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**Environmental Monitoring for the Hot Dry Rock
Geothermal Energy Development Project
Annual Report for the Period July 1975—June 1976**

Compiled by

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ENVIRONMENTAL MONITORING
FOR THE
HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROJECT
ANNUAL REPORT FOR THE PERIOD JULY 1975 THROUGH JUNE 1976

Compiled by
Roland A. Pettitt

ABSTRACT

For the last four years, the Los Alamos Scientific Laboratory has been investigating the feasibility demonstration of a technique for extracting geothermal energy from hot dry rock existing at moderate depths beneath the surface of the earth. In the hot dry rock (HDR) concept, a manmade geothermal reservoir would be formed by drilling an initial borehole into a region of hot rock, creating a large fracture at the bottom of the hole, then intersecting the fractured area with a second borehole. The heat contained in this underground reservoir would then be brought to the surface by the circulation of water through the system.

The objectives of this environmental monitoring report are to provide a brief conceptual and historical summary of the Hot Dry Rock Geothermal Project, a brief overview of the environmental monitoring responsibilities and activities of the Los Alamos Scientific Laboratory, and descriptions of the studies, problems, and results obtained from the various monitoring programs. Included are descriptions of the work that has been done in three major monitoring areas: (1) water quality, both surface and subsurface; (2) seismicity, with a discussion of the monitoring strategy of regional, local, and close-in detection networks; and (3) climatology. The purpose of these programs is to record baseline data, define potential effects from the project activities, and determine and record any impacts that may occur.

The development of the hot dry rock geothermal energy resource and associated energy

extraction technology is a new field of endeavor, with no established environmental guidelines. It is doubtful if the problems encountered and solutions devised in traditional geothermal systems will apply directly to hot dry rock development. Therefore, the impacts that are encountered in this project will be of particular value in making future environmental assessments for this type of energy resource development in other locations in different geologic settings.

By the end of the reporting period, there had been no unacceptable impacts on the environment in any of the three monitoring areas.

I. INTRODUCTION^{1,2}

In its broadest sense, geothermal energy is all of the heat in Earth's interior. Most of this energy, unfortunately, is now useless to man because of difficulties in locating and utilizing it. However, as these obstacles are overcome, power produced from geothermal sources should increase to the point at which it can satisfy a significant fraction of man's total energy needs.

The Earth's physical nature is now widely enough understood so it is probably safe to state that, simply by drilling a sufficiently deep hole, rock can be reached that is hot enough to be potentially useful as an energy source. There are many approaches by which energy can be extracted from the hot rock at the bottom of such a hole and transported to the surface, and by which it can then be used beneficially. The problems of geothermal energy, therefore, derive not so much from questions about the possibility of recovering and using heat from geothermal reservoirs as from those about economics. How can this heat be recovered and used at a competitive price?

Until now, geothermal energy has been used commercially only where nature has created a geologic situation in which heat from Earth's interior is transported to the near-surface by convective circulation of steam or very hot water. A hydrothermal reservoir of this type usually leaks, thereby creating obvious surface expressions of its presence -- fumaroles, geysers, or hot springs. Where these indications are found, holes are drilled and steam or hot water is recovered through them for use at the surface.

A. Present Uses of Geothermal Power

1. Dry Steam. When the hot fluid in a geothermal reservoir is superheated (dry) steam, it need only be permitted to issue from a drilled hole, be passed through a centrifugal separator to remove any entrained particles, and be fed into a turbogenerator to produce electrical power. The world's two largest producers of geothermal power, at Larderello, Italy, and The Geysers in northern California, use natural dry steam in this way and provide relatively clean, very economical power.

2. Superheated Water. Natural hydrothermal systems in which the reservoir fluid is hot water are much more numerous than are those in which it is steam, as is suggested by the relatively common occurrence of hot springs in many parts of the world. The amount of thermal energy contained in subterranean hot water is enormous. Large-scale development of liquid-dominated geothermal systems has, however, been undertaken only at Wairakei, New Zealand, and Cerro Prieto, Mexico, for generating electricity and in Iceland, Hungary, and the Soviet Union for space heating, although there are smaller developments at several other places around the world.

3. Hot Dry Rock. Even in dry-steam or superheated-water reservoirs, much more than half of the thermal energy is contained in the reservoir rock. The heat is there even when steam or water is entirely absent. At sufficient depth, rock hot enough to be potentially useful as an energy source exists everywhere, and initial studies suggest that in many places it is at depths shallow enough to be reached at moderate cost with existing drilling equipment.

A recent survey³ of all available regional heat-flow data indicates that about 7% of the western heat flow province of the United States -- about 95 000 square miles in the 13 western states -- is underlain, at a depth of 5 km (16 400 ft), by hot, but essentially dry, rock at temperatures above 290°C (550°F).

B. Environmental Assessments of Geothermal Development^{4,5}

Any power production system will have some impact upon the environment into which it is placed. However, of those forms presently utilized (coal- or gas-fired plants, nuclear plants, etc.), geothermal systems appear to have the least detrimental environmental impacts. In fact, numerous environmentalists believe

that this source of energy may prove to be the cleanest source of power available to man.⁶

1. Esthetic Impact. Land usage and landscape scarring by geothermal systems will approximate that of other energy production systems, mitigated to some extent perhaps by smaller plant size and the absence of fuel storage and handling yards. Support operations such as mines, fuel processing, and transportation do not exist, so the environmental effects are solely site dependent. However, steam or water collection systems are generally required and these can be unsightly from an esthetic standpoint. Also, because of noise, odor, and visual impact, geothermal development has not been generally compatible with residential or recreational land use.

2. Environmental Impacts. Major environmental problems usually arise in hydrothermal developments in one of the two general areas: concentration of undesirable minerals and ground subsidence,⁷ or gaseous and particulate emissions.

Mineral Concentration and Ground Subsidence. Traditionally, the mineralized water from steam condensation or unflashed mineralized water from wet steam fields has been drained into nearby surface water systems. This has resulted in both chemical and thermal pollution which in most countries is no longer acceptable. Furthermore, the removal of hot water from large underground systems has, in some cases, caused subsidence of the surface. Removal of large quantities of water has also had the effect of aquifer depletion in cases where the natural recharge rate is slower than that of removal.

The solution to both these problems has been attempted by reinjection of the mineralized water into the producing formation through unproductive wells or wells especially drilled for that purpose.⁸

Although microearthquake activity seems to be commonly associated with geothermal regions, earthquakes of an intensity to cause surface disruption are less common than in geologically similar regions not containing the heat. However, studies by the U. S. Geological Survey (U.S.G.S.) and controlled earthquake experiments at Rangely, Colorado, suggest that significant earthquake activity can be induced by the injection of large volumes of fluid under high pressure into active vault systems. This was further evidenced by the earthquake experience at the Rocky Mountain Arsenal near Denver, Colorado (see Sec. V).

Therefore, some degree of caution must be practiced when reinjection operations are to be accomplished.

Another problem incurred with reinjection is that of aquifer pollution. Pumping large quantities of mineralized water back into these formations tends to increase the concentration within the total aquifer, and damage can occur to culinary water supplies which are connected to the system. Even in a multilayer (stratigraphic) system where culinary water is taken from shallow subsurface layers and hot water from much deeper layers, pollution of the culinary water supply can occur if the recharge systems for the two layers are connected at some point within the geologic formations of the region.

Air Pollution. The most publicized noxious material causing air pollution from geothermal steam power plants is hydrogen sulfide gas.⁹ In addition to this, there are undoubtedly other gaseous chemicals, e.g., mercuric compounds, ^{210}Pb , ^{222}Rn , etc., which affect the environment when allowed free discharge to the atmosphere.

Although particulate emission from geothermal steam plants may not be readily apparent, it can occur. Direct contact condensers concentrate the particulates (boron, arsenic, fluorides, and free ammonia) as much as five-fold through the evaporation process at the cooling tower. Water leaving the tower as drift-loss will contain equivalent concentrations in the droplets. Atmospheric dispersion and evaporation of the droplets will leave a dust of these materials on the surrounding land.

3. Hot Dry Rock Geothermal Development. The foregoing discussions of esthetic and environmental impacts pertain to experience gained in previously developed dry- or liquid-dominated geothermal systems. The development of the hot dry rock geothermal energy resource is a new field of endeavor, with no known environmental guidelines. It is doubtful if the problems encountered in traditional geothermal systems will apply in their entirety to the hot dry rock concept. Therefore, the impacts that are seen in this project will be of great value in making future environmental assessments for this type of energy resource development in other areas under different geologic conditions.

C. Objectives of the Environmental Monitoring Report

The objectives of this report are to provide (1) a brief conceptual and historical summary of the Hot Dry Rock Geothermal Project, (2) an overview of the environmental monitoring responsibilities and activities of the Los Alamos Scientific Laboratory, and (3) specific descriptions of the studies, problems, and results obtained from the various monitoring programs from their inception through June 30, 1976.

Included in these monitoring activities are descriptions of the work that has been done in three major areas: (1) water quality, both surface and sub-surface; (2) seismicity, with a discussion of the monitoring strategy of regional, local, and close-in networks; and (3) climatology. These activities are aimed at defining and quantitative recording of potential environmental effects from the project activities.

II. PROJECT BACKGROUND

A. The Hot Dry Rock Concept

For the last four years, the Los Alamos Scientific Laboratory (LASL) has been actively investigating the potential for, and problems associated with, the feasibility demonstration of a technique for extracting geothermal energy in those parts of the United States that contain hot dry rock at moderate depths suitable for utilization.

In the Hot Dry Rock concept, a manmade geothermal reservoir would be formed by drilling into an identified region of hot rock, and then creating within that rock a very large surface area for heat transfer by use of large-scale hydraulic fracturing techniques similar to those developed by the oil industry. After a circulation loop is formed by drilling a second borehole that intersects this fractured region, the heat contained in this reservoir rock would be brought to the surface by the buoyant circulation of water, possibly with no need for pumping. The water in the loop would be kept liquid by pressurization at the surface, thereby increasing the rate of heat transport up the withdrawal hole compared to that possible with steam. Figure 1 is a conceptual diagram of such a manmade geothermal system.

Preliminary experiments and analyses¹⁰ indicate that thermal stresses created by cooling of the hot rock in such a manmade reservoir may gradually

enlarge the fracture system so that its useful lifetime will be extended far beyond the planned 10-15 yr provided by the original reservoir. If these thermal-stress cracks grow preferentially downward and outward into hotter rock, as seems probable, the quality of the geothermal source may actually improve as energy is withdrawn from it.

B. Goals and Activities

The primary goals of the Los Alamos Hot Dry Rock Geothermal Project are to investigate and develop methods of extracting energy economically from hot rock in Earth's crust, and to assist further industrial development and widespread application of this new technology. This work will involve large-scale field studies and demonstrations of drilling into hot rock, fracturing it by hydraulic pressure or by other methods to produce connected circulation paths through it, and then circulating water through these channels to extract the heat and transport it to the surface. It will also include research and development in

Fig. 1.
Conceptual diagram of a manmade HDR geothermal system.

geochemistry, geophysics, heat flow, fluid flow, rock mechanics, instrumentation, data analysis, seismology, environmental effects, system modeling, and related subjects required to make such an energy extraction system successful, economical, and environmentally acceptable.

The initial goal is to produce and demonstrate an experimental geothermal energy extraction system suitable for use in relatively dry, impermeable rocks like the granite of the western and northeastern United States. The second goal is to demonstrate energy extraction at a rate potentially capable of supporting a 10-MW electrical generating plant (see Fig. 2). The third goal is to investigate and develop such modifications of the general method as may be required to make it useful in other geographical locations and geological situations, especially in more permeable rocks.

C. Geologic Setting¹¹ of Project

The initial geothermal source demonstration project area is located on the Jemez Plateau, a part of the western arm of the Rocky Mountains that extends into northern New Mexico (Fig. 3). About a million years ago, the Valles

Fig. 2.
Conceptual diagram of the Hot Dry Rock Geothermal Experimental System.

Fig. 3.
Major structural features and area of investigation in north central New Mexico.

Fig. 4

Plan view of Valles Caldera showing location of rhyolite domes, geothermal well locations within the caldera and the Fenton Hill site (after Smith, Bailey, and Ross, 1970).

Caldera was formed when a large volcano erupted violently and then subsided into its own empty magma chamber. The Jemez Plateau is part of an apron of volcanic ash ejected during the eruptions. A subsequent series of smaller volcanic events is now represented by a number of rhyolite domes along the inner periphery of the caldera (Fig. 4). As a result of this vulcanism, a large amount of heat is still retained in rocks underlying the entire area within a few kilometers of the surface.

D. Site Selection

In April 1972, four test holes from 150-230 m (500-750 ft) deep were drilled on the western exterior slope of the caldera. They were cored and cased for geologic investigations and thermal gradient measurements. A deeper test hole (Geothermal Test Hole No. 1, GT-1) was drilled in May and June of 1972 to provide additional geological information and temperature data, and to investigate drilling problems in the area. This hole reached a depth of 785 m (2575

ft) and extended 143 m (470 ft) into the Precambrian basement rocks, where the bottomhole temperature was about 100°C.¹²

On the basis of these studies and field experiments, the site on the Jemez Plateau about 32 km (20 air miles) west of Los Alamos was selected as being appropriate for development of the first dry rock energy experiments (Fig. 5). This has been designated as the Fenton Hill site (Technical Area 57, or TA-57). It is a gently sloping area on top of a mesa that was burned over in a forest fire in 1971, so site preparation involved minimal leveling and no destruction of live timber. It is immediately adjacent to an all-weather state highway and to power and telephone lines, and is crossed by a forest road.

The first exploratory drill hole at this site was designated Geothermal Test Hole No. 2 (GT-2); the second, Energy Extraction Hole No. 1 (EE-1).

E. Drilling and Testing Progress

1. Hole GT-2. Drilling of GT-2 began in February 1974. Serious problems encountered in drilling the Permian-age red beds¹³ and the Pennsylvanian-age shales and limestones required that a string of 34-cm-diam (13-3/8-in.) casing be set to a depth of 488 m (1600 ft). The Precambrian granitic surface was reached at 733 m (2404 ft), and a second string of 27.3-cm-diam (10-3/4-in.)

Fig. 5.

Aerial view of the Fenton Hill Site (TA-57), looking west. Borehole GT-2 is on the left, EE-1 is in the center.

casing was set from the surface to 773 m (2535 ft). Drilling continued to 2042 m (6700 ft) using 24.4-cm-diam (9-5/8-in.) bits.

At this depth, a series of hydrology experiments was performed to determine the permeability of the deeper granitic rocks. Hydraulic fracturing experiments were also conducted using methods and equipment developed by the oil well services industry. Although the rock at this depth seemed to be broken by extensive natural fractures, water leak-off was slight.

As a result of these experiments, the Fenton Hill site was judged suitable for further development of the geothermal project. The hole was deepened to 2932 m (9607 ft) and a 185-m-long (608-ft) liner was cemented into the bottom section of the hole to facilitate seating of packers for future fracturing experiments. The equilibrium bottomhole temperature was 197°C (386.6°F).

Additional fracture experiments were performed through perforations in the liner and in the open hole below the liner. A near-vertical, 122-m-radius (400-ft) fracture was created near the bottom at an initial pumping pressure of 12.1 MPa (1750 psi).

2. Hole EE-1. The second hole was located 77 m (252 ft) northeast of GT-2 (Fig. 5). Drilling began in May 1975 and was completed in October at a depth of 3064 m (10 053 ft) and a bottomhole temperature of 205.5°C (402°F). EE-1 was cased to 1957 m (6420 ft) with three strings of casing, the deepest being 27.3 cm (10-3/4 in.) in diameter.

Directional drilling techniques were used below this casing to angle EE-1 toward the fracture at the bottom of GT-2. The hole was drilled through a 205-degree spiral, turning counterclockwise from an initial northwest heading to a northeast heading. On October 14, 1975, the GT-2 fracture was determined to be intersected from the borehole directional guidance data. After the intersection was confirmed by limited circulation through the fracture system, EE-1 was cased to 2926 m (9600 ft) with a 19.4-cm-diam (7-5/8-in.) casing for subsequent pressurized flow and heat extraction experiments. Circulation tests between the two holes are currently being conducted to determine the dimensions and characteristics of the downhole reservoir system.

The predominant Precambrian rock in both holes is banded granitic gneiss. In one section, biotite schists are interlayered with the gneiss which is intruded by unfoliated monzogranite dikes. A relatively extensive and homogenous biotite-granodiorite body was encountered at depth. Drill cores show numerous

fractures, usually well sealed or healed. These two holes constitute the bulk of existing drilling experience in hot granitic rocks using conventional oil-field equipment.¹⁴

III. ENVIRONMENTAL MONITORING BACKGROUND¹⁵

A. Overview of LASL Environmental Monitoring

In 1943, a wartime laboratory was established at Los Alamos; its singular mission was the development of a fission bomb. This project culminated in the detonation of the first atomic bombs in 1945 and the end of World War II.

Expansion of Laboratory efforts since that time has incorporated numerous programs to develop peaceful uses of nuclear energy, with an increasing diversification into nonnuclear areas, such as solar and geothermal energy. Environmental assessment of the continuing operations at the Los Alamos Scientific Laboratory has been carried out in accordance with Federal Regulations. Many long-term environmental studies are under way as part of ongoing research and monitoring programs designed to continually document interactions of Laboratory activities with the environment and to permit re-evaluations as knowledge increases.

