THE D.O.E. HOT DRY ROCK PROGRAM*

by

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ABSTRACT

Hydraulic fracturing has been used to create and subsequently to enlarge the first hot dry rock heat-extraction loop at Fenton Hill, New Mexico. Encouraging results prompted the DOE to expand this project into a program of national scope. The elements of that Program and their present status are discussed.

Emphasis is given the ongoing Fenton Hill Project where techniques and information developed in the existing research system will soon be used to produce a multiply-fractured engineering system in hotter rock at the same site. Recent results from research loop operation and progress in constructing the engineering system are reported.

Although acoustic mapping and system geometry indicate that the primary hydraulic fractures are essentially vertical, relatively low fracturing pressure and absence of a sharp breakdown suggest that at Fenton Hill fracture initiation occurs by reopening of old natural fractures rather than by initiation of new ones. Flow patterns and temperature behavior suggest opening of additional old fractures as the loop is operated. Except where the hot fluid leaves the crack system to enter the production well, flow impedances are very low without either artificial propping or inflation by pressurization.

INTRODUCTION

In September 1977, researchers at the Los Alamos Scientific Laboratory (LASL) demonstrated the successful establishment of the first hot dry rock

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(HDR) geothermal energy-extraction loop at their Fenton Hill test site in northern New Mexico. Results of testing this system over the ensuing year were extremely encouraging and motivated the DOE Division of Geothermal Energy (DOE/DGE) to expand the Fenton Hill HDR Project into a program of national scope — the "Hot Dry Rock Geothermal Energy Development Program" (HDR Program"). This paper presents the current status and recent results of the various elements of the HDR Program, with emphasis on the continuing Fenton Hill Project.

ENERGY-EXTRACTION CONCEPT

In its broadest sense, hot "dry" rock is crustal rock containing heat energy at temperatures of commercial interest but which will not spontaneously produce indigenous fluid at a rate adequate for economic energy extraction. The basic HDR concept is therefore to "mine" the heat energy from such rock by artificially introducing the heat transport fluid from the surface and, when required, artificially creating or increasing the effective permeability of the rock to provide the required subterranean heat-exchange area. A spectrum of engineering implementations is thus possible. For any given site, the specific approach to energy extraction will depend upon the temperature and nature of the formation, its permeability and porosity, its capability (if any) to self-produce, local availability of water, and other factors.

OBJECTIVE AND SCOPE OF THE PROGRAM

The overall objective of DOE's HDR Program is to demonstrate the commercial feasibility of geothermal energy derived from hot dry rock resources. It is DOE's intent to attain this objective within the 1980's decade subject, of course, to meeting the anticipated rate of technological progress and to the appropriation of requisite funds. The program is field-managed by the LASL, in conjunction with DOE's Albuquerque Operations Office as associate program manager, under the aegis of the DOE/DGE.

The scope of the program presently encompasses application of the concept only to formations of very low permeability (i.e. a few microdarcies, or less). The approach for this application, as illustrated conceptually in Figure 1, consists of: (a) drilling two wells — an injection well and a production well — through the sedimentary cover into the relatively impermeable formation of interest; (b) connecting these wells through a man-made fracture system of appropriate size, created by hydraulic, pneumatic, or other means; and (c) forming a closed circulation loop by connecting the two wells at the surface through a suitable heat exchanger and conversion system.

PROGRAM STRUCTURE AND PLAN

The HDR Program consists of four major elements which derive logically from the Program's objective:

- Resource Evaluation
- Technology Development
- Institutional Issues Analyses
- Commercial Feasibility Assessment

