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THE POTENTIAL OF HYBRID GEOTHERMAL/
COAL FIRED POWER PLANTS IN ARIZONA

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ABSTRACT

Arizona has abundant coal resources, and is currently operating coal-fired power plants at five locations in Arizona. In addition, Black Mesa coal of Arizona is being pumped by pipeline in a water slurry across Northern Arizona for use in the Mohave power plant units just across the border in the extreme southeast of Nevada.

The City of Burbank and the Ralph M. Parsons Company studies, funded by the DOE, showed several advantages for hybrid geothermal/coal fired power plants, as follows:

- a. The estimated cost of producing electricity in hybrid plant is about 18.3 mills/KWH, compared to 19.3 mills/KWH in an all-coal fired power plant.
- b. The coal requirements for a given plant can be reduced about 12-17 percent.
- c. The geothermal brines can be used for power plant cooling water, and in some cases, as boiler feedwater.

Arizona is believed to have geothermal resources overlapping four of the plant sites of coal-fired power plants, namely, St. Johns, Springerville, Tucson and Willcox. Since coal is now considered economical for these plant sites, the utilization of geothermal energy should provide additional benefits. Critical savings in the use of conventional groundwater for power plant cooling is especially important to Arizona. Seven other possible power plant sites, having geothermal resources were suggested -- Pinta, Flagstaff, southeast Kingman, northeast of Wenden-Salome, southeast Phoenix (west of Goodyear), Eloy and Clifton. Additional reductions in power costs (over those shown in the City of Burbank study) might be achieved for situations where an all-coal plant cannot be sited near a coal source due to environmental,

institutional constraints, or other economical factors.

The hybrid plant utilizes the geothermal energy much more efficiently than present concepts for all geothermal plants with respect to extraction of available work from the geothermal fluid. The overall efficiency of an all-geothermal plant is normally about 40 to 50 percent. The overall geothermal efficiency of the hybrid plant described in the City of Burbank study was estimated at 80 percent. These efficiency estimates are based on actual work derived from the geothermal fluid as compared to its available work.

In summary, these sites for new hybrid geothermal/coal-fired power plants all have unique site characteristics. Obviously, more detailed studies are required; these become so complicated that they are beyond the scope of this project. Such studies should be done by the industries and utilities that might benefit from possible hybrid plants at one or more of these locations.

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INTRODUCTION

The sharp increase in the price of oil and natural gas during the past ten years has increased the importance of coal as a source for electricity generation. Extensive coal resources are available in the United States, including the State of Arizona. Furthermore, improved materials and technology have resulted in a improvement of electrical generating facilities such that overall efficiencies have been increased from about 33 to about 39 percent. Various method of cogeneration are still being investigated which could lower further the cost of energy.

Other studies have been conducted to advance the knowledge of energy conversion. The Department of Energy, Division of Geothermal Energy, together with the City of Burbank initiated a program to study the technology and economics of combining geothermal energy with a coal-fired power plant. The study (completed in 1978) evaluated the available technology and concluded that the hybrid plant has a thermodynamic advantage over a conventional coal-fired plant. The study also evaluated actual geothermal sources in California, Nevada and Utah, concluding that some sites are more economical than all-coal-fired power plants while other are not.

Eventually, three reports were received on the study conducted by the City of Burbank under DOE funding, including the detailed system design verification of a hybrid geothermal/coal fired power plant, conducted by The Ralph M. Parsons Company for the City of Burbank (1,2,3). The latter report was extensive in nature, comprising a conceptual design, cost estimate and economic analysis of a one-unit 715 MW hybrid geothermal/coal fired power plant.

These detailed reports made it possible to use their results to evaluate several possibilities of future hybrid geothermal/coal fired power plants in Arizona. This report summarizes the pertinent results of the City of Burbank studies, and then applies them to the geothermal and coal resources of Arizona for possible future utilization.

Pertinent Results of City of Burbank Studies

It was found in an early part of the City of Burbank study that using geothermal energy in a hybrid plant reduces the coal requirements, given a prescribed plant output; or, alternatively, permits a higher plant output, given a fixed coal supply. Some geothermal resources can supply heat to the coal plant in excess of 249°C (480°F) and 34.5 bar (500 psi). Therefore, any uses of heat in an all-coal plant, at temperatures and pressures below these values, are subject to replacement by geothermal energy.

In a conventional power plant most of the low temperature heat for various plant requirements are supplied by steam extraction. In a hybrid geothermal power plant in addition to steam preheating, a considerable amount of energy could be withdrawn from the geothermal resource for these purposes which include (a) coal drying and beneficiation, (b) air preheating, (c) flue-gas reheating, and (d) general heating.

Because piping high-temperature geothermal fluid over large distances is generally impractical, the hybrid plant should be located near the geothermal resource area. In general, the geothermal resource is not optimally sited with respect to sources of coal, fresh water, or transmission networks. Therefore, despite its thermodynamic superiority, the hybrid plant's economic competitiveness depends heavily upon bringing coal close to the geothermal resource at an economical price. In summary, the site for a coal-fired power plant is generally a compromise between many various geographical and

economical parameters such as:

- . Distance from the coal mine and cost of coal transport.
- . Distance from the user site.
- . Land availability.
- . Water availability, quality and cost.
- . Distribution power lines.
- . Alternative consumers during off-peak hours.
- . Future expanding consumption.

When considering a hybrid power plant there is no flexibility in choosing the site. The plant must be located near the geothermal resource area as the transport of geothermal water over large distances is generally impractical. An economical analysis would assess the cost of all the other factors, determining if the project is economical or not.

The City of Burbank study considered ten Known Geothermal Resource Areas (KGRAs) of varying resources and environmental characteristics as shown on Figure 1, as follows:

1. Brawley, Imperial County, California;
2. Coso Hot Springs, Inyo County, California;
3. East Mesa, Imperial County, California;
4. Long Valley, Mono County, California;
5. Niland, Imperial County, California;
6. Surprise Valley, Modoc County, California;
7. Beowawe, Eureka and Lander Counties, Nevada;
8. Brady-Hazen, Churchill and Lyon Counties, Nevada;
9. Roosevelt Hot Springs, Beaver County, Utah;
10. Monroe-Joseph, Beaver County, Utah.

In determining the optimum hybrid plant at each of the sites, common

Figure 1. Locations of Geothermal Resources in City of Burbank Study

economic assumptions and component cost models were used. Variations in the economics of the plant from site to site was due mainly to variations in temperature of geothermal resource, cost of coal, cost of makeup water, cost of electrical transmission, seismic factors, and climatic parameters. Siting guidelines were summarized as shown in Figure 2.

