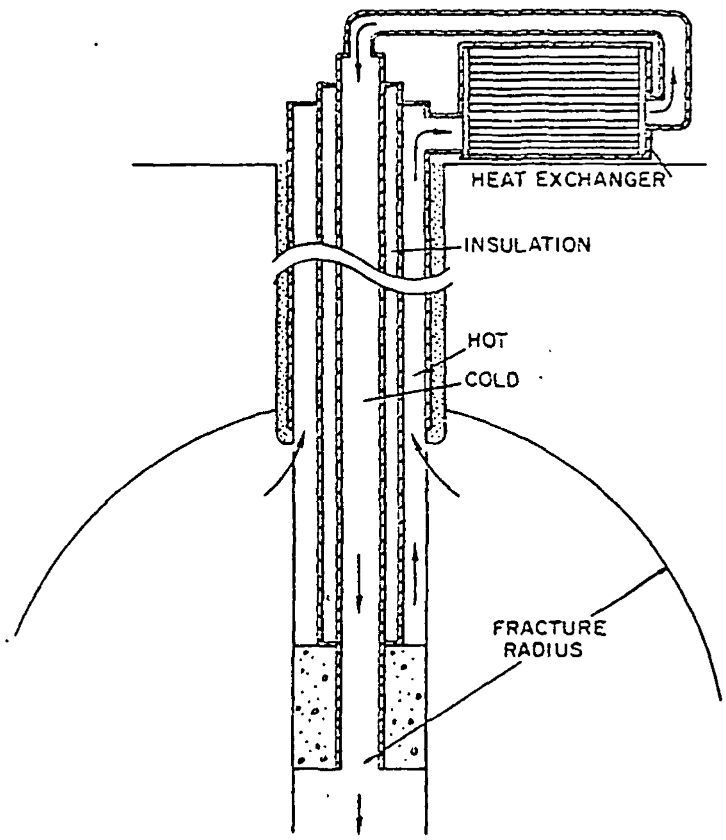


Fig. D-10. Concentric-pipe, one-hole, heat extraction system (Ref. 25).

around the borehole, would return to the hole at a higher level (above the packer) and would then flow back to the surface through the annulus between the two pipes. With this arrangement, if buoyant forces were insufficient to maintain the desired flow rate, then the fluid could be pumped mechanically. Here the obvious problem is that the long concentric pipes themselves represent an excellent heat exchanger. Unless the surface of the central pipe was very well insulated, most of heat extracted from the rock would be transferred from the ascending hot water in the annulus to the descending cool water in the central pipe, and would simply recirculate downhole instead of being brought to the surface. Insulation capable of controlling this in a low-temperature geothermal environment is apparently available, and the West Germans plan to experiment with such a system.[26] Insulating materials which would probably have economically long lives at higher temperatures in the presence of a high-velocity flow of impure water are also available, but at present they appear to be too expensive to be considered for this use. The use of a double-walled central pipe with an insulating material between its walls, as suggested in Fig. D-10, would also be very expensive, but would permit readily available insulation to be used.

An alternative, originally proposed by Robert W. Rex, is a "push-pull" (or "huff-puff") mode of operation through a single cased borehole. Water would be pumped down the hole until sufficient pressure was developed in the permeable zone to inflate its void spaces elastically. It would be stored there until it was sufficiently heated and then, by reducing pressure at the wellhead, permitted to flow back to the surface through the same hole, driven by the elastic restoring forces in the rock and in the compressed fluid itself. If necessary, its return could be assisted by a downhole pump. By using two or more such systems in different phases of the injection-heating-recovery cycle, a continuous supply of hot water could be produced at the surface. Here again the principal problem is one of heat exchange, in this case between the ascending hot water and the well casing and the cement and rock around it. Having been cooled by water injected during the first phase of the cycle, these would extract a large fraction of the heat from the ascending water during the recovery phase. The results of LASL analyses and field experiments suggest that a more advantageous application of the "push-pull" concept may be to increase the residence time of fluid in a permeable zone between two wellbores, as is discussed below.

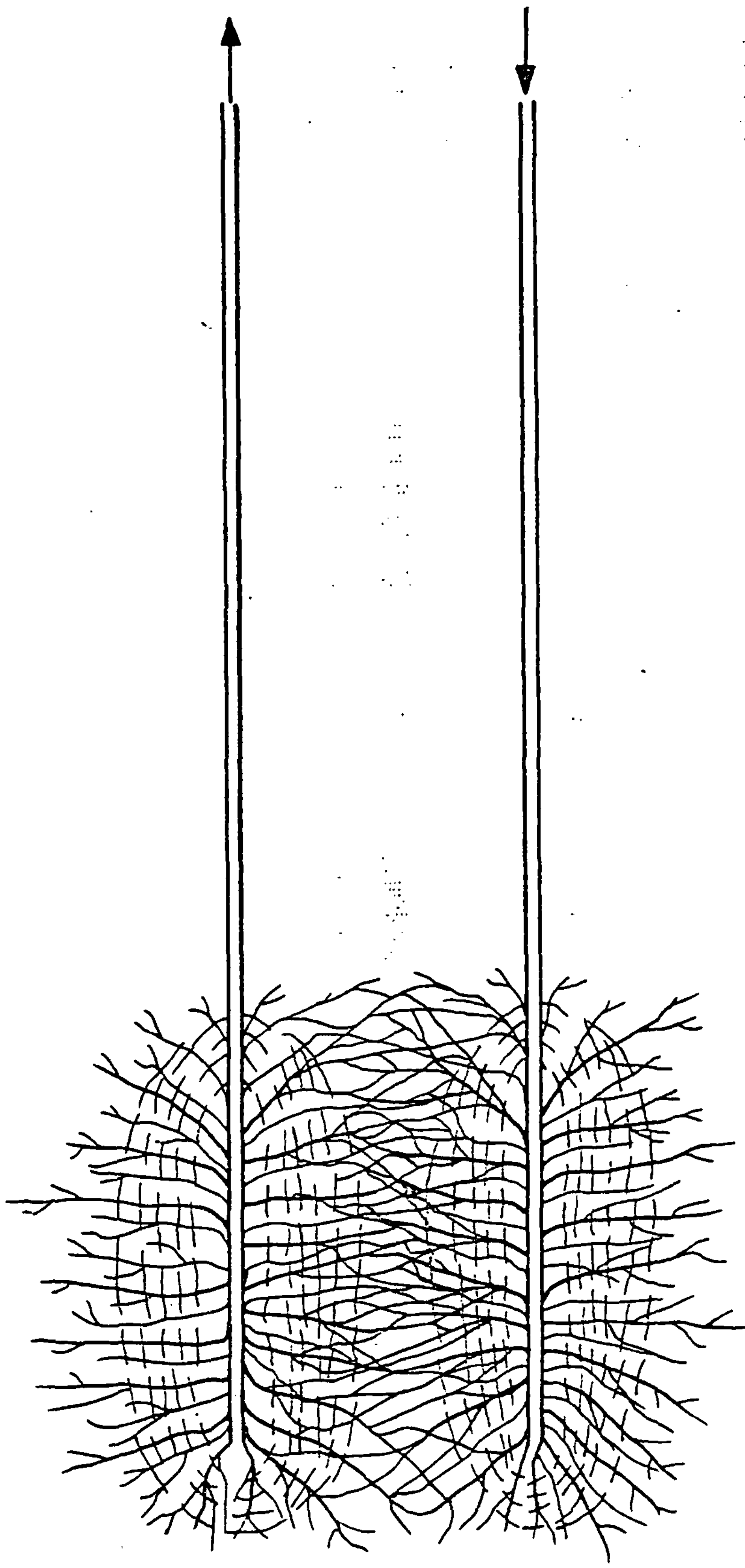
To avoid the heat-exchange and heat-storage problems inherent in injecting and recovering fluid through the same hole, most proposed systems for extracting energy from hot dry rock involve the use of separate injection and recovery wells, connected at depth through a region of enhanced permeability. Thus, Diadkin and Pariisky[7] propose drilling two holes of approximately equal depth, connecting them through the hot rock by means of overlapping fracture systems produced by detonating explosives in both holes, and flowing water horizontally from one hole to the other through those fractures (Fig. 11). To the degree that the fracturing itself has been effective, this should in time effectively sweep nearly all of the useful heat out of the fractured volume. This general method should, of course, be equally useful if the permeable zone were natural or had been created by some other means such as chemical leaching or thermal-stress cracking. If the permeable region were very large, an array of holes rather than a single pair might be used to advantage.

In the hot dry rock system being investigated at LASL (Fig. D-12), fluid circulation again is through a permeable zone connecting two boreholes, but at least initially the flow is primarily vertical and through a single, substantially planar crack rather than a three-dimensional array of cracks. (However, as has been discussed, it is anticipated that thermal-stress cracking will eventually cause this to develop into a three-dimensional fracture system.) In this case, it is expected that buoyant forces will assist both in distributing the fluid over the exposed rock surfaces and in transporting it from the point of entry into the fracture to an exit at a higher level.[23]

While drilling two holes is likely to be more expensive than drilling just one at a larger size, there are important advantages in using separate injection and recovery wells--particularly when the highest possible temperature in the effluent fluid is required. On the other hand, a one-hole system avoids the problem of insuring that an underground connection with low flow-impedance and high effective heat-transfer area is made through the hot reservoir rock between two separated holes.

4. Operating Mode. Except in one-hole "push-pull" systems, it has so far been implicitly assumed that heat extraction would be accomplished by continuous recirculation of water around a closed loop. However, other modes of fluid circulation are evidently possible.

Fig. D-11. Injection and recovery wells connected through fractures produced by detonating explosives in both boreholes.



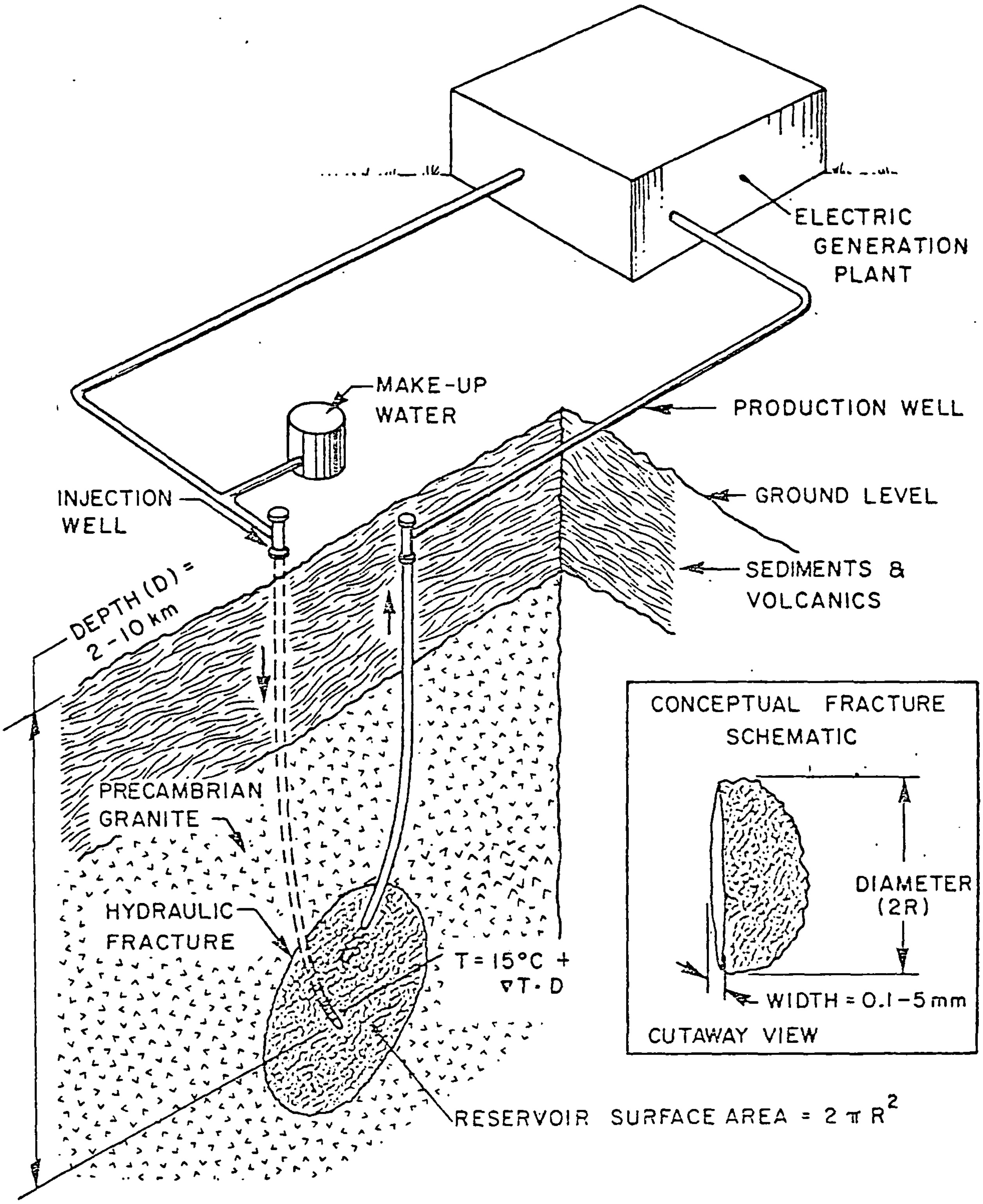


Fig. D-12. Injection and recovery wells conected through hydraulic fractures.

For example, if water is plentiful locally and does not dissolve so much mineral matter from the reservoir that it presents a disposal problem, a "once-through" system might be used, in which hot water from the recovery well is simply delivered to the customer and not returned to the well field for reinjection. This would greatly increase the distances over which relatively low-temperature heat could be distributed economically.

With a connected two-hole heat-extraction system, there is the obvious possibility of direct short-circuiting of much of the fluid from one well to the other through one or a few major flow channels. If this occurs or if there is simply not enough heat-transfer surface in the permeable region to maintain the required effluent temperature at the required flow rate, then a type of "push-pull" operation may be useful. With the recovery well shut in, water would be pumped into the injection well to pressurize and elastically inflate the permeable region, stored there until it had been sufficiently heated, and then recovered through the other well. By increasing the mean residence time of fluid in the manmade reservoir, this would result in a higher, more nearly uniform temperature in water entering the recovery well. By avoiding the alternate heating and cooling involved in a "push-pull" operation in a single wellbore, this would also greatly reduce both the temperature loss in the ascending column of hot water and the danger that the well casing and the cement around it would be damaged by large-amplitude temperature cycles.

Finally, it is often suggested that the heat be brought to the surface in steam rather than hot water. The obvious advantage is that this would minimize the mass transport of dissolved solids, reducing corrosion and scaling problems in the well casing and surface plant and the danger of plugging the reinjection well and the formation around it. Against this must be weighed the disadvantages. (a) Most of the solids dissolved by the water as it was heated within the reservoir would be redeposited in the zone in which boiling occurred, whether in the formation or in the wellbore, possibly plugging the system there. (b) In addition, unlike water, steam becomes more viscous as it is heated. Boiling within the formation would therefore result in an increasing tendency of steam to short-circuit along the coolest available path to the recovery well whereas water (with a negative temperature coefficient of viscosity) will tend to distribute itself among the hottest paths. (c) With the same pressure drop and flow-channel or wellbore diameter, the mass-flow rate of steam is much less than that of liquid water, so that--at the same reservoir temperature—less heat per unit time would be delivered to the surface by steam than by hot water.[25] (d) Finally, when boiling occurs in the ascending water column, the heat of vaporization is absorbed from the water itself, and its temperature decreases accordingly. If the water is to be flashed to steam at the surface anyhow, this makes no particular difference. However, if it is to be passed through a heat exchanger and its useful heat transferred to a second fluid, the higher temperature maintained by avoiding boiling may considerably increase the efficiency with which that heat can ultimately be used. At LASL, it has so far been considered that the net advantage is in favor of continuous circulation of pressurized water, but this may not always be true. It is quite possible that in other circumstances the disadvantages noted may be outweighed by decreased corrosion and scaling problems or by the reduced initial cost and maintenance problems of using a steam lift instead of a mechanical pump to bring the hot fluid to the surface.

Undoubtedly there are other possibilities for developing and operating heat-extraction systems in hot dry rock of very low initial permeability. However, those already discussed represent a sufficient variety to indicate the desirability of experimenting with several field systems in the varied subsurface environments that nature actually provides.

B. Low But Significant Matrix Permeability. Even in the complete absence of large-scale fracture systems, it is not unusual to encounter geologic formations in which the permeability of the rock matrix is insufficient to permit the buoyant circulation that forms and maintains a hydrothermal system, but still is too great to contain the circulating fluid in a manmade heat-extraction loop of the types discussed above. This is most likely to occur in "tight" sedimentary rocks such as well-cemented sandstones and greywackes, but it may also occur in porous volcanics and in finely fractured rocks of any kind. When it does occur, there are several possible ways in which useful heat-extraction systems might be developed.

1. Stimulation. When natural steam or hot water can be produced from a geothermal well but, because of inadequate permeability around the borehole, the production rate is too low to be economically attractive, then a "stimulation" treatment may be all that is needed--as is often the case in petroleum, natural-gas, and water wells. Such treatments are usually based on one of the methods described above for increasing permeability around a borehole: hydraulic or explosive fracturing, or selective chemical attack. If this aproach is unsuccessful, it may still be possible to achieve a useful heat-production rate by any of several other methods, all of which are designed to minimize fluid loss to the formations around the reservoir volume being exploited.

2. Pressure Reduction in the Wellbore. For a geothermal fluid to flow into a well, it is evidently necessary that fluid pressure in the well be less than that at the same level in the formation around the well. In some hydrothermal fields the local hydrology is such that the pore pressure in the geothermal reservoir is above normal hydrostatic pressure at the same depth, so that an artesian flow of hot water from the well will occur naturally. In others the pore-pressure field is at or only slightly below normal hydrostatic pressure, so that the density decrease in the water as it is heated is sufficient to cause artesian flow to continue once an upward flow of hot water in the well has somehow been initiated (which may be done, for example, by releasing air or nitrogen in the well below the level to which it fills naturally with water). The further reduction in mean fluid density that results from permitting part of the hot water to flash to steam in the well accelerates this flow, and creates the "steam lift" that is now usually used to produce fluids from hot-water reservoirs. It also reduces fluid pressure in the bottom of the well, steepening the pressure gradient around it and increasing the rate at which water from the reservoir flows into it.

A similar reduction in pressure in the lower part of the hole can be produced by using a downhole pump, which adds cost and maintenance problems to the system but has advantages. If the reservoir temperature is too low to permit boiling in the recovery well, such a pump may be essential simply to lift fluid out of the well. However, even in very high-temperature systems, a pump is useful in keeping downhole pressure in the well below that of the reservoir, thus preventing fluid loss, while also keping the upper part of the well sufficiently pressurized to prevent boiling there. This is likely to reduce scaling and corrosion problems, and will certainly increase mass flow rate at the surface, avoid the temperature reduction that accompanies boiling, and increase the rate of energy production from the well.

