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**ENVIRONMENTAL ANALYSIS
FOR GEOTHERMAL ENERGY
DEVELOPMENT IN THE
GEYSERS REGION-EXECUTIVE SUMMARY**

CONSULTANT REPORT

Prepared by: SRI INTERNATIONAL

**CAEC-011
MAY 1978**

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INTRODUCTION

Harnessing geothermal reserves to produce electrical power is considered to be "cleaner" than many of the other ways of producing energy, but it is not without its share of environmental problems, some of them potentially severe, such as air pollution.

Questions about environmental effects from geothermal energy development in California center around the Geysers-Calistoga Known Geothermal Resource Area (KGRA) in the northern part of the state. In 1960, Pacific Gas and Electric Company (PG&E) began operation of an 11-megawatt (MW) dry-steam-driven power plant in the geysers region. Today, PG&E has eleven power generating units on line, producing more than 500 MW of electricity using geothermal steam from wells developed by the Union Oil Company. So far, only moderate environmental impacts have resulted from development of this energy resource. But the extent of the geothermal reserves in the Geysers-Calistoga KGRA points to the likelihood that the region will undergo heavy development in the future. This prospect has given rise to concern over the possible effects that this concentrated energy development could have on the local environment and how these effects might be minimized.

To accurately predict the environmental effects that can be expected to occur under the rapid and expanded development of a natural resource requires a

comprehensive and systematically organized base of quantitative information. Recognizing the need for such a data base for the Geysers-Calistoga KGRA, the California Energy Resources Conservation and Development Commission (CERCDC), which is giving priority to the accelerated development of geothermal resources, contracted with SRI International (formerly Stanford Research Institute) and its subcontractor, Earth Sciences Associates, to perform three tasks:

- Formulate a master baseline environmental assessment (MEA) for application throughout the Geysers-Calistoga KGRA.
- Determine the amount of air pollution in the form of hydrogen sulfide (H_2S) gas from present geothermal resource development in the Geysers-Calistoga KGRA, and evaluate methods of controlling H_2S emissions.
- Define the type and amount of meteorological measurements and analyses necessary to adequately assess the local air quality impacts of H_2S in the Geysers-Calistoga KGRA.

These tasks were completed in May 1977 and documented in three volumes.* Reported here are the essential results of that study.

**Environmental Analysis for Geothermal Energy Development in the Geysers Region, Volume I: Summary; Volume II: Master Environmental Assessment; Volume III: Appendices*, prepared by Stanford Research Institute, Menlo Park, California 94025, for the State of California Energy Resources Conservation and Development Commission, 1111 Howe Avenue, Sacramento, California 95825 (Contract 4-0133), May 1977.

GEOHERMAL RESOURCE DEVELOPMENT

The Geysers-Calistoga KGRA is located about 80 miles north of San Francisco and covers about 580 square miles within Lake, Sonoma, Mendocino, and Napa counties.

Character of the Resource

The geothermal resources of this region are among the more easily identified because of the way in which the heat reaches the surface. The source of heat lies relatively near the earth's crust in molten rock, or magma. The temperature difference between the heat source and the earth's crust causes the heat to rise. Deep fissures or faults in the earth's crust in the Geysers-Calistoga region allow water in a permeable bed of rock just below the surface to come into contact with the subterranean heat source. This heated water rises to the surface to emerge as steam or hot water in the familiar form of fumaroles and hot springs.

The Geysers-Calistoga KGRA contains two types of geothermal reservoirs: vapor (dry steam)-dominated, and liquid (hot water)-dominated.

In a vapor or dry steam dominated system, saturated steam and water coexist within the heat reservoir.

When a well is drilled into the reservoir, the pressure decreases as the flow is established, superheating the steam. This steam is then piped to conventional steam turbines to generate electricity. This generation method is the only one presently in use at the Geysers.

In a liquid (hot water)-dominated system, tapping the heated water causes only a portion of the fluid to flash to steam. This steam may be separated from the hot water at the surface and fed to steam turbines. The hot water and steam condensate are discharged at the surface or reinjected into the ground. Alternatively, the heat in the water and steam may be transferred to a secondary fluid with a lower boiling point. The secondary fluid then drives a turbine in a closed cycle.

Steps in Developing the Resource

Developing a geothermal resource, such as those contained in the Geysers-Calistoga KGRA, is similar to

oil and gas field development, with the addition of the technologies of electrical power plant and transmission line construction.

The basic steps are:

- *Exploration* — Airborne surveys, ground surveys, ground and spring water sampling, shallow drilling, and subsurface rock sampling take place.
- *Test drilling* — A drill pad is cleared, a heavy-duty oil drilling rig is assembled, and drilling takes place for 45 to 60 days. Test wells can range from a few hundred to several thousand feet. If and when steam is encountered, the well is production tested.
- *Production testing* — A steam-producing well is tested to determine flow rate, temperature of steam, pressures, composition of other gases mixed with the steam, and so on. The well is also cleaned of drilling debris. Then the well is shut in until other connecting pipes can be set up.
- *Field Development* — Additional wells (normally 10 to 15) are drilled, tested, and shut in until a field of wells with enough combined steam to run a generator is developed. One well does not produce sufficient steam to run the large electric generators used by utilities. Aboveground steam pipelines are installed to carry the steam to sites where the power generators are to be installed. The steam supply must be adequate to run a generator for at least 30 years to justify building a generating unit. However, replacement wells are necessary over the 30 years so that field development can continue throughout the life of the generating unit or as other units are added.
- *Full-scale energy production and transmission* — Power generating units are built and transmission lines from the site to switching stations are constructed. The generation of commercial power requires three separate systems: the turbine generator, the condenser and cooling system, and the electrical systems. Buildings are constructed to house this equipment as well as electrical equipment such as transformers, circuit breakers, and on-site power supplies.

Estimates of Future Expansion

At present, PG&E has 11 geothermal units operating in the Geysers-Calistoga KGRA region, producing a total of 502 MW of electrical power. Four additional units have been proposed, which would bring the capacity to 908 MW by 1980. In terms of what this capacity would mean to the energy supply of the state, about 1000 MW is the energy required for a city of 1 million people.

