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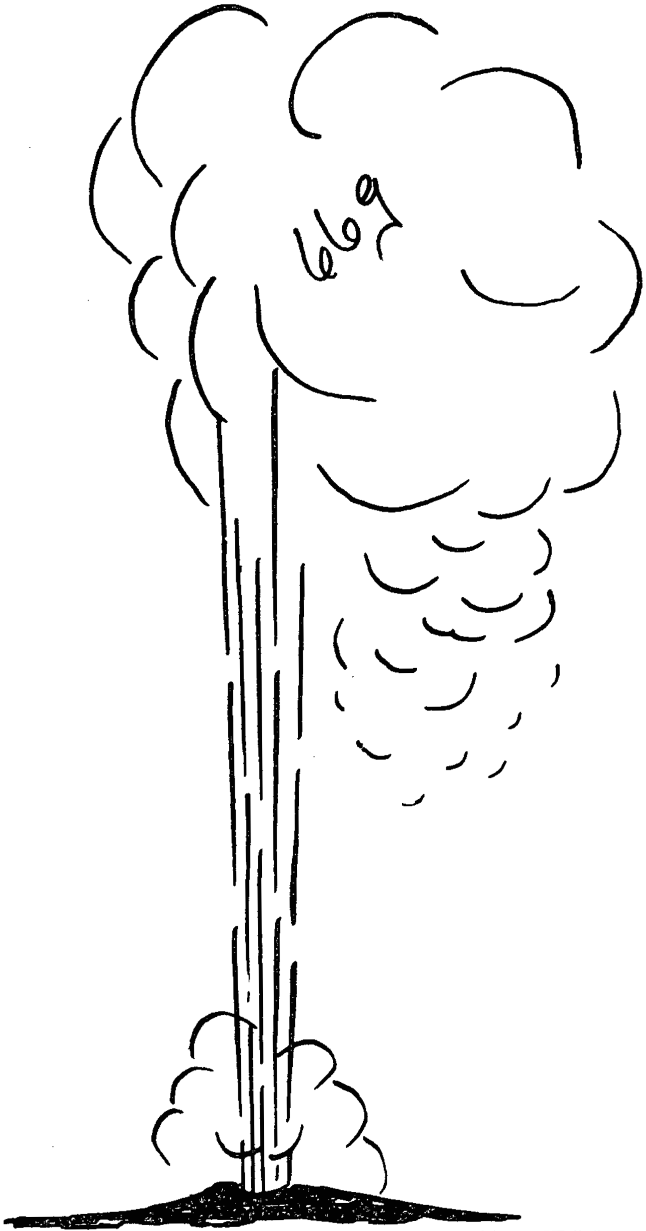

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DIRECT APPLICATION OF GEOTHERMAL ENERGY

By
Gordon M. Reistad

Work Performed Under Contract No. AC01-78ET20501

Oregon State University
Corvallis, Oregon

and

American Society of Heating, Refrigerating and
Air-Conditioning Engineers, Inc.
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U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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Direct Application of Geothermal Energy

Sponsored by the
American Society of Heating, Refrigerating and
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and
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PREFACE

In 1978 the first formal ASHRAE committee-work on geothermal energy was initiated by the formation of the Task Group on Geothermal Energy Utilization. Since that time, the Task Group has worked to make information, regarding geothermal energy, available to the members of the society in a form that would both show the potential for use of geothermal energy and illustrate necessary considerations for the design of systems that are to incorporate geothermal energy as an energy supply. This report was started shortly after the formation of the Task Group and has an objective similar to that indicated above as representative of the overall work of the Task Group. The purpose of this report is to present in a single work, an overall treatment of direct geothermal applications with an emphasis on the above-ground engineering. It accomplishes this by (i) describing the type of geothermal resources and their general extent in the U.S., (ii) considering briefly the potential market that may be served with geothermal energy, (iii) illustrating the evaluation considerations, special design aspects and application approaches for geothermal energy use in each of the applications, (iv) summarizing the present applications in the U.S., and (v) providing a bibliography of recent studies and applications.

It is hoped that this work will be useful to ASHRAE members and others engaged in this field in furthering the cause of energy conservation by rapid development of geothermal applications.

ACKNOWLEDGEMENT

The Task Group on Geothermal Energy Utilization was instrumental in formulating the shape of this report. The members of the Task Group at the time of formulation were:

John Austin

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Marshall Conover

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Glenn Coury

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Three of the Task Group Members served as reviewers for the work. They are:

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1. INTRODUCTION

In the recent early period of substantial interest in alternative energy supplies just after the oil embargo of 1973, the national emphasis on the use of geothermal energy was almost exclusively directed toward production of electricity. This occurred even though there have been a number of direct geothermal operations, basically for space heating, that have been in existence for several decades and in some instances since the 1800s. More recently, it has become evident that much of our overall geothermal resource appears better suited for direct applications than for electrical production. In the last several years, there have been substantial efforts directed toward the direct use of geothermal energy for space and domestic water heating, industrial processing and, to a considerably lesser extent, cooling. Presently, geothermal energy is a practical source of energy that is being used, being planned for in quite a number of new installations and one that should be considered a candidate for "fueling" a particular operation until it is ruled out.

Figure 1.1 schematically illustrates the direct utilization of one type of geothermal resource. Such systems may be considered to consist of five subsystems: (i) the production system consisting of the producing wellbore and associated wellhead equipment, (ii) the transmission and distribution system that transports the geothermal energy from the resource site to the user site and then distributes it to the individual user loads, (iii) the user system itself, (iv) the disposal system which can be either surface disposal or injection back into a formation which may or may not be the same as that from which it was originally produced, and (v) a peaking/backup system.

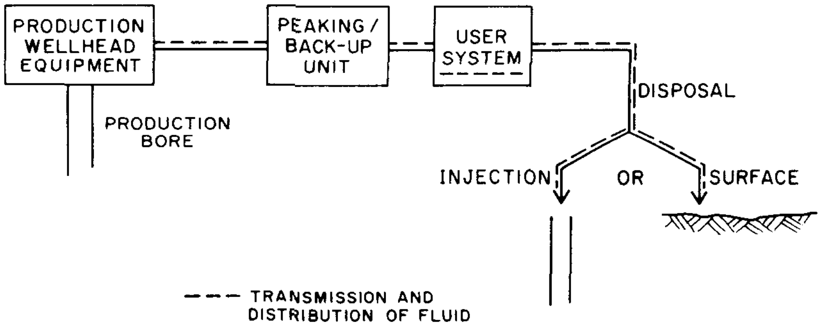

Figure 1.1 Basic geothermal direct utilization system.

The realization of an overall geothermal system of this type requires consideration of the entire system, from the resource through the user system to the disposal. The resource location and its characteristics (temperature, allowable fluid flow rate, fluid quality, etc.) are particularly important because (i) geothermal energy is not available at all localities and geothermal fluids cannot be economically transmitted over more than a few tens of kilometers and (ii) the characteristics of the available resource provide basic system design inputs and may or may not be appropriate for the particular application for which an energy supply is being sought. For the most economic and satisfactory operation of the overall system, the user system should be specially designed for use of the geothermal fluids. To a large extent the equipment to be used is off-the-shelf equipment but is different equipment than that which has been traditionally used in the same application operated with conventional energy supplies. This is the area where thermal system design for geothermal energy use is substantially different than the designs for conventional fueled and solar systems. For geothermal energy systems, the design must be specially directed at (i) using the available resource temperature and flow rate, (ii) achieving an appropriate temperature drop of the fluid that is normally much greater than that specified for fluid loops in conventional systems, and (iii) complying with the fluid composition. The transmission and distribution system and the peaking/back-up system are designed using conventional techniques to provide economic and reliable operation. The main concerns in the disposal system design are that the fluid be disposed of in an environmentally acceptable manner and injected as necessary to maintain production.

The purpose of this report is to illustrate how geothermal energy can be used for space heating and cooling, domestic water heating, and industrial processing. It accomplishes this by (i) describing the types of geothermal resources and their general extent in the U.S., (ii) considering briefly the potential market that may be served with geothermal energy, (iii) illustrating the evaluation considerations, special design aspects, and application approaches for geothermal energy use in each of the applications, and (iv) summarizing the present applications in the U.S. The emphasis is on the engineering applications of the use of geothermal energy with topic (iii) being considered in depth and topics (i), (ii), and (iv) being presented in summary fashion.

2. THE RESOURCE

2.1 Description

In its broadest sense, geothermal energy is the thermal energy within the earth's crust; the thermal energy in the rock and the fluid (water, steam, or water with large amounts of dissolved solids in it) that fills the pores and fractures within the rock. It is not however, the residual thermal energy from the earth's origin. Calculations have shown that the earth, starting from a completely molten state, would have cooled off and become completely solid many thousands of years ago were there not an additional energy input other than that from the sun. At this time, it is generally believed that the ultimate source of geothermal energy is radioactive decay which has occurred, and is still occurring, within the earth (Bullard, 1973). Through phenomena such as plate motion and vulcanism some of this energy had become concentrated at relatively high temperatures near the surface of the earth. In addition, energy transfer from the deeper parts of the crust to the earth's surface by conduction (and also by convection in regions where geologic conditions and the presence of water permit) results in the general condition of thermal energy of elevated temperature at depth.

Because of variation in the volcanic activity, radioactive decay, rock conductivities and fluid circulation, various regions have different heat flows (through the crust to the surface) as well as different temperatures at a particular depth. The "normal" increase of temperature with depth (the normal geothermal gradient) is about 30°C/km of depth (16.5°F/1000 ft), with gradients of about 10 to 50°C/km (5 to 27°F/1000 ft) being common. The areas that have the higher temperature gradients and/or higher than average heat flow rates are of the most interest as economic resources. However, with the presence of certain geological features, even areas with normal gradients may be valuable resources.

Recent works (Muffler et al., 1980; Nichols, 1978) involving the geothermal resources of the U.S. have categorized the resources into five basics types:

Igneous point sources
Deep convective circulation in areas of high regional heat flow
Geopressure
Concentrated radiogenic heat sources
Deep regional aquifers in areas of near normal gradient.

The igneous point resources are those associated with magma bodies which have resulted from relatively recent (up to 10,000 years ago) volcanic activity. These bodies heat the surrounding and overlying rock by conduction and convection as permitted by the rock permeability and fluid content in the rock pores.

Deep circulation of water in areas of high regional heat flow can result in hot fluids existing near the surface of the earth. Such resources are commonly referred to as hydrothermal convection systems. This is the basic type of geothermal resource that is presently in widespread use. The fluids existing near the surface have risen from natural convection circulation between the hotter deeper formation and the cooler formations near the surface. The passageway that provides for this deep circulation must consist of fractures and faults of adequate permeability.

The geopressure resource, present over a wide region in the Gulf Coast area, consists of regional occurrences of confined hot water in deep sedimentary strata, 76MPa(11000 psi) are common. The resource in the Gulf Coast also contains methane dissolved in the geothermal fluid.

Radiogenic heat sources exist in various regions as granitic plutonic rocks that are relatively enriched in uranium and thorium. These plutons thus have a higher heat flow than the surrounding rock, and if the plutons are blanketed by sediments of low thermal conductivity, elevated temperatures can result at the base of the sedimentary section. This resource has been identified as occurring in the eastern U.S. Such systems also have been identified in the western U.S., but there they are of secondary importance relative to both igneous point sources and regions of high heat flow.

Deep regional aquifiers of commercial value can occur in deep sedimentary basins, even in areas of only normal temperature gradient. The requirements are that the basins be sufficiently deep to allow usable temperature levels at the prevailing gradient and that the permeabilities within the aquifer be adequate for flow in the aquifer.

The thermal energy in the geothermal resource systems exists primarily in the rocks and only secondarily in the fluids that fill the pores and fractures within them. Presently, for the most part, thermal energy is extracted by bringing to the surface the hot water or steam that occurs naturally in the open spaces in the rock. Where rock permeability is low, the energy extraction rate is low. In order to extract the thermal energy from the rock itself, a recharge of water into the system must occur as the initial water is extracted. In permeable aquifers, or where natural fluid conductors occur, the produced fluid may be injected back into the aquifer some distance from the production hole to pass through the aquifer again and recover some of the energy in the rock; such a system has been termed a stimulated or forced geoheat recovery system (Bodvarsson, 1974; Bodvarsson et al., 1976). This type of system is presently in operation in France (BRGM, 1978). For recovering energy from relatively impermeable rock, research is now underway to evaluate the feasibility of creating artificial permeability by fracturing (hydraulic and thermal stress) and then extracting the thermal energy by injecting cold water into the fractured system through one well and removing the heated fluid through a second well. This technology is referred to as "hot dry rock" because it has been directed, thus far, at quite hot rock bodies. Los Alamos Scientific Laboratories (LASL) is presently directing a major program in this area (Brown et al., 1979 and numerous other LASL reports).

2.2 Temperatures

The temperature of fluids produced from the earth's crust and used for their thermal energy content vary from slightly less than about 15°C (59°F) to 360°C (680°F). The lower value represents the fluids used as the low temperature energy source for heat pumps and the higher temperature represents an approximate value for the hottest system presently in development (for electrical power generation).

Figure 2.1 shows examples of the temperature as a function of depth for the several cases of (A) near normal gradient 25°C/km (13.7°F/1000 ft), (B) high gradient of 68°C/km (37°F/1000 ft) and (C,D) convective systems (from Combs et al., 1980). Note that in conductive systems, (A) and (B), the temperature increases rather steadily with depth. In the convective systems, the temperature is relatively constant with depth throughout the permeable horizon, but increases with depth above and below this. To achieve high temperatures, either very deep drilling or convective systems that originate at depth and provide circulation to shallower regions are necessary.

For purposes of this report, the following classifications of resources by temperature level will be used:

High Temperature	$T \geq$ 150°C (302°F)
Intermediate Temperature	90°C (194°F) $\leq T \leq$ 150°C (302°F)
Low Temperature	15°C (59°F) $< T <$ 90°C (194°F)

It is generally considered that electricity generation is not presently economically feasible for resources with temperatures below about 150°C (302°F) and this is the reason for the division between high temperature and intermediate temperature systems. The 90°C (194°F) division between intermediate and low temperatures is common in resource inventories but is somewhat arbitrary. However, at 90°C (194°F) and above, applications such as district heating can be readily implemented with equipment used in conventional applications of the same type, while at lower temperatures such applications require, for the most part, redesign to take the greatest advantage of the geothermal resource.

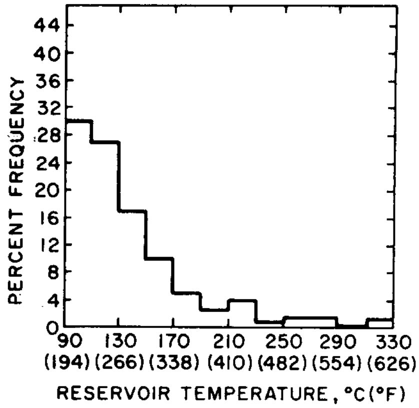

Figure 2.2 Percent frequency of identified hydrothermal convection systems by reservoir temperature in 20°C classes; 1978 data (from Muffler et al., 1979).

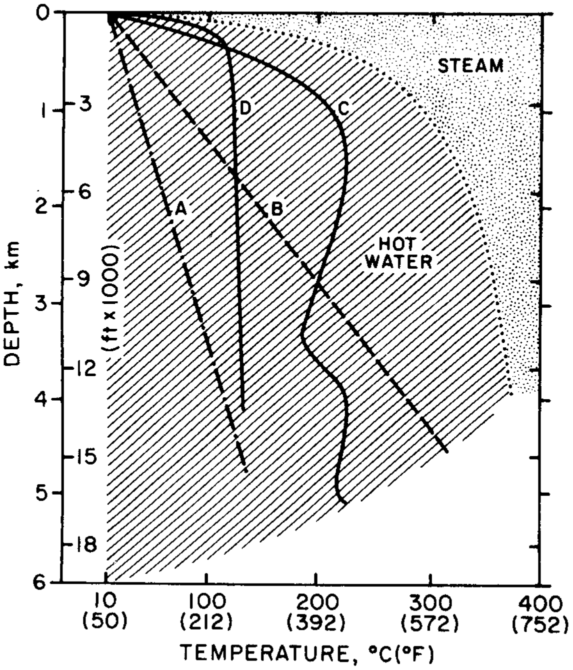

Figure 2.1 Representative temperature-depth relations in the earth's crust. A - Near normal temperature gradient; B - High conductive gradient; C and D - Temperature depth relations resulting from convective flow (from Combs et al., 1979).

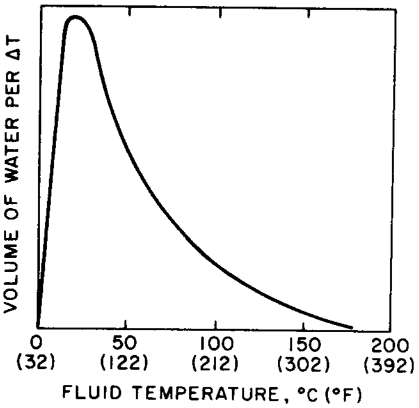

Figure 2.3 A probable distribution for geothermal fluids (from Kunze and Forsgren, 1978).

It is important to realize that the geothermal systems at the lower temperature levels are more common. Figure 2.2 from Muffler et al., 1979, shows the percent frequency of identified convective systems by reservoir temperature for temperatures above 90°C (194°F). Below 90°C (194°F), the available information is inadequate to obtain a reliable chart like that of Figure 2.2, but Figure 2.3 presents a schematic of what might be expected for the distribution over the more complete temperature range (from Kunze and Forsgren, 1978).

2.3 Geothermal Fluids

The geothermal energy is extracted from the earth through some fluid medium. Presently, this is the naturally occurring fluids in the pores and fractures as mentioned previously, but in the future it may also be an additional fluid that is introduced to the geothermal system and circulated through it to recover the energy. Also, as mentioned previously, the latter situation is now in the research stages.

The fluids that are presently being produced are either steam, hot liquid water or a two-phase mixture of both. These may contain various amounts of impurities. Of principal concern are the dissolved gases and the dissolved solids.

The geothermal systems that produce essentially dry steam are referred to as vapor dominated. These systems are very valuable resources, but unfortunately they are also apparently quite rare. The Geysers development (Barton, 1970; Dan et al., 1976) for electricity generation is the only confirmed system of this type in the U.S. that is currently being developed. Although two other resources have been identified as being of this type, they are not being planned for development because they are located in national parks (Yellowstone and Mt. Lassen). In these systems the principal impurity of concern is the dissolved gases.

Hot water systems (referred to as liquid dominated) are much more common than the vapor dominated systems. They can be produced either as hot water or as a two-phase mixture of steam and hot water, depending on the pressure maintained on the production system. If the pressure in the production casing or in the formation around the casing is reduced below the saturation pressure at that temperature, some of the fluid will flash and a two-phase fluid will result. If the pressure is maintained above the saturation pressure, the fluid will remain as a single phase. In these water dominated systems, both dissolved gases and dissolved solids are of significance. For such fluids, the quality varies substantially from site to site, and in fact varies from water of potable quality to fluids that have over 300,000 ppm dissolved solids. The U.S. Geological Survey classifies the degree of salinity of mineralized waters as follows:

Dissolved Solids, ppm	Classification
1,000 to 3,000	Slightly saline
3,000 to 10,000	Moderately saline
10,000 to 35,000	Very saline
More than 35,000	Brine

Thus, geothermal fluids range all the way from non-saline to brine, depending on the particular resource.

Table 2.1 presents the composition of fluids from a number of geothermal wells in the U.S. The list illustrates the types of substances and the range of concentrations that can be expected in the fluids. Although there is great site dependency, in general, the harshness of the fluid increases with increasing temperature.

This work will concentrate on systems produced as a single-phase hot liquid.

2.4 Life of the Resource

Although the radioactive decay that appears to be the ultimate source of geothermal energy continues, and can be expected to continue for many thousands of years, geothermal energy in a specific locality is generally not renewable. Only in areas that are active in volcanic activity would a particular resource be expected to be renewed. The energy that is to be mined from what are now considered geothermal resources was built up over a period of many millions of years and could not be restored at the rate at which it would be withdrawn in any economic application. As a result, each resource must be developed with a certain life of the development in mind. The usual procedure is to expand the area that is developed as additional capacity is required and/or initial energy production rates start to drop off.

2.5 Environmental Aspects

Because in the direct use of geothermal resources, the application is directly coupled to the production, the overall environmental aspects of the use and the production of the geothermal energy must usually be considered by the user. The primary environmental issues and a very brief discussion of each are presented in Table 2.2. The reader is referred to the bibliography on "Legal, Institutional and Environmental" for complete details of the environmental aspects of the direct use of geothermal energy. Willard et al., 1980, considers, specifically, the concerns in regard to direct applications.

Table 2.1 Representative Fluid Compositions from Geothermal Wells in Various Resource Areas of the U.S.

	RESOURCE AREA					
Location	Boise* ID	Klamath Falls** OR	Beowawe* NV	Raft River* ID	Baca* NM	Salton Sea* CA
Temperature °C (°F)	80(176)	94(201)	132(270)	146(295)	171(340)	250(482)
Species in Fluid	Concentration (ppm or (mg/l))***					
Total Dissolved Solids	290		855	1319	6898	(220,000)
SiO_2	160	119	329	91.8	835	(350)
Na	90	231	214	368	2010	(5,100)
K	1.6		9	65	541	(12,500)
Li	0.05		Trace	1.1		(220)
Ca	1.7	36		52	36	(23,000)
Mg	0.05	0.2		1.9		(150)
Cl	10	61	50	611	3770	(133,000)
F	14		6	5.5		
Br				<2.5		
I				0.035		
SO_4	23	484	89	63	58	
S				<0.2	2.2	
NO_3				0.19		
P				<0.003		
NH_4				4.53		
NH_3			3			
H_2S	Trace		6.1			
HCO_3	70	51	41	86.6	118	
CO_3	4		168		0	
CO_2	0.2					
Al	Minor		0.2			(0.04)
As	0.05					(1)
B	0.14		1	0.3		(350)
Ba	0.2			0.4		(270)
Cr	Minor					(0.6)
Cu	0.08		Trace			(8)
Fe	0.13			3.2		(1,300)
Mn	0.01		Trace	0.08		
Ni	Trace			3.5		(2.4)
Sr	0.01			1.3		(500)
Ti	Trace		Trace			
V			Trace			
Zn	Trace-Minor					
Hg	0.02					
Si				44		
H_2	0.0054					
He	0.0016					
CH_4	0.065					
N_2	18.51					
O_2	0.0029	3.1				
Ar	0.62					
Comments:	Well name unknown. Near old penitentiary.	Wendling Well	Vulcan Well 2	Well RRGE I	Well Baca II. Flashed fluid sample.	

* Data from Cosner and Apps, 1978.

** Data from Lund et al., 1976.

*** Most analyses are for liquid samples only and do not reflect the non-condensible gases.

Table 2.2 Primary Environmental Issues That May Arise in Specific Applications of Geothermal Resources

Issue	Potential Environmental Impact	Comments
Ecological	Damage to plants and animals.	Many geothermal resources are located in sensitive areas where there is a potential impact of this nature. With proper planning and design, this problem can be minimal.
Air Quality	Emission of various gases into the atmosphere.	Certain resources have some H_2S, radon or other non-condensible gases, which must be properly designed for.
Noise	Noise pollution.	Primarily a problem during drilling or testing. Can be minimized by proper noise abatement procedures.
Surface Water Quality	Degradation of water quality from thermal, chemical or natural radioactive properties of disposed fluids.	Proper disposal system design and planning for accidental releases are required to minimize the impact on water quality.
Land Use	Conflict of geothermal use of land with other uses such as agriculture, recreation, etc.	Since surface area required for geothermal development is relatively small, this issue can usually be readily resolved.
Geological Alteration	Subsidence and/or induced seismic activity.	Subsidence can be a problem in sedimentary resource areas when fluid injection is not used. Induced seismicity is not a major concern except for cases of deep high pressure fluid injection.
Water Supply and Hot Springs Alteration	Alteration of existing and potential water supplies or hot springs activities due to withdrawal of geothermal fluid and/or energy or injection of geothermal fluids.	Geothermal development near water supplies and hot springs may be restricted or prohibited because hydrologic information is usually inadequate to predict the impact of the development.
Archaeological/ Cultural Resources	Destruction of archaeological areas and/or infringement on cultural resources (historical, paleontological).	May restrict areas to which development is possible. Conduct archaeological survey of prospective development area and do not develop problem areas.
Socio-economic	Change in existing economic structure, population and social patterns.	Primarily a concern for large-labor intensive developments in sparsely populated areas. Can be controlled with adequate planning.

2.6 Location and Extent of Geothermal Resources in the U.S.

In the initial stages of the renewed interest in geothermal energy during this past decade, it was felt that essentially only the western states and the Gulf Coast states had geothermal resources that could be economically developed in the near term. As alluded to previously however, recent discoveries of potential in concentrated radiogenic heat sources and deep regional aquifers in areas of near normal temperature gradient indicate that most of the states in the U.S. have geothermal resources that may be presently economically exploitable. Peterson, 1979, indicates that 37 of the states have such resources (see Figure 2.4). At this time the extent of the geothermal resources is, to a large degree, unknown. However, the U.S. Geological Survey (USGS) and the U.S. Department of Energy (DOE) presently have extensive resource assessment programs (Muffler et al., 1979; Grim et al., 1978) that continue to improve the state of knowledge on a regional basis. The latest comprehensive report is the USGS Circular 790 (Muffler et al., 1979) which discusses and depicts the regional distribution of geothermal energy in the U.S. based on the latest available public information at the time of the writing of the report. An evaluation of the resources in the Eastern U.S. was not made in USGS Circular 790 because of the absence of data at the time of report compilation. However, there is an active resource evaluation program underway in the Eastern U.S., and results can be found in a series of progress reports to the DOE (Costain et al., 1976, 77, 79).

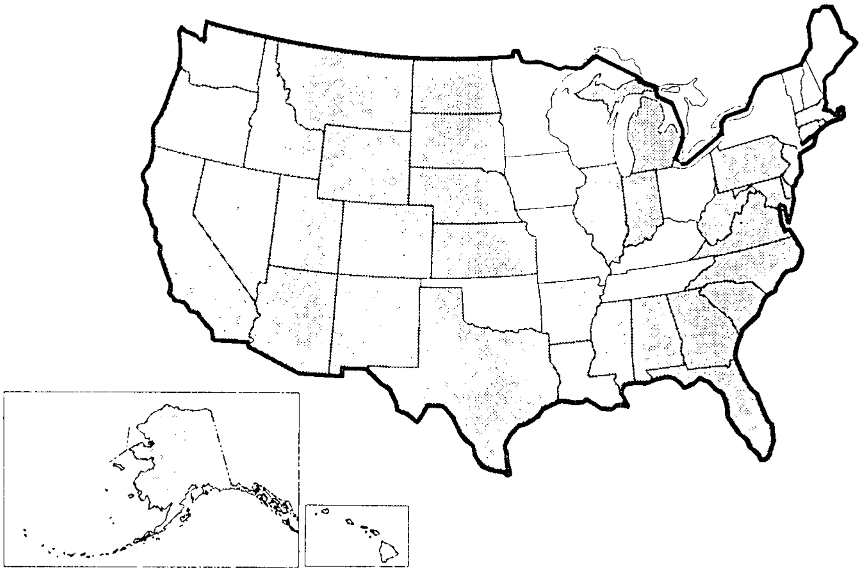

Figure 2.4 States with known or potential low temperature geothermal resources (from Peterson, 1979).

3. PRESENT USE AND POTENTIAL MARKET

3.1 Present Use

Presently, geothermal energy is being used at a significant level in the U.S. and other countries. The Geysers resource area in Northern California, where electricity is being produced at a rate of over 700 megawatts (MW_e), is the largest single geothermal development in the world. The total electricity generation in the world is rapidly expanding with an expected capacity increase of a factor of 5 to 7 by 1985 from the 1300 MW_e level in 1976 (Roberts et al., 1978). The direct application of geothermal energy for space heating and cooling, water heating, agricultural growth related heating and industrial processing represents over 7000 megawatts of thermal energy (MW_t). The direct applications are expected to increase by a factor of 2 to 4 by 1985 (Roberts et al., 1978). Of the present 7000 MW_t, the U.S. portion is only about 85 MW_t with the major applications occurring in Iceland, New Zealand, USSR and Hungary. Table 3.1 illustrates the uses by country.

Table 3.1 Worldwide Direct Application of Geothermal Energy (Lund, 1979).

Country	Space Heating/Cooling (MW_t)	Agriculture/ Aquaculture (MW_t)	Industrial Processes (MW_t)
Iceland	680	40	50
New Zealand	50	10	150
Japan	10	30	5
USSR	120	5100	--
Hungary	300	370	--
Italy	50	5	20
France	10	--	--
Others	10	10	5
USA	75	5	5
TOTAL	1245	5570	235

The present direct use in the U.S. is mainly for space and water heating in residences and institutional buildings. Klamath Falls, Oregon and Boise, Idaho have a long history of a significant amount of use in this category. A dozen or so additional localities have had minor amounts, and many more communities have either recently started using geothermal energy or are planning for its use. Installations in Klamath Falls and Boise are representative of both long standing application and recent adaptation in modern well engineered systems. A large number of residences in Klamath Falls have for many years used single shallow wells with downhole heat exchangers for heating (Culver and Reistad, 1978). The Oregon Institute of Technology campus is completely heated with geothermal energy. It represents a fairly large application where three wells, to a depth of 600 m (1970 ft), produce flows of up to 28 l/s (450 GPM) at 89°C (192°F) for heating 46,500 m^2 (500,000 ft^2) of floor space (Lund, 1979). A district heating system that will initially serve 14 government buildings, with subsequent expansion to 115 private commercial buildings is in the development stage in Klamath Falls. Boise, Idaho has had a geothermal district heating system in operation since the 1890s (Wells, 1971). The total served load decreased in the middle of this century, but that trend was reversed in 1977 when several state agency laboratory buildings were connected to the system (Austin, 1978).

