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Environmental Investigations Associated with the LASL Hot Dry Rock Geothermal Energy Development Project

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ENVIRONMENTAL INVESTIGATIONS ASSOCIATED WITH THE LASL HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROJECT

by

Kenneth H. Rea

ABSTRACT

The Los Alamos Scientific Laboratory (LASL) is currently evaluating the feasibility of extracting thermal energy from hot dry rock (HDR) geothermal reservoirs. The concept being tested involves drilling two deep holes into HDR, connecting these holes by hydraulic fracture, and bringing thermal energy to the surface by circulating water through the system.

This report is an overview of the environmental studies that LASL has conducted relative to its HDR Geothermal Energy Development Project. Because HDR geothermal technology is a new field of endeavor, environmental guidelines have not been established. We anticipate that LASL's research will lead to the techniques necessary to mitigate undesirable environmental impacts in future HDR developments.

To date, results of environmental investigations have been positive in that we have found no undesirable environmental impacts.

I. INTRODUCTION

The expanding population and concomitant increases in technology have resulted in an increasing demand for workable forms of energy. An energy source becomes feasible when it meets several criteria, the first of which is economic feasibility. The ongoing depletion of the world's fossil fuel supply and increased public concern over environmental degradation have contributed to a steady cost increase in using these resources. This cost increase has created a market in which use of currently undeveloped forms of energy may be economically competitive. Geothermal energy, heat generated in deep earth structures and transported to the earth's surface, is one alternative. It is attractive in that its use eliminates many of the environmental problems associated with the use of fossil fuels, yet it has an almost unlimited potential for meeting future energy demands.

Geothermal energy was first used in a large-scale power plant in Larderello, Italy, shortly after the turn of the century. It is now used in New Zealand, Japan, Mexico, the U.S.S.R., and the United States. Its use has resulted in a classification scheme that consists of three major categories: dry steam, hot water, and hot dry rock (HDR) reservoirs. Hot water reservoirs may be subdivided further into relatively low-temperature hot water aquifers and superheated (wet steam) systems.[1]

Little attention has been paid to HDR reservoirs because of a lack of technical knowledge necessary to extract energy from them. The Los Alamos Scientific Laboratory (LASL) is in the process of

demonstrating how energy from HDR systems can be extracted economically and used to produce electric power.[2]

In this report I will discuss, in general terms, the LASL HDR project and LASL's efforts in environmental research relative to this project. Although there are several publications on many of the subjects covered in this report, this is the first report in which we have consolidated the material. We hope this report can serve as a general reference for HDR investigations and as a vehicle from which more specific reports can be written.

II. HDR CONCEPT

LASL's concept of using heat from HDR reservoirs involves drilling two deep holes into the geothermally active substrate, connecting these holes by a hydraulically made fracture, and circulating water through the system to a heat exchanger at the surface (Fig. 1). The heat exchanger heats a secondary fluid to drive turbines to generate electricity. Cold water (water that has passed through the heat exchanger) is recycled through the fracture, reheated, then recirculated through the heat exchanger.[3] This concept is a closed-loop system (similar to the cooling system of many cars) whose main features are minimal water loss, relatively low noise levels, and few of the other problems associated with development and use of hydrothermal systems (such as the Geysers in California).

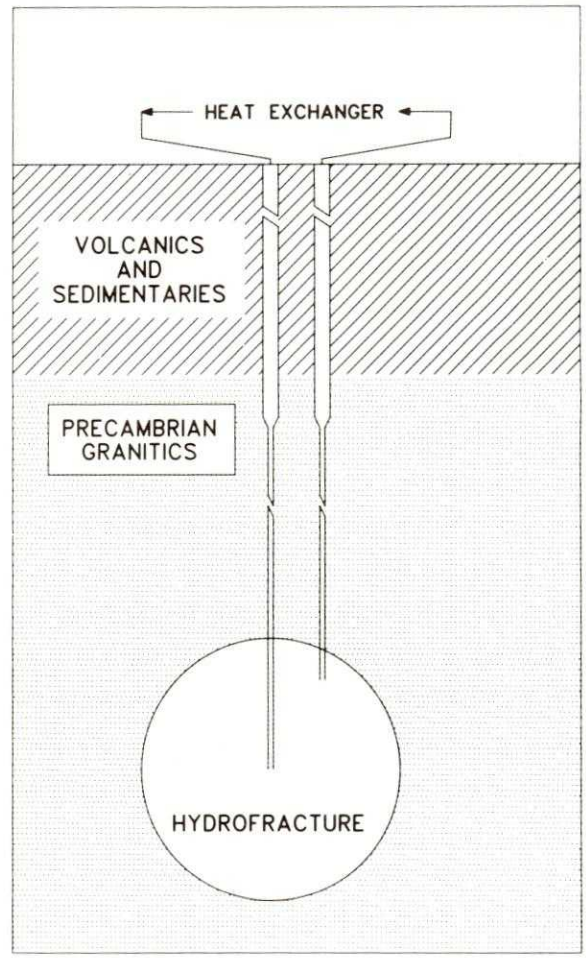

Fig. 1.
LASL's HDR concept.

III. POTENTIAL ENVIRONMENTAL HAZARDS

Actual environmental hazards associated with this HDR energy extraction system are currently unknown. The LASL HDR project is the first attempt to apply drilling and hydraulic fracturing technology to this type of granitic deep earth structure, so we cannot anticipate what harmful emissions and/or other problems will occur.[4] Scientists working on this project have speculated that amorphorus silica may precipitate out of the circulating fluid in the heat exchangers, thereby causing a scaling problem that would require disposal of tons of this material.[5] Other scientists feel that silica precipitation can be prevented by recycling the silica-saturated water through the system. This question will be addressed with the completion of LASL's HDR energy extraction demonstration facility.

Another potential problem is noise created by large fans forcing air through the heat exchangers. This noise may adversely affect the wildlife within the area that are sensitive to sound.

Other major potential problems are those associated with excessive concentrations of undesirable minerals or salts in the geothermal fluids, ground subsidence, gaseous and/or particulate emissions, and degradation of the area's esthetic quality.[6]

Land usage and landscape scarring from geothermal electric power production are similar to those from fossil fuel electric energy production.[1]

However, geothermal production does not include many of the support operations, such as mines, fuel processing, fuel handling yards, and fuel transportation. Most problems associated with geothermal production are confined to the site area. Power transmission lines, excessive noise from venting wells or well blowouts, offensive gaseous emission odors, and degradation of the site area have made existing geothermal developments incompatible with residential or recreational land use.[7]

Disposal of mineralized water from steam condensation or unflashed mineralized water from wet steam fields into both surface and ground water systems has caused thermal and chemical pollution of fresh water systems and has killed natural aquatic flora and fauna.[8]

Other problems associated with water removal from geothermal reservoirs are ground subsidence and aquifer depletion. When the removal rate of water from underground aquifers exceeds natural recharge, subsurface pressure is reduced and pressure equalization often results in ground subsidence at the surface.

These water-related problems have been mitigated by reinjecting the mineralized waters into the producing formation. However, controlled earthquake experiments at Rangely, Colorado, indicate that significant earthquake activity may be induced by high-pressure fluid injection into active fault zones.[9] Therefore, fluid reinjection activities must proceed with extreme caution. Care must also be taken to protect fresh water aquifers during reinjection. In many cases the deep hot water or steam producing formations are under shallow fresh water aquifers that supply potable water. Contamination can occur when reinjecting water into zones that allow natural recharge into both aquifers.

Aquifer contamination should not be a problem with HDR energy extraction because neither high-pressure reinjection into fault zones nor large volume water removal from natural aquifers will occur. Water used to charge the system is supplied by tank trucks carrying water to the site and/or from a water supply well drilled at the site. Make-up water from external sources will be added to the system as necessary.

Particulate and gaseous emissions can occur with hydrothermal electric power production. These emissions (boron, arsenic, fluorides, and free ammonia) occur as drift-loss from cooling towers. Evaporation can cause up to a fivefold increase in concentration of these particulates at the cooling tower. Water droplets, leaving the tower as drift-loss, may contain equivalent concentrations of these materials. These wind-carried droplets are deposited over surrounding countryside, and subsequent evaporation leaves a fine dust of these particulates on anything contacted by the water droplets.[1]

These forms of air pollution should not occur with HDR energy facilities. Nevertheless, air-quality measurements will have to be taken before conclusive statements can be made about the lack of atmospheric contamination from HDR energy use.

IV. PROBLEM DEFINITION AND JUSTIFICATION

LASL's project to extract thermal energy from an HDR geothermal reservoir is the first of its kind in the world. This project involves application of drilling technologies to penetrate deeply into a granitic basement, create a fracture system, and withdraw usable thermal energy by circulating fluids through the system. LASL is doing detailed studies to determine both environmental and technological requirements and is creating a data base from which guidelines for future HDR developments can be formulated.

With development of extraction technology and the increasing need for energy, development of geothermal energy systems should expand rapidly in the near future. Geothermal heat in the United States, at a depth of 10 km (6 miles), has been estimated to be equal to burning one quadrillion (1,000,000,000,000,000) tons of coal.[7] This energy could heat all the homes in the United States for several thousand centuries.