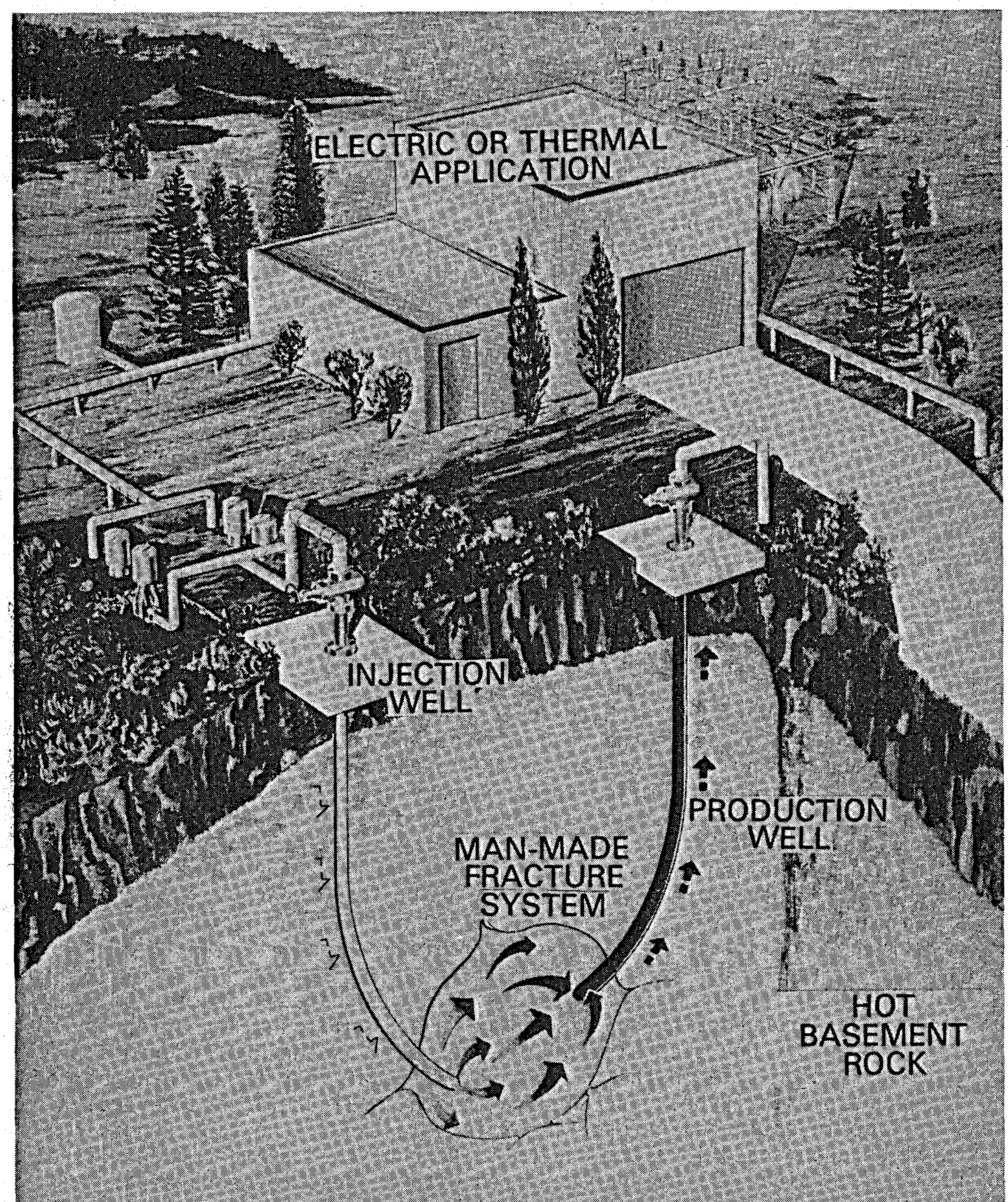

Fig. 1. Hot Dry Rock Geothermal Energy Extraction Concept

The resource evaluation element is aimed at better identifying the accessible US resource base and estimating the fraction thereof that constitutes an economic resource. The dominant element, both in priority and in allocated funding, is technology development which includes the establishment of HDR systems at two reservoir-demonstration sites. Analysis of institutional issues which bear upon the economics, or constrain the development, of HDR systems — either nationally or regionally — forms an important supportive element. These three elements then interact in the fourth where economically-oriented studies, culminating in a detailed commercial feasibility analysis, will ultimately assess the commercial potential of HDR-derived electricity and space/process heat.

The current program schedule is given in Figure 2. By fiscal year 1987, with a final resource evaluation completed as well as the testing of the two demonstration reservoirs, adequate data will be available to complete the commercial feasibility analysis. The results will enable the DOE to make a final decision on whether or not to proceed with a commercialization program for this technology.

The status and results to date in each of the program's elements are discussed in the following sections.

RESOURCE EVALUATION

The objective of this element, as noted previously, is to obtain a realistic estimate of the economic HDR resource of the United States. The work is a coordinated effort with the U.S. Geological Survey (USGS) which has the primary charter to assess the resources of the country. The program is compiling and analyzing data relevant to HDR obtained largely from the USGS, state, and other sources. Limited supplementary geophysical measurements are being sponsored by the program in regions of specific interest for HDR. These data are being provided to the USGS as well. The early products will be a series of jointly published geophysical maps: geothermal gradient, regional rock properties, depth to basement, etc. A preliminary geothermal gradient map, shown in Figure 3, was published in FY1980 and will be updated periodically as additional data become available.

A derivative effort within this element is the characterization of promising sites throughout the US which may have significant potential for future development. One such site will be selected as the HDR Program's second demonstration site in the first part of fiscal year 1982. A number of candidates are presently being studied, as shown in Figure 4, and several others will be investigated before Site 2 is selected. A host of promising sites will be documented in a compendium to be published at the end of fiscal year 1985. Each site will be characterized with respect to geophysical characteristics, proximate market potential and local institutional constraints.

TECHNOLOGY DEVELOPMENT

(A) FENTON HILL PROJECT

At present, the only operational HDR energy-extraction system is LASL's research system at the Fenton Hill, NM site (Figure 5). The downhole portion