The cost of coal, delivered to each site, was estimated as shown in Table 1 below.

Schematics of an all-coal-fired power plant and a hybrid geothermal/coal fired power plant (with feedwater preheat only by geothermal) are shown in Figures 3 and 4, respectively.

Table 1. ESTIMATED COST OF DELIVERED COAL

SITE LOCATION	\$/Tonne (\$/Ton)	SITE LOCATION	\$/Tonne (\$/ton)
California Sites:		Nevada Sites:	
Brawley	\$31.90 (\$29.00)	Beowawe	\$24.75 (\$22.50)
Coso	\$30.70 (\$27.90)	Brady-Hazen	\$28.05 (\$25.50)
East Mesa	\$31.90 (\$29.00)	Utah Sites:	
Long Valley	\$33.00 (\$30.00)	Monroe-Joseph	\$17.52 (\$15.93)
Niland	\$31.90 (\$29.00)	Roosevelt	\$20.00 (\$18.18)
Surprise Valley	\$33.00 (\$30.00)		

^aFigures based on 750-MW plants. Costs for 250-MW case less than 1.0 percent higher.

The results of the City of Burbank study on this phase of its program are given in Table 2. All costs of generating electricity include the cost of delivering coal to the hybrid plant at the geothermal resource site, and the cost of delivering the power to the Victorville substation in Southern California.

Figure 2. Siting Guidelines Used in City of Burbank Study

Figure 3. Fossil-Fired State-of-the-Art Power Cycle.

Figure 4. The Feedwater Preheat Geothermal/Coal Fired Hybrid Power Cycle.

Table 2. FIGURE-OF-MERIT VALUES FOR COST-OPTIMIZED 750-MW HYBRID PLANTS

SITE	GEO THERMAL TEMP, °F	COST OF POWER MILLS/kWh	F	F _g	F _f	ψ
Roosevelt	524	20.5	1.07	1.72	1.08	10.9
Monroe-Joseph	350	21.0	2.04	2.12	2.04	30.0
ALL-COAL REFERENCE: ^a	--	22.7	1.0	--	1.0	--
Beoware	420	24.3	1.07	2.27	1.08	18.3
Coso	500	25.4	1.06	1.69	1.07	11.7
Brawley	500	25.8	1.09	2.03	1.10	12.1
Niland	644	26.4	1.04	1.52	1.05	12.1
Brady-Hazen	417	26.4	1.08	2.38	1.08	19.2
East Mesa	392	28.4	1.03	1.73	1.03	22.7
Long Valley	350	30.6	1.03	1.91	1.03	31.6
Surprise Valley	375	30.6	1.03	1.86	1.03	26.8

^aUtah site.

It was found that a hybrid geothermal/coal fired power plant was always more economical than a coal-fired plant alone, when coal costs were equal. In Table 2, the cost of power at the eight sites listed below the "all-coal reference" coal-fired power plant was higher in all cases because delivered coal costs were higher.

The study also pointed out some other interesting facts. It defined some "Figure-of-Merit" values and calculated them for each case. For the plant at Roosevelt, a value of $F = 1.07$ means that a fixed thermal and coal input will produce 7 percent more power in a hybrid plant than when used in separate plants. A value of $F_g = 1.72$ means that the same hybrid plant would obtain 72 percent more useful work from the geothermal resource than would an all-geothermal plant using the same resource. Conversely, a value of $F_f = 1.08$ means that the same hybrid plant would obtain 8 percent more useful work from the given coal input than would an all-coal plant. A value of $\psi = 10.9$ means that a hybrid plant would produce 10.9 times more power than an all-geothermal plant using the same resource.

System Design Verification by Ralph M. Parsons Company

A well-known power plant contracting company, The Ralph M. Parsons Company of Los Angeles, made for the City of Burbank a detailed design and economic study to verify the results obtained in the earlier work on a hybrid geothermal/coal power plant (3). This work comprised a conceptual design, cost estimate, and economic analysis of a one-unit 715 MW hybrid geothermal/coal fired power plant. In addition to the use of geothermal fluid for feedwater heating, this work also investigated its use for additional power generation, condensate and cooling tower makeup water, coal beneficiation, air preheating, flue gas preheating and plant space heating requirements.

The results of the Ralph M. Parson study were within 10 percent of the earlier City of Burbank study, and also provided some additional insight into hybride geothermal/coal fired power plants. Some of these points are summarized herein, for use in looking at the geothermal/coal situation for future power plants in Arizona. The most pertinent results of interest to Arizona involve (a) backing out the use of coal by using geothermal energy and (b) replacing potable groundwater by geothermal brines in the cooling towers and condensate makeup water in the power plant. These two results can be analyzed from the Ralph M. Parsons Company cases shown in Table 3.

TABLE 3. ESTIMATED AVERAGE ANNUAL COST FOR ELECTRICAL POWER (1976 Dollars)

Cost Item	Case 1 ^a		Case 2 ^b		Case 3 ^c	
	750 MW Net*		715 MW Net*		715 MW Net*	
	M\$/yr	Mills/kWH	M\$/yr	Mills/KWH	M\$/yr	Mills/KWH
Coal	43.725	7.824	35.139	6.615	33.887	6.380
Operations (O/M)	11.880	2.126	13.207	2.486	13.703	2.580
Geothermal (O/M)	--	--	1.786	0.329	1.786	0.329
Transmission	15.594	2.936	15.594	2.936	15.594	2.936
Depreciation	27.752	4.966	30.956	5.828	31.207	5.875
Cooling Water	1.166	0.209	1.298	0.244	--	--
Other	2.100	1.280	1.347	0.254	1.347	0.254
Total Estimated Cost of Power at Victorville	107.17	19.341	99.327	18.692	97.524	18.354

*Factoring of costs is not linear with respect to plant electrical generating capacity.

^aCase 1 -- All Coal Fired Plant (Estimated by City of Burbank).

^bCase 2 -- Hybrid Geothermal/Coal Fired Plant with geothermal feedwater heating only (Estimate by Ralph M. Parsons Company).

^cCase 3 -- Hybrid Geothermal/Coal Fired Plant with feedwater heating, air preheating, flue gas reheating and plant space heating by geothermal energy (Estimate by Ralph M. Parsons Company).