Wastes generated as by-products of the Laboratory operation include common sanitary and solid wastes, as well as uncommon wastes such as radioactive, chemical, and high-explosive contaminated materials. The ordinary sanitary liquid wastes and solid wastes are treated and disposed of by standard procedures: conventional sewage treatment plants, lagoons, septic tanks, and sanitary land fill.

Uncommon wastes receive suitable special treatment to meet appropriate standards prior to release to the environment. This special treatment includes removal of radioactivity, detoxification of chemical agents, subsurface retrievable storage in controlled areas, burning, and filtering. A continuing, comprehensive monitoring program, including procedures ranging from continuous monitoring of some effluents to regular periodic sampling of air, water, and soil and biological materials at on- and off-site locations, has documented that no significant environmental impacts have resulted from the Laboratory operation.

The continuing comprehensive environmental monitoring program ensures that any adverse trends, should they develop, will be detected at an early time so that appropriate mitigating actions can be taken before significant effects occur. An internal Quality Assurance program reviews all new proposals during the design process to permit consideration of possible safety and environmental consequences prior to construction or program initiation.

B. Fenton Hill Geothermal Site Description

1. Natural Setting. The Fenton Hill site for the geothermal experiment is located on the Jemez Plateau to the west of the Valles Caldera. The surface of the plateau is tuff, consolidated from the volcanic ash that flowed out of the large volcanic peak whose subsequent collapse created the Valles Caldera. Deep erosion of this soft tuff and of the underlying sedimentary rocks has cut the plateau into flat-topped mesas and steep-walled canyons. The Fenton Hill site is on a mesa top at an elevation of about 2650 m (8700 ft) (Fig. 6).

This is a relatively cool, semiarid region, with an average annual air temperature of about 4.5-10°C (40-50°F), depending on the elevation, and an average annual precipitation of about 35-56 cm (14-22 in.). The mesa tops and higher slopes are forested mainly with Ponderosa pine and some fir and spruce. Groves of aspen and oak are found in the higher canyons with some willow and poplar in the valleys at lower elevations. Wildlife is plentiful on the Jemez Plateau and includes deer, elk, coyotes, bears, bobcats, and a variety of rodents; turkeys, falcons, golden eagles, and many other birds; and rainbow and brown trout in the streams.

The site is located in the Jemez Ranger District of the Santa Fe National Forest. About 20 km² (5000 acres) of this forest were burned over in a major fire in 1971, and the site is within the burned area. Most of the standing timber at this site was cut, and reforestation with seedling pines, aspen, and grasses was started by the U. S. Forest Service (Fig. 7).

2. Cultural Features. There are no known historical or archeological sites of interest within or near the demonstration site. The only community near this site is a small village, La Cueva, population less than 50, about 2.4 km (1.5 mi) by air or 5 km (3 mi) by road to the southeast. A developed campground and several summer cabins are closer to the site, the nearest being

Fig. 6.

Aerial view of Fenton Hill before construction. The drilling site is to the right of center, just beyond the highway.

Fig. 7.

Ground surface view of Fenton Hill. The GT-2 drilling site was subsequently located on the middle ridge.

about 1.5 km (1 mi) away. The terrain is such that the site is not visible from any campground or inhabited place. It is, however, directly visible from the state highway which passes along its eastern edge. Access and utilities are available with minimal additional disturbance to the environment.

3. Subsurface Studies. The geology and hydrology of the area have been studied in relation to siting the geothermal experiment. The first deep hole (GT-2) at the site penetrated through about 137 m (450 ft) of Cenozoic volcanics and about 730 m (2400 ft) of Permian and Pennsylvanian sediments to reach the Precambrian granitic basement. Perched water occurs in the volcanics and sediments, and a saturated ground water zone occurs in the sedimentary rock immediately above the granitic rock. These zones are isolated from the geothermal experimental hole by a cemented casing which extends from the surface down into the granite. Studies of fault activity and seismicity conducted before deep

drilling was started showed the site to be relatively free of active faults and that regional seismicity is at a low level of activity.¹⁶ A regional study of surface and subsurface water quality was initiated in 1971 to establish background data.¹⁷

4. Continuing Environmental Studies. Geologic and seismic studies are continuing as an integral part of the geothermal experimental program. Specially funded environmental studies were started in FY76* to develop detailed information on biotic inventories, ecological processes, physical processes such as hydrology and meteorology, and changes that may occur during the course of the geothermal experiment. The objective of the environmental studies is to provide a basis for assessing the impacts of energy production from dry geothermal sources in absolute and relative terms, both for this specific project and for guideline use on other future projects in different areas and conditions.

C. Environmental Responsibilities

The area chosen for the geothermal experiment is on U.S. Government land, part of the Santa Fe National Forest under the jurisdiction of the Department of Agriculture. The Jemez District Ranger of the Santa Fe National Forest (S.F.N.F.) completed an Environmental Analysis Report and determined that initial operations, through the drilling phases, were acceptable from environmental and public land use points of view. A Memorandum of Understanding between the AEC (now ERDA) and the U.S.D.A., Forest Service, S.F.N.F. (Contract AT (29-0) - 2213, signed November 30, 1973) was written to define the land, the basis of use and responsibilities of both parties.

The Forest Service will not give permission to operate a large heat extraction circulation loop until LASL assures no on-site pollution from silica or other mineral separation residue. The Forest Service continues a cooperative management attitude by reviewing subprojects and general site conditions. It was agreed that the responsibility for the Environmental Impact Assessment required for the overall project would be ERDA's (and LASL as an ERDA contractor) and that the Forest Service analysis report would be incorporated therein.

D. Environmental Assessment

An environmental assessment was prepared during program definition and prior to formal establishment of the HDR program. This was the initial step in

* Funded by the Division of Biomedical and Environmental Research (DBER), ERDA; to culminate in a detailed report at a later date. 15

fulfilling requirements of the National Environmental Protection Act (NEPA) and ERI (AEC) for environmental evaluation and protection. The assessment concluded that the experimental operation would cause no unacceptable environmental disturbance.

When the program was established, a draft environmental assessment was prepared and distributed to appropriate parties within the AEC (at that time the agency sponsoring the R & D program). The lack of experimental results and specific knowledge of some possible impacts justified the decision to proceed with caution and use this experiment to provide the information on which to base an impact statement for future developments at Fenton Hill (beyond the circulating loop demonstration phase) or similar projects elsewhere.

E. Environmental Impact at Fenton Hill Site

1. Construction and Drilling. Site preparation, minor construction, and drilling operations have taken place since initiation of operations at the Fenton Hill site early in 1974. These actions have resulted in minor but observable impacts.

About 0.03 km² (7 acres) of land were cleared of stumps and dead timber remaining from the 1971 forest fire, and of mixed grasses and seedlings planted for revegetation after the fire. Most of this area was leveled for placement of drilling equipment and trailers containing instrumentation and personnel facilities. Some excavation and damming was necessary to create a settling pond and three pits for controlling and handling drilling fluids. Construction activities included installing an electrical transformer pad, building fences to enclose parts of the area, stringing a 120-m (400-ft) electric service line from the existing transmission line, and installing some road drainage culverts. A number of seismic monitoring stations have been established in the vicinity, each involving a hole approximately 3 m (10 ft) deep for instrument placement and covered by a small weather enclosure (see Sec. V).

During drilling operations there are some emissions in the form of exhausts from equipment motors, noise, and circulation of drilling fluids. The drilling fluids are retained in the impoundments until solids are settled out (Fig. 8). The solids are removed to an old quarry site on Forest Service lands for disposal.

2. Fracturing. Potential environmental effects may be associated with the creation and operation of the induced fracture circulation system. The major possibilities that must be considered include induction of seismic effects, heat rejection, mineral disposal, and ground subsidence.

The combination of careful site selection with regard to both existing faults and natural earthquakes, controlled injection and operating pressures, and modest fluid volumes, make it appear that the earthquake hazard associated with the proposed demonstration is extremely small. Nevertheless, the risk must be taken seriously. A local seismic net including the area, and on-site micro-seismic instrumentation at Fenton Hill, has been used for real-time monitoring of acoustic signals generated by fracturing events during creation and operation of the downhole fracture system (reservoir). No surface signals have been observed that can be correlated with any of these activities. If signals interpretable as precursors to a significant seismic event were to be detected, then system pumping pressure would promptly be reduced. According to water injection experiences at the Rocky Mountain Arsenal in Colorado, this action should avoid triggering a damaging earthquake. To establish a base line of natural seismic activity, measurements of the natural seismic background in the area are being made continuously (see Sec. V).

3. Circulation System By-products. During experimental operation of the initial heat extraction loop, the circulating water will extract heat and dissolve minerals from the hot basement rock and transport them to the surface. The heat will be rejected from a forced draft, air-cooled heat exchanger (Fig. 9) at a maximum rate of about 10 MW(t), and dissipated as a rising plume of warm air. The buoyant plume will rise rapidly even in a strong crosswind, so that local heating at or near ground level is expected to be negligible.

The mineral composition of the granite comprising the downhole reservoir contains mostly iron, potassium, sodium, calcium, and magnesium as hydrated oxides of aluminum and silicon, pure quartz, and some carbonates. Dissolved material brought to the surface will resemble the products of the natural weathering of granite,¹⁸ and should not be objectionable. An important part of the program is directed toward controlling the dissolution and reprecipitation of such minerals. Present estimates indicate a total dissolved solids (TDS) content of less than 500 ppm for fluid circulating in a 200°C reservoir with dissolved silica (SiO_2) as the major component.

Fig. 8.

Water scrubber at end of drilling exhaustline used to remove cuttings when drilling with compressed air. Drilling fluids are retained in settling ponds shown on right and left.

Fig. 9.

Heat exchanger unit being lowered to ground at the Fenton Hill site; EE-1 tower on the right.

As heat is removed from the circulating fluid, it is possible that its temperature will decrease to a point where the concentration of SiO_2 becomes supersaturated with respect to amorphous silica, and scale can potentially deposit within the heat exchanger tubes or within the surface plumbing of the cold reinjection leg of the system. Although operational procedures may prevent or at least reduce the deposition problem, an estimate of the worst case can be made. For a 10-MW(t) system, as much as 730 kg (1600 lb) of material per day might precipitate and need to be disposed of in an acceptable manner. Any unusable by-products of the operation will be disposed of by methods meeting State and Federal regulations and approved by the Forest Service.

4. Surface Effects. Laboratory experiments using core samples from the first deep hole indicate there will be no gaseous emissions. Since the

circulation system is a closed loop, there should be no chemical or thermal pollution of surface or ground water.

Ground surface subsidence is not expected to occur. The fracture system will be created at great depth, approximately 3400 m (10 000 ft). The fracture is expected to be pancake-shaped, with a radius of a few hundred meters, and vertically oriented. Even after several years of circulation, a porous zone is not expected to be more than about a meter (a few feet) thick. Thus, the overlying competent crystalline rock should provide adequate support. Furthermore, pressure will be maintained to at least a hydrostatic level in the zone during the entire experiment and the fracture will be left filled at the conclusion. Ground levels and tilt are being monitored before, during, and after the experiments in order to fully document the actual situation.

IV. WATER QUALITY MONITORING^{17,19,20}

A. Potential Environmental Impact

The major surface water drainage in the area of the site is the Jemez River, the Rio Guadalupe, and their tributaries. Stream flow in the Rio Cebolla, a tributary of the Rio Guadalupe, is impounded at Fenton Lake. Ground water occurs in the Valle Toledo and Valle Grande in the Valles Caldera and in volcanics and sediments adjacent to the caldera. Ground water is also found in the alluvium along streams in the area. Shallow wells along the streams supply domestic water for campgrounds and cabins in the area. Water for the larger villages is supplied by wells or springs. Thermal and mineral springs discharge into the Jemez River and its tributaries.

The Fenton Hill site is bounded on the east by San Antonio Creek and on the west and northwest by the Rio Cebolla (Fig. 10). Lake Fork Canyon, to the south, drains the immediate area of the site and is tributary to the Rio Cebolla. Lake Fork Canyon and the canyon to the north of the site have only intermittent streams. The preliminary geologic and hydrologic investigations made during initial geothermal test drilling in the Jemez Mountains and the Fenton Hill site provided a basis for selecting the locations of the water quality monitoring stations.

Possible contamination of the surface water or the ground water of the drainage area of the Fenton Hill site has been considered since the inception

of the demonstration project. Leakage into the streams, or into the aquifer or natural springs, is highly unlikely because the operating procedures require total surface impoundment of drilling fluids and blockage by the insertion of casing in the geothermal holes to isolate the water-bearing zones in the volcanic and sedimentary rocks.

There are, however, several other operators in the immediate area. The activities include geothermal drilling on Redondo Creek by a commercial oil company, construction activities in the La Cueva area, and logging operations in the Jemez River watershed. If any of these activities were to contribute pollutants to the water supply, it might be important to the HDR project to show that the origin was elsewhere.

B. Water Monitoring

A preliminary study of the quality of surface and ground water was made in 1973 of the water quality in the Jemez River and Rio Guadalupe drainage areas to establish background data prior to the initiation of the hot dry rock experiments. The data compiled prior to 1971 were taken from a literature search, whereas data from 1971 through 1973 were collected from field surveys. Analyses were reported from 17 surface water stations, 15 mineral and thermal springs, and 53 ground water stations (wells, test holes, and springs).¹⁷

Additional water quality data were obtained in 1974 from surface water samples taken in the vicinity of the Fenton Hill site and from springs along Lake Fork Canyon and the Jemez River.¹⁹ In 1975, water quality at 9 surface water stations, 14 ground water stations, and from the drilling and testing operation at Fenton Hill was studied as a monitor of potential environmental impact of the geothermal project on the hydrology of the Jemez Mountains.²⁰

Routine chemical analyses were made for silica, calcium, magnesium, sodium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, total hardness, total dissolved solids, conductance, and pH. Analyses were made following methods given in Ref. 21. The discussion of the surface and ground water quality is made according to the group of predominant ions and TDS (total dissolved solids). The annual mean and the standard deviation of principal ions and TDS are compared in Table I for 1974 and 1975. The indicated variation (+) from the annual mean does not indicate the precision of individual analyses but is the deviation of the distribution of analyses at a single station.

C. Surface Water

Surface water in the tributaries to the Jemez River (Redondo, Sulphur, and San Antonio Creeks) is monitored because of geothermal development within the Valles Caldera. The Rio Cebolla below Lake Fork Canyon and the Rio Guadalupe above the Jemez River are monitored because of the contributions of ground water from volcanic rocks underlying the Fenton Hill site and surface water running from the site.

Analyses of surface water from nine stations along the Jemez River (Fig. 11), the Rio Guadalupe, and their tributaries are tabulated in this section. Station locations are shown by capital letters in Fig. 10 and are keyed to the analyses shown in Appendix A, Table A-I. The base flow of these streams is principally from a shallow ground water source in the Valles Caldera, from perched aquifers in volcanics, and from thermal or mineral springs. Each of the base flow sources has a particular chemical characteristic which may be modified by additional runoff from precipitation.

There are four general types of surface water in the area, based on predominant ions: (1) sodium and chloride, (2) calcium and sulfate, (3) calcium and bicarbonate, and (4) sodium and bicarbonate.

The principal ions in base flow at Locations U, R, and S are sodium and chloride (Table I). Location U, Redondo Creek, drains a small basin in the Valles Caldera. The maximum discharge at time of sample collection was estimated

Fig. 11.

U.S.G.S. Scientist (Frank Trainer) performs field analyses of surface water sample collected along the Jemez River (1975).

at 15 ℓ/s . Locations R and S are on the lower reach of the Jemez River (Fig 10). The maximum discharge at the two stations at time of sample collection was estimated at 910 and 680 ℓ/s , respectively.

The principal ions in base flow at Locations N, T, and Q are calcium and bicarbonate (Table I). Location N, San Antonio Creek, drains the western and northern parts of the Valles Caldera. The maximum discharge at the station at time of sample collection was estimated at 100 ℓ/s . Location T and Q are on the Rio Cebolla and Rio Guadalupe (Fig. 10). The maximum discharge at the two stations at time of sample collection were estimated at 85 and 250 ℓ/s , respectively.

The principal ions in base flow at Locations V and F are calcium sulfate (Table I). Locations V and F are on Sulphur Creek. Drainage at Location V is from a small interior basin of the Valles Caldera. Location F is the combined flow of Sulphur Creek and Redondo Creek. The maximum discharge at both stations at time of sample collection was estimated at 30 ℓ/s .

The principal ions in base flow at Location J are sodium and bicarbonate (Table 1). Location J is below the confluence of the east fork of the Jemez and San Antonio Creek, on the Jemez River. The area drained is the combined basins within the Valles Caldera (Fig. 10). Maximum discharge at time of sample collection was estimated at 450 ℓ/s .

The chemical quality of surface water varies widely with stream discharge due to variations in precipitation in the drainage area. Runoff from precipitation in 1975 was greater than in 1974, resulting in greater dilution of the normal quality of water making up the base flow in the streams. The concentration of constituents at individual stations will vary during the year due to differences in amount of stream flow at the time the samples were collected. The variations in chemical quality that were observed in 1975 at individual stations will vary during the year due to differences in amount of stream flow at the time the samples were collected. The variations in chemical quality that were observed in 1975 at individual stations and slight declines in predominant ions and TDS when compared to previous analyses are not considered significant.