The two main uses of geothermal energy in the agricultural growth applications are for heating of greenhouses and aquaculture facilities. Some of these have existed for a number of years, but there have been many new ones developed over the past several years.

The main industrial uses of geothermal energy in this country are food processing applications. It is presently used in milk pasteurizing and vegetable dehydration.

Worldwide, there are a wide variety of direct applications as illustrated in Table 3.2. With a few notable exceptions, the main ones fall into the categories indicated above; space and water heating, space cooling, agricultural growth applications and food processing. The main exceptions are diatomaceous earth processing in Iceland, and pulp and paper processing in New Zealand.

3.2 Potential Impact

Geothermal energy, in terms of the fluids produced, is restricted to temperature levels that are substantially lower than those which we have become accustomed to from fossil fuels. As illustrated above, the maximum temperature of a producing field at this time is 360°C (680°F) and the usual resource is expected at much lower temperatures. These temperatures are much lower than the 1500°C (2700°F) and higher temperatures that can be obtained from combustion of oil, natural gas, etc. Fortunately, the temperature level required for much of the energy in an industrialized nation lies in a range that can be met with geothermal energy which occurs in the temperature ranges indicated above. Figure 3.1 presents a widely published illustration of the approximate temperature required for many applications. Space heating and cooling as well as sanitary waterheating represent uses that are both significant in scale (representing a total of about 25 percent of the U.S. energy consumption) and readily accommodated by the low and intermediate temperature geothermal resources. Much of the process heat requirements also occur at such temperature levels. There have been a number of estimates of the amount of energy consumed at various temperature levels in the process industries, and the greatly accelerated interest in energy conservation, etc. that has occurred in the recent past has spurred efforts for more detailed evaluation. Consequently, the most recent estimates are based on much greater data bases than the earlier ones and are much more accurate. Figure 3.2 presents results from such a study. As presented, it represents a cumulative plot of the energy use at or below a particular temperature. Since the total industrial heating requirements represent more than 25 percent of the U.S. energy consumption, the results from Figure 3.2 along with the space heating and cooling and sanitary water heating energy requirements indicate that a very significant portion of the total energy use in the U.S. lies in a temperature range for which geothermal energy is applicable.

Table 3.2 Direct Applications of Geothermal Energy.

Country/Locality	Description of Application	Associated Power (MW)	Comments	Sources
• Argentina	Total	Small	Space heating and drying	Roberts et al. (1978)
• Chile	Total	Small	Desalination pilot plant	Roberts et al. (1978)
• Czechoslovakia	Total	90	Space and water heating; mineral baths	Roberts et al. (1978)
Bohemian Massif		20		
West Carpathinas		70		
• France	Total	0.5 to 24	Space and water heating	Roberts et al. (1978)
• Germany, West	Total	0.3	Miscellaneous use in 20-50°C range	Roberts et al. (1978)
• Hungary	Total	45 to 1050		Roberts et al. (1978)
	Agriculture	530		Boldizsar (1974)
	District heating	6		
	Industry	2		
	Spas	440	Mineral baths and swimming pools	
Szentes and various other localities	Greenhouse heating	160	Typical greenhouse vegetables plus paprika; typical horticulture; 800,000 m^2 of greenhouse	UNESCO (1973)
Various localities	Heating and cleaning animal shelters	210	Milk rooms, cattlestalls, pigsties, chicken houses	UNESCO (1973)
Szeged	District heating		University clinics and 1200 flats, 226,000 m^3	Einarsson (1973) Boldizsar (1974)
Hodmëzovasarhely	Space heating		Factory and hospital, 172,000 m^3	Einarsson (1973)
Mako	Space heating		Hospital, 80,000 m^3	Einarsson (1973)
• Iceland	Total	360		
Reykjavik	District heating	320	The system's geothermal resources come from the Reykir area (3600 m^3/h at 80°C, 170 MW [th]) and the Reykjavik area (1700 m^3/h at 119°C, 155 MW [th]). Peaking is accomplished from the system's own fossil-fired peaking power plant. System started with 70 houses in 1928.	Zoega (1974)
Olafsfjördur	District heating		System serves the housing of 1000 inhabitants: built in 1944 using only 48°C water about 3 km away from the city. In 1961 deep drilling yielded additional water at 56°C.	Einarsson (1973)
Selfoss	District heating	15	System serves 154,000 m^3 of housing and 75,000 m^3 of public, commercial and industrial buildings (entire city of 2200). Boreholes are located 1.5 km away from the city. System started in 1948. 80 kg/s at 80°C.	Einarsson (1973)
Hveragerdi	District heating		System serves housing in entire city (820) and a therapeutic spa for 140 patients; it also supplies heating for 30,000 m^2 of hothouses. The system was built in 1953 and utilizes a 180°C geothermal field.	Einarsson (1973)
Saudarkrokur	District heating		City of 2000 uses 70°C water from nearby boreholes.	Einarsson (1973)
Various	Greenhouses	16	Glass greenhouses heated by natural steam and/or hot water, either directly or with heat exchangers. 1/3 flowers, 2/3 vegetables (tomatoes, cucumbers, lettuce); cost, $0.91/GJ (1970)	UNESCO (1973)
Various localities	Experimental salmon breeding station	1	Kollafjord experimental fish farm, rearing young salmon to the smolt stage; 7 l/s at 70°C.	Matthiasson (1970)
Reykjavik	Drying fish in shelf dryers	Small	Uses excess water from Reykjavik heating system during summer in local stock-fish processing center.	Lindal (1961)
	Curing of cement building slabs	Small	No details given; reported to occur in two or more countries.	Lindal (1973)
Reykholar	Drying seaweed	20	80 l/s at 100°C; production of 3600 t/yr of dry seaweed.	Matthiasson (1970)
Hveragerdi (Hengill area)	Steam drying of wood		No details given; reported to occur in other places.	Lindal (1961)
Namafjall	Drying of diatomaceous earth	35	Dredging of material from the lake is done only in summer, while the drying plant runs throughout the year; up to 50 t/h of steam at 183°C/10^5 Pa.	Lindal (1973)

Note: Many of the entries on specific applications are from Howard et al., 1975, but original source is cited here.

*The associated power is as reported by the countries in the survey or by the reference. It may be either the power associated with the well flow or the power actually used in the application.

Table 3.2 Direct Applications of Geothermal Energy (continued)

Country/Locality	Description of Application	Associated Power (MW)	Comments	Sources
• Italy	Total	24		Roberts et al. (1978)
Castelnuovo	Greenhouse	0.6	3000 m^2	Barbier (1975)
Galzignano (Padua)	Greenhouse	4	20,000 m^2	
Larderello	Ore processing	15 to 18	Steam at 3 tons/hour is used for processing imported ores (boric acid)	
Larderello	Mineral recovery		No longer in operation; large production before 1966. Mineral recovery of substances from the volatile components that accompany the geothermal steam (boric acid, ammonium bicarbonate, ammonium sulfate, and sulfur)	Muffler (1973) Mazzoni (1948) Garlado (1961) Lenzi (1964)
• Japan	Total	2900		Roberts et al. (1978)
Towada	District heating	2	System constructed in 1963 with 11.5 km transmission line from Sarukuro springs; 14 kg/s at 70°C	UNESCO (1973)
Okawa	District heating	3	System provides heating for 3000 houses from a 12 km transmission line. 22 kg/s at 70°C	UNESCO (1973)
Ukiyama	District heating	0.2	Water is heated to 55°C in fossil-fueled boiler. 12 kg/s at 40°C	UNESCO (1973)
Aomori	District heating	2	Provides heating for 34 hotels and 140 houses, with water from the Asamushi hot spring area. 22 kg/s at 60°C	UNESCO (1973)
Kannawa, Beppu, Oita	Confectionary industry		Daily rice-processing capacity 180 kg; 98°C water, spring source.	UNESCO (1973)
Ibuski	Brewing and distilling	Small	No details given; one well used.	
Various localities	Greenhouse heating	3	Horticulture (various species); vegetables (tomatoes, cucumbers, papayas, melons, bananas, eggplants); 3 types of greenhouses: glass, plastic, vinyl; 15,528 m^2 of greenhouse.	UNESCO (1973)
Minami-Izu Shizuoka	Poultry raising	2	Yoshisawa poultry yard, floor heating and dropping drying for 8000 chickens; 115°C water at 300 l/min.	
Ueda, Beppu, Oita	Poultry raising	Small	Nakamura poultry yard, 1600 chickens.	
Minami-Izu Shizuoka	Reptile breeding	10	Alligators and crocodiles, 20 species; geothermal water mixed with cold to attain 28-32°C; water 1-5°C at 2000 l/min	
Hokkaido and Kogashima prefectures	Eel breeding	Small	Uses water from hot springs	UNESCO (1973)
Shikabe, Hokkaido	Breeding station	10	Hokkaido hot-water hatching center, eels and carp; 70 l/s at 70°C	
Shikabe, Hokkaido	Production of salt from sea water		No longer in operation, formerly about 150 t/yr salt	UNESCO (1973)
	Extraction of sulfur from volcanic gases		Unsophisticated operation that has become uneconomical	UNESCO (1973)
• New Zealand	Total	200		Roberts et al. (1978)
Kawerau	Pulp and paper processing and a small amount of electric power generation	100 to 130	Geothermal energy delivered to mills by 36,287 kg/h of 1.4×10^6 Pa steam and 145,149 kg/h of 6.9×10^5 Pa steam, obtained by flashing wet steam at the well bore; 181,436 kg/h of steam	UNESCO (1973)
Rotorua	Veneer factory		No details given	UNESCO (1973)
Rotorua	Timber drying in kilns		No details given	UNESCO (1973)
Rotorua	Individual space heating of homes plus space cooling of a business.		Over 700 geothermal bores serving many individual applications. City consists of seven areas, three of which have approximately 80 bores at a useful average of 5.1×10^{10} J/d, 70 bores at a useful average of 6.3×10^{10} J/d, and 50 bores at a useful average of 2.0×10^{11} J/d, respectively.	UNESCO (1973) UNESCO (1974)
Various localities	Greenhouse heating		Mushrooms (soil is sterilized and heated by using geothermal fluids directly); tree nursery (seedlings); tomatoes.	UNESCO (1973)
Taupo	Pig-farm heating sterilizing; drying sheet crutchings; drying wool cuttings	Small	Geothermal steam is used to cook and sterilize garbage feed; warm piggery floors to 85°F; hose pens; sterilize and concentrate waste manure; dry sheet crutchings; boil sheet cuttings.	Kerr et al. (1961)

Table 3.2 Direct Applications of Geothermal Energy (continued)

Country/Locality	Description of Application	Associated Power (MW)	Comments	Sources
• Nicaragua	Total	110 to 190		Roberts et al. (1978)
• Peru	Total	Small	Desalination tests in progress	Roberts et al. (1978)
• Philippines	Total	5		Roberts et al. (1978)
Tiwi, Albay	Production of salt from sea water	2.5	Seawater brought 3 km to plant; three grades of salt produced.	Howard et al. (1975)
Tiwi, Albay	Grain drying	2.5		Howard et al. (1975)
• Taiwan	Total	0.6		Roberts et al. (1978)
• Turkey	Total	0.2		
Kizildere	Greenhouse heating	0.2	Hot water passes through radiator; air forced through radiator heats greenhouse; 3.7×10^{12} J per 6 months.	Howard et al. (1975)
• United States	Total	17		ERDA (1976)
Boise, Idaho	District heating	9	This sytem , which continues to serve about 200 houses and 10-12 businesses (1970), is one of the oldest district heating systems. It was built during the 1880s. New system being expanded for space heating.	Wells (1971)
Klamath Falls, Oregon	Individual space heating of homes, businesses, space cooling, and miscellaneous other uses.	6	Space heating of homes is generally accomplished with downhole heat exchange systems. Presently 468 residences are heated geothermally. Some commercial installations withdraw the geothermal fluid, use it in heat exchangers, and discharge the waste water into the sewer system or a discharge area.	Lund et al (1974)
Widespread	Space heating, resorts, greenhouse heating, unknown food processing, miscellaneous other uses.		The level of activity in geothermal applications has increased greatly in the last few years, with new developments of space and water heating, greenhouse heating, and miscellaneous agricultural and industrial applications being widespread. There is substantial activity in the states: Arizona, California, Colorado, Hawaii, Idaho, Louisiana, Maryland, Montana, Nevada, New Mexico, Oregon, South Dakota, Texas, Utah, and Virginia.	
• USSR	Total	150		
Makhach-Kala	District heating	13	Several districts are supplied, one of which has 15,000 inhabitants. 23 kg/s at 63°C plus 70 kg/s, plus others.	UNESCO (1973)
Zgoudidi town, Georgia	District heating	60		UNESCO (1973)
Mendji, Georgia	Space heating and agricultural uses.	20	Meterological station	UNESCO (1973)
Zaichi, Georgia	Space and pool heating	25	Meterological stations, hot houses and baths	UNESCO (1973)
Iserback town, Daghestan	District heating	7	Heating for 7500 inhabitants and industrial users	UNESCO (1973)
Caspiilsk town, Daghestan	District heating	6		UNESCO (1973)
Paratounka, Kamchatka	Space heating	0.6	Three apartment buildings of 48 apartments each.	UNESCO (1973)
Cherkesk, Stavropol	District heating	25	Heating for 18,200 inhabitants, plus industrial uses and hothouses.	UNESCO (1973)
Makhach-Kala and other localities	Greenhouse heating	13 to 4900	1,002,240 tons of tomatoes, cucumbers and other vegetables per year. Reported area varies from 5500 to 25,000,000 m^2 of greenhouses.	UNESCO (1973) Peterson et al. (1975)
Lorinsk	Animal husbandry	Small	Part of the Chukotsk collective farm.	UNESCO (1973)
Various localities	Animal husbandry	Small		
• Yugoslavia	Total	5		Roberts et al. (1978)

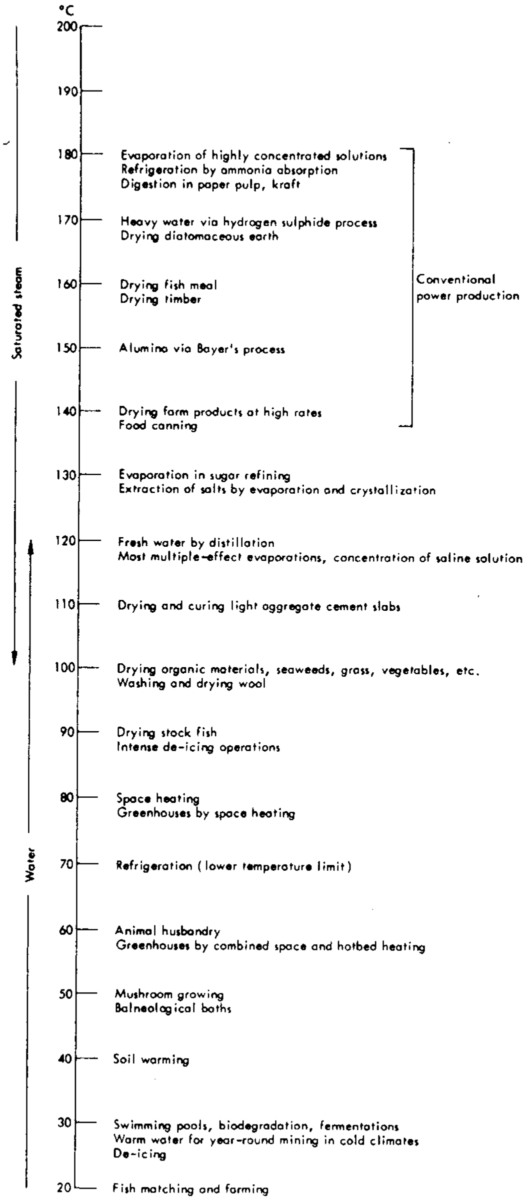

Figure 3.1 Required temperatures (approximate) of geothermal fluids for various applications (from Lindal, 1973).

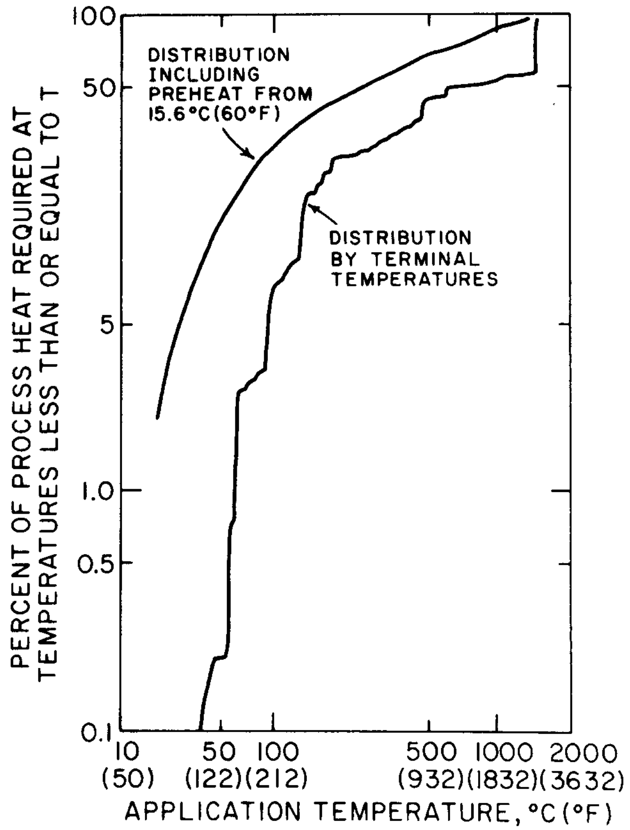

Figure 3.2 Cumulative distribution of process heat requirements (from Peterson, 1979; original source Intertechnology, 1977).

4. DIRECT APPLICATION SYSTEMS

In the previous sections, it was indicated that many processes require thermal energy at a temperature level compatible with geothermal energy and furthermore that geothermal energy can be expected to be exploitable in a majority of the states. Thus, geothermal energy may be a good choice of energy supply for many applications. However, the evaluation of the desirability of using geothermal energy, as well as the proper design for its use, in specific applications, requires consideration of the characteristics of geothermal systems and the interaction with the specific application equipment. In this section, the geothermal system characteristics and the use of geothermal energy in residential, commercial and industrial applications are considered.

4.1 General Systems

Figure 1.1 presented earlier, illustrates a geothermal system in which the geothermal fluid is produced, sent to the application site, used in the application, and then disposed of. In a typical system of this type, the geothermal fluid will be produced from the production borehole by using a line-shaft multistage centrifugal pump*. When the geothermal fluid reaches the surface, it is usually sent to an accumulator from which it is pumped, with standard circulating pumps, through the transportation and distribution systems to the application site. To meet short-term load increases that may occur on a daily basis, it is common to use local storage of the geothermal fluid near the application site. It is also usual to have the geothermal system designed to meet only the base load of the application, and incorporate a peaking station for satisfying the peak loads. The peaking station is most commonly a fossil-fueled unit that will allow the higher loads to be met in either of two ways: (i) increasing the temperature of the fluid supplied to the application by directly heating the geothermal fluid coming from the transportation system, or (ii) increasing the flow rate of fluid supplied to the application (at constant temperature) by heating fluid recirculated from the application and mixing it with fluid coming from the transportation system.

Figure 4.1 shows a somewhat different system than that illustrated in Figure 1.1. In the system of Figure 4.1 the geothermal production system and the disposal system are closely coupled, and they are both separated from the remainder of the system by a heat exchanger. The reason for isolating the production and disposal systems from the rest of the system is to limit the contact of the geothermal fluid with system equipment, thereby reducing problems arising from corrosion and scaling caused by the geothermal fluid. A secondary loop fluid is heated by the geothermal fluid in the heat exchanger. This secondary fluid, usually treated water, is the medium for transferring the energy to the application. The rest of the system in Figure 4.1 remains the same as in Figure 1.1 with the exception that the equipment designs can be based on the properties of the secondary loop fluid for equipment in Figure 4.1, but they must be based on the geothermal fluid properties for application as illustrated in Figure 1.1 The desirability of this secondary loop is obvious when the geothermal fluid is particularly harsh in terms of corrosion and/or scaling. Such a system arrangement is also advantageous when the geothermal fluid is relatively clean and the application requires direct use of the heated fluid in a process where water quality is of utmost concern, such as in the food processing industry. There is an additional environmental advantage for this type of system in that the geothermal fluid is pumped directly back into the ground without loss to the surrounding surface environment.

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* Some wells may free flow adequate quantities of fluid and a pump will not be required. However, the more common commercial size operation is expected to require pumping to provide the required flow rate.

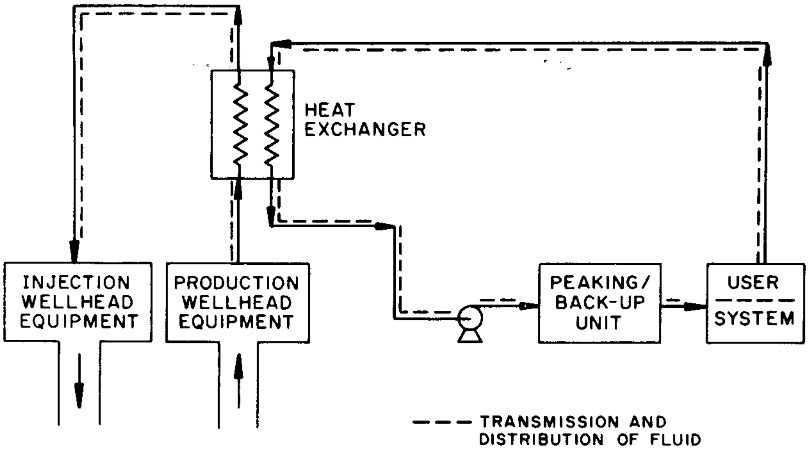

Figure 4.1 Geothermal direct utilization system with wellhead heat exchanger and injection disposal.

4.2 General Characteristics of Geothermal Systems

Geothermal energy systems have several characteristics that greatly influence their applicability and the design for their use. These characteristics arise from (i) the resource, (ii) the applications, and (iii) the interaction between both the resource and the application. The characteristics considered here take the form of either constraints or design variables. The constraints are fixed parameters that are specified for a particular resource and application, and although they cannot be varied for the application under construction, they influence the feasibility of using the geothermal resource in the particular applications. The design variables are those parameters that may be varied to improve the feasibility of geothermal energy use.

The characteristics that have a major influence on the cost of energy delivered from geothermal systems are:

- Depth of the resource
- Distance between resource location and application site
- Cost of capital
- Well flow rate
- Temperature of resource
- Allowable temperature drop
- Load size
- Load factor
- Composition of fluid
- Ease of disposal
- Resource life

Many of these characteristics have a major influence because the costs of geothermal systems are primarily front end capital costs, and the annual operating costs are relatively low.

4.2.1 Depth of the Resource. The well costs are usually the single biggest item in the overall cost of a geothermal system and as the depth of the resource increases, so does the cost of the overall system. Consequently, the relative economic advantage of using geothermal energy decreases significantly as the resource depth increases. The cost of drilling a given well varies greatly from area to area, so it is difficult to estimate costs that will be accurate for a specific well drilling. However, Figure 4.2 presents drilling and completion well costs that have been experienced in wells ranging in depth from 451 m (1500 ft) to 3160 m (10,400 ft) in the U.S. during the period 1974 to 1979. The costs illustrated in Figure 4.2 should be representative of those that would be incurred in drilling for wells in the depth range from about 457 m (1500 ft) to 3048 m (10,000 ft), but extrapolation of the curve is not recommended, particularly for the shallower wells. For the shallower wells, extrapolation of the curve in Figure 4.2 would yield costs that are much higher than the average well cost. Lund et al., 1979 report shallow well drilling and casing costs in the Klamath Basin as follows:

Drilling:	$1.00 per inch of diameter per foot of depth in "soft" rock and $2.50 per inch of diameter per foot of depth in "hard" rock up to 500 feet of depth. For every additional 100-foot increment, add $1.00 per foot of depth.
Casing:	$1.05 per inch of diameter per foot of depth for full depth casings.

These costs are applicable to depths up to about 984 m (3000 ft) for wells that do not require drilling muds, etc. Notice in Figure 4.2 that the cost per additional unit of depth increases greatly as the well depth increases. Because of this, the economic upper limit of well depth appears to be of the order of 3 km (10,000 ft) for developments in the near future.

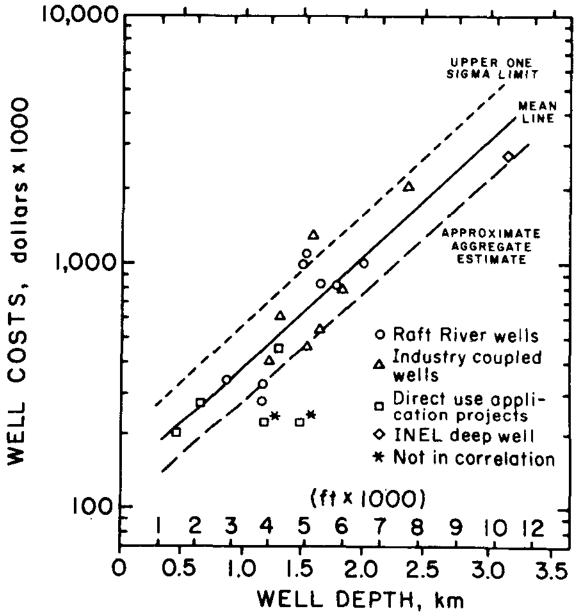

Figure 4.2 Well costs versus depth; corrected to 1978 prices (Chappell et al., 1979).

4.2.2 Distance Between Resource Location and Application Site. The direct use of geothermal energy must occur relatively near to the resource location. The reason is primarily economic, because although the geothermal fluid (or a secondary fluid) could be transmitted over moderately long distances, say greater than 100 km (62 mi), without having too large of a temperature loss, such transmission would not be economically feasible unless there were very special circumstances. The economic limit for the separation distance between the application and the resource depends on many factors attributable to both the application and the geothermal resource, so an accurate specification of it cannot be made in general. However, it is generally considered that under favorable conditions, economic viability can be achieved for separation distances as great as several tens of kilometers.

4.2.3 Cost of Capital. In a system where the costs are due primarily to capital costs, an increase in the interest rate that has to be paid for borrowed capital has nearly the same influence as an equal percentage increase in the capital costs themselves. Consequently, as the interest rate increases, the economic position of a particular geothermal system is decreased.

4.2.4 Well Flow Rate. The energy output from a production well varies directly with the flow rate of fluid. Thus, the energy cost at the wellhead varies inversely with the well flow rate. Typical good resources have production rates of the order of 25 to 50 l/s (400 to 800 GPM) per production well. The Boise, Idaho system wells have been operating for about 80 years at a flow of about 50 l/s (800 GPM) for each well bore (Kunze et al., 1976). The deep wells in the Klamath Falls, Oregon area used for heating the Oregon Institute of Technology have production rates of about 28 l/s (444 GPM) (Lund, 1979). Typical production rates in the French heating systems are about 29 l/s (460 GPM) per production unit (Rybach, 1979).

4.2.5 Temperature. In geothermal systems, the available temperature is that associated with the prevailing resource. This temperature is an approximately fixed value for a given resource. It seems that the temperature should be able to be increased with deeper drilling. However, because of the natural convection that occurs in the fluid dominated systems, which are the only ones being used at this time, the temperature is relatively uniform throughout the depth of the resource, and drilling deeper into the resource will provide basically a constant temperature (see Figure 2.1). If drilling is continued clear through the producing region into a region that is not permeable enough to permit the natural convection, the temperature will rise, but usually inadequate flow occurs to yield an economic resource. Deeper drilling at the same area can, however, possibly result in recovery of energy at a higher temperature in the event that deeper separate aquifers (producing zones) occur. Such an increase in temperature is also theoretically possible in the yet unproven hot dry rock type systems.

The temperature limitation can present a severe restriction on the potential applications. Quite often, in fact, it requires a re-evaluation of the commonly accepted application temperatures since these have been developed in systems fueled by conventional fuels where the application temperature could be selected at any value within a relatively broad range without a major change in the overall system design or energy efficiency. In the use of geothermal energy the application temperature must be lower than the produced fluid temperature except in the use of heat pumps where the application temperature may be somewhat greater than the produced fluid temperature.

4.2.6 Allowable Temperature Drop. The power output from the geothermal well is directly proportional to the temperature drop of the geothermal fluid that is effected by the user system since the well flow rate is limited. Consequently, a larger temperature drop means a decreased energy cost at the wellhead. If there is a loop fluid such as in Figure 4.1 and the maximum loop fluid temperature approaches the geothermal supply fluid temperature, the loop fluid must also have a reasonably large temperature drop across the user system. This is in great contrast to many conventional and solar systems that circulate a heating fluid with a very small temperature drop, where less than 10°C (18°F) drops are not uncommon. Consequently, a different design philosophy and different equipment are required.

Although it is important to have a goal of a large ΔT, the maximum ΔT in a single application is not always the most desirable because of the expense of heat exchange equipment at low approach temperatures. For this reason, cascading the geothermal fluid to uses with lower temperature requirements can be of advantage in achieving a large ΔT.

