CHAPTER 4

UTILIZATION

Work Group

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INTRODUCTION

State of the art

Direct utilization of geothermal energy for space and process heating for the most part, utilizes known technology. Basically, hot water is hot water whether from a boiler or from the earth. The utilization of geothermal energy requires only straightforward engineering progress rather than revolutionary advances and major scientific discoveries. The technology, reliability, economics and environmental acceptability have been demonstrated throughout the world.

It must be remembered that each resource is different and the systems must be designed accordingly. Granted, there are problems with corrosion and scaling, generally confined to the higher temperature resources, but most of these problems can be surmounted by materials selection and proper engineering designs. For some resources, standard engineering materials can be used if particular attention is given to the exclusion and/or removal of atmospheric and geothermally generated gases. For others, economical designs are possible which limit geothermal water to a small portion of the overall system by utilizing highly efficient heat exchangers and corrosion resistant materials in the primary side of the system.

Summary of utilization

Direct utilization of geothermal energy was probably practiced by early man for cooking and heating. Recorded history shows uses by Romans, Chinese, Japanese, Turks, Icelanders, Central Europeans and the Maori of New Zealand for bathing, cooking and space heating. These uses have continued to today where, for example, over 1500 hot-spring resorts exist in Japan, visited by 100 million guests every year.

Early industrial applications include the use by the Etruscans of boric acid deposited by the steam and hot water at Lardarello, Italy. They used the deposits to make enamels to decorate their vases. Commercial extraction of the acid started in 1818, and by 1835, nine factories had been constructed in the region. Municipal district heating was first undertaken in Reykjavik, Iceland in 1928.

Today, over 7000 megawatts thermal (MWt) are utilized in the world for space heating and cooling (space conditioning), agriculture and aquaculture production and for industrial processes. Of this figure, over 1200 MWt are used for space heating and cooling; approximately 5500 MWt for agriculture, aquaculture, and animal husbandry; and over 200 MWt for industrial processes.

Typically, the agriculture-related uses utilize the lowest temperatures, with values from 80-180°F (27-82°C) being typical. Use of wastewater has wide applications here. The amount and types of chemicals and dissolved gases, such as boron, arsenic and hydrogen sulfide, are a major problem for this use. Heat exchangers and proper venting of gases may be necessary in some cases to solve this problem. Almost all of the agricultural-related energy utilization is in the Soviet Union where over 5000 MWt are reported being used.

Space heating generally utilizes temperatures in the range of 150-212°F (66-100°C), with 100°F (38°C) being used in some marginal cases and heat pumps extending this range down to 55°F (13°C). The leading user of geothermal energy for space heating is Iceland, where over 50 percent of the country is provided with geothermal heat. The only known cooling is in Rotorua, New Zealand, at the International Hotel; however, many other applications are presently being considered.

Industrial processing typically requires the highest temperatures, using both steam and superheated water. Temperatures up to 300°F (150°C) are normally desired; however, lower temperatures can be used in some cases, especially for drying of various agricultural products. Though there are relatively few examples of industrial processing use of geothermal energy, they represent a wide range of applications, from drying of wool, fish, earth and lumber to pulp and paper processing and chemical extraction. The two largest industrial uses are the diatomaceous earth drying plant in Iceland and the paper and wood processing plant in New Zealand. A visual representation of the required temperature for various direct-thermal uses is shown in Figure 1 (Lienau/Lindal, 1974). Here both water and saturated steam are shown and cascading can be easily visualized.

°F	°C		
392	200		
374	190		
356	180	Evaporation of highly conc. solutions Refrigeration by ammonia absorption digestion in paper pulp, Kraft	Temp. range of conventional power production
338	170	Heavy water via hydrog. sulphide proc. Drying of diatomaceous earth	
320	160	Drying of fish meal Drying of timber	
302	150	Alumina via Bayers proc.	
284	140	Drying farm products at high rates Canning of food	
266	130	Evaporation in sugar refining Extraction of salts by evaporation and crystalisation	
248	120	Fresh water by distillation Most multiple effect evaporations, concentr. of saline sol. Refrigeration by medium temperatures	
230	110	Drying and curing of light aggreg. cement slabs	
212	100	Drying of organic materials, seaweeds, grass, vegetables, etc. Washing and drying of wool	
194	90	Drying of stock fish Intense de-icing operations	
176	80	Space heating Greenhouses by space heating	
158	70	Refrigeration by low temperature	
140	60	Animal husbandry Greenhouses by combined space and hotbed heating	
122	50	Mushroom growing	
		Balneological baths	
104	40	Soil warming	
86	30	Swimming pools, biodegradation, fermentations Warm water for year-around mining in cold climates De-icing	
70	20	Hatching of fish; fish farming	

FIGURE 1. The approximate temperature required for various geothermal uses.