In view of the substantial commercial potential for energy production in the KGRA, CERCDC, in conjunction with ERDA (now part of the U.S. Department of Energy), asked the Jet Propulsion Laboratory (JPL), Pasadena, California, to develop recommendations and rationale that would allow for full development of

geothermal energy in the KGRA in an environmentally acceptable manner. JPL prepared scenarios for each subregion of the KGRA as a basis for evaluating the benefits and impacts of geothermal development in these areas. JPL estimates for future electric on-line capacity were based on the assumption, drawn mainly from leasing activity, that geothermal resources exist within the KGRA far beyond those now being considered for development. These estimates call for a total capacity of 5600 MW of electricity after the year 2000. PG&E estimates fall somewhat below those of JPL, with about 990 MW forecast between 1980 and 1985, and a total future capacity of between 4000 and 5000.

ESTIMATED FUTURE ON-LINE ELECTRICAL CAPACITY							
Locations	1976 (MWe)	1980 (MWe)	1985 (MWe)	1990 (MWe)	1995 (MWe)	2000 (MWe)	> 2000 (MWe)
Geysers-Calistoga KGRA							
Current field	502	900	1000	1000	1000	1000	1000
Sonoma extension			500	1000	1200	1400	1400
Lake County (Cobb)			500	700	800	800	800
South Clear Lake				200	500	600	600
North Clear Lake				100	200	400	500
Mendocino County				100	200	300	800
Napa County						50	500
Totals	502	900	2000	3100	3900	4550	5600
Incremental increases		400	1100	1100	800	650	1050
Source: Jet Propulsion Laboratory, Pasadena, CA.							

HIGHLIGHTS OF THE MASTER ENVIRONMENTAL ASSESSMENT

Perspective

The purpose of a master environmental assessment (MEA) is to provide a basis for making rapid site-specific environmental assessments so that timely decisions can be made on whether or not to proceed with new geothermal development sites. The first major environmental study for the Geysers region was published in 1973 in a multivolume report on all KGRAs prepared by the U.S. Bureau of Land Management preparatory to competitive bidding for leases of federal lands. In February 1975, a more detailed blanket environmental assessment of the expanded Geysers-Calistoga KGRA, being prepared by the California Department of Conservation, was nearly completed when the project was terminated. With these two reports as starting points, and within the limited resources available, SRI reviewed essentially all information relating to geothermal development in the Geysers-Calistoga region. Information contained in more than 250 documents, many of which were not available to the general public, was reviewed and distilled to produce a balanced and comprehensive baseline MEA. The MEA contains the pertinent information available today, but, for it to serve its purpose over the long term, it will be necessary to update the MEA as newer, more definitive information is developed. (This will be especially true for hot water systems, which have not yet been developed at the Geysers-Calistoga KGRA.) Consequently, information in the MEA on environmental effects of geothermal resource development applies mainly to dry steam systems with additional information to be added on hot water system impacts as they become known.

The Setting — Environmental and Socioeconomic

The Geysers-Calistoga KGRA is a scenic region of mountains, steep canyons, hilly uplands, terraced valleys, and flat lake-basin terrain. The physiography of the area is divided into four zones: the Northern Highlands, Clear Lake, Mayacamas Mountains, and the Palisades. Elevations range from 160 feet in the

Napa Valley in the southeastern corner of the KGRA to over 4700 feet at Cobb Mountain in the central portion. The historically active San Andreas, Hayward, Calaveras, and Concord faults are all within 100 km of the KGRA, and approximately 19 potentially active faults lie nearby within the KGRA. No major earthquakes, however, have been recorded in the region to date.

The semipermanent high pressure system of the Pacific Ocean dominates the weather of the KGRA. Historically, the climate of the region has been extreme — stormy, rainy, and cool winters (November-April), as the "Pacific High" moves south permitting storms to move into and across the northern and central portions of the state, and calm, hot, dry summers (May-October), as the high moves north to block Pacific storms from moving in from the north and west. Throughout the year, local weather in the KGRA, especially the wind pattern, is strongly influenced by the rugged and varied terrain, particularly in the southwest where there are many deep and steeply sloped box canyons.

The KGRA contains eleven watersheds. The Mayacamas Mountains, trending northwest-southeast, are the major drainage divide. The three watersheds to the southwest flow generally west into the Russian River Basin, while the remaining eight flow east into the Sacramento River Basin. About 88% of the annual precipitation of the region, which ranges from 25 inches along the northern boundary to 80 inches on the crest of the Mayacamas Mountains near the southern boundary, occurs during the wet season (November-April), and most of that moisture becomes runoff. As a result, streamflow is intermittent in the area. In general, water is in short supply within the KGRA with the demand increasing.

Although the water quality of a few streams has been spot-sampled, no comprehensive study has been made. However, in general, the water ranges from medium to excess hardness with a sodium hazard for

irrigation, especially during low flow months. In addition to sodium, KGRA waters contain varying amounts of boron, ammonia, nitrates, and mercury. High sedimentation and turbidity during periods of high runoff are problems in certain stream locations.

Vegetation in the region forms a complex mosaic of oak and conifer forest, chaparral and grassland, with sharp boundaries between adjacent types of growth. Soils of the KGRA vary from the prime agricultural types found in the valleys, to clayey and marshy types concentrated in a number of scattered locations. Soils with erosion potential are located in the Mayacamas Mountains, in the hills east of Clear Lake, and along the Napa/Lake county line east of Mt. St. Helena, and along Big Canyon and Anderson Creeks. Landslides are a fairly common occurrence in the KGRA. They take the form of rockfalls and mudflows and are caused by slope steepness, the nature of the surface and subsurface material, rainfall, earthquakes, and human activity.

Most of the animals in the KGRA are small mammals (rodents, raccoon, opossum, marten, and fisher), reptiles, and game and song birds, with lesser numbers of deer, wild pig, coyote, and bear. Fishing for bass, catfish, and bullhead in the fisheries of Clear and Thurston Lakes and for trout in the fisheries of Cole and Kelsey Creeks, as well as in other streams, offers a popular form of recreation in the region.

Agricultural land use in the KGRA is generally particular to the type of topography — grazing and forestry (pine and fir) in the mountains, with orchards, vineyards, pastures, and other crops occupying the shallower slopes and valley floors. Recreational and light commercial land use is centered along the highways and in community centers. The primary commercial centers of the KGRA are St. Helena, Calistoga, Middletown, Kelseyville, Lakeport, and Clear Lake Highlands. Commercial and industrial land uses, excluding geothermal development, are located only within the Napa and Lake county portions of the KGRA.