4.2.7 Load Size. It is advantageous to have large-scale applications because of the gain from economy of scale, particularly in regard to reduction in resource development and transmission system costs. However, it appears that in many instances the applications will not be extremely large and the more usual application will probably be one that will have one to several production wells. For these smaller developments, it is important to properly size match the application with the production rate from the geothermal resource because the energy output from the geothermal system comes in discrete sizes corresponding to one well increments. Figure 4.3 shows a schematic diagram of initial investment, at the wellhead, as a function of production rate illustrating the step costs for one well, one well being pumped and two wells (Coulbois and Herault, 1976). The lowest priced energy, for the range of production illustrated, occurs for an application sized to use a production rate just less than that which would require the second well.

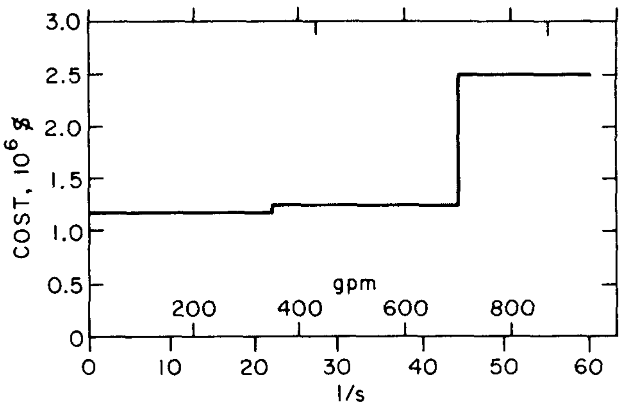

Figure 4.3 Cost of the geothermal water investment at the wellhead in terms of yield - Dogger aquifer, Parisian region (Coulbois and Herault, 1976).

4.2.8 Load Factor. The load factor, defined as the ratio of the average load to the designed capacity of the installed system, effectively reflects the fraction of time that the initial investment in the system is working. Again, because the geothermal system costs are primarily initial investment rather than operating costs, this factor significantly impacts the viability of using a geothermal system. As this factor increases, so does the economic position of using geothermal energy. The two main ways of increasing it are to select applications where it is naturally high and to use peaking equipment so that the load which the geothermal system is designed for is not the application peak load, but rather a reduced load that occurs over a longer period.

4.2.9 Composition of Fluid. As indicated previously, the quality of the produced fluid is very site specific and may vary from potable to heavily brined. The quality of the fluid greatly influences two main aspects of the system design; those of (i) fluid treatment/material selection to avoid corrosion and scaling effects and (ii) the disposal or ultimate end use of the fluid.

Although the specifics of dealing with the corrosion and scaling problems are to be considered later, at this point it must be indicated that for fluids that are particularly harsh, the main way of handling them is to isolate them from most of the system equipment by the use of heat exchangers of specially selected materials located near the resource as illustrated in Figure 4.1. Furthermore, to protect the environment, these very harsh fluids must be disposed of by injection. On the other hand, the more mild fluids may be dealt with by material selection for application equipment. In addition they may be able to be used in a consumptive end use such as agricultural irrigation if they are of sufficiently good quality.

Thus, the quality of the fluid may necessitate extra equipment or special disposal systems which increase the cost of the geothermal system, or it may allow additional end uses of the fluid, possibly decreasing the cost of the geothermal energy for a particular application.

4.2.10 Ease of Disposal. Depending on the particular resource and applicable environmental regulations, special systems, such as cooling, treatment and/or injection disposal may be required. The ease with which this can be accomplished directly influences the economics of the applications. For example, when injection of the fluid is required, if the local geological structure is such that this can be accomplished with shallow wells and small pumping requirements, the economics are much better than when deep wells and/or large pumping requirements occur.

4.2.11 Resource Life. The life of the resource has a direct bearing on the economic viability of a particular geothermal application for obvious reasons. At this point in time, there is not a lot of experience in the U.S. on which to base projections of resource life for heavily developed geothermal resources. However, the experience we do have, in the U.S. and worldwide, suggests that the resources can readily be developed in a manner that will allow resource lifes of 30, 40, 50 years and greater.

4.3 Equipment and Materials

The primary equipment components used in geothermal systems are pumps, heat exchangers, storage vessels and piping. Some aspects of these components are unique to geothermal applications, but many of the equipment components are of routine design. However, the great variability and general tendency of the geothermal fluid to be harsh in terms of corrosion and scaling requires that particular attention be directed at limiting corrosion and scale build-up, rather than system clean-up.

In this section, the special considerations of dealing with the geothermal fluid are first presented, followed by a discussion of the typical equipment.

Corrosion and scaling can be limited by (i) proper system and equipment design and (ii) treatment of the geothermal fluid. The first of these methods is routinely used in geothermal applications at this time while the second method is in the development stage. There has however, been substantial interest in the second method so it also merits consideration, and will be treated briefly at this point, before the more extensive discussions on system design.

Fluid treatment is the addition of corrosion and/or scaling inhibitors to the geothermal fluid, usually as it comes from the production system. Such treatment has the major drawback that very large quantities of geothermal fluid are used in most applications and therefore large quantities of the chemical additives are also required, making such treatment expensive. Treatment to prevent corrosion has the additional disadvantage that the added substances are of such a nature that EPA may require removal of all of the added chemicals from the system effluent stream prior to disposal. The chemicals added for scale control need not be removed prior to disposal. The work by Philips et al., 1977 discusses the primary aspects of brine treatment in geothermal systems and contains an extensive related literature listing.

In the proper system and equipment design for limiting corrosion and scaling, there are three primary concepts:

- Restrict the number of equipment components that come in contact with the geothermal fluid, particularly for the harsher geothermal fluids.
- Select component designs that can either be easily cleaned or that provide continuous cleaning during operation for those equipment items that are particularly sensitive to corrosion deposits and scale buildup.
- Select proper materials for those components that come in contact with the geothermal fluid.

The first two of these concepts are illustrated by specific examples. As discussed previously, the system shown in Figure 4.1 limits corrosion and scaling problems in surface equipment by limiting the contact of the geothermal fluid to the production well, the injection well and a wellhead heat exchanger. A following section on heat exchangers depicts various heat exchanger designs where a major feature of each design is either the ease of cleaning or the continuous cleaning of the heat transfer surface on the geothermal fluid side.

The third factor is important in all systems and will be considered in detail now.

4.3.1 Materials Selection.

The proper selection of materials for a geothermal application requires knowledge of the chemical composition of the geothermal fluid under consideration. Unfortunately, the composition of the fluid varies from resource to resource, and to some extent, even from well to well within the same resource. This, along with the fact that the presence of just minor amounts of certain substances can greatly influence the amount of corrosion or scaling that can occur, substantially limits the applicability of generalized rules of thumb for material selection in geothermal systems. The technology for selection of materials for use with geothermal fluids is still in the development stage with much work having recently been done and follow-on work continuing (see selected bibliography section entitled "Corrosion, Scaling and Materials Selection"). The work by DeBerry et al., 1978 represents one of the latest efforts to widely treat material selection for these applications, and it is the main reference for the discussion that follows.

The chemical species that are the major offenders regarding corrosion and scaling from geothermal fluids are listed in Table 4.1.

Table 4.1 Major Corrosion and Scaling Substances Contained in Geothermal Fluids. (DeBerry et al., 1978)

SUBSTANCE	MAJOR IMPACT (Corrosion or Scaling)	FORM
Hydrogen	Corrosion	Ion
Chlorides	Corrosion	Solid
Hydrogen Sulfide	Corrosion	Gas
Carbon Dioxide	Corrosion	Gas
Ammonia	Corrosion	Gas
Sulphates	Corrosion	Solid
Oxygen	Corrosion	Gas
Transition Metals	Corrosion	Solid
Silicates	Scaling	Solid
Carbonates	Scaling	Solid
Sulfides	Scaling	Solid
Oxides	Scaling	Solid

Generalized considerations concerning the corrosive effects of these are as follows (DeBerry et al., 1978):

Hydrogen ion (pH) - The general corrosion rate of carbon steels increases rapidly with decreasing pH, especially below pH 7. Passivity of many alloys is pH dependent. Breakdown of passivity at local areas can lead to serious forms of attack, e.g., pitting, crevice corrosion and stress corrosion cracking.

Chloride - Chloride causes local breakdown of passive films which protect many metals from uniform attack. Local penetration of this film can cause pitting, crevice corrosion, or stress corrosion cracking. Uniform corrosion rates can also increase with increasing chloride concentration, but this action is generally less serious than local forms of attack.

Hydrogen Sulfide - Probably the most severe effect of H_2S is its attack on certain copper and nickel alloys. These metals have performed well in seawater but are practically unusable in geothermal fluids containing H_2S. The effect of H_2S on iron-based materials is less predictable. Accelerated attack occurs in some cases and inhibition in others. High-strength steels are often subject to sulfide stress cracking. H_2S may also cause hydrogen blistering of steels. Oxidation of H_2S in aerated geothermal process streams increases the acidity of the stream.

Carbon Dioxide - In the acidic region, CO_2 can accelerate the uniform corrosion of carbon steels. The pH of geothermal fluids and process streams is largely controlled by CO_2. Carbonates and bicarbonates can display mild inhibitive effects.

Ammonia - Ammonia can cause stress corrosion cracking of copper alloys. It may also accelerate the uniform corrosion of mild steels.

Sulfate - Sulfate plays a minor role in most geothermal fluids. In some low chloride streams, sulfate will be the main aggressive anion. Even in this case, it rarely causes the same severe localized attack as chloride.

Oxygen - The addition of small quantities of oxygen to a high-temperature geothermal system can greatly increase the chance of severe localized corrosion of normally resistant metals. The corrosion of carbon steels is sensitive to trace amounts of oxygen.

Transition Metal Ions - "Heavy" or transition metal ions might also be included as key species. Their action at low concentrations on most construction materials is ill-defined. However, the poor performance of aluminum alloys in geothermal fluids may be due in part to low levels of copper or mercury in these fluids. Salton Sea, California geothermal fluids contain many transition metal ions at greater than "trace" concentrations. Some oxidized forms of transition metal ions (Fe^{+3}, Cu^{+2}, etc.) are corrosive, but these ions are present in the lowest oxidation state (most reduced form) in geothermal fluids. Oxygen can convert Fe^{+2} to Fe^{+3} which is another reason to exclude oxygen from geothermal streams.

Table 4.2 lists the usual metals that might be considered for use in geothermal systems along with indications of (i) the expected forms of corrosion that might occur, (ii) the fluid species and system factors that would cause corrosion and (iii) use limitations. After the composition of the geothermal fluid has been evaluated, Table 4.2 can serve as a guide for materials selection. Table 4.3 also presents general guidelines based on experience with the various metallic materials in geothermal applications.

4.3.2 Pumps. Pumps are used for three primary purposes in geothermal applications: production, circulation and disposal. For circulation and disposal, whether surface disposal or injection, standard state-of-the art hot water circulating pumps, almost exclusively of the centrifugal design, are used. These are routine engineering design selections with the only special consideration being the selection of appropriate materials. The production pumps on the other hand are not such a routine selection because of two main factors:

- There is usually only one production pump per production borehole so pump redundancy is not easily built into the system, and therefore a most reliable unit is desired.

- There is a substantial amount of development work currently being devoted to production pumping systems, particularly at the higher temperatures.

There are, however, production pump systems that have worked well in many applications.

The production well pumps fall into two classifications, "Wellhead Pumps" and "Downhole Pumps". Pumps of both classifications have the pump itself located down in the wellbore but the "Wellhead Pumps" have the driver located at the wellhead.

Wellhead Pumps - These pumps are usually referred to as vertical lineshaft pumps, or just lineshaft pumps. An above-ground driver, typically an electric motor, rotates a vertical shaft extending down the well the length of the pump. The shaft rotates the pump impellers within the pump bowl assemby which is positioned at such a depth in the wellbore that adequate NPSH will be available when the unit is operating.

Lineshaft pumps have their long vertical shafts supported in basically two different ways. One way is to have bearings inside a tube that is concentric to the shaft and of slightly larger diameter. This is referred to as an enclosed lineshaft pump. The other way (open lineshaft) is to have the bearings supported from the column pipe, and there is no tube that encloses the shaft.

In the enclosed lineshaft pump, a lubricating fluid is pumped or gravity fed through the tube to lubricate the bearings. Oil has been used successfully in this application for some geothermal systems but there has been little experience with its use in systems that have temperatures greater than 150°C (302°F). In some of the higher temperature systems, water has been pumped through the tube to provide the lubrication. Water can lead to mineral deposits on the bearings and it is recommended that the water used be treated as necessary to minimize these deposits.

The bearings in open lineshaft pumps are lubricated by the production fluid as it moves up through the column pipe. Such pumps are widely used in domestic water supply systems but have been used with little success in geothermal application (Lienau et al., 1980).

The realiability of lineshaft pumps decreases as the pump setting depth increases because of the lineshaft bearings. Nichols, 1978, indicates that at depths greater than about 243 m (800 ft) reliability is questionable even under good pumping conditions.

Downhole Pumps - The primary type of downhole pump is the electrical submersible pump. The electrical submersible is a commercially available product that can be readily used for geothermal resources at temperatures below about 120°C (248°F). Units to operate at resource temperatures above this value are presently being tested.

Table 4.2 Forms and Causes of Corrosion for Metals in Liquid Geothermal Streams and Ways to Prevent Attack (from DeBerry et al., 1978).

Material	Major Forms of Corrosion	Main Environmental Factors	Limits and Precautions	Other Comments
Mild and Low Alloy Steels				
	uniform	pH chloride flow velocity	Rapid rate increase below pH 6. Rapid rate increase above 2% Cl^-. Limit flow to 5-7 fps.	Air in-leakage is a major hazard; local flashing in pipes can cause very high flowrates and erosion/corrosion. Avoid direct impingement on steel.
	pitting, crevice	temperature chloride scale	Susceptibility increases with increasing temperature and chloride concentration. Remove all scale; avoid deposits.	See [*] for low alloy additions. Avoid mechanical crevices.
	hydrogen blistering	H_2S	Use void-free materials.	Possible at very low H_2S concentrations.*
	galvanic coupling	electrical contact with more noble metal	Avoid coupling close to large area of cathodic metal.	More severe when material has porous coating or scale.
Stainless Steels				
ferritic alloys	pitting, crevice	chloride scale stagnant or low flow oxygen	In general susceptibility increases with increasing concentration and temperature. Avoid scale deposits. Avoid stagnant or low flow conditions. O_2 greatly increases susceptibility.	Lower alloys may also have high uniform rates in severe environments; O_2 is a hazard. Higher alloys are much more resistant; Cr and Mo most effective alloying agents.*
	intergranular	chloride, temperature	Avoid by proper welding and heat treating procedures.*	
austenitic alloys	stress corrosion cracking	chloride oxygen temperature	Complex interaction; depending on other factors, cracking can occur for $Cl^- > 5$ ppm; $O_2 \sim 100$ ppb; $T > 60^\circ C$	Hazard increases with increase in Cl^-, O_2, T; some alloys more resistant; protect exterior surfaces.*
	pitting, crevice	chloride temperature scale stagnant or low flow oxygen	See ferritics above. Avoid scale deposits. Avoid stagnation or low flow conditions. O_2 greatly increases susceptibility.	Resistance increase with Mo content; avoid mechanical crevices.
	intergranular	chloride, temperature	Avoid by proper welding and heat treating procedures.*	
martensitic alloys	as above sulfide stress cracking	as above H_2S, temperature, stress, hardness	As above. More severe at lower temperatures; use low strength levels where possible.	General corrosion resistance depends on composition.*
cast alloys	as above			See comments for equivalent wrought alloy; good crevice corrosion resistance needed for pumps and valves.
Titanium Alloys				
	crevice, pitting	chloride temperature pH	Max. temperature for resistance depends on chloride and pH.*	Several alloys have much better resistance than pure Ti. Precracked Ti may undergo stress corrosion cracking.
	galvanic coupling	electrical contact with more active metal	Coupling to large area of more active metal may cause hydrogen embrittlement of Ti.*	
Nickel Alloys				
	crevice, pitting	chloride, temperature	Similar to stainless steels except higher alloys more resistant to crevice corrosion; high flow rates.	Resistance depends on alloy composition.* May be susceptible to hydrogen embrittlement when coupled to steel.
Cooper Alloys				
	pitting, uniform dealloying	H_2S chloride, temperature	H_2S as low as 0.1 ppm can cause attack.	Usefulness limited in H_2S environment.
	stress corrosion cracking	ammonia, pH	See [*] for pH and alloy dependence.	
Other Metals				
cobalt alloys			Avoid galvanic coupling to steel or other active metal.	Several alloys have good sulfide stress cracking resistance at high strength.*
zirconium and tantalum				Resistant to low pH, hot chloride solutions.
aluminum	pitting, crevice	Hg and Cu ions, pH, chloride, temperature	Poor results obtained in geothermal tests.	May be useful as exterior construction material.

*For further detail, see source reference.

Table 4.3 General Guidelines for Material Use in Geothermal Systems (from DeBerry et al., 1978).

MATERIAL TYPE	USE IN GEOTHERMAL SYSTEMS
Mild Steel	By taking appropriate precautions, mild steels can be used for thick-walled applications in contact with most geothermal fluids. Thin-walled applications will be limited by the susceptibility of these materials to localized attack such as pitting and crevice corrosion. High-salinity geothermal fluids will cause high uniform corrosion as well as localized corrosion and will severely limit the use of low carbon steels. The application of mild steels to geothermal environments requires that precautions be taken for aeration, flow rate, scaling, galvanic coupling, exterior surfaces and steel specifications.
Stainless Steel	The uniform corrosion rate of most stainless steels is low in geothermal fluids, but many are subject to the more serious forms of corrosion: pitting, crevice corrosion, stress corrosion cracking, sulfide stress cracking, intergranular corrosion and corrosion fatigue. Stainless steels have been used in geothermal environments, but care must be taken in their selection and application.
Titanium and Titanium Alloys	Titanium and its alloys have given good results in all but the most extreme environments when tested for geothermal applications. Titanium was used successfully for hydrogen and oil coolers exposed to aerated cooling water/condensate at the Cerro Prieto, Mexico geothermal facility. Two other heat exchanger materials had failed in this environment.
Nickel Based Alloys	High nickel alloys are frequently used to combat severe corrosion problems. The Ni-Cr-Mo alloys appear to be the most applicable to high temperature geothermal fluids. Similar alloys containing iron in place of molybdenum face competition from the most resistant stainless steels, but may find application when their mechanical properties are desirable. Cupronickels will have limited usefulness in geothermal streams containing even trace quantities of H_2S.
Copper Based Alloys	The use of copper alloys in geothermal fluids is severely limited by the relatively high concentrations of sulfide found in most sources. The Raft River KGRA*, with a low sulfide concentration of 0.1 ppm, appears to be an exceptional case. However, even in this fluid the performance of copper-nickel alloys (Monel 400, 70Cu/30 Ni, and 90 Cu/10 Ni) was very poor. Dealloying of some copper alloys was observed. However, some nickel-free brasses and bronzes gave acceptable performance.
Cobalt Alloys	Cobalt alloys may find application in services requiring high strength combined with resistance to sulfide stress cracking and in services requiring wear resistance.
Zirconium and Tantalum	Zirconium and tantalum may be considered for severe, hot acid chloride service such as injection nozzles for acidifying fluid with hydrochloric acid.
Aluminum Alloys	Aluminum alloys have not shown good resistance in tests conducted in direct contact with geothermal fluids. Low levels of transition metal ions, especially copper and mercury, greatly increase localized attack of aluminum alloys. These ions are present in most liquid-dominated geothermal fluids.

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* KGRA - Known Geothermal Resource Area

The electrical submersible pump system consists of three primary components that are located downhole: the pump, the drive motor and the motor protector. The pump is a vertical multistage centrifugal type. The motor is usually a three-phase induction type that is oil filled for cooling and lubrication. The cooling of the motor is accomplished by heat transfer to the pumped fluid moving up the well. The motor protector is located between the pump and the motor and has the primary function of isolating the motor from the well fluid while at the same time allowing for pressure equalization between the pump intake and the motor cavity.

The electrical submersible pump is considered to be a good candidate for geothermal well pumping because it has several advantages over the lineshaft pumps, particularly for wells requiring greater pump bowl setting depths. As the well gets deeper, the submersible becomes less expensive to purchase and easier to install. Moreover, it is less sensitive to vertical well deviation and the poor assembly conditions that normally exist at the wellhead. Although it is reported that the breakover point is at a pump depth of about 50 m (164 ft), with the submersible being desirable at pump depths greater than this and the lineshaft being preferred at shallower pump settings, the lineshaft has been much more widely used for geothermal applications than the electrical submersible with lineshaft pumps being typically used for depths of as much as 90 to 150 m (295 to 492 ft).

A recent development in submersible pumps that permits easy removal of the pump without removing the wellhead discharge pipe improves the desirability of the submersible units. In this newer unit, the submersible pump assembly is suspended in the wellbore with a cable. Pump servicing is accomplished merely by lifting the unit with the cable and removing it from the well piping through a stripper valve. Such a procedure can allow the pump to be removed without the use of well "kill fluids" to hold back the flow as would be required in the usual pump service operations.

Another type of downhole geothermal pumping system has been worked on since 1972 (Sperry, 1977). This system has a turbine and pump located downhole with a condenser at the surface and piping serving as a steam generator. It uses thermal energy from the geothermal fluid to drive the turbine, which drives the pump. Since this latter system is in the development stage it will not be considered further here.

4.3.3 Heat Exchangers. The systems in both Figures 1.1 and 4.1 use heat exchangers that have contact with the geothermal fluid. For the system of Figure 4.1, one or more large heat exchangers probably are located near the wellhead, whereas in the system of Figure 1.1, air and/or a process fluid might be heated by the geothermal fluid in a heat exchanger. The trend, at this time, is to isolate the geothermal fluid coming in contact with either complicated systems or systems that cannot readily be designed to be compatible with the geothermal fluids. For instance, the geothermal fluid would routinely be used directly to heat processing water in many industries, but would not usually be used directly in the evaporator of a heat pump (because of the complicated and expensive system) or in the extended surface coils of a building heating system (because the extended surface coils are almost exclusively made out of copper-based materials that are not compatible with most geothermal fluids, and also because the building system is complicated and expensive).

The principal types of heat exchangers used or being seriously considered for use in transferring energy from the geothermal fluid are:

- Plate
- Shell and Tube
- Downhole
- Direct Contact
- Plastic Tube

The first three types listed are presently used in many geothermal installations.

Plate heat exchangers. Use of plate heat exchangers is becoming widespread in geothermal applications. Among others, they are being used for low temperature applications in France, high temperature applications in Iceland and low and medium temperature applications in the U.S.

The plate heat exchanger, as illustrated in Figure 4.4, consists of a series of stamped plates that are placed one behind the other with seals between consecutive plates. A few or many plates can be stacked together. They are held in place by long bolts that extend through header plates and which when tightened press the plates against one another and compress the seals.

In use, the geothermal fluid is routed along one side of each plate with the heated fluid routed along the other side. The plates can be readily manifolded for various combinations of series and parallel flow. These heat exchangers have been widely used for many years in the food processing industry and in marine applications. They have two main characteristics that make them desirable for many geothermal applications:

- They are readily cleaned. By loosening the main bolts, the header plate and the individual heat exchanger plates can be removed and cleaned.
- The stamped plates are very thin and may be made of a wide variety of materials. When expensive materials are required, the thinness of the plates allows this type of heat exchanger to be much less expensive than other types.

These heat exchangers have additional characteristics that influence their selection in specific applications:

- Approach temperature differences are usually smaller than those for shell and tube heat exchangers.
- Pressure drops are usually larger than those for shell and tube heat exchangers.
- Heat transfer per unit volume is usually larger than for shell and tube heat exchangers.
- Applications are restricted for temperatures less than 260°C (500°F) because of limitations on elastomeric gaskets.
- Increased capacity can be accommodated easily; all that is required is the addition of plates.

The closer approach temperatures are particularly important in low temperature geothermal applications.

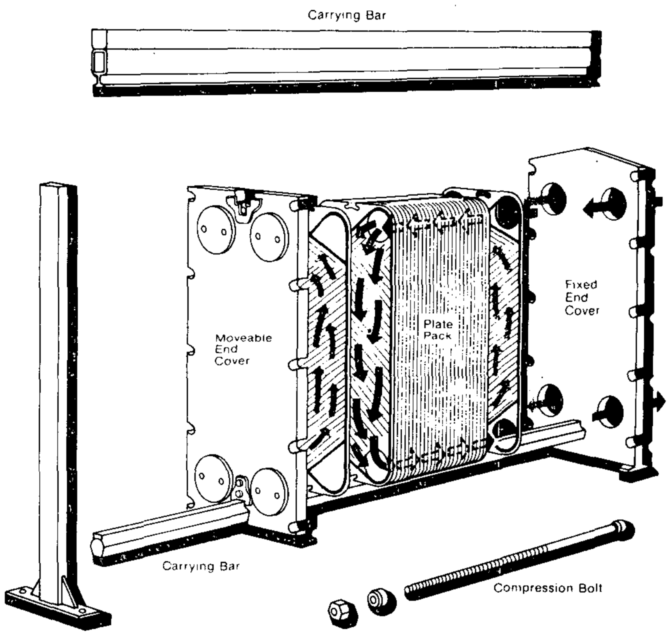
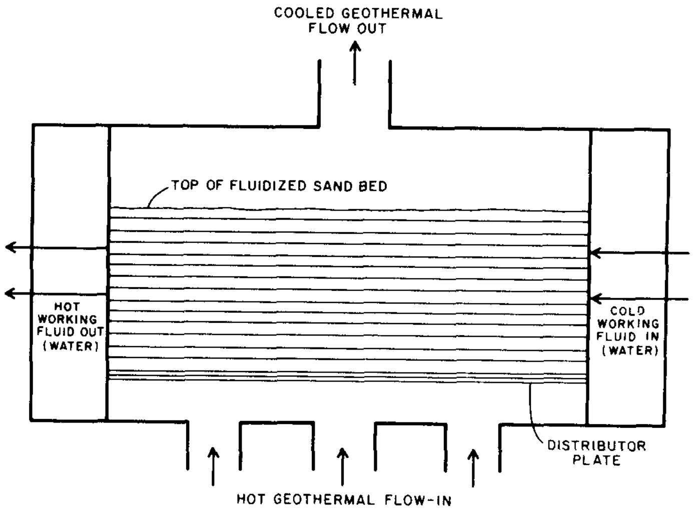


Figure 4.4 (at left)

Plate heat exchanger (courtesy of Alfa-Laval).

Figure 4.5 (at right)

Schematic of horizontal arrangement of a liquid-fluidized-bed heat exchanger (from Allen and Grimmett, 1978).



Shell and tube heat exchangers. This commonly applied type of heat exchanger is being used in a limited number of geothermal applications. It has limited application because the plate heat exchanger appears to have economic advantage when specialized materials are required to minimize corrosion. However, when mild steel shells and copper or silicon bronze tubes can be utilized, the shell and tube heat exchanger are usually more economical. When these units are used, with the geothermal fluid passing through the tube side, the tubes should be in a straight configuration to facilitate mechanical cleaning.

Two specialized designs of shell and tube heat exchangers are being developed for geothermal energy use with geothermal fluids that have a high potential for scaling. These are the "fluidized bed" and "APEX" (Advanced Geothermal Energy Primary Heat Exchanger) concepts. Figure 4.5 illustrates the type of fluidized bed heat exchanger being developed for geothermal applications. Its primary application is in use with fluids with high scaling potential. It consists basically of a shell-and-tube heat exchanger with the geothermal fluid (the scaling fluid) passing through the shell side. The fluid passes up through a bed of particles, such as sand, which surrounds the tube bundle. The bed is fluidized by the fluid flow and provides a constant scrubbing action against the tubes keeping them from scaling and, as a side benefit, increasing the heat transfer rate. The configuration can accommodate either horizontal or vertical tube bundle assemblies. Because of the rapid mixing in the fluidized bed, the shell side temperature distribution approaches isothermal and thus, to get the energy out of the geothermal fluid, such heat exchangers must operate with series staging. The APEX type of heat exchanger is similar to the fluidized bed design in that a scouring agent such as sand is used to help keep the heat transfer surface clean. But in the APEX design the abrasive material is injected into the geothermal stream just before the geothermal stream enters the tubes of a shell and tube heat exchanger. As the geothermal stream leaves the heat exchanger, it enters a disengaging zone and the abrasive material and any precipitated solid material is removed (Adams and Gracey, 1977).

Downhole heat exchangers. In shallow geothermal resource areas, heat exchangers located within the wellbore can have applicability for relatively small scale direct applications (Culver and Reistad, 1978). These downhole heat exchangers are presently used in a number of localities in the U.S.

Figure 4.6 shows a typical installation. The exchanger consists of pipes or tubes suspended in the cased wellbore. A secondary fluid is circulated from the user system through the exchanger. Geothermal fluid passes by the exchanger because of thermosyphoning caused by cooling from the heat exchanger. The systems with higher outputs have perforations in the well casing near the bottom and just below the water level to promote thermosyphoning.

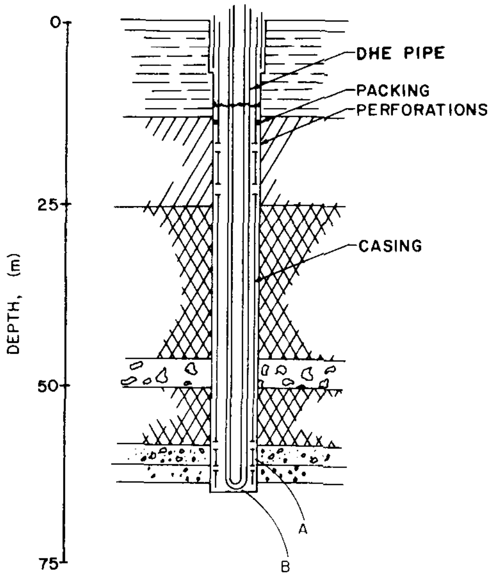


Figure 4.6 Typical downhole heat exchanger (DHE) installation (from Culver and Reistad, 1979).