Examples of current utilization

Traditionally, direct use of geothermal energy has been on a small scale by individuals. Surface hot springs were utilized and shallow wells could be justified with on-the-spot use or short transmission distances in uninsulated pipes or channels. However, at today's prices for development and hardware, the cost savings of these individual uses are often marginal. Large-scale use demands require more production and can thus justify deeper wells, longer transmission distances, more sophisticated utilization and lower temperatures.

Most of present-day developments involve large-scale projects, such as district heating (Iceland), greenhouse complexes (Hungary) or major industrial use (New Zealand). Heat exchangers are also becoming more efficient and better adapted to geothermal use, allowing the use of lower-temperature waters and highly saline fluids. Heat pumps are extending geothermal development into traditionally non-geothermal countries, such as France, Austria and Denmark, as well as the eastern U.S.

Space conditioning. The most famous space-heating project in the world is the Reykjavik municipal heating project, serving about 97 percent of the 113,000 people in the capital city of Iceland. At present, a total of 1.0 x 10^{10} gallons (3.8 x 10^{10} liters) of geothermal fluid are used annually to supply 16,000 homes with space heating. One field supplies water through two 14-inch and one 28-inch (35 and 70 cm) diameter pipeline over a 12-mile (19-km) distance. Insulated storage tanks (6.9 x 10^6 gallons; 2.6 x 10^7 liters) are used to meet peak flows and provide an emergency supply in the event of breakdown in the system. A fossil-fuel fired peaking station is used to boost the 176°F water to 230°F (80-110°C) during 15 to 20 of the coldest days of the year. The city is served by 9 pumping stations, distributing fluid through 200 miles (320 km) of pipelines. The entire system provides 1840 GWh per year or 420 MWt (including the peaking station; Lienau/Zoega, 1974).

An example of individual home space heating is in Klamath Falls, Oregon, where over 400 wells are used for space heating, using waters from 100-230°F (38-110°C). The principal heat-extraction system is the closed-loop downhole heat exchanger utilizing city water in the loop (Lund et al., 1974). Larger examples of space heating in Klamath Falls include the Oregon Institute of Technology campus, where three wells up to 1800 feet (550 m) deep produce up to 450 gpm (28 l/s) of 192°F (89°C) water and heat approximately 500,000 ft^2 (46,000 m^2) of floor space. The geothermal water is pumped from the well using deep-well turbine pumps and, in most cases, is used directly in the heating system for each building. The annual operating cost of the campus system is approximately $30,000, a savings of almost $250,000 per year when compared with the cost of heating with conventional fuel. Other notable uses in the community include the 311-bed Merle West Medical Center hospital and nursing home, where the present worth of a 20-year savings due to a geothermal-retrofitted heating system is over one million dollars, and Maywood Industries, where 118°F (48°C) water is used for heating a large manufacturing building (Geo-Heat Utilization Center Bulletin, Lienau, 1977; Higbee, 1978).

Agriculture and aquaculture. In Hungary, greenhouse heating is second only to the USSR, with over 13 million ft^2 (1.2 million m^2) being geothermally heated. Many of these greenhouses are built on rollers, so they can be pulled from their location by tractors, the ground cultivated with large equipment, and then the greenhouse returned to its location. In addition, to minimize cost, much of the building-structure pipe-supporting system also acts as the supply and radiation system for the geothermal fluid. About 60 wells are used for animal husbandry projects, mainly for heating and cleaning of animal shelters. Priority is given to agricultural use of geothermal energy in Hungary, as this increases the volume and variety of production.

Some experimental work is being performed with grain, hay, tobacco and paprika drying. In these cases, hot water supplies heat to forced-airheat exchangers and 120-140°F (49-60°C) air is blown over the product to be dried (Lienau/Boldizar, 1974).

