EVALUATION OF GEOTHERMAL
COOLING SYSTEMS FOR ARIZONA

D.H.WHITE - PRINCIPAL INVESTIGATOR
L.A.GOLDSTONE - PROJECT MANAGER

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DEPARTMENT OF CHEMICAL ENGINEERING
THE UNIVERSITY OF ARIZONA
Tucson, Arizona 85721

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State Contractor:
Arizona Solar Energy Commission
James F. Warnock, Jr., Director
Frank Mancini, Ph.D., Associate Director
1700 West Washington
Phoenix, Arizona 85007

Prepared by
Don H. White, Principal Investigator
Larry A. Goldstone, Project Manager
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ABSTRACT

Arizona consumes nearly 50 percent more electricity during the peak summer season of May through part of October, due to the high cooling load met by electrical-driven air conditioning units. These cooling loads are concentrated in the metropolitan areas of Phoenix and Tucson. This study evaluates two geothermal-driven cooling systems that consume less electricity, namely, absorption cooling and heat pumps.

Adsorption cooling requires a geothermal resource above 105°C (220°F) in order to operate at a reasonable efficiency and capacity. Geothermal resources at these temperatures or above are believed existing in the Phoenix and Tucson areas, but at such depths that geothermal-driven absorption systems have high capital investments. Such capital investments are uneconomical when paid out over only five months of operation each year, but become economical when cascaded with other geothermal uses. There may be other regions of the state, where geothermal resources exist at 105°C (220°F) or higher at much less depth, such as the Casa Grande/Coolidge or Hyder areas, which might be attractive locations for future plants of the high-technology industries.

Geothermal assisted heat pumps have been shown in this study to be economical for nearly all areas of Arizona. They are more economical and reliable than air-to-air heat pumps. Such systems in Arizona depend upon a low-temperature geothermal resource in the narrow range of $15.5 - 26.6^{\circ}\text{C}$ ($60 - 80^{\circ}\text{F}$), and are widely available in Arizona. The state has over 3,000 known (existing) thermal wells, out of a total of about 30,000 irrigation wells.

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INTRODUCTION

One of the major electrical power problems in Arizona is the heavy demand over 5 to 6 months of the summer, due to the demand for electrical-driven mechanical air conditioners for cooling. This peak seasonal demand is costly, because power generating capacity must be provided, or electricity transmitted over longer distances from outside the State of Arizona.

Thus, there is an incentive to utilize a non-electrical energy for cooling in Arizona. Geothermal energy could provide such a source by using either absorption cooling or heat pumps. This study evaluates these systems for geographical areas in Arizona that have high demand for cooling and also appear to have geothermal resources.

NEED FOR NON-ELECTRICAL COOLING IN ARIZONA

The high demand for electrical power is concentrated in the two major metropolitan areas of Arizona, Phoenix and Tucson, where both people and industrial plants needing cooling are located. The peak seasonal demand is usually over the period of May 1 through mid-October, as shown in Figure 1. Manufacturing is the chief contributor to the economy of metropolitan Phoenix, especially high technology of electronics, computers and basic solid state industries. Manufacturing provided 91,000 jobs in the county of Maricopa (mostly the Phoenix area) in 1979 or about 17 percent of the labor force. The projection of energy consumption in Maricopa County is shown below in Table 1.

Figure 1: Seasonal Peak Electric Loads in Arizona

Table 1. MARICOPA COUNTY ENERGY-USE PROJECTIONS ⁽¹⁾ (Trillion Btu)

User Class	1978 ⁽²⁾	1985 ⁽³⁾	2000 ⁽³⁾	2020 ⁽³⁾
Residential	34.48	31.46	27.61	30.21
Commerical	40.48	44.66	61.60	124.52
Industiral	59.33	62.89	78.69	119.37
Total	134.29	139.01	167.90	274.10

- (1) Excludes transportation and conversion and transmission losses from the generation of electricity.
- (2) 1978 figures for each sector were developed from Arizona Energy Use, 1978 done by the Division of Economic and Business Research, University of Arizona.
- (3) Projections were developed by making use of growth rates for each user class, from work done by the New Mexico Energy Institute.

Further energy details are given in Geothermal Development Plan: Maricopa County (1).

Metropolitan Tucson is the State's second largest population center, about 40 percent the size of metropolitan Phoenix. It has equally high temperatures during the period of late April through early October. Manufacturing, especially military missiles, electronics and computer auxiliaries provided 17,000 jobs in 1979, less than 20 percent of the manufacturing base of Phoenix. Consequently, energy consumption is about 25 percent of that in metropolitan Phoenix but still several-fold larger than any

other area in the State. Energy projections for Pima County, concentrated in metropolitan Tucson, are given in Table 2.

Table 2. PIMA COUNTY ENERGY-USE PROJECTIONS ⁽¹⁾ (Trillion Btu)

User Class	1978 ⁽²⁾	1985 ⁽³⁾	2000	2020
Residential	12.54	11.44	10.04	10.98
Commercial	14.72	16.24	22.40	45.28
Industrial	7.55	8.00	10.00	15.17
Total	34.81	35.86	42.44	71.23

(1) Excludes transportation, conversion and line losses.

(2) Developed from Arizona Energy Use 1978, by the Division of Economic and Business Research, University of Arizona.

(3) Projections derived from growth rates from state projections performed by New Mexico Energy Institute.

Further details can be found in the Geothermal Development Plan: Pima County (2).