D. Ground Water

Ground water samples are collected on a routine schedule from the water supply for the village of Jemez Springs (two sources), La Cueva (one source), and three springs and one well adjacent to the Fenton Hill site. In addition

TABLE I
A COMPARISON OF PREDOMINANT IONS AND
TOTAL DISSOLVED SOLIDS AT SURFACE WATER STATIONS
1974 - 1975
(in milligrams/liter)

Location	Sodium and Chloride					
	1974			1975		
	Na	Cl	TDS	Na	Cl	TDS
U (Redondo Creek)	40	94	312	12(+3)	27(+11)	149(+22)
R (Jemez River)	60(+32)	76(+45)	411(+99)	53(+34)	65(+46)	349(+127)
S (Jemez River)	84(+41)	116(+56)	483(+144)	63(+32)	81(+40)	376(+120)

Location	Calcium and Bicarbonate					
	1974			1975		
	Ca	HCO ₃	TDS	Ca	HCO ₃	TDS
N (San Antonio Creek)	16(+3)	70(+16)	190(+31)	13(+6)	69(+20)	159(+31)
T (Rio Cebolla)	21(+2)	88(+4)	160(+14)	17(+3)	65(+13)	123(+25)
Q (Rio Guadalupe)	54(+8)	187(+34)	292(+73)	38(+14)	129(+53)	170(+16)

Location	Calcium and Sulfate					
	1974			1975		
	Ca	SO ₄	TDS	Ca	SO ₄	TDS
V (Sulphur Creek)	90	364	680	57(+31)	248(+133)	440(+204)
F (Sulphur Creek)	43(+8)	120(+41)	338(+75)	30(+5)	48(+20)	212(+40)

Location	Sodium and Bicarbonate					
	1974			1975		
	Na	HCO ₃	TDS	Na	HCO ₃	TDS
J (Jemez River)	18(+8)	69(+19)	174(+37)	12(+4)	53(+13)	129(+27)

to the routine samples, four springs and two test holes were sampled during 1975. Station locations are shown on Fig. 10 and are keyed to analyses given in Appendix A, Table A-II.

Two types of ground water, based on principal ions, occur at the seven routine sampling locations. The principal ions used for discussion are (1) sodium and bicarbonate and (2) sodium and chloride.

The principal ion combinations in water at Locations 4, 27, 31, and JS-2, -3, -4, and -5 are sodium and bicarbonate (Table II). Locations JS-2, -3, -4, and -5 are springs which supply water for the village of Jemez Springs. Springs JS-2 and -3, located east of the village, flow from the east and west fork of Church Canyon, respectively. Samples are collected in the main part of the village and represent combined flow from the two springs. Springs JS-4 and -5, located north of the village on the west side of the Jemez River, were collected for a combined sample from the northern end of the village. Location 4, Horse-shoe Spring, supplies a part of the water at La Cueva. Location 27, Hofheins Flowing Well, is located near San Antonio Creek at La Cueva and is completed in the siltstones of the Abo Formation. Location 31, Cold Spring, is a small spring in the volcanic rocks of Lake Fork Canyon.

Slight decreases in the averages of principal chemical constituents in water from six springs and wells were observed during 1974 and 1975. There is a normal seasonal variation in chemical concentrations due to differing amounts of recharge to the aquifer yielding water to the springs or wells. The seasonal or annual variations in concentrations are not considered significant.

The principal ions in water from Locations JF-1 and -5 are sodium and chloride (Table II). JF-1 and -5 are thermal and mineral springs associated with the Jemez Fault. They are located west of Jemez River north of the village of Jemez Springs. The principal ions in water from JF-9, Madera Spring, are also sodium and chloride. Madera Spring, located on the Jemez Fault, is not a routine monitoring station but is included with this group. These and other springs associated with the Jemez Fault that discharge into the Jemez River at the north of the village affect quality of water below the village as measured at surface water Locations R and S.

Principal ions and water from Locations RV-1, -2, -4, and -5, H-2 (Valle Toledo), and H-7 (Valle Grande) are sodium and bicarbonate (Table II). Samples from these locations are not collected on a routine schedule but were collected to supplement data for 1975. The RV series are thermal springs that discharge

TABLE II
A COMPARISON OF PREDOMINANT IONS AND
TOTAL DISSOLVED SOLIDS AT GROUND WATER STATIONS
1974 - 1975
(in milligrams/liter)

Location	Sodium and Bicarbonate					
	1974			1975		
	Na	HCO ₃	TDS	Na	HCO ₃	TDS
JS-2, -3 (WS Jemez Spring)	18(+1)	84(+5)	214(+31)	13(+1)	68(+8)	144(+37)
JS-4, -5 (WS Jemez Spring)	16(+2)	89(+23)	169(+17)	13(+1)	75(+1)	172(+25)
4 (Horseshoe Spring)	17(+2)	74(+4)	181(+23)	15(+2)	63(+6)	155(+22)
27 (Hofheins Flowing Well)	141	444	576	113(+10)	394(+15)	510(+31)
31 (Cold Springs)	17(+4)	69(+5)	201(+67)	12(+2)	60(+4)	125(+15)

Location	Sodium and Chloride					
	1974			1975		
	Na	Cl	TDS	Na	Cl	TDS
JF-1 (Limestone Spring)	260(+50)	378(+58)	1260(+119)	198(+69)	305(+100)	1110(+170)
JF-5 (Soda Dam)	772(+171)	1470(+20)	3950(+36)	837(+85)	1360(+11)	3600(+172)
JF-9 (Madera Spring)	--	--	--	728	302	2800

Location	Sodium and Bicarbonate (Supplemental Stations)					
	Previous Analysis			1975		
	Na	HCO ₃	TDS	Na	HCO ₃	TDS
RV-1 ^a (San Antonio Warm Spring)	--	59	149	27	58	244

TABLE II (CONT.)

Location	Previous Analysis			1975		
	Na	HCO ₃	TDS	Na	HCO ₃	TDS
RV-2 ^b (San Antonio Hot Spring)	22	58	202	22	56	166
RV-4 (Spence Spring)	53	120	250	49(+0)	124(+6)	250(+11)
RV-5 (McCauley Spring)	22	92	180	20(+1)	75(+1)	151(+4)
H-2 ^a (Test Hole, Valle Toledo)	--	48	111	11	36	114
H-7 ^a (Test Hole, Valle Grande)	--	55	125	14	44	122

^aAnalysis 1949.

^bAnalysis 1973.

from recent volcanics along San Antonio Creek and the east fork of the Jemez (Fig. 10). Test Holes H-2 and H-7 were exploratory holes drilled in the Valles Caldera for a water supply study in 1947. The concentrations of constituents measured in 1975 vary from previous data, but the variation is within expected normal seasonal fluctuation.

E. Water Quality at Fenton Hill Site (TA-57)

Samples of water used in drilling operations and testing of holes GT-2 and EE-1 were analyzed in the same manner as the other water samples (refer to Appendix A, Table A-III).

Water samples of residual fluids from drilling operations as well as runoff from precipitation at the lower pond at GT-2 were collected in January 1975. This water was released slowly into Lake Fork Canyon to allow dilution with spring runoff during March and April. The residual solids in the pond were removed and buried. No adverse effects have been detected at any time. Subsequent fluids have been received into the upper and lower ponds at GT-2 while tests were conducted. The sample from the EE-1 pond was taken during drilling

operations and is drilling fluid. Control is maintained and no fluids from the ponds are released except under controlled conditions.

F. U.S.G.S. Surface Water Stations

Three surface water gauging stations have been operated by the U. S. Geological Survey on the Jemez River and Rio Guadalupe. The operation of stations near Locations J and Q have been supported by LASL for the past 2 yr. The third station near Location R is a permanent station of the Geological Survey.

The station at Location J is on the Jemez River below the confluence of the East Fork of the Jemez and San Antonio Creek (Fig. 10). The drainage area above the station is 448 km^2 (173 mi^2). Discharge at the station includes the runoff from the Valles Caldera as well as adjacent areas. Partial records from the station began in 1949. The maximum recorded discharge occurred on April 21, 1958, and was $71 \text{ m}^3/\text{s}$ ($2500 \text{ ft}^3/\text{s}$). The minimum discharge for the period 1960-75 was $0.09 \text{ m}^3/\text{s}$ ($3.3 \text{ ft}^3/\text{s}$) and maximum $29.2 \text{ m}^3/\text{s}$ ($1030 \text{ ft}^3/\text{s}$) (Table III). The annual volume of water passing the station for the same period ranged from 13.9 hm^3 ($11.3 \times 10^3 \text{ ac-ft}$) to 58.2 hm^3 ($47.2 \times 10^3 \text{ ac-ft}$).

The station at Location Q is on the Rio Guadalupe above the confluence with the Jemez River (Fig. 10). The drainage area above the station is 609 km^2 (235 mi^2). Discharge at the station includes the western rim of the caldera and the flanks of the mountains to the west. Canyons with intermittent streams north and south of the Fenton Hill site drain into the Rio Guadalupe. Partial records from the station began in 1951. The maximum discharge recorded was $40.8 \text{ m}^3/\text{s}$ ($1440 \text{ ft}^3/\text{s}$) on April 21, 1958. The minimum discharge for the period 1960-75 was $0.09 \text{ m}^3/\text{s}$ ($3.4 \text{ ft}^3/\text{s}$) and the maximum was $32.2 \text{ m}^3/\text{s}$ ($1350 \text{ ft}^3/\text{s}$) (Table IV). The annual volume of water passing the station for the same period ranged from 12.8 hm^3 ($10.4 \times 10^3 \text{ ac-ft}$) to 89.9 hm^3 ($72.9 \times 10^3 \text{ ac-ft}$).

The station at Location R is on the Jemez River below the confluence of the Rio Guadalupe (Fig. 10). The drainage area above the station is 1220 km^2 (470 mi^2). Discharge at the station includes runoff passing through the stations at Locations J and Q as well as some runoff from the southern rim of the caldera. Partial records of stream discharge and volumes of water passing the station are available starting in 1936. The maximum discharge recorded at the stations was $167 \text{ m}^3/\text{s}$ ($5900 \text{ ft}^3/\text{s}$) on April 21, 1958). The minimum discharge for the period 1960-75 was $0.24 \text{ m}^3/\text{s}$ ($8.3 \text{ ft}^3/\text{s}$) and the maximum was $64 \text{ m}^3/\text{s}$ ($2260 \text{ ft}^3/\text{s}$).

TABLE III
SURFACE WATER RECORDS OF THE JEMEZ RIVER
NEAR BATTLESHIP ROCK, LOCATION J

Year	Discharge m^3/s (ft ³ /s)			Annual Volume hm^3 (10 ³ ac-ft)
	Min	Max	Mean Annual	
1960	0.17 (6.0)	11.5 (405)	0.96 (34)	30.3 (24.6)
1961	0.28 (10.0)	17.0 (600)	1.10 (40)	36.6 (29.7)
1962	0.27 (9.8)	11.0 (390)	0.93 (33)	29.6 (24.0)
1963	0.23 (8.0)	13.0 (450)	0.57 (20)	17.5 (14.2)
1964	0.20 (7.0)	8.5 (300)	0.51 (18)	15.7 (12.7)
1965	0.20 (7.0)	9.1 (320)	0.71 (25)	22.2 (18.0)
1966	0.16 (5.6)	9.6 (340)	0.62 (22)	19.6 (15.9)
1967	0.15 (5.0)	3.3 (115)	0.45 (16)	13.9 (11.3)
1968	0.17 (6.0)	11.0 (390)	0.96 (34)	30.9 (25.1)
1969	0.09 (3.3)	10.2 (360)	1.00 (36)	32.4 (26.3)
1970	0.19 (6.6)	8.2 (290)	0.79 (28)	25.2 (20.4)
1971	0.19 (6.9)	2.4 (86)	0.45 (16)	14.1 (11.4)
1972	0.23 (8.0)	4.5 (160)	0.57 (20)	17.9 (14.5)
1973	0.24 (8.6)	24.1 (850)	1.80 (65)	58.2 (47.2)
1974	0.23 (8.0)	4.0 (140)	0.57 (20)	17.9 (14.5)
1975	0.24 (8.7)	29.2 (1030)	1.40 (49)	43.8 (35.5)

TABLE IV
SURFACE WATER RECORDS OF THE RIO GUADALUPE
NEAR LOCATION Q

Year	Discharge m/s (ft /s)			Annual Volume hm^3 (10 ³ ac-ft)
	Min	Max	Mean Annual	
1960	0.12 (4.2)	10.5 (370)	1.20 (42)	37.7 (30.6)
1961	0.16 (6.0)	10.8 (380)	1.30 (45)	39.9 (32.4)
1962	0.12 (4.4)	13.3 (470)	1.20 (43)	38.6 (31.3)
1963	0.10 (3.6)	5.4 (190)	0.54 (19)	17.1 (13.9)
1964	0.09 (3.3)	2.8 (100)	0.45 (16)	14.3 (11.6)
1965	0.17 (5.9)	9.3 (330)	1.20 (41)	36.9 (29.9)

TABLE IV (CONT.)

Year	Discharge m ³ /s (ft ³ /s)			Annual Volume hm ³ (10 ³ ac-ft)
	Min	Max	Mean Annual	
1966	0.11 (3.9)	4.5 (160)	0.68 (24)	21.1 (17.1)
1967	0.10 (3.5)	5.7 (200)	0.40 (14)	12.8 (10.4)
1968	0.14 (5.0)	11.0 (390)	1.20 (44)	39.1 (31.7)
1969	0.24 (8.3)	8.5 (300)	1.40 (49)	43.9 (35.6)
1970	0.22 (7.9)	9.3 (330)	1.00 (36)	32.9 (26.7)
1971	0.12 (4.3)	3.1 (110)	0.62 (22)	19.9 (16.1)
1972	0.11 (3.9)	2.8 (100)	0.62 (22)	19.4 (15.7)
1973	0.22 (7.9)	32.2 (1350)	2.80 (100)	89.9 (72.9)
1974	0.18 (6.2)	3.4 (120)	0.59 (21)	19.1 (15.5)
1975	0.24 (8.6)	14.4 (510)	1.80 (65)	55.4 (44.9)

TABLE V

SURFACE WATER RECORDS OF THE JEMEZ RIVER
NEAR JEMEZ PUEBLO NEAR LOCATION R

Year	Discharge m ³ /s (ft ³ /s)			Annual Volume hm ³ (10 ³ ac-ft)
	Min	Max	Mean Annual	
1960	0.28 (10.0)	16.8 (595)	2.10 (74)	66.5 (53.9)
1961	0.45 (16.0)	24.9 (880)	2.50 (87)	77.8 (63.1)
1962	0.40 (14.0)	19.2 (675)	2.30 (81)	72.3 (58.6)
1963	0.27 (9.6)	17.0 (600)	1.20 (42)	37.7 (30.6)
1964	0.31 (11.0)	9.6 (340)	0.99 (35)	31.1 (25.2)
1965	0.45 (16.0)	11.3 (400)	1.90 (68)	60.7 (49.2)
1966	0.28 (10.0)	12.7 (450)	1.40 (51)	45.6 (37.0)
1967	0.27 (9.7)	9.9 (350)	1.00 (36)	31.9 (25.9)
1968	0.42 (15.0)	21.8 (770)	2.40 (84)	75.5 (61.2)
1969	0.45 (16.0)	14.2 (500)	2.60 (92)	81.7 (66.3)
1970	0.42 (15.0)	13.2 (465)	1.80 (65)	57.8 (46.9)
1971	0.24 (8.3)	6.8 (240)	1.20 (42)	37.4 (30.3)
1972	0.28 (9.9)	6.5 (230)	1.30 (46)	40.8 (33.1)
1973	0.37 (13.0)	64.0 (2260)	4.80 (170)	161.2 (130.7)
1974	0.31 (11.0)	4.8 (170)	1.10 (38)	34.2 (27.7)
1975	0.48 (17.0)	48.0 (1710)	3.40 (120)	103.4 (83.9)

(Table V). The annual volume of water passing the station ranged from 31.1 hm^3 ($25.2 \times 10^3 \text{ ac-ft}$) to 161.3 hm^3 ($130 \times 10^3 \text{ ac-ft}$).

The stream flow characteristics at the three stations are well defined with over 16 yr of continuous records. The annual volumes of water at the stations at Locations J and Q can be estimated from records of the station near Location R. Linear regressions of the mean annual discharge of stations at Locations J and Q (y variable) versus the station at Location R (x variable) have excellent correlations with the goodness of fit equations as shown in Figs. 12 and 13.

Using data from these regressions, a hydrograph was prepared to estimate the annual volumes of water passing stations at Locations J and Q using the station at Location R for control (Fig. 14). The station at Location R is a permanent station of the U. S. Geological Survey. It is equipped with a digital as well as a standard water-stage recorder; thus the day, hour, and peak discharge can be determined.

The discharge at the three stations ranged from $0.09 \text{ m}^3/\text{s}$ ($3.3 \text{ ft}^3/\text{s}$) to $64 \text{ m}^3/\text{s}$ ($2260 \text{ ft}^3/\text{s}$) during the period 1960-75. The station ratings are accurate to only $\pm 10\%$; thus with the variable discharge, any small increase or decrease in flow would be impossible to determine. The U. S. Geological Survey has concurred that no additional useful data can be obtained by continued operation of the stations near Locations J and Q at this time. The stations were abandoned in June 1976.