In Japan, greenhouses cover about 157,000 ft^2 (14,600 m^2), where a variety of vegetables and flowers are grown. Many large greenhouses are operated as tropical gardens for sightseeing purposes. Raising poultry through the use of geothermal energy has been a very successful enterprise. Here, under-the-floor heating is utilized in sheds where 40,000 chickens are raised annually. Another successful business is breeding and raising carp and eels. Eels are the most profitable and are raised in 10-in diameter by 20-ft long (25-cm by 6-m) earthenware pipes. Water in the pipes is held at 73°F (23°C) by mixing hot-spring water with river water. The adult eels weigh from 3-1/2 to 5-1/4 oz (100-150 g), with a total annual production of 8400 lbs (3800 kg). Alligators and crocodiles are also raised in geothermal water. These reptiles are being bred purely for sightseeing purposes. In combination with greenhouses offering tropical flora, alligator farms are offering increasingly large inducements to the local growth of the tourist industry (Japan Geothermal Energy Assoc., 1974).

Excellent examples of greenhouse operation exist in the U.S., the largest being the Honey Lake Hydroponic Farms complex near Susanville, California. Cucumbers and tomatoes are grown in a hydroponic system. Heat is provided to the greenhouses by geothermal fluid. At present, 30 greenhouses have been constructed, with expansion planned to over 200 units. Channel catfish are raised by Fish Breeders of Idaho near Buhl, using geothermal water. Using 6000 gpm (380 l/s) of 90°F (32°C) water, approximately 500,000 lbs (230,000 kg) of fish are raised annually (GRC Special Report No. 5, Ray, 1979).

Industrial processes. An example of industrial processing is the use of geothermal steam for the Tasman Pulp and Paper Company in New Zealand. Here, 100-125 MW (18 tons/hr steam) of thermal energy are used for the lumber drying, black liquor evaporation, and pulp and paper drying. The total investment cost for geothermal is $6.8 million, the majority of which is for well development. This amounts to approximately $70 per kWt and will reduce the price of energy to 70 percent that of conventional fuels for an annual savings of $1.3 million. The annual maintenance costs are 2 percent of the capital cost (Lienau/Wilson, 1974).

In northern Iceland, a diatomaceous slurry is dredged from Lake Myratn. This slurry is transported through a pipeline and held in storage ponds. The 80 percent moisture is then removed in large rotary-drum driers using high-temperature geothermal steam. The plant produces 27,000 tons (24,494 t) of diatomite filteraids per year, most of which are used in beer processing in Germany (Lienau, 1974).

Two industrial-processing uses of geothermal energy are of note in the U.S.: Medo-Bel Creamery in Klamath Falls, where low-temperature fluid is used for pasteurizing milk, and Geothermal Food Processors at Brady Hot Springs, Nevada, where high-temperature fluid is used for dehydration of onions and other vegetables (GRC Special Report No. 5, Belcastro, 1979; GRC Bulletin, vol. 7, no. 5, Nov/Dec 1978).

A major direct-thermal project in the U.S.A. in the development stage is the conversion of the Ore-Ida Foods, Inc., plant located in Ontario, Oregon. The Ore-Ida project involves drilling three production wells to a depth of 6000 feet (1.8 km) to obtain 800 gpm (50 l/s) at a temperature of 300°F (150°C). The geothermal energy would replace 55 percent of the energy now supplied by natural gas and fuel oil for potato processing (Lienau, 1978).

Summary: A summary of the present world-wide direct use of geothermal energy is as follows (GRC Special Report No. 5, Lund, 1979):

TABLE 1

Worldwide direct use of geothermal energy

Country	Space Heating/ Cooling (MWt)	Agriculture/ Aquaculture (MWt)	Industrial Processes (MWt)
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

Benefits of direct applications

The main advantages of direct utilization of geothermal energy are:

1. High conversion efficiency (80-90 percent).

2. The use of low-temperature resources, which are numerous and readily available.

3. The use of many off-the-shelf items for exploitation (pumps, controls, pipe, etc.).

4. Short development time as compared to electrical energy development.

5. Lower-temperature resources require less expensive well development (and shallower in some cases), can be drilled with conventional drilling equipment in many cases and the water can be transported 20-40 miles (32-64 km).

All of these advantages give a favorable economic situation when compared to conventional fuel. At present-day prices, the geothermal application will cost about the same or less than the corresponding annual fossil-fuel cost. Due to the expected escalation of fossil-fuel prices, the costs of the geothermal system will decline. Most geothermal direct-use systems will pay for themselves in 5-10 years from savings in conventional fuel. Detailed economic evaluations are presented in Chapter 5, Economics.