The utilization of geothermal energy for cooling might generate a future high demand in the Casa Grande Coolidge and/or Hyder areas, where the necessary geothermal resources are believed to exist. These areas also have the necessary interstate highways and other features to possibly attract industry over the next 20 to 30 years. Safford and San Bernardino areas may

have the necessary geothermal resources, but are too remote to attract a large number of manufacturers of sufficient size to impact upon the high cooling demand of the State of Arizona. Therefore, this study has limited its scope to the two major cooling demand areas of Phoenix and Tucson, and the two potential cooling demand areas of Casa Grande/Coolidge and Hyder.

GEO THERMAL RESOURCES

Metropolitan Phoenix

Geothermal resources in Maricopa County are shown in Figure 2. In 1973 Geothermal Kinetics Systems, Inc. drilled No. 1 Power Ranches to 2,806 m (9,207 ft) and No. 2 Power Ranches to 3,186 m (10,054 ft), which showed 117.8°C (244°F) at 2,768 m (9,080 ft) in No. 1 and 120°C (248°F) at 2,783 m (9,130 ft) in No. 2 (3). However, very little liquid flow was obtained. There was conjecture that the drilling muds used had blocked the flows.

On the Western Phoenix area, near Luke Air Force Base, pumped wells 300-600 m (985-1,970 ft) deep discharge 35-56°C (95-133°F) water at rates exceeding 3,000 l/m (792 gpm). Also, eight pumped wells at Mesa produce water at 37°C to 54°C (99° to 129°F) from depths of only 90 to 300 m (295 to 985 ft) (3).

It is also known that a vast reservoir of water up to depths of about 4,000 m (13,123 ft) lies under metropolitan Phoenix. It is believed that temperatures in the range of 120°C (248°F) would be found if more extensive drilling were done in the area. More details are given in the Geothermal Development Plan for Maricopa County (1).

Metropolitan Tucson

Geothermal resources in Pima County are shown in Figure 3. The industrial areas are growing along the railroad and Interstate Highway I-10 to the northeast and to the southwest. In the latter area, Exxon drilled an oil

Figure 2. Locations of Potential Geothermal Resource Areas in Maricopa County

Figure 3: Locations of Potential Geothermal Resources in Pima County

and gas test well to 3,827 m (12,555 ft), showing a 146.7°C (296°F) bottom-hole temperature (3). However, this was taken during geophysical logging only 20 hours after drilling stopped, and before temperature equilibrium was established.

In the Tucson area more than 20 wells ranging in depth from 60 to 400 m (197 to 1,312 ft) discharge 30°C to 35°C (86 to 95°F) water. Tucson Electric Power Company drilled a 760 m (2,493 ft) deep well, which produced 52°C (126°F) water containing 485 mg/l total dissolved solids (3). Further details on geothermal resource are given in the Geothermal Development Plan for Pima County, but unfortunately no deep drilling has been done except for the Exxon well (2).

Casa Grande/Coolidge Area

The geothermal resources of the Casa Grande/Coolidge area is shown on the map for Pinal County, shown in Figure 4. At least 20 hot irrigation wells have been drilled in the valley fill of the Coolidge area to depths between 126-915 m (413 - 3,000 ft) giving water temperatures between 32°C (90°F) and 72°C (162°F) (3). Geothermal Kinetics - Amax Exploration No. 1 Pima Farms geothermal test well was drilled in 1974 to 2,446 m (8,024 ft). Bottom hole temperature was 102°C (216°F). Geochemical thermometers indicate reservoir temperatures of 105°C (221°F) to 111°C (232°F) (see Glossary of Geological Terms).

More details on the geothermal resources of this area are given in the Geothermal Development Plan for Pinal County (4). It would appear that if further deep drilling were done, additional geothermal resources of about 110°C (230°F) temperature would be found.

Hyder Area

The location of the geothermal resources in the Hyder area are shown in

AREAS FAVORABLE FOR DISCOVERY OF GEOTHERMAL RESOURCES

AMAX GEOTHERMAL TEST WELL

0 16
miles

Figure 4. Locations of Potential Geothermal Resource Areas in Pinal County

Figure 5. More than 20 pumped wells 20-500 m (66-1,640 ft) deep produce water at 30°C (86°F) to 45°C (113°F) at rates exceeding 4,000 l/min (1057 gpm), and are used for irrigation (3). Projections of thermal gradients indicate that 200°C (392°F) temperatures may be encountered at depths as shallow as 2,000 m (6560 ft), assuming a continuation of the most favorable thermal gradients (5). Further details are given in the Geothermal Development plan for Yuma County and in the report on utilizing geothermal energy for irrigation pumping (5,6).

Limitations of Geothermal-Driven Absorption Cooling in Arizona

There is a potential of utilizing geothermal-driven cooling systems in Arizona. This would help alleviate the seasonal peak demand for electrical power currently existing in the Phoenix and Tucson areas. It might help industry develop in the future in the Casa Grande/Coolidge and Hyder areas, which would also help alleviate the population congestion in metropolitan Phoenix and Tucson. However, there are two serious limitations to the near-future use of such systems, as follows:

1. Geothermal-driven absorption cooling systems need a temperature of about 120°C (250°F) to utilize its capital investment efficiently. Even so, as will be shown later on, its capital investment is several-fold that of electrical-driven mechanical refrigeration units. Thus, capital costs per unit of cooling are high.
2. Peak cooling systems in the Phoenix and Tucson areas need operate only five months at full capacity, two months at partial capacity, and then stand idle for five months. Alternative uses for the geothermal energy over 5-7 months must be found to minimize capital costs; uses which can be integrated in a practical and economic manner with the geothermal-driven absorption cooling system.