G. Summary

The quality of surface water in the drainage area of the Jemez River and Rio Guadalupe varied slightly at individual locations due to variation in stream flow. The predominant ions at each location remained the same; however, annual average concentrations of these ions and total dissolved solids decreased slightly in 1975 compared to 1974. The chemical constituents in ground water from routine sampling locations, springs, and one well, varied slightly during the year. There was also a slight decrease in 1975 in the predominant ions and total dissolved solids when compared to similar data in 1974.

Supplemental samples were collected from five springs and two test holes. The chemical quality of water from these sources has remained about the same when compared to previous analyses.

Fig. 12.

Regression analyses showing relationship between mean annual discharge at gauging stations near Locations J and R.

Fig. 13.

Regression analyses showing relationship between mean annual discharge at gauging stations near Locations Q and R.

Fig. 14.

Hydrograph to estimate volume of flow near Locations J and Q (ordinate) from U.S.G.S. records from gauging stations near Location R (abscissa).

Stream flow characteristics of the Jemez River and Rio Guadalupe are well defined with over 16 yr of continuous records at three gauging stations. Stations near Location J on the Jemez River and at Location Q on the Rio Guadalupe were abandoned in June 1976. Regression analyses of the mean annual discharge at the two stations versus the mean annual discharge at the permanent U.S.G.S. station near Location R indicate a very good correlation. The regression provides a means of estimating the annual volume of water at Location J and Q from the records of the gauging station near Location R.

V. SEISMIC MONITORING

A. Potential Effects Due to Project Activities

Upon initiation of the Hot Dry Rock Geothermal Project it was recognized that various possible seismic effects, both natural and induced, should receive close attention from the environmental point of view. The seismic questions can be divided into two categories: (1) the mechanisms and rates of occurrence of

nearby natural earthquake activity and their implications for project siting and operations, and (2) how might project activities, especially those connected with massive fluid injection and withdrawal operations, affect the local seismic background levels and/or lead to triggering of damaging earthquakes? This latter question has received considerable attention in both scientific and public circles because of the discovery in 1966 that injection of fluids into a deep disposal well at the Rocky Mountain Arsenal was responsible for triggering earthquakes near Denver, Colorado.²²

Although seismological site selection studies for TA-57 were completed in 1973 and the continuing monitoring of natural seismicity on a regional basis is being carried on somewhat independently of the requirements for on-site seismic environmental monitoring, a brief review of some of these studies is necessary in order to place the rationale and results of the on-site monitoring program in proper perspective.

At the time of the original investigation into the cause of the Rocky Mountain Arsenal earthquakes, the hypothesis was advanced that the earthquakes were initiated because the pressurized fluid entered deep fractures in the highly stressed basement rock and supported that part of the normal stress across the fracture equivalent to the fluid pressure. Thus, the frictional resistance to sliding along the fracture in response to ambient tectonic stresses is lowered, and for a combination of sufficiently high pressures, ambient stress levels, and open fracture area, the rock formations will slip and generate an earthquake. The energy radiated by the earthquake will depend on the area of the fracture or fault over which slip occurs, the amount of slip, and the amount of stress relieved in the process. More recently, this model has been largely confirmed by controlled experiments at an oil field near Rangely, Colorado, which has been undergoing waterflood operations for the secondary recovery of petroleum since 1957.²³ Several of the most important factors controlling or indicating the possibility of earthquake triggering by fluid injection are: (1) the presence of known faults or large subsurface fractures, (2) high levels of ambient tectonic stress (often - but not always - indicated by preexisting or ongoing seismic activity), and (3) a hydrologic regime dominated by subhydrostatic pressures below the water table.

1. Local Fault Systems. Details of the survey to determine the proximity and probable activity of faults in the Fenton Hill geothermal project area are discussed by Slemmons.¹⁶ For the purposes of this report, his conclusions can

be summarized as follows (Slemmons' fault map is included here as Fig. 15). As seen or inferred from surface geology, the major fault system that is nearest to the geothermal site is the Jemez Fault Zone. Within this zone, the Virgin Canyon Fault and the Jemez Springs Fault trend northeast and pass within about 4 km and 7 km, respectively, of the Fenton Hill experimental site. The steeply dipping Jemez Fault Zone is considered by most geologists to be the principal western boundary fault of the Rio Grande Rift in this area. However, the offsets on the Jemez Fault Zone are somewhat smaller (only about 30 m in the past 1.1 million years) than several other regional fault systems (e.g., the Pajarito Fault system near the Los Alamos townsite, approximately 35 km to the east, shows offsets ranging from 125 m to nearly 300 m) and are 1 to 2 orders of magnitude smaller than those on major faults of the Basin and Range Province of California and Nevada. In addition, the Battleship Rock formation of 100 000-yr age is not offset by the Jemez Springs Fault.²⁴ The relative natural seismic quiescence of the immediate project area is also confirmed by available historical information on felt earthquakes and by recent instrumental recording of microearthquakes in the Jemez Mountains.

2. Definition of Terms. In order to clarify the terminology used to define the geographical extent and locations of the four seismic networks discussed in this report, the following descriptions are given:

Regional Net (or events). LASL seismic network (or seismic events) located in north-central New Mexico, usually considered to be within about 110 km of Los Alamos (Fig. 16).

Local Net. Seismic stations of the regional net that are located close to GT-2; Barley Canyon (BRC), Lake Fork Canyon (LFC), and La Cueva (LCV) (Fig. 17).

Close-In Net. The nine seismic stations located around the Fenton Hill site which were installed by J Division (Fig. 17).

On-Site Net. The six microseismic stations at the Fenton Hill site which were installed by Q Division (Fig. 17).

Fig. 15.
Mapped faults of the Valles Caldera and Jemez Mountain area.

Fig. 16.
The regional seismic network in north-central New Mexico.

Fig. 17.
Location of seismic stations at the Fenton Hill area comprising the local, close-in and on-site network.

B. Regional Historic and Instrumental Seismicity

1. Regional Earthquakes. The State of New Mexico can be considered to be a region of moderate-to-low earthquake risk.²⁵ The historical record of shocks that were felt by people or that damaged structures goes back only to 1849. Although the earthquake activity indicated by such historical records is heavily biased by population density, it is fairly clear from these records and from subsequent instrumental records that the part of the state having the highest level of seismicity has been and continues to be along the Rio Grande Valley between Socorro and Santa Fe, where events up to Richter magnitude 6 have occurred.²⁴ The largest earthquake reported within 100 km of the Fenton Hill geothermal site is the Cerrillos event of 28 May 1918 (located approximately 30 km southwest of Santa Fe) for which Sanford²⁶ has estimated a local magnitude (M_L) value of 5.5. The epicenters of felt earthquakes prior to 1962 and the stronger events from 1962 through mid-1973, as located by distant seismic stations for a region within 1 degree (110 km) of Fenton Hill, are shown in Fig. 18. The parameters of felt shocks in this region from January 1928 through mid-1973 are given in Appendix B, Table B-I. Even though it is biased by population density variations, Fig. 18 shows a complete absence of perceptible earthquakes in the center and somewhat to the west of the Valles Caldera.

2. Regional Microearthquakes. Figure 19 presents a map showing the epicenters of microearthquakes within approximately 1 degree (110 km) of the Fenton Hill geothermal site for the period from September 1973 through December 1975. These data are taken from a set covering a somewhat larger region of northern New Mexico.²⁴ They are derived by incorporating with the regional net data the additional arrival time readings from a few seismic stations in New Mexico operated by other agencies (e.g., Albuquerque Seismic Center of the U.S.G.S and New Mexico Institute of Mining and Technology at Socorro). Figure 20 extends the local earthquake data coverage from January 1, 1976, to a cutoff date of May 15, 1976. This latter set should be considered provisional in the sense that the readings from the stations of other agencies have not yet been received and incorporated in the LASL location calculations. However, these corrections should be negligible except for improving the location confidence for the few events south of 35.5°N. Table B-II in Appendix B (abbreviated from the larger list in Ref. 24) presents more detail for the events observed to December 31, 1975.

Fig. 18.

Locations of earthquakes within 110 km of Los Alamos, modified from Sanford, 1976.²⁶

Fig. 19.

Locations of Microearthquake epicenters in north-central New Mexico, September 1973 through December 1975.

Fig. 20.

Preliminary locations of microearthquake epicenters in north-central New Mexico; January 1, 1976 to May 15, 1976.

3. Local Microearthquakes. Analysis of the records from the regional and close-in network stations for the 2-3/4-yr period from September 1, 1973 through May 1976 have revealed that no natural microearthquakes greater than the threshold of magnitude 0.5 occurred within 10 km (6 mi) of the Fenton Hill geothermal site. The natural shocks that have occurred closest to the Fenton Hill site both took place within the last year of monitoring. (Some shocks smaller than magnitude 0 were probably present but the present seismic station density and distribution is inadequate to obtain reliable location and depth solutions.) A magnitude 0.7 microearthquake occurred at 2:21 a.m. local time near Cerro Pelado about 17 km southeast of Fenton Hill on May 28, 1975 (see Appendix B, Table B-II and Fig. 19). The tectonic significance of such a small isolated event is unclear at present. More clearly significant is the $M_L = 3.2$ earthquake that took place ~22 km (~14 mi) to the northwest on September 29, 1975 (Table B-II). This event, at a depth between 15 and 20 km was preceded by two minor foreshocks

on September 25 and 27, 1975 and by many aftershocks; only those of magnitude greater than 0.5 are listed in Table B-II. The main shock was strong enough to be recorded on sensitive seismographs anywhere within the state but was just below the threshold that would lead to minor damage of certain manmade structures if the event had occurred directly under a town or city. This earthquake is the strongest of several events located near the north-trending Nacimiento fault system during the past 2-3/4 yr. These epicenters indicate that the Nacimiento fault system, which passes approximately 15 to 20 km to the west of the Fenton Hill site, is a seat of continuing but moderate seismic activity. It has required more than 2 yr of regional monitoring for this particular trend to become clearly evident.

The special recordings carried out using the surface stations of the close-in and on-site networks during the hydraulic fracturing experiments during FY75 and FY76 were unable to detect seismic signals from, or in very close proximity to, the subsurface fractures. The only seismic sensors that have recorded signals from hydraulic fracturing or fracture inflation in the granite have been the special 3-axis borehole geophone packages positioned downhole close to the fractures being created. (See later in this section; also refer to the HDR Annual Report.²⁷) These acoustic signals have been used to help determine the nature and location of the fractures.²⁸

4. Regional and Local Seismic Station Network. Installation of the first high-gain continuously telemetered stations in the vicinity of Los Alamos and the Jemez Mountains was begun in 1972. By the fall of 1973 enough stations (6) were operational so that it was possible to independently locate microearthquakes within about 100 km of Los Alamos down to a magnitude threshold of approximately 0.5 to 1.0. This network has been expanded and now consists of 13 stations covering north-central New Mexico and northeastern Arizona.²⁴ Figure 16 shows the locations of presently operating stations in the vicinity of the Valles Caldera and Los Alamos. Table B-III (Appendix B) lists coordinates and other pertinent data for this continuously recorded network. Of special interest for environmental monitoring purposes at the geothermal site are the local net stations LCV, LFC, and BRC. LCV is a 3-axis station installed within 450 m of the planned site of geothermal test wells about 5 months prior to initiation of drilling GT-2 (Fig. 17). BRC and LFC are special borehole (125-m-deep) stations, installed at the beginning of FY76 in order to provide augmented

detection and location capability for $M_L < 0$ events within 5 km of the site. Two other sets of stations are also shown on Fig. 17. Both the on-site array and the close-in networks were surface stations installed specifically in an attempt to detect seismic signals from hydraulic fracturing experiments carried out in FY75 and FY76. (See Ref. 24 for a discussion of these experiments.) The operation of the close-in network has now been terminated; the on-site array stations are now operated on a nearly continuous basis as part of the seismic environmental program. (See Sec. V, B.5.) The methods used for seismic event locations with these networks are discussed in more detail in Refs. 24 and 27.

5. On-Site Surface Microseismic Array. Six surface microseismic stations have been installed and maintained at TA-57. The initial intent of installing the on-site system was two-fold. The first, to monitor seismic activity generated at the site as a precautionary measure to guarantee that the heat extraction experiments would be environmentally safe. The second was to provide data for determining the shape and orientation of the hydraulic fracture.

Attempts to determine fracture orientation from seismic data acquired at the surface stations have not been successful. Energy released from events during fracture extension is relatively small. The complex transmission properties of the overlying sediments make it difficult to estimate the characteristics of seismic events that might emanate from fracture pressurization. (However, crack extension has been observed using downhole geophone packages positioned at depths close to the fracture.)

The six-seismic-station array around the geothermal test site is operated continuously. Five stations are located on a circle with a radius of approximately 0.8 km from the GT-2 borehole (Figs. 17 and 21). The sixth station is located 152 m north of the borehole. Each station contains three short-period seismometers and associated battery-powered line-driving amplifiers. Two vertical seismometers in each station are set up with a gain differential of 20 dB. The more sensitive vertical seismic amplifier has a gain factor of 64 dB or a voltage gain of 1585. The third seismometer is positioned along a line intersecting GT-2, and its amplifier also has a gain factor of 64 dB.

The short-period seismometers are Teledyne Geotech Model S-13 instruments. Their natural frequency is 1 Hz; their inertial mass is 5 kg. These seismometers have a generator constant of 629 Vs/m and a coil resistance of 3600 ohms. The low-noise line-driving amplifiers have a frequency response of 0.1 to 100 Hz.

The output of each amplifier is transmitted over a twisted-pair shielded instrumentation cable (Beldon 8778) to a central recording station located near the GT-2 borehole. The cable is terminated at the recording station in a high-gain differential amplifier used to improve the signal-to-noise ratio (common-mode rejection) by approximately 60 dB. The conditioned signal is then multiplexed for FM recording on a 14-track analog magnetic tape recorder. The less-sensitive vertical seismometer signal from each station is also recorded on a strip chart for quick-look detection of pertinent events. A time-code generator synchronized to WWV (world time) provides a standard IRIG time code for recording on the magnetic tape and a slow code (also synchronized to WWV) for presentation on the strip chart. A schematic diagram of the seismic system is shown in Fig. 22.

Figure 23 shows the layout of a typical station as originally constructed. A 1.2-m-diam hole was drilled 3 m deep and cased with corrugated metal pipe. A wet concrete mixture was poured into the bottom of each hole to provide a smooth level base for the seismometers. The corrugated metal pipe was set on a rubber pad to decouple the surface noise from the concrete pad. The line-driving amplifiers were mounted on a plywood frame to electrically isolate the electronics from ground.

The Fenton Hill site is located in an area of high-incident local thunderstorms, especially during the summer months. To prevent damage to electronic equipment from lightning activity, each amplifier output lead was wired through a gas-filled protector (spark gap) to ground. This protector has a striking voltage of 500 to 900 VDC and a response time of less than 1 μ s to impulses of peak currents up to 20 000 amperes. The device, however, did not operate satisfactorily at lower striking voltages and did not protect the long cable lines running to the recording station. Figures 24 and 25 show the extent of lightning damage to one portion of a 760-m cable line and a junction box (splice) located close to the damaged cable. Some damage from lightning was also experienced in the central recording station equipment.

The gas-filled lightning protectors were replaced with bi-polar TransZorbs (manufactured by General Semiconductor, Inc.). The TransZorb is a semiconductor transient suppressor with a risetime of 5 kV/ns. It will operate over a wide range of breakdown voltages depending upon the reverse stand-off voltage specified. A 1.5 KE 51 CA TransZorb was wired from ground to each long-line conductor in both the seismic station and in the central recording station.

Fig. 21.

Location of on-site surface microseismic array stations.

Fig. 23.

Typical on-site surface seismic stations as originally constructed.

Fig. 22.

Schematic diagram of on-site surface seismic array stations.

Fig. 24.

Lightning damage to a long seismic cable line.

Fig. 25.

Lightning damage to a seismic cable junction box.

Since installation of the transient devices, there has been no electronic component failure due to lightning surges, with the exception of the TransZorb units themselves.

The S-13 seismometers are sealed and are specified to operate continuously under 31 m of water. The amplifier and battery pack are weather-sealed but are not adaptable to complete immersion. During the snow runoff in the spring of 1974, the stations filled with water and several weeks of downtime occurred while amplifiers were repaired. The amplifiers and battery pack were therefore relocated in an all-weather building (Fig. 26). (Addition of the metal shed

Fig. 26.

Typical on-site surface seismic station as constructed with an all-weather building.

directly over the station has resulted in increased background noise due to atmospheric conditions). A cross-sectional diagram of the updated station is shown in Fig. 27. The on-site surface seismic stations now require minimal maintenance, which includes replacement of the battery pack about every 6 months.

Fig. 27.
Cross-sectional diagram of on-site surface seismic station.

6. On-Site Microseismic Measurements. The on-site microseismic array described in the preceding paragraphs has monitored all of the hydraulic fracturing experiments conducted in the two deep boreholes at Fenton Hill. In addition, background seismic data have been monitored and collected for use in environmental studies. To date, after scores of fluid injections at surface pressures exceeding 300 bars (4500 psi) and volumes up to 640 000 ℓ (160 000 gal), no surface seismic activity associated with the fracturing experiments has been detected by this array. The only monitoring studies now in progress are to insure identification of seismic events should they occur. All records which cover experimental pumping periods and off-duty periods are given close scrutiny. Suspect signals are studied in detail.