The economics are greatly enhanced where cascading (multi-stage use) is considered. The Japanese optimize cascading where geothermal fluids are first used for electrical power production, then space heating, cooking and bathing (Otake). Here, an attempt is made to "squeeze" the "last drop of energy" from the fluid. Lower-temperature cascading could consider space heating, agriculture, bathing (swimming pools) and snow melting. Low- and intermediate-temperature geothermal resources can also be used to meet the base load of an energy demand. Heat pumps and fossil fuel can then be used to meet the peak demands, thus conserving the resource and minimizing capital investments (Ryback, 1979).

SPACE CONDITIONING

General background

In areas of the United States requiring significant heat for space conditioning, the most widely used residential space heating systems are forced air, circulating water and radiant electric resistance. Recently, restrictive actions initiated in several states limit new installations of electric resistance systems. In any event, forced-air and circulating-water residential heating systems will remain popular in the foreseeable future regardless of the energy being utilized. More recently, the use of heat pumps has become popular. Figure 2 illustrates these commonly used heating systems, all of which are adaptable to geothermal energy.

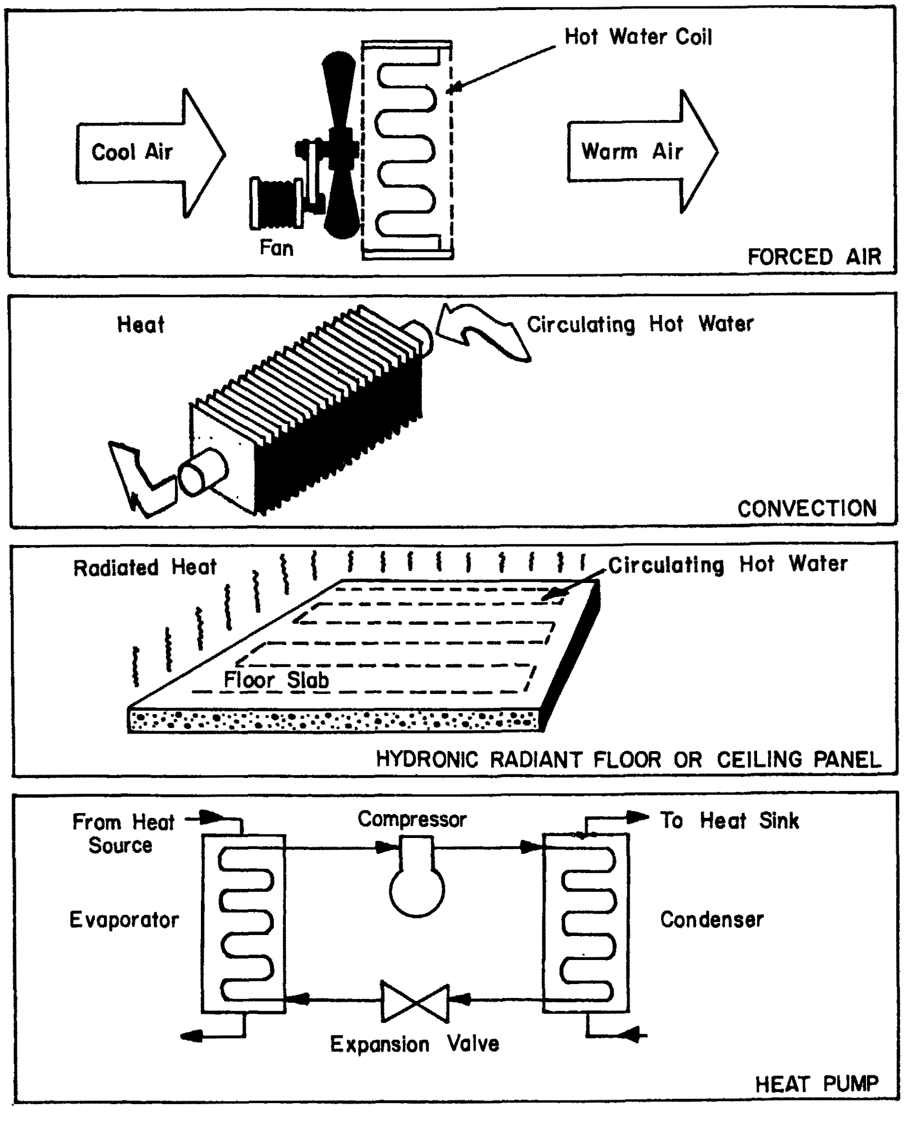

FIGURE 2. Space-heating systems suitable for geothermal applications (source: EG&G Idaho, Inc.).