Because most known geothermal resource areas are not over water aquifers or they have inadequate water supplies, development of HDR systems should dominate this energy industry in the future. Although the exact relationship is not known, it has been estimated that >90% of the nations's known geothermal resource areas fall into an HDR classification.[10]

Ecological studies of HDR technology are being made at LASL's HDR energy extraction demonstration facility to develop ecologically sound

methodologies to be used in future developments. Information gained from these studies will be used to establish a data base from which ecological work relative to HDR geothermal development may proceed. This study should also establish guidelines on the types of problems to be encountered, environmental parameters to be monitored, and sampling techniques to be used.

V. OBJECTIVES

LASL initiated the ecological investigation so that it could quantitatively describe some aspects of the ecosystem surrounding the facility and identify the types and amounts of chemicals released during the construction and demonstration phases of this facility. Specific objectives are to (1) develop an environmental resource data base at the site, (2) determine differences in composition and quantity of ecosystem components near the facility and at adjacent control sites, and (3) identify in effluent waste water soluble chemical constituents and other materials that might degrade the water quality of the area.

VI. AREAS OF ENVIRONMENTAL INVESTIGATION

Environmental assessment of the LASL HDR site can be divided into five major categories: geology, hydrology, seismology, climatology, and biology. Information from each category is necessary to describe the local environs adequately and to cover major areas of potential environmental impact. By following fluctuations in these data over an extended period, we should gain an understanding of the mechanisms that cause these impacts. This information will be used to formulate methods that will prevent future occurrences that lead to adverse environmental impacts.

A. Geology

The LASL HDR facility is located on the Jemez Plateau, ~35 km west of Los Alamos, in north-central New Mexico (Fig. 2). LASL selected this site after examining the results of a preliminary

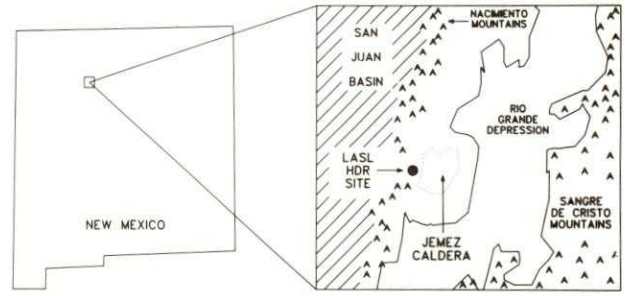

Fig. 2.
Location of the LASL HDR site in north-central New Mexico.

geological investigation of the region and data taken from a series of shallow test holes used to measure subsurface temperature gradients.

The Valles Caldera is the collapsed center of an inactive volvano that deposited ash on parts of the Jemez Mountain range ~1.1 million years ago.[11] The flanks of this volcano have an extruded volcanic ash surface. Intrusive and extrusive basalts are found at higher elevations. The western flank of this volcano, now known as the Jemez Plateau, extends into the north south oriented Nacimiento Mountain range, which separates this Plateau from the San Juan Basin. The Nacimiento Mountains are much older than the Jemez Plateau, probably having their origin linked to the Laramide Orogeny during the latter part of the cretaceous period of the Mesozoic era. Thus, the Jemez Plateau is bounded on the east and west by mountains that are >3000 m high.

The Jemez Plateau drains to the south into the Rio Grande. The two major drainages, the Rio de las Vacas and the Jemez River, have eroded major canyon systems into the surface of the Plateau. The western branch of the Jemez River, San Antonio Creek, drains a large portion of the Valles Caldera. This creek is separated from Cebolla Creek, a tributary to the Rio de las Vacas, by a part of the Jemez Plateau. The location of LASL's HDR facility in relation to the major drainages and state roads is shown in Fig. 3.

The Plateau surrounding LASL's HDR facility ranges in elevation from 2500 to 2800 m. The numerous small drainages that dissect the Plateau account for its broken surface and rough topography.

In 1972, a geological classification of this area was made[11] to identify and classify materials (sediments

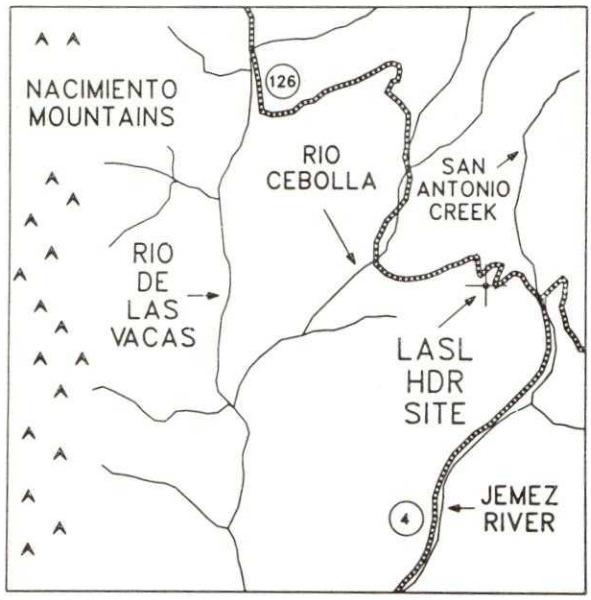

Fig. 3.
Location of the LASL HDR site with respect to major drainages and state roads.

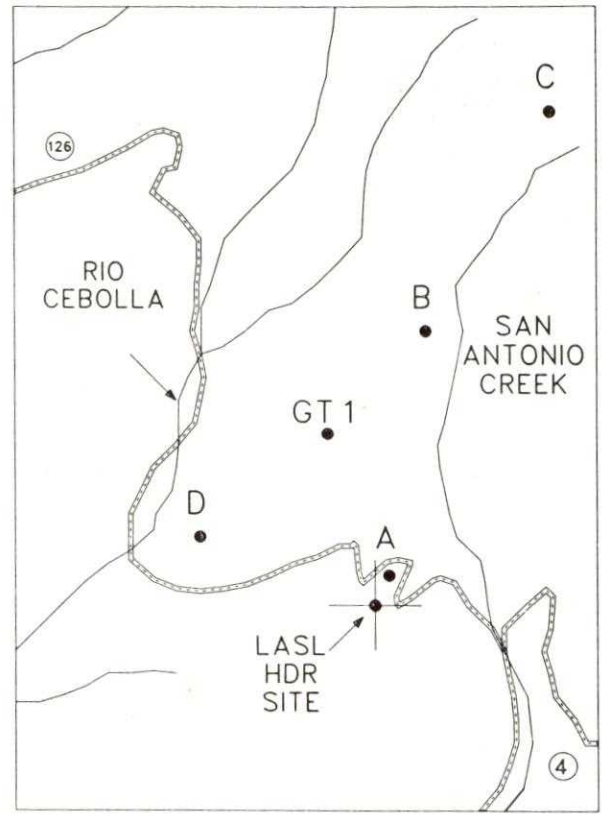

Fig. 4.
Location of heat-flow test holes.

and rock) that might cause drilling problems and to provide a data base for interpreting heat-flow measurements. In addition, the basic geological data were used to help locate the seismic monitoring stations and to interpret hydrological data with respect to quality, quantity, flow rate, and flow direction of subterranean aquifers.

The geological classification was made by supplementing published data with data obtained from four shallow test holes drilled in the vicinity of the LASL HDR site. The test holes ranged from ~150 to 225 m in depth. After core samples were taken, the holes were cased for geological and heat-flow investigations (Fig. 4). Granite test hole No. 1 was drilled during May and June, 1972, to a depth of 785 m. It terminated in Precambrian basement rock. Drilling of the Precambrian rock was of extreme interest because in LASL's HDR project hydraulic fracturing and loop connection take place in such materials. Core samples were taken and tested visually and chemically to determine which elements within the matrix might cause environmental problems if released at the surface.

Five ages of rock outcroppings, Precambrian, Pennsylvanian, Permian, Mesozoic, and Cenozoic, are found in this region.[11] The Precambrian rock masses underwent a period of deformation, followed by the deposition of Paleozoic sediments. After sedimentation, the area dried and was eroded into a peneplain that subsequently underwent mild water cutting or some other form of deformation which resulted in a valley under the current location of the LASL HDR site. This area was covered with Pennsylvanian rock, then covered with rocks from the lower Magdalena group. These rocks were deposited into lowlands and shallow seas until an uplifting or period of thrust faulting occurred to the west. Concurrent with the thrust faulting, which resulted in the Nacimiento Mountains, the area was being covered with the upper Magdalena rock masses. Sedimentation eventually reached continental proportions; at this same time, Permian and Mesozoic rocks were being deposited into this area. This was accompanied and/or followed by a period of erosion on the Nacimiento Mountains, which predated the volcanism of the Pliocene epoch. This volcanic activity started with extrusions of basaltic rock followed by latites and rhyolites. It culminated with the gargantuan eruption of hot ash

that covered the Jemez Plateau with Bandelier tuff and resulted in the formation of the Valles Caldera. Erosion following the volcanic activity has altered the Jemez Plateau into what exists today.