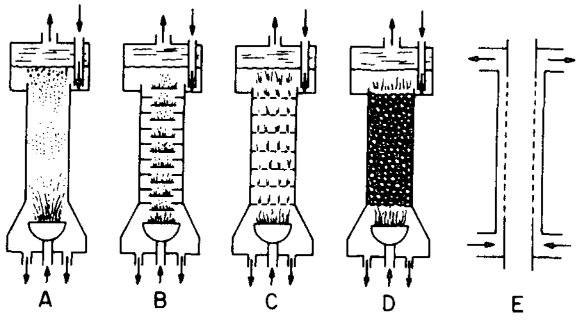


Figure 4.7 Schematic of various types of direct contact counter flow devices: (A) spray tower, (B) baffle tower, (C) perforated plate tower, (D) packed tower, and (E) wetted wall tower (from Jacobs, 1977).

These systems have not been tested in a large number of resource areas, so their general applicability is still somewhat in question at this time. In resource areas like that at Klamath Falls, Oregon, where over 400 downhole heat exchanger systems are in operation, it appears that economic desirability relative to surface heat exchanger systems exist when a single well output, typically less than 0.8 MW_t, is adequate for the application and the wells are relatively shallow, up to about 200 m (656 ft).

Direct contact heat exchangers. As another approach to cope with corrosion and scaling tendencies of some geothermal fluids, direct contact heat exchangers are being developed. In these, the geothermal fluid is brought into direct contact with another fluid that will vaporize at the desired recovery temperature and then separate from the geothermal fluid. Similar direct contact heat exchange is very common in oil refineries but there, the exchange is between relatively clean fluids. Figure 4.7 shows schematics of various configurations of direct contact heat exchange systems. The use of these systems is still in the development stage but they do appear to have a good potential for application if the particular application can readily make use of a vapor heating medium. One such application is the binary cycle power plant, which is the main application for which these units have been investigated to date. The systems do have the difficulty that the dissolved gases in the geothermal fluid end up mixed with the secondary vapor and must then still be dealt with.

Plastic tube heat exchangers. Plastic tube heat exchangers that have been developed for heat recovery from corrosive sources appear to have good potential for application in geothermal systems of a limited temperature range. Because the commonly used fan-coils have copper based tubes, they are unsatisfactory for most geothermal fluids. Plastic tube heat exchangers with an upper temperature limit of 50°C (122°F) and designed for air heating are presently commercially available. These could be used in low temperature geothermal applications to a limited extent, but more importantly, it appears that developing products will have a higher allowable temperature (of the order of 93°C (200°F)) and, consequently, much greater applicability. Such units will be substantially larger than the present fancoil units but the corrosion and scaling resistance appears to outweigh the increase in size (Lienau et al., 1980).

4.3.4 Piping. Standard low-carbon steel pipe is the most common type of pipe used for transmission and distribution lines in geothermal applications. This type of pipe has been the least costly for many installations and, when selected with adequate corrosion allowances, has given acceptable lifetimes. Because the mild steel is subject to severe corrosion when free oxygen is present in such systems, it is necessary to maintain a tightly sealed system.

Other types of piping, particularly those made of non-metallic materials, appear to have applicability in geothermal systems. However, many of the available ones have only been used in limited geothermal applications or are in the development stage.

Fiberglass reinforced plastic (FRP) pipe is being increasingly used for geothermal applications at temperatures up to about 100°C (212°F). The primary advantage responsible for its use is its non-corrosive nature (particularly in regard to external corrosion in direct buried lines). FRP pipe also has some advantage over steel pipe in that expansion considerations are not so severe and there is less pressure drop for a given flow rate in the FRP pipe. Disadvantages of the FRP pipe are its temperature limitation and its pressure limitation in the larger sizes, particularly at the higher end of the temperature range.

The use of PVC plastic pipe in geothermal applications is much more restricted because of the temperature limitation, with the maximum recommended temperature being about 52°C (125°F).

Asbestos cement pipe has been used in a number of geothermal applications, primarily disposal lines, with good success (Lienau et al., 1980). Recent studies have presented different conclusions regarding the economy of using asbestos cement piping: Lund et al., 1979, found that an asbestos cement based transmission line was the most expensive of the various acceptable alternatives, while Costello et al., 1980, reported that its use is more economical than carbon steel for transmission lines with diameters less than 406 mm (16 in).

A variety of non-metallic materials, particularly concrete polymer composites, plastics and refractories, are being evaluated for their use in geothermal applications through Brookhaven National Laboratory (Kukacka et al., 1976 through 1979). The concrete polymer composites have shown exceptional promise in uses as liner material even at temperatures up to about 240°C (464°F).

The types of piping specified for the main distribution lines in a recent district heating development are illustrated in Figure 4.8 (Lund et al., 1979). Figure 4.8a illustrates a steel pipe in a concrete tunnel with removable lids. This system (very widely used in Europe) is desirable because, (i) there is good access to the pipe for future development, maintenance and repair, (ii) there is good assurance that the exterior of the pipe will remain dry, and (iii) the concrete duct may be oversized to provide reduced overall cost with future expansion of the systems. The primary disadvantage of this type of system is its high cost. The system illustrated in Figure 4.8b is a direct buried FRP pipeline. It was selected for that portion of the overall development where no future pipe installations were envisioned. The primary reason for selecting this system is that the first cost of a direct buried system is much lower than that for a concrete tunnel system. With the direct buried system, FRP pipe rather than steel is selected to minimize external corrosion.

a. Steel pipe in a concrete tunnel with removable lids.

b. Direct buried insulated FRP pipe.

Figure 4.8 Main distribution lines in a geothermal district heating system (Lund et al., 1979).

Typical small business or residence piping connections in geothermal district heating systems in this country will probably follow the experience in Europe or Iceland where steel or FRP piping insulated with urethane foam covered with a plastic jacket is direct buried at a depth just below the frostline.

4.4 Residential and Commercial Applications

The primary applications for the direct use of geothermal energy in the residential and commercial area are space heating, sanitary water heating and space cooling. Space and sanitary water heating is quite widespread while space cooling is presently used in a relatively few instances. Since the sanitary water heating or at least pre-heating is accomplished almost universally when space heating is, these will be discussed together and then geothermal cooling will be considered.

4.4.1 Space and Sanitary Water Heating.

4.4.1.1 Examples of present systems. There are many present types of geothermal heating installations, the largest ones being located outside the U.S., but the U.S has examples of both modern and long-lived systems. The recent retrofitting of government buildings in Boise, Idaho is a good example of a modern moderate sized installation. Figure 4.9 illustrates the use of the geothermal fluid in the retrofitted system. The system obtains geothermal fluid at 77°C (170°F) from the Warm Springs Water District which has grown out of a historic heating district that dates back to 1892 (Austin, 1978). This geothermal fluid is used in two main equipment components for heating of the structures; a plate heat exchanger that has the purpose of supplying energy to a closed heating loop which has been previously heated by a natural gas boiler (the natural gas boiler remains as a standby unit), and a water-to-air coil that is used for preheating ventilation air. In this retrofit application, it was necessary to replace the original air handling unit water coils that were designed to operate with 82°C (180°F) water with larger coils designed to operate with 66°C (150°F) fluid. Because this application is a demonstration project, and really a test bed for many concepts, many different materials were used for the piping and heat exchange system exposed to the geothermal fluid. For the major transmission piping, two types of asbestos pipe were used: transite and temptite. Also, black steel, coated steel, cast-iron and a limited amount of copper piping were used. The plate heat exchanger is made of stainless steel and the preheat coil is made with copper tubes. In this system, it has been found that proper control is crucial for economical operation, and a major goal of control should be to extract a large amount of energy from each unit of geothermal fluid by discharging at the lowest feasible temperature at part load conditions as well as at the design point (Hull and Simmons, 1979). After leaving the heat transfer equipment, the geothermal fluid goes to a spray cooling pond with fluid discharge to the Boise River.

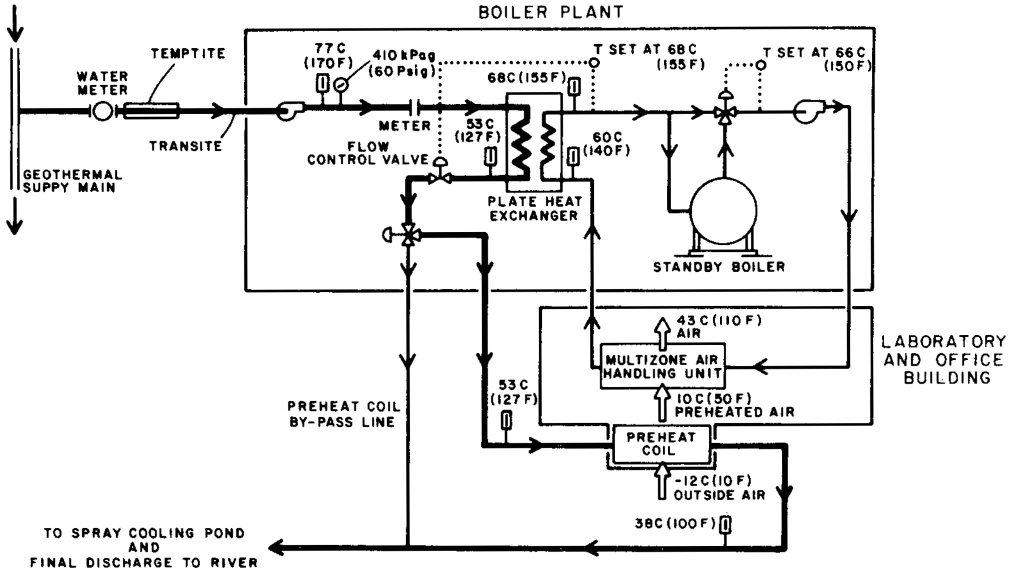


Figure 4.9 Heating system schematic (Austin, 1978).

The system which provides the heating of the Oregon Institute of Technology campus is also a relatively modern installation, but it was designed and built before the recent extensive interest and research on geothermal energy in this country and for that reason, it does not necessarily represent the type of system that probably would be designed for the same application at this time. Figure 4.10 shows a layout of the heating system. Three hot water wells have been drilled quite close to the campus. These wells are at depths varying from about 400 to 600 meters (1800 to 1950 ft), and can be individually pumped (with lineshaft pumps) at a rate of up to about 28 l/s (450 GPM). The fluid temperature is about 90°C (194°F) and as the outside temperature drops, two wells must be pumped simultaneously to provide up to 47 l/s (750 GPM) for heating the 26,500 m^2 (500,000 ft^2) of floor space. Throughout the system, the geothermal fluid is used directly in the terminal equipment within the buildings. Both hot water convectors and forced air units are used. This direct use of the geothermal fluid in the terminal equipment components is the part of the system that would probably not be done if the system were being designed today. A fair number of corrosion problems have arisen in this direct use, mainly due to the action of hydrogen sulfide on copper based equipment parts (Mitchell, 1980). Even with these difficulties, the geothermal system appears very cost effective, with the net savings relative to a conventional fueled system being reported at over $200,000 per year (Lienau, 1979). Disposal of the spent geothermal fluid in this system is to the storm drain system. The average temperature of the discharged fluid is 49 to 54°C (120 to 130°F).

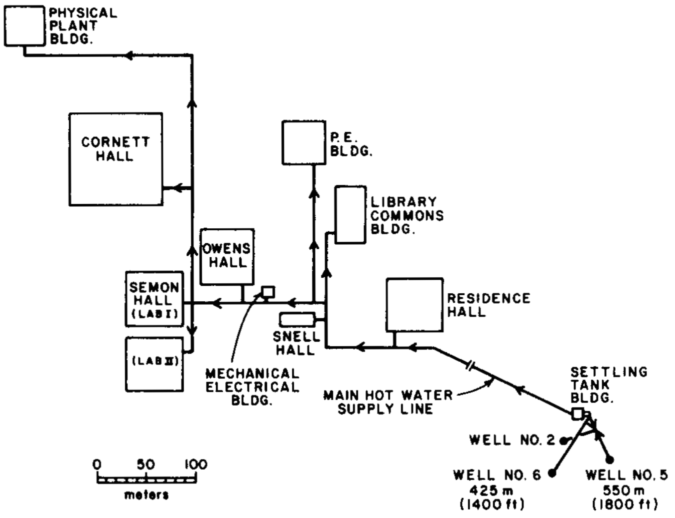


Figure 4.10 Oregon Institute of Technology geothermal heating system (Lienau, 1979).

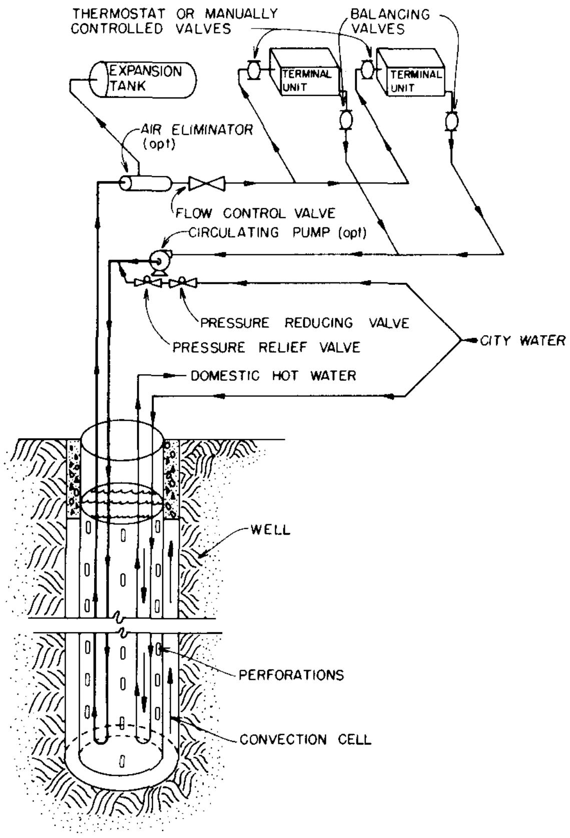


Figure 4.11 Typical connection of a downhole heat exchange system for space and sanitary water heating (Reistad and Culver, 1979).

Individual residence systems have been used in the Klamath Falls area since the 1920s. These systems use downhole heat exchangers as illustrated in Figure 4.6 previously. The use for a typical residence is illustrated in Figure 4.11. Water from the community supply system is used in a closed loop for the space heating, with make-up being accomplished through a pressure reducing valve. The sanitary hot water is supplied by connecting the city water supply to one leg of a downhole heat exchanger and the other leg of the downhole heat exchanger to the hot water supply piping within the residence. Typically, the space heating loop will be constructed of 5.08 cm (2 in) pipe and the water heating loop made with 2.54 cm (1 in) pipe. These systems have the advantages that they are relatively simple, requiring a minimal amount of wellhead equipment and avoiding any disposal associated problems. Such systems, however, are limited in their overall applicability, with their most desirability being for shallow resources and applications that have a thermal power requirement that is less than the output of a one well installation (Reistad and Culver, 1979).

The most extensive geothermal district heating system is that of Reykjavik, Iceland. This system uses resources beneath the city itself and resources from the Reykir area located about 15 km (9.3 mi) east of the city. At the end of 1977, the system was served by about 1400 l/s (22,000 GPM) at 85°C (185°F) from the wells around the Reykir area and 300 l/s (4700 GPM) at 128°C (260°F) plus 180 l/s (2800 GPM) at 103°C (218°F) from the resources beneath Reykjavik. About 16,000 houses are presently connected, with over 100,000 people being served. The system is schematically illustrated in Figure 4.12. The fluid is pumped out of the boreholes with deepwell pumps set at about 120 m (393 ft) depth, through collecting pipelines to the area's main pumphouse. Fluids at or above 100°C (212°F), pass through a dearator at the main pumphouse to remove dissolved gases. The fluid is then pumped through the high-temperature mains to the various district stations within the city. Fluids below 100°C (212°F) are held in open cisterns at the main pumphouse before being pumped into distribution mains. Since the system uses resources with quite different temperatures, two types of final distribution systems have developed. In the oldest part of the system, which was designed for a fluid supply temperature of about 85°C (185°F), a single-pipe design is used where the warm water is supplied to the house for heating and domestic use and then drained to the sewer. The availability of fluids from the Reykjavik area at temperatures too high for safe direct use led to a two-pipe design whereby a sufficient quantity of cooled water from the residences is collected in return water storage tanks for subsequent mixing with the high-temperature water in order to achieve the desired distribution temperature for heating and domestic use.

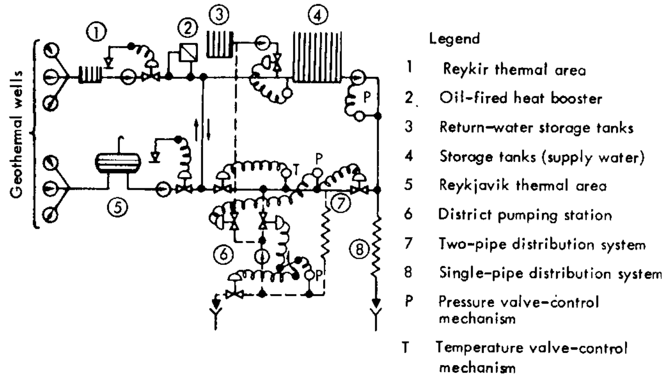


Figure 4.12 Schematic diagram of Reykjavik geothermal heating system (Zoega, 1974).

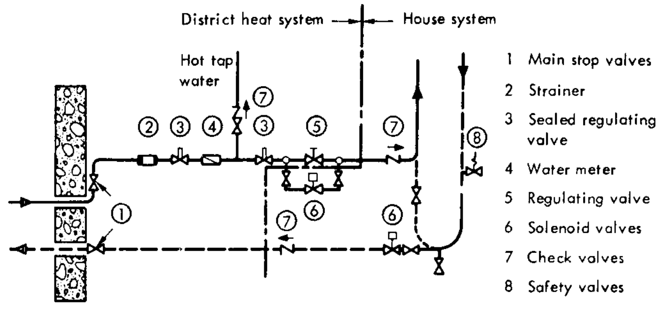


Figure 4.13 House connection for two-pipe Reykjavik system. A thermostat controls the supply of hot water to and from radiators in order to achieve the desired room temperature (Zoega, 1974).

Standard house connections for a two-pipe system are shown in Figure 4.13. The supply solenoid valve (6) is controlled by a room thermostat and a high-temperature limit switch controls the solenoid valve in the return line from the radiators. Demand is limited by a sealed regulating valve and consumption is measured with an integrating water meter.

The piping is all-welded black steel pipe laid underground. Piping of 7.6 cm (3 in) diameter or larger are laid in concrete channels and insulated with rock wool insulation. Smaller pipe is insulated with polyurethane foam and has an outside protective coating of high-density polyethylene.

The peak heating requirements of this system are met by increasing the temperature of the supply water in an oil-fired boiler plant.

The recent development of apartment heating from relatively low temperature geothermal resources in France, a country that has not been considered to have lucrative goethermal resources, has widened the interest in geothermal energy for direct applications. In several locations around Paris, fluid in the 49 to 71°C (120 to 160°F) range is being withdrawn from relatively deep horizontal sedimentary horizons. After being used, the fluid is injected back into the aquifer through a second borehole some distance away from the production well and the fluid passes through the aquifer again, drawing energy from the aquifer rocks. The geothermal system is referred to as a doublet and is being extensively studied. Figure 4.14 illustrates a schematic of the typical system. The wellbores may be either nearly vertical or slanted, and there are systems of both types presently in operation. Regardless of the way in which the wellbores are drilled, where they intersect the permeable horizontal aquifer they are about 1 km (3280 ft) apart. The oldest system of this type is of the order of 10 years old at this time, and this is too early to tell if the systems are performing close to what is expected. In these systems, the fluid that is injected back into the aquifer is heated up by the rock as it travels slowly from the injection point to the production point. For a period of time, the fluid that is produced will be relatively constant in temperature, with the injected fluid having been heated to the original temperature of the permeable rock. But at some time, the temperature of the produced fluid will start decreasing in temperature. Figure 4.15 shows the predicted temperature decrease for a typical system as presently being designed. Because such systems have a constant temperature output for a long time before the temperature starts decreasing, it will be some time yet before predictions such as that illustrated in Figure 4.15 can be confirmed from the present operating systems.

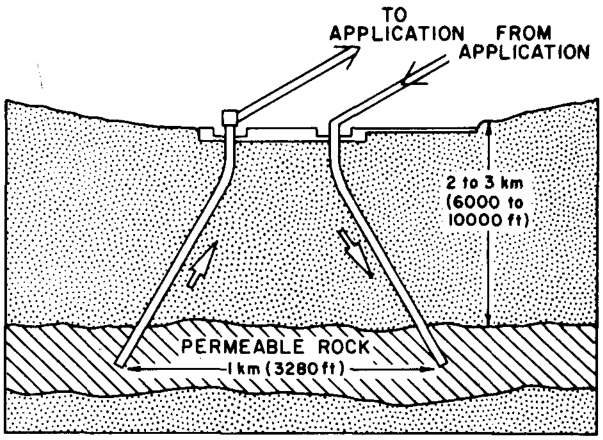


Figure 4.14 Schematic representation of the "doublet" system (Rybach, 1979, after BRGM, 1978).

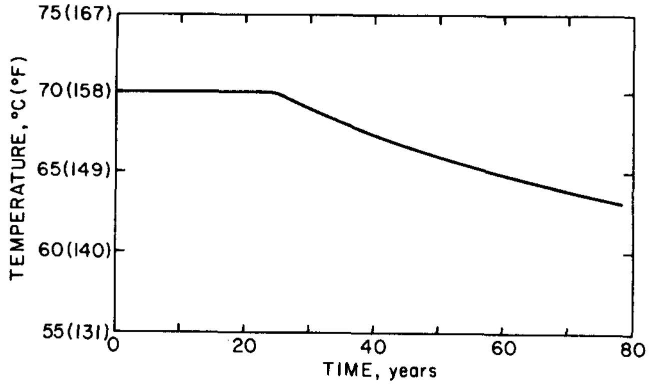


Figure 4.15 Temperature drawdown for a doublet system. Model calculation for a doublet spacing of 1300 m (4265 ft), production/reinjection rate of 55.5 l/s (880 GPM) aquifer thickness 40 m (131 ft), porosity 15% (Rybach, 1979, after BRGM, 1978).

Because the temperature of the resource is at the lower end of the scale in these French applications, a number of different systems have been considered (BRGM, 1978). Figure 4.16 shows one type of system that is being used. The system has the geothermal fluid separated from the buildings and the major equipment components by use of a surface heat exchanger, typically a plate heat exchanger and a closed loop heating circuit. A heat pump is used to reduce the return temperature of the closed loop heating fluid so the geothermal fluid can be cooled to a low temperature before injection. In this application, the apartment buildings being heated have two different types of terminal equipment, one group of buildings having radiant floor panels, with the other group of buildings having conventional wall radiators. The group of buildings that has the wall radiators also has the domestic water heated with the geothermal system while the other group does not. The buildings with the floor panels are supplied with heating fluid at about 55°C (131°F) with a return temperature of about 30°C (86°F), while the other group of buildings is supplied with heating fluid at about 60°C (140°F) that returns at about 40°C (104°F).

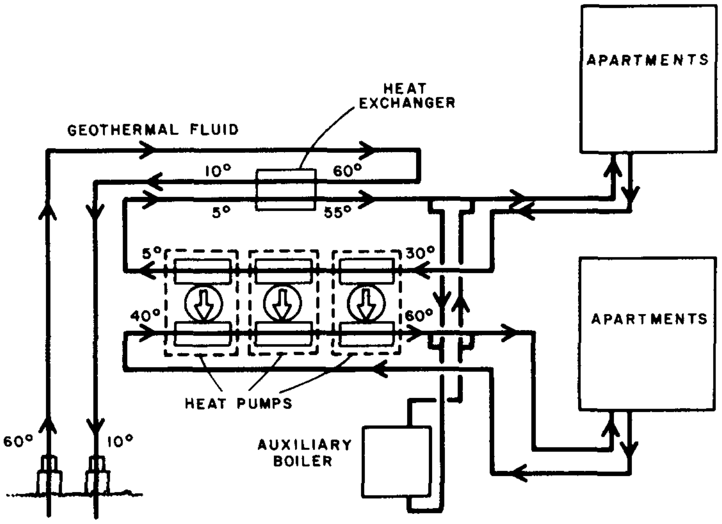


Figure 4.16 Simplified flow diagram of the geothermal heating installation at Creil. The upper block (2000 apartments) is equipped with floor panels, the lower block, where domestic hot water is supplied as well (2000 apartments), has conventional radiators. Temperatures in °C (Rybach, 1979, after BRGM, 1978).

Many other geothermal heating installations are in existence (see Table 3.2), but the ones described previously illustrate a representative cross-section of the types of systems. Table 4.4 lists geothermal heating projects that are presently being developed in the U.S. with partial support from the federal government.

Table 4.4 Geothermal Space Heating Projects in an Advanced State of Development as Demonstration Projects in the U.S., 1980. (USDOE, 1979).

TYPE OF APPLICATION	LOCATIONS
District Heating	Boise, ID; Klamath Falls, OR; Monroe, UT; Pagosa Springs, CO; Susanville, CA; Elko, NV.
Hospital	Marlin, TX; Pierre, SD; Butte, MT.
School	Box Elder, SD; Philips, SD.
College and Hospital	Corsicana, TX.
YMCA Space and Water Heating	Klamath Falls, OR.
Greenhouse	Salt Lake City, UT.
Prison	Salt Lake City, UT.
Heating and Cooling	El Centro, CA.
Apartment Heating	Reno, NV.

4.4.1.2 Types of terminal heating equipment. The types of heating equipment used in geothermal space heating installations are (i) radiant panel, (ii) baseboard or wall convectors, (iii) forced air, and (iv) heat pump. All of these except for the radiant panel systems are typically used in geothermal systems in the U.S. at this time. The selection of one type over the other is strongly dependent on the supply fluid temperature. Several techno-economic studies of the relative economic position of the various types of terminal systems lead to the following characterization (Culver, 1976; Engen, 1978; and Bodvarsson and Reistad, 1979):

- The heat pump system is the economically preferred system for fluid supply temperatures up to about 43 to 49°C (110 to 120°F).
- Forced air units are probably the most desirable type of residential heating system in the U.S. because of the general acceptance of these units and the ease of adapting filtration, humidity control or cooling. These systems have applicability for fluid supply temperatures ranging from about 49°C (120°F) (the top end of where the heat pump is applicable) upward.
- Baseboard convector systems appear to be the most economic at supply temperatures above about 60°C (140°F).
- Radiant floor panel systems can use water at supply temperatures as low as about 38°C (100°F), but are quite expensive.

4.4.1.3 Feasibility of space heating applications. In addition to the general characteristics of geothermal applications discussed previously, there are several factors that have a major influence on the feasibility of space heating from geothermal resources. These factors are listed in Table 4.5. The first of these, the type of terminal unit and its interaction with regard to temperature, have been discussed previously. The second, the alternative energy cost factor, is self-explanatory in that as the competing energy costs rise, the feasibility of the geothermal application increases when all other factors remain constant. The remaining factors affect the costs of the distribution system and the load characteristics. Factors that affect the distribution system costs are important because in district heating systems, whether based on geothermal, solar or conventional energy supplies, the distribution costs represent a significant part of the heating cost. These distribution costs, like the geothermal production system costs, are to a large extent due to front-end capital expenses and several of the factors previously discussed in consideration of the influence of the production system capital costs are also applicable in regard to the influence of the distribution system capital costs. The load characteristics directly influence the feasibility of geothermal space heating. In general, the feasibility increases as both the peak requirement and the load duration (i.e. load factor) increase. It increases as the peak requirement increases because this usually means that the average load has increased and therefore the system can benefit from economy of scale, which is particularly important in the user lines of the distribution system. The feasibility increases as the load factor increases because, as discussed previously, an increase in load factor improves the economics of a primarily capital cost system of which type both the geothermal production and the distribution systems are.

Table 4.5 Major Factors that Influence District Heating Feasibility.

Type of terminal unit

Alternative energy costs

Climate

Type of residential unit

Density of units

Total number of units

Type of financing for distribution system

For space heating, the prevailing climate dictates both the peak design and the load duration throughout the year (degree days). Figure 4.17 shows the temperature versus duration curve for temperatures at which space heating is required for a particular location. The residence heating system is typically designed not for the minimum temperature, but for the ASHRAE 97 1/2 percentile design point; the resulting load represents the peak design load. Unless auxiliary heating within the space is provided (not usual), the district heating system must also be designed to meet this peak load. Since the energy requirement is approximately proportional to the difference in temperature between the inside and outside temperatures, a power scale can be superimposed on Figure 4.17 as illustrated. As presented, the power curve also includes a contribution for the yearly average water heating rate. The geothermal system itself will typically be designed to be capable of meeting only about 60 percent of the peak design load, which as illustrated in Figure 4.17 (crosshatched area) satisfies much more than 60 percent of the yearly energy requirements, typically about 85 to 90 percent. Designed in such a manner, the distribution system will operate with a load factor dictated by the climate and system served with representative values being 0.25 to 0.35 for locations like New York City, New York; Portland, Oregon and Boise, Idaho, and the geothermal production system will operate with a load factor of (1/0.6) times that of the distribution system.