In general, the Geysers-Calistoga KGRA is a quiet area, rural in character, peopled in large part by those who have been drawn to the pleasant, slower paced life offered by the region. The population is increasing, not as a result of birthrate but through immigration. Per capita incomes are somewhat lower than the state average, with considerable unemployment evident, and on that basis the KGRA is considered to be economically depressed.

GEYSERS-CALISTOGA KGRA

POPULATION (1975)

• Lake County	24,100
• Sonoma County	241,000
• Mendocino County	58,510
• Napa County	90,697

MAJOR INDUSTRIES

- Agriculture (stock raising, dairying, orchards, vineyards, grain growing)
- Tourism/Recreation
- Forest Products

Environmental Impacts of Geothermal Development

As in any resource recovery program, geothermal development can affect the environment in many ways and in varying extent. Some environmental effects have already occurred as a result of current geothermal development in the Geysers region, but they have been localized and relatively moderate. The major concern now is what will happen to the environment of the region under more widespread development. Consequently, the impacts outlined in the MEA heavily emphasize the *potential* for damage.

Mechanical disturbance of the earth in steam-well development and in power plant and transmission line construction, and the operation of the geothermal facility once it is constructed, affect the environment in three general categories:

- Quality of the physical/chemical environment (air and water quality, land use, stability of the earth, noise).
- Quality of the habitats of biological species — plants and animals.
- Quality of the economic, social, and cultural environment.

Air Quality

Air quality could be affected by dust from construction, emissions from heavy vehicles/equipment, and steam and noncondensable gases, particularly H_2S , emitted to the atmosphere from geothermal wells, steam gathering systems, and power plants. Natural sources of H_2S in the KGRA emit an estimated 120 lb/day. However, the dominant H_2S emissions come from man-fostered sources: well drilling and testing, steam cooling and venting, and well blowout. How much of this H_2S is emitted to the air depends on the amount of the gas contained in the steam. How far it travels depends on the local meteorological conditions. Measurements of H_2S under different meteorological conditions around the edge of the Geysers area indicate that H_2S concentrations are heaviest along the ridge of the Mayacamas Mountains, with air pollution potential being higher during the summer months when the atmosphere tends to be more stable and air stagnation is more prevalent.

Other potential air pollutants from geothermal steam — sulfur dioxide, ammonia, carbon dioxide, radon 222, and trace metals — are generally in such low concentrations that they do not contribute to pollution in the region.

Along with tangible air pollutants comes noise. Noise is generated by well drilling and testing, steam venting, and station operation, as well as support activities, such as vehicle traffic. There can be occasional venting through mufflers or an occasional pipeline leak. If a well has production potential, it is vented continuously through a small orifice to prevent the steam from condensing in the well. Bleed lines through which the wells are vented are fitted with mufflers. The noise that accompanies development will affect those who do the drilling and those (animals and birds, as well as people) who happen to be nearby.

Water Quality

Potential sources of water quality degradation are the clearing and grading of the land for access roads and construction, the loss of drilling fluid, the condensation of vented steam, and well casing failure or blowout.

Clearing and grading the land could cause sediment build-up in nearby surface streams. As more roads and well sites are constructed, new watersheds could be affected, with sediment transferred downstream to accumulate in the network of watercourses fanning out

from the watershed. Sediment production will increase following initial construction and will decrease as the disturbed areas restabilize. Sediment build-up can be minimized by leaving undisturbed buffer areas between construction areas and drainage ditches.

Drilling mud and chemicals that escape from sump ponds pose a potential water quality problem. Sumps for drilling waste, which were often constructed on steep slopes, have contaminated adjacent ground or surface waters fairly frequently through seepage or embankment failure.

Water for drilling is taken from streams adjacent to the drilling site. A decrease in late summer water flow, as a result of withdrawing water, as well as an increase in sediment rate could be detrimental to fish and other water species in the KGRA.

There is the possibility of groundwater contamination, although little, if any, reduction in flow rate or increase in temperature or chemical composition has occurred since the operation of geothermal plants began in the KGRA in 1960. Casing production and reinjection wells to sufficient depth can prevent geothermal fluids from mixing with groundwater — if casing failure is discounted. But, since roughly 20% of the fluid produced is reinjected, extensive site development could have some deleterious impact on groundwater. Erosion and percolation of wastes are also a consideration in terms of potential groundwater contamination.

If patterns of groundwater and surface water flow are altered, this could diminish the amount of water available for domestic, agricultural, and industrial needs.

Land Stability

By disrupting the land surface, road and trail construction, well drilling, well pad preparation, and power plant and transmission line construction all contribute to instability of the ground surface. The Geysers-Calistoga KGRA is especially vulnerable to this effect because so few of the potential geothermal sites are on level ground. The generally steep terrain (30% to 70% slopes) requires major cut and fill work. To provide room for a drilling operation, for example, takes between one and three acres of cut and fill. A mainline road disturbs about 30 feet of earth from the top of the cut to the bottom of the fill. Disturbing the land in this fashion can lead to erosion and landslides.

Extracting fluid from the geothermal reservoirs could also cause local subsidence of the ground surface, although to date only a small amount of subsidence has been noted in the area surrounding currently producing wells.

The region is already fairly active seismically, and there is some concern that additional resource development could increase the likelihood of earth tremors through withdrawal of geothermal fluids or their reinjection into the ground. Recent research, however, suggests that microearthquakes are not caused by steam extraction but are common to the same geologic environs that contain the geothermal source. Earth tremors could cause landslides and well blowouts, ruptured steam lines, downed transmission lines, and generating plant damage, although power plants and steam lines are designed to minimize damage from seismic sources.

Clearing and cut and fill operations will destroy native plant life at geothermal sites, but, in time, vegetation will reestablish itself in these areas. Woodland and grass cover normally return in two to three years, while steep rocky cuts, where most of the soil has been stripped away, take longer to revegetate. Chapparal is slow growing and can take from 5 to 20 years to recover, depending on the characteristics of the site.

Wildlife Habitats

The impacts on animals and fish will stem partly from the mechanical disruption of their normal habitats and partly from the effects that go along with geothermal power generation — noise, and air and water emissions. In general, habitats of existing wildlife surrounding geothermal facilities will be destroyed or altered in the development phases, with the eventual and at least partial recovery of some of these habitats in the long term. Some animal species will adapt to the intrusion of their habitats, and some new habitats conducive to warm water species may be created in the area. The actual extent of habitat alteration has not yet been determined, but overall it is expected that the relative wildlife populations will change, with probably somewhat fewer game animals than now make their home in the KGRA.