Figure 5. Locations of Potential Geothermal Resource Areas in Yuma County

The Lithium Bromide-Water ($\text{LiBr-H}_2\text{O}$) Absorption Cycle is the most common system used in absorption cooling (7-13). A fluid, usually water or brine, is sent through a tube bundle into the evaporator (see Figure 6). The pressure in the shell of the evaporator is under vacuum, so that water sprayed over the tube bundle will evaporate at a low temperature. Heat is thus removed from the fluid in the tube bundle and used as the 'heat of vaporization' for water vaporizing in the shell. Next to the evaporator is the absorber, holding a solution of LiBr and water. LiBr has an affinity for water vapor. Thus, as the water vapor forms in the evaporator, it is drawn into the absorber giving off heat of solution. Condensing water is supplied to remove this heat. As more H_2O collects in the absorber, the $\text{LiBr-H}_2\text{O}$ solution weakens; to maintain its ability to absorb, the solution must be held at a certain concentration. This is accomplished by pumping the weak solution to the generator section.

In the generator a hot fluid is fed through a tube bundle, where it exchanges heat with the weak solution. Water from the solution is vaporized, thus increasing the concentration to the desired level. The strong solution is then fed back to the absorber. The water vapor flows into the condenser section where it is cooled and condensed to liquid. It is then returned to the evaporator where the cycle continues.

Ideally, geothermal resources of 134°C (273°F) would be found in several locations in metropolitan Phoenix and Tucson, which would allow the absorption cooling system to operate most economically. A cooling system of 2,700 tons refrigeration (32,400,000 Btu/hr) was evaluated in considerable detail.

FIGURE 6: ABSORPTION COOLING CYCLE

Geothermal Powered Air-Conditioning System

Geothermal Wells Assumptions

A preliminary schematic of this proposed system is shown in Figure 6.

Temperature of geothermal fluid	134°C
Flow rate per well	240,000 kg/hr
Salinity	2,000 ppm
Depth per well	3,000 m
Distance from well to site	1 km
Distance between wells	300 m
Depth per reinjection well	2500 m
Distance of reinjection well from site	1 km
Distance between reinjection wells	200 m

LiBr Absorption Chiller

Given conditions:

Cooling load	9495 KW
Entering chilled water temp.	18.33°C
Leaving chilled water temp.	7.22°C
Entering condensing water temp.	29.44°C
Entering hot water temp.	115.5°C
Leaving hot water temp.	107.8°C
Hot water flow rate	960,000 Kg/hr
Pressure drop limits in all tubes (pressure head)	9.14 m

Summary of Pumping Power (General System)

<u>Pump</u>	<u>Total Hp</u>
Downhole geothermal, 4 @ 200 Hp	800
Geothermal brine circulation, 2 @ 300 Hp	600
Hot water pump, 1 @ 300 Hp	300
Chilled water pump, 1 @ 125 Hp	125
Condensing water pump, 1 @ 350 Hp	<u>350</u>
TOTAL	2,175

In order to have more accurate data for economic evaluation, recommendations and price quotations were requested and received from three leading manufacturers of large absorption cooling systems, namely, Carrier, Trane and York. A summary of several recommended systems are shown below in Table 3 in terms of 1979 dollars.

Table 3. COMPARISON OF ABSORPTION COOLING SYSTEMS

	Company A	Company B		Company C	
		System A	System B	System A	System B
Price (Total	\$344,000	\$380,000	\$375,000	\$365,000	\$425,000
Efficiency, %	72.66	66.18	65.71	70.46	70.24
No. of Machines	5	2	3	2	3
Capacity of each Machine (tons)	540	1350	900	1350	900
Total capacity, tons	2,700	2,700	2,700	2,700	2,700
Capital Cost, \$/ton	127.4	140.7	138.9	135.2	157.4

The system proposed by Company A was selected for further economic evaluation.

System Equipment Costs

In the following section the cost of the designed system is given.

Geothermal Powered - LiBr Absorption System

Geothermal Wells, 4 @ 1,000 gpm 3000 m deep	\$3,000,000
Downhole pumps	150,000
Brine circulation pump	30,000
Piping	175,000
Heat exchangers	200,000
Hot water pump	17,500
LiBr absorption equipment	345,000
Chilled water pump	7,000
Condensing water pump	20,000
Cooling towers	<u>125,000</u>
TOTAL CAPITAL COST	\$4,069,500

Boiler Fired - LiBr Absorption System

Boilers	\$135,000
Hot water pump	17,500
LiBr Absorption equipment	345,000
Chilled water pump	7,000
Condensing water pump	20,000
Cooling tower	<u>125,000</u>
TOTAL	\$649,500

The above cooling system, 2700 ton of refrigeration, when equipped with storage for cooling water could provide a peak cooling load of 4500 tons of refrigeration. Thus, the major portion of the chilled water is produced at

night during off-peak cooling load time and off-peak electricity rate time. During July, for example, the chiller can store chilled water during the night and also operate during the day, resulting in a constant unit operation. During the other months, the unit could operate only part of the day.

The initial capital investment in the geothermal subsystem for cooling processes is extremely high, totaling an estimated \$4,069,500 for a 2700 ton refrigeration system. A boiler-fired absorption unit of the same size would be only \$649,500 capital investment. On the other hand, the operating costs are very small compared to a conventional unit.

Such a system will definitely become economical if a cascade utilization of geothermal energy is employed. The spent geothermal water has a high enough temperature to be used in various industrial and domestic processes requiring temperature around 100°C (212°F). Otherwise the payout period becomes too long based on current economic factors.

Heat pumps Using Low-Temperature Geothermal Resources

As can be seen, geothermal-driven absorption cooling systems may eventually be used in the Phoenix/Tucson areas, but will depend largely upon (a) the cost of electrical power continuing to rise and/or (b) the geothermal resource being used more fully throughout the year by integration with other uses. A second system that might utilize geothermal resources (in this case at much lower temperature) involves heat pumps.