The Nacimiento Mountains currently have many outcrops of Precambrian granitics and gneiss that protrude through layers of Pennsylvanian and Permian limestones, sandstones, and shales. The western slopes of this mountain range show large bodies of Mesozoic sediments, but they do not extend eastward onto the Jemez Plateau in the vicinity of the LASL HDR site. The Jemez Plateau is typically composed of a surface layer of Cenozoic volcanic rocks overlying Permian, Pennsylvanian, and Precambrian rock masses.

Cenozoic volcanic rocks fall into two age groups. The exposed surface (the younger rocks) form what is called Bandelier tuff, and the buried (older) rocks form Abiquiu tuff and the Tschiocoma formation. Bandelier tuff is a nonwelded-to-welded rhyolite tuff that ranges from light to dark gray. It is composed of crystals and crystal fragments of quartz, sanidine, glass shards, some mafic minerals, rock, pumice, latite, and rhyolite in a fine-grained ash matrix. This tuff layer thins to the west and southwest as one moves away from its source at the Valles Caldera.

The Tschiocoma formation is typically between Bandelier tuff (on the top) and Abiqui tuff (on the bottom). This formation is a thin pyroclastic flow of dark gray latite that contains thin lenses of light gray clay. It is composed of plagioclase phenocrysts, quartz, biotite, hornblende, and augite in a fine-grained clay matrix.

Abiqui tuff, which usually overlies the Permian rocks, is a white-to-light gray tuffaceous sandstone and conglomerate. The conglomerate consists of a gravel of pebbles and sand particles weathered from Precambrian crystalline rocks.

Permian sandstones have irregular bedding planes that indicate a fluvial form of deposition. However, because this was the time of continental sedimentation, this flood plain may have been inundated periodically by marine waters. These rocks (the Abo formation) are typically arkosic siltstone, sandstone, and shale. The Abo formation consists of layers of these materials with small calcareous inclusions of white-to-dark gray clay. Shale, the dominant material within the formation, ranges from light to dark red. Particulates within this formation include quartz granules, feldspar, and small pieces of igneous rock. Heavy erosion of the Abo formation during the Cenozoic volcanic depositions created an extreme variation in the thickness of this formation on the Plateau.

Beneath the Abo formation are Pennsylvanian limestones, shales, and arkose. These rocks form the Magdalena group, which is made up of the Sandia formation and Madera limestone. The Madera limestone underlies the Abo formation and is typically found in two layers. It is an arkosic limestone containing both gray and red arkosic shale overlying a dark gray limestone with insets of gray shale and is interspersed with beds of sandstone.

The Sandia formation, found below the Madera limestone, is also split into two sections. Its upper part is a clastic member made up of dark brown-to-brownish green sandstone, arenoceous shale, and limestone. Its lower part is a dark gray siliceous limestone that is discontinuous in areas.

Precambrian granitic rocks form a basement beneath the Sandia formation. These rocks are coarse-grained granite with large insets of microcline feldspars and a quartz-feldspar lenticular gneiss. Minerals found in these rocks include hornblende, biotite, epidote, sphene, apatite, zircon, and magnetite. These granitics are cut in places by ~150-mm-thick quartz veins and have a few dikes of black intrusive rock. These granitics range from brownish gray to red for the granite, and pinkish gray to red for the gneiss.

B. Seismology

Historically, New Mexico is an area of low-to-moderate seismic risk. Records of shocks felt by people or causing structural damage date back to the mid-1800s. These records, coupled with instrumental measurements, show the greatest earthquake activity region is centered along the Rio Grande Valley between the cities of Socorro and Santa Fe in the central part of the state.[12]

Although historical records do not show much earthquake activity in or around the Jemez Plateau, a seismological survey to locate faults and past seismic events and seismological monitoring to

record shocks were deemed necessary.[12,13] These data were used to document the absence of large seismic events within the region and to check the LASL HDR site for induced seismicity from circulating water through deep earth structures. A survey was done in 1971 to determine the proximity and probable activity of faults near the site.[14] This survey shows that the Jemez fault zone is the nearest major fault system to the site. Two northeast trending faults within this zone, the Virgin Canyon fault and the Jemez Springs fault, pass within 4 and 7 km, respectively, of the site. Field checks of both faults indicate their displacement (rate of movement per year) is far below that of major active faults in the western United States. It is highly improbable that these faults would be activated by experimentation at the LASL HDR site because of their distance from the site, the fact that they trend away from the site, and their relatively low displacements. Two sets of seismic nets (close-in and on-site) were established to measure seismic activity in the vicinity of the site and to supplement measurements taken from three stations (Barley Canyon, Lake Fork Canyon, and La Cueva) of an existing regional net. The regional net, established to measure seismic events important to LASL, is not directly linked to the LASL HDR project. This net is composed of 12 high-gain, continuously telemetered stations located ~150 km from Los Alamos. The regional net was started in 1972 with establishment of the first station at LASL; by 1973, enough stations were functional to locate epicenters of microearthquakes [Richter's magnitude thresholds (M_L) >0.5] up to 100 km from Los Alamos.[4]

The La Cueva station, located ~450 m north of the site, contains a three-axis system of seismometers. The Barley Canyon and Lake Fork Canyon systems are special borehole (125-m-deep) stations that were established in 1975 to augment the detection and location capabilities of M_L <0 seismic events within 5 km of the site.

The close-in and on-site seismic nets were established during 1975 and 1976 to detect signals from the ~2900-m-deep hydraulic fracturing experiments. The close-in seismic net consists of nine surface stations located ~1500 to 2000 m from the site. The on-site seismic net has six stations; one is ~200 m from the site, and the rest are ~750 m from the site in a circular configuration.

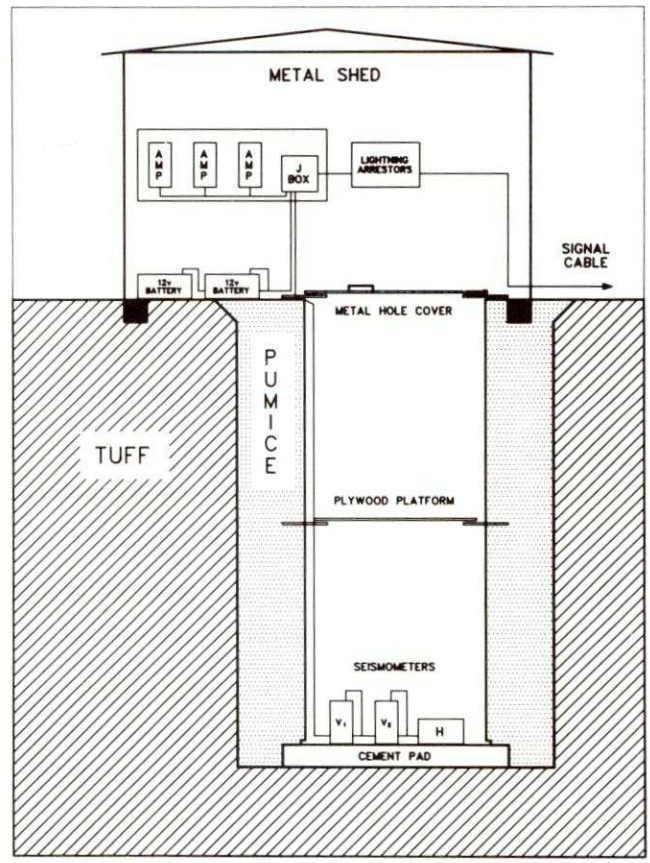

Fig. 5.
Cross section of a seismic station at the LASL HDR site.

Figure 5 shows a typical surface station that contains three short-period seismometers coupled to battery-powered line-driving amplifiers. Two of the seismometers are fixed vertically; the third is fixed horizontally, oriented parallel to an imaginary line intersecting the site. Signals from these stations are transmitted by cable to a recording trailer at the site.

Microseismic events recorded by the regional network of seismic stations in northern New Mexico show that no events greater than the threshold value M_L = 0.5 have occurred at the site since 1973. Microseismic activity recorded near the facility is discussed below.

The first event recorded whose epicenter was near the facility occurred in the early morning of May 28, 1975. This was a single shock (M_L = 0.7) ~17 km southeast of the site. Because this was a singular event, its significance remains unclear.

A larger event was recorded later that year, on the 29th of September. This activity was preceded by two shocks, recorded on the 25th and 27th of September, and was followed by a series of aftershocks in a classical earthquake fashion. The main shock (M_L = 3.2) took place ~22 km northwest of the site and was of such magnitude that sensitive instruments throughout the state measured it. This being one of several events associated with the Nacimiento Mountains fault zone demonstrates that this is still an active fault system. As of January 1977, no other significant shocks have been recorded near the site by this seismic network.

During 1975 and 1976 attempts were made to measure the noise generated by hydrofracturing experiments at depths of ~2900 m within boreholes penetrating the Precambrian granitic rocks. Because surface stations of both the close-in and on-site seismic nets were unable to separate these events from background noise, special downhole geophones were installed to monitor these activities. To date, the seismic nets have not recorded a measureable surface seismic event caused by the LASL HDR project.