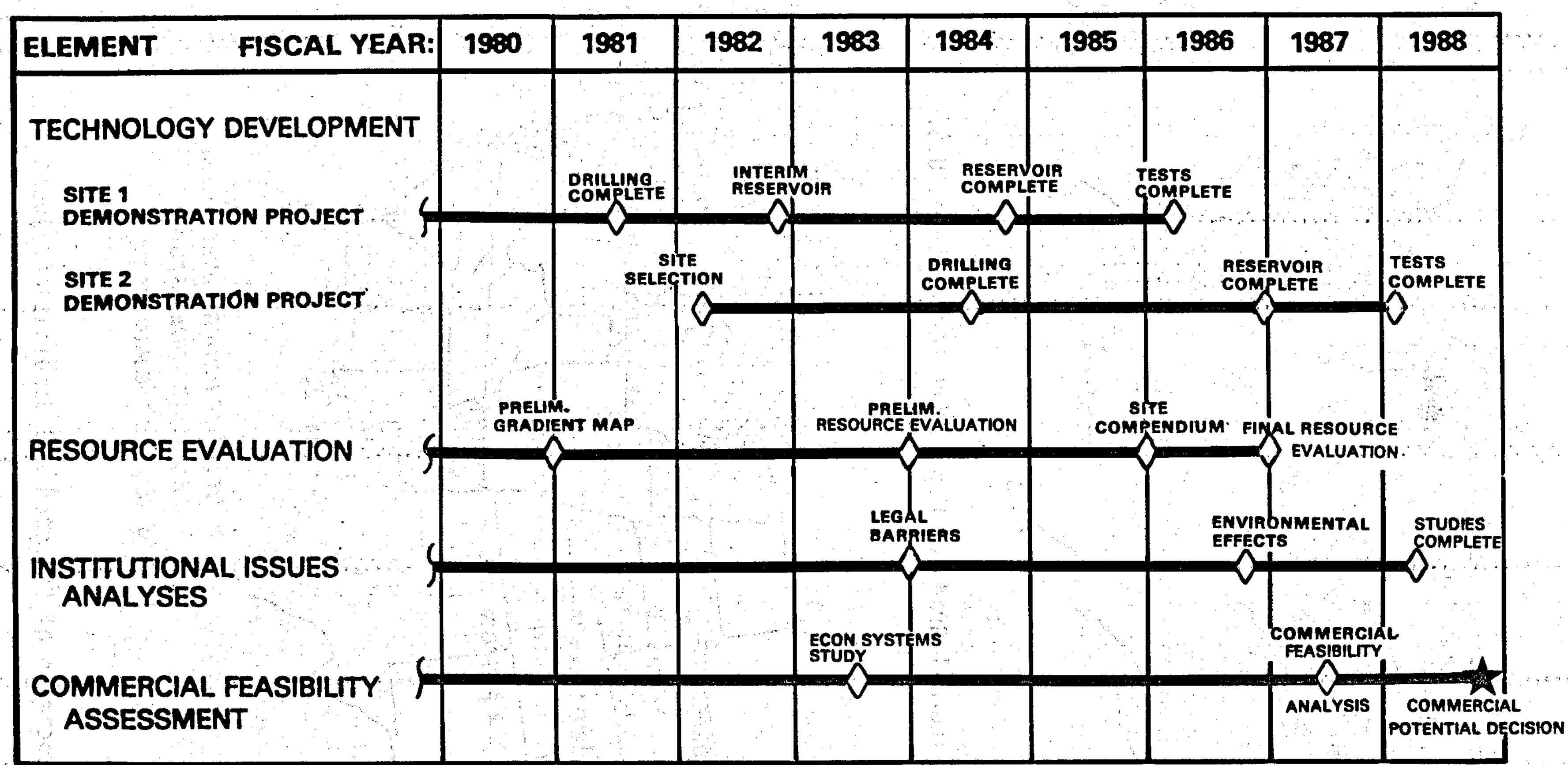

Fig. 2. Hot Dry Rock Program Milestone Schedule

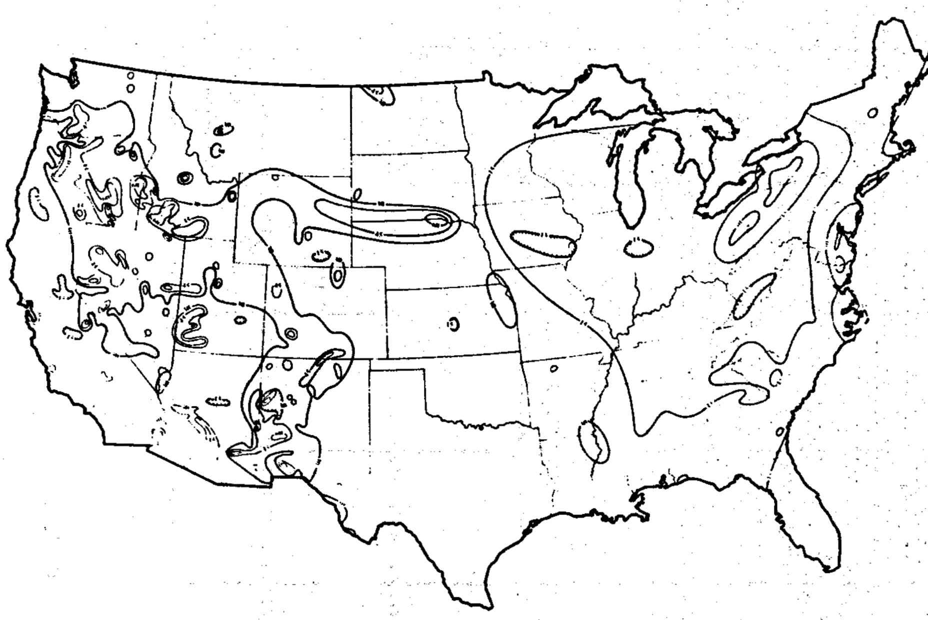

Fig. 3. Thermal Gradient Map of the Conterminous U.S.