A heat pump is a system that transfers heat by means of a compression - expansion cycle of a refrigerant fluid. When heating is required, the system takes low temperature heat from a heat source and gives it up to the conditioned space at a higher temperature than the heat source. When cooling and dehumidification is desired, the thermal cycle is reversed and becomes identical to a refrigeration process. The system removes heat from the

indoors and discharges it to a heat sink, which could be at a higher temperature than the conditioned space.

The operating principle of the heat pump is identical to the thermodynamic cycle governing the conversion between heat energy and mechanical work. The second law of thermodynamics states that the maximum efficiency of a cycle operating between a heat source and a heat sink with T_2 and T_1 consecutively is:

$$\text{Efficiency} = \frac{T_2 - T_1}{T_2}$$

and the Coefficient of Performance (COP) is:

$$\text{COP} = \frac{T_2}{T_2 - T_1}$$

In actual systems the heating COP is defined:

$$(\text{COP})_h = \frac{q_h}{q_t} = \frac{\text{Total useful heat output}}{\text{Heat equivalent of total energy input to operate the system}}$$

Similarly the COP for cooling is:

$$(\text{COP})_c = \frac{q_c}{q_t} = \frac{\text{Useful refrigeration produced}}{\text{Heat equivalent of total energy input to operate the system}}$$

Two types of heat pumps are in general use 1) air to air, which is the most common one, as the outside air is the most convenient heat source or heat sink, and 2) water to air which is usually used for systems larger than domestic units. The water supply may be a closed loop system, such as a cooling tower or it might be a lake, a stream, or a well.

The purpose of this report is to show that the use of geothermal well water as the heat source and heat sink is theoretically acceptable and economically more beneficial than conventional systems.

Heating

The heat pump system consists of several components as follows:

1. compressor
2. condenser
3. expansion valve
4. evaporator

When working in the heating mode the system works as shown in Figure 7. The motor-driven compressor pressurizes the refrigerant vapor isentropically to high pressure and temperature. At this point the vapor temperature is higher than the indoor temperature. The vapor enters the indoor coil, which functions as a condenser. The refrigerant releases heat to the indoor air while it liquifies. The high pressure is relieved when the liquid refrigerant passes through the expansion valve and its temperature also drops to a temperature lower than the heat sink. As a result of this, the liquid refrigerant partially vaporizes. In this state the refrigerant enters the outdoors evaporator, where it absorbs energy from the well water until it vaporizes completely. The vapor enter the compressor and another cycle begins through the loop.

Cooling

From a refrigeration standpoint, a heat pump is similar to a conventional refrigeration system. The system operates in the same manner as for heating, but the evaporator absorbs heat from the conditioned space, thus cooling it while the condenser discharges the heat to the heat sink - the well water. The cooling mode of a heat pump is shown in Figure 8. The changeover between

Figure 7. Schematic of a Heat Pump System Operating in the Heating Mode

Figure 8. Schematic of a Heat Pump System Operating in the Cooling Mode.

heating and cooling is accomplished by a four-way valve which switches between the indoor and outdoor heat exchangers. The indoor heat exchanger becomes the evaporator and the outdoor one becomes the condenser.

Principle of Operation of a Geothermal-Driven Heat Pump

The principle of operation of a vapor-compression refrigeration cycle can be illustrated conveniently with the aid of a Pressure Enthalpy Diagram as shown in Figure 9. Step I is a throttling process in which hot liquid refrigerant at the condensing pressure, P_c , passes through the expansion valve, where its pressure is reduced to the evaporator pressure, P_e . In this step some vapor is produced and the state of the mixture of liquid refrigerant and vapor entering the evaporator is shown by point A. Since the expansion process is isenthalpic (constant enthalpy) the following relation holds

$$\text{Enthalpy of mixture entering evaporation} = \text{enthalpy of vapor at } P_e \cdot f + \text{enthalpy of liquid at } P_e \cdot (1-f)$$

In this expression, f is the percentage mass of liquid vaporized. In equation form

$$h_{ve} f + h_{le} (1-f) = h_a$$

l = liquid

v = vapor

In a real process the throttling process is not completely isenthalpic and some of the refrigeration effect in evaporator is lost.

Step II represents the vaporization of the remaining liquid. In this step heat is absorbed from the surrounding, thus producing a cooling effect at the evaporator. The specific refrigeration effect is

Figure 9. Principles of a Refrigeration Cycle on a Pressure - Enthalpy Diagram.

$$q_r = h_{vc} - h_a$$

If the desired rate of refrigeration requires a heat transfer rate of q_{refrig} , the rate of mass flow of refrigerant necessary is

$$\dot{m}_r = \frac{q_{\text{refrig}}}{h_{vc} - h_a}$$

At the entrance to the compressor (point C) all the refrigerant is in the vapor phase. Usually point C is chosen to be slightly in the superheated vapor region to protect the compressor from working against liquid.

Step III represents the compression of refrigerant from pressure, P_e , to P_c . The step requires work input from an external source and if the heated vapor leaving the compressor is at the condition represented by point B, the compression work is:

$$w_c = \dot{m}_r (h_{vd} - h_{ve})$$

In an idealized cycle analysis the compression step is usually assumed to be an isentropic process and is actually close to one. Nevertheless, heat losses from the compressor, overcoming the friction work and other mechanical losses require an excess of energy over the idealized calculated work.

Step IV represents the condensation of the refrigerant. Actually sensible heat is first removed in the substep IVa as the vapor is cooled at constant pressure from T_d (point B) to T_c (point D) and latent heat is removed at the condensation temperature T_c , corresponding to the saturation pressure P_c in the condenser until all the refrigerant is liquified (point E). The heat transfer rate from the condenser is:

$$q_c = \dot{m}_r (h_{vd} - h_{1a})$$

The heating cycle is similar to that of cooling, except that the condenser is functioning as the heater of the conditioned space and the evaporator uses the well water as the heat source.