C. Climatology

The Jemez Mountain range is typical of most southwestern mountains in its general weather patterns. The climate is characterized by localized convective shower activity during the summer and more regional major storms during the winter. Total precipitation received generally increases at higher elevations; however, the irregular terrain causes irregularities in the storm patterns.

Temperatures of the region are generally mild, with few days exceeding 32°C in the summer, and few nights dropping below −18°C in the winter. Nevertheless, extreme diurnal fluctuations in temperature can occur. For example, in the spring, daytime temperatures may rise to 20°C and nighttime temperatures may drop below freezing (0°C).

Although some generalizations about the weather patterns can be made, specific events in these mountains tend to be localized. This localization makes it impossible to extrapolate weather events from one area to another. Because of the lack of climatological information at or near the site, we had to measure a few basic weather parameters to determine the climatic regime of the area and to characterize prevailing wind patterns. These data will be used to determine where potential environmental contaminants released from the site will go and to explain variations in biological measurements that may be linked directly to climatological phenomena.

A weather station was established in 1975 ~150 m west of the site. Its location, which is as close to the site as possible (Fig. 6), minimizes the effects of surrounding terrain and structures upon air flow patterns. The station consists of a Meteorology Research Incorporated (MRI) mechanical weather station and a weighing bucket rain gauge. The MRI mechanical weather station is mounted on top of a collapsible 9-m tower and records wind run, wind direction, and temperature on a pressure sensitive strip chart. The weighing bucket rain gauge, located ~10 m west of the tower, records precipitation on a strip chart attached to a revolving drum.

Another weighing bucket rain gauge is located on the Plateau ~1500 m west of the site. This gauge, on the periphery of the area set aside for ecological studies, will be used to compare precipitation between the two locations. Some localized convection showers dump large quantities of moisture in non-uniform patterns in this mountainous terrain.

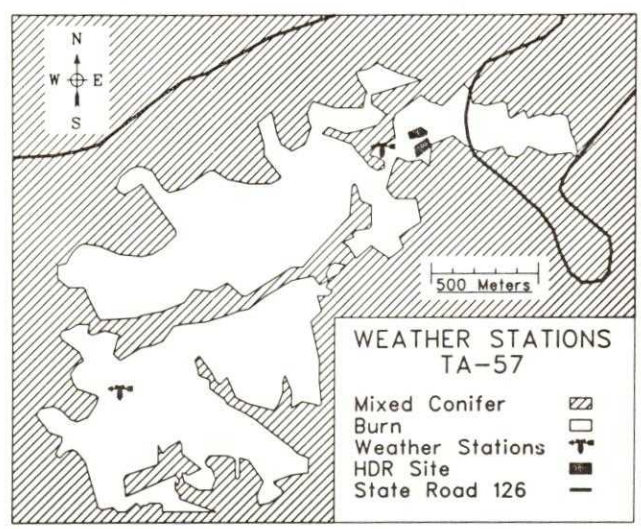

Fig. 6.
Location of the weather stations at the LASL HDR site.

Data recorded by these instruments are reduced into hourly averages and put into a form that can be read by a computer. Computer programs check the data for key punch errors, missing cards, and suspicious looking numbers. Once checked, the data are manipulated into monthly summaries in both graphical and tabular forms.

The weather station at the site has been recording data continuously since it became operational in January 1976. Although no conclusions can be made about weather patterns from such a small data base, several interesting, but expected, phenomena are evident from these data.

Air flow patterns have a distinct seasonal shift. During January the air flow is primarily from the northwest. Air flow patterns shift as the seasons progress into summer; an almost complete reversal is seen during August. Figures 7 and 8 show the normal seasonal sequence of continental air flow patterns.

Precipitation at the site also followed the pattern expected for semiarid southwestern mountain ranges. During the winter months, precipitation was a more or less random event and did not follow a predictable pattern, as shown in the precipitation summary for February 1976 (Fig. 9). However, during the summer, regional storms are replaced by localized convective activity, which generally builds over the mountains during the morning and results in showers during the afternoon (Fig. 10).

Table I gives 1976 summaries by month for temperature, precipitation, and wind power. These data show that it was fairly dry at the site in 1976—only 35.66 cm of precipitation was recorded. The long-term average annual precipitation in Los Alamos is ~45 cm, which indicates that the Jemez Plateau (~300 m higher) should receive >50 cm of precipitation in any given year. However, this low amount of precipitation at the site is consistent with the drought conditions in the southwestern United States during 1976.

Temperatures at the site were relatively mild with the extremes being between −23° and 27°C for winter and summer, respectively. These temperature ranges probably are typical in that Los Alamos seldom exceeds 32.2°C in the summer and seldom drops below −18°C in the winter. Large diurnal variations in temperature, however, can occur. For example, on August 2, 1976, the ambient air temperature changed from 4°C at 5 a.m. to 19°C at 4 p.m., for a change of 15°C in 13 h.

March was the windiest month of the year with an average wind power of 38.4 W/m^2. The transition between winter and summer air flow patterns also began in March. The summer months were relatively calm, indicating that the southeast air flows associated with summer convective activity are not as strong as the northwest flows during the winter.

D. Hydrology

The LASL HDR site is situated near major drainages that support natural fisheries and contribute water supplies to several small towns and villages. Any degradation of these surface waters must be documented and related to the HDR facility.

In addition to the surface water problem, the potential exists for pollution of aquifers because of the nature of the HDR experiment. Base line data were established to document the water quality of the region before and after setting up the HDR facility.

In 1973, a preliminary study was made of both surface and ground waters in drainages surrounding the site. This study relied on both a literature search for information before 1971 and summaries of field data collected between 1971 and 1973.[15]

In 1974, additional data were taken from springs in the Lake Fork Canyon and on the Jemez River and from several surface locations adjacent to the site. In 1975 and 1976, 9 surface water stations and 14 ground water stations were monitored in the various drainages. These data were augmented by samples taken from storage ponds and borehole fluid at the site.[16,17]

Chemical analyses were made to determine levels of silica, calcium, magnesium, sodium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, and total hardness. Measurements were also made for total dissolved solids, conductance, and pH. All analyses were conducted according to the procedures outlined in Ref. 18.

Results of the chemical analyses for water quality are summarized in Tables II, III, and IV.[15-17] These data represent one ground water station, one surface

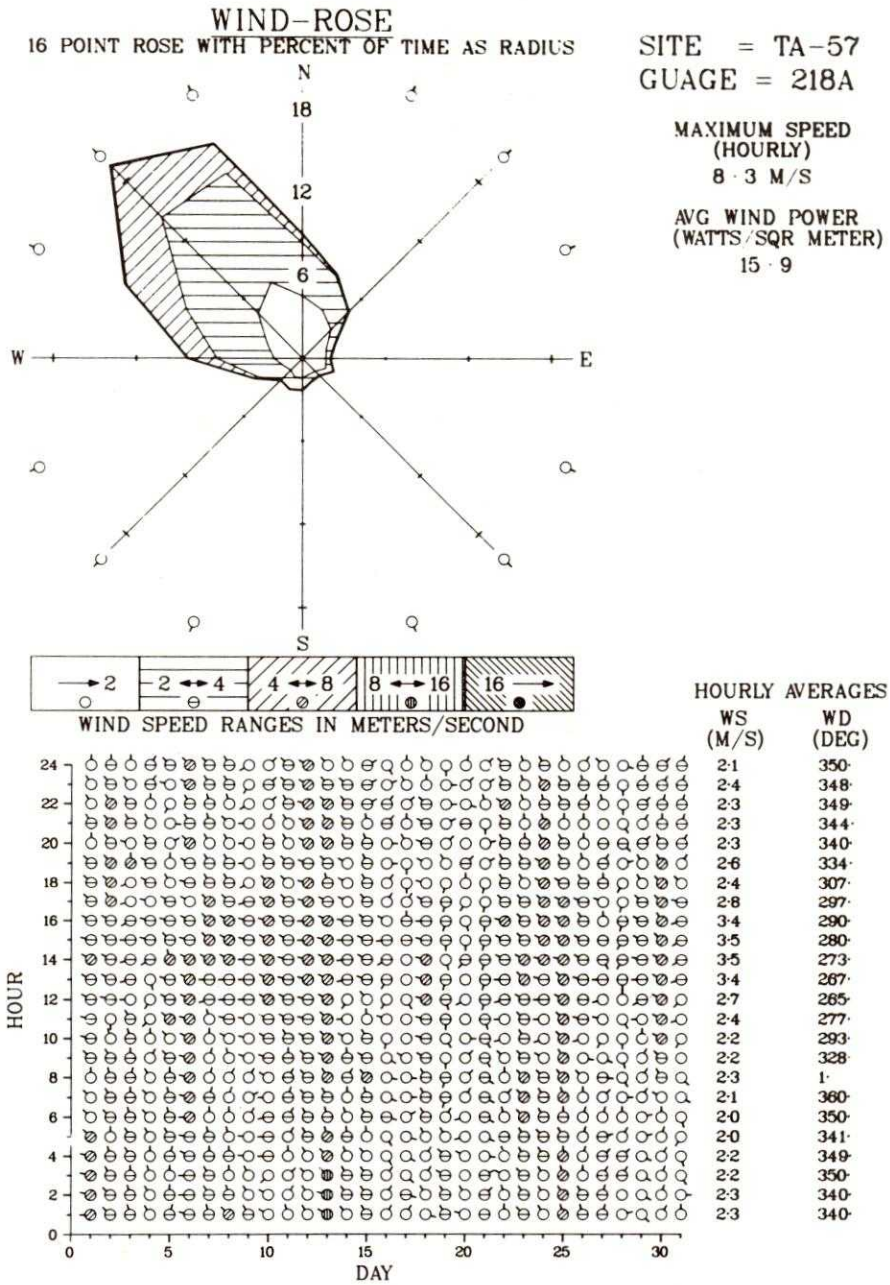

Fig. 7.
Wind analysis for January 1976 at the LASL HDR site.

water station, and the two holding ponds at the HDR site. No significant differences were observed in either the surface or ground water samples. However, some fluctuations did occur seasonally within years and seasonally between years.