The key results of an economic analysis (summarized above) were based on an 85% plant capacity factor, 5% per annum inflation rate, 5% per annum operating and maintenance (O/M) escalation rate, 8% per annum coal cost escalation rate and bond interest for capitalization at 6% annually. For Case 2, the total capital cost, estimated at \$385,841,000 in 1976 dollars for the plant within the battery limits was converted to dollars per year equivalent annual cost in 1976 dollars, taking into account interest during construction, inflation, 30 year economic life, and the cost of money. The other two cases were treated in the same manner.

Important conclusions that are of interest to Arizona are as follows:

1. Hybrid geothermal/coal power plants can be economically attractive, producing power at lower costs than an all-coal power plant.

2. The coal must be transported to the geothermal resource site, in order to have favorable economics.
3. Critical savings in the use of conventional groundwater for cooling towers and boiler feedwater makeup can be achieved by using the geothermal brines. This goes beyond the economic savings, because it helps alleviate environmental concerns about power plant siting in the Western United States (including Arizona) where water sources are scarce.
4. Additional reductions in power costs (over those shown in the City of Burbank study) might be achieved for situations where an all-coal plant cannot be sited near a coal source due to environmental, institutional constraints, or other economical factors.
5. The hybrid plant utilizes the geothermal energy much more efficiently than present concepts for all geothermal plants with respect to extraction of available work from the geothermal fluid. The overall efficiency of an all-geothermal plant is normally about 40 to 50 percent. The overall geothermal efficiency of the hybrid plant described in the City of Burbank study was estimated at 80 percent. These efficiency estimates are based on actual work derived from the geothermal fluid as compared to its available work.

For Case 2 above, annual fuel consumption for the hybrid plant is 1,933,000 tons of coal. Coal consumption for an all coal fired plant of the same generating capacity as the hybrid plant, with the same heat rate calculated for the all-coal plant, is estimated at 2,195,000 tons per year. Therefore, an estimated net coal savings of 252,000 tons per year or 13 percent would be realized with the hybrid plant.

In Case 2 above, cooling tower makeup water and condensate makeup water requirements for the hybrid geothermal/coal fired power plant were provided from surface and ground water sources near Roosevelt Hot Springs, Utah. It was estimated in the City of Burbank Report that the cost of cooling water for a 750 MW hybrid plant was approximately 0.23 mills per kilowatt hour, or about \$1,300,000 per year.

The advantages of using spent geothermal fluids for makeup water are significant since the quantity of raw water to be purchased in an area where ground and surface water are scarce and costly, is considerably reduced. Likewise, spent geothermal fluid that is not used for makeup water must be reinjected into the ground at additional cost.

Average continuous makeup water requirements at full load for the hybrid plant were estimated at 50,000 pounds per hour for condensate makeup and 4,500,000 to 5,200,000 pounds per hour for cooling tower makeup. The total geothermal fluid flow for the hybrid plant, at full load is 4,600,000 pounds per hour. Approximately all the geothermal fluid leaving the feedwater and condensate heating system can be treated and used for condensate and cooling tower makeup water.

For Case 3 above, where geothermal brines are used for makeup, the estimated cost for providing geothermal makeup water to the hybrid plant is \$2,720,000. This cost is more than compensated by savings in the cost of fresh raw water makeup that would be required in a conventional plant. Consequently the total electrical energy cost for the hybrid plant with geothermal makeup water systems is lower than for the base case hybrid plant. Therefore, it was concluded that the hybrid geothermal/coal fired power plant should include the geothermal makeup water systems.

The City of Burbank study also discussed the possibility of using geothermal energy for coal beneficiation. The desirability and economic feasibility of coal beneficiation is highly dependent on the coal characteristics, the site location, and applicable emission standards to be met. Furthermore, in a hybrid geothermal/coal fired power plant, the geothermal fluids will have a bearing on the feasibility of coal beneficiation along with the fact that the power plant is located remote from the coal source. As a result, no reliable assessment of the cost and benefits from coal beneficiation can be made on the basis of generic studies or generalized analysis as it relates to a specific situation. In general, the reduction of ash through beneficiation of only the high ash coal, or coal containing above 9 percent ash would appear desirable.

It was pointed out that for Utah coals, the most feasible beneficiation system is the wet physical separation process, which is a gravity separation system, consisting of wet jigging, wet screening, multi-stage wet cycloning and centrifugation to effect an ash reduction to a content in the range of 6 to 7 percent. A small portion of exposed pyrites sulfur, approximately 25 percent, would also be simultaneously removed. This particular system of coal beneficiation represents a lower capital and operating cost. It is preferred because the Utah coals are generally of high quality having low ash and low sulfur content such that only a relatively small amount need be processed.

The cost of coal beneficiation for Roosevelt Hot Springs, Utah, was estimated at \$1.43 per ton of beneficiated coal in Base Year (1976) costs and \$1.14 per ton in average annual costs in 1976 dollars. This includes capital, operating, and maintenance costs. This cost is in addition to the cost of coal delivered to the site. Assuming an 85 percent capacity factor for the coal beneficiating system and the availability of corresponding amounts of

coal which would require beneficiation to maintain the system at process capacity, this would amount to an additional first year coal cost of \$1,350,000 and \$1,060,000 expressed in Base Year (1976) and average annual costs, respectively. However, none of these economics were included in the three cases shown in Table 3.

Finally, the use of geothermal energy in the hybrid geothermal/coal fired power plant may be utilized to good advantage for combustion air preheating, flue gas reheating, and for plant space heating. For Case 3 above, the estimated additional capital of \$300,000 for providing these other systems is more than compensated by savings in the cost of coal that would be consumed in a conventional plant for these services. Consequently, the total energy cost for the hybrid plant with these other systems is lower than for the base case hybrid plant. Therefore, it is concluded that the hybrid geothermal/coal fired power plant should include the geothermal combustion air preheating, flue gas preheating and plant space heating systems.

Examining the cost of electricity for a hybrid power plant for the City of Burbank project, it is seen that the costs are distributed as follows:

	<u>Percentage of Total Cost, %</u>
Depreciation	10
Plant Operations	10
Geothermal Well Cost	1
Geothermal Well Operations	1
Coal Feedstock	56
Cooling water	1
Electricity Transmission (300 mi)	<u>11</u>
TOTAL	100

As seen above, the cost of coal accounts for more than half of the price of the delivered electricity. The base cost of coal (1976) at the mine mouth is \$16.50/tonne (\$15/ton), while the price of coal delivered at the power plant site as shown in Table 1 could be as much as doubled.

Most of the cost difference results from coal transportation cost. Therefore, the distance of the geothermal source from the coal mine, reflecting the cost of coal transportation, can play a decisive role in determining the economical success of a hybrid power plant.