Economic, Social and Cultural Environment

Using the land for geothermal projects — changing public access to public lands (or private access to private lands), or changing the character of the land — will influence the economy of the region. It is estimated that full development of the KGRA could re-

quire up to 41,000 acres, or roughly 11% of the total acreage, if one assumes 800 acres is necessary for a single plant producing about 110 MW of electricity. Use of the land for power production may deny its use to wildlife, but through a network of roads and trails it may also make fire protection easier for scenic and hitherto inaccessible land, as well as open up inaccessible land for recreation.

On the other hand, some land, once pristine in nature, will be the site of a geothermal development, and from one economic point of view removing this land from public access could mean a heavy cost in terms of tourist dollars, a mainstay of the economy in the KGRA. Expanded geothermal development will inevitably change the character of the land on which it is carried out from scenic/recreational to industrial, where the tradeoffs are not measurable on an equal footing. The relative measure of economic impact is the size of the local payroll from a given geothermal project and not the size of the entire expansion program.

Little discomfort or economic hardship will be directly caused by a population increase fostered by geothermal development. Except for the personnel who operate a plant, those who work on the geothermal project before it becomes operational will be mainly transients whose needs will not tax local services to any great degree. In fact, the population influx is expected to be relatively gradual. All in all, those who live in the KGRA are more likely to be affected by environment impacts than by economic or social impacts stemming from population increase. Local property values could decline as a result of industrial development and the local quality of life could be diminished by changing from a rural to an industrialized society.

The natural aesthetic character of the KGRA will undergo change, but with careful planning it should be possible to design geothermal facilities so that they blend into the natural setting as nearly as possible. This will require thoughtful placement of man-made structures, use of compatible color, and restoration of landscapes and vegetation.

ENVIRONMENTAL MATRIX FOR VAPOR-DOMINATED GEOTHERMAL SYSTEMS

ASPECTS OF THE ENVIRONMENT	EXPLORATION	PRODUCTION DRILLING AND TESTING	PARALLEL FIELD DEVELOPMENT OPERATIONS	PLANT CONSTRUCTION	FULL-SCALE OPERATIONS
	<ul style="list-style-type: none"> Mapping/field studies Drilling pad construction Test drilling (shallow & small diameter) Temporary roads/traffic Equipment operation Abandonment 	<ul style="list-style-type: none"> Well drilling & construction (production & reinjection) Well stimulation Accidental blowouts Well testing/venting, ponding/reinjection 	<ul style="list-style-type: none"> Land clearing and roads/vehicular traffic Gathering systems Equipment activities Service living quarters Water, sewage, temp., elect. & other supporting services 	<ul style="list-style-type: none"> Structures & improvements Vehicular traffic/equipment Activities Special construction activities (e.g. blasting) Electric transmission systems Supporting services (e.g., water, elect., etc.) 	<ul style="list-style-type: none"> Cooling towers Venting (during short-term outages) Well-head bleeding Reinjected Recharge, stimulation & redrilling Corrosion & scale control Gaseous, liquid, & solid wastes Work force movement Abandonment
PHYSICAL/CHEMICAL					
Air quality	H*	L/H	L	L	L/H
Noise	H	M/H	M	M	L/M
Water quality (Surface)	L	L/H	L/M	L	L/H
Water quality (Groundwater)	L	L/H	L	L	L/H
Soils/erosion	L	L/M	L/M	L/M	L
Land subsidence	L	L/M	L	L	L
Seismicity	L	L	L	L	L
BIOLOGICAL:					
Terrestrial flora and fauna	L	L/M	L/M	L/H	L
Wetlands, Marshes	L/M	L/M	L/M	L/H	L
Aquatic	L	L/M	L/M	L/H	L/H
SOCIAL/CULTURAL:					
Land & water use (Consistency)	L	L/H	L/H	L/H	L/H
Scenic/aesthetic	L	L/M	L/H	L/H	L/H
Safety	L	L/M	L/M	L/M	L
Services burden	L	L/M	L/M	L/M	L

*H = High potential impacts
long term and/or great
intensity

M = Moderate potential impacts
major short term and/or
overshadowed effects

L = Low/negligible potential
impacts minor and/or
short-term

SOURCE: Adapted from "A Technology Assessment of Geothermal Energy Resource Development" NSF/RANN, April 15, 1975

CONTROL TECHNOLOGY FOR HYDROGEN SULFIDE EMISSIONS

The air pollutant of most concern in the Geysers-Calistoga KGRA is the hydrogen sulfide (H_2S) gas contained in the geothermal fluid. At low concentrations in air, this gas is readily detectable by its telltale "rotten egg" smell. At higher concentrations, the toxicity of H_2S can cause moderate-to-severe (fatal) respiratory and other physiological damage, and, at the concentrations that pose the greatest danger, the olfactory sense is lost and therefore also lost is the sense of danger.

Although the H_2S in geothermal steam is ordinarily diluted when it reaches the atmosphere to levels that generally present no hazard, more concentrated emissions of the gas from a geothermal development complex could reach workers in the drilling fields and power plants and neighboring populations if such emissions were not controlled.

The control of H_2S emissions is complex, as is any pollution control problem. Many factors — technical, economic, legal — play a part in the development of sound environmental controls. At the core of the H_2S control problem are three interrelated elements: adequate regulatory standards, effective controls that can be applied at acceptable cost, and a comprehensive set of meteorological measurements on which to base requirements.

Estimates of H_2S Emissions

Estimated H_2S emissions for the Geysers geothermal development are divided into power plant emissions and pre-power plant, or steam venting emissions.

The estimates shown for power plants are instantaneous rates based on full load operation, while the vent emissions are annual average rates. Because the pollution potential is related to instantaneous rates of emission rather than to annual average rates, the contribution of steam venting to air pollution can be greater than shown. Venting is usually intermittent and large quantities of H_2S (up to several hundred pounds per hour) can be emitted during venting. If a plant is not fitted with controls it makes little difference whether the emissions come from the plant

ESTIMATED H_2S EMISSIONS — 1975

	lb/hr	% of Total
Power plant	1574	88
Steam vents		12
Uncontrolled well*	73	214
Bypassing	61	
Well testing	28	
& cleanout		
Pipeline	31	
Well drilling	9	
Well bleeds	7	
Natural fumaroles	5	
Total	1788	100

Source: PG&E and Union Oil

*Thermal No. 4 Uncontrolled since 1957

or steam vents. However, if a plant is fitted with control equipment, bypassing steam to the atmosphere during forced plant shutdown is equivalent to total failure of the emission control system.