These data show that there is little difference between the ground water (potable supply) and surface water adjacent to the site. The ground water is slightly higher in silica (SiO_2), whereas the surface water is higher in calcium (Ca). This difference is expected because of the soil and rock material in contact with these waters.

The water from the holding ponds at the site has been used for various experiments. These waters

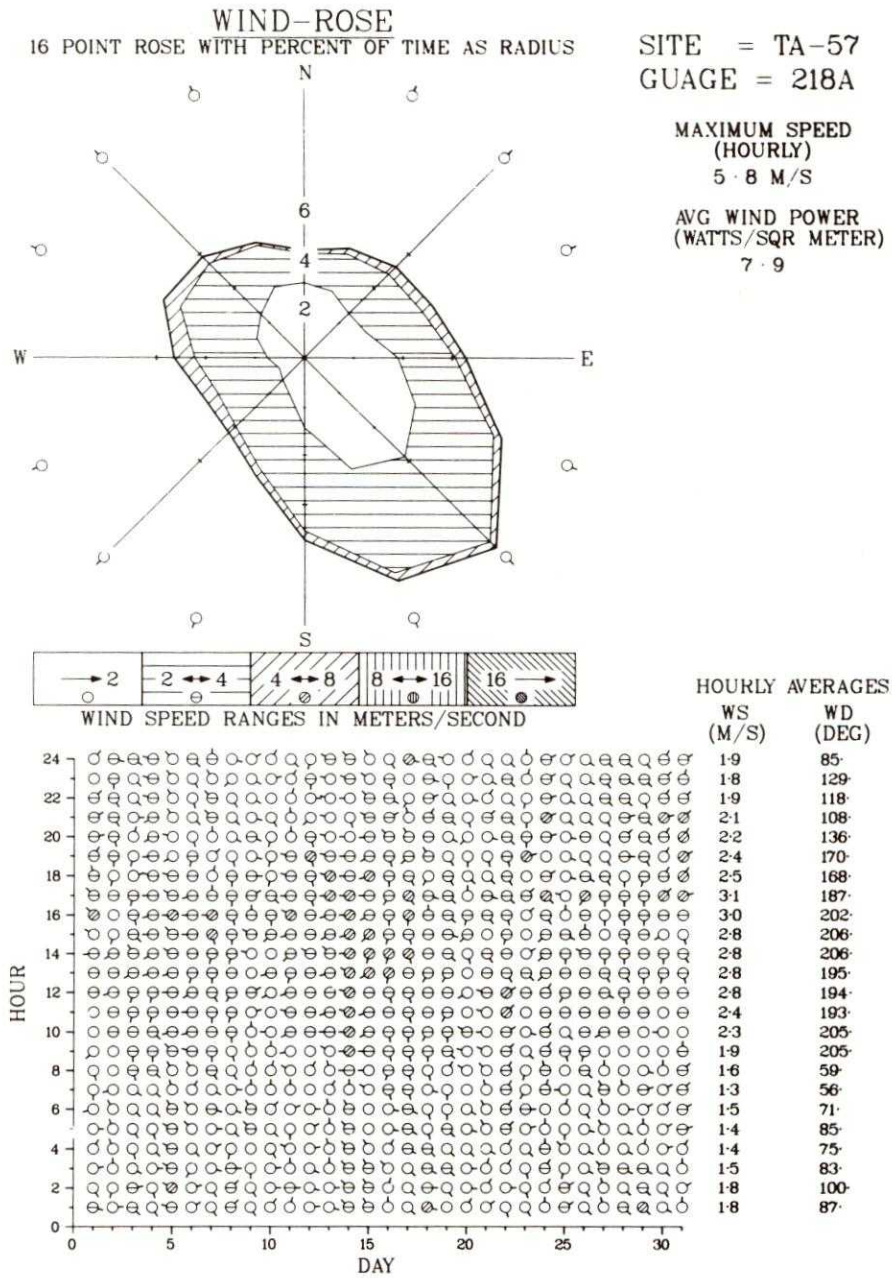

Fig. 8.
Wind analysis for August 1976 at the LASL HDR site.

have become contaminated by various elements and compounds that have changed their chemical composition (see Table IV). Nevertheless, these waters can be cleaned by various processes and released into the local environs.

E. Biology

During 1976 studies were initiated to measure various characteristics of birds, small mammals,

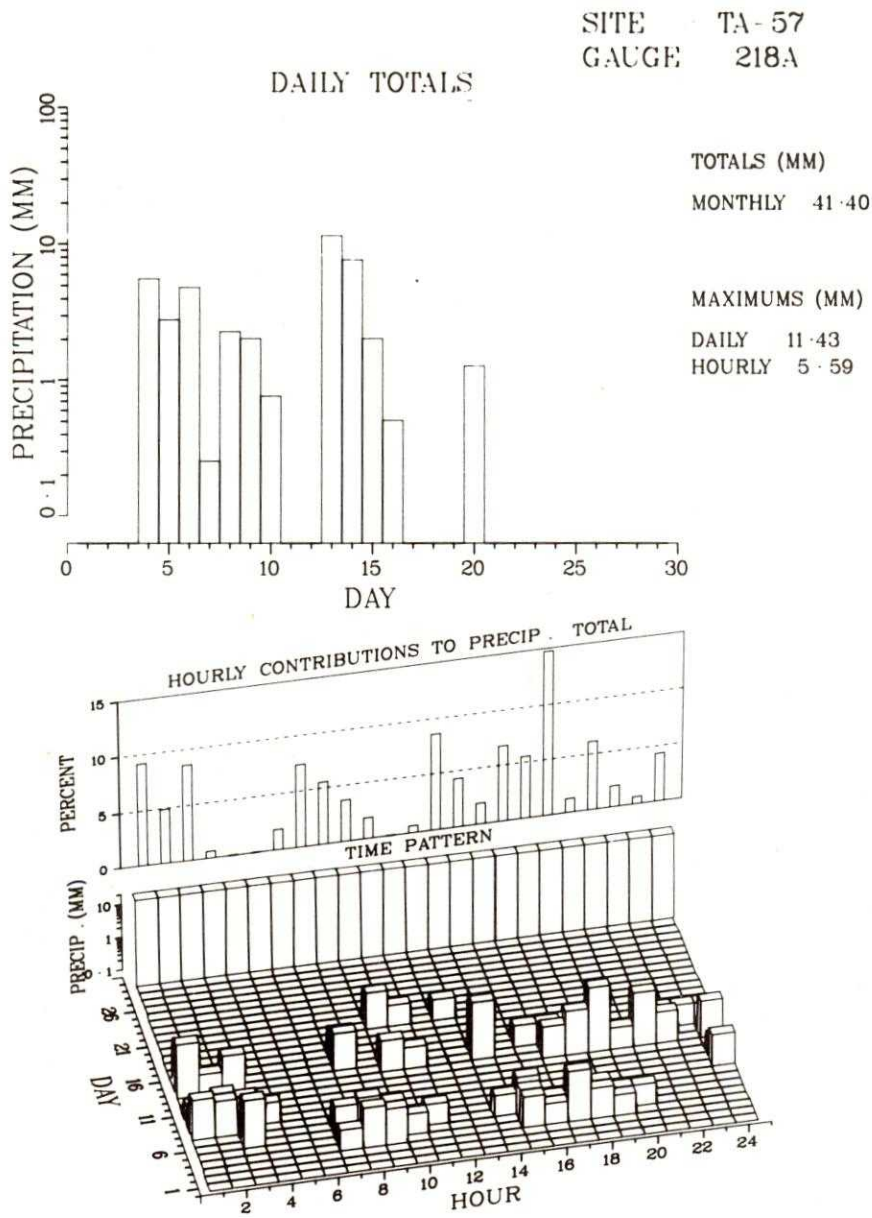

Fig. 9.
Precipitation analysis for February 1976 at the LASL HDR site.

elk, and vegetation at the site. These studies establish base line data from which we can compare future measurements.