Whether a well has been stimulated or not, a reduction in fluid pressure downhole--by whatever means--increases the pressure gradient around the borehole and the rate at which water flows into it from the reservoir. However, in low-permeability formations, this may not be sufficient to make the well economically productive. If it is not, several possibilities remain for creating pressurized flow systems in which precautions are taken to minimize fluid loss to the reservoir rock around the system.

3. Flow Between Parallel Fractures. Total flow rate through a low-permeability formation can be increased by increasing either the pressure gradient in the formation (e.g., by reducing pressure in the recovery well) or by increasing the cross-sectional area through which flow occurs (for example, by a stimulation treatment). A possible method of doing both while also minimizing fluid loss has been suggested by R. M. Potter of LASL. As is shown in Fig. D-13, his proposal is to drill a row of three boreholes to approximately the same depth, and from them to produce three parallel hydraulic fractures of roughly the same size. Pressurized water injected through the central borehole would flow horizontally outward from the central fracture, be collected in the other two fractures, and returned to the surface through the two outer holes. Fluid loss could be minimized by keeping downhole pressure in the two recovery wells at or below the natural pore pressure in the reservoir rock. Unless considerable short-circuiting occurred through natural or induced large cracks in the rock between the hydraulic fractures, the heat from that rock should be swept out very effectively by the slow advance of the injected water, and the temperature of water entering the recovery wells should remain essentially constant until the front of cool water finally broke through to them. (This would greatly simplify the problem of efficiently using heat from the system.

4. Reduced Permeability. Another general approach to reducing fluid loss by permeation of formations around the borehole is simply to reduce the permeabilities of those formations. As has been discussed, except where

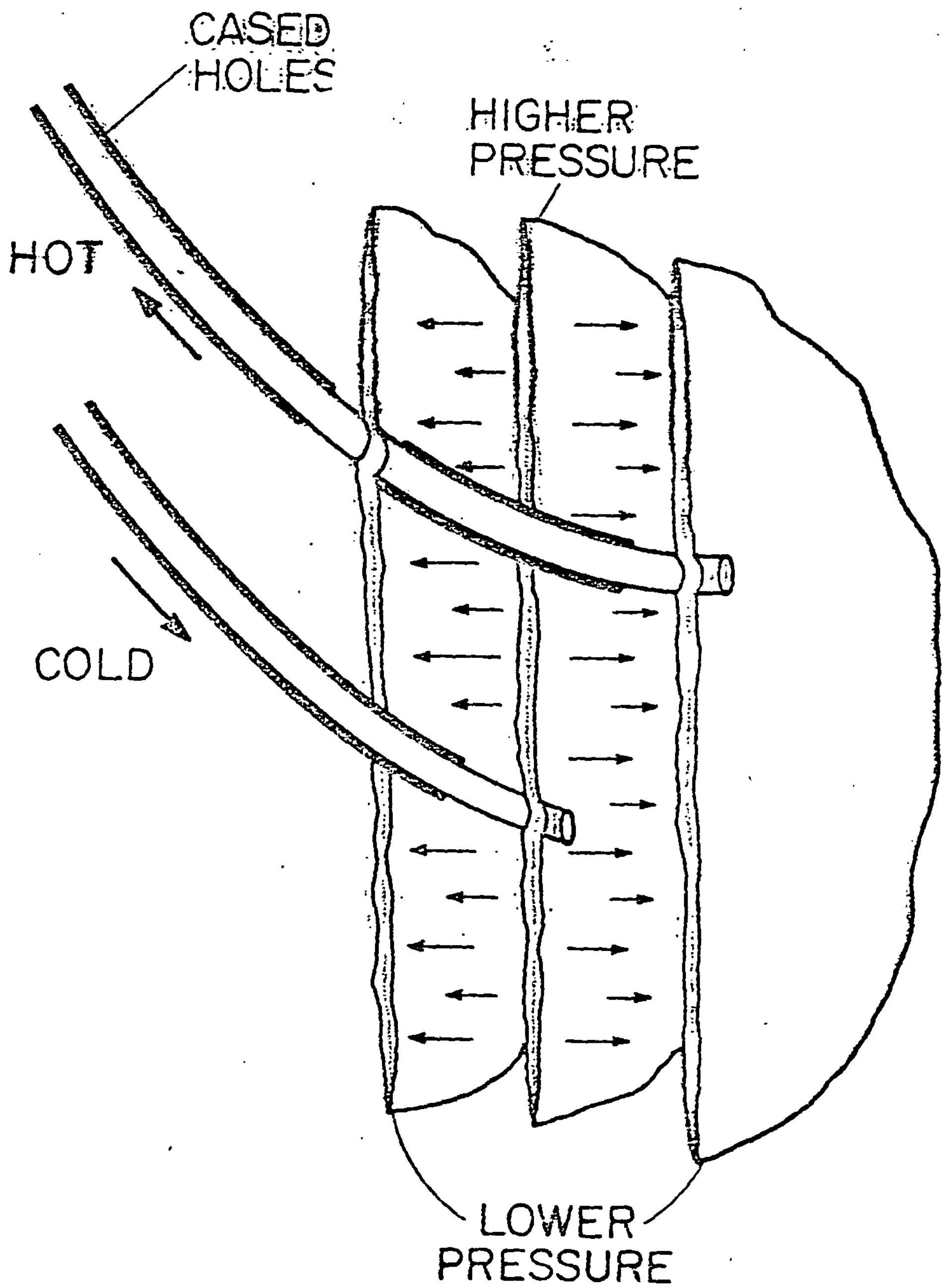


Fig. D-13. Heat extraction by pressurized flow between parallel hydraulic fractures.

there is or has recently been active faulting or major seismic activity, the permeability of any given formation can be expected to decrease as it is penetrated more deeply. An obvious possibility, therefore, is to continue to deepen the hole until permeability is low enough to satisfactorily contain a pressurized hot dry rock system. This will also progressively increase the reservoir temperature which, within limits imposed by possible equipment, materials, and geochemical problems, is generally desirable--but must of course be balanced against what may be a large increment of drilling cost. An alternative to deeper drilling is to reduce the permeability of the rock that surrounds the active circulation system. Suggested methods include filtering out on the rock surfaces of fine particles, for example of bentonite; chemical additions which will accelerate certain mineral alterations that result in a volume increase, such as the production of clays from feldspars; and the injection of materials that will gel or polymerize or react with each other in the void spaces of the formation outside the circulation loop.

There are then, again, an interesting variety of possibilities for extracting geothermal energy from hot formations whose initial permeabilities are significant bt not sufficient to yield natural steam or hot water at commercially useful rates. Several of them appear to deserve investigation in field experiments, and some may merit development of pilot- or demonstration-scale heat-extraction facilities.

C. Thin Permeable Layers. There are several geologic situations in which a relatively thin, essentially two-dimensional, permeable zone may occur naturally within a formation whose initial permeability is very low, or along the contact between two such formations. Physically, this is not unlike a hydraulic fracture within a rock of low permeability except that the heat-exchange surfaces are unbounded at their edges, so that some special arrangement is required to recover any fluid that is injected into the permeable layer.

For this system geometry, when indigenous fluids are insufficient to maintain a productive hydrothermal reservoir, Bodvarsson and Reistad[27] propose a "forced geoheat extraction" method of fluid circulation in which water is introduced into the permeable region through one or more injection wells and heated as it flows toward an array of appropriately located recovery wells. If the permeable zone dips steeply, as it may in a brecciated fault zone or along an intruded dike, the tendency of the heated water to rise buoyantly may permit it to be collected quite effectively with a relatively simple hole array, as is suggested in Fig. D-14. If the permeable zone is more nearly horizontal, for example along the interface between successive layers of a flood basalt, a more elaborate hole array will probably be required to avoid excessive fluid loss from the periphery of the active system. This will probably resemble one of the hole arrays developed for water-flooding systems in oil fields, which are described below. In either situation, down-hole pumps will probably be required to keep pressure in the collecting sections of the recovery wells low enough so that the heated fluid will tend to flow toward them instead of escaping from the system between wells.

D. Widely-Spaced Large Fractures. With the exception of a few very large reservoirs in sedimentary basins, nearly all of the major hydrothermal areas so far investigated occur as relatively small, elongate regions along fault systems.[28] The principal flow paths for geothermal fluids are evidently open fractures associated with those faults, and successful completion of a productive steam or hot-water well is in general contingent upon drilling through one or more such fractures. Because the population density of fractures decreases with increasing distance from the major fault zone, so does the probability that a drilled hole will encounter at least one of them. However, until the fracture density drops essentially to zero, a stimulation treatment--which may be as straightforward as directionally redrilling the lower part of the hole--is likely to be successful.

It is, then, primarily at the peripheries of fault-associated hydrothermal systems that low-permeability rocks containing relatively large but widely separated fractures are commonly found. In this circumstance, the obvious approach to achieving commercial energy production is first to attempt to stimulate dry or relatively unproductive holes by one of the methods described above and then, if that fails, to undertake development of some type of hot dry rock system such as those already discussed.

E. Thick Permeable Formations. When a relatively thick, unproductive, permeable zone is encountered rather than a thin permeable layer, a somewhat different heat-exchange mechanism and fluid-circulation pattern may be used

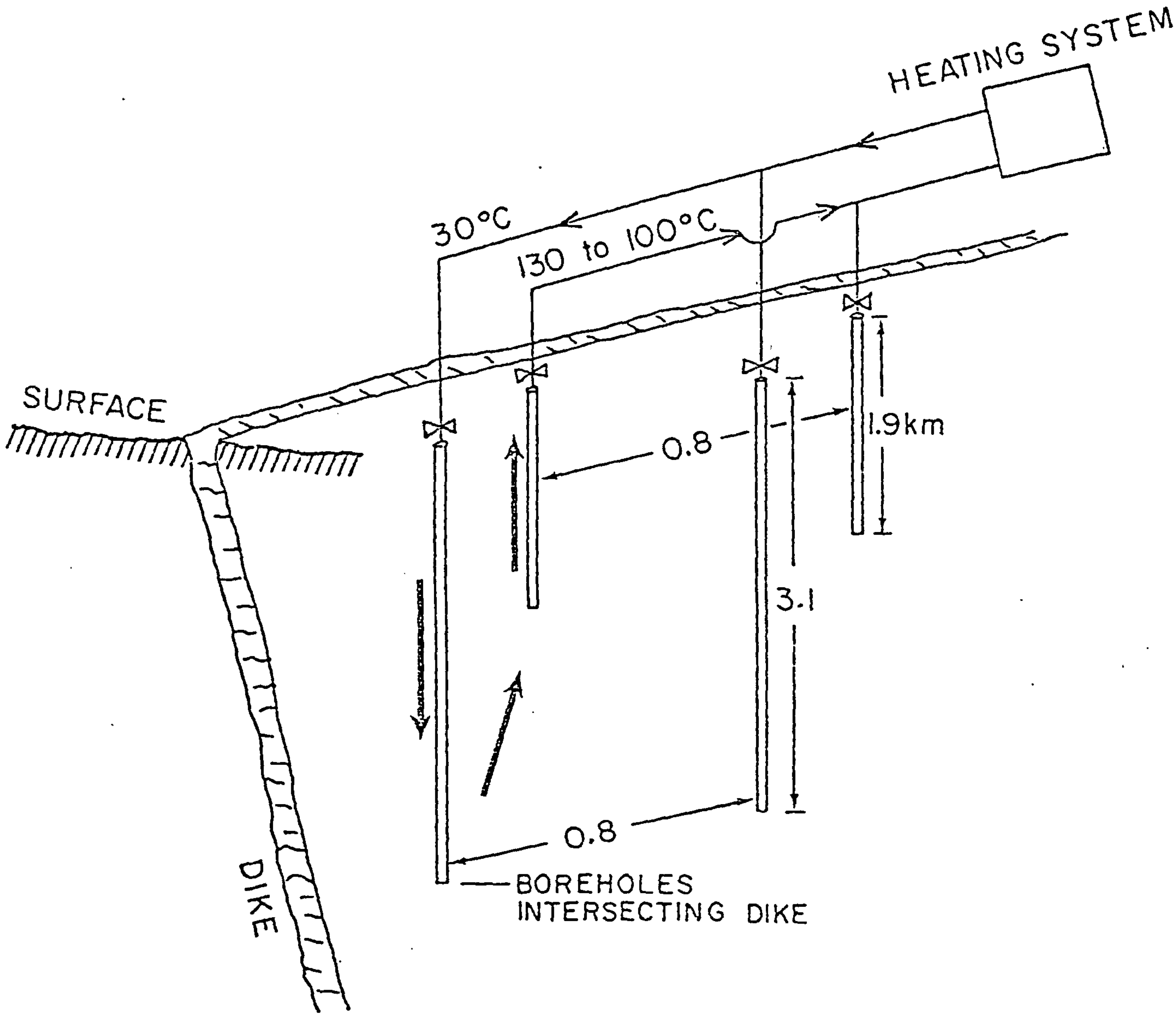


Fig. D-14. Upflow system of forced geoheat extraction using an open dike with a geothermal gradient of 50°C/KM (Ref. 29).

to advantage. Instead of, in effect, flowing over a hot surface, the fluid permeates a three-dimensional porous body. Because of its higher viscosity, the cool fluid entering the formation tends to maintain a definite "cold front" that sweeps the less-viscous hot water ahead of it into the recovery well. To use the full thickness of the permeable zone to advantage, it is desirable in both the injection and the recovery wells that most of that zone communicate directly with the wellbore--usually through a slotted liner or a series of casing perforations, unless the formation is sufficiently competent to remain intact without casing.

This is, of course, very similar to the water-drive systems used to increase recovery of petroleum, and like them it will normally require that an array of holes (Fig. D-15) rather than a single pair be drilled--to control fluid loss into the surrounding formation. As was discussed in connection with flow between parallel fractures, it has the advantages that a relatively large volume of rock is swept by the heat-transport fluid, so that a very large amount of heat can ultimately be extracted, and that the temperature of the fluid entering the recovery well should remain nearly constant until the "cold front" of the injected fluid finally breaks through it into the well.

III. CONCLUSIONS

There are a wide variety of system geometries, construction methods, and operating modes that may be commercially useful for extracting geothermal energy from hot dry rock in the varied geological environments in which it naturally occurs. In the present state of knowledge, it is impossible to model most of them accurately enough so that their performances and economics can be predicted with confidence. At this time, therefore, their potential advantages, problems, and commercial usefulness can only be investigated semi-empirically--by actually creating and operating relatively large experimental systems in the field. Several of the systems described above appear to have sufficient promise so that they merit this type of investigation.

Fortunately, as is discussed in Appendix E, a large number of areas of immediate geothermal interest have already been identified, representing a wide variety of geologic environments and geographic locations. A judicious selection among them will permit experimental development of hot dry rock energy systems of several kinds in local situations representative of very large geothermal energy resources of several important types.

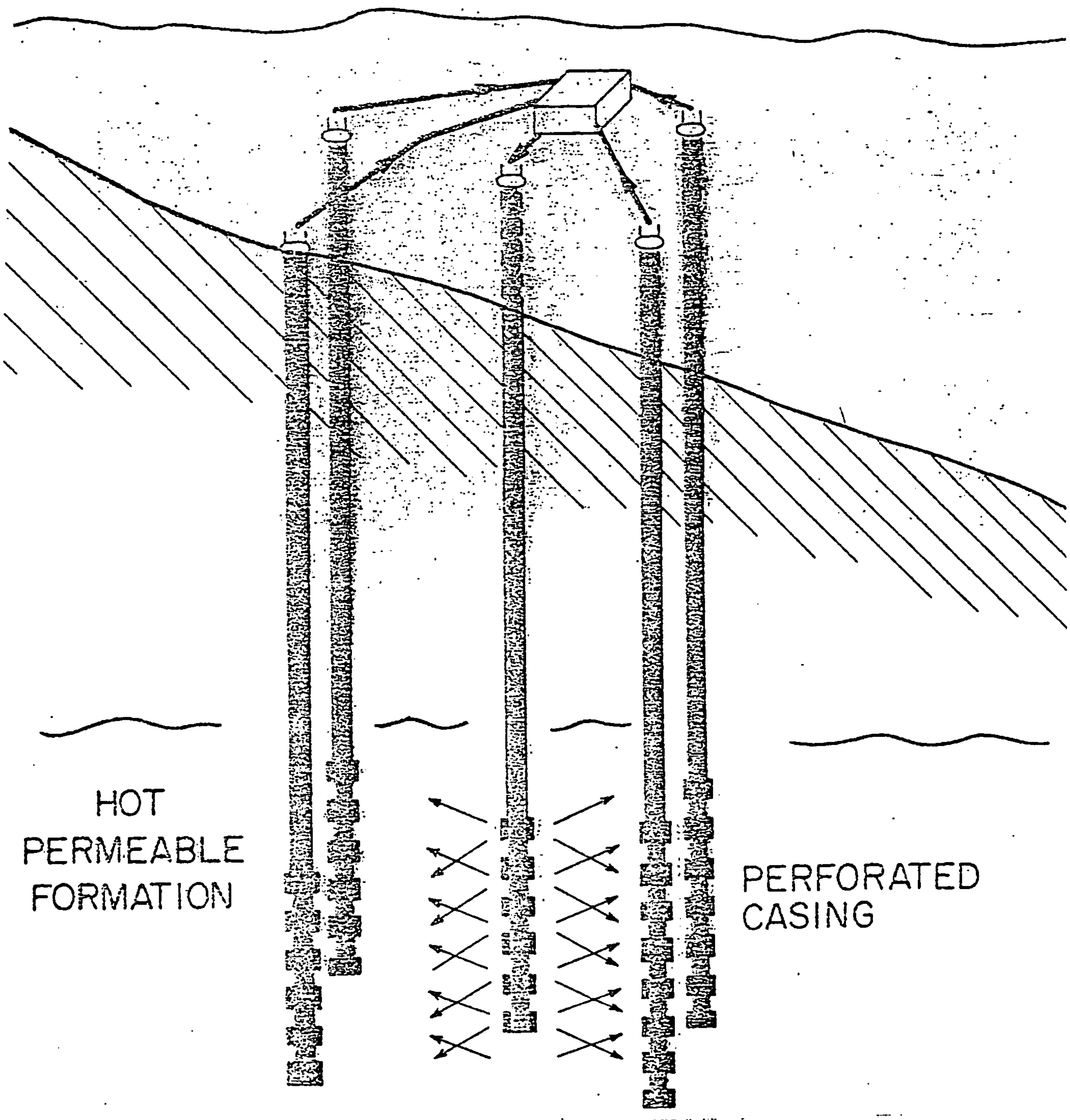


Fig. D-15. "Five-spot" hole array for a water-flooding operation.

REFERENCES

1. P. J. Smith, "Towards Universal Geothermal Power," Nature 257, 10-11 1975).

2. J. W. Lund, G. G. Culver, and L. S. Svanevik, "Utilization of Intermediate-Temperature Geothermal Water in Klamath Falls, Oregon," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources (Government Printing Office, Washington, D.C., U S, 1976), pp. 2147-2154.