An actual heat pump is less efficient than the idealized cycle assumed. It is known that an actual heat pump would be approximately 50 % as efficient as a Carnot cycle heat pump. The difference between the ideal Carnot cycle and the real system accounts for the unideality of the cycle, power used for fans and safety devices and for different losses throughout the cycle.

Experimental results show that COP for an air to air heat pump is less dependent on the heat sink temperature than in theoretical calculations and it usually varies between 2-5. This means that for each unit of mechanical energy invested in the process, about 2-5 energy units of cooling are obtained.

Most commercial heat pump units can operate with geothermal sources in the range of 7°C (45°F) to 35°C (95°F). The optimum temperature of geothermal sources depends on the ratio between the heating load and the cooling load. If the annual heating load is larger than the annual cooling load, such as in Northern Arizona, an optimum temperature of the geothermal water will be in the upper range. In areas where the annual cooling/heating demand is 60%/40% of the energy required for domestic comfort, such as in Tucson and Phoenix, a lower temperature water source would be more advantageous. Usually, the optimum temperature range of the geothermal source is 13°C (55°F) to 27°C (80°F).

The conventional air-to-air heat pump, working in the cooling mode, absorbs heat from the conditioned space being cooled at 21°C (70°F) to 26°C

(80°F) and transfers it to outside air at temperatures of 26°C (80°F) to 43°C (110°F). By using the water source as a heat sink at a lower temperature than the ambient air, the coefficient of performance (COP) of the unit will improve; thus requiring a smaller heat pump unit and using less energy. The efficiency of the heat pump in the cooling mode increases as the temperature of the water decreases.

In the heating mode, the process is reversed. For a conventional air-to-air system, the conditioned space is heated by energy absorbed from ambient air at low temperature. By using a heat source at 15°C (60°F) to 26°C (80°F), the same advantages as in the cooling mode are evident; higher efficiency and a smaller heat pump unit. The temperature of the water source utilized as a heat source and as a heat sink with the same heat pump unit should be close to the comfort temperature range of 21°C (70°F) to 26°C (80°F).

An additional advantage of a water source heat pump is the ability of the unit to operate at critical ambient conditions without problems. Air-to-air heat pump units are not widely used in areas where the ambient temperature is close to the freezing point. The condensate on the outside heat exchanger can freeze and lower the efficiency of the unit. The problem is usually solved by reversing the cycle for a short time or by a small electrical heating element. Both alternatives are very costly when cold ambient conditions prevail for a long time. Usually when ambient temperature are below the freezing point for long periods, an alternative heating system is required.

At the other extreme of very high ambient temperatures, most air conditioning units overload and become unoperative until the unit cools down. As this problem occurs in the most extreme conditions when cooling is most needed, then for reliability a back-up unit must be installed. Water source heat pump performance is not influenced greatly by ambient temperature

conditions as its heat source and heat sink are at constant temperatures.

Most off-the-shelf air-to-air heat pumps are designed with a primary performance emphasis on the cooling mode for extreme conditions. When the temperature of the geothermal source is known, proper sizing of the heat pump components can improve the unit COP and allow a larger temperature drop of the source fluid. This reduces fluid consumption per unit of energy output.

Summarizing, the advantages of the water source heat pump, it becomes obvious that in addition to lower operating cost, the reliability of the system is improved at extreme conditions. Other advantages of the geothermal heat pump are:

1. A smaller unit is required, because the water source heat pump is less sensitive to extreme ambient conditions.
2. Stand-by unit is not necessary.
3. A back-up heating system is not required, even when ambient air temperatures are below the freezing point.
4. Proper sizing of the pump components can double its COP.

Potential of Geothermal Heat Pumps in Arizona

When attempting to estimate the economic feasibility of using a geothermal source, many problems arise. The results of the analysis depend on such variables as the depth of water, the distance between the well and the user site, the cost of drilling the well, the water temperature, the consumers purpose, and intensity of using the geothermal source. Each geothermal energy project must be analyzed for its own merits and disadvantages. Therefore, instead of investigating one project in depth we chose to review several projects in order to establish general guidelines for the economical utilization of geothermal water sources.

In September 1978, "The Water Well Journal" reported the results of its

own demonstration of a water source heat pump project (14). The 60,000 Btu/hr unit installed in a private house near Columbus, Ohio, supplies all heating, cooling and domestic hot water requirements. The COP of the unit is 3.2 - 3.4, and the total energy cost for a 4-month period was \$235 (when only heating was required). An air-to-air heat pump operating cost would have been double. The savings of the water source heat pump, are \$184 compared to natural gas, \$289 compared with fuel oil, and \$606 compared with electricity. The analysis compares only the operating cost and is therefore incomplete.

A second project estimated the replacement of heating and cooling equipment for a 99-bed skilled nursing facility (15). The proposed system consisted of self-contained individual room air-conditioners using heat pump plus circulated water from a near-by geothermal source at 29°C (85°F). The typical heating load was determined to be 7000 Btu/hr and the cooling demand 7.3 MBH at design conditions. The cost per room for the conventional unit was determined to be about \$800 less than the geothermal system; whereas the latter could reduce the annual electrical consumption by 25 percent. Although the potential of saving energy in the long run was good and the heat pump system proved to be economical, the investors chose the conventional system with the lower initial investment and lower risk.