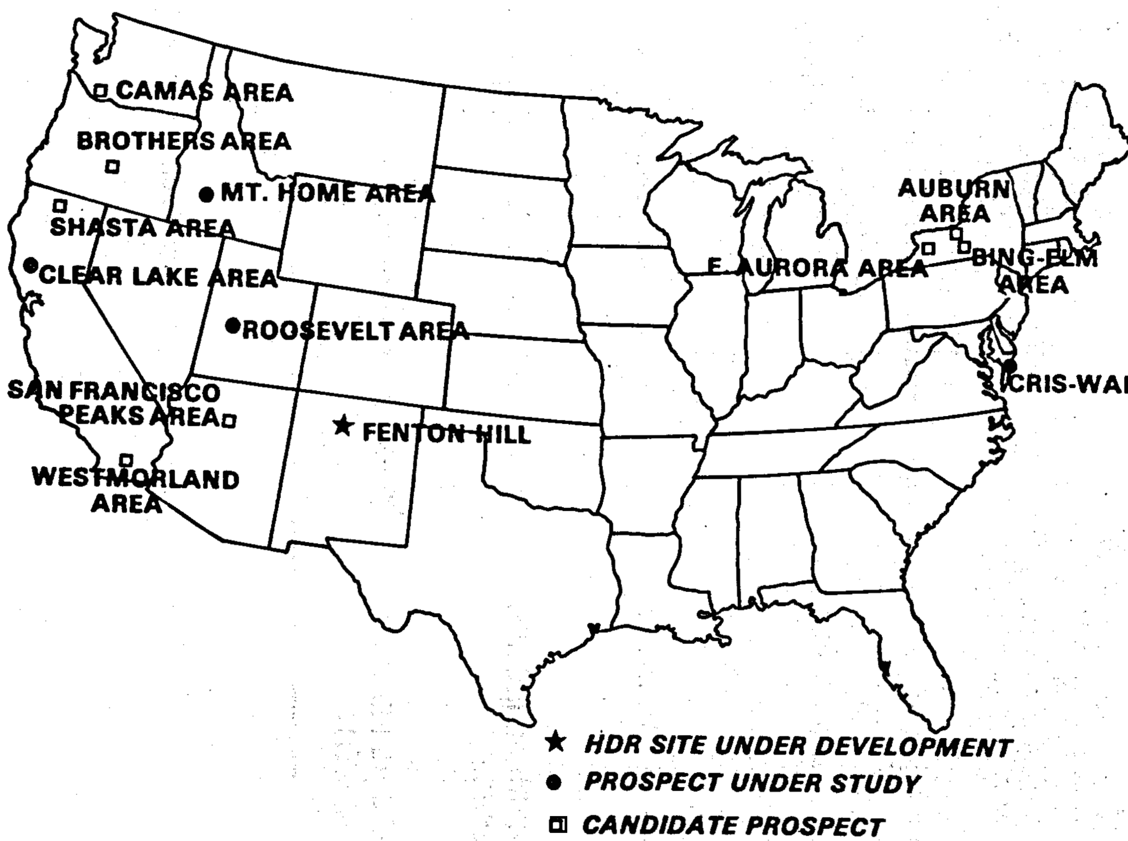

Fig. 4. Location of Selected and Candidate Prospect Areas

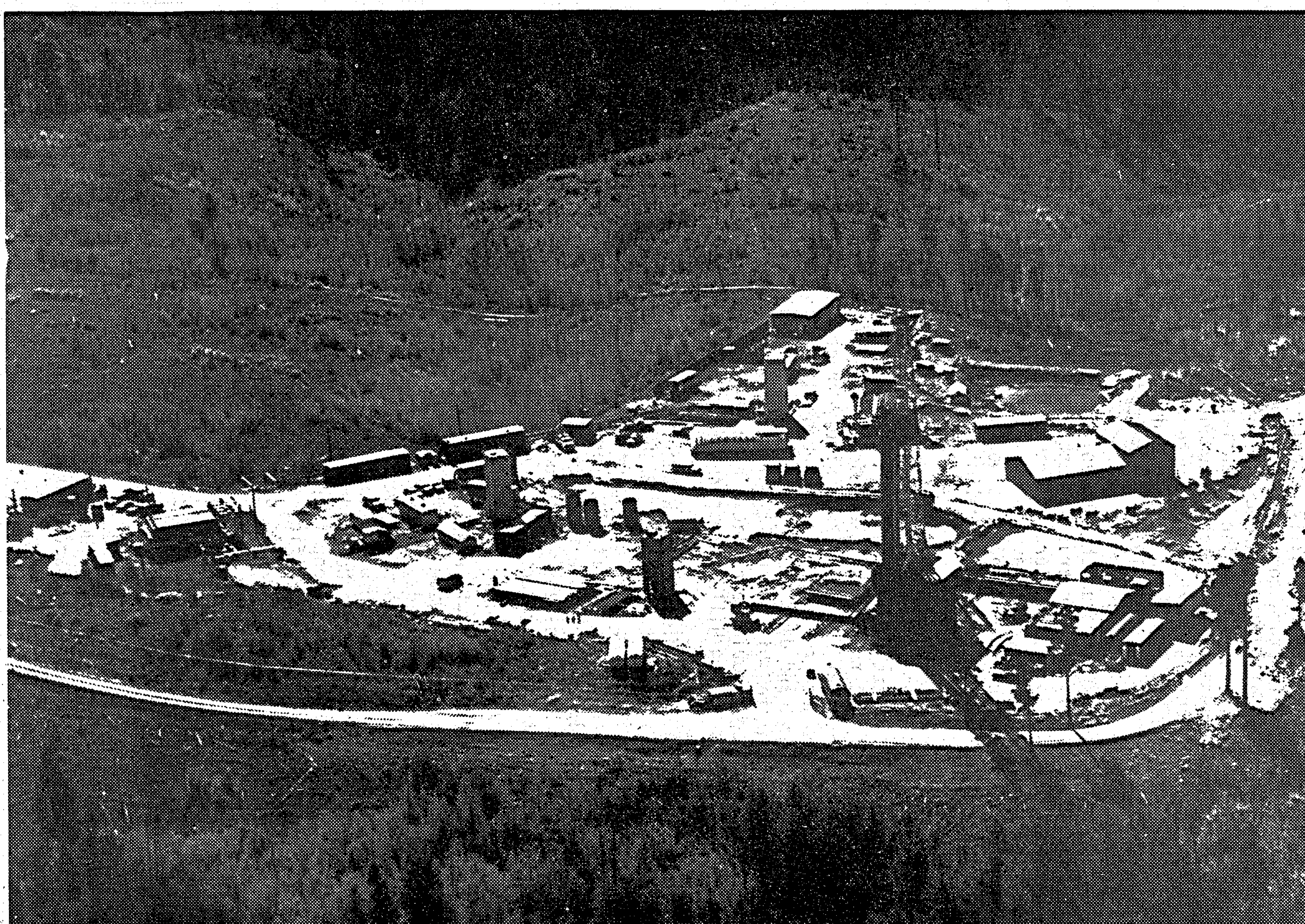

Fig. 5. Fenton Hill, New Mexico Site

of this research system, as originally established, consisted of a relatively small (circa 8000 m^2) fracture complex which connected the injection well, EE-1, and production well, GT-2, through a series of high-angle natural joints, as shown in Figure 6(a). The essentials of this geometry have been established through numerous well logs, downhole interwellbore acoustic transmission experiments and extended flow tests. The smooth and continuous form of the pressure history curve generated during fracturing indicates that an old sealed fracture was probably reopened (and possibly extended) rather than virgin rock matrix having been fractured. Three operational runs were conducted on this original research reservoir. Run Segment 1, a 100-h initial check-out and feasibility demonstration test was conducted in September 1977. In Run Segment 2 - a 75-day accelerated drawdown test conducted between January and April 1978 - preliminary answers were obtained, on an accelerated time scale, to questions concerning what would have been long-term effects in a commercial-size reservoir. Those preliminary answers were both enlightening and very encouraging:

- DRAWDOWN PREDICTABILITY - The somewhat simplified model of the downhole fracture system used in LASL's computations is mathematically adequate to represent drawdown. Specifically, the original research system behaved like a simply-fractured reservoir with an effective heat transfer area of about 8000 m^2 as shown by the lower curve and data of Figure 7. Whereas the numbers are particular to this system, the results indicate that the modeling methodology should be applicable to both the next (engineering) system at Fenton Hill and other sites.

- MAKEUP WATER REQUIREMENTS - Water loss to permeation quickly declined to less than 1-1/2% of the circulation rate (under 0.2ℓ/s), once the initial pore field saturation was achieved. This result, although obtained specifically for the Fenton Hill formation, is tentatively extrapolable to other sites where matrix permeability is in the units-to-tens of microdarcies range and indicates that makeup water requirement will not be a major constraint in such formations.