1. Vegetation. Three major vegetative complexes or community types are found at the site. Typical climax vegetation found at 2600-m elevation in northern New Mexico is a mixed coniferous forest or broad ecotone between upper elevational spruce-fir communities and lower elevational ponderosa pine communities. A wildfire in 1971 destroyed parts of this climax vegetation at the site, resulting in the formation of two additional community types. The fire scar was aerially seeded with a mixture of higher elevation pasture grasses and

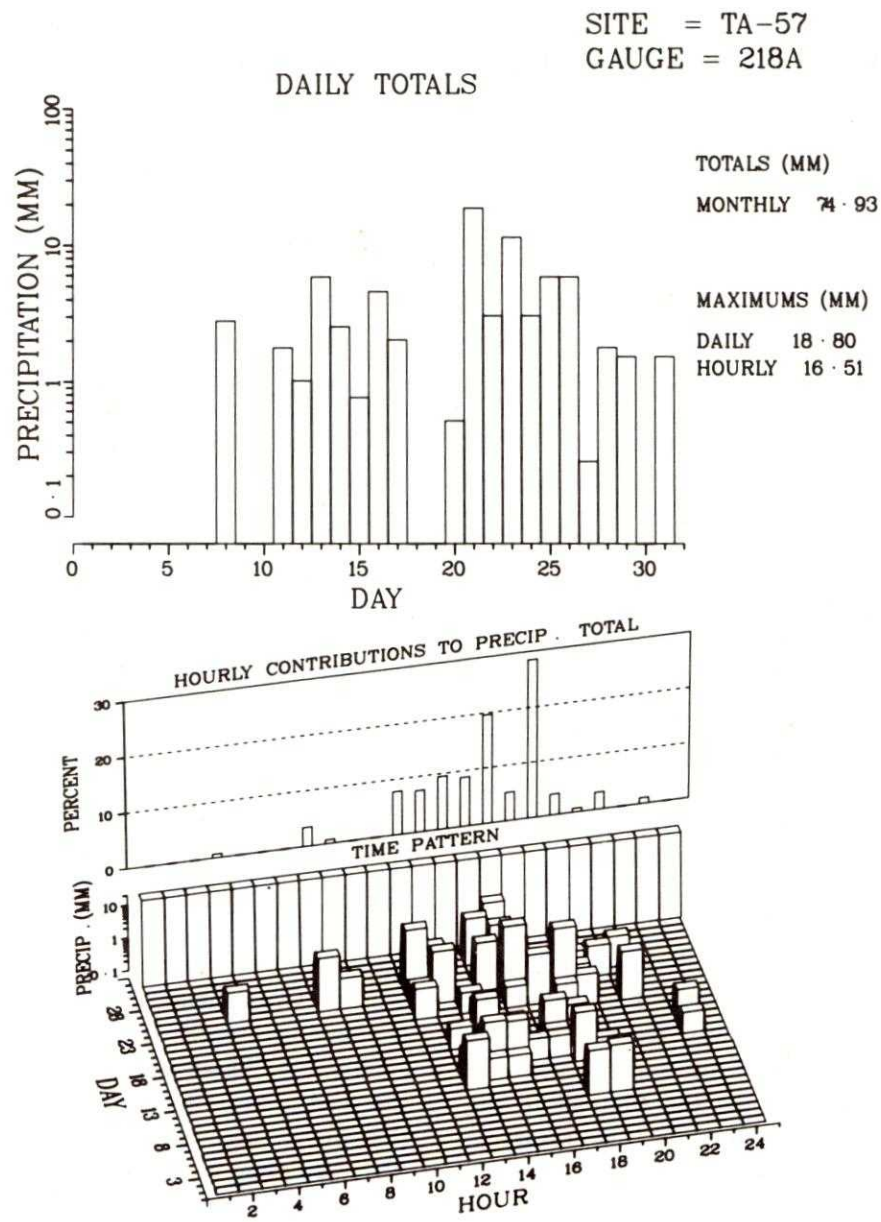

Fig. 10.
Precipitation analysis for July 1976 at the LASL HDR site.

legumes shortly after the fire. One year later, ponderosa pine tree seedlings were planted 3 to 5 m apart. The resultant secondary succession has developed into a grass-forb community interspersed with small stands of aspen suckers.

Transects placed in each community type to measure cover and density of the species were read in the spring, summer, and fall during the 1976 field season. The locations of these transects, 5 in the mixed coniferous forest, 3 in the new growth aspen, and 16 in the grass-forb community, are shown in Fig. 11. Taxonomic voucher specimens were collected and are on file at LASL.

Dual sets of transects in the grass-forb community were used to protect against unavoidable loss of the transects nearest the site. These transects

TABLE I

TEMPERATURE, PRECIPITATION, AND WIND SUMMARIES FOR 1976

	Temperature (°C)			Precipitation (mm)	Wind Power Average (W/m^2)
	Av	Max	Min	Total	
January	−6	9	−23	4.8	15.9
February	−3	9	−17	41.4	24.7
March	−3	10	−17	17.5	38.4
April	2	13	−13	21.1	26.9
May	7	19	−6	45.0	16.8
June	14	27	2	6.1	20.9
July	14	26	5	74.9	7.9
August	13	24	5	69.1	7.9
September	10	22	−1	45.7	7.4
October	3	18	−8	4.8	13.9
November	−1	13	−23	17.5	10.8
December	−4	9	−14	8.6	9.6
Total				356.6	201.1
Average	3.8	16.6	−9.2	29.7	16.8

were placed in an area previously used as a temporary heliport for United States Forest Service smoke jumpers. This area was reserved by the Forest Service for this type of future activity should the need arise. A wildfire on the Plateau to the southwest of the site in 1976 made it necessary to use this area again as a heliport. Excessive trampling associated with this activity resulted in these transects being discarded after the fire.

After summarizing the 1976 plant population field data by community type, we selected 15 dominant species from which to characterize all community types. Only those species that contributed at least 0.1% cover in any community type were selected. The cut-off point of 0.1% cover eliminated those species that did not contribute significantly to the total vegetative biomass, yet it left enough species so that a good cross section of the dominants was found within all community types.

Table V gives the average cover and density of the dominant species by community type. No unanticipated results are found in these data, which show the grass-forb community is dominated by members of the Gramineae family, especially timothy (*Phleum pratense*) and orchard grass (*Dactylis glomerata*). These two species, which were part of the seed mixture broadcast over the area following the burn, are somewhat intolerant of shade. Although they are found in the understory of the aspen community, there are very few found in the mixed coniferous community.

As expected, the mixed coniferous community is dominated by tree species with a rich understory of shrubs. Douglas fir and white fir species (*Pseudotsuga menziesii* and *Abies concolor*), respectively, make up about three-fourths of the aerial tree cover within this community type, with the rest being predominantly ponderosa pine. Aspen has cover values equivalent to several of the understory shrubs.

Unlike the other two communities, the aspen community is dominated by aspen (*Populus tremuloides*). However, there is an understory of

TABLE II

WATER QUALITY ANALYSIS FOR SAN ANTONIO CREEK[a]

	1974	1975	1976	Mean
Silica[b]	47.8	51.0	51.3	50.0
Calcium	16.2	16.7	15.0	16.0
Magnesium	2.6	3.0	5.6	3.7
Sodium	14.8	12.7	13.3	13.6
Carbonate	0	0	0	0
Bicarbonate	69.6	70.0	62.7	67.4
Sulfate	9.4	6.4	6.8	7.5
Chloride	4.8	2.3	3.0	3.4
Fluoride	1.1	0.9	1.2	1.1
Nitrate	0.2	0.1	0.1	0.1
Total dissolved solids	190.0	159.3	168.3	172.5
Total hardness	50.4	54.7	60.7	55.3
Specific conductance (mS/m)	15.2	17.0	16.2	16.1
pH	7.7	8.0	7.5	7.7

[a]Surface water station near the HDR site.
[b]Chemical analyses in milligrams/liter.

TABLE III

WATER QUALITY ANALYSIS FOR HORSESHOE SPRING[a]

	1974	1975	1976	Mean
Silica[b]	78.5	83.7	73.3	78.5
Calcium	11.0	10.7	12.3	11.3
Magnesium	3.5	2.7	3.7	3.3
Sodium	17.2	15.0	16.3	16.2
Carbonate	0	0	0	0
Bicarbonate	74.0	62.7	65.7	67.5
Sulfate	6.0	3.8	3.2	4.3
Chloride	10.0	4.7	3	5.9
Fluoride	0.3	0.2	0.3	0.3
Nitrate	0.2	0.2	0.2	0.2
Total dissolved solids	181.0	154.7	171.3	169.0
Total hardness	42.0	38.7	46.0	42.2
Specific conductance (mS/m)	15.5	13.8	14.7	14.7
pH	7.5	7.2	7.8	7.5

[a]Ground water station near the HDR site.
[b]Chemical analyses in milligrams/liter.