The peak heating and cooling loads for the McKale Center at the University of Arizona were estimated based on a design summer temperature of 40.5°C (105°F) and a design winter temperature of -1.0°C (30°F). For these design temperature a cooling load rate 20,916 MBH and a heating load rate of 13,544 MBH were determined. Heat pumps are usually rated in terms of tonnages; one ton of refrigeration is defined as 12,000 Btu/hr and is roughly the same rate of energy transfer as heat required to freeze one ton of ice in

a day. Heating and cooling load rates expressed in tons are as follows:

$$(20,916 \text{ MBH}) \left(\frac{1000 \text{ Btu/hr}}{1 \text{ MBH}} \right) \left(\frac{1 \text{ ton of cooling}}{12,000 \text{ Btu/hr}} \right) = 1743 \text{ tons of cooling}$$

$$(13,544 \text{ MBH}) \left(\frac{1000 \text{ Btu/hr}}{\text{MBH}} \right) \left(\frac{1 \text{ ton of heating}}{12,000 \text{ Btu/hr}} \right) = 1129 \text{ tons of heating}$$

According to Wehlage (16) experience has indicated that units which operate at a level below the design load usually give the best performance in actual service. Operation at five percent below the design load is generally assumed. Therefore:

$$\text{Cooling Load} = 1743 - (0.05)(1743) = 1656 \text{ tons}$$

$$\text{Heating Load} = 1129 - 0.05(1129) = 1073$$

There is evidence (17) for the existence of an underground slightly-warm geothermal water source in the proximity of McKale Center, more precisely around the intersection of Campbell and 2nd Street, about 400 feet from the building. The average water temperature is estimated to be about 86°F (30°C).

Preliminary economical calculations show that the most economical air conditioning system for a high peak load not frequently used is a system employing a storage system, with several small size heat pumps and one medium size unit. The alternative is to have a large back-up system for cooling and heating to meet the peak loads.

Even when the load are continuous, as in the case of a shopping mall, or an industrial park, the night time is used to recharge the storage while the overall size of the air conditioning system could be reduced.

The optimum temperature of the water source depends on the ratio between the annual heating load and the annual cooling load. The optimum temperature of the water source for McKale Center was found to be 25°C (77°F) which is very close to the well temperature.

Employing a cold water storage, which accumulates cold water during off-peak hours, could reduce significantly the size of the cooling unit. Thus the required flow rate of the geothermal well could be reduced to about 800 gpm. The incremental cost of the water source is low -- approximately \$100,000 because of the shallow depth of the well. The effluent water could be used for landscape irrigation and does not need to be reinjected into the ground. The incremental capital investment would have a payout in an estimated 6-8 years.

Taking into account the advantages of the geothermal heat pump, it becomes evident that this system could compete economically with the conventional electrical system. In hotels, industrial, commercial and office buildings and even high standard residential areas, where reliability of the conditioning system is important to the point of requiring a back-up unit for extreme conditions, the geothermal system might become economical. In these cases, the lower difference in the initial investment between the geothermal unit and a conventional system, plus the savings from the operational cost in the long run and the very low risk of finding a geothermal source at optimal temperature, make the geothermal heat pump advantageous and economical compared to conventional systems.

Other economical analysis of various projects show that geothermal water at temperatures between 37°C (100°F) to 104°C (220°F) cannot be used economically for cooling processes. The technology is available; a heat pump could boost the geothermal water temperature and an absorption chiller could

provide cooling. This system could be used only for a specific projects where the geothermal water could be further utilized. At water source temperatures higher than 104°C (220°F), the adsorption cooling unit performs at a sufficiently high efficiency to become economical.

An apartment complex to be constructed in Oregon, including 75 unit - 900 square feet each, an enclosed activity wing of about 11,000 square feet and an outdoor swimming pool, was the candidate of economic feasibility study for using geothermal energy as a heat source (18). The project compared several options:

1. Conventional electrical system
2. Geothermal water of 65°C (150°F) at 2500 foot depth.
3. Geothermal water of 26°C (80°F) air-to-air heat pump.
4. Geothermal water of 26°C (80°F) water-to-air heat pump.

The conventional electric system required the lowest capital cost of \$110,000, but had the highest operating cost (\$111,876) for the first year. The lowest operating cost was achieved by System No. 2 above, \$11,585 for the first year. The operating cost of System No. 3 was \$95,000 and about \$65,000 for the fourth system. The research concluded that while the savings of the second system are dramatic, the lower temperature geothermal source is also economical, if the higher temperature geothermal water of 65°C (150°F) cannot be used.

A study performed by W.R. Acorn Engineering Associates of Tucson, Arizona for the Geo-Heat Center of the Oregon Institute of Technology examined the potential savings available through utilization of geothermal hot water (19). The project consisted of a 200-unit hotel and a 300-unit apartment complex, to be served by a common geothermal system. The geothermal well (1850 ft deep) located nearby could supply 52°C (125°F) water at more than the

required flow rate. The study investigated the economic feasibility of utilizing geothermal source water for space heating and cooling, domestic water and swimming pool heating and by-product utilization for landscape irrigation. The incremental cost of the geothermal system beyond a conventional system was estimated at \$433,000.

As the quality of the geothermal water in the Tucson area is fairly good, direct utilization by fan coils for space heating was proposed. The swimming pool was to be heated by a heat exchanger. The study assumed 80% of the domestic hot water requirements could be satisfied by the geothermal system utilizing a "plate and frame" heat exchanger. A portion of the cooled geothermal water was directed to an aesthetic pond where it was further cooled by means of an artesian fountain. The water was then used for landscape irrigation. The remaining portion of geothermal water was reinjected into the ground.