Forced-air heating systems transport heated air through distribution ductwork to outlet fixtures referred to as diffusers. The source of heat for such systems can be in many forms. Furnaces fueled with natural gas, propane or fuel oil are probably the most common in single residential dwellings. In all of the furnace-type systems, the open flame provides heat to a multichambered heat exchanger device over which a fan circulates air to the space being heated.

Another device used extensively to provide heat to the forced-air system is the electric resistance duct heater. As the name implies, electric heating coils are installed directly in the ductwork through which the air is circulated.

In large, multiple-dwelling and commercial systems, a steam coil or hot-water coil is often used like the electric duct heater to provide heat to the moving air. The source of hot water or steam in a conventional system is a boiler utilizing various fuels or energy sources.

When considering new geothermal heating installations, or the ease of retrofit, the forced-air system is undoubtedly the most adaptable.

Finned-tube hot-water coils are manufactured in a variety of size and water-flow combinations that allow a maximum amount of heat to be extracted from the water. This, then, provides for satisfying a desired heat load while minimizing the size of accessory equipment, such as piping and controls.

The circulating hot-water or hydronic system, just as steam systems, uses a multiplicity of heat-distributing units. These units include radiators, convectors, baseboard, finned-tube and radiant-piping grids. The method of transferring heat to the conditioned space in all cases includes a radiant or convective heat transfer and usually a combination of both transfer mechanisms.

Any of the hydronic systems, properly designed and with automatic controls, can usually provide a more uniform space temperature than forced-air systems. When considering new installations of this type for geothermal, the design and component selections are straightforward once the geothermal resource temperature, flow and chemical characteristics are known. In retrofit situations, however, unless a match of combined temperature and flow can be obtained between the geothermal source and the original design parameters, a satisfactory and economically attractive conversion becomes difficult. For example, a system designed for 50 gpm (3 l/s) flow at 180°F (82°C) may require additional flow if the geothermal temperature is below the 180°F (82°C) original design.

In addition to the more popular heating systems just discussed, the water-to-air heat pump for residential and commercial applications has recently gained increased acceptance. This off-the-shelf device allows for the economic utilization of the marginal geothermal resource down to temperatures as low as 55-60°F (13-16°C). The heat-pump application adapts well to the forced-air system in retrofit situations and has the added benefit of providing cooling in summer months with no additional equipment cost. Off-the-shelf units are available to operate on water temperatures from 55-90°F (13-32°C), with custom-designed units for temperatures above 90°F (32°C).

Between 60°F and 90°F (16-32°C), standard heat pumps will have Coefficients of Performance (COP) of about 3 when used to provide space and low-temperature process heat. This means the heat output will be about 3 times the electrical input.

Large capacity custom-designed water-to-water heat pumps are also available that can boost the temperature of an inadequate or mismatched geothermal resource to an acceptable range for economic utilization. Where output temperatures of above 120°F (49°C) are required, COP of standard units drops off and the application may require special designs utilizing multi-stage compressors and special gases. Temperatures up to 230°F (110°C) are obtainable with COP's of about 2 and are readily adaptable to utilization of both geothermal waters and waste hot waters from

from other processes. A typical two-stage unit is shown in Figure 3.