Calibration of Nacimiento Earthquake. Fortunately, a small earthquake along with well-defined numerous after-shock sequences occurred on September 29, 1975 (see Sec. V, B.3) in the Nacimiento Mountains west of Fenton Hill. These earthquakes, which originate at depth in Precambrian basement rock similar to that underlying Fenton Hill, have provided a standard for calibration of the array. Seismic signals from these events (Fig. 28), arising from essentially a point source, traveled through the basement rock and then upward through the sediments and were recorded on vertical seismometers in each of the stations. These seismometers with a natural period of 0.8 s have a magnification of 10 000. The 240-s duration of the main shock yields a magnitude of $M_L \approx 3.0$ when estimated by the duration method used by the Seismology Group at LASL.²⁹ That same method, when applied to the signals recorded by the regional and close-in nets,²⁴ yields a magnitude of 3.2 (Ref. 30). This earthquake was assigned a preliminary magnitude of 2.8 by the Albuquerque Seismological Center.²⁴ By assuming an average value of about 3.0 for the magnitude of this event, the on-site array can be calibrated in terms of M_L vs maximum signal amplitudes.

A total of 132 detectable aftershocks were recorded during the 3-1/2 h following the main Nacimiento shock. Figure 29 shows a plot of the logarithm of the cumulative number of events vs local magnitude. Since the magnitude scale is linear with log amplitude, a single calibration point defines the abscissa in terms of local magnitude. The magnitude of the smallest event detectable by this array arising from a source 25 km away is then 0.6. Scaling to a distance of 3 km, which is the depth of the hydraulic fractures, gives -0.5 as the magnitude of the smallest detectable event from this depth.

Fig. 28.

Seismograms of the September 29, 1975 Nacimientos earthquake and aftershock sequence. The recordings of the main event are shown as the thick tracings at the bottom of the chart, and the aftershocks are shown as thinner, smaller tracings above the main event. These recordings are from the vertical seismometers in five of the on-site array stations.

Seismic Signals from Hydraulic Fracturing. Analysis of downhole signals associated with the hydraulic fracturing show that these events have a magnitude range of -6 to -3. The extremely small size of these events and their associated high frequencies are the reasons why they have not been detectable by the surface array.

To date the seismic response from hydraulic fracturing at its present level is completely undetectable by surface measurements. However, downhole measurements are adequate to monitor the very weak signals present during fracturing and to detect any significant increases in the size of the events. The response of the on-site seismic array should allow adequate differentiation between local microseismicity and fracture-induced activity.

C. Seismic Monitoring Evaluation and Strategy

1. Seismic Evaluation. From the standpoint of contemporary seismicity and its relation to environmental monitoring at the Fenton Hill site, several items are pertinent:

○ An estimate of seismic risk from natural events can be made from the microearthquake recording carried out since September 1973. Because of the moderate levels and sporadic nature of earthquake activity in New Mexico, one must exercise caution in extrapolating the results to too small an area or too long a time interval. Figure 30 shows a plot of cumulative number versus magnitude for all earthquakes detected since September 1, 1973, within 225 km of Los Alamos (an included area of 160 000 km²). An extrapolation of these data using the fitted $b = 0.77$ slope projects the maximum probable earthquake for this area per century to be a magnitude 6.6 event. Because the slopes of such curves may be biased by observational selection effects giving rise to incomplete coverage of the smaller events, some investigators prefer to impose the slope constraint of $b = 1.0$ on the data. When this is done, the present seismicity rates correspond to a maximum probable earthquake per century of $M_L = 5.6$, in close agreement with similar instrumental studies of other parts of the state. The $M_L = 5.6$ projection is, however, somewhat smaller than projections (~ 6.0) made on the basis of historical damage reports.

Fig. 29.

Cumulative events versus local magnitude plot of the September 29, 1975 Nacimiento earthquake and aftershock sequence. The slope of -1 obtained from this plot is typical for aftershock sequences from small earthquakes.

Fig. 30.

Magnitude - frequency relationship for all earthquakes within 225 km of Los Alamos; September 1973 through December 1975.

O Although considerable caution must be exercised when making long-term projections for areas much smaller than that considered above, the observed distribution of seismicity in the Jemez region indicates that $M_L > 1$ earthquakes are almost completely absent from the central part of the Jemez Mountains.²⁴ The explanation of this phenomenon is probably the same as that proposed for a similar situation in the Yellowstone Caldera complex:^{31,32} that strain energy at shallow depths is being relieved by creep rather than by brittle failure. This interpretation is supported by data on tectonic and geologic structure, historical earthquake records, and other geophysical evidence including gravity and aeromagnetic, and high heat flow data.

2. Seismic Monitoring Strategy. When it had been determined that the Hot Dry Rock Geothermal site is sufficiently removed from obvious faults and active seismic zones, then the principal purpose for close-in seismic monitoring is to provide a base line of data from which changes in activity levels can be detected and/or provide information from which activities connected with geothermal operations can be clearly distinguished from those from other (usually natural) sources. These objectives might be ideally achieved by continuous operation of a network able to locate (including depths) events within about 10 km of the site to a precision of about 300 m. Focal mechanism determinations for the stronger events could materially aid in interpreting the causes of any observed events. The present regional network is capable of locating events in the vicinity of Fenton Hill with a relative accuracy of the order of ± 5 km independent of readings from LCV, BRC, LFC or any of the on-site array stations. Incorporation of readings from these latter stations improves the location confidence for the regional net somewhat, but not to the ± 300 -m optimal precision. Experience with the triggered earthquakes both at Denver and at Rangely showed that induced events occurred up to 6 or 7 km from the bottoms of the injection wells. In order to more accurately determine hypocenters and focal mechanisms for a source within such a source volume centered several kilometers beneath the surface, a network of approximately 8 to 12 surface stations located with average interstation spacings of about 3 or 5 km within a radius of 10 km from the geothermal wells would provide optimal coverage.

The present on-site monitoring station coverage as shown in Fig. 17 is limited in the respect that it is largely concentrated within 1 km of the test wells and is only able to provide reliable locations and minimal focal mechanism

information within this range. It is also subject to occasional high background noise level interference from equipment operating nearby. Inasmuch as no significant nearby seismic sources have as yet been detected in relation to fluid injection experiments to date, the present station coverage can probably be considered adequate as long as continuous monitoring is maintained and the site continues to be seismically inactive. In case of a change in seismic behavior, the two shallow (150-m) boreholes (labeled B and C in Fig. 17) would receive high priority for installation of additional instruments.

The present negligible levels of seismic activity, both from natural causes and in association with fluid injection, are very encouraging from the environmental and safety viewpoints. However, this possibly may be a consequence of the rather modest pressures and injected volumes that have been employed to date at the Fenton Hill site. At the Rocky Mountain Arsenal well near Denver, more than 165 million gallons (6.25×10^8 liters) of fluid were injected into a layer of Precambrian gneiss at the bottom of a 3671-m (12 045 ft) disposal well between March 1962 and February 1966. Before pumping began, the reservoir pressure was believed to have been between 20 and 100 bars subhydrostatic; after cessation of injection, pressures had been raised to approximately 7 bars subhydrostatic. Local earthquake activity began a month after pumping had begun when over 4 million gallons of fluid had been injected. Hundreds of earthquakes were documented over the next few years, the largest having magnitudes of $M_L = 5.0$ and 5.3 (Ref. 22). Total injection pressures were somewhat smaller (200-300 bars versus 300-400 bars for Denver) for the more porous sandstone formations in the Rangely experiments; the largest triggered earthquakes at Rangely were $M_L = 3.1$ events. In contrast, for the Fenton Hill wells, the total accumulated volume of unrecovered fluids up until May of 1976 was of the order of 120 000 gallons, but the greatest subhydrostatic pressure differential at Fenton Hill was approximately 50 bars prior to pumping. In addition to differences in regional tectonic stresses and geological formations, triggering at the site may be more unlikely because the high temperatures are more favorable for inelastic creep. In any case, the conditions under which potentially severe levels of triggering could be initiated are difficult to determine with confidence and it is prudent to maintain a meaningful local seismic monitoring program.

D. Other Activities in the Area and Adjacent Regions

In pinpointing the cause of observed seismic signals in the Jemez Mountain area, the question arises that in addition to natural events, there is the possibility of confusing other manmade sources with those arising because of geothermal activities at Fenton Hill. As indicated above, the regional network has a location accuracy of ± 5 km or better for events having magnitudes above $M_L = 1/2$ to 1 over most of the area of the Jemez Mountains. Any significant source beyond about 10 km from Fenton Hill can reasonably be assumed to be unconnected with project activities. Three classes of man-caused sources need to be considered in this connection: (1) mine blasting operations, (2) possible triggered earthquakes from the filling of Cochiti reservoir on the Rio Grande, and (3) possible induced seismic signals connected with the Union Oil Company geothermal development at sites on the Baca Location property approximately 7-10 km east of the LASL Fenton Hill site (Fig. 17).

1. Mine Blasting. The closest significant mining activity to Fenton Hill is the Earth Resources Company open pit copper workings at the mouth of Senorita Canyon (near Cuba, NM) about 23 km northwest of Fenton Hill. Ripple fired charges of less than 1000 lb of ammonium nitrate usually occur at shift change times during working days and do not appear as noteworthy events on the regional network records. During most of FY76 the mine has been either closed or only operated intermittently. The blasting location can easily be identified by the arrival times of the seismic waves at the Eureka Mesa station less than 5 km northeast.

2. Filling of Cochiti Reservoir. Cochiti Reservoir is 42 km southeast of Fenton Hill, and events at the two sites are easily separable by arrival time readings at regional network stations.

3. Union Oil Geothermal Development Area. The Union Oil development program involves utilization of steam or hot water from wells along Redondo Creek on the Baca Location property. Not enough information is available concerning details of fluid injection or withdrawal to adequately evaluate whether triggered seismicity is a credible possibility. No significant seismic events have been observed at the seismic stations from this area during FY76. Since the Fenton Hill and Union Oil Co. areas are separated by only 7-10 km,

events approximately midway between the two could be difficult to assign as to which operation was responsible. If a number of events were to occur, improved locations could be obtained by deployment of portable high-gain self-recording seismograph units.

E. Summary

1. Studies of records from the regional, close-in, and on-site seismic stations during and prior to FY76 have shown no seismic activity -- either natural or man-induced -- greater than $M_L = 1.0$ within 10 km of the Fenton Hill geothermal facility.
2. The relative paucity of natural earthquakes in this area can probably be attributed to relief of tectonic strain by creep in the hot subsurface rocks.
3. The likelihood of triggering significant earthquake activity by massive fluid injection or withdrawal operations is difficult to assess from present knowledge, but the possibility still remains because only comparatively small volumes of fluid have been involved in experiments up to the present time.
4. The presently operating seismic stations within 5 km of the Fenton Hill site are sufficient to detect the onset of low levels of activity within 10 km, but the number and distribution of stations is marginal if location precisions of better than ± 1 km (including depth) or focal mechanism information is required.
5. In the event that increased nearby seismic activity is detected by the ongoing monitoring network, consideration should be given to the immediate deployment of six to eight additional stations in the area in order to obtain unambiguous data from which the details and probable causes of the phenomena can be deduced.

VI. CLIMATOLOGY MONITORING

A. General Weather Conditions at Los Alamos

Because many local climate features are strongly influenced by the irregularity of the terrain of the Jemez Mountains, no single description suffices for the entire area. Major patterns are, however, evident in the long-term records accumulated at the LASL central administration site on the eastern edge of the mountains, and some variations are known from shorter records made at other locations. Climatological information on the western side of the mountains is sparse. (The following statements describing the weather on the eastern side apply generally also to the western side.)

1. Precipitation. The Jemez area generally has a semiarid, continental mountain climate. The Los Alamos average annual precipitation is slightly more than 45 cm (18 in.), 75% falling during May through October. At lower elevations, near the Rio Grande, it may be as low as 20 cm (8 in.) annually, and in the high mountains to the west, 40 cm (20 in.) or more. Rainfall, much of it released as thundershowers, reaches its peak in August when 0.25 cm (0.1 in.) or more is expected 1 out of 4 days. Hail may accompany the more severe thunderstorms, but damage from large hailstones is infrequent. Flooding is limited to localized flash floods in the canyons. Most of the winter precipitation falls as snow, the annual average snowfall being about 125 cm (49 in.). Up to 260 cm (100 in.) of snow may fall in the higher elevations in the vicinity of TA-57.

2. Temperature. Maximum daytime temperatures reach 32.2°C (90°F) on an average of only 2 days a year. Freezes have been recorded in all months except July and August. Winters are cold, but at this elevation warming under cloudless skies is rapid even in winter. During January, the coldest month, daytime shade temperatures can be expected to be above 0°C (32°F) most of the time, and an average winter includes only 18 days when the mercury stays below freezing. Winter nighttime temperatures drop below freezing from November through mid-April, but below -18°C (0°F) readings only occur about once a year.

3. Winds. Winds on the eastern side are generally light, less than 4 m/s (10 mph) nearly 80% of the time. Surface winds vary considerably with the time of day. During the night, about 10 p.m. to 8 a.m., when stable thermal

stratification is common, the dominant direction is from the northwest, influenced by downslope drainage from the Jemez Mountains and mostly less than 3 m/s (7 mph). During the day, about 8 a.m. to 4 p.m., when unstable conditions prevail, the winds are more uniformly distributed in direction, being most common in northwest or southeast directions and generally less strong than at night. Much more short-term directional variation occurs with moderate northwest and light easterly winds and is probably due to afternoon thermal convection. A transition period, between 4 to 10 p.m., when stability conditions are near neutral, has the lowest winds, predominately from the northwest. Wind measurements at sites near the eastern ends of the mesas indicate predominantly southerly directions. These effects are indications that the dominant northwesterly drainage flow is well organized closer to the Jemez Mountains but weakens and gives way to southerly flow created by air channeling through the Rio Grande Depression to the east. Within the canyons, convection circulations are established by greater solar heating of the north canyon walls.

4. Storm Tracks. A 70-station rain gauge network in the Los Alamos area has provided tentative indications of two primary thunderstorm tracks. The more common track apparently originates in the Jemez Mountains and sweeps in an easterly direction, diminishing in intensity as it moves. The second, less common but accounting for more heavy rains, leads up from the Rio Grande Valley and diminishes as it moves north and west.

The large-scale meteorological patterns affecting the area reflect its position in the southern Rocky Mountains. At its latitude of 36°N, the polar front with its associated migratory cyclonic disturbances is active in the winter but recedes northward in summer, giving way to the subtropical anticyclone. Winter and spring winds tend to be stronger and more variable, typically with a westerly component. The two characteristic storm tracks affecting the area have their origins in the eastern Ocean off the southern California coast and the plains of eastern New Mexico and west Texas. The former moves west-to-east through the area, primarily in winter, and accounts for light precipitation. The latter forms on the southern extremity of the polar front and depends on Gulf of Mexico moisture and warm air for its development. Heavy precipitation can occur in these storms, but usually falls well to the east.

Wind directions above ridge tops along the Jemez Mountains are most frequently southwesterly, less frequently west through northwesterly. Other wind

directions, though infrequent, occur in connection with transition cyclonic storms. In summer, the upper winds tend to be light westerly on the large scale, but due to the high incidence of orographic convection, the daytime winds at all altitudes may be quite chaotic on the mesoscale, leading to a complex transport problem.

B. Monitoring Strategy at Fenton Hill

Due to a dearth of climatological information at TA-57, the collection of such information was deemed necessary to determine what type of climatic regime exists, when and where major storm events occur and come from, and what wind patterns prevail within the area. This background information is needed to determine where any potential environmental contaminants released by this project might go.

1. Weather Station Site. This task was initiated in December 1975, by the installation of a weather measuring station in a clearing approximately 150 m to the west of the center-of-disturbance of the dry geothermal energy extraction experimental site. The two pieces of equipment used at this station are a weighing-bucket rain gauge with a wind shield, and a mechanical weather station mounted on a 9-m tower (Figs. 31, 32).

This location minimizes the effect of surface air flow pattern disruption by surrounding terrain and structures. The choice of instrumentation was based on the need for simplicity and high reliability over an extended period of time.

2. Equipment and Operation. The weighing-bucket rain gauge records the accumulation of precipitation on a strip chart (in inches) mounted on a revolving drum. These strip charts will record 1 wk of data before replacement. The weather station records the current wind speed, wind direction, and temperature on the pressure-sensitive strip chart which is capable of holding 1 month of data. This station is visited weekly by a technician who changes charts and does the required preventive maintenance.

All data are reduced from the strip charts into hourly averages which are recorded on coding forms for key-punching and subsequent computer analysis. Several programs have been written to utilize the data in 1-month blocks. The first (CHECKER) checks the data set for suspicious data points and/or missing data. The second (TABLES) tabulates the data, and the next three (RAINANL,

Fig. 31.

Weighing-bucket rain gauge with wind shield at the Fenton Hill site. Tower for the mechanical weather station is on the right.

Fig. 32.

Mechanical weather station on top of the 9-m tower at the Fenton Hill site.

TEMPANL, and WINDANL) summarize the data and present it in graphical form. The graphical summaries aid in detection of any patterning of climatological events and give close scrutiny of the data.