- GEOFLUID CHEMISTRY - A near-equilibrium composition was achieved in the circulating water, which remained at less than 2000 ppm total dissolved solids. Except for a slightly high terminal fluoride concentration (~9 ppm), this is virtually drinking water and scarcely deserves to be called a "brine" compared to the hydrothermal brines. No evidence of corrosion or scaling was detected in the flow loop. Although these compositional data are highly Fenton Hill specific, they lend credence to the qualitative prognosis that HDR geofluid chemistry should generally be manageable.

- OPERATIONAL CONSTRAINTS - A number of stop/start transients were imposed on the system, many of them inadvertent, because of brief power outages on the local utility. Although no major operational constraints were indicated, some minor freezing problems were encountered, which pointed to the need for careful attention to surface system design at HDR sites with similar moderate-to-severe winter climate and comparatively pure water geofluid.

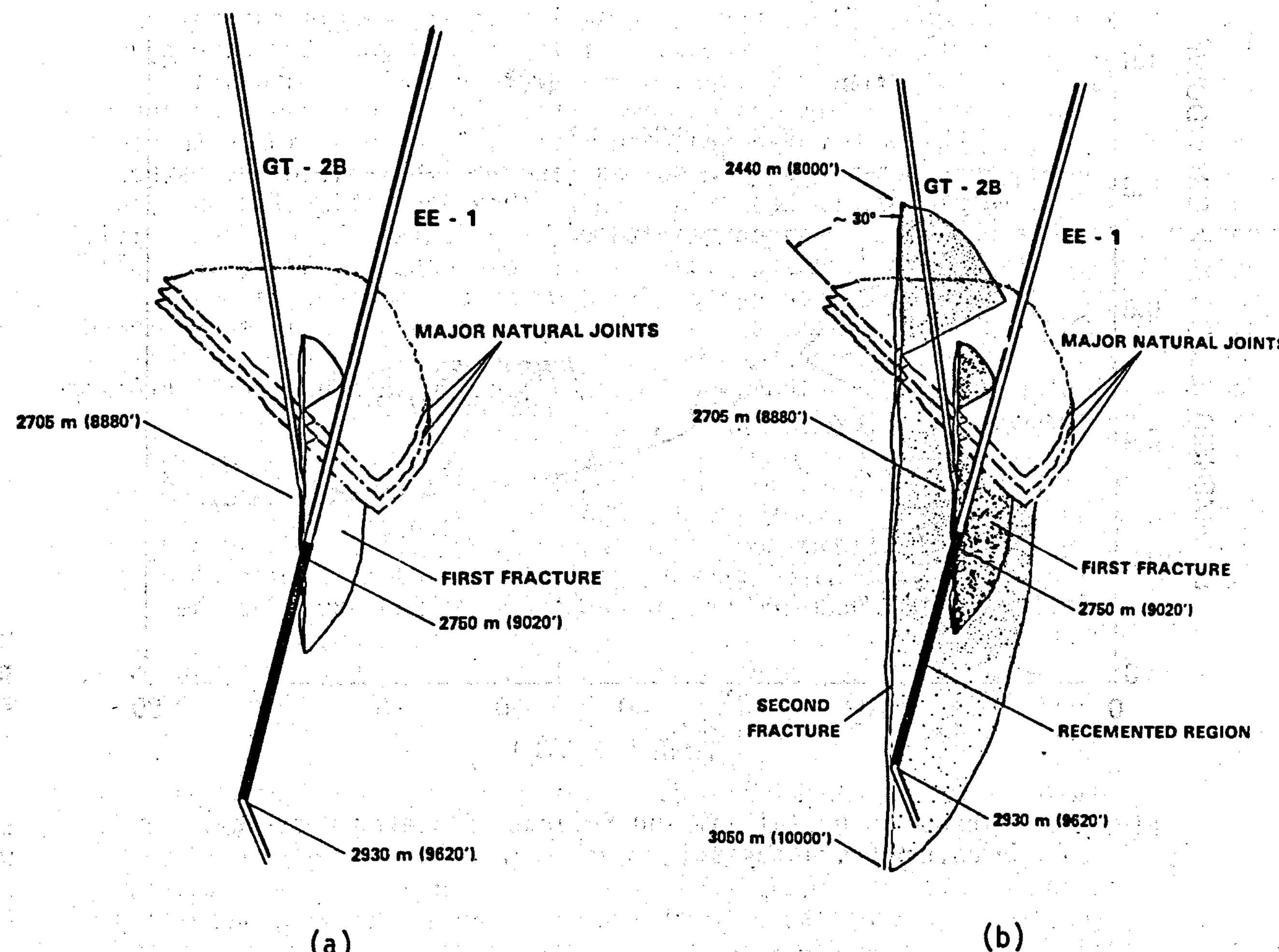

Fig. 6. Initial (a) and Enlarged (b) Research Reservoir Configuration

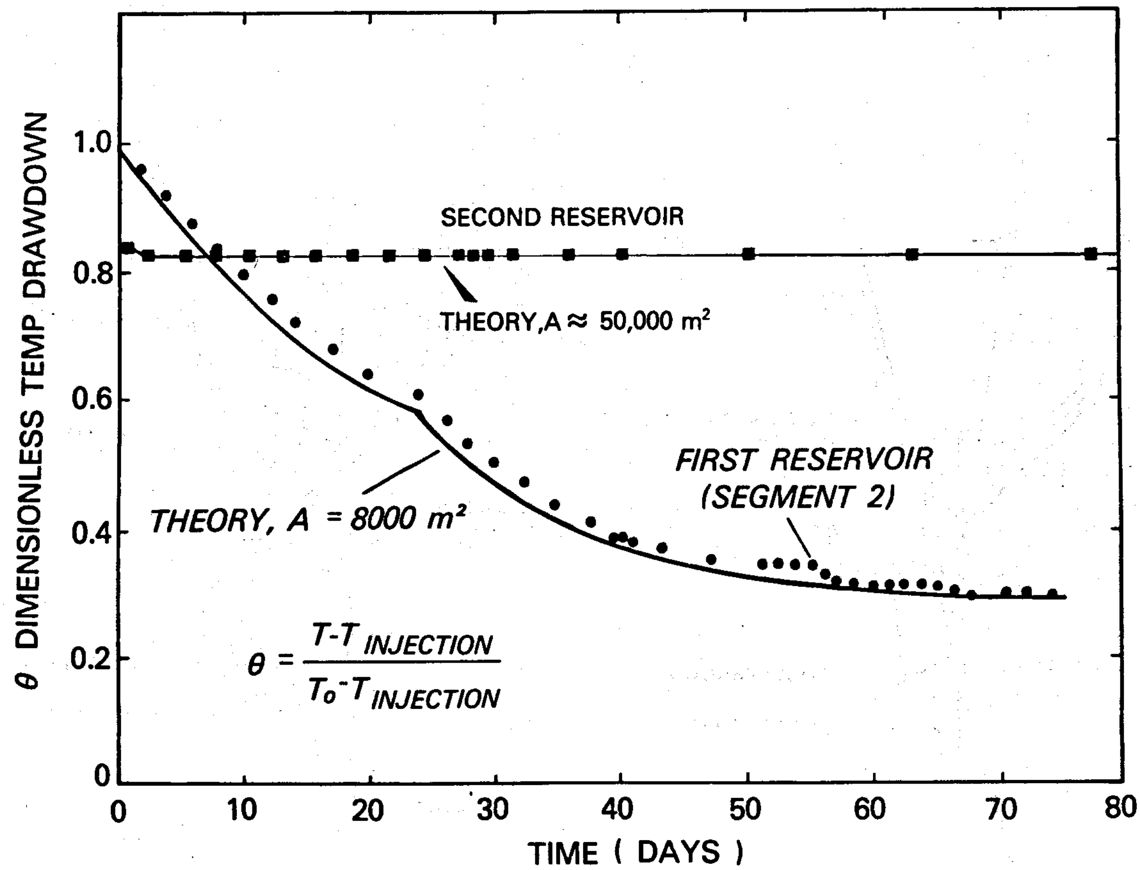

Fig. 7. Comparison of Initial and Enlarged Research Reservoir Drawdown Characteristics

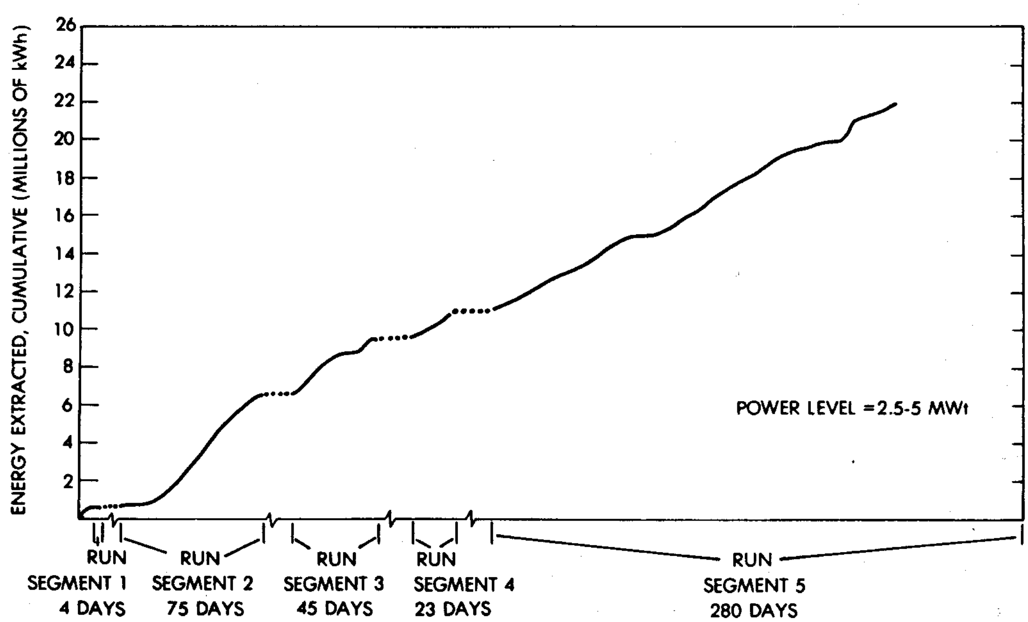

Fig. 8. Thermal Energy Extracted from Fenton Hill HDR Research Reservoir

- ENVIRONMENTAL EFFECTS - Perhaps most encouraging, no detrimental environmental effects were observed. In particular, under extremely careful monitoring, there was absolutely no evidence of affecting the composition of local aquifers or other hydrological effects and there was no detectable induced seismicity.