TABLE IV

WATER QUALITY ANALYSIS FOR HOLDING PONDS[a]

	1974	1975	1976	Mean
Silica[b]	61.4	49.3	119.2	76.6
Calcium	56.2	42.2	24.2	40.9
Magnesium	5.9	3.2	5.8	5.0
Sodium	868.1	120.0	358.3	448.8
Carbonate	213.5	77.5	55.7	115.6
Bicarbonate	1006.9	244.5	386.3	545.9
Sulfate	492.4	173.7	159.8	275.3
Chloride	831.5	145.0	271.7	416.1
Fluoride	3.1	1.1	11.3	5.2
Nitrate	26.3	0.8	1.6	9.6
Total dissolved solids	3840.2	1210.5	1345.7	2132.1
Total hardness	163.5	119.0	84.7	122.4
Specific conductance (mS/m)	482.3	171.8	215.7	289.9
pH	9.3	8.4	8.1	8.6

[a]Water holding ponds at the HDR site.
[b]Chemical analyses in milligrams/liter.

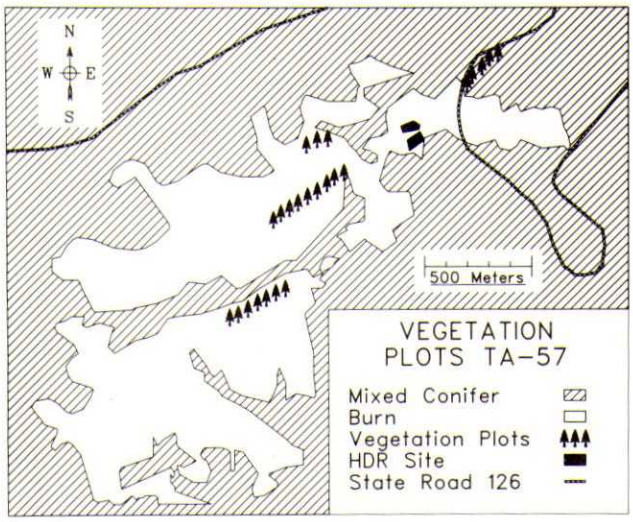

Fig. 11.
Location of vegetation transects at the LASL HDR site.

shrubs and grass that represents species from both the mixed coniferous and grass-forb communities.

The mixed coniferous community has ~50% more aerial cover than the other communities. This represents almost four times the aerial cover found in the grass-forb community and about one-third more aerial cover than is found in the aspen community.

The same types of differences seen in vegetation parameters between the various communities are seen within the nonliving ground cover. Table VI gives the average ground cover by category for each community. The grass-forb community is dominated by dead grass, the mixed coniferous community has a ground cover dominated by needles, and the aspen community is dominated by leaves. The amount of exposed bare ground is greatest under the grass-forb community and smallest within the mixed coniferous community.

2. Small Mammals. The primary consumers or herbivores are one of the more abundant forms of wildlife in any ecosystem. Because small mammals feed on a large cross section of plant material, they are easily affected by toxic elements released into the environment. Studies were made to determine

TABLE V

AVERAGE PERCENTAGE OF COVER AND DENSITY (No./m²) OF THE DOMINANT SPECIES AT THE LASL HDR SITE, SUMMER 1976

	Grass Forb		Mixed Conifer		Aspen	
Species	**Cover**	**Density**	**Cover**	**Density**	**Cover**	**Density**
Agropyron spicatum	0.3 ± 0.6	0.5 ± 1.0[a]	---	---	---	---
A. trachycaulum	0.7 ± 1.1	1.8 ± 3.0	---	---	---	---
Blepharoneuron tricholepis	---	---	0.2 ± 0.3	0.5 ± 0.8	---	---
Dactylis glomerata	3.7 ± 2.6	3.8 ± 3.8	---	---	0.9 ± 0.8	2.8 ± 2.4
Koeleria cristata	0.4 ± 0.5	0.8 ± 0.9	0.1 ± 0.1	0.5 ± 0.5	0.3 ± 0.5	1.6 ± 2.2
Phleum pratense	6.8 ± 4.2	10.0 ± 5.0	---	---	1.0 ± 0.8	2.9 ± 1.6
Sitanion hystrix	---	0.1 ± 0.2	0.4 ± 0.3	2.5 ± 1.8	---	---
Berberis repens	1.8 ± 1.2	3.0 ± 2.9	0.4 ± 0.7	1.4 ± 2.8	2.0 ± 1.6	4.6 ± 3.3
Arctostaphylos uva-ursi	---	0.1 ± 0.1	4.6 ± 5.2	13.0 ± 17.0	28.0 ± 36.0	0.8 ± 0.6
Chimaphila umbellata	---	---	0.2 ± 0.5	0.7 ± 1.4	---	---
Quercus gambelii	0.4 ± 0.7	0.1 ± 0.2	3.6 ± 3.6	0.9 ± 0.9	3.1 ± 5.4	0.5 ± 0.8
Pinus ponderosa	0.1 ± 0.2	0.1 ± 0.1	10.0 ± 13.0	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1
Populus tremuloides	0.5 ± 1.0	0.1 ± 0.2	3.8 ± 6.3	---	29.0 ± 5.4	27.0 ± 8.7
Fir *(Pseudotsuga menziesii)* and *Abies concolor*	---	---	27.0 ± 31.0	0.3 ± 0.4	---	---

[a]$\bar{x}$ ± s.
[b]Less than 0.1.

TABLE VI

AVERAGE PERCENTAGE OF GROUND COVER BY COMMUNITY TYPE

	Grass Forb	Mixed Conifer	Aspen
Bare	38.0 ± 8.4[a]	4.9 ± 5.4	12.6 ± 10.2
Grass	29.5 ± 10.1	1.5 ± 1.4	4.9 ± 0.4
Stick	14.2 ± 6.1	18.9 ± 7.8	20.9 ± 12.5
Gravel	10.2 ± 4.6	0.3 ± 0.8	0.2 ± 0.9
Bark	2.9 ± 2.5	4.2 ± 3.0	13.6 ± 21.5
Leaf	3.7 ± 1.6	23.4 ± 23.4	47.4 ± 21.3
Cobble	1.2 ± 1.1	2.3 ± 3.7	0.2 ± 0.4
Feces	0.3 ± 0.6	0 ± 0	0.2 ± 0.9
Rock	0 ± 0	0 ± 0	0 ± 0
Needle	0 ± 0	41.0 ± 22.6	0 ± 0
Cone	0 ± 0	2.6 ± 4.4	0 ± 0

[a]$\bar{x}$ ± s.

small mammal populations surrounding the HDR site. These data represent a base line for one of the potential bioindicators of environmental impacts from the LASL HDR project.

Small mammals were livetrapped within each community to determine the trap susceptibility of the various species and their relative abundance among the communities. We set up one trapline per community (Fig. 12) and ran all three traplines simultaneously during each trapping session.

Two trapping sessions were held during the 1976 field season. The first session was held in midsummer before the rodent populations reached maximum numbers. The second trapping session was held in late summer-early fall to measure peak populations. We compared the data from the two sessions to determine whether the time of trapping has any affect on the interpretation of results.

Each trapping session consisted of two nights of prebaiting to familiarize the rodents with the traps, followed by three consecutive nights of trapping. Traps baited with a mixture of rolled oats and peanut butter were set up in the late afternoon and examined the following morning. This schedule prevented animals from being trapped during the hot part of the day and drastically reduced the chances of mortality as a result of heat exhaustion. A large square of cotton in each trap gave the rodent something to burrow in; this reduced the death rate from excessive traumatization.

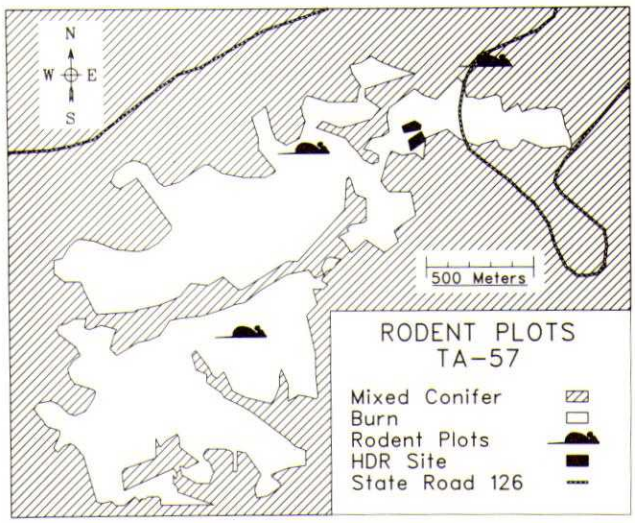

Fig. 12.
Location of small mammal traplines at the LASL HDR site.

The rodents were classified by species, sex, and age. They were weighed, then marked by a standard toe amputation technique. Dead specimens were tagged, frozen, and stored. We will use these specimens to compare elemental body burdens with specimens caught in the future if we encounter significant changes in rodent populations or if releases should occur at the HDR site.

In addition to trapping by community type, traps were set up in six areas (three downwind and three down the principal drainage from the site) to establish a data base from which to compare future trapping results. These comparisons will be used to determine if a gradient is established within these rodent populations as a result of the LASL HDR project, and if this project is adversely affecting the local environs.