The weather station has performed very well to date with little loss of data. The only problem encountered so far was the freezing of the wind direction vane during two nights in February when freezing temperatures followed a very wet snow.

The hourly tabulations of wind direction and speed, temperature, and rainfall for the month of January 1976 are included in Appendix C as a typical example of data collection. Graphical monthly summaries of wind, temperature, and rainfall are also included in Appendix C for the months of January through April.

C. Summary

Until a considerably larger data set has been collected (2-yr minimum) very little can be deduced about the climatological events that have been experienced. No definite weather patterns can be established with such short-term data; information will continue to be collected as described. It is interesting to note a shift in the wind pattern from that of a strong flow from the northwest in

the winter months to a more variable flow during entry into the summer convective season.

Another rain gauge is scheduled to be operative by July 1, 1976 about 1.6 km (0.75 mi) from the existing gauge. It is also tentatively planned to install a wide-angle, time-lapse camera, recording at the rate of 1 frame/min, to obtain a photographic summary of cloud and weather patterns at the site.

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APPENDIX A
DETAILED WATER QUALITY DATA

This appendix records the detailed surface water quality data, Table A-I, and ground water quality data, Table A-II, and the Fenton Hill water data, Table A-III, for the year 1975.

TABLE A-I

SURFACE WATER QUALITY

Location ^a	Sulphur Creek above San Antonio Creek (F)			Jemez River below Battleship Rock (J)			San Antonio Creek above Sulphur Creek (N)			Rio Guadalupe above Jemez River (Q)			Jemez River above Rio Guadalupe (S)		
Date of Collection (1975)	9/30	12/8		5/28	9/30	12/8	5/28	9/30	12/8	5/28	9/30	12/8	5/28	9/30	12/8
<u>Chemical Analysis (mg/l)</u>															
Silica (SiO ₂)	32	34		33	49	53	42	51	60	17	30	27	42	50	57
Calcium (Ca)	26	33		13	14	14	14	22	14	23	41	50	20	49	51
Magnesium (Mg)	5	3		4	2	2	4	3	2	2	9	6	10	5	5
Sodium (Na)	15	18		7	14	15	6	15	17	11	14	16	27	84	80
Carbonate (CO ₃)	0	0		0	0	0	0	0	0	0	4	5	0	10	6
Bicarbonate (HCO ₃ as CaCO ₃)	20	14		38	62	60	56	96	58	68	156	163	98	188	192
Sulfate (SO ₄)	61	34		14	9.7	13	8.0	4.9	6.4	10	2.6	7.2	15	14	17
Chloride (Cl)	19	37		3	7	4	<1	3	3	<1	4	4	35	96	111
Fluoride (F)	0.2	0.2		0.3	0.7	0.9	0.5	1.1	1.1	0.2	0.5	0.7	0.4	0.9	1.0
Nitrate (N)	<0.1	<0.1		0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	<0.1	0.1	0.1	0.1
Total dissolved solids	184	240		98	144	144	136	194	148	152	182	176	240	420	470
Total hardness (as CaCO ₃)	88	96		48	46	44	54	68	42	68	140	148	106	144	148
Specific conductance (umho/cm)	260	340		140	165	180	150	190	170	140	330	340	340	740	785
pH	8.0	7.2		7.6	7.6	7.2	8.0	8.0	8.1	7.8	8.4	8.3	8.1	8.4	8.3
Temperature (°C)	5	0		6	9	1	6	8	0	6	13	6	7	15	6
Discharge estimated (l/s)	30	30		-	340	450	-	90	110	-	140	230	-	570	680

^a For location see Fig. 10.

TABLE A-I (cont)

SURFACE WATER QUALITY

Location ^a	Jemez River below Rio Guadalupe (R)				Rio Cebolla below Lake Fork Canyon (T)			Redondo Creek (U)			Sulphur Creek above Redondo Creek (V)		
Date of Collection (1975)	3/12	5/28	9/30	12/8	5/28	9/30	12/9	5/28	9/30	12/8	5/28	9/30	12/8
Chemical Analyses (mg/l)													
Silica (SiO ₂)	--	22	51	56	43	38	41	28	30	33	41	50	54
Calcium (Ca)	42	25	46	50	14	18	19	15	16	19	22	72	78
Magnesium (Mg)	4	2	7	6	1	2	2	3	2	4	4	10	14
Sodium (Na)	40	11	86	75	7	11	13	10	11	16	8	23	25
Carbonate (CO ₃)	0	0	0	0	0	0	0	0	0	0	0	0	0
Bicarbonate (HCO ₃ as CaCO ₃)	144	74	184	192	50	72	74	28	34	32	0	0	0
Sulfate (SO ₄)	--	11	23	16	7.0	1.6	3.0	10	7.0	8.6	96	305	344
Chloride (Cl)	56	5	100	102	<1	2	2	18	23	39	<1	6	8
Fluoride (F)	0.8	0.2	1.1	1.0	0.2	0.5	0.5	0.2	0.1	0.2	0.2	0.5	0.6
Nitrate (N)	0.4	0.1	0.1	<0.1	0.1	0.1	<0.1	0.2	0.2	0.1	0.1	0.3	0.3
Total dissolved solids	332	176	428	460	138	94	136	162	124	162	206	530	584
Total hardness (as CaCO ₃)	120	72	146	148	40	54	58	52	48	64	72	200	252
Specific Conductance (μmho/cm)	490	200	700	785	110	165	175	175	165	230	220	695	750
pH	7.9	8.0	7.7	8.3	7.4	7.9	7.9	7.8	7.5	7.2	4.7	3.9	4.0
Temperature (°C)	--	7	15	6	8	15	4	3	5	0	4	5	0
Discharge estimated (l/s)	--	--	710	910	--	85	85	--	15	15	--	30	30

^a For location see Fig. 10.

TABLE A-II
GROUND WATER QUALITY

Location ^a	Water Supply, Jemez Springs: Church Canyon East and West (JS-2,-3)			Water Supply, Jemez Springs: Sino and Agua Durme Springs (JS-4,-5)			Water Supply, La Cueva: Horseshoe Spring (4)			Limestone Spring, West of Battleship Rock (JF-5)			Mineral and Thermal Spring, Soda Dam (JF-5)		
Date of Collection (1975)	5/28	9/30	12/8	5/28	9/30	12/8	5/28	9/30	12/8	5/28	9/30	12/8	5/28	9/30	12/8
Chemical Analysis (mg/l)															
Silica (SiO ₂)	60	28	23	80	71	71	87	79	85	44	49	52	53	34	45
Calcium (Ca)	14	15	17	14	15	13	11	11	10	108	126	42	220	162	142
Magnesium (Mg)	3	5	3	4	4	5	2	3	3	30	11	12	61	22	22
Sodium (Na)	12	13	14	13	14	13	13	16	16	150	168	277	830	756	926
Carbonate (CO ₃)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bicarbonate (HCO ₃ as CaCO ₃)	60	68	76	74	76	74	56	68	64	320	502	324	660	814	800
Sulfate (SO ₄)	15	5.0	9.5	5.0	0.4	3.5	8.0	2.6	<1.0	31	26	26	36	48	33
Chloride (Cl)	3	3	7	<1	3	4	3	7	4	190	349	375	1350	1350	1370
Fluoride (F)	0.4	0.4	0.5	0.3	0.4	0.5	0.2	0.1	0.2	1.5	2.4	2.1	2.3	3.1	2.7
Nitrate (N)	0.3	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.4	0.1	0.1	1.1	0.1	<0.1
Total dissolved solids	186	126	120	196	174	146	180	140	144	932	1270	1138	3800	3508	3496
Total hardness (as CaCO ₃)	46	58	56	52	56	54	36	40	40	360	362	156	800	494	494
Specific conductance (µmho/cm)	150	160	170	150	175	170	130	135	150	1600	2300	1900	6400	6100	6600
pH	7.4	7.9	7.4	7.8	8.2	7.6	7.2	7.2	7.3	7.4	7.4	7.7	7.1	6.9	7.0
Temperature (°C)	9	17	8	10	19	11	16	20	17	12	16	12	39	39	39

^a For location see Fig. 10.

TABLE A-II (cont)

GROUND WATER QUALITY

Location ^a	Cold Spring, Lake Fork Canyon (31)			Hofheim Flowing Well (27)			San Antonio Warm Springs (RV-1)	San Antonio Hot Springs (RV-2)	Spence Spring (RV-4)		McCauley Spring (RV-5)	
Date of Collection (1975)	5/28	9/30	12/9	5/28	9/30	12/9	8/14 ^b	8/12	9/24 ^c	12/9	9/24 ^d	12/9
Chemical Analysis (mg/l)												
Silica (SiO ₂)	56	54	52	68	63	72	97	83	65	68	53	59
Calcium (Ca)	10	14	14	26	30	28	6	6	7	7	10	10
Magnesium (Mg)	4	5	2	10	8	8	<1	<1	2	2	4	5
Sodium (Na)	10	14	12	109	124	107	27	22	49	49	19	20
Carbonate (CO ₃)	0	0	0	0	0	0	0	0	0	0	0	0
Bicarbonate (HCO ₃ as CaCO ₃)	60	57	64	410	390	382	58	56	120	128	76	74
Sulfate (SO ₄)	6.0	5.3	<1.0	5.0	2.6	2.3	10	7.0	15	16	3.5	5.0
Chloride (Cl)	3	4	4	2	8	5	6	14	8	10	4	4
Fluoride (F)	0.7	1.2	0.9	1.0	0.9	1.0	1.3	0.9	0.6	0.7	0.8	1.0
Nitrate (N)	0.2	0.1	0.1	0.8	0.9	0.9	0.8	0.3	<0.1	0.1	0.3	<0.1
Total dissolved solids	138	110	128	534	476	522	244	166	242	258	154	148
Total Hardness (as CaCO ₃)	52	56	46	104	108	102	18	16	26	28	40	44
Specific conductance (umhos/cm)	130	140	160	750	670	740	120	195	290	280	170	170
pH	7.5	7.8	7.3	7.5	7.6	7.7	7.6	7.5	8.0	8.3	7.9	8.0
Temperature (°C)	6	7	8	13	21	16	38	41	41	40	32	30

^aFor location see Fig.10.^bCollected R.L. Borton, SEO, flow 0.6 l/s.^cCollected R.L. Borton, SEO, flow 1.0 l/s.^dCollected R.L. Borton, SEO.

TABLE A-II (cont)

GROUND WATER QUALITY

<u>Location ^a</u>	<u>Valle Toledo Test hole (H-2)</u>	<u>Valle Grande Test hole (H-7)</u>	<u>Madera Seep (JF-9)</u>
<u>Date of Collection (1975)</u>	<u>11/16^b</u>	<u>11/6^c</u>	<u>12/9</u>
<u>Chemical Analysis (mg/l)</u>			
Silica (SiO ₂)	51	75	33
Calcium (Ca)	7	6	16
Magnesium (Mg)	<1	1	40
Sodium (Na)	11	14	728
Carbonate (CO ₂)	0	0	56
Bicarbonate (HCO ₃ as CaCO ₃)	36	44	1620
Sulfate (SO ₄)	<1.0	1.4	300
Chloride (Cl)	2	2	302
Fluoride (F)	1.8	0.3	5.0
Nitrate (N)	0.2	0.2	<0.1
Total dissolved solids	114	122	2800
Total hardness (as CaCO ₃)	20	18	206
Specific conductance (μmho/cm)	90	90	4620
pH	7.7	7.4	8.5
Temperature (°C)	15	18	11

^a For location see Fig. 10.

^b Collected R. L. Borton, SEO, flow 13 to 19 *ℓ/s.*

^c Collected R. L. Borton, SEO, flow 0.5 *ℓ/s.*

TABLE A-III
FENTON HILL SITE WATER QUALITY

<u>Source</u>	<u>Lower Pond</u>		<u>Upper</u>	<u>Mud</u>
	<u>GT-2</u>	<u>GT-2</u>	<u>Pond</u>	<u>Pit</u>
			<u>GT-2</u>	<u>EE-1</u>
<u>Date Collected (1975)</u>	<u>1/28</u>	<u>9/30</u>	<u>9/30</u>	<u>9/30</u>
<u>Chemical Analysis (mg/l)</u>				
Silica (SiO ₂)	--	19	70	59
Calcium (Ca)	29	33	26	81
Magnesium (Mg)	1	2	4	6
Sodium (Na)	--	99	96	165
Carbonate (CO ₃)	310	0	0	0
Bicarbonate (HCO ₃ as CaCO ₃)	570	120	120	168
Sulfate (SO ₄)	--	128	33	360
Chloride (Cl)	470	56	37	17
Fluoride (F)	2.0	0.5	1.1	0.9
Nitrate (N)	2.2	0.4	0.4	0.3
Total dissolved solids	2600	478	500	1264
Total hardness (as CaCO ₃)	76	92	82	226
Specific conductance (μmho/cm)	3400	740	650	2080
pH	11.0	8.0	7.4	7.4

APPENDIX B
SUMMARIES OF SEISMIC DATA

The historical record of regional earthquakes from 1928 to 1973 are summarized in Table B-I and indicates that New Mexico is a region of moderate to low earthquake risk. Locations and magnitudes of microearthquakes recorded in 1975 are given in Table B-II.

The locations, elevations, station characteristics, and installation dates for the regional seismic net are shown in Table B-III for reference.

TABLE B-I

REPORTED EARTHQUAKES IN THE VICINITY^a OF LOS ALAMOS FROM JANUARY 1, 1928 TO SEPTEMBER 1, 1973

Year	Date	Hour MST	Locality of Report	Distance from Los Alamos km	Maximum Reported Intensity M.M.	Magnitude M _L	Remarks
1930	March 23	12:00	Albuquerque ^b	95	IV	3 1/2	Very brief shock that shook houses and rattled dishes.
1930	Dec. 3	14:36	Albuquerque	95	V-VI	4 1/2	Two distinct shocks. Cracked plaster and broke dishes. Felt area about 18000 sq. mi.
1931	Feb. 3	16:45	Albuquerque	95	V	4	
1931	Feb. 4	21:48	Albuquerque	95	VI	4 1/2	Hundreds left houses, many in pajamas, and many reported they were thrown from bed.
1936	Sept. 9	05:55	Albuquerque	95	IV	3 1/2	Two shocks.
1947	Nov. 6	09:50	San Antonito	85	V-VI	4 1/4	Dishes jarred from shelves. Cracked plaster at one location. Felt within a 16-km radius.
1952	August 17	03:45	Los Alamos	0	V	4	Felt by all. Slight damage to walls of houses. Doors and dishes rattled. Felt in Espanola, 25 km from Los Alamos.
1952	Oct. 7	02:20	San Juan Mtns., Carson Nat'l Forest	110	V	4	Felt at Antonito and 15 miles west of there at Osier, Colorado; also at Chama and Tres Piedras, New Mexico.
1954	Nov. 2	10:00	Albuquerque- Bernalillo	80	IV	3 1/2	Felt along 32 km of the Rio Grande Valley from Albuquerque to Bernalillo.
1954	Nov. 3	13:39	Albuquerque- Bernalillo	80	V	4	Felt most strongly at Bernalillo. Windows, doors rattled. Loose objects shifted.
1955	August 12	09:20	Turquoise Trading Post- 25 km SW of Santa Fe	40	V	4	Plaster cracked in wall. At Santa Fe (25 km NF) and Bandelier Natl. Monument (25 km NW) dishes, windows, etc., rattled.
1956	April 25	20:30	Sandia Mtns.	90	V	4	Sharp jolt. Awakened many and frightened few in Tijeras Canyon. Loose objects rattled. Maximum extent of felt area--28 km.

TABLE B-I (cont)

Year	Date	Hour MST	Locality of Report	Distance from Los Alamos km	Maximum Reported Intensity M.M.	Magnitude M_L	Remarks
1969	July 4	07:43	San Juan Pueblo ^c	35	IV	3.5	Felt most strongly 10 and 20 km north of Española.
1970	Nov. 28	00:40	Albuquerque ^c	80	V	3.7	Felt in Albuquerque, most strongly in the NW and SW sections of the city.
1971	Jan. 4	00:39	Albuquerque ^c	80	VI	3.9	Felt most strongly at Corrales (about 20 km northeast of Albuquerque).
1971	Dec. 5	22:18	N. E. Jemez Mtns. ^c	25	V	3.3	Minor damage in the Abiquiu-Los Alamos area.
1973	March 17	00:43	Abiquiu ^c	30	V	3.7	Felt in Los Alamos area.

(Based on U.S. Department of Commerce publications entitled U.S. Earthquakes and information supplied by S.A. Northrop, 1972)

^aShocks located within 111 km (1° of arc on the surface) of Los Alamos.

^bWeak shocks, maximum reported intensity $\leq$ III, in the vicinity of Albuquerque have not been listed.

^cAlso located instrumentally by New Mexico Stations.