After some minor modifications to the surface plumbing to permit higher flow rates, Run Segment 3 was conducted during the period September to October 1978. In this segment, comprising about 786 operating hours, three distinct flow experiments were conducted back-to-back. The first of these was a series of transient flow-dependent impedance measurements; the second consisted of interwellbore acoustic attenuation surveys under shut-in conditions; and the third (and longest) was a continuous-flow experiment under high back pressure. This run segment was terminated prematurely because of the development of a major (∿3.5ℓ/s) leak behind the casing in the injection well. In the high-back-pressure operation it was observed that reservoir flow impedance declined significantly, from over 200 kPa-s/ℓ to about 55 kPa-s/ℓ.

The leak observed at the end of Run Segment 3 was due to final degradation of already degenerate cement in the annular space behind the casing of the injection well. Recementing was necessary and, in the process, access to the vertical fracture emanating from the EE-1 wellbore at 2750 meters was shut off. A new and much larger fracture was initiated (probably also a reopening of an old, sealed fracture) further down the wellbore and extended upward until it too communicated with the GT-2 well through the same system of natural joints, as seen in Figure 6(b).

Since the enlargement of the research reservoir was effected, two extended heat-extraction runs have been made. Run Segment 4 was conducted during October and November of 1979 for a total operating duration of 551 hours. The thermal drawdown data — or rather lack thereof — indicated that the effective heat transfer area had been increased by not less than a factor of 6. The second test, Run Segment 5, began near the end of February 1980, is presently in progress, and is scheduled to conclude about 15 December 1980. The enlargement of the reservoir is confirmed by the very gradual thermal drawdown, indicated by the upper data in Figure 7, and the effective heat transfer area of the research reservoir is now believed to be of the order of 50,000 m^2.