The utilization of geothermal water was found to be economical except for space cooling. As the geothermal water exceeds the temperature for heat pump utilization, other technologies were examined. A two-stage evaporative cooling system was investigated and proved to be not technically feasible. A heat pump was considered as a means for providing high temperature water to operate an absorption water chiller. The study concluded that the operating cost of the system for the early 1980's was higher than for a conventional system; therefore, the proposed geothermal process was abandoned.

Assuming that a geothermal source at 121°C (250°F) could be found in a deeper well, direct utilization of the geothermal water in an absorption chiller becomes feasible and economical. Savings of \$23,000/year could be achieved compared to conventional electrical systems even at today's cost for electricity. The study concluded that this alternative should be further

considered, only if evidence of 121°C (250°F) geothermal source is found.

A similar economical analysis conducted for the city of Boise, Idaho, compares a conventional compression expansion cycle with an absorption unit. The calculated cooling load was 325 tons refrigeration (20). The efficiency of the adsorption system is highly dependent on the inlet water temperature:

at 88°C (190°F), the efficiency is 43%

at 82°C (180°F), the efficiency is 36%

at 76°C (170°F), the efficiency is 25%

For an inlet temperature of 76°C (170°F) the nominal unit size chosen was 1300 tons refrigeration (TR), with a capital cost of about \$130,000. Approximate price of the installed absorption unit is about \$250,000.

A conventional electrical refrigeration unit of 350 TR would cost about \$70,000. The operating cost of the electrical refrigeration unit is about 18 times the operating cost for an absorption unit.

The economical analysis concluded that the system could become economical even at 93°C (200°F) geothermal water, depending upon the cost of the geothermal well.

Discussion of Geothermal-Driven Heat Pump Systems

Today's technology enables us to capture the geothermal energy and put it to useful utilization. High temperature geothermal sources can be used for residential and industrial purposes that require heating below the temperature of the geothermal sources. Cooling can also be provided economically by means of absorption system when the geothermal temperature exceeds 95°C (200°F). Nevertheless high temperature geothermal sources are limited, the risk involved in drilling, together with the large incremental cost over

conventional systems prevents the expansion of geothermal energy development for absorption cooling.

Heat pump technology is not a new discovery. Air to air heat pumps are widely used for cooling and heating, but the cogeneration of a heat pump with a low temperature geothermal source is fairly new. A ground water source at temperature of 15°C (60°F) to 26°C (80°F) can be used as a heat source and as a heat sink with the same heat pump.

This cogeneration will increase the efficiency of the heat pump, will require a lower capacity unit and will increase the reliability of the system. These advantages will result in operating cost savings which could pay for the incremental investment. Both residential units and larger projects prove to be economical at today's energy prices, which assures that in the future the water source heat pump will become more popular. Generally, this type of project will require an initial investment 4 to 6 times higher than a conventional system. However, the operating cost will be reduced by 25% to 50%. Today, in most cases, despite the economical advantage in the long run, the conventional system will be used because of the novelty of the water source heat pump. Therefore, it is necessary to explain and advertise the potential of the water source heat pump.

CONCLUSIONS

The climatic conditions in the State of Arizona cause a heavy demand for cooling during five summer months. Most of the cooling is required for space conditioning in manufacturing and commercial buildings, followed by the domestic requirement. Evaporation cooling is used at many places in Arizona, but is not comfortable as it results in high relative humidities.

Two geothermal-assisted cooling systems, with proven technologies, can be utilized in Arizona. Adsorption systems can be operated with geothermal

sources at temperature of 76.6°C (170°F) but the efficiency falls below 25% and they become uneconomical. Geothermal sources at temperature of 104°C (220°F) and higher may become economical if the incremental investment of the geothermal system over a conventional system is not very high, or if the price of fossil and electricial energy continue to rise. The geothermal system capital cost depends heavily on the depth of the geothermal water. When the geothermal water is available at a medium depth, the incremental cost of a geothermal - assisted adsorption cooling has a short payout period. The spent geothermal water from the adsorption cooling system has a sufficiently high temperature to be utilized in a cascade system for other purposes. When this type of cogeneration is practical, utilization of the adsorption cooling could become economically successful.

Heat pump systems require a low temperature geothermal source. These water sources are usually available at low depth and could increase the efficiency and the reliability of the heat pump. These geothermal sources are available throughout most of Arizona at low cost.

Utilization of these two geothermal-assisted cooling processes in centralized system with storage capacity could help alleviate the high peak of electricity demand during the day time in the summer, thus keeping the electricity cost from raising and postponing at least for a while the construction of new power plants. Such systems would be beneficial in Arizona, especially in the metropolitan areas of Phoenix and Tucson.

A summary of these conclusions is as follows:

1. For most predicted geothermal resources in Arizona, their use for absorption cooling is uneconomical. This is due mainly to (a) the high capital cost of the geothermal-driven absorption cooling system and (b) that it is needed at full capacity for only five months of the year. The capital costs are about six-fold of a conventional electrical-driven mechanical refrigeration unit.
2. Geothermal-driven absorption cooling systems are economical in Arizona, if one or more of the following criteria exists:
 - a. Very shallow, reasonably hot geothermal resource, to reduce capital investment.
 - b. Geothermal resource temperature is higher than 105°C (220°F) when absorption cooling units operate at maximum efficiency and capacity.
 - c. The geothermal-driven system should include a cold water storage, thus requiring a smaller size cooling unit and a smaller flow rate of the geothermal well.
 - d. Alternative utilization of the geothermal source, when cooling is not required.
 - e. Cascade utilization for domestic and industrial purposes could be employed without a large capital initial investment. This would allow continuous operation the year around, and would become economical.
3. Heat Pump Units could be used in cogeneration with low-temperature geothermal water, to increase the efficiency and the reliability of the cooling system.