TABLE B-II

EPICENTRAL SOLUTIONS FOR NORTHERN NEW MEXICO LOCAL AND NEAR REGIONAL EARTHQUAKES

YEAR	MONTH	DAY	ORIGIN TIME (GMT)	EPICENTER		MAGNITUDE (^M L)	FOCAL DEPTH (km)
				N LATITUDE	W LONGITUDE		
1975	May	16	07:26:22.5	36° 29'	104° 42'	2.4	
1975	May	21	04:46:59.0	36° 58'	107° 13'	2.0	
1975	May	28	09:21:38.8	35° 46'	106° 32'	0.7	
1975	June	21	05:41:35.2	36° 05'	104° 02'	2.5	
1975	June	26	07:03:43.4	36° 57'	105° 27'	3.4	
1975	June	27	01:39:24.7	34° 10'	106° 56'	2.2	39
1975	June	27	14:31:38.1	35° 00'	105° 02'	1.8	
1975	June	28	07:20:23.2	34° 07'	106° 55'	2.4	
1975	July	2	02:34:22.8	34° 22'	106° 52'	1.5	
1975	July	18	15:26:54	34° 37'	106° 47'	1.1	
1975	July	20	07:44:37.8	34° 34'	106° 44'	2.1	
1975	Aug.	19	23:06:26.9	36° 23'	104° 44'	1.6	
1975	Aug.	25	12:21:14.6	35° 44'	105° 47'	0.8	17
1975	Aug.	29	18:01:50.8	36° 13'	106° 53'	0.8	8
1975	Sept.	4	06:25:24.1	35° 13'	106° 27'	1.5	
1975	Sept.	6	03:46:50.4	36° 11'	106° 14'	2.3	17
1975	Sept.	7	00:24:07.6	36° 11'	106° 14'	1.3	12
1975	Sept.	7	13:43:27.9	36° 11'	106° 14'	1.4	11
1975	Sept.	10	01:01:48.2	36° 44'	105° 40'	2.0	
1975	Sept.	15	07:19:54.2	36° 11'	106° 14'	1.1	12
1975	Sept.	17	00:07:23.9	36° 05'	104° 15'	1.8	
1975	Sept.	18	01:48:17.5	36° 06'	106° 53'	1.0	33

TABLE B-II (cont)

<u>YEAR</u>	<u>MONTH</u>	<u>DAY</u>	<u>ORIGIN TIME</u> (GMT)	<u>EPICENTER</u>		<u>MAGNITUDE</u> (M_L)	<u>FOCAL DEPTH</u> (km)
				<u>N LATITUDE</u>	<u>W LONGITUDE</u>		
1975	Sept.	25	03:39:04	36° 07'	106° 15'	1.0	15
1975	Sept.	25	15:28:50.2	36° 00'	106° 52'	0.5	38
1975	Sept.	27	12:07:21.4	36° 00'	106° 52'	0.8	
1975	Sept.	29	11:09:42.4	36° 00'	106° 52'	3.2	19
1975	Sept.	29	11:14:20.8	36° 00'	106° 52'	0.5	15
1975	Sept.	29	11:17:07.6	36° 00'	106° 52'	1.2	16
1975	Sept.	29	12:53:46.2	36° 00'	106° 52'	1.1	
1975	Sept.	29	13:17:19.2	36° 00'	106° 52'	2.0	16
1975	Sept.	29	14:19:42.6	36° 00'	106° 52'	0.5	13
1975	Sept.	29	14:47:02.2	36° 00'	106° 52'	0.5	15
1975	Sept.	29	17:29:15.8	36° 00'	106° 52'	0.5	16
1975	Oct.	3	05:43:41.8	34° 08'	106° 54'	1.5	6
1975	Oct.	10	07:12:28.5	34° 38'	107° 32'	1.5	
1975	Oct.	10	11:16:56.7	34° 23'	106° 21'	2.1	
1975	Oct.	17	15:45:02.5	35° 23'	108° 12'	2.4	20
1975	Oct.	31	04:02:15.9	34° 06'	106° 38'	1.4	29
1975	Nov.	5	02:40:12.2	34° 03'	106° 50'	1.7	
1975	Nov.	6	03:38:22.6	34° 36'	105° 41'	0.8	
1975	Nov.	6	12:45:24.6	36° 31'	105° 11'	1.8	
1975	Dec.	3	10:12:20.4	32° 54'	108° 42'	3.6	
1975	Dec.	3	13:41:31.1	35° 47'	106° 10'	1.1	14

TABLE B-III

LOCATIONS OF REGIONAL SEISMIC STATIONS

CODE NAME	GEOGRAPHIC LOCATION	COORDINATES		ELEVATION (METERS)	SEISMO- METER	MAGNIFI- CATION ^a	TELEMETRY (FREQ.=MHz)	DATE INSTALLED
		LATITUDE	LONGITUDE					
BRC	Barley Canyon	35 53 25N	106 42 41W	2261	L4-C	535K	164.5/LL	20 NOV 75
CLP	Clara Peak	36 02 09	106 14 25	2591	SS-1	290K	169.0	7 OCT 73
EUM	Eureka Mesa	36 00 47	106 50 38	2914	L4-3D	280K	M/226.7	13 JAN 76
FCN ^b	Frijoles Canyon	35 46 19	106 15 01	1945	L4-3D	b	LL	7 MAY 73
LCV ^c	La Cueva	35 52 58	106 40 27	2652	L4-3D	570K	LL	5 SEP 73
LFC	Lake Fork Canyon	35 52 37	106 39 53	2451	L4-C	280K	169.0/LL	4 NOV 75
LOA	Los Alamos (TA-49,LASL)	35 49 29	106 17 40	2144	L4-3D	240K	LL	12 JAN 72
MSA	San Antonio Mountain	36 51 33	106 01 04	3322	L4-3D	570K	M/226.7	9 OCT 75
MTL	Mt. Taylor	35 15 07	107 35 47	3335	L4-3D	555K	M/226.7	15 OCT 75
RIO	Caja del Rio	35 45 17	106 10 32	2073	L4-C	420K	166.25	21 FEB 75
SPD	St. Peter's Dome	35 45 28	106 22 10	2566	SS-1	1120K	164.75	18 SEP 73
TSL	Navajo Community College	36 22 20	109 14 37	2012	SS-1	580K	LL	22 MAY 75
TSP	Tesuque Peak	35 47 07	105 46 53	3664	SS-1	1080K	M/226.7	14 OCT 73
TTP	Tetilla Peak	35 36 34	106 12 23	2103	L4-C	530K	164.50	18 MAR 75

LL ~ Land Line L4-C, L4-3D ~ Mark Products

M ~ Microwave SS-1 ~ Kinematics (Ranger)

^aPeak Magnification at ~ 10 HZ

^bClosed

^cFenton Hill site is ~ 300 m south of LCV

APPENDIX C
EXAMPLES OF CLIMATOLOGICAL DATA COLLECTION

Tables C-I through C-IV indicate typical tabulations of wind and precipitation data for the Fenton Hill weather station covering the month of January 1976.

Figures C-1 through C-4 indicate the type of data analyses, reduction, and displays that can be provided for the wind data. These summaries for January through April show, for example, that the prevailing winds came from the NNW during that period.

The precipitation data summary displays for January through April 1976, shown in Figs. C-5 through C-8, illustrate the large contribution provided by the snows in February 1976.

The temperature data analyses and displays are similarly illustrated in Figs. C-9 through C-12.

TABLE C-I

FENTON HILL DAILY WIND DIRECTION DATA

JANUARY 1976

(TABULATED BY HOUR, UNIT OF MEASURE=DEGREES)

HOUR OF DAY																
DAY	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4
1	270+/-	20 285+/-	45 285+/-	40 285+/-	37 315+/-	45 315+/-	42 315+/-	45 360+/-	60 315+/-	52 285+/-	75 285+/-	75 300+/-	60			
2	315+/-	45 315+/-	40 330+/-	57 345+/-	52 360+/-	35 315+/-	42 330+/-	55 345+/-	50 330+/-	60 345+/-	110 180+/-	0 285+/-	62			
3	345+/-	45 345+/-	45 360+/-	70 330+/-	40 330+/-	45 345+/-	55 360+/-	35 15+/-	52 360+/-	60 345+/-	75 330+/-	90 270+/-	90			
4	330+/-	30 330+/-	30 345+/-	107 360+/-	95 330+/-	30 315+/-	20 315+/-	45 330+/-	40 30+/-	55 360+/-	120 225+/-	75 210+/-	110			
5	16+/-	45 360+/-	45 360+/-	60 15+/-	47 330+/-	60 345+/-	52 345+/-	45 360+/-	50 315+/-	45 315+/-	52 310+/-	52 300+/-	60			
6	285+/-	45 270+/-	52 270+/-	60 300+/-	60 280+/-	50 270+/-	57 285+/-	45 285+/-	45 285+/-	45 300+/-	45 285+/-	45 300+/-	60			
7	345+/-	45 330+/-	30 330+/-	30 360+/-	52 345+/-	42 360+/-	30 15+/-	45 15+/-	45 15+/-	75 360+/-	90 345+/-	135 255+/-	45			
8	315+/-	45 345+/-	75 360+/-	60 360+/-	60 345+/-	45 360+/-	35 15+/-	45 30+/-	60 345+/-	75 300+/-	60 285+/-	50 270+/-	30			
9	330+/-	30 330+/-	30 335+/-	30 275+/-	32 275+/-	22 30+/-	60 60+/-	60 30+/-	60 290+/-	72 285+/-	45 280+/-	35 270+/-	50			
10	300+/-	60 300+/-	90 225+/-	75 270+/-	90 270+/-	60 260+/-	50 270+/-	60 300+/-	57 290+/-	50 300+/-	60 300+/-	75 300+/-	60			
11	345+/-	105 30+/-	60 45+/-	45 360+/-	70 30+/-	55 30+/-	60 15+/-	45 30+/-	57 360+/-	45 330+/-	60 300+/-	60 300+/-	60			
12	330+/-	30 330+/-	30 315+/-	15 330+/-	30 330+/-	30 330+/-	30 315+/-	45 315+/-	45 315+/-	45 300+/-	75 285+/-	75 285+/-	52			
13	300+/-	45 285+/-	45 315+/-	45 315+/-	45 345+/-	75 345+/-	75 330+/-	60 330+/-	60 300+/-	57 315+/-	47 315+/-	50 300+/-	60			
14	320+/-	28 325+/-	27 330+/-	27 340+/-	30 355+/-	30 340+/-	30 360+/-	77 30+/-	72 355+/-	47 300+/-	60 270+/-	70 210+/-	70			
15	330+/-	30 325+/-	35 325+/-	35 320+/-	52 355+/-	30 330+/-	50 345+/-	57 320+/-	45 300+/-	45 330+/-	54 355+/-	90 320+/-	50			
16	30+/-	47 30+/-	77 35+/-	75 150+/-	105 150+/-	75 105+/-	15 110+/-	12 100+/-	17 120+/-	20 190+/-	105 290+/-	42 210+/-	120			
17	30+/-	60 105+/-	15 135+/-	42 120+/-	30 105+/-	42 60+/-	30 90+/-	2 95+/-	5 300+/-	165 180+/-	180 180+/-	180 150+/-	150			
18	105+/-	60 330+/-	30 30+/-	90 30+/-	105 330+/-	30 330+/-	30 330+/-	30 330+/-	30 300+/-	30 285+/-	45 285+/-	45 285+/-	45			
19	330+/-	30 330+/-	30 300+/-	30 315+/-	15 330+/-	30 30+/-	62 195+/-	75 195+/-	75 180+/-	90 150+/-	90 180+/-	60 165+/-	75			
20	285+/-	12 330+/-	20 75+/-	180 300+/-	27 255+/-	95 255+/-	105 30+/-	60 45+/-	75 45+/-	75 90+/-	60 180+/-	180 240+/-	120			
21	180+/-	180 45+/-	45 60+/-	30 95+/-	67 115+/-	67 120+/-	27 120+/-	27 125+/-	37 150+/-	62 150+/-	62 165+/-	75 195+/-	90			
22	360+/-	30 345+/-	15 300+/-	30 345+/-	52 180+/-	180 345+/-	50 40+/-	37 360+/-	60 315+/-	105 255+/-	45 270+/-	55 255+/-	47			
23	315+/-	30 330+/-	30 315+/-	45 330+/-	30 330+/-	57 315+/-	42 315+/-	45 315+/-	42 315+/-	75 330+/-	90 315+/-	130 300+/-	120			
24	330+/-	30 330+/-	30 330+/-	30 330+/-	30 315+/-	42 330+/-	30 330+/-	30 315+/-	40 300+/-	60 250+/-	72 270+/-	57 270+/-	60			
25	345+/-	67 330+/-	60 345+/-	45 360+/-	60 330+/-	30 360+/-	60 345+/-	45 320+/-	45 330+/-	30 315+/-	45 315+/-	45 300+/-	60			
26	345+/-	45 330+/-	30 360+/-	55 15+/-	45 15+/-	72 15+/-	52 360+/-	60 315+/-	40 100+/-	160 255+/-	75 285+/-	75 180+/-	160			
27	15+/-	75 15+/-	75 30+/-	62 45+/-	45 75+/-	60 15+/-	60 45+/-	45 95+/-	32 115+/-	27 210+/-	27 285+/-	152 255+/-	75			
28	75+/-	135 180+/-	180 30+/-	57 45+/-	47 30+/-	65 360+/-	60 90+/-	90 150+/-	30 165+/-	62 180+/-	67 150+/-	120 360+/-	150			
29	135+/-	45 120+/-	30 120+/-	27 115+/-	22 75+/-	15 75+/-	22 30+/-	30 30+/-	57 25+/-	65 360+/-	90 270+/-	90 240+/-	60			
30	30+/-	60 15+/-	45 20+/-	57 30+/-	30 15+/-	45 360+/-	60 300+/-	60 330+/-	30 315+/-	45 300+/-	60 300+/-	47 300+/-	60			
31	360+/-	60 90+/-	120 150+/-	60 165+/-	45 210+/-	30 165+/-	45 120+/-	30 135+/-	45 180+/-	180 210+/-	120 255+/-	105 225+/-	62			

TABLE C-I (cont)

FENTON HILL DAILY WIND DIRECTION DATA

JANUARY 1976

(TABULATED BY HOUR, UNIT OF MEASURE=DEGREES)

HOUR OF DAY																													
FAr	13	14	15	16	17	18	19	20	21	22	23	24																	
1	300+/-	70 300+/-	57 285+/-	50 300+/-	50 315+/-	42 315+/-	45 315+/-	37 360+/-	90 330+/-	60 330+/-	57 330+/-	60 360+/-	32																
2	300+/-	55 300+/-	37 300+/-	60 300+/-	60 330+/-	60 310+/-	40 320+/-	40 325+/-	35 320+/-	45 330+/-	30 320+/-	40 360+/-	65																
3	255+/-	60 255+/-	45 270+/-	60 240+/-	30 255+/-	45 250+/-	20 0+/-	45 285+/-	22 330+/-	35 320+/-	37 315+/-	45 0+/-	12																
4	165+/-	130 240+/-	60 265+/-	45 285+/-	45 285+/-	45 300+/-	30 300+/-	37 320+/-	45 330+/-	30 360+/-	60 30+/-	30 30+/-	32																
5	265+/-	45 345+/-	60 315+/-	75 285+/-	70 300+/-	60 330+/-	30 360+/-	117 60+/-	60 95+/-	37 210+/-	90 285+/-	55 315+/-	45																
6	300+/-	30 300+/-	47 285+/-	45 300+/-	55 300+/-	60 285+/-	75 300+/-	60 315+/-	45 330+/-	60 330+/-	57 300+/-	45 315+/-	45																
7	270+/-	65 300+/-	60 315+/-	50 315+/-	45 315+/-	45 330+/-	35 330+/-	35 330+/-	30 345+/-	45 345+/-	50 330+/-	60 315+/-	60																
8	270+/-	60 300+/-	60 300+/-	60 300+/-	60 315+/-	45 330+/-	30 330+/-	30 330+/-	30 315+/-	15 345+/-	45 330+/-	30 330+/-	30																
9	270+/-	60 270+/-	60 285+/-	45 285+/-	45 255+/-	15 240+/-	27 270+/-	30 270+/-	60 270+/-	40 240+/-	60 210+/-	47 240+/-	52																
10	300+/-	60 300+/-	60 300+/-	65 285+/-	50 300+/-	60 315+/-	45 330+/-	60 330+/-	60 15+/-	60 45+/-	45 45+/-	45 45+/-	47																
11	265+/-	55 265+/-	45 300+/-	60 300+/-	60 315+/-	60 315+/-	45 315+/-	15 330+/-	30 330+/-	30 330+/-	30 315+/-	27 315+/-	15																
12	285+/-	45 285+/-	50 270+/-	57 270+/-	60 285+/-	45 285+/-	45 290+/-	35 300+/-	30 300+/-	35 285+/-	45 300+/-	30 300+/-	30																
13	300+/-	60 300+/-	57 285+/-	52 300+/-	55 300+/-	60 345+/-	72 315+/-	42 315+/-	37 330+/-	30 315+/-	20 320+/-	12 320+/-	27																
14	260+/-	65 265+/-	32 270+/-	47 280+/-	45 300+/-	32 300+/-	65 300+/-	45 330+/-	31 320+/-	30 320+/-	30 310+/-	20 330+/-	30																
15	290+/-	48 300+/-	45 295+/-	33 310+/-	37 320+/-	35 330+/-	35 335+/-	35 340+/-	30 350+/-	60 60+/-	67 60+/-	92 60+/-	77																
16	210+/-	62 240+/-	77 265+/-	45 300+/-	60 30+/-	72 35+/-	60 90+/-	67 90+/-	65 40+/-	32 35+/-	42 65+/-	65 150+/-	179																
17	180+/-	180 180+/-	60+/-	180 360+/-	67 30+/-	75 180+/-	72 180+/-	75 330+/-	30 360+/-	57 45+/-	72 330+/-	30 360+/-	60																
18	265+/-	45 265+/-	45 265+/-	45 270+/-	60 300+/-	37 285+/-	27 300+/-	30 290+/-	20 300+/-	30 315+/-	45 360+/-	57 330+/-	30																
19	195+/-	75 185+/-	100 180+/-	67 195+/-	50 195+/-	45 195+/-	75 330+/-	30 45+/-	45 60+/-	60 90+/-	40 90+/-	30 180+/-	30																
20	180+/-	180 220+/-	75 180+/-	120 165+/-	75 210+/-	90 360+/-	62 45+/-	45 180+/-	180 180+/-	180 105+/-	45 45+/-	105 15+/-	67																
21	195+/-	75 195+/-	72 195+/-	72 185+/-	55 190+/-	42 195+/-	17 60+/-	60 75+/-	17 180+/-	92 345+/-	45 55+/-	27 45+/-	47																
22	270+/-	90 300+/-	60 300+/-	57 285+/-	45 315+/-	45 330+/-	30 330+/-	30 330+/-	30 330+/-	30 305+/-	27 330+/-	30 315+/-	40																
23	315+/-	75 300+/-	60 315+/-	75 315+/-	75 315+/-	72 330+/-	30 330+/-	40 360+/-	30 355+/-	35 340+/-	42 340+/-	22 340+/-	22																
24	285+/-	45 285+/-	47 300+/-	60 315+/-	45 315+/-	45 300+/-	60 300+/-	60 330+/-	60 345+/-	75 345+/-	75 330+/-	60 330+/-	60																
25	315+/-	75 285+/-	75 300+/-	60 300+/-	60 300+/-	60 300+/-	57 330+/-	30 330+/-	30 360+/-	32 330+/-	30 330+/-	30 345+/-	45																
26	285+/-	105 300+/-	90 300+/-	60 330+/-	60 295+/-	37 330+/-	60 345+/-	45 360+/-	67 360+/-	65 15+/-	50 345+/-	45 30+/-	57																
27	270+/-	60 150+/-	165 180+/-	180 360+/-	130 295+/-	30 360+/-	90 30+/-	67 180+/-	180 180+/-	180 345+/-	45 15+/-	45 315+/-	105																
28	180+/-	92 210+/-	75 210+/-	62 195+/-	52 195+/-	45 210+/-	60 75+/-	70 135+/-	50 190+/-	30 180+/-	60 180+/-	45 105+/-	45																
29	270+/-	45 285+/-	75 300+/-	60 300+/-	60 315+/-	45 330+/-	30 330+/-	30 45+/-	45 30+/-	60 45+/-	45 15+/-	62 360+/-	65																
30	300+/-	60 300+/-	57 315+/-	45 330+/-	60 315+/-	45 315+/-	45 330+/-	40 330+/-	40 360+/-	60 18+/-	45 30+/-	60 45+/-	30																
31	255+/-	45 240+/-	60 240+/-	60 255+/-	75 285+/-	45 315+/-	47 30+/-	60 30+/-	60 15+/-	45 15+/-	45 15+/-	60 15+/-	45																