It should be noted that as yet, a hybrid plant has not been operated, so on-line experience is lacking. This analysis and related work, however, suggest that an actual hybrid plant would indeed use the nation's fossil and geothermal resources at a greater efficiency and at an attractive cost. In summary, advantages of hybrid plant are listed below:

- . Economically attractive,
- . Can be less capital-intensive,
- . Uses two of the U.S.'s abundant energy resources--coal and geothermal energy,
- . Uses coal and geothermal resources more efficiently,
- . Employs existing technology,
- . Plant cycle can adapt to changes in the resource,
- . Plant continues to produce large amounts of power even if geothermal input falls to zero.

THE POTENTIAL OF HYBRID GEOTHERMAL/COAL POWER PLANTS IN ARIZONA

Based upon the results of the City of Burbank and Ralph M. Parsons Company studies, there are several potential sites for similarly-designed plants in Arizona. Coal-fired power plants in Arizona are located at five

sites, with two additional sites planned, as shown in Figure 5. In addition, there is a coal/water slurry pipeline taking coal from the Black Mesa area of Arizona to the Nevada border near Davis Dam, to supply the Mohave power plant in extreme southeast Nevada, as shown in Figure 6a and 6b. Four of these sites overlap inferred geothermal resources, as shown later on. In addition, this study suggests seven additional geothermal resource areas, where hybrid geothermal/coal fired power plants might be located. It was beyond the scope of this study to make detailed economic evaluations of hybrid plants at these locations because (a) the detailed data needed for such studies are not available and (b) the objectives of geothermal utilization evaluation in Arizona did not include such details. However, this study provides further information on the suggested eleven sites in Arizona for possible future hybrid geothermal/coal fired power plants.

Arizona Coal-Fired Power Plants

Arizona Public Service is the largest public utility in the State of Arizona. Its electrical power plants are listed in Table 4. The large coal-fired plants are: four Cholla units (St. Joseph, Arizona, near Holbrook) and three Navajo units (near Page). In addition, it has five Four Corners units (across the border in New Mexico), where coal already being mined could be shipped to Arizona geothermal resource areas.

Tucson Electric Power Company and the Salt River Project are the other two largest power companies in Arizona. A summary of all electrical power plants, the consumption of fossil fuels (oil and coal), and the consumption of coal alone, now and in the near future, are given in Tables 5, 6 and 7. It was difficult to obtain the data for these tables, as some of the agencies and utilities contacted were unable, or unwilling to provide certain information, especially in regard to resource use. The best estimate of electrical power

Figure 5. Location of Coal-Fired Power Plants in Arizona

Figure 6a. Schematic of Route for Black Mesa Coal Slurry Line in Arizona

Figure 6b. Profile of Elevations Encountered in Route for Black Mesa Coal Slurry Line in Arizona

TABLE 4

ARIZONA PUBLIC SERVICE COMPANY'S ELECTRICAL GENERATING SYSTEM

LOCATION ON MAP	UNIT NAME	TYPE	YEAR IN SERVICE	FUEL	OWNERSHIP	NET ACCREDITED GENERATION	APS SHARE	CAPACITY AVAILABLE TO APS SYSTEM
1	YUCCA: UNIT 1	STEAM	1959	OIL/GAS	APS-SCE-IID	75 MW	33-1/3%	25 MW
1	YUMA: CT 1	C. TURBINE	1971	OIL/GAS	APS	22	100	22
	CT 2	C. TURBINE	1971	OIL/GAS	APS	22	100	22
	CT 3	C. TURBINE	1973	OIL/GAS	APS	57	100	57
	CT 4	C. TURBINE	1974	OIL	APS	56.2	100	56.2
2	DOUGLAS: CT 1	C. TURBINE	1972	OIL	APS	20.7	100	20.7
3	SAGUARO: UNIT 1	STEAM	1954	OIL/GAS	APS	115	100	115
	UNIT 2	STEAM	1955	OIL/GAS	APS	99	100	99
	CT 1	C. TURBINE	1972	OIL/GAS	APS	54.5	100	54.5
	CT 2	C. TURBINE	1973	OIL/GAS	APS	54.5	100	54.5
4	OCOTILLO: UNIT 1	STEAM	1960	OIL/GAS	APS	114.9	100	114.9
	UNIT 2	STEAM	1960	OIL/GAS	APS	114.5	100	114.5
	CT 1	C. TURBINE	1972	OIL/GAS	APS	55.9	100	55.9
	CT 2	C. TURBINE	1973	OIL/GAS	APS	55.9	100	55.9
5	WEST PHOENIX: UNIT 4	STEAM	1948	OIL/GAS	APS	33.3	100	33.3
	UNIT 5	STEAM	1949	OIL/GAS	APS	12.0	100	12.0
	UNIT 6	STEAM	1950	OIL/GAS	APS	63.0	100	63.0
	CT 1	C. TURBINE	1972	OIL/GAS	APS	56.2	100	56.2
	CT 2	C. TURBINE	1973	OIL/GAS	APS	56.2	100	56.2
	WPCC 1	C. CYCLE	1976	OIL	APS	75	100	75
	WPCC 2	C. CYCLE	1976	OIL	APS	75	100	75
	WPCC 3	C. CYCLE	1976	OIL	APS	75	100	75
6	CHILDS: UNIT 1	HYDRO	1909	WATER	APS	1.2	100	1.2
	UNIT 2	HYDRO	1909	WATER	APS	1.2	100	1.2
	UNIT 3	HYDRO	1909	WATER	APS	1.2	100	1.2
7	IRVING: UNIT 1	HYDRO	1916	WATER	APS	1.3	100	1.3
8	TAPCO: UNIT 1	STEAM	1917	OIL	APS	—	—	(NOT OPERATING)
	UNIT 2	STEAM	1917	OIL	APS	—	—	(NOT OPERATING)
9	CHOLLA: UNIT 1	STEAM	1962	COAL	APS	116	100	116
	UNIT 2	STEAM	1978	COAL	APS	235	100	235
10	FOUR CORNERS: UNIT 1	STEAM	1963	COAL	APS	175	100	175
	UNIT 2	STEAM	1963	COAL	APS	177	100	177
	UNIT 3	STEAM	1964	COAL	APS	220	100	220
	UNIT 4	STEAM	1969	COAL	APS-SRP-PSNM	800	15	120
	UNIT 5	STEAM	1970	COAL	SCE-TEP-EPE	800	15	120
11	NAVAJO: UNIT 1	STEAM	1974	COAL	APS-SRP-NPC	750	14	105
	UNIT 2	STEAM	1975	COAL	USBR-TEP	750	14	105
	UNIT 3	STEAM	1976	COAL	LADW&P	750	14	105
UNITS PLANNED AND/OR UNDER CONSTRUCTION								
Due On Line				Planned Capacity				
9	CHOLLA: UNIT 3	STEAM	1980	COAL	APS	250	100	250
	UNIT 4	STEAM	1981	COAL	APS	350	100	350
	UNIT 5	STEAM	**	COAL	APS	350	100	350
12	PALO VERDE: UNIT 1	NUCLEAR	1983	URANIUM	APS-SRP-EPE	1270	29.1	370
	UNIT 2	NUCLEAR	1984	URANIUM	SCE-PSNM	1270	29.1	370
	UNIT 3	NUCLEAR	1986	URANIUM	APS-SCE	1270	29.1	370
	UNIT 4	NUCLEAR	1988	URANIUM	APS-SCE	1270	39.1	497
	UNIT 5	NUCLEAR	1990	URANIUM	LADW&P-SDG&E-EPE-NPC-Anaheim-Burbank-Glendale-Pasadena-Riverside	1270	39.1	497