To date, over 20 million kilowatt-hours of thermal energy have been extracted from the Fenton Hill research reservoir at power levels ranging from 2.3 to 5.0 MW_t, as shown in Figure 8. Recently, a small on-line electric generation experiment has been added as part of Run Segment 5. The generating unit is a 60kVA (net) binary cycle turboalternator package using R-114 halocarbon as the working fluid. It is driven by a fraction of the superheated water produced from the research system and is connected into the site electric mains, providing a part of the base load.

In parallel with evaluation of the research system, planning and construction of an engineering system has been proceeding. Although the research system demonstrated initial technical feasibility of the concept and provided encouraging preliminary answers to some issues of concern, the establishment of a reservoir of more nearly commercial size and (even more important) longevity remains to be demonstrated in the engineering system.

A schematic comparison of the enlarged research system with the engineering system is given in Figure 9. As noted, the former now consists of two nearly vertical wells connected by a 50,000 m^2 fracture system in 200°C rock at about 3 km depth. The new engineering system will be both larger and hotter, consisting of two deeper wells -- EE-2, the injection well, and EE-3, the production well -- to a depth of about 4.5 km with their working sections inclined at 35° to the vertical. These wells will be connected by a multiple fracture system in the 300°C rock with a nominal effective area of 1.5×10^6 m^2. This engineering system, when completed, will be capable of producing 20-50 thermal megawatts with not more than 20% thermal drawdown in 10 years, and could be suitable for possible commercial use when the DOE-sponsored demonstration of the reservoir is complete.

The injection well, EE-2, is now complete to a depth of 4450 m with a bottomhole temperature of 320°C and the production well, EE-3, is being drilled. Establishment of the fracture system is scheduled to begin in 1981.

(B) PLANS FOR SITE 2 PROJECT

A key program activity is the selection of a second experimental HDR site. Development of such a site is necessary to establish: (a) that the reservoir techniques utilized at Fenton Hill or modifications thereof, are applicable in a different formation; and (b) an expanded data base for assessing the commercial feasibility of HDR energy. Survey of the existing data continued through 1978, culminating in the nomination of a number of candidate prospect areas throughout the US. From this listing, the most promising prospect areas were selected for detailed geophysical investigation. Conduct of this field work is now in progress. The anticipated outcome is sufficiently positive characterization to permit selection of a specific site early in 1982.

(C) INSTRUMENTATION AND EQUIPMENT DEVELOPMENT

Another major area of technology development, which directly supports experimental operations at Fenton Hill (and will, subsequently, at Site 2), is directed toward providing the specialized instrumentation and downhole equipment needs of the HDR Program, which are commercially unavailable. Whenever possible, development is accomplished through subcontracts with industry, thereby effecting immediate technology transfer as well. In addition, these developments are coordinated with those of Sandia's Geothermal Instrument Development and Drilling Technology programs, as well as the needs of USGS, to avoid duplication of effort.

During 1978-79, Maurer Engineering proceeded with development of the turbodrill, a high-temperature downhole drilling motor, sponsored jointly by DOE/DGE and the DOE/Division of Fossil Energy Extraction (DFEE). It was successfully field tested in the drilling of well EE-2 and is now being used in the drilling of EE-3 at Fenton Hill. LASL also sponsored improvements in open-hole packer and shock-sub temperature capability. These high-temperature units are being tried in the same drilling program.

Development work also continues on a high-temperature multiconductor instrument cable. Testing is currently in progress of 1000-foot evaluation specimens from several sources.