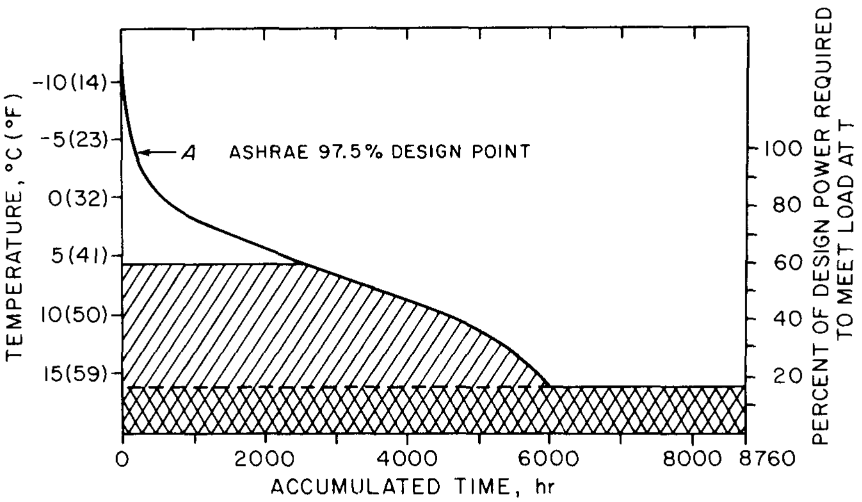
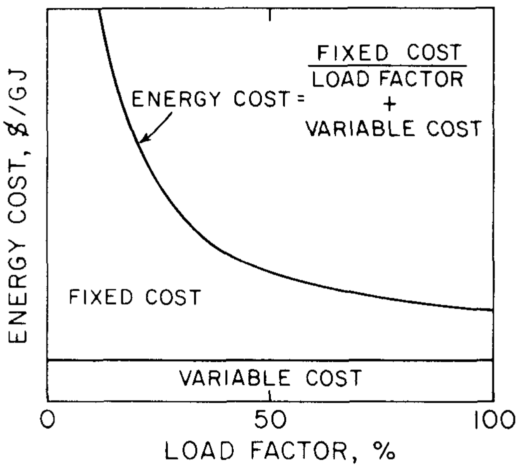


Figure 4.17 The temperature and power for space heating and sanitary water heating versus accumulated time at or below the given temperature for a particular location.

The type of residential unit served greatly influences the feasibility of the geothermal application because it determines the amount of energy that is to be delivered to each user site. Again, as the load at a point increases, the cost to deliver the energy, per unit of energy, decreases. For developments of a fixed housing density (number of housing units per unit of area), those developments with high energy requirements per housing unit will have greater feasibility for district heating than those with small energy requirements. Also, as the density of housing units increases so does the feasibility of district heating. The feasibility of district heating is much better for apartments than for suburban residence heating.

Figures 4.18, 4.19, 4.20 and 4.21 from a recent study of district heating feasibility illustrate the influence of load factor, heat demand density, load size and method of financing on distribution system costs. The specific values of the distribution costs, as illustrated, are not significant since they depend on many factors but rather they are presented here to illustrate the relative influence of the major factors.



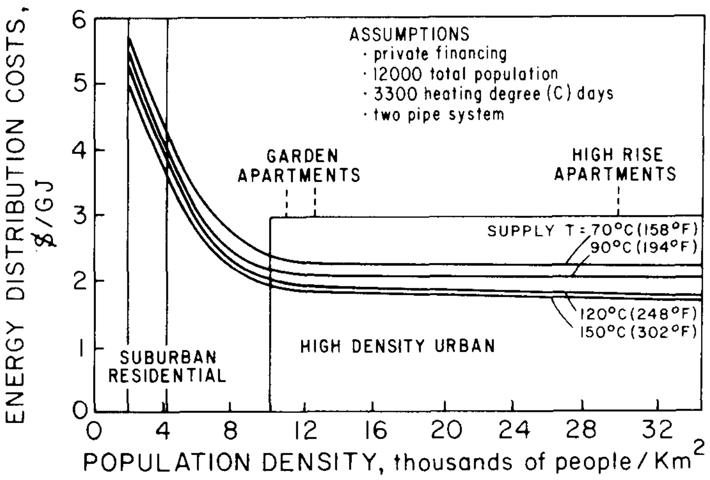
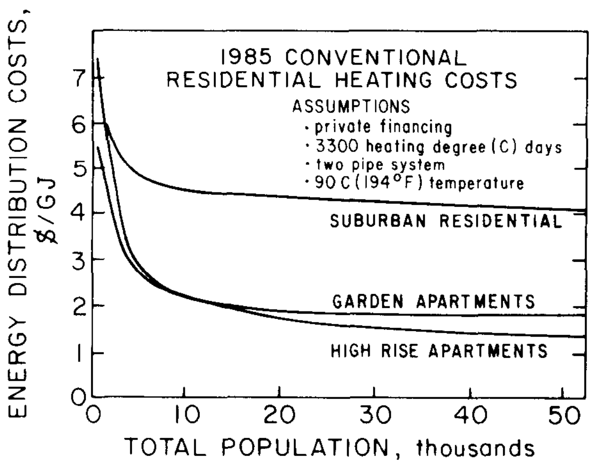


Figure 4.18 Effect of load factor on cost (McDonald, 1977).

Figure 4.19 Effects of density and distribution temperature on costs (McDonald, 1977).



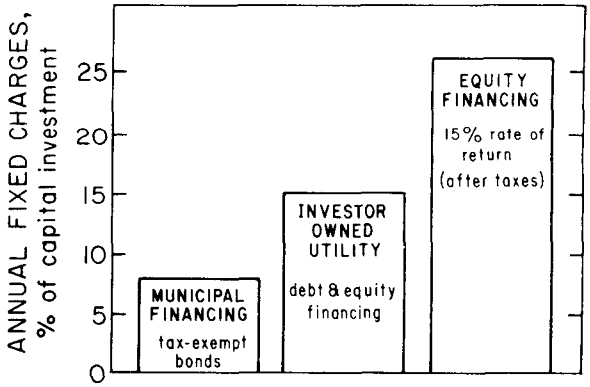


Figure 4.20 Effects of load size and density on costs (McDonald, 1977).

Figure 4.21 Effect of financing on annual costs (McDonald, 1977).

4.4.1.4 Peaking and energy storage. District heating systems have substantial load variations and the overall system design must include provisions for properly meeting them. In addition to the basic geothermal district heating system, peaking and energy storage systems are typically incorporated to meet these load variations.

The load variations can be characterized as arising from three main causes: (i) annual cycles of temperature, (ii) daily cycles of temperature, and (iii) personal habits such as the lowering of thermostats at night, different working hours, shower times, etc.

The annual and daily temperature variations result in the temperature-duration curve considered above in the discussion of the climate. Because a significant daily temperature variation cannot be relied on during periods when the design condition is approached, and the design condition may occur for an extended period, peaking methods rather than storage have been used to date to meet the primary load variations due to temperature change. The two main ways of supplying this peaking are by the use of (i) a fossil fired peaking station, discussed previously, and (ii) variable pumping of the geothermal resource with consequent large drawdown of the geothermal reservoir (Bodvarsson and Reistad, 1979).

Storage has, on the other hand, thus far been used mainly to meet short-term load increases that occur on a daily basis primarily due to personal habits. The storage is typically in large tanks which, using the geothermal experience in Iceland, are designed to hold about 20 percent of the peak flow over a 24-hour interval (Olson et al., 1979).

4.4.1.5 Inclusion of sanitary water heating. The inclusion of sanitary water heating in a district space heating system is beneficial because it increases the overall size of the energy load, the energy demand density and the load factor (see Figure 4.17). For those resources where sanitary water heating to the required temperature is not feasible, preheating is usually desirable.

4.4.2 Space Cooling. The use of thermal energy to drive cooling systems has occurred for many years. However, there has been little use of geothermal energy for cooling, with space cooling in the Rotorua International Hotel at Rotorua, New Zealand being the only widely reported occurrence. The application there uses a lithium bromide/water absorption unit to produce the cooling. Figure 4.22 illustrates the system. Geothermal fluid at about 150°C (302°F) and 600 kPa (87 psia) is passed through a heat exchanger to heat water in a piping circuit to a temperature of about 120°C (248°F). This heated water is used to (i) drive the absorption unit, (ii) provide space heating, and (iii) heat sanitary water.

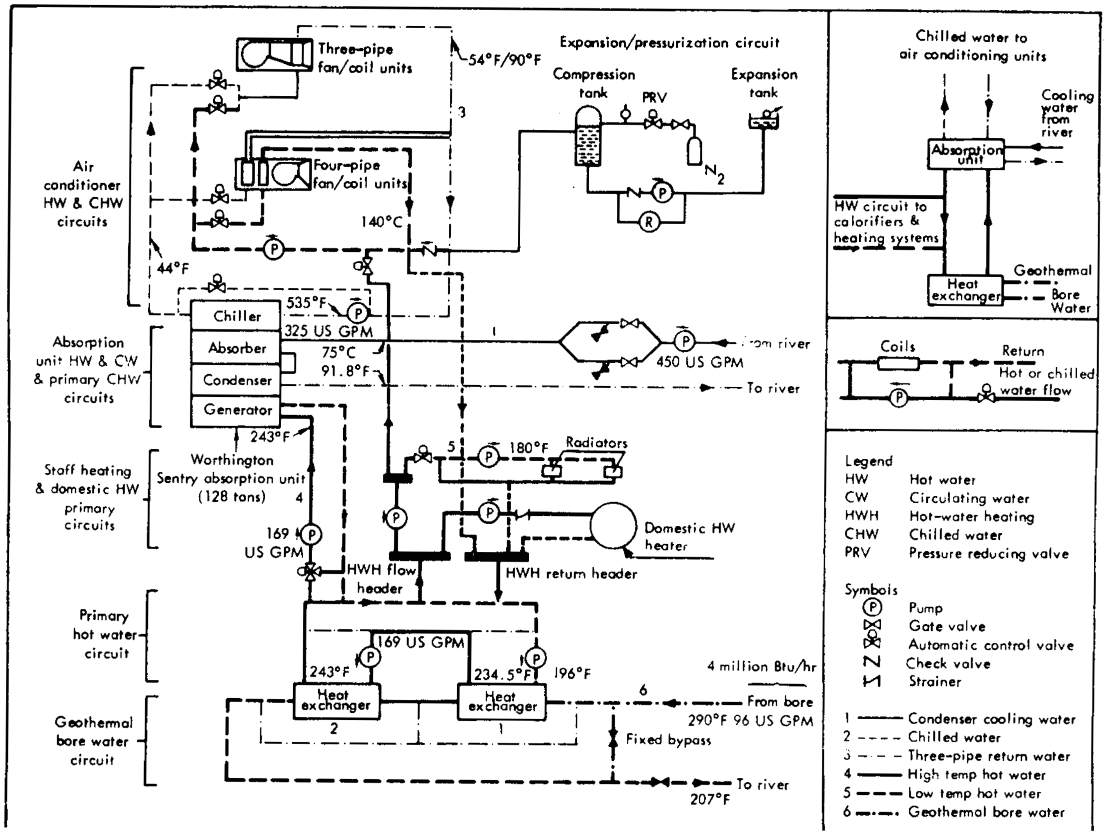


Figure 4.22 Geothermal heating and air conditioning installation in the Rotorua International Hotel, New Zealand (Einarsson, 1973).

In recent years, because of the emphasis on solar energy and waste heat, there has been a substantial amount of interest in various types of systems that can use thermal energy to produce cooling. Table 4.6 lists those types of systems that have received the most attention in recent studies. The most common of these is the absorption system. Figures 4.23 and 4.24 present schematic diagrams of the other two systems, the adsorption and Rankine-cycle engine/vapor-compression refrigeration systems. The renewed interest and consequent research on these systems have greatly improved the potential for widespread application of cooling with geothermal resources. The temperature at which reasonable performance can be obtained, particularly for the absorption systems, has been decreased substantially in new designs.

Table 4.6 Thermal Energy Driven Space Cooling Systems that are the Primary Candidates for Using Solar and Geothermal Energy for Space Cooling.*

Type of System	Current Development Status
ABSORPTION - Lithium-bromide/water absorption system	Commercially produced and widely used; new designs allow operation at lower thermal energy input temperature.
ADSORPTION - Cooling is accomplished by dehumidifying air and then cooling it by adiabatic humidification. Thermal energy reactivates the dessicant used to dehumidify the air.	Experimental development.
RANKINE-CYCLE ENGINE/VAPOR-COMPRESSION REFRIGERATION - Thermal energy drives a Rankine cycle engine which drives a vapor compression refrigeration system. Organic working fluids are normally used in the engines at low resource temperatures.	Small number of applications and demonstration installations.

* There are many other possible systems that can produce cooling from a thermal energy input. Examples of some of the additional systems are steam jet and Stirling cycle systems. These are not considered among the primary candidates because the steam jet systems are less efficient than those listed in this table and the Stirling cycle systems are much less developed than those listed.

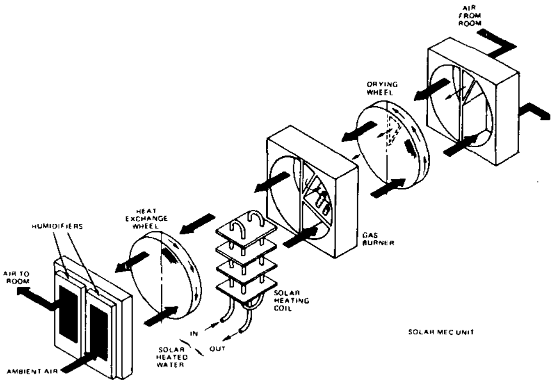


Figure 4.23 Schematic of adsorption cooling system (Newton, 1977).

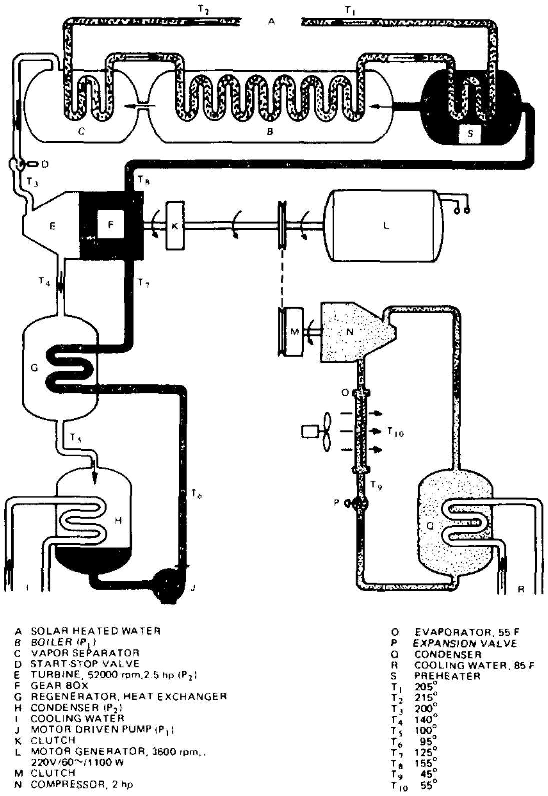


Figure 4.24 Schematic of Rankine-cycle engine/vapor compression refrigeration system (Newton, 1977).

Table 4.6 also indicates the state of development of the various systems. The absorption units are the most developed with widespread commercial production and application. Figure 4.25 shows the capacity and performance of an absorption unit typical of those being developed for space cooling with improved performance at lower temperatures. As illustrated, these units have good performance for heating fluid supply temperatures as low as about 60°C (140°F). Figure 4.26 shows a performance comparison between typical absorption units and Rankine cycle/vapor compression units. The comparison shows a decided advantage for the absorption units over much of the temperature range applicable for direct application of geothermal energy. For solar application some of this performance advantage of the absorption unit may be offset because the absorption units typically have large performance degradation due to intermittent operation. For geothermal systems, such a penalty is not envisioned because of the steadiness of the energy supply. Because the adsorption system is not in commercial production at this time, it is difficult to compare its relative desirability to the other systems. Although initially it appeared that adsorption systems would be able to operate at much lower temperatures than the absorption units, the recent developments in lowering the operating temperatures for absorption units have essentially removed this advantage. It now appears that the adsorption system will have the most applicability in meeting loads where the dehumidification load itself is substantial. Thus, at least for the immediate future, the absorption unit must be considered the most likely candidate for supplying space cooling from geothermal resources.

The use of absorption cooling from geothermal energy requires resource temperatures somewhat higher than the 60°C (140°F) temperature level indicated previously as about the minimum temperature at which reasonable performance can be expected from the absorption units themselves. It can be expected that new applications will occur with resource temperatures as low as about 71.1°C (160°F). However, for the same reasons as discussed previously with respect to space heating, the economics of operation improves as the temperature of the resource increases above this value.

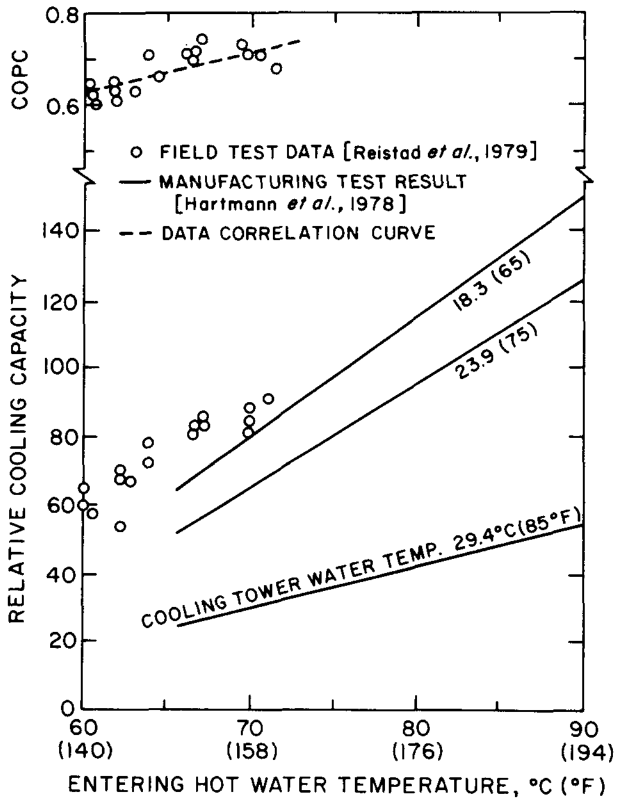


Figure 4.25 Absorption chiller cooling coefficient of performance (COPC) and capacity relative to the rated capacity at 82.2°C (180°F) entering hot water temperature and 23.9°C (75°F) cooling tower water temperature.

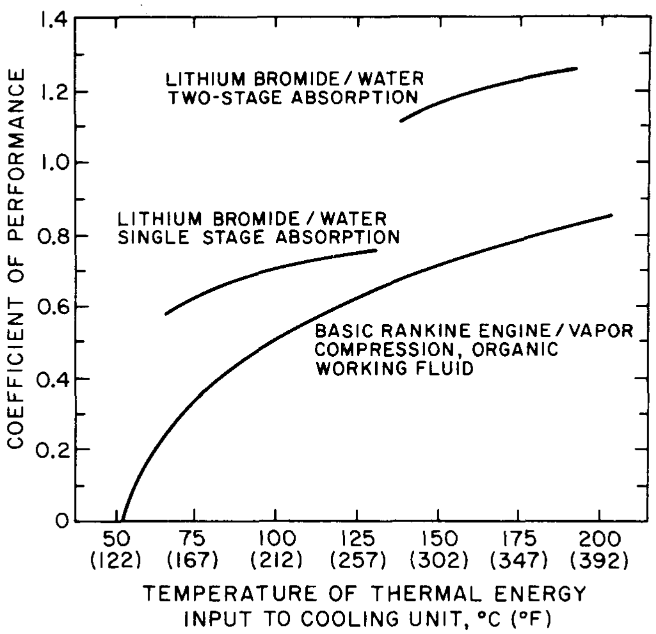


Figure 4.26 Comparison of the overall cooling coefficient of performance of Rankine-cycle/engine/vapor-compression cooling units for air conditioning applications (Ingle, 1979).

Space cooling with absorption units from the same geothermal resource that is used for space heating has the potential to improve the overall economics of the geothermal energy use. The potential for improvement is due primarily to a potentially increased load factor. However, whether or not the providing of space cooling will actually improve the load factor depends on the temperature of the geothermal resource and the ratio of the cooling load to the heating load. The load factor will in general be increased if the peak thermal energy required to operate the cooling system (cooling load divided by the cooling unit coefficient of performance (usually about 0.65 for a single stage absorption unit for the recommended range of operation)) divided by the temperature drop that the cooling unit can extract from the geothermal fluid is less than the heating load divided by the temperature drop that the heating system can extract from the geothermal fluid. Otherwise, the size of the geothermal system will have to be increased because of the space cooling requirement. Since the minimum temperature for absorption cooling is greater than that for space heating, the greatest load factor improvement will occur when the cooling load is less than the heating load and the resource temperature is substantially above the minimum required to operate the absorption unit. It is expected that large scale district systems will require geothermal resources with temperatures of about 93°C (200°F) or greater and that the systems to be used with geothermal resources will be designed to extract a relatively large temperature drop from the geothermal fluid.

The first geothermal space cooling application to be built in the U.S. is presently in the design phase. The city of El Centro, California is planning to use 113°C (235°F) fluid from the Heber resource area for providing about 229 kW (65 tons) of cooling with absorption units (Yamasaki and Sherwood, 1980).

4.5 Industrial Applications*

The use of geothermal energy in industrial applications requires design philosophies similar to those discussed above for space conditioning. However, industrial applications have the potential for much more economic use of the geothermal resource, primarily because of three factors: (i) many industrial applications with year around operation have the potential for greater load factors than most space conditioning applications do, (ii) industrial applications do not requir an extensive (and expensive) distribution system to relatively dispersed energy consumers as is common in district heating, and (iii) industrial applications occur at various temperature levels and, consequently, may be able to make greater use of a particular resource than space conditioning that is restricted to a specific temperature level. Recent studies have tried to take advantage of this last factor by combining several industrial applications into an "integrated" or "cascaded" system wherein the geothermal fluid is used in successive processes at lower and lower temperatures until it is finally discarded from the last process with the lowest temperature requirements.

Because the design aspects of the use of geothermal energy in industrial applications are basically the same as for space conditioning, the presentation here for industrial applications concentrates on, (i) illustrating those applications and basic processes that have temperature requirements such that they are potential candidates for geothermal heating, and (ii) presenting examples of the use of geothermal energy in various existing and proposed applications.

4.5.1 Potential applications. From an engineering viewpoint, a primary prerequisite for the potential use of geothermal energy in a process is that there be a match between the temperature of the geothermal resource and the application. Thus, for a direct use the temperature of the geothermal resources must be somewhat greater than the temperature requirement of the process. However, with the use of heat pumps, the geothermal resource temperature may be somewhat below the required temperature of the application. Because the temperature requirement is so important, it provides an initial screening parameter for considering potential processes.

Table 4.7 lists the temperature and magnitude of use for thermal energy in industrial applications in the U.S. Those applications with major requirements below about 150°C (302°F) are considered to have the most applicability for geothermal energy use for two main reasons: (i) above this temperature, the geothermal resource has potential for use in generation of electrical power and any direct use will face stiff competition from such use, and (ii) the higher temperature applications are more efficiently met with conventional fuels than are the lower temperature applications, while the reverse is true for geothermal resources over a wide temperature range.

The various uses listed in Table 4.7 can be categorized as occurring in the following basic processes:

- Washing
- Cooking, blanching and peeling
- Sterilization
- Evaporation and distillation
- Drying
- Preheating
- Miscellaneous heating
- Refrigeration

Washing. Considerable low temperature thermal energy in the temperature range of about 38 to 93°C (100 to 200°F) is used for washing. The principal users are the food processing, textile and metal-fabricating industries. The plastics and leather industries represent smaller consumers of such energy. The washing may typically be either a consumptive use or a non-consumptive use of the washing fluid. In the consumptive use (usual in the food processing and textile industries) fresh wash water requires heating from the temperature of the available water supply to the required wash water temperature. Such a requirement allows the geothermal resource to be used in an efficient manner since a large temperature drop of the geothermal can be realized. For the non-consumptive use of the wash fluid, (usual in the metal-fabricating industry) the fluid is recirculated for reheating with a 5.5 to 11.1°C (10 to 20°F) temperature change being representative of the reheating process. Such a restricted heating temperature change requires either that the resource temperature be substantially greater than the required temperature or that additional measures be taken to achieve a large temperature change for the geothermal fluid.

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* In the discussion to follow, the term industrial is used to denote agricultural growth as well as the usual industrial applications as listed in the standard industrial classification (SIC) codes.

Table 4.7 Required Temperature and Energy Use in Industrial Processes (Peterson, 1979; after Intertechnology, 1977).

Industry - SIC Group	T** °C	$\dot{Q}$***
1. Iron Ore - 1011		
Pelletizing of Concentrates	1288-1371	39.2
2. Copper Concentrate - 1021		
Drying	121*	1.8
3. Bituminous Coal - 1211		
Drying (including lignite)	66-104*	19.0
4. Sand and Gravel - 1442		
5. Potash - 1474		
Drying Filter Cake	121*	1.09
6. Phosphate Rock - 1475		
Calcining	760-871	0.75
Drying	232*	11.1
7. Sulfur - 1477		
Frasch Mining	163-171	63.0
8. Meat Packing - 2011		
Sausages and Prepared Meats - 2013		
Scalding, Carcass Wash, and Cleanup	60	46.1
Singeing Flame	260	1.12
Edible Rendering	93	0.55
Smoking, Cooking	68	1.22
9. Poultry Dressing - 2016		
Scalding	60	3.33
10. Natural Cheese - 2022		
Pasteurization	77	1.35
Starter Vat	57	0.02
Make Vat	41	0.50
Finish Vat	38	0.02
Whey Condensing	71-93	10.8
Process Cheese Blending	74	0.07
11. Condensed and Evaporated Milk - 2023		
Stabilization	93-100	3.09
Evaporation	71	5.48
Spray Drying	177-204	3.78
Sterilization	121	0.57
12. Fluid Milk - 2026		
Pasteurization	72-77	1.52
13. Canned Specialties - 2032		
Beans		
Precook (Blanch)	82-100	0.42
Simmer Blend	77-100	0.25
Sauce Heating	88	0.21
Processing	121	0.40
14. Canned Fruits and Vegetables - 2033		
Blanching/Peeling	82-100	1.98
Pasteurization	93	0.16
Brine Syrup Heating	93	1.08
Commercial Sterilization	100-121	1.76
Sauce Concentration	100	0.46
15. Dehydrated Fruits and Vegetables - 2034		
Fruit and Vegetable Drying	74-85	6.16
Potatoes		
Peeling	100	0.35
Precook	71	0.50
Cook	100	0.50
Flake Dryer	177	1.15
Granule Flash Dryer	288	1.15
16. Frozen Fruits and Vegatables - 2037		
Citrus Juice Concentration	88	1.40
Juice Pasteurization	93	0.28
Blanching	82-100	2.38
Cooking	77-100	1.49
17. Wet Corn Milling - 2046		
Steep Water Evaporator	177	3.86
Starch Dryer	49*	3.20
Germ Dryer	177	2.03
Fiber Dryer	538	3.09
Gluten Dryer	177	1.39
Steepwater Heater	49	0.81
Sugar Hydrolysis	132	1.99
Sugar Evaporator	121	2.89
Sugar Dryer	49*	0.17
18. Prepared Feeds - 2048		
Pellet Conditioning	82-88	2.40
Alfalfa Drying	204*	17.7
19. Bread and Baked Goods -2051		
Proofing	38	0.89
Baking	216-238	6.75
20. Cane Sugar Refining - 2062		
Mingler	52-74	0.62
Melter	85-91	3.48
Defecation	71-85	0.46
Revivification	399-599	4.18
Granulator	43-54	0.46
Evaporator	129	27.84
21. Beet Sugar - 2063		
Extraction	60-85	4.88
Thin Juice Heating	85	3.25
Lime Calcining	538	3.14
Thin Syrup Heating	100	7.05
Evaporation	132-138*	32.5
Granulator	66-93	0.16
Pulp Dryer	110-138*	17.4
22. Soybean Oil Mills - 2075		
Bean Drying	71	4.27
Toaster Desolventizer	102	6.41
Meal Dryer*	177*	4.60
Evaporator	107	1.71
Stripper	100	0.32
23. Animal and Marine Fats - 2077		
Continuous Rendering of Inedible Fat	166-177	17.4
24. Shortening and Cooking Oil - 2079		
Oil Heater	71-82	0.76
Wash Water	71-82	0.13
Dryer Preheat	93-132	0.63
Cooking Oil Reheat	93	0.34
Hydrogenation Preheat	149	0.39
Vacuum Deodorizer	149-204	0.37
25. Malt Beverages - 2082		
Cooker	100	1.61
Water Heater	82	0.56
Mash Tub	77	0.63
Grain Dryer	204*	9.68
Brew Kettle	100	4.20
26. Distilled Liquor - 2085		
Cooking (Whiskey)	100	3.33
Cooking (Spirits)	160	6.61
Evaporation	121-143*	2.45
Dryer (Grain)	149-204	2.05
Distillation	110-121	8.11
27. Soft Drinks - 2986		
Bulk Container Washing	77	0.22
Returnable Bottle Washing	77	1.34
Nonreturnable Bottle Warming	24-29	0.45
Can Warming	24-29	0.55
28. Cigarettes - 2111		
Drying	104*	0.45
Rehumidification	104*	0.45
29. Tobacco Stemming and Redrying - 2141		
Drying	104	0.26

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* No special temperature required; requirement is simply to evaporate water or to dry the material.