Regulatory Standards for H_2S

Geothermal operations in California are subject to a state air quality standard for H_2S of no more than 30 parts per billion (ppb) (0.030 parts per million) set by the Air Resources Board (ARB). This level corresponds roughly to the odor threshold of H_2S . However, the ARB has not established an unequivocal relationship between H_2S emissions and health effects. The Northern Sonoma County Air Pollution Control District (NSCAPCD) has recognized that emissions from present geothermal production in the county are heavily influencing ambient H_2S concentrations in Lake County as well as those in Sonoma County. Consequently, the NSCAPCD has established regulations that apply to limiting current emissions and those expected from future expansion of geothermal development in the county.

NSCAPCD power plant regulations in 1976* for the current field called for a phased reduction of present emissions, which will require retrofitting existing plants with H₂S abatement systems. By 1978, the maximum allowable six-month average will be 850 lb/hr of H₂S emitted to the atmosphere. For new power plants, built outside the present production zone, emissions must be limited to 10% of the H₂S in the steam that enters the power generating unit, or, 0.4 lb/hr per megawatt of generating capacity (24-hr average), and in no event can more than 80 lb/hr be emitted.

Pre-power plant (well venting) emissions are also covered by NSCAPCD regulations*: by 1979, vent emissions must be reduced to 150 lb/hr within the present production zone. For new plants, vent emissions must not exceed an annual total of 7.5% of the H₂S produced from the steam supplied to the unit for more than 24 hours.

Other counties are expected to adopt comparable rules as geothermal power production spreads within the KGRA.

H₂S Control Technology

To place the effects of control into perspective, two scenarios were postulated on the basis of projected geothermal expansion within the Geysers-Calistoga KGRA.

Scenario 1 assumes that allowable emissions will generally conform to NSCAPCD limits. If existing power plants are retrofitted with controls to meet NSCAPCD limits by 1980, this will bring about a marked reduction of H₂S. But, by 1985, H₂S emissions will again approach 1977 levels, and by 1990 will have exceeded current levels because development will have taken place in a larger geothermal area than at present, as Lake County sites, relatively close to population centers, with 800-1000 MW capacity and emissions of 600-700 lb/hr, begin producing.

Scenario 2 assumes that emissions standards are based on installation of the "best available control technology" so that all new power plants (following PG&E unit No. 12) have allowable emissions of only

PROJECTED HYDROGEN SULFIDE EMISSIONS FROM EXPANDED GEOTHERMAL DEVELOPMENT

Scenario	Source	Emission Factors*	1980 908 MW	1985 1808 MW	1990 2000 MW
			Hydrogen Sulfide Emission		
			lb/hr	lb/hr	lb/hr
1	Power plants	Allowable emission = 0.4 lb/hr/MW	363	723	1200
	Steam venting	Emission = 7.5% of H ₂ S input rate to power plants.	262	522	867
	Total		625	1245	2067
2	Power plants	Allowable emission = 0.4 lb/hr/MW for Units 1-12	255	291	339
	Steam venting	0.04 lb/hr/MW for all subsequent units 90% control of vent emissions	26	52	87
	Total		281	343	426

*H₂S content of steam — 223 ppm_w.
Steam rate to power plant — 17.27 lb/kWh.
H₂S input to power plant — 3.852 lb/hr/MW.
Vent emissions (uncontrolled) = 7.5% of H₂S input to power plants = 0.2889 lb/hr/MW.

*NSCAPCD regulations were amended subsequent to this study.

0.04 lb/hr per megawatt of capacity (roughly the same as 99% control efficiency). Scenario 2 also assumes that pre-power plant (steam vent) emissions are 90% controlled.

Under these assumptions about one-fifth of the emissions projected for 1990 under Scenario 1 occur under Scenario 2. This level of control may not eliminate all H₂S odor problems, but it would be a great help in reducing them and in providing a margin of safety unavailable in Scenario 1.

Sources of H₂S that are candidates for control in the Geysers development are the steam gathering and power generation systems. At present, the steam gathering systems incorporate no means of H₂S removal, but controls are being retrofitted to the power generation systems. Fitting steam gathering systems with controls would mean the relatively simple addition of new equipment. Retrofitting power units that employ direct contact condensers, however, is difficult and expensive both in terms of capital expenditure and loss of power production during conversion.

Fitting steam gathering systems with controls would mean the addition of the following existing equipment:

- Separators to protect wellhead equipment and the steam gathering system from discharge of rocks and dust in the well.
- A motor-operated throttling valve, and motor-operated gate valves to isolate the well and wellhead from the rest of the system.
- Remote control operation of the wellhead from a control station.

These additions would probably reduce steam and consequent venting of H₂S by 80% during bypass, well cleanout before startup, and the heating up of transmission lines at startup. If additional H₂S reduction were required, an absorber would be needed to treat the steam still being vented to the atmosphere. The absorber should remove H₂S directly from the vapor stream and not require condensation of the steam. No absorber of this kind is presently available; however, the "iron oxide box" concept might be adapted to this application. The iron oxide concept is a traditional means of H₂S removal but its adaptation to vented steam would require an experimental development and test program. If it were successfully adapted, it could raise the total efficiency of H₂S control for steam-gathering systems to over 90%.

Controls for other sources of pre-power plant H₂S emissions include vent-gathering systems for pipeline vents (these are partially installed), adaptation of the iron oxide box concept for steam that escapes during well drilling, clean out, test, and well bleeding, and plugging of the shaft of an uncontrolled well (this may require excavation).

Proposed new power units (Nos. 13-15) at the Geysers will feature surface condensers. In these systems H₂S is relatively easy to control. However, all of the power units now installed at the Geysers (1-12) are fitted with direct contact condensers. Fitting this type of unit with controls is inherently difficult and expensive both in capital expenditure and operating cost.

PG&E has adopted the "iron catalyst" or Ferrifloc system for units with direct contact condensers. This system removes H₂S from the condensate. Although it has recognized deficiencies it was chosen because no alternative was considered to be available. (Severe corrosion occurs in cooling water and condenser systems, and insoluble iron salts carried over into blowdown water and reinjected into the steam field may plug injection wells in time.)