3. C. F. Austin and G. W. Leonard, "Chemical Explosive Stimulation of Geothermal Wells," in Geothermal Energy, P. Kruger and C. Otte (Eds.) (Stanford University Press, Stanford, California 1973).

4. G. G. Culver and G. M. Reistad, "Evaluation and Design of Downhole Heat Exchangers for Direct Application," Klamath Falls, Oregon, Oregon Institute of Technology report RLO/2429-3 (August 1977).

5. C. H. Jacoby and D. K. Paul, "Gulf Coast Salt Domes as Possible Sources of Geothermal Energy," in Proceedings, Second United Nations Symposium on THe Development and Use of Geothermal Resources (U S Government Printing Office, Washington, D. C., 1976), pp. 1673-1679.

6. University of ,issouri - Rolla, "Design of a Water Jet Drill for Development of Geothermal Resources," Rolla, Missouri, Rock Mechanics & Explosives Research Center report COO-2677-8 (1977).

7. Y. D. Diadkin and Y. M. Pariisky, "Theroetical and Experimental Grounds for Utilization of Dry Rock Geothermal Resources in the Mining Industry," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources (Government Printing Office, Washington, D. C., U S, 1976),pp. 1609-1618.

8. A. S. Batchelor, "Brief Summary of Some Geothermal Related Studies in the United Kingdom," in "Proceedings of the Second NATO-CCMS Information Meeting on Dry Hot Rock Geothermal Energy," Los Alamos Scientific Laboratory report LA-7021-C (November 1977), pp.27-30.

9. J. B. Burnham and D. H. Steward, "Recovery of Geothermal Energy from Hot, Dry Rock with Nuclear Explosives," in Geothermal Energy, P. Kruger and C. Otte, Eds. (Stanford University Press, Stanford, California, 1973).

10. H. J. Ramey, Jr.; P. Kruger, and R. Raghavan, "Explosive Stimulation of Hydrothermal Reservoirs," in Geothermal Energy, P. Kruger and C. Otte, Eds. (Stanford University Press, Stanford, California, 1973). pp.231-249.

11. H. C. H. Armstead, Oral presentation at Second United Nations Symposium on the Development and Use of Geothermal Resources (May 1975).

12. A. Hunsbedt, A. L. London, and P. Kruger, "Laboratory Studies of Stimulated Geothermal Reservoirs," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources (U S Government Printing Office, Washington, D.C., 1976), pp. 1663-1671.

13. G. M. Sandquist and G. A. Whan, "Environmental Aspects of Nuclear Stimulation," in Geothermal Energy, P. Kruger and C. Otte, Eds. (Stanford University Press, Stanford, California, 1973), pp. 293-313.

14. J. Bernard and J. F. Evano, "Specification of a Model Applicable to Offshore Geothermal Sources with Nuclear Fracturing," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources (U S Government Printing Office, Washington, D.C., 1976), pp. 1554-1558.

15. B. C. Haimson, C. M. Kim, and T. M. Tharp, "Tensile and Compressive Cyclic Stresses in Rock," in New Horizons in Rock Mechanics (American Society of Civil Engineers, New York, 1973), p. 748.

16. H. C. H. Armstead, personal communication, February 1978.

17. M. C. Smith, R. L. Aamodt, R. M. Potter, and D. W. Brown, "Man-Made Geothermal Reservoirs," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources (U S Government Printing Office, Washington, D.C., 1976), pp. 1781-1787.

18. D. V. Power, C. L. Schuster, R. Hay, and J. Twombley, "Detection of Hydraulic Fracture Orientation and Dimensions in Cased Wells," J. Petr. Tech. 28, 1116-1124 (September 1976).

19. R. L. Aamodt, "Pressure-Flow Behavior of the Fracture System," in "Proceedings of the Second NATO-CCMS Information Meeting on Dry Hot Rock Geothermal Energy," Los Alamos Scientific Laboratory report LA-7021-C (November 1977), pp. 44-45..

20. S. Nemat-Nasser, "Geothermal Energy: Heat Extraction fro Hot Dry Rock Masses," J. Pressure Vessel Tech. 99, 612-613 (1977).

21. H. D. Murphy and R. D. McFarland, "System Models," in "Proceedings of the Second NATO-CCMS Information Meeting on Dry Hot Rock Geothermal Energy," Los Alamos Scientific Laboratory report LA-7021-C (November 1977), pp. 63-64.

22. C. S. Robinson, R. M. Potter, B. B. McInteer, J. C. Rowley, D. E. Armstrong, R. L. Mills, and M. C. Smith, "A Preliminary Study of the Nuclear Subterrene," Los Alamos Scientific Laboratory report LA-4547 (April 1971).

23. F. Harlow and W. Pracht, "A Theoretical Study of Geothermal Energy Extraction," J. Geophys. Res., 77, 7038 (1972).

24. I. T. Aladiev, V. P. Trusov, A. D. Peredery, E. M. Strigin, E. V. Saperov, and V. K. Fardzinov, "Heat and Mass Transfer Processes in Aquifer Systems with Artificially Increased Fracturing," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources (U S Government Printing Office, Washington, D.C., 1976), pp. 1529-1535.

25. M. Smith, R. Potter, D. Brown, and R. L. Aamodt, "Induction and Growth of Fractures in Hot Rock," in Geothermal Energy, P. Kruger and C. Otte, Eds. (Stanford University Press, Stanford, California, 1973), pp. 251-268.

26. P. L. Ernst, "Exploitation of Geothermal Energy in Germany," to be published in PAGEOPH (1978).

27. G. Bodvarsson and G. M. Reistad, "Econometric Analysis of Forced Geoheat Recovery for Low-Temperature Uses in the Pacific Northwest," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources (U S Government Printing Office, Washington, D.C., 1976), pp.1559-1564.

28. J. R. McNitt, "The United Nations' Approach to Geothermal Resources Assessment," in Geothermal Resource Assessment and Reservoir Engineering, (ENEL Direzione Studi e Ricerche, Rome, Italy, 1977), pp. 328-350.

29. G. Bodvarsson, "A Secondary Recovery Method for the Extraction of Geothermal Energy," Corvallis, Oregon, Oregon State University report RLO-2227-T21-1 (July 1976).

APPENDIX E

THE NATURES AND LOCATIONS OF POTENTIAL HDR DEVELOPMENT SITES

I. INTRODUCTION

If the technologic development of hot dry rock energy systems is successful, it is hoped that they will be economically useful in many places to produce heat either for direct use, for generating electricity, or both. In principle, heat from this source is accessible from any point on the earth's surface. However, there are both generic and site-dependent constraints on its universal usefulness, many of which can be defined only from the results of large-scale field experiments. In this regard, the following parameters are particularly important, both individually and in their mutual interactions.

A. Hydrogeologic Environment

The combination of geology, hydrology, and local heat flow determines to what depth a hole must be drilled to reach any required temperature, and the difficulty and cost of drilling to that depth. More than anything else, the physical characteristics of the hot depth. More than anything else, the physical characteristics of the hot formation determine what method of heat extraction may be effective in removing heat from it--whether buoyant circulation through man-made fractures, forced circulation through natural or created permeability, water-flooding, or some other method. Its chemical and mineralogical compositions largely control the magnitude and difficulty of the corrosion and scaling problems that can be expected in recovering the heat. If the initial permeability of the formation is insufficient, the appropriate method of increasing it--hydraulic fracturing, explosive fracturing, selective chemical attack, or some combination of these or other techniques--will be determined jointly by its physical and its mineralogical nature. Finally, where the geothermal gradient is low, formations are cavernous or poorly consolidated, mineral solubilities are high, faulting is active, or permeabilities are large, the extraction of geothermal energy may prove to be impractical because of drilling depth or difficulty, corrosion or scaling problems, seismic risk, or excessive water loss. The questions raised by these variables are crucial with regard to the probable success of a hot dry rock system at any given location, and in general they can be answered only through field experiments in a wide variety of geologic situations.

B. Geographic Location

Demographic, political, and climatological characteristics, together with local traditions and industrial and employment patterns, strongly affect the quality, quantity, and load-factor of the thermal-energy requirement in any given locality. These variables, interacting with the characteristics of the subsurface geology and the availability of water and of distribution systems, strongly affect the type of geothermal development that may be attractive there. At this point, the probability that local market requirements for energy can be satisfied wholly or in part by hot dry rock systems can be established only by field experiments in a variety of braodly distributed geographic locations.

C. Technology, Unit Cost, and Environmental Acceptability

Commercial development of a hot dry rock system will not be undertaken at any location until the potential developer is confident that a practical technology exists to create a system there, that energy from it can satisfy an existing need, that the unit cost of the energy that it produces will be at least competitive with that of energy from other available sources, and that it can be constructed and operated within the constraints of the community's air- and water-quality standards and other environmental and siting regulations. To establish the degree of confidence needed to make investment in such a system become attractive at a particular location will require that at least one--and probably more than one--comparable system has been developed and operated successfully in a closely similar situation. Some degree of redundancy in the development of hot dry rock systems should be accepted, particularly in the demonstration phases of the HDR program.

To examine all of these variables rigorously would require the creation and operation of an unreasonably large number of experimental, pilot, and demonstration systems. Because the cost of each such system is high in money, time, and effort, it is important to estimate what minimum number of systems will be required to develop both the information and the credibility required to attract the initial commercial investments in hot dry rock energy sources. One approach to making this estimate is through consideration of the local geology of areas in which geothermal energy might be immediately useful.

II. NATURE AND DISTRIBUTION OF HOT DRY ROCKS

Occurrences of naturally heated crustal rock at usefully high temperatures and accessible depths can be classified in many different ways. Because they interact so strongly with the method and cost of extracting heat, the variables of permeability and burial depth of the hot rocks offer a basis of classification that is particularly useful to this discussion. Such a classification is attempted in Table E-I, and is elaborated in the paragraphs that follow.

A. Very Low Permeability Formations

As is discussed in Appendix D, where the initial permeability of the hot rock is very low (for example, less than one millidarcy) the extraction of heat from it will depend upon the creation of flow channels and heat-transfer surface around the borehole by some means such as hydraulic fracturing, explosive fragmentation, or solution or water-jet mining. Nearly impermeable hot rocks of many types exist in nature, at a variety of burial depths, among which are the following.

1. Crystalline Intrusives and Glassy Extrusives, Thermally Metamorphosed Country Rock Associated with Them, and Regionally Metamorphosed Rock in Areas Where Mountain Building Has Occurred. Examples include granites, rhyolites, gabbros, basalts, gneisses, and schists. These may occur at or near the surface or deeply buried beneath it.

a. At or Near the Earth's Surface.

- In areas of active or geologically recent volcanism, generally in the western third of the United States. Here geothermal gradients are commonly sufficient so that temperatures high enough for generating electricity are likely to be encountered at shallow to moderate depths (of the order of 1 - 3 km). Because such areas are often remote from population centers and because electricity is economically transportable over long distances whereas heat as such is not, thermal reservoirs of this type would probably be used chiefly for electrical generation.
- In older areas of silicic batholith formation, where normal heat flow may be supplemented significantly by the internal heating that results from decay in situ of naturally occurring unstable isotopes,

Table E-1

FIG. 1

HOT DRY ROCK RESERVOIR TYPES
CLASSIFIED BY TYPE OF PERMEABILITY

Permeability	Rock Type	Depth	Geologic Setting	Typical Occurrences
Very Low	Crystalline or Volcanic	Shallow	Area of recent volcanism Ancient volcanism, high internal heating Ancient volcanism, low internal heating Exposed plutonic and metamorphic rocks	Jemez Mtns., Mt. Hood Conway granite Adirondack Mountains Canadian shield
		Deep	Pluton or batholith Buried "basement"	Eastern Coastal Plain Northwestern Nebraska
	Massive Sedimentary	Any	Deep basin or Great Plains	Indiana Basin, Permian Basin
	Evaporite	Any	Salt domes and beds	Louisana, Kansas
Low But Significant, Few Large Fractures	Crystalline	Any	Finely fractured by recent tectonism	Eastern Sierra Nevada
	Volcanic	Any	Porous basalts and ash-flow tuffs	Hawaii, New Mexico
	Metamorphic	Any	Near recent intrusive rock	Central Utah
	Sedimentary	Deep	Region of high heat flow	Imperial Valley
Permeable Layer in or Between Very Low Permeability Formations	Any	Any	Brecciated fault zones	Central California
	Crystalline or Volcanic	Any	Contact with country rock	Columbia Plateau
	Sedimentary	Deep	Thinly bedded sandstone or conglomerate	Gulf Coastal Plain
Low Matrix, Some Large Fractures	Crystalline	Any	Region of active or recent faulting	Southwestern Utah
High	Any	Any	Porous lens or bed	Wyoming, Gulf Coast

chiefly of uranium and thorium. This occurs, for example, in some of the granites of New England. Here, because geothermal gradients are generally lower than in areas recently active, the choice will usually be between relatively shallow development to produce heat for direct use or much deeper systems to achieve temperatures sufficient for generating electricity.

- In exposed "basement" rock, such as the Canadian shield in the northcentral United States. Here the geothermal gradient is normally too low to be interesting for development except as a possible future source of very low-grade heat.

b. <u>Deeply Buried.</u> Unless there has been active circulation of ground water to great depth, the combination of normal heat flow and the insulation provided by overlying layers of poorly conductive sedimentary and volcanic rocks can be expected to produce relatively high temperatures in igneous and metamorphic rocks at attainable drilling depths (for example, 3 - 6 km). Two types of geothermal reservoirs of this nature are of particular interest.

- Plutons, such as those underlying the coastal plain of the eastern United States, in which conductive heat flow from the lower crust and mantle may be supplemented significantly by the internal heat generation that results from the *in situ* decay of unstable isotopes.

- Buried "basement" rocks in regions of above-normal heat flow. These are commonly the upper sections of eroded Precambrian granites, in which little radiogenic heating is expected. There are, however, broad areas in which (for reasons that are not well understood) regional heat flow is high--for example, in a wide band across the northern Great Plains. Here, beneath the insulating sediments, relatively high basement-rock temperatures may occur at moderate depths.

2. <u>Dense, Massive, Unfractured, Sedimentary Rocks of Almost Any Type.</u> Most sedimentary deposits have thermal conductivities sufficiently lower than those of dense crystalline rocks so that, at the same heat flow, geothermal

gradients through them are significantly higher. Further, although it seems not to have been generally recognized, the concentrations of unstable isotopes in certain sandstones, shales, and coals, are much greater than in granites, and the probability of significant internal heat generation is correspondingly greater. In many of the sedimentary basins of the Midwest, Great Plains, Gulf Coast, and Basin-and-Range Province, high temperatures have been observed at moderate depths in holes drilled in the course of petroleum and natural-gas explorations. Where such holes have been unproductive of hydrocarbons, the possibility of development for geothermal energy obviously exists.

3. Salt Domes. Hundreds of salt domes (diapirs) are known to exist along the Gulf Coast, in which heat flow is reported typically to be of the order of 4 - 7 times normal (Ref. 1). Although the thermal conductivity of the salt composing such domes is also very high, the geothermal gradients in them are of the order of twice normal, and they are therefore attractive as potential sources of geothermal energy.[1] Several possible methods of extracting heat from them are discussed in Appendix D, all of which depend upon circulating a fluid within a large cavity mined in the salt dome by dissolving the salt locally in water.

B. Formations Having Low but Significant Permeability

Where the permeability of the hot rock is too low to permit the buoyant circulation involved in formation of a productive natural hydrothermal system, it may still be high enough (for example, a few millidarcies) so that fluid losses from hot dry rock systems of the type considered above would be excessive. As is discussed in Appendix D, there are several alternative development methods which might be useful for energy extraction in this circumstance, including stimulation by chemical or mechanical methods and pressurized circulation between parallel hydraulic fractures. "Matrix" permeabilities in this range, not significantly supplemented by large natural fractures, are sometimes observed both in metamorphic basement rock and in deeply buried sediments such as graywackes and cemented sandstones. It is possible that they may also be found in breccias, old basalt flows, zeolitic zones, welded tuffs, and finely fractured rocks of any type in regions of geologically recent faulting or earthquake activity.

C. Permeable Layers Within Very Low Permeability Formations

There are several siturations in which relatively thin, essentially two-dimensional, permeable zones are known to exist within or between formations whose permeabilities otherwise are very low. One obvious case is a brecciated zone along a fault. Another is a thin bed of porous sandstone between layers of shale. A third is a layer of conglomerate along an eroded basement-rock surface, itself covered by a bed of shale or massive limestone. A fourth is a zone of thermal contraction or thermal-stress cracking which may exist along the contact between an intrusive such as granite or an extrusive such as basalt and the initially cooler country rock which it has penetrated or covered. In any such case, if rock temperatures are high and the natural supply of water is inadequate to produce or to maintain a hydrothermal system, the possibility exists of extracting heat by forcing water through the permeable zone. (This is the "Forced Geoheat Recovery" system described by Bodvarsson[2] and discussed in Appendix D.)

D. Low Matrix Permeability, Some Large Fractures

This is the typical geological situation in most of the world's natural hydrothermal "reservoirs," with the exception of a few very large ones in sedimentary basins. The fractures are normally associated with geologically recent fault activity and their population density varies widely, often decreasing rapidly with distance from a major fault zone. In developing or extending a steam or hot-water reservoir of this type, it is normal for some of the drilled holes to be dry simply because they have not encountered a major fracture. They can often be made productive by a stimulation treatment as straightforward as sidetracking and redrilling the lower part of the hole until such a fracture is intersected, although other stimulation methods, such as hydraulic fracturing, are of course also possible. In general, development of an HDR system in this environment would be considered only if stimulation techniques had already been tried and had not been successful.

E. Highly Permeable Formations

At the depths at which temperatures of geothermal interest are reached, a highly permeable formation is normally saturated with water and is therefore more likely to be a hydrothermal than a hot dry rock reservoir. However, unsaturated permeable beds of considerable horizontal and vertical extent may occasionally be encountered, as is indicated for example by the rather common occurrence of "perched" water tables in which a productive aquifer is separated by an impermeable layer from an essentially dry, permeable formation beneath it. The typical case is a bed or lens of sandstone with less-permeable sedimentary formations above and below it. It may, however also occur in layered volcanic rocks such as flood basalts and ash-flow tuffs, and is the extension into three dimensions of the essentially two-dimensional situation discussed in Sec. C, above. From a thick, hot, highly permeable formation, energy extraction on a very large scale should be possible by the use of an array of holes and a water-flooding system similar to those developed for the secondary recovery of petroleum.

III. GEOGRAPHIC LOCATION

The variety of geologic environments discussed above and of heat-extraction systems appropriate to them (Appendix D) indicates both the requirement for extensive field experiments at a large number of locations and the need for thoughtful selection of these locations so that, as far as possible, each is representative of a type of energy resource large enough to be of potential commercial interest. The site-selection process must therefore be a major component of the early years of the Federal Hot Dry Rock Program, and it should of course take into account the characteristics of the local market for energy and the quantity and quality of the heat required to supply that market.