** Required application temperature

*** Process heat used for application, 10^{12}k J/yr.

Table 4.7 Required Temperature and Energy Use in Industrial Processes (Peterson, 1979; after Intertechnology, 1977). (continued)

Industry - SIC Group	T** °C	$\dot{Q}$***
30. Finishing Plants, Cotton - 2261		
Washing	100	16.2
Dyeing	100	4.7
Drying	135	23.4
31. Finishing Plants, Synthetic - 2262		
Washing	93	37.9
Dyeing	100	16.0
Drying and Heat Setting	135	24.5
32. Logging Camps - 2411		
33. Sawmills and Planing Mills - 2421		
Kiln Drying of Lumber	149	66.9
34. Plywood - 2435		
Plywood Drying	121	53.4
35. Veneer - 2436		
Veneer Drying	100	61.0
36. Wooden Furniture - 2511		
Makeup Air and Ventilation	21	6.0
Kiln Dryer and Drying Oven	66	4.0
37. Upholstered Furniture - 2512		
Makeup Air and Ventilation	21	1.5
Kiln Dryer and Drying Oven	66	0.9
38. Pulp Mills - 2611		
Paper Mills - 2621		
Paperboard Mills - 2631		
Building Paper - 2661		
Pulp Digestion	188	267
Pulp Refining	66	185
Black Liquor Treatment	138	173
Chemicals Recovery - Calcining	1038	101
Pulp and Paper Drying	143	404
39. Solid and Corrugated Fiber Boxes - 2653		
Corrugating and Glue Setting	149-177	22.8
40. Alkalies and Chlorine - 2812		
Mercury Cell (to be phased out by 1983)		6.8
Diaphragm Cell	177	86.6
41. Cyclic Intermediates - 2865		
Ethylbenzene	177	3.0
Styrene	121-177	37.0
Phenol	121	0.47
42. Alumina - 28195		
Digesting, Drying, heating	138	119.4
Calcining	1204	37.2
43. Plastic Materials and Resins - 2821		
Polystyrene, suspension process		
Polymerizer Preheat	93-102	0.107
Heating Wash Water	88-93	0.068
44. Synthetic Rubber - 2822		
Cold SBR Latex Crumb		
Bulk Storage	27-38	0.189
Emulsification	27-38	0.091
Blowdown Vessels	54-63	0.912
Monomer Recovery by Flashing and Stripping	49-60	4.319
Dryer Air Temperature	66-93	3.864
Cold SBR, Oil-Carbon Black Masterbatch		
Dryer Air Temperature	66-93	0.534
Oil Emulsion Holding Tank	27-38	0.030
Cold SBR, Oil Masterbatch		
Dryer Air Temperature	66-93	1.15
Oil Emulsion Holding Tank	27-38	0.095
Cold SBR, Oil Masterbatch		
Dryer Air Temperature	66-93	1.15
Oil Emulsion Holding Tank	27-38	0.095
45. Cellulosic Man-made Fibers - 2823		
Polyester	<288	51.6
Nylon	<279	44.0
Acrylic	<121	24.8
Polypropylene	<282	4.1
46. Noncellulosic Fibers - 2824		
Rayon	<100	39.9
Acetate	<100	39.7
47. Pharmaceutical Preparations - 2834		
Autoclaving and Cleanup	121	19.88
Tablet and Dry-capsule Drying	121	1.05
Wet Capsule Formation	66	0.05
48. Soaps and Detergents - 2841		
Soaps:		
Various Processes in Soap Manufacturer	82	0.53
High-Temperature Processes	254	0.002
Spray Drying	260*	0.001
Detergents:		
Various Low-Temperature Processeds	82	0.38
High-Temperature Processes	260	0.001
Drum-Dried Detergents	177*	0.33
Spray-Dried Detergents	260*	0.020
49. Organic Chemicals, N.E.C. - 2869		
Ethanol	93-121	6.0
Isopropanol	93-177	12.0
Cumene	121	1.0
Vinyl Chloride Monomer	121-177	9.0
50. Urea - 2873215		
High-Pressure Steam-Heated Stripper	191	5.35
Low-Pressure Steam-Heated Stripper	143	0.94
51. Explosives - 2892		
Dope (Inert Ingredients)		
Drying	149	0.006
Wax Melting	93	0.12
Nitric Acid Concentrator	121	0.07
Sulfuric Acid Concentrator	93	0.02
Nitric Acid Plant	93	0.23
Blasting Cap Manufacture	93	0.01
52. Petroleum Refining - 2911		
Crude Distillation		
Atmospheric Topping	343	290
Vacuum Distillation	227-427	193
Thermal Operations	291-543	162
Catalytic Cracking	607	471
Delayed Coking	482	237
Hydrocracking	268-432	96
Catalytic Reforming	496	525
Catalytic Hydrorefining	371	55
Hydrotreating	371	131
Alkylation	7-171	62
Hydrogen Plant	871	131
Olefins and Aromatics	649	131
Lubricants		26
Asphalt		101
Butadiene	121-177	63
53. Paving Mixtures - 2951		
Aggregate Drying	135-163*	92.9
Heating Asphalt	163	5.20
54. Asphalt Felts and Coatings - 2952		
Saturator	204-260	1.60
Asphalt Coating	149-204	1.30
Drying (Steam)	177	3.50
Sealant	149-204	0.60
55. Tires and Inner Tubes - 3011		
Vulcanization	121-171	6.52

Table 4.7 Required Temperature and Energy Use in Industrial Processes (Peterson, 1979; after Intertechnology, 1977). (continued)

Industry - SIC Group	T** °C	$\dot{Q}$***
56. Plastics Products - 3079		
Blow-Molded Bottles		
High-Density Polyethylene	218	3.71
57. Leather Tanning and Finishing - 3111		
Bating	32	0.099
Chrome Tanning	29-54	0.063
Retan, Dyeing, Fat Liquor	49-60	0.16
Wash	49	0.036
Drying	43*	2.16
Finishing Drying	43*	0.14
58. Flat Glass - 3211		
Melting	1260-1482	52.8
Fabrication (including Tempering and Laminating)	799-1093	3.7
Annealing	499	6.2
59. Glass Containers - 3221		
Melting-Firing	1482-1593	104.0
Conditioning	816-1093	44.56
Annealing	649	13.51
Post Forming	649	1.50
60. Hydraulic Cement - 3241		
Drying	135-163*	8.0
Calcining	1260-1482	494.0
61. Brick and Structural Tile - 3251		
Brick Kiln	1371	74.2
62. Clay Refractories - 3255		
Refractories Firing	1816	9.5
63. Concrete Block - 3271		
Low-Pressure Curing	74*	12.96
Autoclaving	182	5.72
64. Ready-Mix Concrete - 3273		
Hot Water for Mixing Concrete	49-88	0.36
65. Lime - 3274		
Calcining	982	137.0
66. Gypsum - 3275		
Kettle Calcining	166	10.5
Wallboard Drying	149	11.79
67. Treated Minerals - 3295		
Expanded Clay and Shale		
Bloating Process	982	30.7
67. Treated Minerals - 3295 (cont'd)		
Fuller's Earth		
Drying and Calcining	593	6.72
Kaolin		
Calcining	1040	1.5
Drying	110*	13.4
Expanded Perlite		
Drying	71*	0.23
Expansion Process	871	1.8
Barium		
Drying	110*	0.36
68. Blast Furnaces and Steel Mills - 3312		
High-Temperature Uses	1482	3480
69. Ferrous Castings		
Gray Iron Foundries - 3321 (73% of heat)		
Malleable Iron Foundries - 3322 (10% of heat)		
Steel Foundries - 3323 (17% of heat)		
Melting in Cupola Furnaces	1482	154
Mold and Core Preparation	149-246	124.1
Heat Treatment and Finishing	482-982	17
Pickling	38-100	160
70. Primary Copper - 3331		
Smelting and Fire-Refining	1095-1371	34.37
71. Primary Zinc - 3333		
Pyrolytic Reduction	1300	1.1
72. Primary Aluminum - 3334		
Prebaking Anodes	1093	8.59
73. Galvanizing - 3479		
Cleaning, Pickling	54-88	0.012
Galvanizing (melting zinc)	454	0.015
74. Motors and Generators - 3621		
Drying and Preheat	66	0.045
Baking-Prime and Paint Ovens	177	0.140
Oxide Coat Laminations	816-927	0.76
Annealing	816	0.71
75. Motor Vehicles - 3711		
Baking-Prime and Paint Ovens	121-149	0.31
Casting Foundry	1454	24.0
76. Inorganic Pigments - 2816		
Drying Chrome Yellow	93	0.079

Cooking, blanching and peeling. The food processing industry uses thermal energy to cook, blanch and aid in the peeling of many food items. These processes are accomplished in either a batch or continuous-flow mode. In the blanching or peeling operation, the produce comes in direct contact with a hot fluid. The hot fluid must have closely controlled properties and would have to be heated through a heat exchanger if geothermal energy were to be used as the energy source. These processes typically occur at temperatures in the range of 77 to 104°C (170 to 220°F). Cooking is accomplished both where the product comes in direct contact with the hot fluid and where the product is in containers which are in turn heated by the hot fluid. Cooking occurs over the temperature range of 77 to 104°C (170 to 220°F) with most of the cooking occurring at about 100°C (212°F).

Sterilization. Thermal energy is required at temperatures ranging from 104 to 121°C (220 to 250°F) for sterilization in a wide range of processes. These processes could utilize geothermal energy to heat the sterilizing water. Much of the sterilization can occur continuously, but equipment washdown and sterilization quite often occur periodically.

Evaporation and distillation. Many industries use evaporators and distillers for concentrating solutions or separating various products. The temperature requirements vary over a wide range depending on the products involved and the specific designs chosen. In many applications water is the fluid being evaporated. In these instances, the typical operating temperatures lie in the range of 82 to 121°C (180 to 250°F).

For geothermal application, optional economic operation requires that more stages of evaporation at lower temperatures be designed for as compared to designs based on conventional fuels.

Applications of evaporation and distillation that appear to have potential for geothermal energy use are sugar and organic liquor processing.

Drying. The drying of products occurs in many industries and is a large consumer of thermal energy in the temperature range appropriate for direct applications of geothermal resources. In most drying applications heated air is passed around or through the product to achieve the desired drying rate. Major products that require large amounts of drying energy are pulp and paper, textiles, farm products (grain, beet-pulp, beverage-malt, alfalfa, tobacco and soybean meal), lumber and plywood, and food products (sugar and dehydrated foods).

Preheating. Many industries consume large quantities of steam or high temperature water that has been heated from the local water supply temperature to the required use temperature. Geothermal energy can provide preheating for this water from the supply temperature to a temperature near that of the geothermal resource, and thereby decrease the load on the conventionally fueled heating equipment.

Miscellaneous heating. Thermal energy is used in many types of heating applications to maintain a space or product at a temperature which is elevated relative to the surroundings. Examples of such heating are space heating in industrial and agricultural applications (greenhouses and livestock facilities), warming of plant beds (open field soil warming and mushroom growing) and maintaining sewage digester tanks at operating temperatures.

Refrigeration. Industrial cooling can be accomplished with geothermal energy by several methods. The required refrigeration temperature strongly influences the type of system that will be selected. For refrigeration temperatures above the freezing point of water, the situation is analogous to space cooling and, as discussed previously, the lithium bromide/water system presently appears to have the most applicability. For refrigeration temperatures below about 0°C (32°F), either the Rankine engine/vapor compression system or an absorption system with a refrigerant other than water is the logical choice. Breindel et al., 1979, evaluated absorption refrigeration systems for refrigeration temperatures of 0°C (32°F) to -40°C (-40°F) with geothermal resource temperatures of 100°C (212°F) to 149°C (300°F). They investigated both the conventional ammonia/water system and an organic absorption refrigeration system using R-22 as the refrigerant and dimethylformamide (DMF) as the absorbent. Their conclusion was that the organic system requires more heat exchange area but results in better performance than the ammonia/water system. Table 4.8 illustrates a comparison of the two units for a fixed resource temperature of 149°C (300°F) and variable cooling temperature. In this application, the geothermal fluid is used only in the generator of the absorption unit and a representative design would be for the geothermal fluid to enter at 149°C (300°F) and leave at 121°C (250°F). Such high leaving temperature is characteristic of the design of such systems, because as the leaving temperature is decreased the efficiency of the refrigeration cycle decreases. Consequently, such a system should be coupled with a cascaded use to make proper use of the geothermal fluid.

At resource temperatures above about 150°C (302°F) a Rankine cycle engine/vapor compression unit may have applicability.

4.5.2 Present and Proposed Applications. The primary industrial applications that are presently in operation in the U.S. are in the area of agricultural growth and food processing. The heating of greenhouses is probably the most widely spread application, with many projects having been developed over the past several years. There are numerous developments in California, Oregon and Idaho, with a few occurring in other states. The geothermal fluid is typically used in natural convection coils located throughout the space or in forced-air convectors located at the ends of the greenhouses. Aquaculture has also received increased attention over the past several years, with geothermal heated facilities occurring in several states. Idaho currently has the largest production of aquaculture from geothermally heated facilities. In these applications, the geothermal fluid has been mixed directly with the water in which the fish grow.

Geothermal energy has been used for many years in the pasteurization of milk in Klamath Falls, Oregon. In this operation, the geothermal fluid is used in a plate heat exchanger to heat the milk to the appropriate temperature. For over 30 years, the only major problem has been the recurring corrosion of the pipelines.

Table 4.8 Comparison of R-22/DMF and NH_3/H_2O Absorption Refrigeration Systems at a Geothermal Supply Temperature of 149°C (300°F) (Breindel et al., 1979).

Cold Space Temperature	0°C (32°F)		-20°C (-4°F)		-40°C (-40°F)	
Refrigerant Pair	NH_3/H_2O	R-22/DMF	NH_3/H_2O	R-22/DMF	NH_3/H_2O	R-22/DMF
Number of Stages	1	1	1	2	2	2
Refrigeration Efficiency, %	25	41	25	40	20	24
Coefficient of Performance	0.75	1.20	0.40	0.63	0.2	0.24
Pump Power, kW/kW_c* (HP/ton)	0.025 (0.12)	0.038 (0.18)	0.057 (0.27)	0.049 (0.23)	0.098 (0.46)	0.104 (0.49)
Heat Exchange Surface Area, m^2/kW_c (ft^2/ton)	0.74 (28)	1.08 (41)	0.95 (36)	1.80 (68)	1.95 (74)	3.12 (118)
Capital Cost, $\$/kW_c$ (\$/ton)	119 (420)	151 (530)	219 (770)	264 (930)	418 (1470)	478 (1680)
RGU, kg/s kW_c** (lb fluid/hr-ton)	9.4×10^{-3} (263)	6×10^{-3} (167)	1.4×10^{-2} (385)	8.5×10^{-3} (238)	2.1×10^{-2} (588)	1.8×10^{-2} (500)

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* kW_c represents kW of cooling.

** Refrigeration geothermal utilization - geothermal fluid flowrate per unit of refrigeration. As RGU increases, the overall cost of geothermal supply increases. A minimum cost system requires a trade-off between equipment costs and geothermal fluid costs.

In 1978, a large vegetable dehydration facility was constructed at Brady Hot Springs, Nevada. This system, schematically illustrated in Figure 4.27, uses geothermal fluid for the washing and preparation phase of the operation as well as the extensive drying phase. The geothermal fluid which enters the processing facility at about 135°C (275°F) leaves at a temperature that varies from about 45°C (113°F) to 85°C (185°F), with the processing and the outside air temperature. The fluid is discharged to surface disposal. Experience has shown an improved product quality because, (i) the geothermal fluids are not hot enough to scorch the products as could occur with the usual natural gas heated systems, and (ii) the geothermal fluids are bacteria free (relative to usual surface fluids used for the washing process) and result in lower bacteria counts for the produced products.

On a worldwide basis, there are two primary applications that show the potential for large scale application of geothermal energy. These are the use of geothermal energy in pulp and paper processing in New Zealand and diatomaceous earth production near Namafjall, Iceland. The pulp, paper and wood processing plant of the Tasman Pulp and Paper Company, located in Kawerau, New Zealand, was the first major industrial development to utilize geothermal energy for heating purposes. The plant site was located because of the availability of geothermal energy. The geothermal energy was first used for timber drying in kilns and wood preparation in 1957 and for use in the pulp and paper operation in 1962. The resource is of a very high quality and the production designs incorporate flashing of the wet steam mixture at the wellhead and transmission of only the dry steam fraction. Steam at pressures of 689 to 1379 kPag (100 to 200 psig) are used for the various heating requirements of the pulp, paper and wood processing plant. This system has been operating quite satisfactorily and has a power output of about 100 to 125 MW. A unique feature of the plant is the standby 10 MW non-condensing turbo-alternator which is given priority for the geothermal steam in the event of a failure in the external electrical power supply. The production of diatomaceous earth at Namafjall, Iceland is a significant development for geothermal energy in industrial applications (see Figure 4.28), not only because it is a currently operational large scale application, but also because it serves as an example of the way in which cheap geothermal energy can make a process economic when, with conventional energy resources, the process could not be justified. Following the discovery of rich deposits of high-grade diatomite on the bottom of Lake Myvatn, technical and economic studies indicated that only by the use of potentially cheap geothermal energy from the nearby Namafjall high-temperature geothermal field could the recovery and drying of the diatomite be competitive with conventional diatomite production from comparatively dry land.

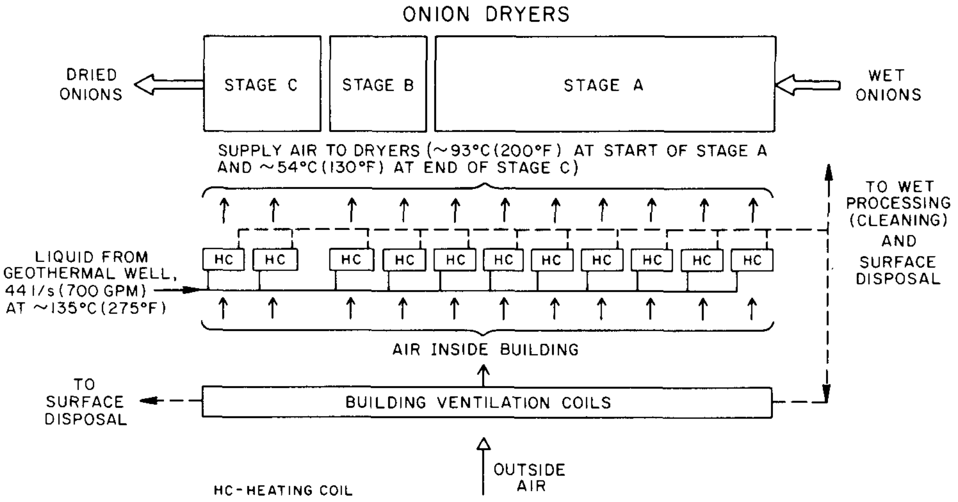

Figure 4.27 Schematic flow diagram of onion dehydration facility using geothermal energy (Rodzianko, 1979; McCabe, 1980).

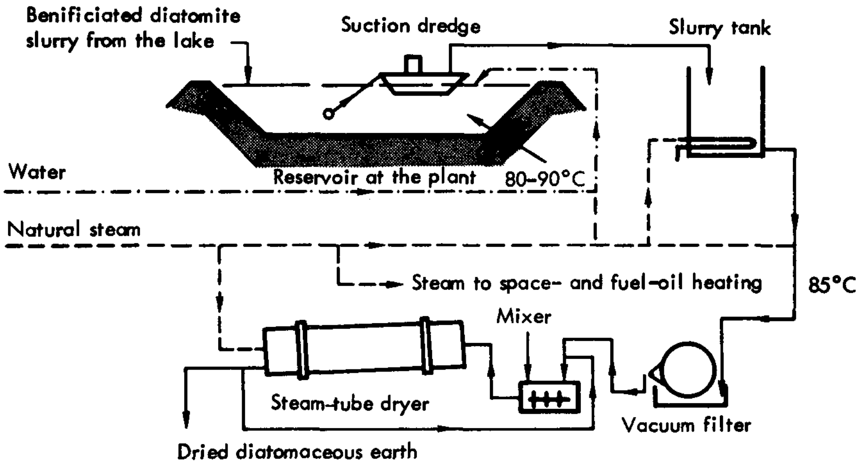

Figure 4.28 Flow diagram of the "wet end" of a diatomaceous earth plant illustrating where geothermal steam and water are used (Howard et al., 1975).

In late 1967, operation of the diatomaceous earth plant began with a production rate of 10.9 x 10^6 kg/year (24 x 10^6 lbs/year). In 1970, it was expanded and production increased to 21.8 x 10^6 kg/year (48 x 10^6 lbs/year). The geothermal fluid that is used corresponds to a well condition of 250°C (482°F) and a pressure of at least 3.90 MPag (566 psig). The fluid is flashed to provide saturated steam at 1.03 MPag (150 psig) pressure that is transmitted to the earth plant. In the plant, the energy is used for drying, slurry heating, space heating and deicing storage reservoirs during winter (see Figure 4.28). The total consumption during the winter amounts to about 45.4 x 10^3 kg/hr (1 x 10^5 lbs/hr) of the 1.03 MPag (150 psig) steam.

A very large variety of industrial processes have recently been studied for the potential application of geothermal energy. These include: (i) food processing (sugar refining, barley malting, preserved fruit and vegetable processing and potato processing), (ii) agricultural growth, (iii) pulp and paper processing, (iv) lumber and crop drying, (v) ethanol production, and (vi) integrated systems. The bibliography section of this report contains many listings for these applications under the headings "General Direct Applications", "Agricultural Growth" and "Industrial".

Those projects that are presently in the most advanced stage of development in the U.S. are listed in Table 4.9.

Table 4.9 Geothermal Direct Use Industrial Applications in an Advanced State of Development as Demonstration Projects in the U.S., 1980 (USDOE, 1979).

TYPE OF APPLICATION	LOCATIONS
Agribusiness	Rapid City, SD; Kelly Hot Springs, CA.
Food Processing	Boise, ID; Idaho Falls, ID.
Aquaculture	Mecca, CA.
Sugar Processing	Brawley, CA.

5. CLOSURE

The direct application of geothermal energy is occurring in various localities and regions of the U.S. and other countries. Through such application, geothermal energy holds the promise of becoming a much more widely used domestic energy source which can decrease dependence on foreign energy. With proven or potential resources occurring in many of the states of the U.S., geothermal energy should be considered a potential energy source for heating applications requiring temperatures up to about 150°C (302°F), or slightly higher, until it is ruled out. For those situations in which geothermal energy appears to have applicability, it is necessary that the energy system be designed in a manner which recognizes that geothermal energy is different than thermal energy generated in a fossil fired boiler system. This work, in addition to giving an overview of geothermal energy, has attempted to delineate the major factors that must be considered in the design of such energy systems as well as given examples of present systems and presented references for recent designs and studies of many applications.

6. REFERENCES CITED

1. J.F. Adams and C.F. Gracey: Wellsite Verification Testing of an Advanced Geothermal Primary Heat Exchanger (APEX) (Aerojet Liquid Rocket Co. Report 2146-.02-F, November 1977).

2. C.A. Allen and E.S. Grimmett: Liquid-Fluidized-Bed Heat Exchanger Design Parameters (DOE Report, ICP-1153, Allied Chemical, Idaho Chemical Programs, Idaho National Engineering Laboratory, April 1978).

3. J.C. Austin: A low temperature geothermal space heating demonstration project (Geothermal Resources Council, Transactions, Vol. 2, July 1978).

4. E. Barbier: Private communication (Italian National Research Council, Pisa, 1975).

5. D.B. Barton: Current status of geothermal power plants at The Geysers, Sonoma County, California (Geothermics, Special Issue, No. 2, Vol. 2, part 2, 1970).

6. G. Bodvarsson and G.M. Reistad: Performance and Feasibility of Forced Geoheat Recovery for Low Temperature Applications (Final Report to U.S. DOE, Report No. RLO-2227-T36-4, June 1979).

7. G. Bodvarsson and G.M. Reistad: Econometric analysis of forced geoheat recovery for low-temperature uses in the Pacific Northwest (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol 3, 1976).

8. G. Bodvarsson: Geothermal resource energetics (Geothermics, Vol 3, 1974).

9. T. Boldizsar: Geothermal energy use in Hungary (Proceedings International Conference on Geothermal Energy for Industry, Agricultural and Commercial-Residential Uses, Oregon Institute of Technology, Klamath Falls, Oregon, U.S.A. 1974).

10. B. Breindel, R.L. Harris and G.K. Olson: Geothermal absorption refrigeration for food processing industries (ASHRAE Transactions, Vol. 85, part 1, 1979).

11. BRGM; La Geothermie en France (Orleans, France, 1978).

12. M.C. Brown, R.B. Duffield, C.L.B. Siciliana and M.C. Smith; Hot Dry Rock Geothermal Energy Development Program, Annual Report, Fiscal Year 1978 (DOE Report LA-7807-HDR, Los Alamos Scientific Laboratory, University of California, April 1979).

13. E. Bullard: Basic theories (Geothermal Energy; Review of Research and Development, (UNESCO, Paris, France, 1973)).

14. R.N. Chappell, S.J. Prestwich, L.G. Miller and H.P. Ross: Geothermal well drilling estimates based on past well costs (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

15. J. Combs, J.K. Applegate, R.O. Fournier, C.A. Swanberg and D. Nielson: Exploration, confirmation and evaluation of the resource (Geothermal Resources Council, Special Report No. 7, Direct Utilization of Geothermal Energy: Technical Handbook, 1980).

16. S.R. Cosner and J.A. Apps: *A Compilation of Data on Fluids from Geothermal Resources in the United States* (DOE Report LBL-5936, Lawrence Berkeley Laboratory, Berkeley, California, May 1978).

17. J.K. Costain: Geothermal exploration methods and results - Atlantic Coastal Plain (Geothermal Resources Council, Special Report No. 5, *A Symposium of Geothermal Energy and its Direct Uses in the Eastern United States*, April 1979).

18. J.K. Costain, L. Glover III and A. Krishna Sinha: *Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States* (DOE Report VPI-SU-5648-1 through 5, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, December 1977 through March 1979).

19. J.K. Costain, L. Glover III and A. Krishna Sinha: *Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States* (DOE Report VPI-SU-5103-5, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, September 1977).

20. J.K. Costain, G.V. Keller and R.A. Crewdson: *Geological and Geophysical Study of the Origin of the Warm Springs in Bath County, Virginia* (DOE Report TID-28271, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, April 1976).

21. R.M. Costello, T. Ammerlaan, S.V. Cabibbo and L.E. Kukacka: Economic assessment of using non-metallic materials in the direct utilization of geothermal energy (*ASHRAE Transactions*, Vol. 86, part 1, 1980).

22. P. Coulbois and J. Herault: Conditions for the competitive use of geothermal energy in home heating (*Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources*, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

23. G.G. Culver and G.M. Reistad: *Evaluation and Design of Downhole Heat Exchangers for Direct Applications* (U.S. DOE Report No. RLO-2429-7, December 1978).

24. G.G. Culver: *Optimization of Geothermal Home Heating Systems* (Geoheat Utilization Center, Oregon Institute of Technology, Klamath Falls, Oregon, 1976).

25. F.J. Dan, D.E. Hersam, S.K. Kho and L.R. Krumland: Development of a typical generating unit at The Geysers Geothermal Project--a case study (*Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources*, San Francisco, California, May 1975).

26. D.W. DeBerry, P.F. Ellis and C.C. Thomas: *Material Selection Guidelines for Geothermal Power Systems* (DOE Report ALO-3904-1, Radian Corporation, Austin, Texas, September 1978). (Contains extensive literature of materials selection citations.)

27. S.S. Einarsson: Geothermal district heating (*Geothermal Energy: Review of Research and Development*, (UNESCO, Paris, France, 1973)).

28. I.A. Engen: *Residential Space Heating Cost: Geothermal vs Conventional Systems* (TREE-1182, Idaho National Engineering Laboratory, February 1978).

29. ERDA: *A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future* (Vol. 1-2, ERDA 76-1, 1976).

30. P.J. Grim, C.R. Nichols, P.N. Wright, G.W. Berry and J. Swanson: State maps of low-temperature geothermal resources (*Geothermal Resources Council, Transactions*, Vol. 2, July 1978).

31. D. Hartmann and W. Biermann: Prototype energy retrieval and solar system (Presented at Solar Outlook '78, Washington, D.C., March 1978).

32. J.H. Howard, Editor: *Present Status and Future Prospects for Non-Electrical Uses of Geothermal Resources* (ERDA Report UCRL-51926, Lawrence Livermore Laboratory, University of California, Livermore, California, October 1975).

33. G. Hull and G. Simmons: A retrofitted geothermal heating system (*ASHRAE* Journal, May 1979).

34. W.D. Ingle III: Direct heat activated cooling adapted to geothermal energy (Geothermal Resources Council, Special Report No. 5, *A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States*, April 1979).

35. Intertechnology Corporation: *Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat* (Final Report, Vol. 1, 2 and 3, February 1977, Col. 28-29-1 NTIS, Springfield, Virginia 22161).

36. H.R. Jacobs: Evaluation and design considerations for liquid-liquid direct contact heat exchangers for geothermal applications (ASME Publication, 77-HT-2, August 1977).

37. R.N. Kerr, R. Bangma, W.L. Cooke, F.G. Furness and G. Vamos: Recent developments in New Zealand in the utilization of geothermal energy for heating purposes (*Proceedings United Nations Conference on New Sources of Energy*, Rome, Italy, 1961, (United Nations, New York, 1964) Vol. 3, Paper G/52).

38. L.E. Kukacka et al.: *Alternate Materials of Construction for Geothermal Applications* (Brookhaven National Laboratory Progress Reports 1976 through 1978).