A possible alternative to the Ferrifloc system is "upstream" purification in which the steam is desulfurized at the inlet pressure and temperature before it enters the turbines. This scheme would have the advantages of protecting turbines against corrosion caused by H₂S, which is a current problem, and of removing the sulfur from the steam before necessary venting took place. Two methods of upstream purification are being tested at the Geysers. The commercial success of the concept is still problematical, and even if it were assured, full-scale development would be six to ten years away.

If the Ferrifloc system proves to be either inadequate or infeasible in practice, the only practical alternative appears to be the modification of the power units either to replace direct contact condensers with the surface type, or perhaps to convert direct contact types to surface condensers. This would mean that the modified plants could use the same emissions control system installed in Units 13-15 and later installations. Modification would call for a major reconstruction problem, but its cost would probably be competitive with any control system featuring 99% efficiency.

Another possible alternative to the Ferrifloc system may be the use of sulfur dioxide as a reaction agent to oxidize H₂S with the resulting precipitation of elemental sulfur, which then could be readily removed. This process is little understood and has not been

demonstrated, but theoretically it appears to offer enough potential to warrant further exploration.

The Stretford absorption and reaction system will be used for H_2S control in new power units with surface condensers. This system will remove almost all of the H_2S from the noncondensable vent gas and convert it to elemental sulfur. Some H_2S will remain in solution in the condensate — perhaps from 10% to 20% of the H_2S that enters with the steam. The condensate will be added to the cooling water without treatment and the H_2S will be stripped from the solution in the cooling tower and discharged to the atmosphere, as is now done in plants with direct contact condensers. This process will lower the overall control efficiency to about 80% to 90%, depending on how much H_2S is retained in solution in the condensate.

It should be practicable to treat the relatively small amount of condensate with a chemical oxidizing agent to convert the H_2S that remains in solution to elemental sulfur or some nonvolatile sulfur compound. Agents that may be useful in this application are hydrogen peroxide, ozone, and possibly sulfur dioxide.

If it were possible, technically and economically, to use this method of treating dissolved H_2S to convert 90% of it to readily removable form, this would raise the overall control efficiency to 98-99%. The emission control system as a whole would then qualify as the "best available control technology."

The additional cost for application of "best available control technology" at a new 110-MW power unit equipped with a surface condenser and Stretford system should be approximately as follows:

Condensate treatment (hydrogen peroxide)	0.9 mill/kWh
Wellhead vent control	0.7 mill/kWh
Hydrogen sulfide absorber for steam vent	0.9 mill/kWh
Total incremental cost	2.5 mills/kWh

Condensate treatment with hydrogen peroxide and installation of the wellhead vent control system are measures that could be undertaken immediately. The H_2S absorber for the steam vent would first have to be developed through the laboratory and pilot-plant stages.

The projected delivered cost of power from the future Unit 14 operating at 80% capacity is 21.5 mills/kWh, including the associated costs for the Stretford system and surface condenser, which may be about 1.0 mill/kWh. The incremental control cost would then add 12% to the delivered cost of the power, raising the delivered cost to 24.0 mills/kWh. The total cost of H_2S control (including the Stretford system and surface condenser) would be 3.5 mills/kWh.

METEOROLOGICAL/CLIMATOLOGICAL DATA BASE FOR HYDROGEN SULFIDE PREDICTIONS

Data Requirements

A primary task of the county air pollution control official is to maintain H₂S levels below the 30 ppb standard in the area within his jurisdiction. In the Geysers-Calistoga KGRA, acceptable air quality cannot be maintained unless emissions are controlled, and it is the regulatory official's job to determine the extent to which controls are necessary. The need for a common regional data base has become apparent, and a new agency — the Geothermal Resource Impact Projection Study (GRIPS) Commission — has been formed to consider major environmental impacts, including those on air quality.

The type of information and tools necessary for regulatory officials to make objective and sound assessments of the air quality impact of proposed power plant or drilling activity and for developers to use as guidelines include the following:

- An air quality meteorological data base that represents all climatological conditions temporally and provides adequate spatial resolution for the KGRA.
- Development of site assessment techniques through analysis of the air quality-meteorological data base in terms of pollution dispersion potential.
- Mathematical models to predict long- and short (including episodic)-term air quality impacts of proposed power plants or wells.
- Increased understanding of the origins of complaints: specific correlations of odor complaints with H₂S measurements.
- Potential controls along with the quantification of their technical and economic feasibilities.

Existing Data Base

As geothermal power production has increased, so has concern over the odoriferous H₂S emissions attributable to geothermal resource development. This

has prompted efforts in recent years to measure ambient H₂S concentrations throughout the area and to characterize the meteorological processes that govern the concentration and transport of the gas.

A number of agencies have sponsored data collection including federal and state groups, local control authorities, the Northern Sonoma and Lake County Air Pollution Control Districts, utilities (PG&E), and steam suppliers (Union Oil, Aminoil, Pacific Energy, Shell Oil, Magma, and McCulloch Oil). Some H₂S studies have been jointly sponsored and through these cooperative efforts there has been free exchange of information and little redundancy in collection.

Although the information generated by these studies is adequate as a general basis for determining the potential H₂S pollution problem, it is not considered sufficient for the analyses on which to base long-range planning for geothermal development.

Meteorological and Climatological Data — The data bank of meteorological and climatological measurements for the KGRA is incomplete. Precipitation and air temperature measurements at ground level are available in fair quantity, but data on pollutant transport and dispersion are scarce. To develop accurate predictions for H₂S transport and dispersion, such variables as vertical temperature gradient, wind speed and direction, horizontal air trajectory, atmospheric stability, mixing depth, and diffusivity are important. However, field programs are underway to collect information to add to that already on hand.

Air Quality Measurements — At the request of the state Air Resources Board, PG&E conducted a study in 1972 to determine H₂S concentrations in geothermal areas. Air sampling was carried out in 48 locations for 60 days, using Colortec detectors. This study indicated that the frequency and intensity of detectable H₂S decrease as the distance from the source increases — H₂S is barely detectable beyond about 10 miles from the source.

PG&E began measuring ambient H₂S in the vicinity of the Geysers power plant in 1970. The Lake County APCD has made H₂S measurements in parts of Lake County, and the ARB has made some short-term H₂S measurements. Results of these measurements revealed concentrations that exceed 30 ppb at infrequent intervals on the Lake County side of the Mayacamas Mountains.