Except at Fenton Hill, New Mexico, where energy extraction investigations are already well advanced, the selection of specific locations for development of experimental systems (and perhaps eventually of pilot and demonstration plants) must await the results of this site-selection process. However, enough is already known from the general literature of geology, hydrology, and terrestrial heat flow, from other geothermal programs, and from HDR investigations now in progress, so that a few generalizations are possible concerning areas which probably will deserve special attention in the near future.

At Fenton Hill, the use of hydraulic fracturing is now being investigated for creation of an energy extraction loop in a granitic intrusive rock of very low initial permeability. It is believed that a similar geologic environment, in which this method of system development may also be useful, will be found in many promising geothermal areas in the Rocky Mountains, the Basin-and-Range Province, the Pacific Coast Ranges, and southern Alaska.

Of particular current interest in this regard are the Coconino Plateau of northwestern Arizona as a possible site for a relatively high-temperature HDR system and the Mt. Hood area near Portland, Oregon, for development as an energy supply either for generating electricity or for direct use as heat, or both.

The granites of New England can probably also be developed by hydraulic fracturing. Here the Conway granite of New Hampshire, in which normal heat flow may be significantly supplemented by in situ radiogenic heating, is of special interest.

A series of buried plutons has been discovered under the Atlantic coastal plain near such cities as Savannah, Georgia; Charleston, South Carolina; Wilmington, North Carolina; and Ocean City, Maryland.[3] In addition to significant internal heat generation, these have the advantage of a thick insulating cover of coastal sediments which has conserved their heat and increased the geothermal gradients above them. If useful hydrothermal systems are not discovered in the overlying sediments, hydraulic fracturing may be a suitable method of developing energy extraction loops in the plutons themselves.

Relatively intense geothermal anomalies near Buffalo and Syracuse, New York, are now being investigated, and may also result from the presence of buried plutons. Their proximity to major population centers makes them attractive for detailed study in the near future.

Areas of abnormally high heat flow have been identified at many locations in the sedimentary basins of the midwest and in the Great Plains states. Exploration in such areas may discover productive hydrothermal systems or may identify hot dry rock of any of several types: massive sedimentary formations or buried basement rock requiring fracturing to permit fluid circulation; "tight" sedimentary beds in which either forced circulation or chemical attack to increase permeability would be required; or thick, permeable formation from which large amounts of heat could be extracted by water-flooding operations. Of particular interest in this general type of geology are anomalous areas near such cities as Indianapolis, Indiana; Moline, Illinois; and Dallas, Texas; along the borders between Iowa and Nebraska, Nebraska and South Dakota, and Montana and North Dakota; and in the oil-shale areas of northern Colorado and southern Wyoming.

Many of the salt domes under the Gulf Coastal Plain show high geothermal gradients, and investigations of heat extraction by circulation of brine through solution-mined cavities would clearly be desirable. Several areas in eastern Texas and western Louisiana have both numerous salt domes and relatively high regional heat flow, and so are of immediate interest.

Particularly in the flood basalts along the Columbia and Snake Rivers in Oregon and Idaho, there are attractive possibilities for recovery of low-grade geothermal energy by forced circulation of water through permeable zones between successive basalt flows or along the contacts of steeply dipping dikes that have penetrated them.

Recent deep drilling in the Imperial Valley of California has shown that at least in some areas the sediments which normally produce concentrated brines are underlain by hot rock of low but appreciable permeability (of the order of a few millidarcies). Here forced circulation between parallel hydraulic fractures may represent a practical heat-extraction method, if it does not interact with the tectonic stress field in the area in such a way as to increase the seismic risk.

On the basis of information that is already available, a large number of additional areas could be listed here which appear to deserve detailed investigation on the bases of technical interest and of geographic location. It is evident that the initial major difficulty in the selection of areas for detailed characterization, and then of specific sites for field experiments, will not be the problem of finding locations that merit such investigations. Instead it will be the question of choosing from a long list of excellent candidates the few representative areas that should be examined first. To a considerable degree, this choice will undoubtedly be based on the proximity and interest of potential users of geothermal heat.

REFERENCES

1. C. H. Jacoby and D. K. Paul, "Gulf Coast Salt Domes as Possible Sources of Geothermal Energy," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, (U.S. Government Printing Office, Washington, D.C., 1976), pp. 1673-1679.

2. G. Bodvarsson and G. M. Reistad, "Econometric Analysis of Forced Geoheat Recovery for Low-Temperature Uses in the Pacific Northwest," in Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, (U.S. Government Printing Office, Washington, D.C., 1976), pp. 1559-1564.

3. J. K. Costain, L. Glover III, and A. K. Sinha, "Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States," Virginia Polytechnic Institute and State University report VPI-SU-5103-3 (1977).

APPENDIX F

DETERMINATION OF RESOURCE POTENTIAL

Two goals must be achieved to insure that hot dry rock geothermal energy can be a substantial alternative energy source. First, extraction techniques must be developed for extracting the energy economically from hot rock which does not exhibit sufficient permeability for the formation of natural hydrothermal systems. Second, HDR potential must be shown to have a wide distribution in a variety of geographic and geologic settings. Only when these goals have been reached is industry likely to move into the field of HDR energy extraction.

It is thus imperative that reliable estimates of the magnitude, location, and depth of the hot dry rock be obtained as rapidly as possible. The staff of the Federal Hot Dry Rock Program is dedicated to achieving this goal, utilizing the expertise of the USGS and LASL, and relying on data from a variety of additional sources, including other DOE/DGE-funded geothermal programs. In particular, data generated by the State Co-op, Industry-Coupled, and Precommercial DOE Programs will be of great benefit to this resource evaluation. Valuable data will also undoubtedly be contributed by the regional hydrothermal-resource assessments now being made under DOE sponsorship.

Evaluation of the magnitude and nature of HDR must be considered as consisting of two major activities. The first entails generation of accurate, detailed, geothermal-gradient maps of the entire United States. Such maps are clearly necessary to estimate rock temperatures existing at any drilling depth determined to be potentially economic at a particular time. This activity must be given initial consideration because the occurrence of sufficiently high heat content in the rocks is fundamental for any useful geothermal resource. The second activity is an evaluation of the permeability and fluid content of the potential reservoir rock. This evaluation may well be the most difficult part of the task, and the part most subject to error.

A number of techniques can be used to provide direct or indirect evidence of the temperature at depth. The most unequivocal of these is the actual measurement of temperature in deep boreholes at depths below those at which hydrologic perturbations occur. Even this technique is fraught with problems, however. Deep boreholes are not randomly distributed throughout the U.S.; for the most part they have been drilled for oil or gas production, and therefore they are generally concentrated in the deep sedimentary basins. Often the measurement of temperature in them has been only incidental, with little care being taken, causing many measurements to be grossly in error. Hydrologic perturbations were frequently not recognized and, in most cases, thermal equilibrium was not attained before the measurement was made. Holes drilled specifically for gradient or heat-flow measurements are usually shallow, and may be subject to unknown hydrologic disturbances.

Less-direct evaluations of the variation of temperature with depth can be made from Curie-point-depth determinations, measurements of seismic-wave attenuation, chemical geothermometers (SiO_2 and Na-K-Ca), geoelectromagnetic measurements, and the presence of young volcanic rocks. The results of these measurements may be combined with traditional field geology, tectonics, and geophysics (gravity, aeromagnetics) to interpret, evaluate, and extrapolate the limited gradient data in order to generate the required maps.

Large numbers of temperature measurements have been made in deep oil and gas wells. These data have been compiled by the American Association of Petroleum Geologists and the USGS into a gradient map of the U.S. and, although the data may contain many errors, this map serves as a good starting point for a determination of the distribution of HDR. LASL is currently combining these gradient data with estimates of the depth to basement, basement lithology, and estimated thermal conductivities to obtain estimates of the temperature at any selected location and depth. Preliminary maps have been generated for depths of 3, 6, 9, and 10 km. The computer program used to generate these maps is now being refined, and other types of data will be incorporated into the program.

Geophysical, geological, and geochemical data needed for determining the potential of HDR are widely dispersed in U.S. and State Government reports, in professional journals, and in company files. Industrial subcontractors will be used to compile all available nonproprietary data and generate maps of the U.S. at a scale of 1:5 000 000. Initially this effort will concentrate on gravity, geoelectromagnetic, and aeromagnetic data. Later, compilations of heat-flow, geochronologic, seismic-attenuation, and tectonic data will be made and published as maps.

These maps will aid in extrapolating the limited gradient data to those areas for which data are not available. In some cases, they will also delineate areas or provinces of higher-than-normal gradient.

As mentioned above, the evaluation of the permeability and fluid content of the potential reservoir rocks is probably the more difficult of the two major activities. Despite evidence from the drilling of geothermal systems and deep petroleum reservoirs, and observations made in deep mines, considerable controversy exists as to the nature and magnitude of permeability in hot crustal rocks. It has been well demonstrated that, despite the best efforts to avoid it, dry wells do occur in essentially all known hydrothermal fields. It is also well known that many deep mines are dry as well as hot. This would imply that hot, impermeable rock is relatively common in the upper crust. Naturally productive geothermal wells, however, demonstrate that some types of permeability do exist in hot rock at some depths and locations. Criteria must be developed that permit the prediction and evaluation of this permeability.

We have adopted a working hypothesis that except in areas of moderate to high seismic activity, rock hot enough to be exploitable will seal itself in time by a variety of physical and chemical processes. These processes, which include thermal creep, rock alteration, and fracture filling, eventually produce an essentially impermeable reservoir. Only when a geothermal reservoir is very young or is in a seismically active region is it likely to be sufficiently permeable to allow the development of a natural geothermal system.

In FY79, LASL will begin an examination of geological, geochemical, and geophysical techniques for testing this hypothesis. Geoelectromagnetic and seismic methods appear to offer the greatest potential for recognizing these sealed reservoirs.

Another parameter requiring examination during an evaluation of HDR potential is the orientation of the existing stress field in the reservoir rock. Orientation of artificially produced hydraulic fractures is primarily controlled by the orientation of the stress field. If this orientation can be accurately predicted, uncertainties and costs of engineering an HDR system can be significantly reduced, thereby helping to make this energy source competitive with other energy sources. During FY79, all available information on the orientation of stress fields will be compiled and displayed on maps of regional tectonics. During FY80 and 81, new stress measurements will be made, both on the surface and downhole. These data will be used to update the stress-field maps and to predict the orientation of the field at the new sites chosen for drilling.

APPENDIX G

SITE SELECTION

A critical element within the Federal Hot Dry Rock Plan is the identification of additional sites for evaluating methods of geothermal energy extraction. Normally, site-selection or exploration programs, for whatever resource, are controlled both by the expected geological and geophysical parameters and by a complex group of economic, environmental, and institutional factors. Exploration for HDR is similarly controlled, but additional constraints are imposed by the fact that we are searching for a new type of energy resource, not presently under commercial development and whose economic viability remains to be demonstrated. To encourage this development, confidence in the resource must be developed in the potential user. Extraordinary care is required to ensure that successful sites are chosen initially, in order to generate this confidence as rapidly as possible.

Before discussing the geological and geophysical criteria for site selection, it is pertinent to review the economic, environmental, and institutional factors and the other constraints that influence the exploration program. First, the value of any resource is controlled by many factors, such as the price of alternatives, the cost of extraction, grade or quality, and size of deposit, proximity of a user, tax incentives, etc. All of these factors will eventually influence the value of an HDR resource. In designing an exploration program for HDR we have assumed that if the reservoir temperature is sufficiently high for electrical generation, then the location of the site is relatively less important, because power-line networks are usually not far away. However, if reservoir temperatures are only sufficiently high for direct utilization, then the proximity of a user becomes critical and large sparsely populated areas of the country may be eliminated from consideration at the present time. In the future, however, as confidence in HDR grows, users may move to the resource, removing this constraint.

Land ownership will undoubtedly play an important part in site selection, particularly in the final stages when an actual drill site is chosen. It will probably be much easier to obtain permits for drilling on Federal than on private lands, although the time required for permitting may still be long. Exploration may also be severely restricted on certain Federal lands such as

National Parks and Monuments, dictating change in the most geologically effective program. These subjects are discussed in greater detail in Appendix J.

Because at this time the existence of HDR has been demonstrated at only one site, the most effective techniques for exploration for it are yet to be determined. However, based on experience in mining and oil exploration, certain techniques appear to have potential. These techniques can be evaluated only by application and eventual confirmation by drilling. We are thus constrained to test as many geological, geophysical, and geochemical exploration techniques as possible, with the goal of determining the most cost-effective assemblage. This is particularly true in the case of lower-temperature resources for direct utilization, where the value of the resource is relatively low. The mutual reinforcement of positive indications by the various techniques will be emphasized.

A further constraint is imposed by the need to build user confidence. One way to accomplish this is by demonstrating the existence of HDR in a variety of geologic environments (see Appendix E). It is important that our site-selection program be designed to maximize the probability of locating sites in a number of these different environments. Some factors related to geologic variety must be used when developing a priority list for future site selection and assessment.

Exploration for any type of geothermal resource--vapor-dominated, water-dominated, or HDR--and the subsequent selection of a drilling site may be considered a two-step process. First, a heat source is located and then the permeability and fluid content of the potential reservoir are evaluated. Location of a heat source is clearly a necessary but not a sufficient criterion for HDR site selection; low-permeability rock must also be present if current energy extraction techniques are to be used. Higher-permeability, hot, reservoir rocks identified during this work may be suitable as hydrothermal sites, or if of intermediate permeability, they may require modification of the present HDR heat-extraction techniques. Considerable spinoff to other DGE programs should occur thoughout the site-selection process.

Geothermal heat sources may be roughly classified into three types: (1) igneous-related, (2) related to high mantle heat flow, and (3) related to radioactive decay of uranium, thorium, and potassium. Type 1 sources are the result of magmatic intrusions into the shallow crust. The magma in this case has acted as a heat-transfer agent, transporting thermal energy from the mantle to the upper crust where it may be accessible for exploitation. Essentially all of the presently exploited geothermal systems are related to igneous heat sources. The amount of energy transferred by these intrusions to the crustal rocks is a function of their size, shape, depth of emplacement, age, and composition. Large, young plutons of silicic composition emplaced at shallow depth apparently are most effective as heat-transfer agents and yield the highest-grade heat sources. Because there is great variety in intrusion type and composition, it will be necessary to choose several igneous-related sites for evaluation.

Types 2 and 3 heat sources can best be discussed in terms of the reduced heat-flow equation of Birch, Roy, and Decker.[1] These workers noted a linear relationship ($q=q^*+DA$) between heat flow (q) and heat generation (A) in holes drilled in plutonic rocks of New England. In this equation, q^* is the reduced heat flow coming from the mantle, and D is the thickness in kilometers of the radioactive layer. Similar linear relations have been observed in other geologic provinces. Potentially useful heat sources result from high values of either q^* or DA. Type 2 sources result from high mantle heat flow, q^*, and Type 3 from high values of DA.

Large areas of the crust, such as the Battle Mountain High in Nevada and the Rio Grande Rift in New Mexico, are characterized by high values of q^*. Although gradients in these areas are not as high as near magma chambers, the large surface areas affected, when multiplied by reasonable drilling depths, yield huge volumes of hot rock. Their large surface area also means that Type 2 heat sources are more widely distributed (occupy a larger fraction of the land area) than are the igneous-related Type 1 sources.

Heat sources in the eastern U.S. related to radiogenically derived heat offer considerable promise for direct utilization, and perhaps in some cases even for electrical generation. The absence of other alternative energy sources in areas where these geothermal heat sources have been identified makes Type 3 heat sources valuable targets for exploration and site selection.

Site-selection activities are conducted at two scales: regional reconnaissance and detailed exploration. Literature searches are being used to identify large regions or provinces which appear to have high geothermal potential. After these regions are identified, geologic maps are prepared at a scale of 1:62 500 using existing and new data. Particular emphasis is given to the structural geology, age, distribution, and petrology of igneous rocks, and the petrology of potential reservoir rocks. Concurrently, reconnaissance geophysical surveys are run. Depending on previous work done in the area, gravity, MT, or aeromagnetic surveys may be performed. Shallow heat-flow measurements may also be made at this time.

The results of these investigations will be used to construct regional geologic models to be used for evaluation of the HDR geothermal-energy potential. A priority list of sites selected for detailed investigation will be established and presented to the Site-Selection Committee of the Program Development Council (Appendix C) for review and comment. Although final site selection is the responsibility of the Federal Program Manager, it is expected that the Site-Selection Committee will assist in this selection.

It is anticipated that reconnaissance work in progress in FY78 by LASL, USGS, and industrial and academic groups will identify three prospects of sufficiently high potential to warrant detailed investigation in FY79. Each of these prospects will encompass an area of approximately three townships, that is, about 100 square miles. Detailed geological, geophysical, and geochemical investigation will commence at these prospects at the beginning of FY79, with the objective of targeting a drill site within one of the prospects by the end of FY79. Prime subcontractors will be used at two of the locations to develop and implement an exploration and assessment program for the prospect. At the third prospect LASL will serve as the prime contractor, developing and implementing an independent exploration and assessment program. Thus, by the end of FY79, it will be possible to compare and evaluate these three different exploration and assessment philosophies and sets of techniques.

Although the prime subcontractors will be allowed considerable freedom in developing their own exploration and assessment programs, certain tasks must obviously be completed in order to determine whether or not a drilling site can be located within the prospect. These tasks will be specified, as will a short list of required techniques. A list of additional techniques that may be applicable will also be provided to the subcontractor. It is expected that the subcontractor will build his program largely from these lists of techniques, but innovative thinking in the application of new techniques will be encouraged.

The results of the three detailed prospect investigations will be summarized in reports that will be submitted to the Site-Selection Committee for review and consideration as additional HDR sites.

During FY79, and each subsequent year, reconnaissance work will continue in new areas to define new prospects for detailed investigation.

REFERENCE

1. F. Birch, R. F. Roy, and E. R. Decker, "Heat Flow and Thermal History in New York and New England," in Studies of Appalachian Geology: Northern and Maritime, W. White and E-an Zen, Eds., (Interscience, New York, 1968).

APPENDIX H

HDR SITE DEVELOPMENT SCENARIOS

Introduction

To permit accurate scheduling and estimation of funding requirements for the program, it was necessary to perform a detailed analysis of the activities involved in the development of an HDR site. A generic approach was taken for two alternative scenarios: (a) a site upon which an electric generation pilot plant would ultimately be built; and (b) a site whose development would lead to a direct-use thermal pilot plant. The results were taken to apply to any HDR site "n", where $n \geq 2$. Site 1 — the Fenton Hill site — is anomalous, since as the first test site it did not follow the proposed development scenarios, and since it was and continues to be the scene of various types of supporting R&D (instrumentation, equipment, reservoir techniques, etc.).

Terminology and Assumptions

The scenarios analyzed begin (time=o) at the point of selection of a "prospect" — a geographic area about 100 square miles in extent which, from provisional geophysical reconnaissance and socioeconomic data, appears to merit detailed evaluation as a possible locale for an HDR site. Each scenario then leads through a series of activities which culminates in the operation of one of the two types of pilot plant. This series of activities is conveniently subgrouped into four major categories which are appropriately entitled by their respective end-point milestones:

- Prospect Evaluation and Site Selection
- Reservoir Establishment
- Reservoir Assessment
- Pilot Plant Establishment

These activity groups are executed essentially in sequence (with modest overlap on long-lead planning and procurements), positive results in a given group being prerequisite to final commitment to the next group.