39. J.F. Kunze and K.F. Forsgren: The economics of the heat pump as a device to assist in geothermal district space heating (*Geothermal Resource Council, Transactions*, Vol. 2, July 1978).

40. J.F. Kunze, A.S. Richardson, K.M. Hollenbaugh, C.R. Nichols and L.L. Mink: Nonelectric utilization project, Boise, Idaho (*Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources*, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

41. D. Lenzi: Utilisation de l'energie geothermique pour la producion de l'acide boriquet et des sous-produits contenus dans les 'soffione' (*Proceedings of the United Nations Conference on New Sources of Energy*, Rome, 1961, Paper G/59).

42. P. Lienau, M. Conover, R.L. Miller, G. Culver, J. Balzhiser, R.G. Campbell, L.E. Donovan, G. Reistad, J. Austin, L.A. Fisher and R.C. Niess: Utilization (Geothermal Resources Council, Special Report No. 7, *Direct Utilization of Geothermal Energy: Technical Handbook*, 1980).

43. P.J. Lienau: Materials performance study of the OIT geothermal heating system (*Geo-Heat Utilization Center Quarterly Bulletin*, Oregon Institute of Technology, Klamath Falls, Oregon, June 1979).

44. B. Lindal: Industrial and other applications of geothermal energy (*Geothermal Energy: Review of Research and Development*, (UNESCO, Paris, France, 1973)).

45. B. Lindal: Geothermal heating for industrial purposes in Iceland (*Proceedings United Nations Conference on New Sources of Energy*, Rome, 1961 (United Nations, New York, 1964)).

46. J.W. Lund, P.J. Lienau, G.G. Culver and C.V. Higbee: Klamath Falls geothermal heating district (*Geothermal Resources Council, Transactions*, Vol. 3, September 1979).

47. J.W. Lund: Worldwide direct application review (Geothermal Resources Council, Special Report No. 5, *A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States*, April 1979).

48. J.W. Lund, J.F. Silva, G.G. Culver and P.J. Lienau: *Corrosion of Downhole Heat Exchangers* (Report 76-3, Geo-Heat Utilization Center, Oregon Institute of Technology, Klamath Falls, Oregon, 1976).

49. J. Lund, G. Culver and L. Svanevik: Utilization of geothermal energy in Klamath Falls (*Proceedings International Conference of Geothermal Energy for Industrial, Agricultural and Commercial-Residential Uses*, Oregon Institute of Technology, Klamath Falls, Oregon, 1974).

50. M. Matthiasson: Beneficial uses of heat in Iceland (*Proceedings of Conference on Beneficial Uses of Thermal Discharges*, New York State Department of Environmental Conservation, 1970).

51. A. Mazzoni: The steam vents of Tuscany and the Larderello Plant (Amonina Arts Grafiche, in English, Bologna, 1948).

52. B.C. McCabe, Jr.: Geothermal Food Processes, Inc., Reno, Nevada, personal communication, 1980.

53. C.L. McDonald: An evaluation of the potential for district heating in the United States (Proceedings Miami International Conference on Alternative Energy Sources, Clean Energy Research Institute, University of Miami, Coral Gables, Florida, December 1977).

54. D.A. Mitchell: Performance of typical HVAC materials in two geothermal heating systems (ASHRAE Transactions, Vol. 86, part 1, 1980).

55. P. Muffler, J. Costain, D. Foley, E.A. Sammel and W. Youngquist: Nature and occurrence of the resource (Geothermal Resources Council, Special Report No. 7, Direct Utilization of Geothermal Energy: Technical Handbook, 1980).

56. L.J.P. Muffler, Ed.: Assessment of Geothermal Resources of the United States--1978 (U.S. Geological Survey Circular 790, 1979).

57. L.J.P. Muffler: Geothermal resources (U.S. Mineral Resources, U.S.G.S., Paper 820, 1973).

58. A.B. Newton: Solar cooling (Applications of Solar Energy for Heating and Cooling of Buildings, ASHRAE, 1977).

59. C.R. Nichols: Direct utilization of geothermal energy: DOE's resource assessment program (Direct Utilization of Geothermal Energy: A Symposium, Geothermal Resources Council, February 1978).

60. K.E. Nichols and A.J. Malgieri: Technology Assessment of Geothermal Pumping Equipment (DOE Report ALO-4162-2, Barber-Nichols Engineering Company, Arvada, Colorado, September 1978).

61. G.K. Olson, D.L. Benner-Drury and G.R. Cunnington: Multi-Use Geothermal Energy System With Augmentation for Enhanced Utilization: A Non-Electric Application of Geothermal Energy in Susanville, California, (Final Report DOE-ET-248447-1, Aerojet Energy Conversion Company, Sacramento, California, February 1979).

62. Eric A. Peterson: Possibilities for direct use of geothermal energy (ASHRAE Transactions, 1979, Vol. 85, part 1).

63. R. Peterson, N. El-Ramly and J.M. Dermengian: The electric and nonelectric geothermal industry in the United States (Geothermal World Directory 1975/76).

64. S.L. Phillips, A.K. Mathur and R.E. Doebler: A Study of Brine Treatment (EPRI Report ER-476, Lawrence Berkeley Laboratory, Berkeley, California, November 1977). (Contains literature search of 348 citations.)

65. G.M. Reistad, G.G. Culver and M. Fukuda: Downhole heat exchangers for geothermal systems: Performance, economics and applicability (ASHRAE Transactions, Vol. 85, part 1, 1979).

66. G.M. Reistad, M.B. Larson, W.C. Layton and S. Krishna: Analysis of System Performance of the Prototype Energy Retrieval System (Final Report to U.S. DOE, Bonneville Power Administration, September 1979).

67. V. Roberts et al.: Geothermal Energy Prospects for the Next 50 Years, Electric Power Research Institute Report EPRI-ER-611-SR, February 1978).

68. P. Rodzianko: A case history of direct-use geothermal applications (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

69. L. Rybach: Geothermal resources: an introduction with emphasis on low-temperature reservoirs (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

70. Sperry Research Center, Sudbury, Massachusetts: Feasibility Demonstration of the Sperry Down-Well Pumping System (DOE Report COO-2838-1, May 1977).

71. UNESCO; H.C.H. Armstead, Ed.: Geothermal Energy: Review of Research and Development (UNESCO Press, Paris, 1973).

72. U.S. DOE Direct Heat Application Summary presented at the Geothermal Resources Council Annual Meeting, September 1979.

73. M. Wells; Early development of western geothermal resources (Journal of the West, Vol. X, No. 1, 1971).

74. S. Willard, W.N. Byrd, M. Crittenden, R.V. Glacosie, S. Province and D. Sacarto: Legal and institutional considerations (Geothermal Resources Council, Special Report No. 7, Direct Utilization of Geothermal Energy: Technical Handbook, 1980).

75. R.N. Yamasaki and P.B. Sherwood: The El Centro geothermal energy heating and cooling field experiment (ASHRAE Transactions, Vol. 86, part 1, 1980).

76. J. Zoega: The Reykjavik municipal heating system (Proceedings International Conference on Geothermal Energy for Industrial, Agricultural and Commercial-Residential Uses, Oregon Institute of Technology, Klamath Falls, Oregon, 1974.

7. BIBLIOGRAPHY

The bibliography listing in this section is separated into the following six categories:

General
Direct Applications
Corrosion, Scaling and Material Selection
Resources
Legal, Institutional and Environmental
Economics and Financing

For the first two categories, an attempt has been made to include all major works that are relevant. In the last four categories however, no attempt has been made to list all references, but rather selected works are presented that are either the major references in the area or contain extensive reference listings themselves.

The "Direct Applications" category is further separated into five sub-groupings. They are:

General Applications
General Equipment
Residential and Commercial
Agricultural Growth
Industrial

General

H.C.H. Armstead, Ed.: Geothermal Energy: Review of Research and Development (UNESCO Press, Paris, 1973).

H.C.H. Armstead: Geothermal Energy (E. & F.N. Spon Ltd., London, 1978).

L. Belteky: Development and utilization of thermal waters in Hungary (Geothermics, Vol. 1, 1972).

G.L. Blake: Semiannual Progress Report for the Idaho Geothermal Program, October 1, 1977 to March 31, 1978 (DOE Report TREE-1728, EG&G Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, Idaho, July 1978).

G.L. Blake: Semiannual Progress Report for the Idaho Geothermal Program, April 1 to September 30, 1978 (DOE Report TREE-1295, EG&G Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, Idaho, November 1978).

G. Bodvarsson: Utilization of geothermal energy for heating purposes and combined schemes involving power generation, heating and/or by-products (Proceedings United Nations Conference on New Sources of Energy, Rome, 1961, Paper GR/5(G)).

G. Bodvarsson and D.E. Eggers: The exergy of thermal water (Geothermics, Vol. 1, 1972).

G. Bodvarsson: Geothermal resource energetics (Geothermics, Vol. 3, 1974).

P.N. Cheremisinoff and A.C. Morresi: Geothermal Energy Technology Assessment (Technomic Publishing Co., Inc., Westport, Connecticut, 1976).

Department of Energy, Division of Geothermal Energy: Pacific Region Federal Geothermal Commercialization Plan, Working Draft (Prepared by San Francisco Operations Office for Pacific Region Program Manager, October 1978).

Department of Energy-Division of Geothermal Energy, DOE-Idaho Operations Office, EG&G Idaho, Inc. and University of Utah Research Institute Earth Science Laboratory: Regional Hydrothermal Commercialization Plan--Rocky Mountain Basin and Range Region (July 1978).

ERDA: A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future (Vol. 1-2, ERDA 76-1, 1976).

A.A. Field: Geothermal energy rediscovered (Heating/Piping/Air Conditioning, January 1975).

C.D. Fredrickson: Analysis of Requirements for Accelerating the Development of Geothermal Energy Resources in California (DOE Report JPL-PUB-77-63, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, November 1977).

J.D. Garnish: Progress in geothermal energy (Endeavour, Vol. 2, No. 2, 1978).

Geothermal Resources Council: Expanding the Geothermal Frontier, Vol. 3 (Reno, Nevada, September 1979).

Geothermal Resources Council: Geothermal Energy: A Novelty Becomes a Resource, Transactions, Vol. 2, Sections 1 and 2 (Hilo, Hawaii, July 1978).

Geothermal Resources Council: Geothermal: State of the Art, Transactions, Vol. 1 (San Diego, California, May 1977).

J. Goguel: Geothermics (McGraw-Hill Book Company, 1976).

J.A. Hanny and B.C. Lunis: Hydrothermal Commercialization Baseline for the States of Idaho, New Mexico, Colorado, South Dakota and Wyoming (DOE Reports, EG&G Idaho, Inc., Idaho Falls, Idaho, 1979).

IGCC, Interagency Geothermal Coordinating Council: Geothermal Energy Research, Development and Demonstration Program; Third Annual Report (DOE Report DOE-ET-0090, EGCC-4, March 1979).

IGCC, Interagency Geothermal Coordinating Council: *Geothermal Energy Research, Development and Demonstration Program*; *Second Annual Report* (DOE Report DOE-ET-0039-1, IGCC-3, April 1978).

S. Komagata, H. Nakamura and U. Minokara: The status of geothermal utilization in Japan (*Geothermics*, Special Issue No. 2, Vol. 2, part 1, 1970).

P. Kruger and Carel Ott, Editors: *Geothermal Energy* (Stanford University Press, 1972).

J.F. Kunze: *Geothermal R&D Project Report for Period October 1, 1976 to March 31, 1977* (ERDA Report TREE-1134, EG&G-Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, Idaho, May 1977).

J.F. Kunze: *Geothermal R&D Project Report for Period April 1, 1977 to September 30, 1977* (DOE Report TREE-1256, EG&G Idaho, Inc., Idaho National Engineering Laboratory, Idaho Falls, Idaho, March 1978).

C.B. McFarland, Jr.: Resource temperature as a measure of geothermal potential (*Geothermal Resources Council, Transactions*, Vol. 1, May 1977).

R.T. Meyer and R. Davidson: *Southwest Regional Geothermal Operations Research Program, Summary Report, First Project Year, June 1977 to August 1978* (DOE Report IDO-10080, Western Energy Planners, Ltd., Denver, Colorado, December 1978).

S.L. Milora and J.W. Tester: *Geothermal Energy as a Source of Electrical Power* (The MIT Press, Cambridge, Massachusetts, 1976).

National Academy of Sciences: *Geothermal Resources and Technology in the United States* (National Research Council Report, Washington, D.C., 1979).

G. Palmason and J. Zoega: Geothermal energy development in Iceland 1960-1969 (*Geothermics*, Special Issue No. 2, Vol. 2, part 1, 1970).

R. Peterson, N. El-Ramby and J.M. Dermengian: The electric and nonelectric geothermal industry in the United States (*Geothermal World Directory*, Bicentennial Edition, 1975-76).

K. Ragnars, K. Saemundsson, S. Benediktsson and S.S. Einarsson: Development of the Namafjall Areas, Northern Iceland (*Geothermics*, Special Issue No. 2, Vol. 2, part 1, 1970).

J. Reitzel: *Utilization of U.S. Geothermal Resources* (EPRI ER-382, Systems and Energy Group of TRW Inc., Redondo Beach, California, December 1976).

V. Roberts et al.: *Geothermal Energy Prospects for the Next 50 Years* (Electric Power Research Institute Report EPRO-ER-611-SR, February 1978).

J.H. Smith: Geothermal development in New Zealand (*Geothermics*, Special Issue No. 2, Vol. 2, part 1, 1970).

A.M. Stone: Geothermal in Hungary (*Geo-Heat Utilization Center Quarterly Bulletin*, Vol. 3, No. 4, July 1978).

G. Sukharov, S. Vlasova and Y. Taranukha: 1970, Utilization of thermal waters from oil deposits of the Caucasus (*Geothermics*, Special Issue No. 2, Vol. 2, part 1, 1970).

System Development Corporation: *Regional Systems Development For Geothermal Energy Resources, Pacific Region (California and Hawaii)* (U.S. DOE Report DOE-ET-28432-1 and 2, March 1979).

A.N. Tikhonov and I.M. Dvorov: Development of research and utilization of geothermal resources in the USSR (*Geothermics*, Special Issue No. 2, Vol. 2, part 2, 1970).

United Nations: *Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources*, San Francisco, May 1975 (Published by Lawrence Berkeley Laboratory, Berkeley, California, 1976, Vols. 1, 2 and 3).

United Nations: Proceedings of the United Nations Symposium on the Development and Utilization of Geothermal Resources, Pisa, Italy, September/October 1970 (Published in special issue of Geothermics, Vols. 1 and 2).

United Nations: Proceedings of the United Nations Conference on New Sources of Energy, Vols. 2 and 3 (Rome, August 1961).

E.F. Wehlage: The Basics of Applied Geothermal Engineering (Geothermal Information Services, West Covina, California, 1976).

M. Wells: Early development of western geothermal resources (Journal of the West, Vol. X, No. 1, 1971).

Direct Applications

General applications

D.A. Anderson and J. Lund, Eds.: Direct Utilization of Geothermal Energy: Technical Handbook (Geothermal Resources Council, Special Report No. 7, 1980).

G. Bodvarsson and G.M. Reistad: Econometric analysis of forced geoheat recovery for low-temperature uses in the Pacific Northwest (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

G. Bodvarsson et al.: Systems Study for the Use of Geothermal Energies in the Pacific Northwest, Final Report prepared for the USAEC, Report No. RLO-2227-T19-1, November 1974).

T. Boldizsar: Geothermal energy use in Hungary (Proceedings International Conference on Geothermal Energy for Industry, Agricultural and Commercial-Residential Uses, Oregon Institute of Technology, Klamath Falls, Oregon, U.S.A. 1974).

K.E. Brown: The Madison formation--problems of direct use (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

W.L. Cooke: Some methods of dealing with low enthalpy water in the Rotorua area of New Zealand (Geothermics, Special Issue 2, Vol. 2, part 2, 1970).

S.S. Einarsson: Utilization of low enthalpy water for space heating, industrial, agricultural and other uses (Geothermics, Special Issue 2, Vol. 2, part 2, 1970).

D.B. Elmer: Direct heat applications of geothermal energy resources and the second law of thermodynamics (Geothermal Resources Council, Transacations, Vol. 1, May 1977).

J. Farquhar, R. Grijalva and P. Kirkwood: Non-Electric Applications of Geothermal Energy in Six Alaskan Towns (DOE Report IDO-1622-4, Pacific-Sierra Research Corp., Santa Monica, California, November 1977).

L.L. Fassbender, C.H. Bloomster and A.H. Schilling: Feasibility of potential geothermal energy applications for Riverside, California (Geothermal Resources Council, Transactions, Vol. 2, July 1978).

Geothermal Resources Council, Davis, California: A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, Special Report No. 5 (DOE Grant No. ET-78-G-03-2118, April 1979).

Geothermal Resources Council: Direct Utilization of Geothermal Energy: A Symposium (DOE Conference, January 31--February 2, 1978, San Diego, California).

J.P. Gries: Geothermal Applications of the Madison (Pahasapa Aquifer System in South Dakota (DOE Report IDO-1625-2, South Dakota School of Mines and Technology, Rapid City, South Dakota, September 1977).

J.H. Howard, Editor: Present Status and Future Prospects for Non-Electrical Uses of Geothermal Resources (ERDA Report UCRL-51926, Lawrence Livermore Laboratory, University of California, Livermore, California, October 1975).

R. Huggins et al.: Northeast Oregon Geothermal Project (Eastern Oregon Community Development Council, LaGrande, Oregon, January 1978).

R.N. Kerr, R. Bangma, W.L. Cooke, F.G. Furness, G. Vamos: Recent developments in New Zealand in the utilization of geothermal energy for heating purposes (Proceedings United Nations Conference on New Sources of Energy, Rome, Italy, 1961, (United Nations, New York, 1964) Vol. 3, Paper G/52).

J.F. Kunze: Fluid heat management for direct geothermal energy applications (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

J.F. Kunze and A.S. Richardson: National Programs Definition Study for the Non-Electrical Utilization of Geothermal Energy (INEL Report ANCR-1214, June 1975).

P.J. Lienau and J.W. Lund, Eds.: Multipurpose Use of Geothermal Energy (Proceedings of the International Conference on Geothermal Energy for Industrial, Agricultural and Commercial-Residential Uses, Published by the Geo-Heat Utilization Center, Klamath Falls, Oregon, October 1974).

A.B. Longyear et al.: Susanville Geothermal Energy Project (ERDA Report SAN-1077-4, City of Susanville, July 1976).

J.W. Lund: Worldwide direct application review (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

M. Matthiasson: Beneficial uses of heat in Iceland (Proceedings of Conference on Beneficial Uses of Thermal Discharges, New York State Department of Environmental Conservation, 1970).

H.C. Meal and H. Guillamon-Duch: Substitution value of geothermal energy as process heat and electric power (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

C.R. Nichols and K.W. Hollenbaugh: Geological Aspects of an Assessment of the National Potential for Non-Electrical Utilization for Geothermal Resources (ERDA ANCR-1213, Aerojet Nuclear Company, Idaho National Engineering Laboratory, Idaho Falls, Idaho, June 1975).

Eric A. Peterson: Possibilities for direct use of geothermal energy (ASHRAE Transactions, 1979, Vol. 85, part 1).

F.C. Paddison: A prospectus for geothermal energy - the Atlantic Coastal Plain (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

G.M. Reistad, B. Yao and M. Gunderson: A thermodynamic study of heating with geothermal energy (ASME Journal of Engineering for Power, Vol. 100, No. 4, 1978).

G.M. Reistad, W.E. Schmisseur, J.R. Shay and J.B. Fitch: An Evaluation of Uses for Low to Intermediate Temperature Geothermal Fluids in the Klamath Basin, Oregon (Bulletin No. 55, Engineering Experiment Station, Oregon State University, March 1978).

G.M. Reistad: Analysis of Potential Nonelectrical Applications of Geothermal Energy and Their Place in the National Economy (Lawrence Livermore Laboratory, Rept. UCRL-51747, 1975).

G. Reistad, L. Boersma, L. Davis, J. Ringle and W. Schmisseur: A Systems Analysis of the Economic Utilization of Warm Water Discharge From Power Generating Stations (Oregon State University Engineering Experiment Station Bulletin 48, 1974).

D.G. Swink and R.J. Schultz: Conceptual Study for Total Utilization of an Intermediate Temperature Geothermal Resource (INEL Report ANCR-1260, April 1976).

W.J. Toth: Geothermal energy markets on the Atlantic Coastal Plain (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

U.S. DOE Direct Heat Application Summary Presented at the Geothermal Resources Council Annual Meeting, September 1979.

VTN-CSL: Economic Study of Low Temperature Geothermal Energy in Lassen and Modoc Counties, California, prepared for State of California Division of Oil and Gas and the Energy Resources Conservation and Development Commission, April 1977.

R. Weissbrod and W. Barron: Cost analysis of hydrothermal resource applications in the Atlantic Coastal Plain (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

General equipment

C.A. Allen and E.S. Grimmett: Liquid-Fluidized-Bed Heat Exchanger Design Parameters (DOE Report ICP-1153, Allied Chemical, Idaho Chemical Programs, Idaho National Engineering Laboratory, April 1978).

R.W. Blakemore: Geothermal Pump Test Facility (DOE Report ALO-3715-1, Barber-Nichols Engineering Company, Arvada, Colorado, September 1978).

B. Breindel, R.L. Harris and G.K. Olson: Geothermal absorption refrigeration for food processing industries (ASHRAE Transactions, Vol. 85, part 1, 1979).

D.J. Cerini: Demonstration of a Rotary Separator for Two-Phase Brine and Steam Flows (DOE Report TID-28519, Biphase Energy Systems, Research-Cottrell, Santa Monica, California, January 1978).

L.T. Cole and C.A. Allen: Liquid-Fluidized-Bed Heat Exchanger Flow Distribution Models (DOE Report ICP-1151, Allied Chemical Corporation, Idaho Chemical Programs, January 1979).

G.G. Culver and G.M. Reistad: Evaluation and Design of Downhole Heat Exchangers for Direct Applications (U.S. DOE Report No. RLO-2429-7, December 1978).

E.L. Ghormley and J.L. Stern: Geothermal Heat Exchanger Test at Heber, California (EPRI ER-572, The Ben Holt Company, Pasadena, California, August 1978).

E.S. Grimmett, A.F. Fanous and C.A. Allen: Advances in liquid-fluidized-bed heat exchanger development (ASME Publication, 77-HT-66, August 1977).

H.R. Jacobs: Evaluation and design considerations for liquid-liquid direct contact heat exchangers for geothermal applications (ASME Publication, 77-HT-2, August 1977).

H.R. Jacobs, S.B. Plass, A.C. Hansen and R. Gregory: Operational limitations of direct contact heat exchangers for geothermal applications (ASME Publication 77-HT-5, August 1977).

H.R. Jacobs, R.F. Boehm and A.C. Hansen: Application of Direct Contact Heat Exchangers to Geothermal Power Production Cycles (DOE Report IDO-1549-8, Mechanical Engineering Department of the University of Utah, Salt Lake City, Utah, January 1978).

D.H. Kihara, Hi Chang Chai and G.S. Shimozono: A parametric study of a heat exchanger designed for geothermal power plant application (ASME Publication, 77-HT-1, August 1977).

K.E. Nichols and A.J. Malgieri: Technology Assessment of Geothermal Pumping Equipment (DOE Report ALO-4162-2, Barber-Nichols Engineering Company, Arvada, Colorado, September 1978).

G.M. Reistad, G.G. Culver and M. Fukuda: Downhole heat exchangers for geothermal systems: Performance, economics and applicability (ASHRAE Transactions, Vol. 85, part 1, 1979).

Sperry Research Center, Sudbury, Massachusetts: Feasibility Demonstration of the Sperry Down-Well Pumping System (DOE Report COO-2838-1, May 1977).

W.B. Suratt and Chang-Ou Lee: Study and Testing of Direct Contact Heat Exchangers for Geothermal Brines (DOE Report ORO-4893-2, DSS Engineers, Inc., Fort Lauderdale, Florida, November 1978).

W.B. Suratt and G.K. Hart: Testing of direct contact heat exchangers for geothermal brines (ASME Publication, 77-HT-4, August 1977).

A.V. Sims: Geothermal Direct Contact Heat Exchange (ERDA Report SAN-1116-1, The Ben Holt Company, Pasadena, California, June 1976).

I. Sheinbaum: Direct contact heat exchangers in geothermal power production (ASME Publication, 75-HT-52, August 1975).

M.W. Urbanek: Development of Direct Heat Exchangers for Geothermal Brines (DOE Report LBL-8558, UC-66d, DSS Engineers, Inc., Fort Lauderdale, Florida, June 1978).

E.F. Wehlage: The role of heat transfer in solving geothermal energy problems to accelerate its effective application (ASME Publication, 75-HT-57, August 1975).

Residential and commercial

S. Arnorsson, K. Ragnars, S. Benediktsson, G. Gislason, S. Thorhallsson, S. Bjornsson, K. Gronvold and B. Lindal: Exploitation of saline high-temperature water for space heating (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

D.J. Atkinson: Geothermal development in Reno (Geothermal Resources Council, Transactions Vol. 2, July 1978).

J.C. Austin: A low temperature geothermal space heating demonstration project (Geothermal Resources Council, Transactions, Vol. 2, July 1978).

Benner-Drury, D. and K. Unmack: Improving utilization of low temperature geothermal resources with augmentation (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

C.H. Bloomster, L.L. Fassbender and C.L. McDonald: Geothermal Energy Potential for District and Process Heating Applications in the U.S.: An Economic Analysis (BNWL-2311, Battelle Pacific Northwest Laboratories, Richland, Washington, August 1977).

G. Bodvarsson and G.M. Reistad: Performance and Feasibility of Forced Geoheat Recovery for Low Temperature Applications (Final Report to U.S. DOE, Report No. RLO-2227-T36-4, June 1979).

BRGM: La Geothermie en France (Orleans, France, 1978).

BRGM: La Geothermie en France (Bulletin du Bureau de Recherches Geologiques et Minieres, Deuxieme Series, Section 2, 1975).

J.B. Briggs and C.J. Shaffer: Seasonal Heat Pump Performance for a Typical Northern United States Environment (TREE-1181, Idaho National Engineering Laboratory, October 1977).

W. Burrows: Geothermal energy resources for heating and associated applications in Rotorua and surrounding areas (Geothermics, Special Issue No. 2, Vol. 2, part 2, 1970).

W. Burrows: Utilization of geothermal energy in Rotorua, New Zealand (Proceedings International Conference on Geothermal Energy for Industry, Agriculture and Commercial-Residential Uses (Oregon Institute of Technology, Klamath Falls, Oregon, U.S.A., 1974).

P. Coulbois and J. Herault: Conditions for the competitive use of geothermal energy in home heating (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

G.G. Culver: Optimization of Geothermal Home Heating Systems (Geoheat Utilization Center, Oregon Institute of Technology, Klamath Falls, Oregon, 1976).

B. Delisle, O. Kappelmeyer and R. Haenel: Prospects for geothermal energy for space heating in low-enthalpy areas (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

L.E. Donovan: Geothermal--a viable and economic comfort heating system choice (Geothermal Resource Council, Transactions, Vol. 2, July 1978).

Direction des Etudes et Recherches: Le Chauffage Geothermique Avec Pompe a Chaleur (Chatou, France, 1978).

L.E. Donovan and A.S. Richardson: Feasibility/Conceptual Design Study for Boise Geothermal Space Heating Demonstration Project Building Modifications (ERDA Report ANCR-1246, Aerojet Nuclear Company, Idaho Falls, Idaho, September 1975).

I.M. Dvorov and N.A. Ledentsova: Utilization of geothermal water for domestic heating and hot water supply (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

EG&G: Geothermal Space Heating (1978).

S.S. Einarsson: Geothermal space heating and cooling (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

S.S. Einarsson: Geothermal district heating (Geothermal Energy: Review of Research and Development, (UNESCO, Paris, France, 1973).

I.A. Engen: Residential Space Heating Cost: Geothermal vs Conventional Systems (TREE-1182, Idaho National Engineering Laboratory, February 1978).

N.N. Gunaji, L. Chaturvedi, E. Thode, L. LaFrance, C. Swanberg and A. Walvekar: A geothermal field near New Mexico State University and its potential as campus energy supplier (Geothermal Resources Council, Transactions, Vol. 2, July 1978).

G. Hull and G. Simmons: A retrofitted geothermal heating system (ASHRAE Journal, May 1979).

W.D. Ingle III: Direct heat activated cooling adapted to geothermal energy (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

J. Karkheck, J. Power and E. Beardsworth: The Technical and Economic Feasibility of U.S. District Heating Systems Using Waste Heat from Fusion Reactors (BNL-50516, Brookhaven National Laboratory, Upton, New York, February 1977).

J. Karkheck, J. Power and E. Beardsworth: Prospects for district heating in the United States (Science, Vol. 195, March 1977).

J. Karkheck and R.G. Tessmer Jr.: Methodology for Modelling Geothermal District Heating for Residential Markets (DOE Report BNL-24261, April 1978).

J.G. Keller and J.F. Kunze: Space Heating Systems in the Northwest--Energy Usage and Cost Analysis (ANCR-1276, INEL, 1976).

B. Kohler: The economic and environmental aspects of district heating in Sweden (District Heating, October-November 1973).

J.F. Kunze and K.F. Forsgren: The economics of the heat pump as a device to assist in geothermal district space heating (Geothermal Resource Council, Transactions, Vol. 2, July 1978).