TABLE C-II
FENTON HILL DAILY WIND SPEED DATA
JANUARY 1976
(TABULATED BY HOUR, UNIT OF MEASURE=METERS/SECOND)

HOUR OF DAY																								
DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	4.5	4.2	4.5	4.5	4.0	1.5	.9	1.5	2.2	2.7	3.1	3.6	3.6	4.0	3.6	3.1	2.9	2.9	3.4	1.6	2.2	1.6	1.6	1.6
2	2.2	3.4	2.0	2.5	1.5	3.6	2.9	2.2	2.2	1.6	1.6	2.2	3.6	3.6	3.6	3.6	4.7	3.6	4.5	3.6	4.9	4.5	3.1	3.1
3	3.6	3.1	3.1	3.4	2.7	2.7	2.0	2.0	2.2	2.2	1.6	2.2	2.0	2.2	2.2	1.5	1.1	6.7	1.5	2.0	2.0	1.5	1.5	1.5
4	1.5	1.1	.9	.4	1.1	.9	1.1	.9	.9	1.1	1.5	1.6	1.6	2.7	3.6	2.2	1.6	2.2	3.4	2.2	1.5	1.5	2.7	2.9
5	2.2	2.0	1.6	2.5	2.5	2.5	2.7	2.0	2.5	1.6	4.0	2.5	3.1	4.5	3.6	3.1	2.2	1.6	.9	1.1	.9	.9	1.6	2.5
6	2.2	2.2	3.1	2.9	2.2	4.0	4.5	4.5	4.5	3.4	5.4	7.2	7.6	3.6	3.6	2.7	1.6	2.7	3.1	4.7	3.6	3.1	4.9	4.0
7	3.1	2.5	2.5	2.2	2.5	1.6	2.0	1.6	1.6	1.6	1.5	2.5	3.6	4.5	4.0	4.0	2.7	2.7	1.6	3.1	3.6	3.1	2.5	2.5
8	4.5	3.6	1.6	2.2	1.5	1.6	1.6	.9	1.5	1.6	2.2	3.4	3.1	4.0	4.5	4.0	3.1	2.9	2.2	1.6	1.6	1.5	2.7	3.1
9	2.5	1.6	1.5	.9	.4	1.6	1.1	1.5	.9	1.6	2.7	3.6	2.9	3.4	2.5	2.0	1.6	1.5	1.5	1.6	1.5	.9	1.5	1.5
10	1.1	1.1	1.6	2.0	2.7	2.2	1.5	1.6	2.9	2.7	3.6	4.0	4.7	4.5	4.9	5.4	4.9	6.7	3.6	2.7	1.6	1.6	2.5	1.5
11	1.1	1.1	1.5	1.5	1.6	2.5	2.0	2.0	2.0	2.2	2.7	3.1	3.1	3.1	3.1	3.1	2.7	1.6	2.5	1.6	1.6	2.7	2.7	2.0
12	1.1	1.5	1.6	1.6	2.5	2.7	2.7	2.9	2.0	2.2	3.1	3.4	4.9	4.9	5.4	6.0	4.9	4.5	3.6	4.5	4.9	5.1	6.5	7.6
13	6.5	6.0	6.0	6.5	4.7	2.5	3.6	5.6	5.4	5.4	4.0	4.9	6.0	5.4	4.0	4.0	3.6	3.1	3.4	4.5	4.0	5.4	5.2	1.6
14	1.5	2.7	3.1	1.6	2.0	1.5	1.5	2.2	2.2	1.5	1.6	2.0	2.1	2.6	2.6	2.2	1.6	.2	1.5	2.0	2.7	3.2	3.6	1.5
15	3.4	3.5	3.1	1.4	1.7	2.5	3.1	4.5	3.7	2.4	1.6	1.7	3.5	3.5	3.5	2.6	2.7	2.3	2.7	2.1	1.6	2.7	2.4	2.6
16	1.4	1.5	1.6	1.9	1.5	2.1	1.5	1.4	1.9	1.5	1.5	1.5	2.5	2.2	3.6	1.9	1.5	1.6	1.5	1.9	2.5	2.2	1.9	.6
17	1.5	2.2	1.6	1.1	.4	1.1	1.6	.9	.9	1.1	1.1	1.5	1.6	1.6	2.2	3.1	1.6	.9	.4	.7	1.1	.9	1.1	.7
18	.4	.9	.9	.4	1.6	2.2	2.7	3.1	3.4	2.9	3.4	4.0	4.2	4.7	3.6	3.6	2.5	1.5	1.5	2.2	3.1	2.2	1.1	1.6
19	2.0	2.2	2.2	3.1	1.6	1.5	2.0	2.2	1.6	1.6	2.5	2.7	2.2	1.6	2.5	2.7	2.2	.7	.7	1.6	1.1	1.6	.7	.2
20	.7	.7	.2	.9	.2	.4	1.6	.9	1.1	1.1	.9	1.1	1.6	2.2	1.5	1.6	1.1	.7	2.5	1.6	2.0	.9	.7	1.1
21	2.2	2.9	2.0	1.5	1.6	2.9	2.9	2.9	2.5	2.7	2.5	2.2	2.2	2.7	2.7	2.2	1.5	.7	.7	.9	.9	.7	.7	.1
22	.2	.7	.4	.4	2.5	.2	1.6	1.6	.9	1.5	1.5	2.0	2.7	3.4	3.4	4.0	3.6	2.7	2.7	2.9	3.4	4.0	3.6	3.6
23	3.1	2.5	3.1	3.4	3.6	4.0	4.7	4.5	2.7	2.9	2.9	3.1	4.9	4.9	3.4	3.4	3.1	1.5	2.0	2.2	1.6	1.6	1.5	1.6
24	1.7	1.6	1.6	2.0	2.5	2.7	2.0	2.7	1.5	1.5	1.5	2.7	3.1	4.2	4.0	5.1	4.5	4.5	5.4	4.9	4.0	3.6	3.6	3.1
25	4.0	4.9	4.5	4.2	3.6	2.9	4.0	6.5	6.7	5.6	5.4	4.9	5.4	5.4	5.4	4.9	4.0	2.9	2.9	2.0	1.6	2.0	2.2	1.6
26	2.2	2.0	1.1	1.5	1.6	1.5	1.1	1.1	.7	1.1	2.0	2.2	2.5	2.7	3.6	3.4	3.6	2.7	1.6	1.6	1.6	2.5	2.7	1.6
27	2.2	2.7	3.6	3.6	2.5	1.1	1.6	2.0	1.1	1.1	1.1	1.6	2.2	2.2	2.0	1.6	1.6	2.0	3.4	3.1	1.6	1.1	2.0	1.1
28	1.5	1.1	2.2	2.9	1.6	1.1	1.5	1.1	1.1	1.5	.9	1.1	2.0	2.2	2.7	2.7	1.5	.9	1.1	2.0	1.6	1.1	1.5	1.5
29	1.5	1.6	1.1	.9	1.6	.9	.9	1.1	1.2	1.6	1.6	2.2	2.7	2.9	3.1	2.9	2.0	1.6	1.5	2.0	1.6	2.2	2.5	2.2
30	1.6	1.5	1.1	1.6	1.5	1.5	1.5	2.0	2.9	4.5	4.5	4.5	5.6	5.1	5.4	7.2	7.6	6.7	5.6	2.9	2.0	2.5	2.9	3.1
31	1.5	1.5	1.6	1.5	.7	1.1	1.1	1.5	.7	1.6	1.5	1.6	2.7	2.9	2.5	2.2	2.0	1.5	1.1	2.0	2.0	2.5	2.0	2.2

TABLE C-III

FENTON HILL DAILY TEMPERATURE DATA

JANUARY 1976

(TABULATED BY HOUR, UNIT OF MEASURE=DEGREE CENTIGRADE)

CAR	HOUR OF DAY																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	-21	-21	-22	-22	-23	-23	-23	-21	-19	-18	-17	-17	-18	-17	-17	-18	-19	-19	-21	-21	-21	-21	-21	-22
2	-23	-23	-23	-23	-23	-22	-22	-22	-20	-17	-14	-12	-14	-15	-15	-17	-17	-18	-18	-18	-18	-18	-18	-18
3	-18	-18	-18	-18	-18	-18	-18	-18	-13	-12	-8	-5	-5	-4	-4	-7	-8	-12	-12	-12	-11	-11	-11	-11
4	-11	-11	-12	-12	-11	-11	-11	-9	-7	-3	-1	-1	-1	-2	-4	-6	-7	-8	-9	-11	-12	-12	-12	-12
5	-12	-12	-12	-12	-12	-12	-12	-8	-8	-8	-5	-1	-1	-2	-2	-5	-5	-7	-7	-7	-8	-8	-7	-8
6	-8	-8	-8	-8	-8	-8	-9	-10	-11	-11	-11	-11	-9	-12	-9	-9	-11	-12	-12	-13	-14	-15	-16	-17
7	-17	-18	-18	-18	-18	-19	-19	-18	-16	-13	-9	-8	-9	-12	-12	-12	-13	-15	-16	-17	-15	-15	-15	-15
8	-13	-14	-15	-15	-14	-13	-13	-12	-8	-5	-2	-2	-1	-2	-1	-2	-2	-2	-4	-4	-4	-6	-4	-4
9	-4	-5	-5	-6	-7	-6	-6	-5	1	3	5	5	4	4	5	3	1	-1	-2	-2	-2	-3	-3	-3
10	-3	-3	-4	-4	-4	-5	-6	-6	-5	-3	-3	-2	-2	-2	-4	-5	-6	-7	-7	-7	-8	-8	-8	-8
11	-11	-11	-11	-11	-11	-11	-11	-8	-7	-5	-2	-1	-1	0	-1	-1	-3	-4	-6	-6	-6	-5	-6	-6
12	-8	-8	-8	-8	-8	-8	-8	-6	-2	-1	0	2	1	0	2	0	-1	-2	-4	-3	-4	-4	-6	-6
13	-8	-8	-7	-7	-7	-8	-8	-7	-7	-6	-4	-2	-2	-3	-3	-4	-6	-7	-7	-7	-8	-8	-8	-8
14	-8	-10	-9	-11	-9	-8	-9	-8	-3	2	4	4	4	4	4	2	-1	-4	-2	-2	-2	-3	-4	-4
15	-5	-6	-6	-6	-6	-6	-4	-4	-5	-2	0	3	3	3	1	-1	-2	-3	-5	-6	-5	-2	-2	-1
16	-1	-1	0	-1	-3	-3	-4	-2	1	5	6	6	6	6	7	6	4	2	0	0	1	2	1	-1
17	-2	-2	-2	-3	-4	-2	-2	-1	3	5	6	6	9	9	7	7	6	2	-1	-1	0	-1	0	-1
18	-2	-2	-1	-2	-2	-1	-2	-2	1	3	6	6	7	6	6	6	4	2	1	1	-1	-1	-1	-1
19	-1	-1	-2	-2	-4	-4	-6	-7	-6	-6	-6	-6	-5	-4	-4	-6	-7	-9	-11	-9	-9	-11	-12	-13
20	-13	-12	-12	-12	-12	-12	-8	-6	-6	-3	0	3	4	3	4	2	-1	-4	-2	-4	-4	-6	-6	-3
21	-2	-1	-1	-2	-2	-2	-2	2	4	4	5	6	5	4	4	4	1	-2	-2	-2	-3	-3	-2	-5
22	-5	-4	-4	-5	-5	-5	-3	-1	2	3	4	5	5	4	4	3	2	0	-2	-1	-1	-1	-2	-2
23	-2	-2	-4	-3	-2	-4	-3	-2	-2	-1	-1	1	-1	-1	2	-1	-1	-2	-2	-3	-4	-4	-5	-5
24	-4	-4	-4	-4	-4	-6	-6	-6	-4	-4	-4	-4	-4	-4	-6	-6	-7	-7	-7	-9	-9	-11	-11	-11
25	-12	-12	-12	-13	-13	-13	-15	-13	-13	-12	-12	-11	-11	-11	-12	-12	-12	-13	-13	-15	-16	-16	-16	-16
26	-17	-18	-18	-18	-18	-18	-18	-18	-14	-10	-10	-8	-8	-7	-9	-11	-12	-13	-15	-15	-14	-13	-13	-13
27	-13	-13	-12	-12	-11	-12	-11	-8	-4	-1	1	2	2	2	2	0	-2	-4	-4	-5	-6	-5	-2	-4
28	-3	-4	-4	-4	-4	-1	-1	-2	1	2	7	8	8	8	6	4	3	2	-1	-1	-1	-2	-4	-4
29	-5	-5	-6	-6	-3	-3	-2	-1	2	4	7	9	7	8	7	7	5	3	2	0	0	0	-1	-1
30	-1	-1	0	0	0	-1	-2	-1	-1	2	4	4	3	4	4	3	1	-1	-2	-3	-4	-5	-4	-3
31	-3	-6	-7	-7	-9	-9	-9	-7	-3	-1	0	3	3	4	4	2	-1	-2	-3	-2	-4	-4	-5	-2

(TABULATION BY HOUR, UNIT OF MEASURE=MILLIMETERS)

[illegible]

Fig. C-1.

Data reduction example, Fenton Hill wind summary, January 1976.

Fig. C-2.

Data reduction example, Fenton Hill wind summary, February 1976.

SITE = TA-57
GUAGE = 218A

MAXIMUM SPEED
(HOURLY)
9.8 M/S

AVG WIND POWER
(WATTS/SQR METER)
38.4

Fig. C-3.
Data reduction example, Fenton Hill wind summary, March 1976.

Fig. C-4.

Data reduction example, Fenton Hill wind summary, April 1976.

Fig. C-5.

Data reduction examples, Fenton Hill precipitation summary,
January 1976.

Fig. C-6.
Data reduction examples, Fenton Hill precipitation summary,
February 1976.

Fig. C-7.
Data reduction example, Fenton Hill precipitation summary,
March 1976.

Fig. C-8.
Data reduction example, Fenton Hill precipitation summary,
April 1976.

Fig. C-9.
Data reduction example, Fenton Hill temperature summary,
January 1976.

Fig. C-10.
Data reduction summary, Fenton Hill temperature summary,
February 1976.

Fig. C-11
Data reduction example, Fenton Hill temperature summary,
March 1976.

Fig. C-12.
Data reduction example, Fenton Hill temperature summary,
April 1976.