In Prospect Evaluation and Site Selection, more localized and area-intensive geological, geochemical, and geophysical studies are conducted which will verify the technical suitability of the locale and aid in identifying specific desirable sites. Parallelling those studies are an analysis of energy markets contained within or proximate to the prospect, and a preliminary assessment of environmental and institutional barriers to site development therein. Given all positive outcomes, the synthesis of these efforts results in selection of a specific site within the prospect.

Reservoir Establishment comprises all the work necessary to create the man-made subterranean heat exchanger of suitable size (surface area) and flow impedance at the selected site. Included are initial exploratory drilling, production drilling, workover and completion operations, downhole fracturing, and evaluative experimentation.

Reservoir Assessment consists of the activities requisite to extracting energy for a period of time and thus defining the key reservoir parameters: life at power level, water requirements, and geofluid chemistry. This group includes design and construction of the surface system, most of which would be usable in conjunction with the pilot plant. The final activity in this group is extraction of a quantity of heat adequate to project reservoir life at the nominal power level.

Pilot Plant Establishment constitutes those activities involved in the design, permit acquisition, construction, activation and checkout of pilot plant of either the direct thermal or electric generation type.

In analyzing the site development scenarios, several important assumptions were made:

(1) Both the electric generation and direct thermal pilot plants extract power from their reservoirs at a nominal 50 MW_t level. The electric pilot plant will thus produce 7-10 MW_e.

(2) Screening of prospects for this initial group of sites will be such that at any selected site:
- a reasonable amount of geophysical knowledge of underlying formations will be available;
- the nature (permeability, compressibility, etc.) of the reservoir formation is such that a twin-well technique will be suitable;
- there is reasonable assurance that no major environmental nor institutional barriers to site development exist;

- if required, an appropriate energy distribution system for the type of pilot plant to be developed is either already in place, or will be provided by the distributor, and no significant portion of such a system will be government funded.

(3) Site development will proceed on a "business-as-usual" basis.

(4) To save time and cost, the first exploratory well will be drilled full diameter for production. The difference in cost from an exploratory "slim" (∿6-1/2-in. cased i.d.) hole is modest, and would render the hole usable — with perhaps some workover — in production of a successfully-established reservoir.

Analysis and Results

Analysis began with the definition of the specific activities in each of the four groups discussed previously. With each activity were associated a range of execution time and cost estimates, expressed as two numerical triplets:

$$(t_o, t_n, t_p)$$

and $$(c_o, c_n, c_p)$$

where the t's are times in months, the c's are costs in constant FY 1979 $K, and the triplets represent respectively "optimistic", "nominal" and "pessimistic" estimates. The estimates were derived from existing data, where possible, by the LASL Hot Dry Rock Project staff working in a modified Delphi mode. Consultation on pilot plant construction data was obtained from a major utility. The "optimistic" times and costs represent the situation where "everything goes right", but not the luxury of a crash program. Likewise, the "pessimistic" times and costs represent a possible string of problems and delays, but not a major catastrophe (e.g., losing a nearly-completed well).

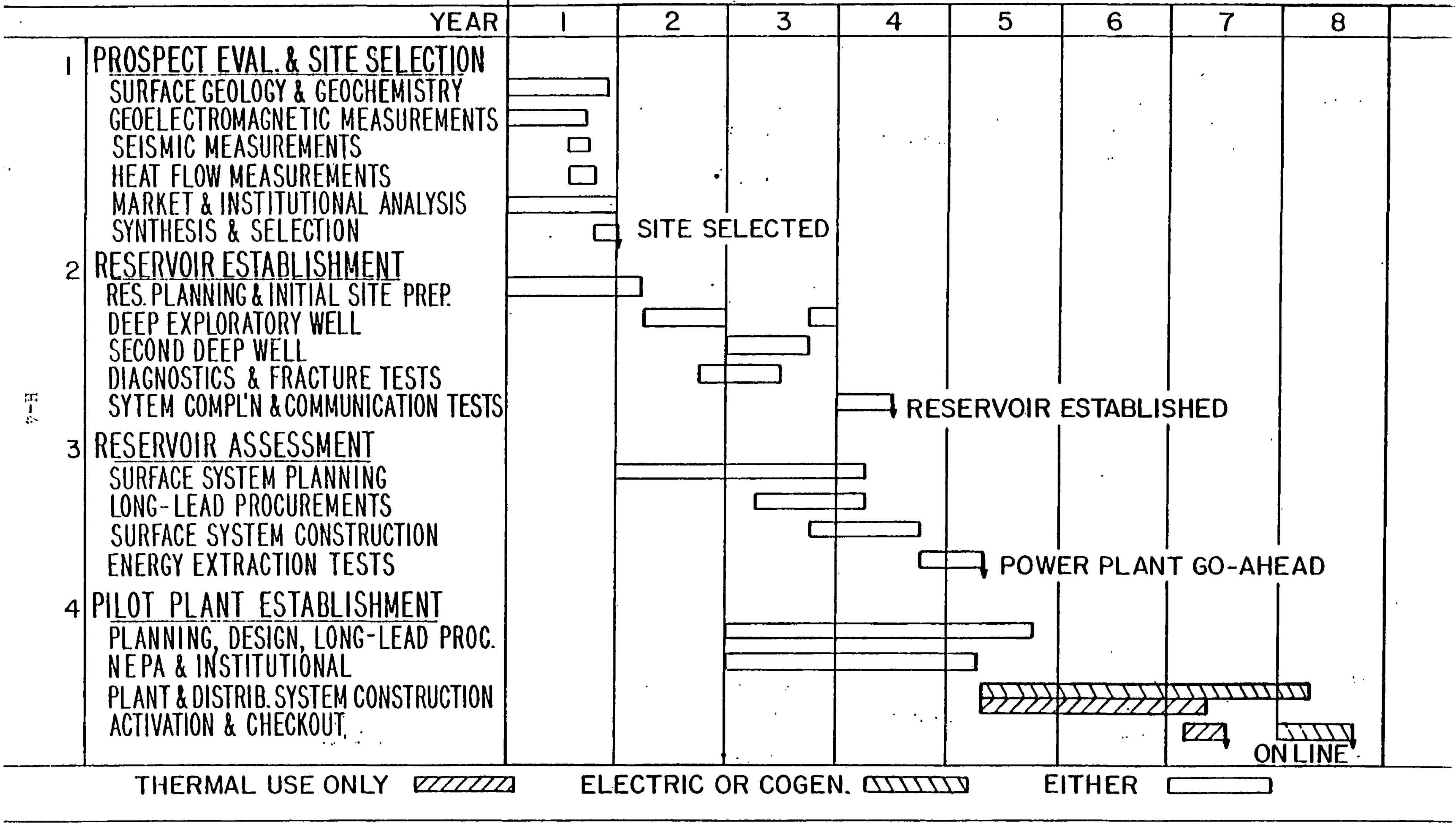
A time-line diagram, presented in Fig. H-1 was then constructed to show the sequencing and interrelationships of these activities. It was determined that, due to commonalities and compensating influences, the time phasing and costs of the two types of sites are essentially the same for the first three groups of activities within the accuracy of this analysis. Significant divergence occurs only in the construction and activation of the pilot plant.

From these relationships, a first-level PERT diagram was constructed as shown in Fig. H-2. The expected (probable) time to each event and the slacks

FIG. II-1

TYPICAL HDR SITE DEVELOPMENT NOMINAL SCHEDULE

(YEARS AFTER SELECTION OF PROSPECT)



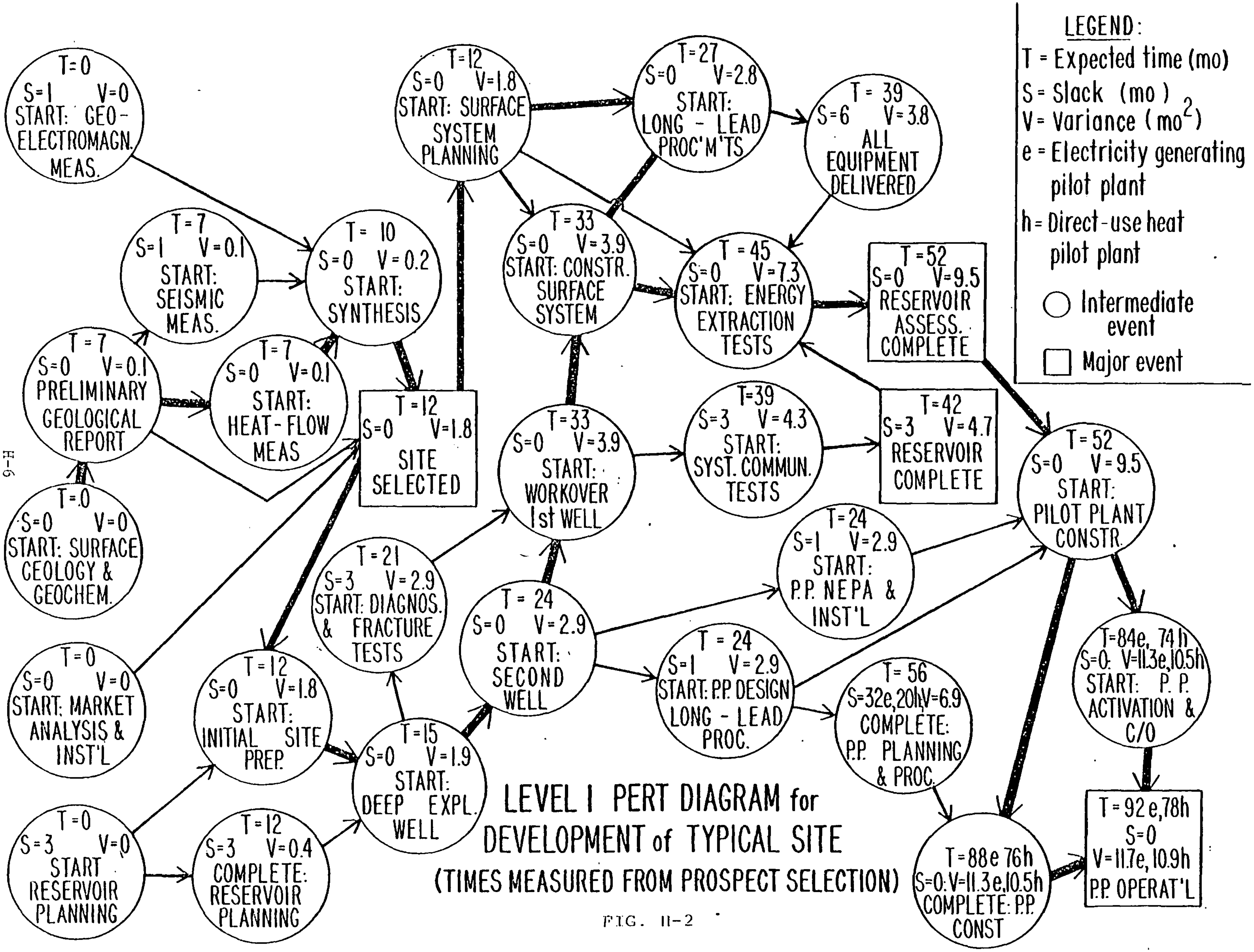
and variances were computed per standard PERT practice. The critical (slack=o) path through the network is shown by the heavy arrows. It should be noted that the critical path is bifurcated at several points, indicating equal schedule criticality in the parallel activities.

The end-to-end time estimate for site development is found in the final "P.P.OPERAT'L" block at the lower right of Fig. H-2. The respective estimates are:

electric (or congeneration) site: 92 months

direct thermal utilization site: 78 months

Corresponding cost estimates were generated from the C-triplet data. All cost computations were carried out in constant FY 1979 dollars. The optimistic-pessimistic spread was assumed to represent roughly a $\pm$ 2σ range. Except in those instances where a lump-sum cost was known to be incurred, costs were assumed to accrue linearly with period of performance. The calculated costs are summarized in Table H-I, in which the expected costs, C_E, are given in \$K and the variances, σ^2, are given in $(\$K)^2 \times 10^{-3}$. The left half of Fig. H-3 shows the annual cost for an electric generation site in bar chart form. The right half of the same figure shows the projected cumulative cost through completion of site development. It can be seen that the expected cost of developing and an electric generation site through the pilot plant stage is about \$28 million in constant dollars. Figure H-4 presents the corresponding information for development of a direct thermal utilization site, for which the expected constant-dollar total cost is \$23 million. The two figures are identical through the fourth year and the \$5 million expected differential is due to the lesser complexity — hence, quicker completion and lower cost — of the thermal pilot plant.



LEVEL I PERT DIAGRAM for DEVELOPMENT of TYPICAL SITE (TIMES MEASURED FROM PROSPECT SELECTION)

FIG. II-2

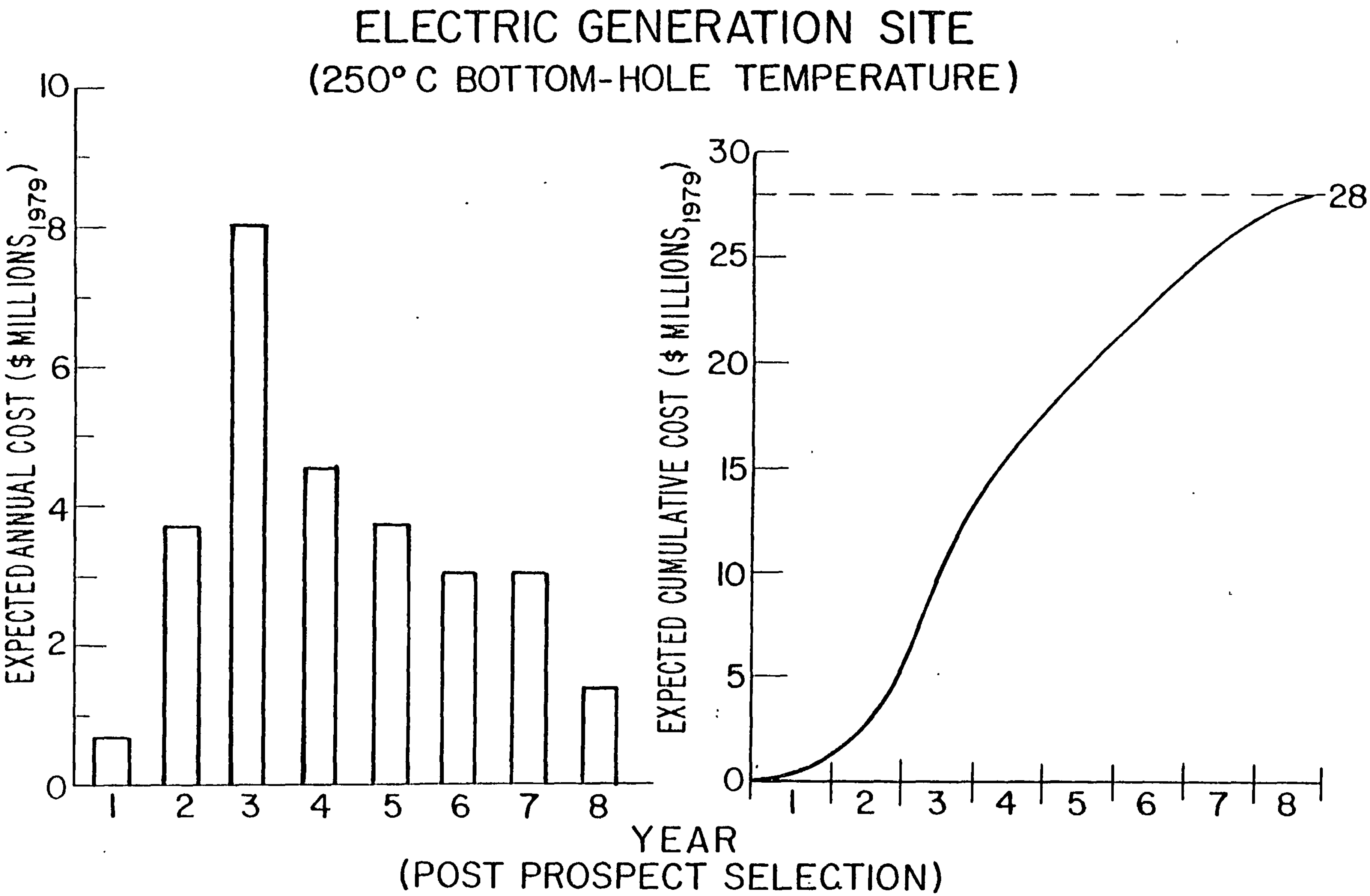
TABLE H-I

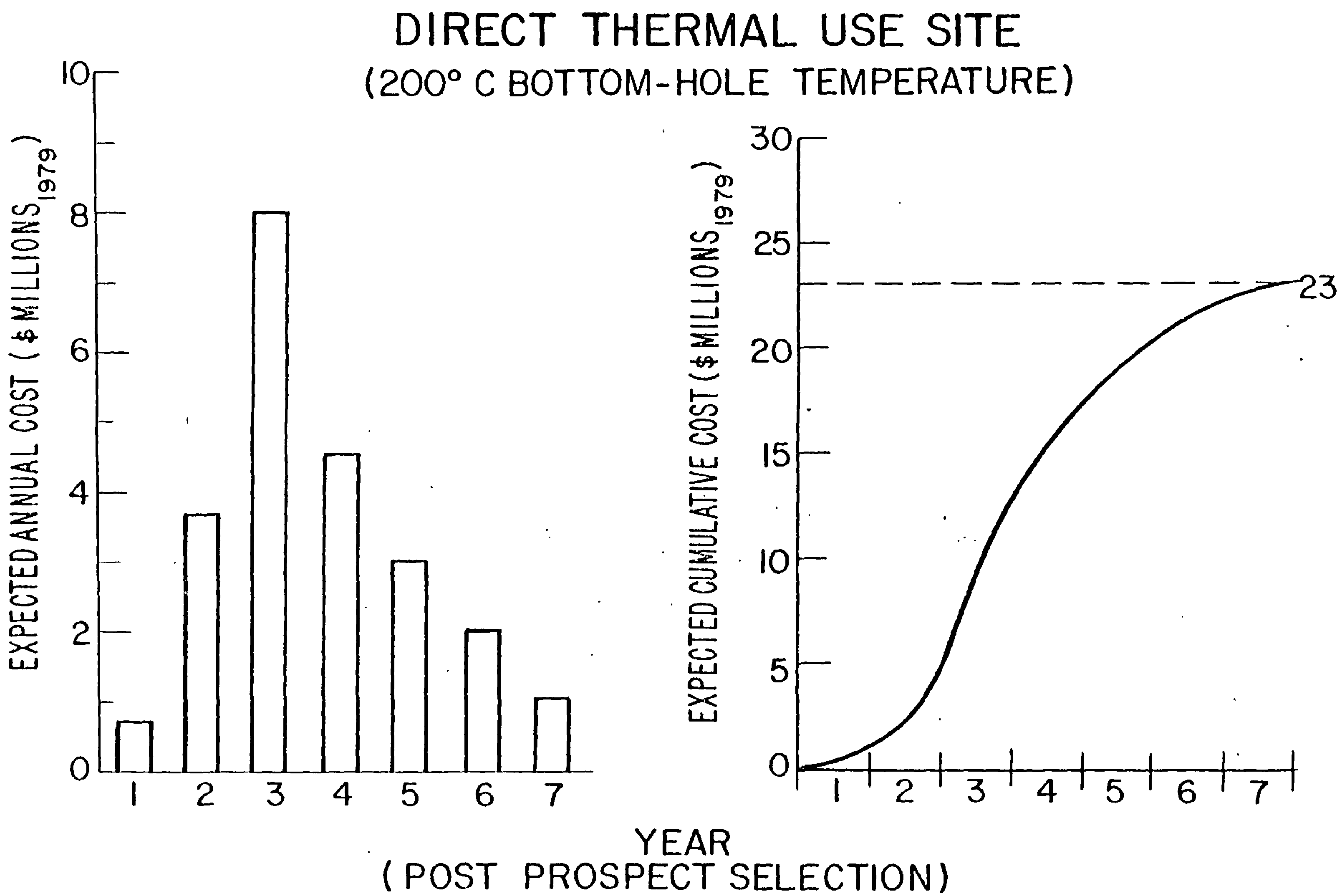
PROJECTED COSTS OF SITE* DEVELOPMENT

(Constant FY1979 Dollars)