** Indefinitely Delayed

TABLE 5. FOSSIL FUEL RESOURCES USED BY POWER PLANTS PROVIDING ELECTRICITY TO ARIZONA

Power Plant and Number of Units	Percent of Generation Available to Arizona	Quantities of Fuels Used for Generation of Electricity for Arizona in 1978		
		Coal (1000 tons)	Oil (1000 bbls)	Gas (1000 MCF)
Navajo - 3	43.2	2,591.1		
Cholla - 2	100.0	984.7	8.9	42.8
Agua Fria - 6	100.0		1,098.1	9,452.2
Ocotillo - 4	100.0		251.7	6,337.8
West Phoenix - 8	100.0		14.0	475.9
Four Corners - 3	100.0	2,361.1	251.7	639.5
Four Corners - 2	32.0	1,189.7	155.1	
Kyrene - 2	100.0		54.1	1,081.7
Saguaro - 4	100.0		402.0	5,315.5
Yuma Axis - 4	100.0		70.7	667.4
Yucca - 1	33.3		26.4	968.5
San Juan - 2	50.0	1,041.1	43.2	
Mohave - 2	10.0	268.4		
Hayden - 1	80.0	1,242.4		
Santan - 4	100.0		461.2	
Irvington - 1	100.0		1,135.3	13,675.0
Demoss-Petrie - 1	100.0		121.0	5,070.0
North Loop	100.0			1,836.3
Peaking Turbines				4,732.2
Apache	100.0	330.6	4.4	
Douglas	100.0		5,429.0	
Total		10,009.1	9,526.8	50,294.8

Sources: Utility reports and personal conversations; Energy Data Reports, Monthly Reports, Cost and Quality of Fuels for Electric Utility Plants, Department of Energy, Energy Information Administration, Office of Energy Data, DOE IEIA-0075/8(78), data for January - December 1978.

TABLE 6. ESTIMATED ANNUAL COAL CONSUMPTION OF FUTURE POWER PLANTS

Power Plant	Percent of Generation Available to Arizona	Date Commercial	Annual Quantity of Coal to be Used for Generation of Electricity for Arizona (1000 tons) ¹
Apache #2	100.0	August, 1979	619.6
Coronado #1	70.0	August, 1979	673.9
Coronado #2	70.0	Late 1980	973.9
Coronado #3	70.0	Indefinite	973.9
Cholla #3	100.0	1980	879.1
Cholla #4	100.0	1981	1,231.3
Cholla #5	100.0	Indefinite	1,231.3
Springerville #1	100.0	June, 1985	1,209.8
Springerville #2	100.0	June, 1987	1,209.8
Springerville #3	100.0	About 1991	1,209.8
Craig #1	29.0	Sept. 1979	1,209.8
Craig #2	29.0	1980	444.9
San Juan #3	50.0	1980	943.7
San Juan #4	60.0	1995	1,133.2
Total			13,479.1

(1) Based on equation in Power Generation in Arizona and its Environmental Implications, Stephen Edgerly Smith, University of Arizona:

$$\text{Fuel Rate (tons/day)} = \frac{\text{MW(th)} \times 3412 \frac{\text{BTU}}{\text{HR-KW}} \times 10^3 \times 24 \frac{\text{HR}}{\text{DAY}}}{\text{Coal heat value} \frac{\text{BTU}}{\text{lb}} \times 2000 \frac{\text{lb}}{\text{ton}}} \times .85 \text{ plant factor}$$

Coal heat values not listed in this source were estimated to be 10,500 $\frac{\text{BTU}}{\text{LB}}$

TABLE 7 - FUTURE AVAILABILITY OF ELECTRICITY PRODUCTION

POWER PLANT	NO. OF UNITS	LOCATION (NEAREST TOWN)	DATE COMMERCIAL	OWNERSHIP BY PERCENTAGE	TYPE OF GENERATION	TOTAL NET CAPACITY (Mw)	NEW CAPACITY AVAILABLE TO AZ UTILITIES ¹
<u>Additions</u>							
Apache	1	Willcox, AZ	Aug, 1979	AEPC 100%	Coal	175	175
Coronado	1	St. Johns, AZ	Aug, 1979	SRP 70%, Other 30%	Coal	350	245
	1	St. Johns, AZ	Late, 1980	SRP 70%, Other 30%	Coal	350	245
	1	St. Johns, AZ	Indefinite	SRP 70%, Other 30%	Coal	350	245
Cholla	1	Joseph City, AZ	1980	APS 100%	Coal	250	250
	1	Joseph City, AZ	1981	APS 100%	Coal	350	350
	1	Joseph City, AZ	Indefinite	APS 100%	Coal	350	350
Springerville	1	Springerville, AZ	June, 1985	TEPC 100%	Coal	350	350
	1	Springerville, AZ	June, 1987	TEPC 100%	Coal	350	350
	1	Springerville, AZ	About 1991	TEPC 100%	Coal	350	350
Craig	1	Craig, Colo.	Sept, 1979	SRP 29%, Other 71%	Coal	400	116
	1	Craig, Colo.	1980	SRP 29%, Other 71%	Coal	400	116
San Juan	1	San Juan, N.M.	1980	TEPC 50%, Other 50%	Coal	468	234
	1	San Juan, N.M.	1995	TEPC 60%, Other 40%	Coal	468	281
Palo Verde	1	Buckeye, AZ	1982	APS 29.1%, SRP 29.1% Other 41.8%	Nuclear	1,270	739
	1	Buckeye, AZ	1984	APS 29.1%, SRP 29.1% Other 41.8%	Nuclear	1,270	739
	1	Buckeye, AZ	1986	APS 29.1%, SRP 29.1% Other 41.8%	Nuclear	1,270	739
TOTAL ADDITIONAL CAPACITY						7,771	5,874
PLANNED DECREASES		BEGINNING DATE	ENDING DATE	EXPLANATION		NET CAP. INVOLVED (Mw)	
To Colo - UTE Power Co from SRP		January, 1982	None	Recapture of 30% of Hayden #2		78.3	
<u>Total Decreases</u>						78.3	
OVERALL INCREASE						7,771	5,795.7

being used in Arizona can be summarized in Table 8 below.