In early 1976, SRI set up an 8-station network around the edge of the Geysers to measure H₂S and to relate emissions to meteorological data. As expected, the largest number of violations of the 30 ppb standard were recorded at mountain ridge stations, with all sites experiencing levels of 30 ppb or more on occasion. No significant levels of H₂S were measured at remote locations (Lower Lake, Kelseyville, Lakeport, Healdsburg, and Cloverdale).

Although the existing data fall short of meeting the informational requirements of regulatory agencies, they are nonetheless useful. From these data, it is possible to (1) quantify present H₂S levels near the Geysers, (2) isolate the general surface patterns that can lead to significant H₂S patterns, (3) identify potentially adverse H₂S levels outside the immediate area of the Geysers, (4) characterize the meteorological conditions that cause the geothermal plumes of steam to disperse in air, and (5) estimate the future H₂S levels.

H₂S Impacts on Future Air Quality

Several items of information have to be considered for an analysis:

- The projected schedule of geothermal development, including location and time-phasing.
- The natural concentration of H₂S in the geothermal steam.
- The effectiveness and practicality of emission control technology.
- The standards set regulatory agencies.

All of these were taken into account in postulating the potential H₂S impacts on future air quality for two different scenarios.

Development was assumed to occur within the schedule shown earlier (page 4). It was assumed that expansion on the western side of the KGRA will proceed into areas adjacent to the present development, mainly to the east of it. Additionally, expansion was assumed to take place in the south and north Clear Lake areas, which are isolated from one another and

from the Geysers region. Also considered was the possibility that some areas farthest from the Geysers would be hot water rather than dry steam resources, which would reduce H₂S emission in those areas. Variability in the H₂S content of steam was also considered.

Control levels chosen for the analysis were 90% and 99% efficiency, those considered in the comparison discussed above under control technology. The explicit standards set by the NSCAPCD were assumed, and it was also assumed that emission standards will influence the degree of control exercised by industry: if regulatory agencies deem that 90% control of H₂S emissions is adequate, it is unlikely that industry will incur the cost of installing equipment that will assure 99% control.

Scenario 1 for future H₂S emissions assumed 90% control on all power plants, with steam venting figured on the basis of 7.5% of the H₂S input to the plant.

Scenario 2 followed the emission control schedule of Scenario 1 until mid-1982, after which 99% control of emissions was assumed to be practicable; the same assumption was also made for the 90% control of vent emissions.

With these assumptions and scenarios, it is possible to use an empirical model to establish estimates for potential air pollution in a given area, if that area has a representative sample of air quality and meteorological data.

The analysis considered air quality changes from only H₂S and not other forms of sulfur (SO₂) to which it can be transformed because no significant concentrations of SO₂ have been found in the Geysers region. It was therefore assumed that atmospheric dispersion dissipates concentrations before any wide scale transformation can take place. In essence, the method simplifies the problem by first identifying subareas within the KGRA that can be treated independently and then within these subareas isolating locations that are potentially sensitive to changes in air quality and treating them individually.

To illustrate the impact of the two scenarios, Whispering Pines, a small community east of Cobb Mountain was chosen for the analysis. Whispering Pines qualifies as a sensitive locale in a populated area that is susceptible to future emission changes in view of the heavy schedule of planned geothermal exploration on and around Cobb Mountain.

SCENARIO 1: H ₂ S EMISSIONS (lb/hr) 90% CONTROL*						
Location	1976	1980	1985	1990	1995	2000
Current field	1788	625	700	700	700	700
Sonoma Extension			350	700	840	980
Lake County			350	440	560	560
South Clear Lake				140	350	420
North Clear Lake				70	140	280
Mendocino County				70	140	210
Napa County						30
Total	1788	625	1400	2170	2730	3180

SCENARIO 2: H ₂ S EMISSIONS (lb/hr) 99% CONTROL*						
Location	1976	1980	1985	1990	1995	2000
Current field	1788	625	700	700	700	700
Sonoma Extension			200	235	250	270
Lake County			200	215	225	225
South Clear Lake				15	40	55
North Clear Lake				10	20	40
Mendocino County				10	20	30
Napa County						10
Total	1788	625	1100	1185	1285	1330

*Emission rates are long-term averages computed on the basis of an H₂S content in steam of 223 ppb by weight, the current average concentration in the Geysers.

The results of applying this general estimating method to Whispering Pines indicated that under Scenario 1 (90% emission control) H₂S in the air surrounding the community will decrease as controls are installed, but that, by 1985, when new geothermal facilities have come on line, concentration will again have reached 1976 levels as the effect of controls is negated by the addition of numbers of new pollutant sources. By 1990, the projections show that H₂S concentrations will have increased to the point that violations of the state standard could more than double the number of 1976 violations. Under Scenario 2 (99% control after 1982), however, the number of state standard violations drops to half those of 1976.

Oversimplified as it is, this illustration points to some general conclusions. The air quality impact at any given location will depend on the size and prox-

imity of the geothermal sources. If a location is close to a geothermal field, an increase in the number of installations to tap that field, even if they are equipped with controls, could offset the air quality benefits those controls provide. The change in air quality at any site will depend on future controls, the number of geothermal power production facilities, and the location of the site in relationship to the plants.

Future Data Bank Plan Outline

Depending as they do on detailed emission, meteorological, and climatological data, reliable forecasts of air quality changes must wait for a comprehensive and structured bank of information to be developed. A project to develop that information should consist of two parts: a management program and a technical program.

The management program is necessary to define objectives and outline the required measurements and analyses and to coordinate the various elements of the technical program including data management. Coordination will be a key element in assuring the usefulness of a data program. Also useful will be a basic data management structure. Elements of the structure include the collection of data from various sources in a central location, reduction of data to a standard computer format, the publication of a data catalog, regular dissemination of reports, and the frequent updating of the data file.

Since the data requirements will vary from district to district, the technical program should satisfy the information needs of all control officers within the KGRA. The technical program could be structured within the framework of the GRIPS Commission program. The content of the technical program rests on three elements: monitoring (fixed and mobile), special measurements, and analysis (including modeling).