Year→ / Activity Group↓	1		2		3		4		5		6		7		8		TOTAL	
	C_E	σ^2	C_E	σ^2	C_E	σ^2	C_E	σ^2	C_E	σ^2	C_E	σ^2	C_E	σ^2	C_E	σ^2	C_E	σ^2
A. Electric Generation Site																		
Prospect Eval./ Site Sel.	600	1.5	0	6.8													600	8.3
Reservoir Establ.	50	0.2	3210	91.9	4440	195.0	700	92.5									8,400	379.6
Reservoir Assessmt.			360	4.5	1450	31.3	1740	54.3	250	17.6							3,800	107.7
Pilot Plant Establ.					1900	68.9	1900	68.9	3200	287.8	2710	333.3	2790	334.6	1200	92.1	13,700	1,185.6
Site Managemt.	50	0.4	130	1.6	210	2.6	210	2.6	250	3.6	290	3.6	210	2.6	150	1.9	1,500	18.9
TOTAL	700	2.1	3700	104.8	8000	297.8	4550	218.3	3700	309.0	3000	336.9	3000	337.2	1350	94.0	28,000	1,700.1
B. Direct Thermal Utilization Site																		
Pilot Plant Establ.					1900	68.9	1900	68.9	2500	136.6	1710	125.0	890	33.7			8,900	433.1
Site Managemt.	50	0.4	130	1.6	210	2.6	210	2.6	250	3.6	290	3.6	160	2.0			1,300	16.4
TOTAL	700	2.1	3700	104.8	8000	297.8	4550	218.3	3000	157.8	2000	128.6	1050	35.7			23,000	945.1

*Applies to Site 2 ET SEQ.


ELECTRIC GENERATION SITE
(250° C BOTTOM-HOLE TEMPERATURE)
EXPECTED ANNUAL COST ($ MILLIONS1979)
EXPECTED CUMULATIVE COST ($ MILLIONS1979)
0
2
4
6
8
10
5
15
20
25
30
28
1
3
7
YEAR
(POST PROSPECT SELECTION)


DIRECT THERMAL USE SITE
(200° C BOTTOM-HOLE TEMPERATURE)
EXPECTED ANNUAL COST ($ MILLIONS$_{1979}$)
0
2
4
6
8
10
1
2
3
4
5
6
7
EXPECTED CUMULATIVE COST ($ MILLIONS$_{1979}$)
0
5
10
15
20
25
30
23
YEAR
(POST PROSPECT SELECTION)

APPENDIX I

INSTRUMENT AND EQUIPMENT DEVELOPMENT

I. INTRODUCTION

Essential to the creation of HDR reservoirs are the abilities to accurately determine and control the geometry of wellbores and to ascertain the size, shape, location, and orientation of fractures. The development of specialized instruments and associated measurement techniques will require design and implementation of remote-sensing equipment that can operate in the severe high-temperature and high-pressure environment of deep geothermal wellbores.

Drilling equipment and well-completion materials are marginal today in wellbores where temperatures approach 200°C. New techniques are required to directionally drill in harder rock and at temperatures ranging from 275 to 300°C, with significantly improved accuracies. Major development efforts in the areas of drill-guidance equipment, coring bits, packers, and sidetracking methods are required, concurrent with improvements in directional-drilling techniques. Several of these developments will require relatively large expenditures and must be coordinated with the planning of future HDR sites.

II. CABLE AND CABLEHEAD ASSEMBLIES

Multiconductor armored well-logging cable is used extensively throughout the oil and natural-gas industry as an instrumentation signal-transmission line. Advanced technology in oil-well drilling has extended borehole depths to about 9 km (30 000 ft). The higher temperatures encountered in the deeper boreholes have demanded advancements in the use of insulating and armoring materials in the design and manufacturing of wire-line cable. The adaptation of Teflon as an electrical insulating material has permitted the use of armored cable for operation in geothermal wellbores where temperatures are around 200°C. However, Teflon materials now available for use in wire-line cables are not capable of continuous operation at temperatures approaching 275°C.

The effects of high-temperature and high-pressure environments on electrical-insulating materials are presently unknown. Testing of wire-line cable is generally a by-product of attempts to obtain geophysical information in the field, which has proved to be a very expensive method for determining needed improvements in cable design and manufacturing.

The Teflon fluorocarbons used for insulation materials are of borderline suitability for future exploration of geothermal reservoirs. New transmission-line materials must be developed that will survive the higher temperature environment of still deeper geothermal wellbores for long periods of continuous service. Such materials must also have high tensile and dielectric strength, flexibility, low permeability to conductive liquids, and relative chemical inertness. Sophisticated fracture-mapping and borehole-survey instrumentation now being developed will require cables with much higher frequency response than those now used in the oil and gas industry.

In the longer term, development of fiber-optic cables which may more easily survive high-temperature environments looks promising. In many applications, however, the cable is a two-way link, transmitting operating power downhole as well as data signals uphole. In the foreseeable future, therefore, even fiber-optic cables will probably be hybrids with several power-handling conductors. The development of suitable cables will be a continuous high-cost program for several years.

The primary function of the cablehead assembly is to provide an armored cable-to-instrument electromechanical coupling device that will protect the electrical conductors from the downhole high-pressure and high-temperature fluid environment. The cablehead must also function as a transition area from the downhole high-pressure fluid to the dry, low-pressure environment inside the instrument sonde. The head design should allow the sonde and cable to be separated if the sonde becomes jammed in the wellbore. It should also provide a gripping groove (fishing bell) for overshot fishing tools (Fig. I-1). Materials such as O-ring seals, potting compounds, and electrical insulation must endure the 275°C temperature environment for essentially continuous service.

It is important that cablehead assemblies meet certain "standard" criteria wherever possible. The size, downhole connectors, and sonde makeup assembly including sealing surface and threads should conform to a standard such as that used by the logging service companies to ensure compatibility in the field. This means, of course, that the makeup end of the sonde should also be standardized. The cablehead development must parallel armored-cable improvements. The advancements achieved in the armored-cable development in areas of multiconductors and coaxial-conductor configurations will require a series of standard cablehead assemblies. Coordination of instrument development will be necessary to ensure a minimum of "standard" variations.

III. DOWNHOLE ELECTRONIC SYSTEMS

A major objective in engineering hot dry rock reservoirs is to develop techniques for mapping hydraulic fractures in space and time. Without knowledge of the orientation and radial extent of the target fracture system, intersecting that system at the optimum location would be most difficult. Acoustic techniques were initially investigated at the Fenton Hill Test Site. The promising results of acoustic methods to map fractures in the GT-2/EE-1 system has prompted development of more-sophisticated downhole equipment. Coupled with instrument development in wellbore surveying and reservoir engineering to meet advanced technology requirements, it has become necessary to incorporate associated electronic systems in the downhole sonde. Experience gained at Fenton Hill has taught us that downhole instrumentation must be highly specialized. Multiple downhole signals must be multiplexed for optimum signal-to-noise ratios, and digital electronics should be used.

Some commercial electronic components now exist that will operate in a temperature environment of 200°C. However, at this time, 200°C is the upper limit for electronic technology.

A controlled-environment enclosure (dewar) has been designed and tested that will house and protect electronic systems in the hostile downhole environment of the geothermal wellbore. This dewar has been tested with an external temperature of 275°C for 12 h before the internal temperature reached 85°C. The dewar also successfully passed vertical and horizontal drop tests. The dewar and pressure housing is 15 cm (6 in.) in diameter, designed for use in the HDR system at Fenton Hill. It will be necessary to develop dewars that will be used to house directional-drilling steering equipment that must work in a 7.6-cm (3-in.) diam drill collar at elevated temperatures.

For the longer term, reservoir-engineering technology will require long-term residence of instrument packages in the borehole. It will therefore be necessary to develop a new electronic technology that will permit continuous operation at temperatures greater than 275°C.

IV. BOREHOLE SURVEY INSTRUMENTS (LOGGING)

To determine the condition of the borehole, lithology, permeability, rock competency, and natural fracture zones, a number of logging operations are mandatory. The most useful logs include (but are not limited to) full-wave sonic, spectral gamma, bulk density, electric (resistivity and SP), caliper and neutron activation. Logging operations at Fenton Hill in the GT-2 and EE-1 boreholes provided valuable information concerning the geological and geophysical parameters. The logging program was coordinated primarily with well-logging service companies. However, in the hostile borehole environment equipment frequently failed. The incidence of failures increased with increasing hole temperature. A bottom-hole temperature of 200°C (392°F) appeared to be the upper practical limit for most commercial logging equipment.

Future demands for geophysical logging in hotter geothermal wellbores will require temperature-hardened tools. The residence time of most logging tools is relatively short when compared to reservoir-property and fracture-mapping instruments. Nevertheless, downhole temperatures approaching 300°C will require hardened or thermally protected electronic circuits and high-temperature transducers, seals, and other associated components.

In addition to the above-mentioned tools, instruments for the following logging operations will be necessary for the future HDR drilling program: temperature, induced potential, spinner survey, acoustic log, radioactive iodine, gyro-borehole survey, cement-bond log, and the televiewer. A broad program to both improve and standardize logging equipment for geothermal applications is needed. Such a program could be managed by an organization such as Sandia Laboratories, which presently has a contract with DOE to coordinate the industrial development of logging tools for use throughout the geothermal arena.

V. FRACTURE MAPPING AND BOREHOLE RANGING

The development of instruments and techniques peculiar to the HDR Program can best be accomplished in a field laboratory where an *in situ* environment exists. The Fenton Hill geothermal system has provided such a downhole laboratory to extend the capabilities of available techniques and to develop new techniques.

Properties exhibited by acoustic energy have prompted LASL to pursue acoustic techniques as one method of mapping a fracture system and of determining the relative trajectories of two boreholes. The techniques initially developed at the Fenton Hill site are also applicable to mapping fractures from a single wellbore, certainly a most important consideration for future HDR sites. Acoustic methods have been successfully tested in several mapping and ranging experiments, which include microseismic mapping, shear-shadowing, acoustic reflection, and borehole ranging. To optimize acoustic-signal enhancement and data interpretation, development of more-sophisticated downhole equipment is necessary. A higher-frequency capability must be incorporated in the signal-transmission system composed of the armored instrument cable and the downhole electronics. A reliable and repeatable acoustic source, such as a downhole detonator unit, is required to provide a series of known acoustic pulses.

Other mapping and borehole-ranging methods that have been successfully tested include induced magnetic measurements (flux-gate magnetometer), induced-potential measurements, and sonic-reflection methods (magnetostrictive and piezoelectric devices, Fig. I-2). The results of testing at Fenton Hill have paved the way for design and fabrication of more-sophisticated downhole instrumentation that will survive the hostile environment and allow incorporation of orientation devices within the sonde for both in-casing and open-borehole operations. Confirmation of borehole depth may be achieved with the addition of simple collar locators. It will also be necessary to monitor the internal conditions of the dewar housing and the electronic equipment. Thus, the need for electronic multiplexing systems downhole becomes more demanding.

Other fracture-mapping systems that have been studied and deserve investigation through at least the prototype instrument include the downhole tiltmeter, optical-survey system, low-frequency radar scanning, and *in situ* stress-measuring devices.

For development of a prototype instrument, such as those described above, operation and performance must be specified. A procurement contract awarded to a qualified industrial firm or university will generally cost about $100,000-$250,000 depending upon the degree of complexity of the first prototype tool.

VI. RESERVOIR-PROPERTY MEASUREMENTS

Various downhole instruments are used to measure parameters required to properly assess and model a downhole reservoir. Several reservoir-assessment instruments will be needed that will survive the geothermal-wellbore environment for periods as long as several months. These instruments may be available for some cases where measurements can be accomplished without the use of downhole electronics, such as a temperature probe using thermistors, pressure transducers, geophones, and a sensitive fluid-flow meter. However, the components incorporated in the downhole sonde must, of course, ensure instrument integrity at high temperatures.

A second class of downhole instruments used to measure reservoir properties, while perhaps less sophisticated than those used in fracture mapping, may incorporate orientation devices and collar locators, and require hardened or protected electronic systems. The designs of a borehole-fluid sampler (Fig. I-3), a fluid-tracer injector, a thermal-conductivity instrument, and a multiaxis independent-arm caliper tool may be upgraded for operations at temperatures exceeding 275°C, depending upon the development of electromechanical components. Although the instruments required to measure reservoir properties may be essential to future HDR systems, many of them will also be directly applicable to other geothermal systems. Many of the tools required for the measurement of reservoir properties will be developed at LASL, because much of the technology already exists there from previous instrument designs for evaluation of the Fenton Hill system.

VII. INSTRUMENT CALIBRATION AND TEST FACILITIES

To expedite the development of downhole instrumentation needs to meet the near-term goals of the Federal HDR Program, it will be necessary to fabricate test facilities to simulate the borehole environment. Components must be tested and calibrated at downhole pressures and temperatures. A facility to test the entire instrument package is required to ensure proper sonde operations for extended periods of time, again in a simulated borehole environment (Fig. I-4). Such testing facilities will provide meaningful information with regard to tool design and will greatly facilitate component development.

Once a prototype downhole instrument has been fabricated and has passed preliminary testing, it is necessary to test the sonde in the field under controlled conditions. A test facility for this purpose Downhole Wellbore Environmental Test Stand (DWETS) will not only allow calibration of the entire measurement system (downhole instrument, cable, surface equipment) but will also assist in development of data-interpretation techniques. The DWETS will be available for instrument testing in all areas of geothermal work.

VIII. DRILLING AND COMPLETION EQUIPMENT

A. Introduction

Most equipment for drilling and completion of geothermal wells is identical to or derived from the equipment used in drilling for oil and gas. Because geothermal wells are hotter and frequently in harder formations than are oil and gas wells, it is sometimes advisable to alter the available equipment, and it may be necessary to develop new equipment. Many of the items which will require development for the national program in hot dry rock are those for which development has already been started for the Fenton Hill work. Work in this area required for the national program is as follows.

B. Packers

Open-hole packers are required for sealing the drilled holes during fracturing and for short flow-tests required for system evaluation. The best field result to date is that one brand of packers has held successfully for 14 h at 187°C (370°F) in a 24.5-cm (9-5/8-in.) borehole in granitic rock. Manufacturers are further developing packers to meet more severe requirements. However, the need to have packers that can operate at higher temperatures will be a continuing one as we progress into larger and hotter holes.

C. Turbodrills and Mud Motors

Mud motors and turbodrills that are available today have temperature limitations of less than 200°C. The mud motors have elastomer stators limited to operation below that temperature, and both the mud motors and the turbodrills have elastomers in their bearings and seals that are similarly limited. These motors are essential for accurate directional drilling, which is required particularly for the fracture connections in hot dry rock systems. It is essential that their heat-resistant capabilities be improved.

The effort begun toward improving these motors, the development of a turbodrill by Maurer Engineering, Inc., should (if completely successful) provide a solution to this problem until temperatures greater than 350°C (662°F) are reached. This development should be closely watched, and further programs should be initiated to develop a high-temperature motor if this design is not satisfactory. Also, a larger motor or a larger version of the Maurer motor should be developed to produce larger holes into basement rock. These holes will be necessary to allow for the high fluid-flow rates required for commercial production.

D. Casing Heads

Thermal expansion or contraction of casings in geothermal holes is a current problem. Two solutions have been tried. One is to allow for movement of the casing in the casing head and provide a flexible pressure connection to the heat-exchange system. The other is to place a tensile load on the casing, when it is in its coldest condition, which is sufficient to allow the casing to relax but not expand when the casing is in its hottest condition. A study should be made of these solutions and any others which may appear feasible, and equipment designed to support the solution chosen. Some of the items which could be considered are: (1) casing heads which allow the casing to slide as it expands and contracts; (2) flexible, high-pressure, long-life connectors to attach to the moving casing; (3) load cells and special casing heads which will allow the stresses to be monitored in the casing, and (4) special casing sections containing strain gages to monitor the tension in the casing.

E. Steering Tools and Directional-Logging Tools

With encouragement from the HDR Program, the suppliers of these tools are making them available in the temperature range of 250-275°C. Further temperature hardening of these tools to meet higher temperature requirements should be considered.

F. Muds

The production of hot holes in various formations will undoubtedly require the use of high-temperature muds. Present experience in the HDR Program has been in formations where water appeared to be a satisfactory drilling fluid; however, water may not be a satisfactory drilling fluid in all formations in which drilling will be done. The high-temperature mud work being performed by others should be watched closely, and support should be provided to areas that appear to be valuable for the HDR program.

F. Drilling Speeds and Costs

Tungsten-carbide-insert roller-cone bits have been used for most of the drilling of granitic formations in the HDR Program. These bits have performed satisfactorily and have produced respectable drilling rates of about 2.7 m/h (9 ft/h) at rotational speeds of 40 and 400 rpm. Conventional diamond bits have not proved successful in this drilling program. Tests of the roller-cone bits to determine the best rotational speed and weight combination, made prior to writing specifications for the turbodrill, indicated that much higher drilling rates may be obtained at rotary speeds of 150 rpm instead of 400 rpm.

In an effort to increase drilling speeds and cut drilling costs, an examination should be made of the drill-bit problem and tests conducted to determine optimal drilling methods. This is indeed a complicated area, as there are so many factors that affect drilling speeds and costs. These include bit type, bit design, drilling fluids, flow rates, jet sizes, rotational speeds, bit weights, shock absorbers, and rock properties. Drilling development will probably involve laboratory and field tests and will be expensive--but will pay off handsomely if drilling costs can be decreased.