Table 8. ESTIMATED POWER AVAILABLE TO ARIZONA TO YEAR 2000

Megawatt capacity from hydroelectric plants:	955.8 (11.7%)
Megawatt capacity from coal plants:	3630.6 (44.3%)
<u>Megawatt capacity from gas/oil plants:</u>	<u>3600.8 (44.0%)</u>
Total megawatt capacity available:	8187.2 (100.0%)

The estimated annual resource use for Arizona's portion of this production capacity can be broken down as follows:

Coal:	1.0×10^7 tons
Oil:	9.5×10^6 bbls
Natural Gas:	50.3×10^6 MCF

The additional capacity planned for the future can be divided as follows:

Additional megawatt capacity from coal plants:	3657.0 (62.2%)
<u>Additional megawatt capacity from nuclear</u>	<u>2217 (37.8%)</u>
Total additional megawatt capacity available	5874 (100.0%)

The megawatt capacity to be available in the year 2000, as shown by the current sources plus the future additional production capacity available can be listed as follows:

Megawatt capacity from hydroelectric plants:	955.8 (6.8%)
Megawatt capacity from coal plants:	7287.6 (52.0%)
Megawatt capacity from gas/oil plants:	3600.8 (25.7%)
<u>Megawatt capacity from nuclear plants:</u>	<u>2217 (15.5%)</u>
Total megawatt capacity available in 2000:	14,011.2 (100.0%)

The electrical power transmission system of the State of Arizona is shown as regional sections of the State in Figures 7-12. It should be noted that

transmission lines are provided for power exchange with nearby states and facilities, including coal-fired power plants in New Mexico and hydroelectric power from Hoover Dam.

OVERLAPPING GEOTHERMAL RESOURCES/COAL-FIRED POWER PLANT SITES IN ARIZONA

As stated earlier, coal-fired power plants in Arizona are located at five sites, with two additional sites planned (see Figure 5). In addition, this study suggests seven additional geothermal resource areas, where hybrid geothermal/coal fired power plants might be located. These eleven sites are summarized in Table 9 and discussed in further detail in this section.

Table 9. POTENTIAL SITES FOR GEOTHERMAL/COAL FIRED POWER PLANTS IN ARIZONA

Site No.	Location	Existing Coal Fired Plant
1	St. Johns	Coronado, Salt River Project
2	Springerville	Tucson Electric Power Company
3	Tucson	Tucson Electric Power Company ^a
4	Willcox	Arizona Electric Power Company
5	Pinta	None ^b
6	North Flagstaff	None
7	Southeast Kingman	None ^c
8	Northeast of Wenden-Salome	None ^d
9	West of Goodyear	None ^e
10	Eloy	None
11	Clifton	None

^a In progress of converting gas-fired plant to coal-fired plant.

^b Close to existing coal-fired plants at Joseph City and St. Johns.

^c Close to coal-slurry pipeline to Mohave coal-fired plant.

^d Close to Central Arizona Project canal for Colorado River water.

^e Close to metropolitan Phoenix and nuclear power plant region of State.

Figure 7. Major Electric Transmission Lines in Arizona

Figure 8. Detailed Electric Transmission Lines in Metropolitan Phoenix Area

Figure 9. Detailed Electric Transmission Lines in Metropolitan Tucson Area

Figure 10. Detailed Electric Transmission Lines in Northeast Arizona

Figure 11. Detailed Electric Transmission Lines in East-Central Arizona

Figure 12. Detailed Electric Transmission Lines in Northwest Arizona

Primary Sites

It is obvious from previous studies that the cost of coal and its transportation costs to the power plant site are usually the dominant economic factors. These factors are balanced to some extent by the third most important economic factor, namely, the cost of electric power transmission to use areas. In Arizona there is a fourth important factor, i.e., the source of cooling water. Consequently, most coal-fired power plants sites in Arizona were influenced by the cooling water situation, as shown below:

1. Navajo Units at Page -- Coal is transported from the Black Mesa in Northeast Arizona by a railroad, built especially for this purpose. At Page, large supplies of cooling water are available from the Colorado River.
2. Mohave Units Across Nevada Border -- Peabody Coal Co. constructed a coal/water slurry line to move Black Mesa coal across Northern Arizona to the Nevada border. Again, the use of Colorado River water for cooling was a key factor.
3. Cholla, Coronado and Springerville Sites -- All of these areas have adequate water supplies for cooling, due to (a) water runoff from the White Mountain area and (b) the waters in the valleys serving the Little Colorado River.

The only exceptions in Arizona of bringing coal to a water source are the Willcox and Tucson coal-fired plants, both of which are located near their markets. It should be noted that the Tucson plant is still burning natural gas, but is converting to the less expensive coal.

Two potential primary sites in Arizona for future hybrid geothermal/coal fired power plants are (a) near the existing coal fired power plant units at St. Johns (Coronado units) and (b) near the coal fired power plant units

currently under construction at Springerville.

Potential Hybrid Geothermal/Coal Fired Power Plant at St. Johns

Two Coronado units of 350 MW each are being operated at St. Johns, Arizona, owned 70% by Salt River Project and 30% by others. A third unit is planned for the future, but the date is indefinite. Thus, there may be time to consider the merits of backing out part of its coal requirements by means of geothermal energy. This is suggested as a primary site, because if the power plant site is currently considered attractive, then there may be a sufficient geothermal resource to make it even more attractive.

There is a large potential for geothermal energy in the St. Johns area, as shown on Figures 13-14. The temperature gradients of existing wells, high Na-K-Ca geothermometers and high anomalous SiO_2 geothermometers indicate a possible geothermal anomaly (see Glossary of Geological Terms). Further data by the geologists upon these points for the area are shown in Figures 15-16 (4). More information on the inferred geothermal resources are given in the ADP for the northern counties of Arizona, but unfortunately very little is truly known about the St. Johns area (5). There is adequate cooling water in the area, but still it might be desirable to use geothermal brines for cooling. Some coal would be replaced, and since coal must be transported considerable distance, this would help the economics.