J.F. Kunze, A.S. Richardson, K.M. Hollenbaugh, C.R. Nichols and L.L. Mink: Nonelectric utilization project, Boise, Idaho (Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

P.J. Lienau, J.W. Lund and G. Culver: Klamath Falls geo-heating districts (Geothermal Resources Council, Transactions, Vol. 1, May 1977).

J.W. Lund: The utilization and economics of low-temperature geothermal water for space heating (11th IECEC, 1976).

J. Lund, G. Culver and L. Svanevik: Utilization of geothermal energy in Klamath Falls (*Proceedings International Conference of Geothermal Energy for Industrial, Agricultural and Commercial-Residential Uses*, Oregon Institute of Technology, Klamath Falls, Oregon, 1974).

J.W. Lund, P.J. Lienau, G.G. Culver and C.V. Higbee: Klamath Falls geothermal heating district (*Geothermal Resources Council, Transactions*, Vol. 3, September 1979).

C.L. McDonald: An evaluation of the potential for district heating in the United States (*Proceedings Miami International Conference on Alternative Energy Sources*, Clean Energy Research Institute, University of Miami, Coral Gables, Florida, December 1977).

C.L. McDonald: District heating (*Oakridge Gaseous Diffusion Plant Study Final Report*, SN-RT-12, Exxon Nuclear Co., Inc., Richland, Washington, September 1978).

C.L. McDonald and C.H. Bloomster: *The Geocity Model: Description and Application* (BNWL-SA-6343, Battelle Northwest Laboratories, Richland, Washington, June 1977).

C.L. McDonald, C.H. Bloomster and S.C. Schulte: *GEOCITY: A Computer Code for Calculating Costs of District Heating Using Geothermal Resources* (BNWL-2208, Battelle Northwest Laboratories, Richland, Washington, February 1977).

G.K. Olson, D.L. Benner-Drury and G.R. Cunnington: *Multi-Use Geothermal Energy System With Augmentation for Enhanced Utilization A Non-Electric Application of Geothermal Energy in Susanville, California*, Final Report (DOE-ET-248447-1, Aerojet Energy Conversion Company, Sacramento, California, February 1979).

W.D. Purvine: Utilization of thermal energy at Oregon Institute of Technology, Klamath Falls, Oregon (*Proceedings of the International Conference on Geothermal Energy for Industrial, Agricultural and Commercial-Residential Uses*, Oregon Institute of Technology, October 1974).

D.R. Pitts and R.C. Schmitt: District heating with geothermally heated culinary water supply systems (*Geothermal Resources Council, Transactions*, Vol. 3, September 1979).

L. Rybach: Urban heating from geothermal aquifer in the Paris Basin (Geothermal Resources Council, Special Report No. 5, *A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States*, April 1979).

G. Reynolds: Cooling with geothermal heat, (*Geothermics*, Special Issue No. 2, Vol. 2, part 2, 1970).

A.V. Sims and W.C. Racine: *Feasibility of Geothermal Space/Water Heating for Mammoth Lakes Village, California* (DOE Report SAN-1316-4, The Ben Holt Company, Pasadena, California, December 1977).

H. Sigurdsson: Reykjavik Municipal District Heating Service and utilization of geothermal energy for domestic heating (*Proceedings United Nations Conference on New Sources of Energy, Rome, Italy 1961* (United Nations, New York, 1964), Vol. 3, paper G/45).

P.B. Sherwood and K.L. Newmen: *Engineering and Economic Feasibility of Utilizing Geothermal Heat from the Heber Reservoir for Industrial Processing Purposes at Valley Nitrogen Producers, Inc., El Centro Agricultural Chemical Plant* (DOE Report SAN-1323-3, WESTEC Services, Inc., San Diego, California, September 1977).

R.J. Shannon: Geothermal heating of government buildings in Rotorua (*Proceedings Second United Nations Symposium on the Development and Use of Geothermal Resources*, San Francisco, May 1975, published by Lawrence Berkeley Laboratory, Berkeley, California, Vol. 3, 1976).

L.D. Torgerson and A.S. Richardson: *Feasibility Review for Geothermal Conversion of Existing H&V Systems on the Boise Geothermal Space Heating Project* (ERDA Report ANCR-1256, Aerojet Nuclear Company, Idaho Falls, Idaho, September 1975).

K.A. Wonstolen: District heating: legal and institutional parameters (*Geothermal Resources Council, Transactions*, Vol. 3, September 1979).

J. Zoega: The Reykjavik municipal heating system (Proceedings International Conference on Geothermal Energy for Industrial, Agricultural and Commercial-Residential Uses, 1974 (Oregon Institute of Technology Klamath Falls, Oregon).

Agricultural growth

.O. Baker, R.C. Lebida, W.D. Pyle and R.P. Britch: An Investigation of Selected Alaska Geothermal Spring Sources as Possible Salmon Hatchery Sites, Final Report, January-September 1977 (DOE Report IDO-1624-1, June 1978).

Alvin A. Bishop: Use of Geothermal Water for Agriculture (INEL Report ANCR-1221, June 1975).

K.L. Boren: The use of geothermal fluids to heat a large greenhouse complex (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

D.K. Campbell, F.L. Rose, J.C. Kent, L.R. Watson and J.F. Sullivan: Raft River Geothermal Aquaculture Experiment--Phase II (DOE Report TREE-1370, EG&G Idaho, Inc., August 1979).

G. Dragone and O. Rume: Pilot greenhouse for the utilization of low-temperature waters (Geothermics, Special Issue No. 2, Vol. 2, part 1, 1970).

S.F. Fogleman, L.A. Fisher and A.R. Black: Total Energy Recovery System for Agribusiness: Lake County Study (DOE Report SAN-1327-5, International Engineering Company, Inc., San Francisco, California, April 1978).

S.F. Fogleman, L.A. Fisher, A.R. Black and D.P. Singh: Total Energy Recovery System for Agribusiness (ERDA Report SAN-1327-2, International Engineering Company, Inc., San Francisco, California, May 1977).

J.L. Green et al.: Klamath Basin: A Potential Greenhouse Development Site (Oregon State Agricultural Experiment Station Report, August 1977).

K. Huseby: A Tree Seedling Greenhouse: Design and Costs (U.S.D.A. Forest Service Equipment Development Center, Fort Missoula, Montana, June 1973).

B. Lindal: Greenhouses by geothermal heating in Iceland (United Nations Conference on New Sources of Energy, Rome, Italy, 1961 (United Nations, New York, New York, 1964)).

Oregon State University; Geothermal Resources for Aquaculture, (Proceedings of a workshop sponsored by Pacific Sea Grant Advisory Program, Oregon State University and University of Idaho, Published by Oregon State University Sea Grant College Program, Publication No. ORESU-W-78-001, September 1978).

L. Ray: Channel catfish (Ictalurus Punctatus) production in geothermal water (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

Paul A. Roberts: Fish Culture Utilization of Geothermal Energy (INEL Report ANCR-1220, June 1975).

M.M. Yarosh, B.L. Nichols, E.A. Hirst, J.W. Michel and W.C. Yee: Agricultural and Aquacultural Uses of Waste Heat (Oak Ridge National Laboratory, Rept. ORNL-4797, 1972).

Industrial

A.J. Arnold: Inventory and Case Studies of Louisiana, Non-Electric Industrial Applications of Geopressured Geothermal Resources (DOE Report IDO-1629-4, de Laurel Engineers, Inc., Division of Kidde Consultants, Inc., New Orleans, Louisiana, February 1978).

J.C. Austin: Conceptual design considerations for the use of geothermal energy in a food processing industry (ASHRAE Transactions, Vol. 86, part 1, 1980).

Belcastro: Geothermally pasteurized milk process (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

K.L. Garing and G.E. Coury: Adaptation of geothermal energy to produce alcohol from agricultural commodities (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

Geothermal Resources Council: First geothermal vegetable dryer dedicated (Geothermal Resources Council Bulletin, Vol. 7, No. 5, November/December 1978).

T.J. Gordon, T.C. Wright, E. Fein, T.R. Munson and R.C. Richmond: The Use of Geothermal Heat for Crop Drying and Related Agricultural Applications (DOE Report IDO-1628-4, The Futures Group, Glastonbury, Connecticut, March 1978).

R.L. Harris, G.K. Olson, C.S. Mah and J.H. Bujalski: Geothermal Absorption Refrigeration for Food Processing Industries (DOE Report SAN-1319-1, Aerojet Energy Conversion Company, Sacramento, California, November 1977).

C.D. Hornburg and B. Lindal: Preliminary Research on Geothermal Energy Industrial Complexes (DOE Report IDO-1627-4, DSS Engineers, Inc., March 1978).

C.D. Hornburg and O.J. Morin: Geothermal Resource Utilization--Paper and Cane Sugar Industries (ERDA Report, Contract No. 2-7405 Eng. 48, DSS Engineers, Inc., Fort Lauderdale, Florida, March 1975).

Intertechnology Corporation: Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat (Final Report, Vol. 1, 2 and 3, February 1977, Col. 28-29-1 NTIS, Springfield, Virginia 22162).

P.J. Lienau; Agribusiness Geothermal Energy Utilization Potential of Klamath and Western Snake River Basins, Oregon (DOE Report, IDO-1621-1, Geo-Heat Utilization Center, Oregon Institute of Technology, Klamath Falls, Oregon and Oregon Department of Geology and Mineral Industries and Oregon Department of Economic Development, Portland, Oregon, March 1978).

B. Lindal: Geothermal heating for industrial purposes in Iceland (Proceedings United Nations Conference on New Sources of Energy, Rome, 1961 (United Nations, New York, 1964)).

B. Lindal: The extraction of salt from seawater by multiple effect evaporators using natural steam (Proceedings United Nations Conference on New Sources of Energy, Rome, 1961 (United Nations, New York, 1964)).

B. Lindal: The production of chemicals from brine and seawater using geothermal energy (Geothermics, Special Issue No. 2, Vol. 2, part 1, 1970).

B. Lindal: The use of natural steam in a diatomite plant (Geothermics, Special Issue No. 2, Vol. 2, part 1, 1970).

B. Lindal: Industrial and other applications of geothermal energy (Geothermal Energy: Review of Research and Development, UNESCO, Paris, France, 1973).

B.A. Lokchine and I.M. Dvorov: Applications experimentales et Industrielles de l'energie geothermique en URSS (Geothermics, Special Issue No. 2, Vol. 2, part 2, 1970).

S.C. May, D.J. Basuino, P.T. Doyle and A.N. Rogers: Applications of Geothermal Resources in the Evaporation and Crystallization Industry (DOE Report SAN-1328-1, Bechtel Corporation, San Francisco, California, October 1977).

R.C. Niess: Utilization of geothermal energy with an emphasis on heat pumps (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

R.O. Pearson: Use of Geothermal Heat for Sugar Refining (DOE Report SAN-1317-3, TRW Systems and Energy, Redondo Beach, California, May 1977).

P. Rodzianko: A case history of direct-use geothermal applications (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

J.J. Seidman and E.L. Leventhal: Geothermal energy for sugar beet processing (ASHRAE Transactions, Vol. 86, part 1, 1980).

A.V. Shcherbakow and V.I. Dvorov: Thermal waters as a source for extraction of chemicals (Geothermics, Special Issue No. 2, Vol. 2, part 1, 1970).

A. Valfells: Heavy water production with geothermal energy (Geothermics, Special Issue No. 2, Vol. 2, part 1, 1970).

M. Vorum, G.E. Coury, S.W. Goering and E.A. Fritzler: Non-Electric Utilization of Geothermal Energy in the San Luis Valley, Colorado (DOE Report IDO-1626-3, Coury and Associates, Inc., Lakewood, Colorado, February 1978).

C.M. Wong: Geothermal energy and desalination, partners in progress (Geothermics, Special Issue No. 2, Vol. 2, part 1, 1970).

Corrosion, Scaling and Material Selection

American Society for Testing and Materials Task Group on Geothermal Seals: Proceedings of Technical Seminar (DOE CONF-7806141, Boston, Massachusetts, June 1978).

R.M. Costello, R. Ammerlaan, S.V. Cabibbo and L.E. Kukacka: Economic assessment of using nonmetallic materials in the direct utilization of geothermal energy (Geothermal Resources Council, Transactions, Vol. 3, September 1979).

S.R. Cosner and J.A. Apps: A Compilation of Data on Fluids from Geothermal Resources in the United State (DOE Report LBL-5936, Lawrence Berkeley Laboratory, Berkeley, California, May 1978).

Daedalean Associates, Inc.: The Results of the Initial Feasibility Program on Cavitation Descaling Techniques for Pipes and Tubes Used in Geothermal Energy Plants (DOE Report HCP-T2289-01, Daedalean Associates, Inc., June 1978).

D.W. DeBerry, P.F. Ellis and C.C. Thomas: Material Selection Guidelines for Geothermal Power Systems (DOE Report ALO-3904-1, Radian Corporation, Austin, Texas, September 1978). (Contains extensive literature of materials selection citations.)

F.J. Dodd, A.E. Johnson and W.C. Ham: Material and corrosion testing at the Geyers geothermal power plant (Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, May 1975).

R.C. Feber, editor: Proceedings of Workshop on Scale Control in Geothermal Energy Extraction Systems (DOE Report LA-7664-C, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, October 1977).

P.K. Foster, T. Marshall and A. Tombs: Corrosion investigation in hydrothermal water at Wairakei, New Zealand (United Nations Conference of New Sources of Energy, Rome, 1961).

A. Goldberg and R.P. Kershaw: Evaluation of Materials Exposed to Scale-Control/Nozzle-Exhaust Experiments at the Salton Sea Geothermal Field (Lawrence Livermore Laboratory, University of California, Livermore, California, February 1979).

J.E. Harrar, C.H. Otto, Jr., S.B. Deutscher, R.W. Ryon and G.E. Tardiff: Studies of Brine Chemistry, Precipitation of Solids and Scale Formation at the Salton Sea Geothermal Field (Lawrence Livermore Laboratory, University of California, Livermore, California, January 1979).

A.R. Hirasuna, G.D. Bilyeu, D.L. Davis, C.A. Stephens and G.R. Veal: Geothermal Elastomeric Materials (DOE Report SAN-1308-1, L'Garde, Inc., Newport Beach, California, December 1977).

S. Hermannsson: Corrosion of metals and the forming of protective coating on the inside of the pipes in the thermal water used by the Reykjavik Municipal District Heating Service (Geothermics, Special Issue No. 2, Vol. 2, part 2, 1970).

G.L. Kalousek: Development of Cement for Geothermal Wells (DOE Report BNL-51024, Brookhaven National Laboratory, March 1979).

L.E. Kukacka et al.: *Alternate Materials of Construction for Geothermal Applications* (Brookhaven National Laboratory Progress Reports 1976 through 1978).

P.J. Lienau: Materials performance study of the OIT geothermal heating system (*Geo-Heat Utilization Center Quarterly Bulletin*, Oregon Institute of Technology, Klamath Falls, Oregon, June 1979).

J.W. Lund, J.F. Silva, G.G. Culver and P.J. Lienau: *Corrosion of Downhole Heat Exchangers* (Report 76-3, Geo-Heat Utilization Center, Oregon Institute of Technology, Klamath Falls, Oregon, 1976).

T. Marshall and W. Braithwaite: Corrosion control in geothermal system (*Geothermal Energy, Review of Research and Development*, UNESCO, Paris, France, 1973).

S.L. Phillips, A.K. Mathur, R.E. Doebler: *A Study of Brine Treatment* (EPRI Report ER-476, Lawrence Berkeley Laboratory, Berkeley, California, November 1977). (Contains literature search of 348 citations.)

D.W. Shannon, R.A. Walter and D.L. Lessor: *Brine Chemistry and Combined Heat/Mass Transfer* (EPRI Report ER-634, Battelle Pacific Northwest Laboratories, Richland, Washington, January 1978).

D.W. Shannon: *Geochemical Engineering Program Progress Report for the Period Ending December 1977* (DOE Report PNL-2735, Pacific Northwest Laboratory, Richland, Washington, September 1978).

M.E. Tolivia: Corrosion measurements in a geothermal environment (*Geothermics*, Special Issue No. 2, Vol. 2, part 2, 1970).

O.J. Vetter and D.A. Campbell: *Scale Inhibition in Geothermal Operations--Experiments With Dequest 2060 Phosphonate in Republic's East Mesa Field* (DOE Report LBL-9089, Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, June 1979).

J.C. Watson: *Sampling and Analysis Methods for Geothermal Fluids and Gases* (Pacific Northwest Laboratory Report PNL-MA-572, Pacific Northwest Laboratories, July 1978).

T. Yamagase, Y. Suginohra and K. Yamagase: The properties of scales and methods to prevent them (*Geothermics*, Special Issue No. 2, Vol. 2, part 2, 1970).

Resources

J.H. Altseimer; *Geothermal Well Technology and Potential Applications of Subterrene Devices, - A Status Review* (Los Alamos Scientific Laboratory, Rept. LA-5689-MS, 1974).

D.N. Anderson: Flow chart of critical path in geothermal exploration (*Proceedings, National Conference on Geothermal Energy*, University of California, Riverside; National Science Foundation/RANN, 1973).

D.G. Bebout, V.J. Gavenda and A.R. Gregory: *Geothermal Resources, Wilcox Group, Texas Gulf Coast* (DOE Report, ORO-4891-3, Bureau of Economic Geology, the University of Texas, Austin, Texas, January 1978).

D.G. Bebout, R.G. Loucks and A.R. Gregory: *Geopressured Geothermal Fairway Evaluation and Test-Well Site Location Frio Formation, Texas Gulf Coast* (DOE Report ORO-4891-4, Bureau of Economic Geology, The University of Texas, Austin, Texas, January 1978).

G. Bodvarsson: Dikes as fluid conductors in the extraction of terrestial heat (*Geothermal Energy* 2, 9, 1974).

G. Bodvarsson: Thermal problems in the siting of reinjection wells (*Geothermics*, Vol. 1, 1972).

G. Bodvarsson and J. Zoega: Production and distribution of natural heat for domestic and industrial heating in Iceland (*Proceedings of United Nations Conference on New Sources of Energy*, Rome, Italy, 1961, (United Nations, New York, 1964)).

G. Bodvarsson and G. Palmason: Exploration of subsurface temperature in Iceland (*Proceedings of United Nations Conference on New Sources of Energy*, Vol. 2, Paper G/24, Rome, Italy, 1961, (United Nations, New York, 1964)).

T. Boldizsar: Geothermal energy production from porous sediments in Hungary (*Geothermics*, Special Issue No. 2, Vol. 2, part 1, 1970).

W.C. Bourland and S.S. Farrar: *South Carolina Geothermal Program Final Report* (DOE Report ORO-5104-1, Division of Geology, South Carolina State Development Board, Columbia, South Carolina, 1978).

M.C. Brown, R.B. Duffield, C.L.B. Siciliana and M.C. Smith: *Hot Dry Rock Geothermal Energy Development Program, Annual Report, Fiscal Year 1978* (DOE Report LA-7807-HDR, Los Alamos Scientific Laboratory, University of California, April 1979).

P.M. Brown: Cenozoic and mesozoic aquifer systems of the Atlantic Coastal Plain (Geothermal Resources Council, Special Report No. 5, *A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States*, April 1979).

L.B. Cobb, L. Radford and M. Glascock: *Atlantic Coastal Plain Geothermal Test Holes, New Jersey--Hole Completion Reports* (NVO-1558-1 through 4, Gruy Federal, Inc., Houston, Texas, March 1979).

J.K. Costain: Geothermal exploration methods and results - Atlantic Coastal Plain (Geothermal Resources Council, Special Report No. 5, *A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States*, April 1979).

J.K. Costain, L. Glover III and A. Krishna Sinha: *Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States* (DOE Report VPI-SU-5648-1 through 5, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, December 1977 through March 1979).

J.K. Costain, L. Glover III and A. Krishna Sinha: *Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States* (DOE Report VPI-SU-5103-5, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, September 1977).

J.K. Costain, G.V. Keller and R.A. Crewdson: *Geological and Geophysical Study of the Origin of the Warm Springs in Bath County, Virginia* (DOE Report TID-28271, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, April 1976).

J. Cromling: How geothermal wells are drilled and completed (*World Oil*, Vol. 177, No. 7, 1973).

G.G. Culver, J.W. Lund and L.S. Svanevik: *Klamath Falls Hot Water Well Study* (UCRL-13614, Lawrence Livermore Laboratory, Livermore, California, 1974).

I.G. Donaldson: The simulation of geothermal systems with a simple convective model (*Geothermics*, Special Issue No. 2, Vol. 2, part 1, 1970).

G. Facca: The structure and behavior of geothermal fields (*Geothermal Energy: Review of Research and Development*, (UNESCO, Paris, 1973)).

L. Glover: General geology of the east coast with emphasis on potential geothermal energy regions: a detailed summary (Geothermal Resources Council, Special Report No. 5, *A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States*, April 1979).

P.J. Grim, C.R. Nichols, P.N. Wright, G.W. Berry and J. Swanson: State maps of low-temperature geothermal resources (*Geothermal Resources Council, Transactions*, Vol. 2, July 1978).

B.E. Hankins and O.C. Karkalits: *Geopressured-Geothermal Test of the Edna Delcambre No. 1 Well, Tigre Lagoon Field, Vermilion Parish, Louisiana: Analysis of Water and Dissolved Natural Gas* (DOE Contract No. EY-76-S-05-4937, McNeese State University, Lake Charles, Louisiana, September 1978).

R.H. Hendron: Hot dry rock energy extraction operations (Geothermal Resources Council, Transactions, Vol. 2, July 1978).

J.H. Hill: The Los Alamos Scientific Laboratory hot dry rock geothermal energy development project (Geothermal Resources Council, Transactions, Vol. 2, July 1978).

Y.W. Isachsen: Preliminary Investigation of Two Areas in New York State in Terms of Possible Potential for Hot Dry Rock Geothermal Energy (DOE Report COO-2694-4, Geological Survey, New York State Museum, Albany, New York, September 1978).

O.A. Kremnjov, V. Ja. Zhuravlenko and A.V. Shurtshkov: Technical-economic estimation of geothermal sources (Geothermics, Special Issue No. 2, Vol. 2, part 2, 1970).

R.N. Lane: Geothermal exploration and development drilling programs for 50 heat flow holes and a deep test well (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

R.G. Loucks: Geothermal Resources, Vicksburg Formation, Texas Gulf Coast (DOE Report ORO-4891-2, Bureau of Economic Geology, The University of Texas, Austin, Texas, January 1978).

F.A. Makarenko, B.F. Mauritsky, B.A. Lokshin and V.I. Knonov: Geothermal resources of the USSR and prospects for their practical use (Geothermics, Special Issue No. 2, Vol. 2, part 2, 1970).

J.C. Maxwell: Geothermal exploration methods and results - inland states (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

H. Tsvi Meidav and S. Sanyal: A Comparison of Hydrothermal Reservoirs of the Western United States (EPRI ER-364, Geonomics, Inc., Berkeley, California, December 1976).

J.W. Mercer and C.R. Faust: Reservoir engineering and evaluation (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

L.J.P. Muffler, Ed.: Assessment of Geothermal Resources of the United States--1978 (U.S. Geological Survey Circular 790, 1979).

P.H. Osberg, R. Wetterauer, M. Rivers, W.A. Bothner and J.W. Creasy: Feasibility Study of the Conway Granite As a Geothermal Energy Resource (DOE Report COO-2686-1, August 1978).

R.A. Pettitt: Hot dry rock program in the eastern U.S. (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Directs Uses in the Eastern United States, April 1979).

L. Rybach: Geothermal resources: an introduction with emphasis on low-temperature reservoirs (Geothermal Resources Council, Special Report No. 5, A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, April 1979).

C.R. Scherer and K. Golabi: Geothermal Reservoir Management (DOE Report UCB-SERL-78-5, University of California, Sanitary Engineering Research Laboratory, Berkeley, California, February 1978).

J.H. Sass, W.H. Diment, A.H. Lachenbruch, B.V. Marshall, R.J. Munroe, T.H. Moses, Jr. and T.C. Urban: A New Heat-Flow Contour Map of the Conterminous United States (United States Department of the Interior, Geological Survey, Open-File Report 76-756, Menlo Park, California, 1976).

G. Samuels: Geopressure Energy Resource Evaluation (DOE Report ORNL-PPA-79-2, Oak Ridge National Laboratory, Oak Ridge, Tennessee, May 1979).

G.A. Sudol, R.F. Hamison and H.J. Ramey, Jr.: Annotated Research Bibliography for Geothermal Reservoir Engineering (U.S. DOE Report LBL-8664, GREMP-1, UC66a, August 1979).

D.T. Trexler: *Summary Report of Availability of Geothermal Data for Potential Direct Heat Application in Nevada* (DOE Report, NVO-0671-1, Nevada Bureau of Mines and Geology, Reno, Nevada, September 1977).

R. Trehan, A. Cohen, J. Gupta, W. Jacobsen, J. Leigh and S. True: *Site Specific Analysis of Geothermal Development--Data Files of Prospective Sites* (DOE Report HCP-T4014-01-2, August 1978).

J.W. Tester and J.N. Albright: *Hot Dry Rock Energy Extraction Field Test: 75 Days of a Prototype Reservoir at Fenton Hill, Segment 2 of Phase 1* (DOE Report LA-7771-MS, Los Alamos Scientific Laboratory, University of California, April 1979).

P.M. Wright, D. Foley, C.R. Nichols and P.J. Grim: Western states cooperative direct heat geothermal program of DOE (*Geothermal Resources Council, Transactions*, Vol. 2, July 1978).

F. Williams, A. Cohen, R. Pfundstein and S. Pond: *Site-Specific Analysis of Geothermal Development-Data Files of Prospective Sites, Vol. III* (DOE Report HCP-T4014-01-3, February 1978).

B. Wilkins, Jr.: *Operations Research and Systems Analysis of Geopressured/Geothermal Resources in Louisiana* (DOE Report ORO-5442-1, Office of Advanced Studies and Research, Louisiana State University, Baton Rouge, Louisiana, February 1978).

D.F. White and D.L. Williams, Editors: *Assessment of Geothermal Resources of the United States--1975* (Geological Survey Circular 726, 1975).

G.A. Waring: *Thermal Springs of the United States and Other Countries of the World, A Summary* (U.S. Geological Survey Professional Paper No. 492, 1965).

Legal, Institutional and Environmental

J.W. Aidlin: Development of geothermal laws and regulations in *Preliminary Study Guide, California Department of Oil and Gas/Geothermal Resources Council, Short Course No. 2*, May 1974).

D.N. Anderson: Geothermal laws and regulations in the western United States (*California Department of Oil and Gas/Geothermal Resources Council, Short Course*, 1973).

N.B. Crow: *An Environmental Overview of Geothermal Development: The Geyers--Calistoga KGRA Vol. 4, Environmental Geology* (DOE Report USRL-52496, Lawrence Livermore Laboratory, University of California, Livermore, California, November 1978).

J.F. Dietz: *Geothermal Environmental Baseline Data Acquisition, Heber Region, Imperial Valley, California* (EPRI ER-352, San Diego Gas & Electric Co., San Diego, California, February 1977).

Geonomics, Inc., Berkeley, California: *Geotechnical Environmental Aspects of Geothermal Power Generation at Heber, Imperial Valley, California* (EPRI ER-299, October 1976).

T.C. Gustavson and M.M. McGraw: Potential environmental concerns associated with the development of geopressured-geothermal resources of the United States Gulf Coast (*Geothermal Resources Council, Transactions*, Vol. 2, July 1978).

J.J. McNamara: *Federal Land-Use Planning and the Future of Geothermal Resources Development in the U.S.: An Unfolding History* (Geothermal Resources Council, Special Report 170.6, Davis, California, 1979).

National Conference of State Legislatures Geothermal Policy Project: *Workshop on State Legislative Issues in Geothermal Development* (Geothermal Policy Project, National Conference of State Legislatures, Denver, Colorado, October 1978).

National Conference of State Legislatures Geothermal Policy Project: *Legislative Recommendations on Geothermal Policy* (National Conference of State Legislatures, Denver, Colorado, 1978).

C.R. Schuller, A.H. Schilling, R.J. Cole and G.D. Simon: *Legal, Institutional and Political Problems in Producing Electric Power from Geothermal Resources in California* (Battelle Report, August 1976).

S. Sato and T.D. Crocker: *Property Rights to Geothermal Resources* (RANN Report NSF-RA-770077, published in the *Ecology Law Quarterly*, School of Law, University of California Berkeley, California, 1977).

D.M. Sacarto: *State Policies for Geothermal Development* (National Conference of State Legislatures, Denver, Colorado, November 1976).

Susan G. Spencer, Brent F. Russell and Jacquelyn F. Sullivan, Editors: (*Potential Use of Geothermal Resources in the Snake River Basin: An Environmental Overview*, Vols. 1 and 2, (U.S. DOE Report EGG-2001, September 1979)).

D.L. Warner and D.H. Orcutt: Industrial wastewater-injection wells in United States, states of use and regulation (*Underground Waste Management and Artificial Recharge*, Vol. 2, 1973).

Economics and Financing

H.C.H. Armstead: Geothermal heat costs (*Energy International*, (Brussels, 1969)).

C.A. Bakewell and E.H. Herron: Low-temperature, direct use geothermal energy costs (*Geothermal Resources Council, Transactions*, Vol. 3, September 1979).

R.N. Chappell, S.J. Prestwich, L.G. Miller and H.P. Ross: Geothermal well drilling estimates based on past well costs (*Geothermal Resources Council, Transactions*, Vol. 3, September 1979).

Department of Energy: *Proceedings: NATO-CCMS Conference on the Economics of Direct Uses of Geothermal Energy*, Washington D.C., June 1977 (CONF-770681, NATO-CCMS Report No. 66, July 1978).

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