FUTURE DATA PROGRAM REQUIREMENTS			
Program	Monitoring	Special Studies	Data Management and Analysis
Baseline	<p>Establish KGRA climatological data base for both surface and upper air; other site specific meteorological measurements may be required on occasion.</p> <p>Continue operation of H₂S monitoring network; possibly relocate certain stations. Extend Colortec network to cover new expansion areas.</p> <p>Locate mobile H₂S monitors temporarily in particularly sensitive areas — primarily in populated areas close to new power plants.</p> <p>Maintain routine source quantification and testing program.</p>	<p>Possible need for simple tracer studies using ground-based monitors where new power plant is located in a complex terrain area and close to a populated area.</p> <p>Quantify correlation of odor complaints and H₂S measurements.</p>	<p>Existing analytical techniques will suffice. In general, simple statistical summaries of monitoring data are sufficient. Effects of power plants in non-complex-terrain areas can be calculated using existing simple steady-state models.</p> <p>Consolidate all data into a well-organized computer file in a standard format.</p>
Extended	<p>Expand climatological data base in the vicinity of new geothermal developments. Includes increased spatial and temporal coverage of surface and upper air data. Certain areas may require tower-mounted wind sensors.</p> <p>Continue operation of H₂S monitoring, possibly adding several permanent stations.</p> <p>Use mobile monitors, Colortec cards, and site-specific measurements as above.</p>	<p>Perform tracer studies supported by aircraft measurements to explain atmospheric dispersion in and around the current geothermal production area. Additional tracer studies may be required for some new expansion areas contiguous to the current area.</p> <p>Make periodic measurements for other sulfur compounds and H₂S by-products at downwind locations.</p>	<p>Provide more comprehensive techniques to be used as planning tools. Adapt a transient three-dimensional air quality simulation model to the region. In general, the model need only predict inert pollutants (primarily H₂S, although, with some modification, it may be useful for aerosols).</p> <p>Develop an analytical technique that produces an accurate definition of the three-dimensional wind field given limited observations in space and time.</p>

Cost estimates derived for a comprehensive data program are based on the purchase of new equipment. However, inexpensive short-term lease/borrow ar-

rangements often can be made in conducting a measurement program.

COSTS OF A MEASUREMENT PROGRAM	
Surface wind/temperature stations (chiefly data reduction)	\$5,000 per sta. + \$1500 per yr
Upper Air	
Rawinsonde system	\$20,000 ea. + \$50 per launch
Acoustic sounder	\$10,000 ea. + \$1500 per mo (data analysis)
Monitoring network expansion	
For additional H ₂ S stations	\$50,000 per sta. + \$12,000 per yr operation
For Colortec site	\$800 per site
Mobile monitoring laboratory	\$10,000 to \$25,000 + \$5,000 to \$10,000 per yr. operation
Tracer studies	
Aircraft-supported series	\$150,000 to \$200,000
Ground-based simple series	\$50,000
Data management	
Initial data reduction	\$20,000 to \$40,000
Maintenance update	\$10,000 to \$20,000 per yr
Modeling	\$50,000 to \$100,000

FUTURE RESEARCH NEEDS

The major elements of meteorological/climatological research required were outlined in the previous section. In addition, Lawrence Livermore Laboratory is carrying out a large-scale socioeconomic assessment program for the Geysers-Calistoga KGRA. Additional areas in which research is needed are briefly described below, along with a projected level of effort for each.

Noise

Because the specific sites of future geothermal development are largely unknown and because the noise sources, paths, and receivers are highly variable, a general noise impact analysis at this time could be highly inaccurate. It is therefore recommended that acoustical analyses be made for each development as it occurs to permit more accurate description of the types of noise, source location, land uses that might be affected, and geographic features that could mitigate or enhance noise. A standard noise impact assessment methodology should be formulated for eventual application to each geothermal development, to include definition of a noise measurement system, definition of noise exposure level criteria, acoustical description of noise sources, guidance for specific case analysis, and description of impact assessment procedure. An analysis should also be made of traffic noise impacts.

Means to abate the most obnoxious noises should be developed by pinpointing opportunities for abatement, by designing, constructing, testing, and evaluating a prototype abatement device, and by modifying the design and retesting it, if necessary.

Water Quality

Surface Water — Two tasks are recommended: (1) collect reports of monthly and annual water quality records for major watercourses within the KGRA for a base period of 20 years (1955-1975), and calculate from these records the average normal ranges of sediment and chemical loads for each stream; (2) analyze specific effects caused by existing geothermal development and assess the relative severity of these impacts on water quality in the light of potential future development.

Groundwater — It is suggested that water samples from wells in the KGRA be chemically analyzed to form a basis for determining long-term effects of geothermal development on groundwater. This will require collecting analyses from state, county, and local agencies, possibly on a continuing basis. Some laboratory analyses to fill gaps in the information may also be necessary.

Maps and Surveys

Photointerpretive Landslide Map — Since landslides are one of the most important physical constraints for any type of development in the KGRA, it is recommended that existing maps be revised and aerial photographs of unmapped areas be interpreted to produce one map to a scale suitable for planning, which shows the type and location of instability features within the KGRA.

Vegetation/Habitat Map — To mitigate as much as possible the biological impacts of future development, accurate and well drawn vegetation maps (large and small scale) are needed for planning. Two tasks are recommended: (1) extend, with the aid of computer techniques and ERTs photos, vegetation mapping to cover the entire KGRA; (2) create a simplified overview map of major vegetation patterns from the detailed maps drawn in Task 1.

Land Ownership Map — The degree of local impacts will depend on how close privately owned land and recreational land is to geothermal development sites. And, in this light, the value of improvements on the land is important. Consequently, it is recommended that assessment records be examined to map the pattern of land ownership and value of improvements on private land.

Archeological Map — Only piecemeal archeological surveys have been made in the KGRA to uncover valuable artifacts left behind by earlier Indian inhabitants. Since sites of archeological artifacts are highly vulnerable to disturbance during geothermal development, it is recommended that a map and description of archeological sites in the KGRA be developed on the

RECOMMENDED RESEARCH — Level of Effort	
Program	Level of Effort (man-hours)
Noise	
Impact assessment method	300-450
Abatement method(s)	variable (300 minimum)
Water Quality	
Surface	
Task 1	400-500
Task 2	200
Ground	300
Maps and Surveys	
Landslide	970
Vegetation/habitat	400-500
Land ownership	150
Archeological	400-500
Transportation Planning	450

basis of existing information and by conducting surveys of areas not covered by extant maps. Included in this task is an outline of paths of construction that will avoid damage to such sites.

Transportation Planning

A comprehensive master plan for transportation routes is needed for future KGRA development to minimize short- and long-term ecological disturbance and visual impacts. As a base case, it is recommended that a map of existing roadways and cleared rights of way be prepared showing alternative siting configurations and major arterials through the KGRA. Each site alternative should then be examined for potential ecological disturbance, visual impact, roadway capacity, and costs.