Potential Hybrid Geothermal/Coal Fired Power Plant at Springerville

Tucson Electric Power Company has under construction and will own the first of three 350 MW coal-fired power plants at Springerville, Arizona. The first unit is scheduled for completion in 1985, the second in 1987 and the third in about 1991. It may be possible to modify the design for the 1991 unit in time to utilize geothermal energy in the proposed mode of a hybrid geothermal/coal fired power plant. The geothermal resource data given in

Figures 13-16 for St. Johns is also applicable to Springerville. In addition, further geological work is in progress in the area, and the results of that work should be evaluated when they become available. The same comments on using geothermal brines for cooling and helping the economics by backing out coal, as made for St. Johns, applies also to nearby Springerville.

Secondary Sites

There are two other sites in Arizona where geothermal resources appear to exist at locations of existing coal-fired power plants. These are at Willcox, Arizona and Tucson, Arizona.

Potential Hybrid Geothermal/Coal Fired Power Plant at Willcox

The Apache unit of 175 MW is operated by the Arizona Electric Power Company (AEPC) in the Willcox area. In fact, it is located on the edge of the Willcox Playa, also designated at Willcox Dry Lake (see Figure 17). In the Willcox area, six pumped wells and one artesian well discharge 35°C (86°F) to 54°C (130°F) water, at well depths ranging from 200 m (656 ft) to 450 m (1476 ft) (6). Additional geothermal resource information is given in the ADP of Cochise/Santa Cruz Counties (6).

Since coal must be hauled a considerable distance, by several railroad lines, the proposed hybrid plant would help the economics. As in above cases, the geothermal brine could replace potable water for the power plant cooling.

Potential Hybrid Geothermal/Coal Fired Power Plant at Tucson

The Tucson Electric Power Company currently operates its large Irvington unit on natural gas, but has obtained approval to retrofit the plant to a coal-fired unit. This will take some time to achieve. It may or may not be too late to consider a hybrid geothermal/coal-fired system during this transition, thus backing out a certain amount of coal that must be shipped to Tucson. It could also replace some of the critical potable water of the

Figure 13. Locations of Potential Geothermal Resource Areas in Northern Arizona

Figure 14. Geothermal Resources in the St. Johns, Springerville and Pinta Areas

Figure 15. Anomalous Geothermal Gradients in St. Johns and Springerville Areas

Figure 16. Anomalous Geothermometers and Zone of High Total Dissolved Solids in St. Johns and Springerville Areas

Figure 17. Geothermal Resources in Willcox Dry Lake Region

Tucson basin by geothermal brines for cooling. The cost of producing electric power in Tucson from a hybrid plant should be lower than that for a conventional coal-fired plant. Geothermal resources are believed to exist in the Tucson area as shown in Figure 18, and are adequately described in other reports (7, 8).

Potential Sites

In order to consider other potential sites in Arizona for hybrid geothermal/coal-fired power plants, one should give consideration to the relative costs of transporting coal versus electrical power transmission. Water transport is always the most inexpensive way to move coal. Since no waterway in Arizona can be used for coal transportation, other modes of transport are used. Truck transport becomes competitive with rail or pipeline for low tonnage and short distances (e.g. - less than 50 miles and 1 million tons per year). Railroads and slurry pipelines are usually the alternatives for high tonnage, long distance transport of coal. Railroads often have competitive tariffs when no new trackage has to be constructed. Otherwise, pipelines are more economical. Railroads have also an advantage, whenever there are several delivery points for the coal. It is also important to notice that the price of railroad transportation increases more rapidly than pipelines during inflationary periods.

Transmission of electricity by Extra High Voltage (EHV) accounts usually for about 10% of the price of electricity. The cost of EHV transmission results mainly from the losses of power and the initial investment for the power line.

The losses from transmission for a 250 MW power plant will be 1-2.5% from the total electricity generated for every 100 kilometers of transmission, while for a 750 MW power plant it will be about 1 - 1.7 % loss.

Figure 18: Locations of Potential Geothermal Resources in Pima County

Therefore, new coal-fired power plants in Arizona could be located closer to Phoenix, or even Tucson, for a hybrid geothermal/coal unit, because one could base the location more on the above economics without concern for a source of cooling water -- the geothermal brines would serve that purpose. Secondly, since the cost of transporting coal is cheaper than electricity power transmission, this would also lower electricity generating costs. In summary, these plant sites could lower electricity costs, and reduce cooling water requirements. These comments apply to the seven new sites suggested for consideration below, as follows:

1. Pinta, Arizona -- Located on the AT & Santa Fe railroad, northeast of Holbrook, it would supplement coal-fired plants now existing at St. Johns (south) and at Joseph City (Holbrook). Access to Black Mesa coal could be by railroad or a reasonably short slurry pipeline. The geothermal resources shown for St. Johns on Figures 13-16, also extend to this area.
2. North Flagstaff -- This area may have a geothermal resource, as it is close to the San Francisco Peaks, where the most recent volcanic action in Arizona (some 900 years ago) occurred (see Figure 13). However, there are some questions about having sufficient water and geothermal brine available. There may be mainly hot rocks in the area.
3. Southeast Kingman -- There is a potential geothermal resource area to the southwest of Kingman (see Figure 13). This source is also close to the coal slurry line serving the coal-fired plant near this area, just across the Nevada border (see Figure 6a). Thus, a parallel coal slurry pipeline could be constructed, and the geothermal brines used for cooling water; one would not be concerned

with using the Colorado River for cooling water. Further details on the geothermal resource are in the ADP for the northern Arizona counties (5).

4. Northeast of Wenden-Salome -- This location is close to the open aqueduct bringing Colorado River water to Phoenix and Tucson (see Figure 19). It is also over a potential geothermal resource, as shown on Figure 20. If the dissolved solids content of the water is low, the geothermal brines might be used for cooling water, and later could be blended with Colorado River water in the aqueduct. In general, Arizona appears to have geothermal resources at intermediate or lower temperatures than neighboring states. However, this may be a blessing as, at lower temperatures, the geothermal waters appear to have lower dissolved solids. Thus, they may replace valuable potable water being pumped from the ground.