IX. CEMENTS AND CEMENTING

A. Introduction

Most geothermal engineers agree that the cementing of the casing is the most important operation in the completion of a geothermal well, as the life of the well depends on the integrity of the cement. While this is important in conventional water- or vapor-dominated systems, it is doubly important for HDR systems. The cementing of the casing in the production, or outflow, borehole is largely a routine operation in any type of system at the downhole temperatures that are currently being encountered. However, the successful cementing of the casing in the injection, or inflow, borehole of an HDR system presents some special problems that are not being adequately solved by the use of conventional portland cements.

The stresses that act on the bottom of the injection-hole casing are unique to HDR systems because of the thermal cycling, with resultant contraction and expansion of the casing, that occurs in testing and operating the underground circulation loop. During pumping and flow, the casing may be cooled to a minimum of 38°C (100°F) from an original maximum temperature of 275°C (527°F), and this cycle may occur many times during the lifetime of the well. Portland-cement mixtures, such as those being used today, simply cannot withstand this kind of repeated thermal stressing without rapid deterioration, which may open a leakage path up the annulus between the casing and the rock and allow water to come to the surface, or create a short circuit to the other borehole. In addition, there may be a deleterious action on the cement caused by the geothermal fluid, in combination with the high temperatures and pressures found in HDR wells.

B. Future Needs

To satisfy the HDR cementing requirements, a new approach to cement chemistry and placement techniques is needed. Ideally, we require a cementing material with the following properties:

- low permeability (less than 100 microdarcies),
- high bond strength to steel and rock,
- relatively high tensile strength (even some elasticity),
- ability to be placed and cured at bottom-hole temperatures of 275-300°C,
- chemically inert when cured,
- 20-30-yr life without strength regression,
- self-healing when ruptured, and
- inexpensive.

Not all of these properties may be attainable in one product. If not, then a variety of products might be used in a single cementing operation by placing different cementing materials in stages, with each stage fulfilling its specific function in the cement column around the casing. More expensive types of materials would be used in small amounts, perhaps in conjunction with larger quantities of conventional portland-cement mixtures.

Cementing materials (polymers and resinous cements) that partially fulfill the above requirements are being developed by organizations such as Chevron Oil, Brookhaven National Laboratory, and Southwest Research Institute (SRI). SRI has developed a hydrothermal-setting cement which has been successfully used in the completion of two hot El Paso Natural Gas wells. All of these developments should be encouraged so that the necessary cementing materials will be ready when they are needed.

X. SUMMARY

Much of the instrumentation and equipment developed for the Federal HDR Program will be readily adaptable for use in other geothermal systems. Certainly the logging instruments will be useful for hydrothermal exploration. The fracture-mapping and borehole-ranging equipment may be unique (at least initially) to the HDR Program. The investigation and development of all geothermal systems depend strongly upon the capabilities of the instrumentation and equipment available. All possible resources should therefore be encouraged to engage in a systematic program to improve them.

BIBLIOGRAPHY

1. F. G. West, P. R. Kintzinger, and A. W. Laughlin, "Geophysical Logging in Los Alamos Scientific Laboratory Geothermal Test Hole No. 2," Los Alamos Scientific Laboratory report LA-6112-MS (September 1975).

2. A. G. Blair, J. W. Tester, and J. J. Mortensen, Comps., "LASL Hot Dry Rock Geothermal Project, July 1, 1975 - June 30, 1976," Los Alamos Scientific Laboratory report LA-6525-PR (October 1976).

3. LASL HDR Project Staff, "Hot Dry Rock Geothermal Energy Development Project Annual Report, Fiscal Year 1977," Los Alamos Scientific Laboratory report LA-7109-PR (February 1978).

4. B. R. Dennis, "Materials for High-Temperature Geothermal Borehole Instrumentation Cable," American Institute of Chemical Engineers 85th National Meeting, Philadephia, PA, June 4-8, 1978.

5. J. R. Archuleta and B. E. Todd, "Equipment Development Report, Cablehead Assembly," Los Alamos Scientific Laboratory report to be published.

6. B. R. Dennis, J. H. Hill, E. L. Stephani, and B. E. Todd, "Development of High-Temperature Acoustic Instrumentation for Characterization of Hydraulic Fractures in Hot Dry Rock," 22nd International Instrumentation Symposium, May 25-27, 1976, San Diego, CA.

7. J. R. Archuleta, C. F. Fink, and J. Kurtenbach, "Equipment Development Report, Downhole Fluid Injector," Los Alamos Scientific Laboratory report LA-7151-MS (February 1978).

8. J. R. Archuleta, C. F. Fink, and J. Kurtenbach, "Equipment Development Report, Borehole-Fluid Sampling Tool," Los Alamos Scientific Laboratory report LA-7152-MS (February 1978).

9. P. R. Kintzinger, F. G. West, and R. L. Aamodt, "Downhole Electrical Detection of Hydraulic Fractures in GT-2 and EE-1," Los Alamos Scientific Laboratory report LA-6890-MS (July 1977).

10. W. C. Maurer, J. D. Nixon, L. W. Matson, and J. C. Rowley, "New Turbodrill for Geothermal Drilling," Proc. 12th Inter-Society Energy Conversion Engineering Conference, August 28 - September 2, 1977.

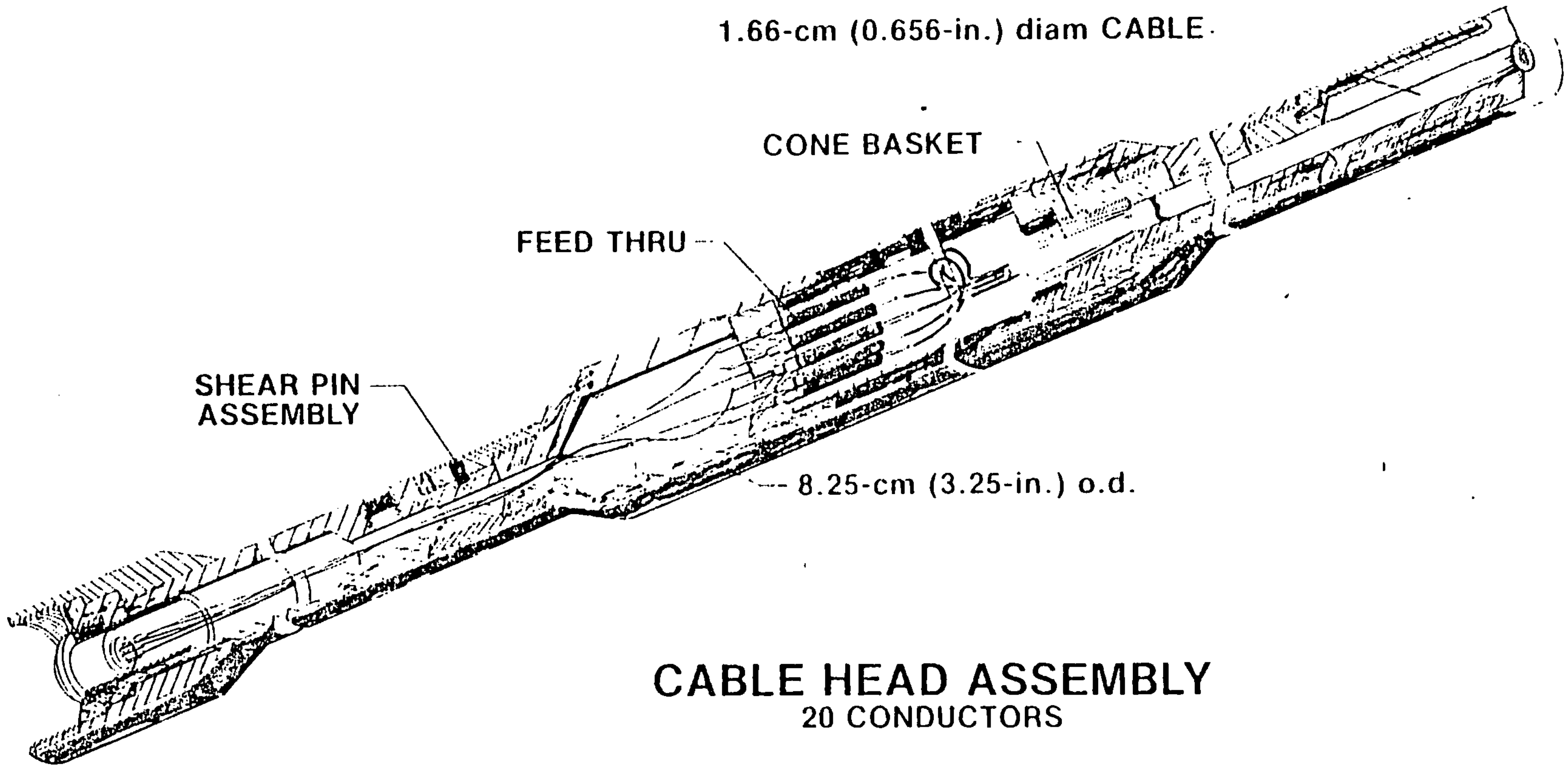


Fig. I-1. High-temperature cablehead assembly.

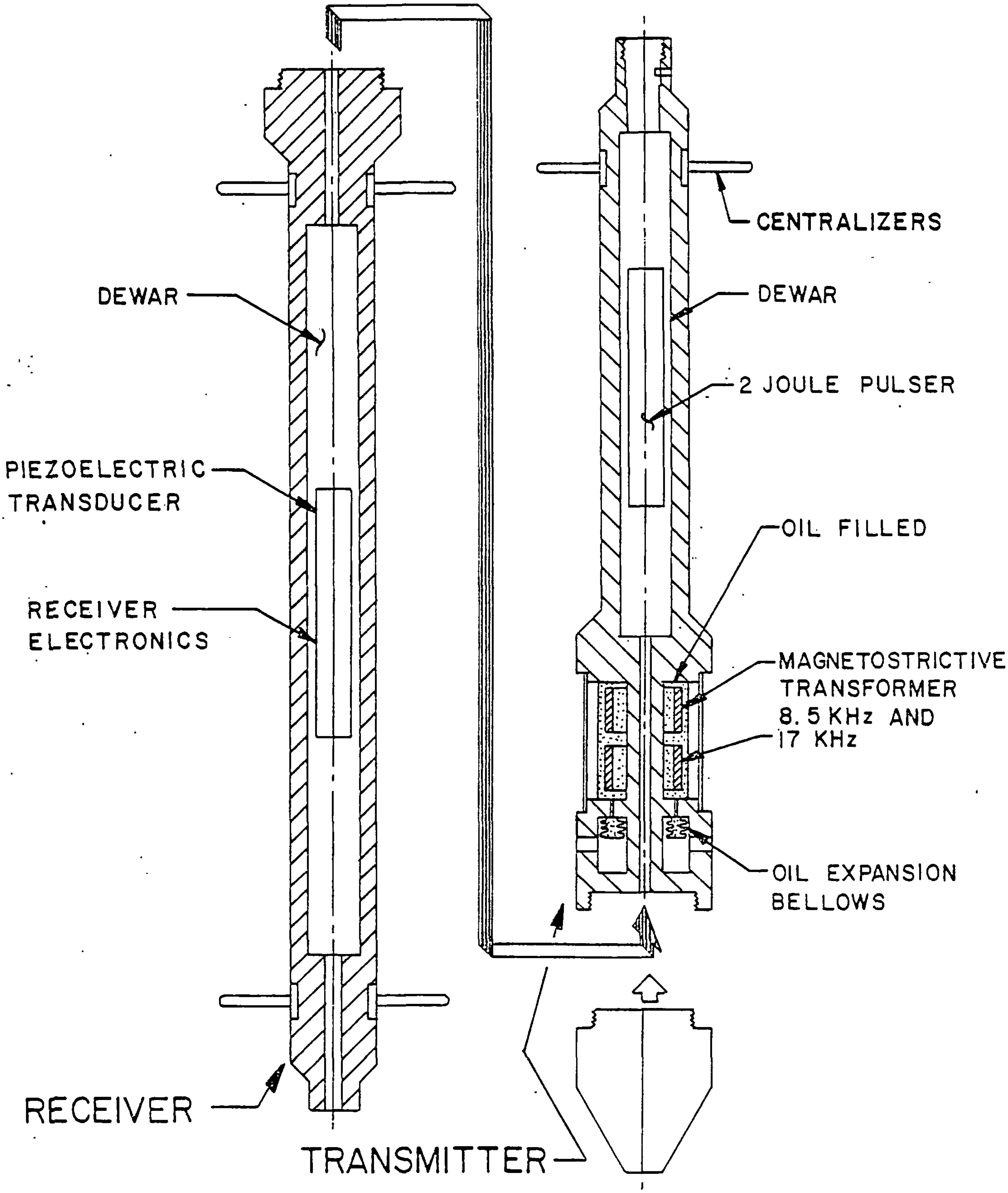


Fig. I-2. Acoustic transceiver.

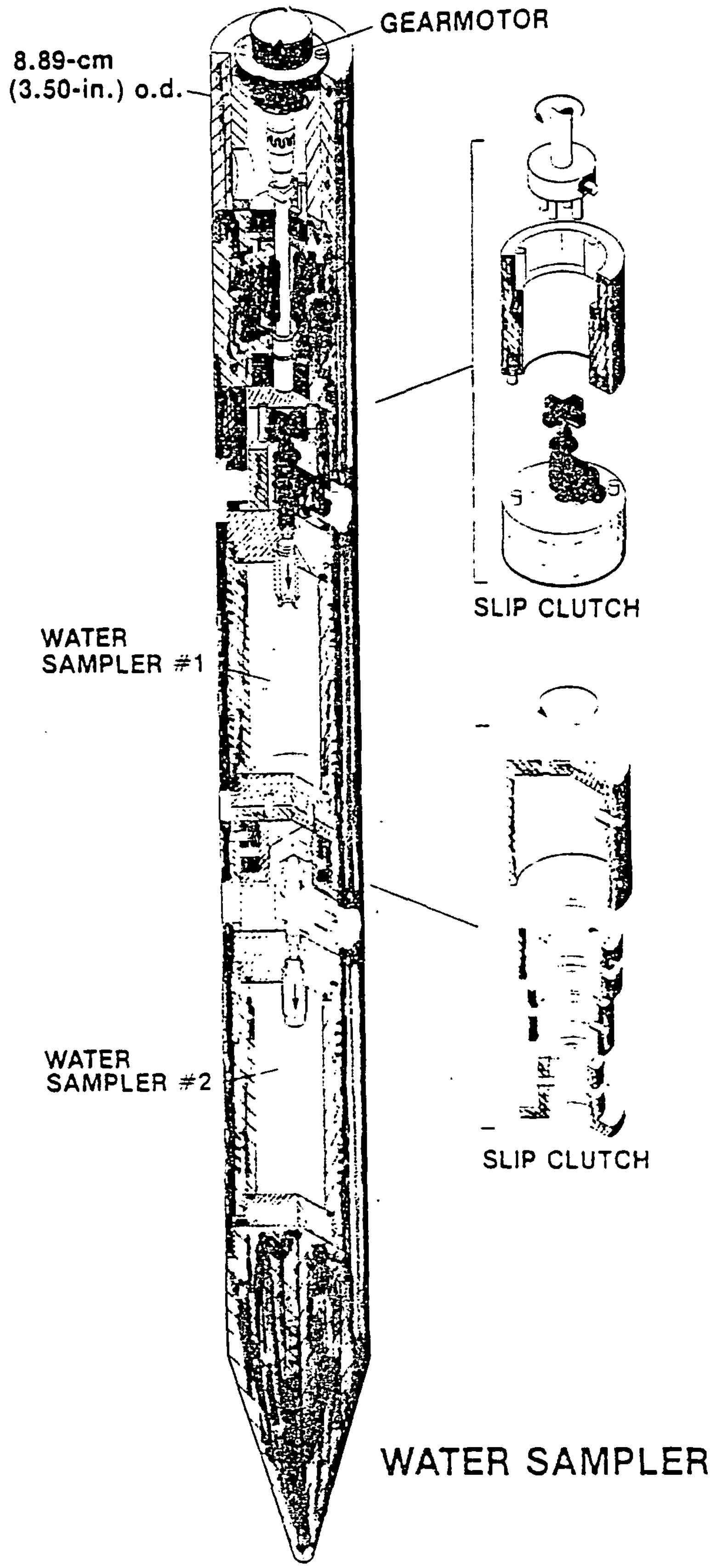


Fig. I-3. High temperature fluid sampler.

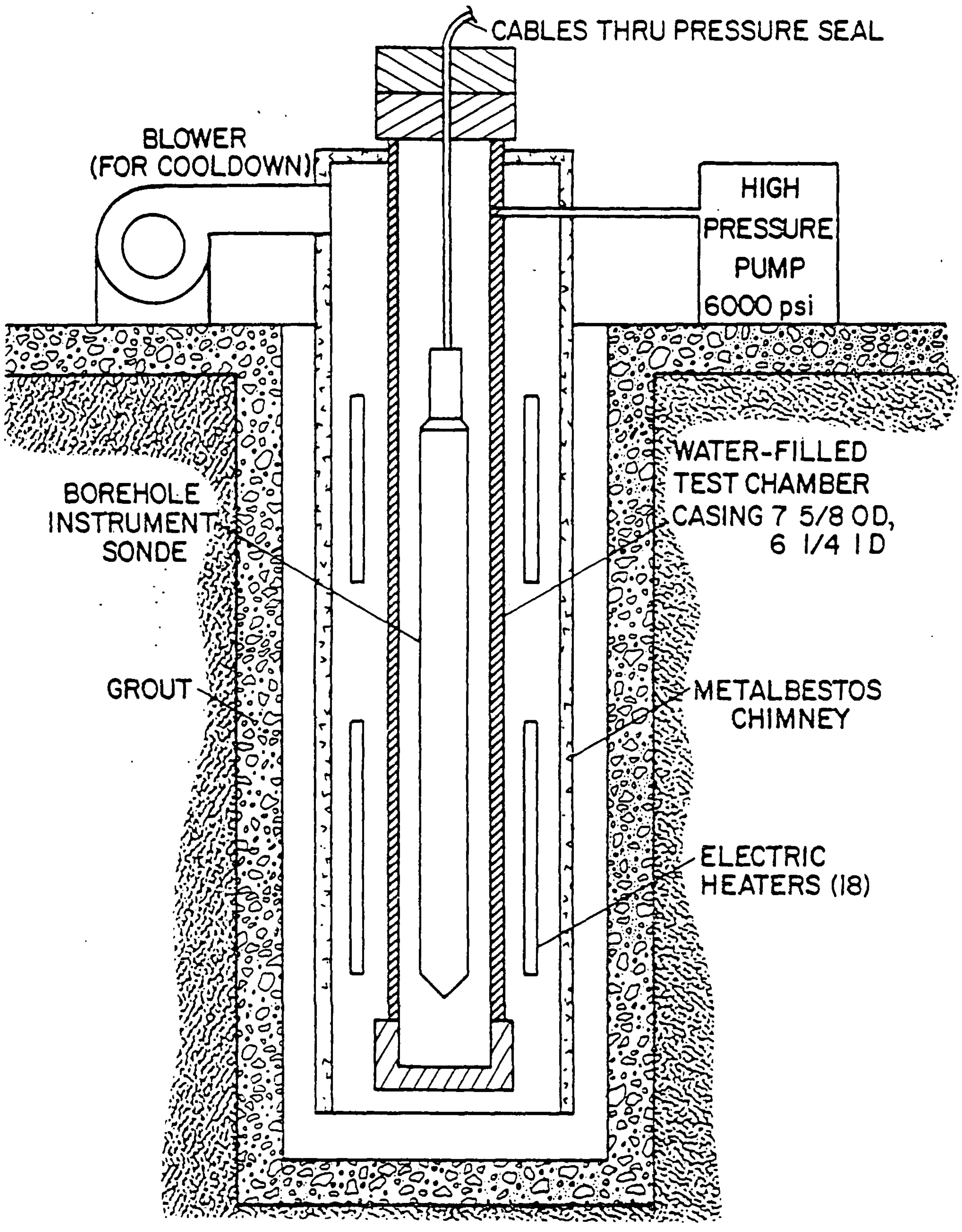


Fig. I-4. Downhole instrument test stand.