4. Geothermal resource to be used as the heat sink and the heat source must fall within a narrow temperature range $15.5 - 26.6^{\circ}\text{C}$ ($60 - 80^{\circ}\text{F}$), but these low-temperature geothermal resources are widespread in Arizona at low depths. Arizona has 3,000 known thermal wells, out of a total of 30,000 irrigation wells.
5. The optimum temperature of a geothermal resource for a heat pump unit depends upon the annual heating and cooling load. At high cooling load, a low-temperature water source would increase the heat pump efficiency and vice versa.
6. The economics of the heat pump system can be improved if the spent water could be useful for irrigation or industrial purposes, and does not need to be reinjected into the ground.

REFERENCES

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.
2. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan - Pima 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 79-9.
3. Witcher, J.C., et al, "Geothermal Resources of Arizona-Map", map prepared by National Geophysical and Solar-Terrestrial Data Center, National Oceanic and Atmospheric Administration, (for the Department of Energy), 1982.
4. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan - Pinal 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 79-11.
5. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan - Yuma 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 81-18.
6. White, D.H. and Goldstone, L.A., 1982, Irrigation Pumping Using Geothermal Energy, 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 81-15.
7. Arkla, "Solaire 300", Arkla Industries, Evanville, Indiana, Oct. 1976.
8. Auh, P.C., "A Survey of Absorption Cooling Technology in Solar Applications", Brookhaven National Laboratory, BNL 50704, July 1977.
9. Carrier, "Hermetic Absorption Liquid Chillers", Carrier Corp., MSD, Syracuse N.Y., 16JB-3P, June, 1975.
10. Jones, W.P., "Air-Conditioning Engineering", Chapter 14, Edward Arnold Limited, London, 1978.
11. Kreith, F., "Principles of Heat Transfer", Intext Educational Publishers, New York, 1973.
12. Reynolds, W.C., and Perkins, H.C., "Engineering Thermodynamics", Chapter 9, McGraw-Hill Book Co. New York, 1970.

13. Trane, "Single-Stage Absorption Cold Generators for Low Temperature Input", Trane Co., Le Crosse, Wis. CS-ABS2, July 1976.
14. "Ground Water Heat Pumps: A Case in Point", Water Well Journal, September, 1978.
15. Wehlaye, F.E., "The Case for Dollars Versus Geothermal Heat Pump", Geothermal Energy, 1980.
16. ibid.
17. Private Communication with Dr. Sol Resnick, Director of the Water Resource Research Center, University of Arizona, 1981.
18. "Economic Comparison of Heating Facilities", Geo-Heat Utilization Center for Technical Assistance, 1981.
19. W.R. Acorn Engineering Associates, "Geothermal Feasibility Study for Decker Land Development", 1982.
20. Preliminary Report on the Geothermal Energy System Plant for the City of Boise, Energy Office Boise, Idaho, "Ground Water Heat Pump", Water Well Journal, Sept. 1978.

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.
2. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Pima 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 79-9.
3. 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.
4. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Pinal 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 79-11.
5. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Yuma 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 81-18.
6. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Cochise - Santa Cruz 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 80-9.
7. Goldstone, L.A. and White, D.H., 1982, Geothermal Development Plan: Northern Arizona 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 80-10.
8. Goldstone, L.A. and White, D.H., 1982, Maryvale Terrace: Geothermal Residential District Space Heating and Cooling, 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 81-11.

9. Goldstone, L.A. and White, D.H., 1982, Geothermal Heating for the Arizona Environmental Research Laboratory Greenhouses, 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 81-12.
10. White, D.H. and Goldstone, L.A., 1982, Irrigation Pumping Using Geothermal Energy, 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 81-15.
11. White, D.H. and Goldstone, L.A., 1982, Geothermal Energy for Copper Dump Leaching, 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 81-15.
12. White, D.H. and Goldstone, L.A., 1982, Geothermal Energy for Copper Flotation Enhancement and Leaching of Tailings, 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 81-10.
13. White, D.H. and Goldstone, L.A., 1982, The Potential of Hybrid Geothermal/Coal Fired Power Plants in Arizona, 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 81-8.
14. Malysa, L.M. and White, D.H., Hahman, W.R., Mancini, F., and Goldstone, L.A., 1980, Arizona Geothermal Institutional Handbook, prepared for the U.S. Department of Energy, Contract No. DE-FC07-79ID12015, and the Arizona Solar Energy Commission: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 80-7.
15. White, D.H. and L.A. Goldstone, 1982, Executive Summary: The Potential of Utilization of Geothermal Energy in Arizona, 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 82-1.

Other related reports include the following:

1. Acorn Engineering Associates, 1982, Geothermal Feasibility Study for Decker Land Development, Tucson, Arizona: Unpub. Report for Oregon Institute of Technology, Contract No. TA 1-82: State of Arizona Bureau of Geology and Mineral Technology Open-File Report.
2. Frank, Helmut J., ed., 1982, Arizona's Energy Future: Making the Transition to a New Mix, Tucson: University of Arizona Press.
3. Johannessen and Girand Consulting Engineers, Inc., 1981, Feasibility Study for Geothermal Water Space Heating for the Safford Federal Prison Camp, Safford, Arizona: Unpub. Report for the Oregon Institute of Technology, Contract No. TA 18-80: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 81-30.
4. Pasqualetti, M.J., Goldstone, L.A. and Stone, Claudia, 1981, Land Use Planning for Geothermal Development-Scottsdale, Arizona, partially funded by the U.S. Department of Energy, Contract No. DE-FC03-80RA50076 and the City of Scottsdale Planning Department: State of Arizona Bureau of Geology and Mineral Technology Open-File Report 81-8.

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^oC. 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.