5. West of Goodyear, Arizona -- This location, west of Goodyear, Arizona, and in the extreme southwest of metropolitan Phoenix, would help serve the large electric demand of Phoenix. A location could be selected that would not pollute Phoenix and would not disturb the geological structures under the nuclear power plant site of that area, say, staying ten miles away from the nuclear plant location. The hybrid plant could use the geothermal brines for cooling, whereas it has been necessary to construct a special water line from Phoenix to the nuclear plant (some 50 miles) to provide it with treated sewage waste water for cooling purposes. The geothermal resource of this area is shown on Figure 21, and detailed in the ADP for Maricopa County (9).

Figure 19. Canal Route of Central Arizona Project for Colorado River Water

Figure 20. Locations of Potential Geothermal Resource Areas in Yuma County.

Figure 21: Locations of Potential Geothermal Resource Areas in Maricopa County

6. Eloy, Arizona -- This location is in the corridor between Phoenix and Tucson, and sufficiently distant from Casa Grande to prevent pollution of this community. The power generated at such a location could be added to the electrical network serving Phoenix and Tucson as well as the growing communities in its vicinity. The geothermal resource is shown in Figure 22, and in the special report on using geothermal energy in irrigation pumping (8).
7. Clifton, Arizona -- This location is near a large copper production operation. It has the State's best geothermal resources, as shown in Figure 23 (10). If sufficient need for additional electrical power develop in the future, an interesting cascade or integrated geothermal system might be designed. First, there is excess water available as runoff in the mountains north of this area, all the way to Springerville. A coal slurry line might transport both coal and this water further south where it is in more demand, analogous to some extent how Northern California water is needed in the more arid Southern California. Secondly, the geothermal resource could be used for its energy in the hybrid geothermal/coal fired power plant, and then in cascade fashion be used for copper dump leaching. The latter would extract the last amount of available energy (all above ambient temperature is beneficial) and simultaneously back out more valuable potable water. Of course, a portion of the geothermal waters should be used for the flotation operations of the copper concentrating plant.

In summary, these seven potential sites for new hybrid geothermal/coal-fired power plants all have unique site characteristics. Obviously, more detailed studies are required; these become so complicated that they are

- AREAS FAVORABLE FOR DISCOVERY OF GEOTHERMAL RESOURCES
- *
 AMAX GEOTHERMAL TEST WELL

0 16
miles

Figure 22. Locations of Potential Geothermal Resource Areas in Pinal County

Figure 23. Locations of Potential Geothermal Resource Areas in Graham and Greenlee Counties

beyond the scope of this project. Such studies should be done by the industries and utilities that might benefit from possible hybrid plants at one or more of these locations.

CONCLUSIONS

1. Arizona has abundant coal resources, and is currently operating coal-fired power plants at four locations that overlap geothermal resources, namely, St. Johns, Springerville, Tucson and Willcox.
2. The city of Burbank study on hybrid geothermal/coal-fired power plants, funded by the DOE, showed several advantages:
 - a. The estimated cost of producing electricity in a hybrid plant is about 18.3 mills/KWH, compared to 19.3 mills/KWH in an all-coal fired power plant.
 - b. The coal requirements for a plant can be reduced about 16-17 percent, depending on the temperature of the geothermal resource.
 - c. The geothermal brines can be used for power plant cooling water, and in some cases, as boiler feedwater.
3. Critical savings in the use of conventional groundwater for cooling towers and boiler feedwater makeup is especially important to Arizona -- it basically replaces the more valuable potable groundwater, which is being depleted in Arizona.
4. Additional reductions in power costs (over those shown in the City of Burbank study) might be achieved for situations where an all-coal plant cannot be sited near a coal source due to environmental, institutional constraints, or other economical factors.
5. The hybrid plant utilizes the geothermal energy much more efficiently than present concepts for all geothermal plants with respect to extraction of available work from the geothermal fluid.

The overall efficiency of an all-geothermal plant is normally about 40 to 50 percent. The overall geothermal efficiency of the hybrid plant described in the City of Burbank study was estimated at 80 percent. These efficiency estimates are based on actual work derived from the geothermal fluid as compared to its available work.

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10. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan - Graham/Greenlee Counties, prepared for the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 79-10.

ADDITIONAL RELATED REPORTS

The following fifteen reports were prepared by the Evaluation of geothermal Utilization group:

1. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Maricopa County, prepared for the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 79-8.
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2. Frank, Helmut J., ed., 1982, Arizona's Energy Future: Making the Transition to a New Mix, Tucson: University of Arizona Press.
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Open-File reports can be obtained by writing to:

State of Arizona Bureau of Geology
845 N. Park Avenue
Tucson, Arizona 85719

or to

Arizona Solar Energy Commission
1700 W. Washington, Room 502
Phoenix, AZ 85007

In addition, reports prepared for the U.S. Department of Energy can be obtained by contract number from

U.S. Department of Energy
Technical Information Center
P.O. Box 62
Oak Ridge, TN 37830

GLOSSARY OF GEOLOGICAL TERMS

Anomalously shallow depth - unusually or unexpectedly shallow depth.

Basin-range graben bound by deep faults - an area usually ten to hundreds of km² in area that has been down dropped along deep faults relative to the surrounding mountains; the grabens become filled with sediments to become valleys.

Curie-depth - the depth at which rocks become hot enough to lose their magnetic properties, ~ 525°C. Curie temperature within 5-10 km of the surface are an indicator of geothermal resource potential.

Deep circulation - the natural movement or flow of ground water, as a result of convection, whereby it descends and becomes heated at depth and then rises toward the surface.

Deep sediment-filled, faulted basin - see basin - range graben.

Depth of Curie-isotherm analysis - technique used to estimate depth to the Curie temperature.

Hot dry rock production - a method for extracting useful heat in a deep dry hole; accomplished by fracturing the hot rock between two deep holes, and pumping cold fluid into one and bringing hot fluid out of the other.

Geothermometer - an empirical formula, based on the temperature-dependent solubility of certain minerals, used for estimating deep fluid temperatures in a geothermal reservoir.

Magnetotelluric survey - an electromagnetic method in which natural electric and magnetic fields are measured. Models of the crust can then be constructed and resistivities at great depth can be predicted.

Major range bounding faults - fractures or fracture zones along which mountains have risen relative to down dropped grabens.

Shallow magmatic intrusion - a body of magma that has intruded its way upward into shallower crust.

Na-K-Ca geothermometer -- (also, quartz geothermometer, chalcedony geothermometer) - see geothermometer.

Tectonic history - the cycle that relates the larger structural features of the Earth's crust to gross crustal movements and to the kinds of rocks that form in the various stages of developments of these features.