APPENDIX J

INSTITUTIONAL ASPECTS

Unlike the exploration and exploitation technology development required for commercialization of HDR geothermal-energy systems, the institutional aspects of their development are those portions which are characteristically variable from one area to another and are based more on social perceptions and political compromises than on science and engineering. Variable social perception is exemplified by the differences in the legislative definitions of "geothermal resource" promulgated by Congress and several states, wherein some relate this thermal resource to water and others to mineral. Variability also exists in the requirements for assessing the wide range of impacts (environmental, economic, land-use, etc.) among the many federal and state agencies involved in the siting of any energy-resource production or conversion facility, including geothermal. Additionally, jurisdictional overlap and regulatory control practices and procedures vary among the state and federal agencies, resulting in confusion and misunderstanding of requirements and timing of action by both government and industry.

The activities perceived to address the institutional aspects of HDR commercialization are categorically organized here as: legal requirements; constraints mitigation; and public understanding. The first activity in the federal program will necessarily be meeting the legal requirements for obtaining the necessary permits, licenses, and leases, as presently required for each phase (resource exploration and development, pilot- and demonstration-facility siting, construction and operation, abandonment and site restoration) of the activities outlined in this plan before that phase actually occurs. This action must occur in a time frame that will meet those requirements in a manner allowing the time schedules established by the plan to be met.

A second activity will be identification of the barriers and constraints to commercialization, and designing mitigation strategies. This function will include analysis of the economic, environmental, and social subsystems of the HDR energy system to determine the sensitivities to and effects from the courses of alternative actions which can be taken to reduce the identified constraints. Once known, mitigating strategies will be designed and recommendations for action will be made.

A third activity will be the appropriate dissemination of the body of knowledge gained from the experiments and demonstrations, to industry and to the public, under the auspices of DGE.

The functions described above will require activities at least to the extent of those described below.

I. LEGAL REQUIREMENTS

During the early regional resource exploration, no permit or licensing activity will be required. However, it is expected that the time period between regional and more-localized area evaluations will be quite short. Therefore, the initial activity will be to assemble the available state land-status maps for those states of the nation presently thought to contain the more-promising HDR areas. These include Arizona, Idaho, Nebraska, Nevada, New Mexico, New York, North Carolina, Oregon, South Carolina, and Washington. (Other states in the eastern and western regions of the nation are also under consideration by DOE and the USGS). This early information is required prior to any detailed exploration, to assess the type of ownership and to identify the governmental management agencies involved in the selected local target areas. Once the potential target areas have been generally located, and based on the area land ownership, the appropriate federal, state, and local legislation and regulations will be obtained and examined. Simultaneously, the relevant government agencies will be contacted to obtain information concerning specific procedures for obtaining the necessary approvals for all of the anticipated activities to be conducted within the jurisdiction of each agency. Notable is the fact that not all public lands (federal or state) are available to exploration for or development of the HDR resource because of existing leases, agency withdrawals, wildlife refuges, military reservations, wilderness areas, wild and scenic rivers, parks and monuments, etc. Other federal and state public lands, although available for lease, are operationally restricted, as for example are Known Geothermal Resource Areas (KGRAs) and some areas classified as being valuable prospectively for geothermal steam and associated geothermal resources but which are actively being considered for change to KGRA, national forests, or grazing lands. These areas must be identified.

Exploration or development activities involving available government lands may require Environmental Assessment Reports (EAR) and/or Environmental Impact Statements (EIS) as part of the administrative permit- or lease-decision process.

The National Environmental Policy Act (NEPA), together with the relevant court decisions and agency regulations and procedures, prescribe the various federal requirements. For example, the issuance of an exploration permit covering national forest lands wherein shallow temperature-gradient holes are to be drilled, requires that an application be made to the Forest Service. The Forest Service, with the advice of the USGS, will review the application and conduct an environmental assessment to determine whether the proposed action may significantly affect the quality of the human environment. A negative judgment will result in a conditional permit being issued. A positive judgment will require an EIS, together with attendant studies and public hearings, before the permit decision is made. The findings by the Forest Service, pursuant to the environmental studies and public hearing, could result in either permit issuance or denial. The same is true for the activities involved in development (pilot or demonstration plant), in obtaining process water, or in solid waste disposal.

Activities involving available state lands are subject to requirements which in some instances are similar to those of the Federal government and in others are quite different. Some states have legislation similar to NEPA: others have limited legislative authority but have developed administrative procedures and regulations that include most of NEPA's provisions; still others act under a series of legislative statutes and attendant regulations, with some including requirements more stringent than those of NEPA.

Activities involving available private lands usually require meeting State regulations and requirements as well as appropriate permit and/or lease requirements of the relevant surface and/or subsurface estate owner.

Specific knowledge of the requirements for each agency involved, together with knowledge concerning the actual function and perceived responsibility of each agency and action-time frames or lead time, will be acquired through personal contact, and appropriate action will be instituted accordingly. These activities will be pursued in a manner which will accommodate first the priority areas established by early exploration, to allow detailed exploration and pilot- and/or demonstration-facility siting in a timely manner.

Additional studies and analyses will be required during the exploration and pilot- or demonstration-facility siting phases. These will include environmental, economic, and social-acceptance studies, and will provide important input to public hearings, EIS's, and government and industry decision-makers. A considerable amount of the necessary data exists in current literature and will be incorporated into these studies, but some field work will also be necessary (for example, site environmental-baseline and operations monitoring).

II. CONSTRAINTS MITIGATION

The development of the information required to meet existing legal provision and that needed for either EAR or EIS positive and negative impact analyses will provide most of the input data both to quantitatively define existing legal constraints and to design appropriate strategies for mitigating or eliminating these constraints. For example, a major constraint to a proposed demonstration facility would exist, in terms of time, should an EIS and public hearing be required by the managing agency for a site located on federal public land; or, in terms of potential loss, if the Bureau of Land Management required that leases be obtained by competitive bid. Both of these constraints could be eliminated through administrative-agency withdrawal of the land, in the public interest, for the purpose of demonstrating commercial feasibility.

Ecomomic analyses which include all portions of the HDR geothermal system (exploration, exploitation, resource management, end uses, etc.), when compared to alternative energy-resource-system analyses, will provide the data necessary for sensitivity analyses, which in turn become valuable input to legislative bodies, industry, and the public, for establishing the priorities necessary for implementive decisions. These sensitivity analyses will point out those areas requiring further research and development to reduce costs or to expand end-use production in order to increase economic efficiency.
The analyses comparing the HDR subsystem components to alternative energy-resource-system components will also provide the input necessary to establish more appropriate address to capital-investment problems presently faced by utilities and the financial community. An additional analysis seemingly necessary is one which compares the several alternative systems in terms of direct and indirect consumer costs as functions of time, and from which

decision strategies can be designed to mitigate the present trend of rapid price increase.

Environmental effects beyond those that are presently embodied in existing regulations, but which in some quarters are considered as being adverse (esthetics, noise, etc.), require investigation and mitigating-strategy development. Recent DOE Environmental Development Plans (EDP) have described environmental issues thought to be constraining to the point of requiring either new control technology development or, as a minimum, the description of existing control technology which--before the fact--can reduce the potential for adverse impact. Those EDP-defined issues relevant to HDR will be incorporated in the environmental effects activity, as will any other known investigations helpful to adverse-environmental-impact mitigation, including those of the EPA and its state counterparts.

The public's perception of the desirability of implementing any of the presently emerging geothermal-energy technologies is unknown. Past experiences have shown the pitfalls of not incorporating public perception into the planning process. This aspect of HDR-commercialization planning needs to be examined to determine the strategies which will best alleviate the potential for undesirable public perceptions. The methodologies of public-attitude measurement, education, remeasurement, and analysis are well known, but need tailoring to HDR in general and for priority pilot- and demonstration-site areas in particular. The public-perception analysis activity will provide political-decision-implementation data equally as important to HDR technology development as the other activities described above.

III. PUBLIC UNDERSTANDING

Although many conferences on geothermal energy have now been held, these have been primarily for the benefit of involved professionals. Widespread dissemination of HDR information to the public has not yet been achieved to the same extent as, for example, solar-energy information, which is seemingly well received. Once the several constraints are understood to the extent that mitigation strategies can be designed, and with prior DGE program Director approval, discussions concerning constraint mitigation will be undertaken with legislative leaders and decision-makers in government and industry.

IV. COURSES OF ACTION

Three different courses of action could be pursued to gain the necessary federal land rights for HDR demonstrations.

1. Interagency agreement(s) could be negotiated between DOE and the relevant land-trust agency(s) covering the prospective federal lands. The agreement(s) could provide: (a) that the demonstration is temporary by its nature, and is not for the purpose of providing a continuing source of power; (b) that all federal, state, and local regulations will be met; (c) that should the facility be turned over to a private company, that company will assume full responsibility for acquiring the necessary permits, licenses, and leases before assuming operations; and, (d) that this action be deemed to be in the public interest and judged not to be a major federal action significantly affecting the quality of the human environment.

2. The DOE could request that the prospective federal lands be withheld, in the public interest, for the purpose of DOE's demonstrating and furthering the viability of HDR technology. The amount of withdrawn acreage is to be reduced within a time period to be specified to--for example--100 square miles, and further reduced to 40 acres within a second time period, also to be specified. It is presently estimated that the two time periods would not exceed 1 yr each.

3. The full permit/lease/public-hearing process could be pursued. Although considerably more time consuming, this course of action would provide industry and the involved regulatory agencies better insight into the relevant issues.

Without specific information concerning the state in which an HDR prospect is located, and the type of land ownership involved (federal, state, local), the lease/permit process requirements can be discussed only generally. However, previous experience has indicated some existing action-time frames which allow approximating the relative differences in approval times for the three possible courses of action discussed above. Based on the assumptions listed below, a path-time matrix indicating relative times by course of action is shown as Table J-I.

Draft plan	3	months
Draft application	3	"
Environmental assessment	6	"
Application processing		
federal	18	"
state	12	"
Public hearing	6	"
Lease sale		
federal	12	"
state	6	"
private	2	"

TABLE J-I

PATH-TIME MATRIX
(in months)

			Federal		State	
Lease-Hold	Permits, Licenses	EIS Process	Land Withdrawal	Administrative Agreement	Land Withdrawal	Administrative Agreement
private	state	32	32	32	32	20
private	federal	38	38	14	38	38
state	state	42	42	42	36	24
state	federal	48	48	24	42	48
federal	federal	54	42	30	54	54

Table J-I indicates the potential for a reduced time requirement, from the full EIS process, if either land withdrawal or appropriate administrative agreements can be arranged. The greatest reductions, seemingly achievable through administrative agreements between the federal agencies, are for those prospective areas located on federal land. These alternative paths will be investigated, dependent on the land ownership, once the specific prospect areas are known.

V. INITIAL ACTIVITY SCHEDULE

None of the prospect areas has yet been selected, and only a tentative list of states in which the prospects may be located has been compiled. Therefore, the permit processes cannot be scheduled now. However, some information can be acquired initially, and the remainder acquired as decisions leading to drilling locations are made, as shown in Fig. J-I. These activities can be conducted in several states simultaneously.

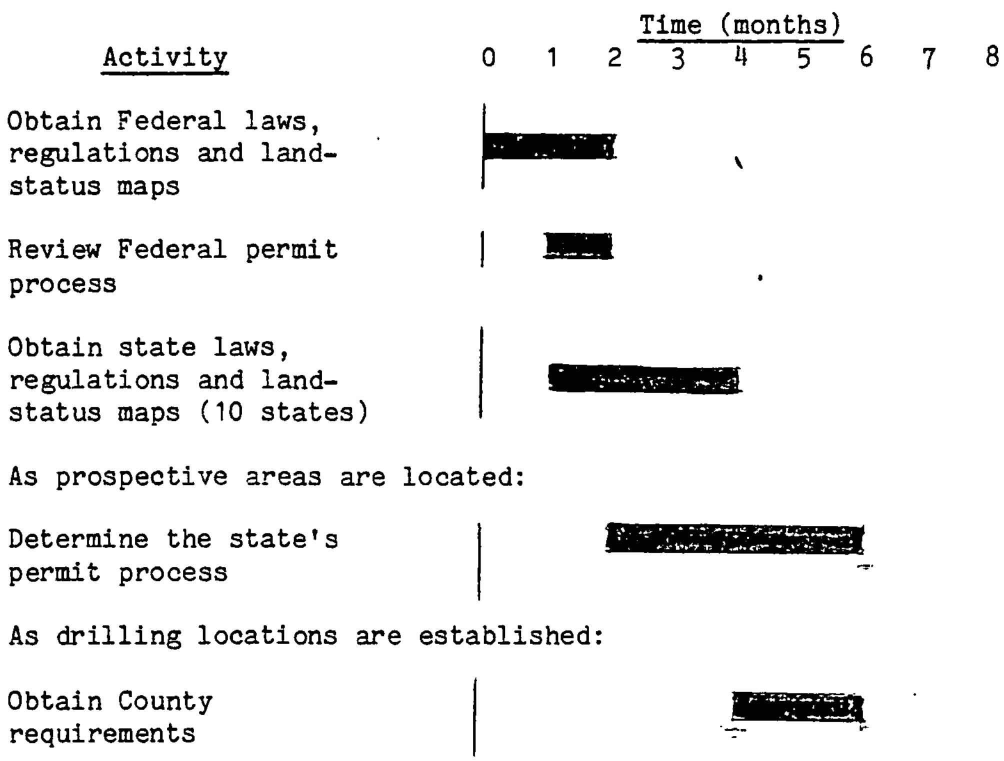


Fig. J-1. Initial activity schedule.

APPENDIX K
MANAGEMENT PLAN

Under the charter granted by DOE/DGE, the Los Alamos Scientific Laboratory has created a management team whose primary mission is to investigate the commercial viability of hot dry rock energy systems and, if they appear viable, to provide a basis for their timely development by industry. The accomplishment of this mission requires that simultaneously: the technologies developed and the information collected by LASL and others be transferred to industry; the constraints to commercialization be mitigated or removed; and the user communities and the public be informed of the advantages to be accrued from the utilization of HDR energy resources.

Organization and Responsibilities

The management team consists of a small core of specialists in the fields of management, technology, and institutions, supported by a limited number of additional dedicated full-time staff. This team and its affiliates are organizationally diagramed in Fig. 3 of the body of this report. Under the Program Manager at LASL and with support from the Associate Program Manager at DOE/ALO, the team will develop, institute, and monitor the sequences of activities necessary to implement the plan outlined in the body of this document. Following detailed planning, the team will conduct the contracting function in a manner designed to obtain the best available contractors from industry, universities, and both industrial and national laboratories, to perform the required tasks. The conduct of this activity will be in conformance with the procedures developed by the LASL and DOE/ALO contract and procurement groups. Joint management overview of the planning and contracting procedures, will serve to coordinate the actions needed to accomplish the many different tasks required to meet the plan's purpose and schedule. The Program Development Council will provide important input to, and foster evaluative introspection concerning, the planning function in terms of systems concepts, site locations, development techniques, contracting organizations and both institutional problems and means of avoiding or overcoming them.

An additional responsibility of the management team is the development and use of industry, government (federal, state, and local), and public interfaces through which information will be channelled. This activity is designed to conduct and coordinate technology transfer to industry and to provide current information to government and education, to interested groups, and to the public. The principal tools for accomplishing this function will be coordinated symposia, forums, publications, and talks to individuals and groups.

The DOE/ALO Associate Manager will provide administrative support to the management team concerning the legalities of its operation pursuant to the responsibilities, goals and objectives of DOE, and its interactions with other federal agencies.

LASL will provide administrative support services in the areas of contracts, procurement, budget control, computer facilities, personnel procedures, publications, public relations, office space, and from its relevant technology R&D activities.

Based upon the results of contracted analyses, strategies for constraint-mitigation will be designed in collaboration with the appropriate interface organizations; for example, environmental-impact constraint-mitigation activities will be designed with the aid of leading environmental groups, and capitalization strategies will be explored with the aid of industry and the financial community.

Reporting and Documentation

A reporting system will be implemented to keep DGE, ALO and LASL management informed of the status, results and problems encountered in the course of the program. In addition to normal telephone communication, maintained on a continuing basis, it is intended that reports and reviews will consist of the following:

a. Informal monthly status letters, submitted to DGE about the middle of each month, covering the previous month's work. This report will discuss progress, plans for the coming month, problem areas (technical or programmatic) and program and resource status.

b. Quarterly technical and management briefings: semi-formal technical and fiscal reviews for DOE/DGE presented orally by key program-management staff. These will be preceded by quarterly reviews in-house to LASL and ALO management, and will include discussions of problem areas.

c. Annual report, submitted shortly after close of the fiscal year, and documenting activities throughout the year, end-of-year status, and projected plans.

c. Special situation and topical reports, one-time or short-term reports as appropriate.

Financial Management

Financial management of the Federal HDR Program includes formulation of the matrix of manpower and operating costs required to support the management organization and the many activities required to plan, implement, and monitor the overall program.

Effective manpower utilization, cost controls, scheduling, and related flow of monies, require a breakdown of the total Federal HDR Program and funds into tasks, manpower, budget allocations, and scheduling which will be included in the reports discussed above.

Sophisticated operations-planning and controls for each task are machine-programmed at the LASL Computer Facility. Specifically, forecasts of manpower and of operating costs (including direct salaries, normal materials and services, major procurements and contracts, and indirect costs) are put into a data base. At the end of each month actual costs and effort are analyzed to provide effective controls of performance and forecasts of what is required to meet program objectives.

Prior to the start of each fiscal year, program and fiscal planning -- including task forecasts of manpower and budget allocations -- will be documented and reviewed with ALO and DOE-DGE Headquarters. Actuals in manpower and costs for each task will be reported in monthly newsletters, quarterly reviews and the annual report.

Many additional financial services and ancillary reports can be made available by the LASL Financial Management Offices and will be used as needed.