Within the three vegetative complexes, the species trapped most often is the deer mouse (*Peromyscus maniculatus*). Summaries are presented in Table VII for both trapping sessions. Table VII shows that the grass-forb community contains the highest numbers of small mammals, yet it has the lowest species diversity.

These relationships were expected because the more closed community types offer more habitats and shelters for small mammals. However, most of the small mammals trapped were primarily herbivores and the grass-forb community has more vegetative biomass within reach of the small mammals. Therefore, the high numbers of small mammals encountered in the grass-forb community could be a result of an abundant food supply, whereas the greater species diversity found in the more closed communities could be an indication of the more diverse forms of shelter.

The high percentage of trappings indicates that these vegetative communities support substantial populations of small mammals. This was also expected because small mammal populations tend to reach high levels in areas that have been disturbed.

3. Elk. With establishment of the grass-forb community on this Plateau following the wildfire in 1971, this area has become an important winter range for the Rocky Mountain elk (*Cervus Canadensis*). Elk, one of the major big-game species

TABLE VII

SMALL MAMMAL TRAPPING SUMMARY OF THE LASL HDR SITE FOR 1976

June 1976

Location	Total Species Captured	Total Captures	Total Marked Individuals	*Peromyscus maniculatus*		*Eutamias minimus*		*Citellus lateralis*		*Microtus montanus*		*Mustela rixosa*		*Sylvilagus audubonii*	
				M	F	M	F	M	F	M	F	M	F	M	F
Aspen	5	62	36	8	10	5	9	1	1	0	0	0	1	1	0
Grass forb	3	48	30	13	11	5	0	1	0	0	0	0	0	0	0
Mixed conifer	4	30	20	6	5	5	2	1	0	0	1	0	0	0	0

September 1976

Location	Total Species Captured	Total Captures	Total Marked Individuals	*Peromyscus maniculatus*		*Eutamias minimus*		*Citellus lateralis*		*Mustela rixosa*		*Neotoma mexicana*	
				M	F	M	F	M	F	M	F	M	F
Aspen	4	50	41	11	10	10	8	0	1	0	1	0	0
Grass forb	2	130	73	42	30	0	1	0	0	0	0	0	0
Mixed conifer	4	42	32	7	13	4	5	0	1	0	0	2	0

of New Mexico, tend to be disturbed by human activity. Therefore, establishment of the HDR site on the edge of this burn may eventually result in elk leaving this area.

A stratified random set of permanently marked counting plots for pellet groups (fecal material) were established and read during mid-1976 to document elk usage of this burn area and to create a data base from which to compare future measurements.

The burned area was arbitrarily divided. Approximately 50% of the plots were adjacent to and 50% of the plots were away from the site (Fig. 13). Each pellet group counting plot was 4 m wide by 22 m long. Plots were examined by two persons who physically removed all pellet groups from the plots and checked each other's work. It was therefore assumed that few, if any, pellet groups were overlooked. Physically removing the pellet groups, rather than marking them, ensures that future examinations will be made on new pellet groups and that the data collected are related to elk usage of the area after establishment of the LASL HDR project.

The pellet group counting plots cannot be fully interpreted from the initial set of readings. However, statistical tests between the two areas are nonsignificant, indicating that elk usage within the grass-forb community has been distributed uniformly in the past.

4. Birds. The avian community is perhaps the most mobile faction of wildlife found in any ecosystem. Typically, the avian component will change constantly throughout the year because of the seasonal emigration and immigration of the various species.

Two extensive plots were established on the Plateau, one adjacent to and one away from the site (Fig. 14), to describe the avian community dynamics and to quantify the impacts on these populations from the facility.

The study plot adjacent to the site (the well site) is ~250 m wide by 500 m long. This plot falls mostly within the mixed coniferous community. Parts of this plot have been encroached upon by expansion of the site. The study plot away from the site (open mesa site), which is ~1000 m west of the site, is ~150 m wide by 1000 m long and predominately falls within the grass-forb community.

Both plots were examined seasonally during 1976 by personnel who walked specific lines through the plots every 50 m. The number and species of birds were recorded, together with personal observations about their suspected activities. These data were reduced into nesting pairs by species per unit area, densities of resident and transient species, and an overall categorization of the avian component of this ecosystem.

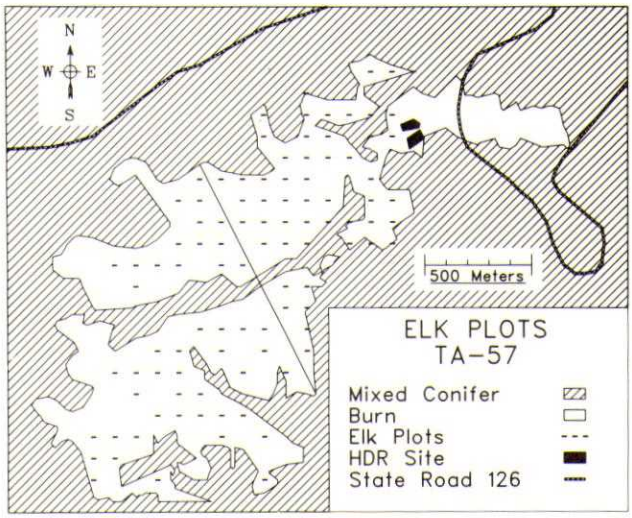

Fig. 13.
Location of elk pellet group counting plots at the LASL HDR site.

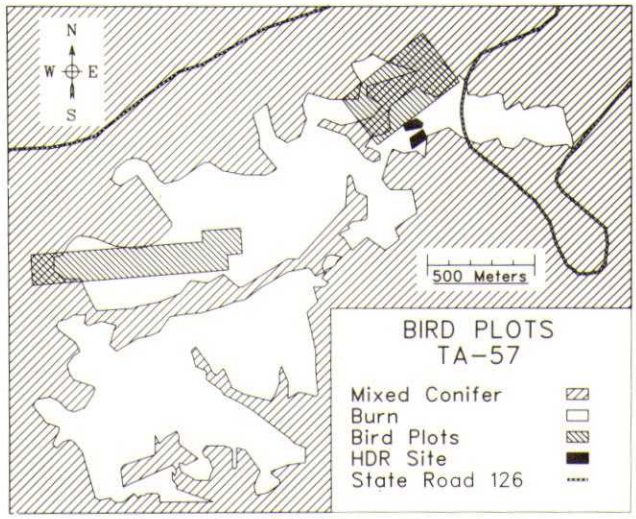

Fig. 14.
Location of bird counting transects at the LASL HDR site.

TABLE VIII

ESTIMATED NESTING POPULATIONS AT THE WELL SITE AND OPEN MESA SITE DURING THE SUMMER OF 1976 (Pairs Per 40.5 hectare)

Species	Well Site	Open Mesa Site
Black-chinned hummingbird	5	4
Common flicker	5	7
Yellow-bellied sapsucker	2	4
Hairy woodpecker	5	2
Traillis flycatcher	2	---
Western wood pewee	5	---
Violet-green swallow	7	---
White-breasted nuthatch	2	---
Pygmy nuthatch	5	---
House wren	5	2
American robin	2	---
Western bluebird	7	2
Warbling vireo	2	---
Yellow-rumped warbler	5	---
Western tanager	12	---
Cassin's finch	2	---
Green-tailed towhee	---	11
Gray-headed junco	7	4
Total	80	36

Of the many transient bird species recorded during the census period, 41 species were identified. The high elevation and cold weather, however, prevented most birds from nesting and becoming residents.

Table VIII gives the estimated nesting populations from data collected from both study plots. The greater number of nesting pairs recorded at the well site can be explained by the community type that dominates the area. The plot adjacent to the site falls within a predominantly mixed coniferous community, whereas the plot away from the site falls within a grass-forb community. The mixed coniferous community should allow more nesting sites and subsequently more nesting pairs of birds.

VII. SUMMARY AND CONCLUSIONS

To date, studies show that the only adverse environmental impact that has resulted from the LASL HDR project has been the necessary destruction of ~2 hectares of vegetative cover during site construction and associated engineering activities. Upon completion of the facility, studies will be made on two other potential environmental problems (air pollution from gaseous and/or particulate emissions and excessive noise). Both forms of pollution are significant in hydrothermal developments.

Drilling activities, hydraulic fracturing, and subsequent circulation of water (pumping at lower pressures than will be used for heat extraction) through the deep earth rock matrix have not induced measurable surface seismic activity, nor have they had a measurable impact on either the surface or ground water quality of the region.

Base line data on the various communities surrounding the LASL HDR facility have been collected and analyzed. Key species have been selected for future, more detailed studies.

Although we cannot make conclusive statements about the environmental impacts of a large-scale HDR facility at this time, we anticipate that use of this energy source (HDR energy extraction) will be more acceptable environmentally than is the current use of fossil fuels. Additional monitoring and research within the ecosystems surrounding the LASL HDR site, both during the construction and implementation phases, will be necessary to validate or disprove this hypothesis.

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