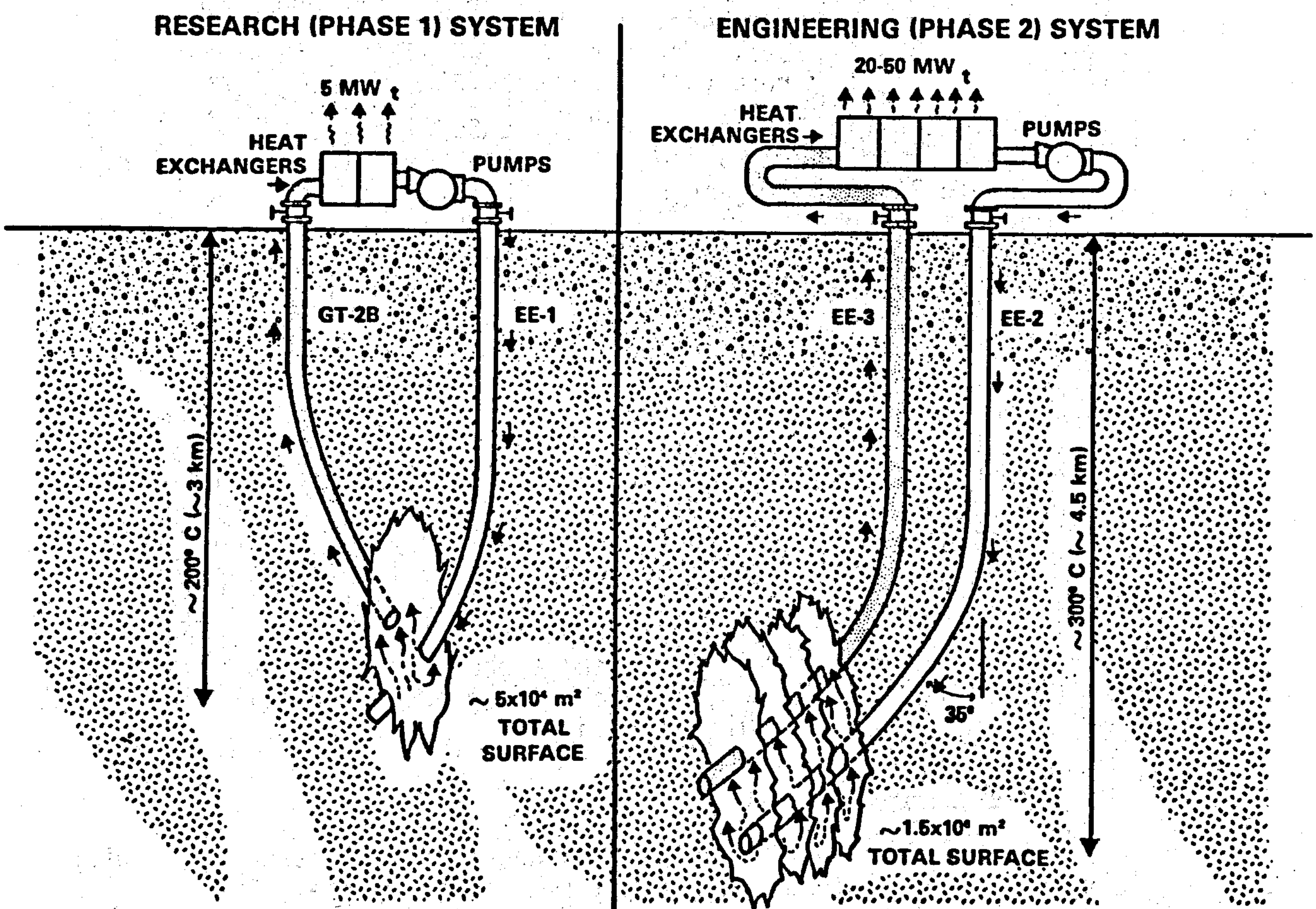

Fig. 9. Comparison of Fenton Hill Research and Engineering Systems

TABLE I

HIGH-TEMPERATURE INSTRUMENTS AND EQUIPMENT
DEVELOPED TO DATE

Item	Developer/Vendor(s)
Temp./Pressure Probe (260°C)	LASL/Bell & Howell
Wellbore Fluid Sampler	LASL/Globe
3-Axis Fluid Sampler	LASL/Mark Products
Mechanical Acoustic Source	LASL/Globe
Multidetonator Acoustic Source	LASL/Reynolds/Vacuum Barrier
Fluid Sample Downhole Injector	LASL/Globe
Self Potential Probe	LASL
Temp./Conductivity Probe (275°C)	LASL
3-Indep.-Arm Caliper/Contour Probe	LASL/Dale Electronics
Wellbore Fluid Velocity Meter	Worthwell-LASL
Radiotracer Injector/Monitor Tool	Worthwell

Major LASL-internal developments are listed in Table I. With the exception of the first item listed, all of these instruments have a temperature capability of at least 275°C. Those recently completed included improved downhole temperature- and velocity-measuring units and a temperature hardened 3-independent-arm caliper tool for borehole gaging. Subcontracted work on fracture-mapping instruments includes: feasibility studies and preliminary design for a radar-based far-field mapping tool and in situ stress measurement device; fabrication of a prototype downhole acoustic transceiver unit utilizing a magnetostrictive driver; and a phased program to develop a high-temperature downhole video system which will produce real-time monochrome images under visible and ultraviolet illumination.

INSTITUTIONAL ISSUES ANALYSES

There are a number of quasitechnical and non-technical issues that will affect the suitability of HDR as an alternative energy source. For convenience, they are categorized as Institutional Issues. They include: (1) legal aspects of HDR development; (2) regulatory issues; (3) environmental effects of intensive development; (4) water availability; and (5) public awareness. The program is examining the extent to which these issues may impact HDR development.

Institutional aspects of HDR development typically differ from one locale to another and depend on subjective factors as well as objective considerations. For instance, the legal definition of "geothermal resource" varies widely among the States. The variance in this case is due largely to differences in the public's perception of geothermal resources rather than a real physical difference among resources.

Similarly, regulatory controls are subject to differing degrees of interpretation and enforcement. As the perception of HDR and its technology varies from one place to another, so will the extent to which HDR development is accepted.

Activities involving institutional issues include environmental studies, legal/regulatory studies, and public relations. Environmental studies are directed at obtaining more definitive information about the effects of commercial-scale HDR development. Although much experience from hydrothermal projects is directly applicable because the effects are similar to those expected from HDR, other environmental aspects of HDR are unique to its application. Careful and continuous environmental monitoring is being done in conjunction with the program's demonstration projects. This operational experience will clarify the environmental issues and help to place them in perspective for the regulatory authorities. A detailed Environmental Analysis Report and an Environmental Impact Assessment have been published for the Fenton Hill Site.

Studies of laws and regulations at both the Federal and State levels are identifying potential barriers to HDR development. Where possible, developmental routes to avoid or eliminate barriers will be suggested. A preliminary legal study was published in 1979 discussing the differences from state-to-state in the definition of the "resource" under which the ownership question would be adjudicated. The study proposed a more consistent sui generis definition.

The interested public, including the geothermal industry, financial community, and regulatory agencies, is being kept informed of the program's progress and findings. This information is being disseminated through discussions and presentations, press releases, a quarterly newsletter, educational materials, brochures, technical reports, and annual conferences.

COMMERCIAL FEASIBILITY ASSESSMENT

Commercial feasibility can best be proven by demonstration combined with appropriate economic analyses; both are deemed essential to reaching the program's goal. Demonstration is implicit in the Technology Development element. Economic analysis, which involves a synthesis of all critical factors affecting the cost of HDR systems, is conducted in this Program element.

Economically-oriented studies have been an ongoing activity in the Program since its inception. Preliminary studies, done by LASL in concert with the University of New Mexico and (at this stage of development) subject to a great many assumptions, have shown that HDR-derived energy costs can be of the right order of magnitude to be competitive with other energy sources in the post-1990 time frame.

A more comprehensive economic systems study is now underway, focusing on the modeling of reservoir establishment and management strategies. The overall study will examine drilling costs, conversion costs and so forth. Sensitivity analyses will identify cost-sensitive factors and through a feedback mechanism, technology improvements which reduce costs will be pursued. The study will include institutional and other factors that influence development costs. As more field data become available, the study will be updated.

The ultimate question to be answered is: Can energy produced through HDR technology compete with that from other energy production technologies in the private marketplace? The answer will come from a final commercial feasibility analysis that accounts not only for technology costs and benefits, but for the availability of resources, market needs, and regulatory requirements.

SUMMARY

The HDR Program is a multifaceted long-range program of national scope aimed at establishing an energy-producing industry. It is a combined development and demonstration program whose elements include: characterizing the resource; cataloging promising sites; developing the reservoir technology, and required tools and instruments; attacking the institutional problems and assessing the commercial feasibility of the concept in the near future.