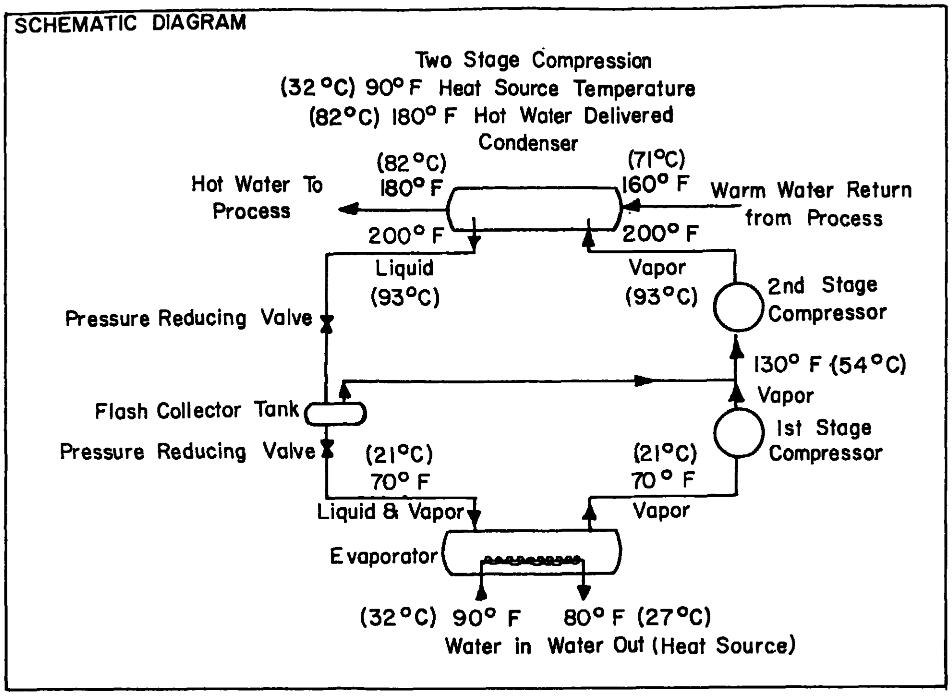

FIGURE 3. Two-stage heat pump (source: GRC Special Report No. 5, 1979).

Geothermal application of heat pumps with COP of much less than about 3 should be investigated carefully from an economical standpoint when this is the only application of the water, since the cost of wells, pumps, etc., must be considered in the overall cost of obtaining the desired output. Where geothermal "waste" water is available from other space or process uses, heat pumps may make an additional use (cascading) very economical.

In considering geothermal for space heating in either new or retrofit installations, the supply of heat for domestic hot water should not be overlooked. With the simple addition of a water-to-water heat exchanger, typical single residential energy savings of 100 Kwhr/day can easily be realized.

Primarily as a result of emphasis in the solar-utilization area, a renewed interest in the absorption cycle for cooling applications is evident. Lithium bromide units are available in more-or-less off-the-shelf sizes that will utilize water temperatures of 180°F (82°C) and above. Custom-designed ammonia-adsorption units are available to utilize water temperatures above approximately 220°F (104°C). Both absorption cycles lend themselves more readily to the larger commercial installations than to the single residential dwelling.

A summary of the temperature ranges for various space heating and cooling devices is shown in Figure 4 (Lund, 1978).

Estimating heating and cooling loads (Rules of Thumb)

During initial phases of preliminary design, it is often necessary for the engineer or contractor to make estimates of building heating and cooling loads. Most experienced engineers have established their own methods or, if you will, "rules of thumb," from which they make these initial estimates.

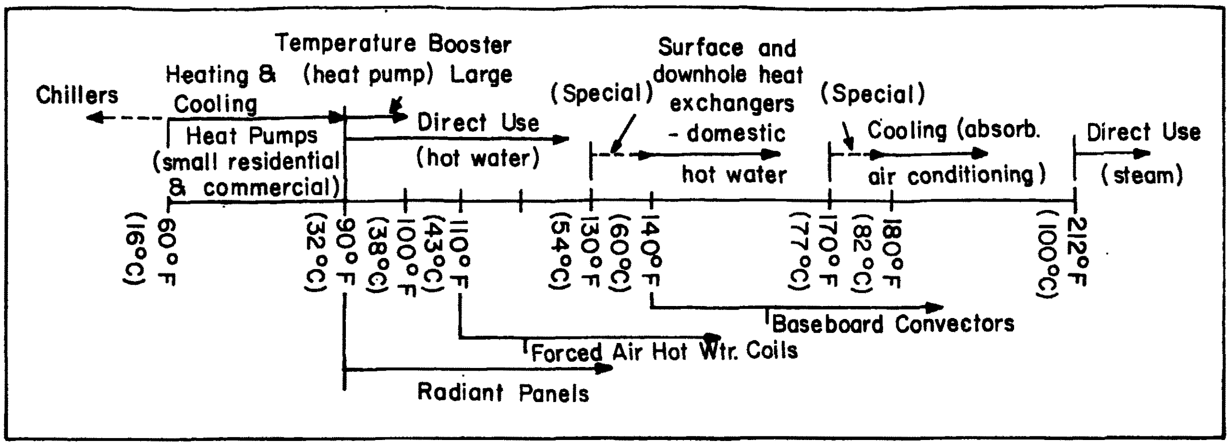

FIGURE 4. Temperature ranges for heating and cooling methods.

All such rules of thumb must be used with caution and careful consideration of the criteria of the particular project and, more importantly, keep in mind that they provide estimates only.

We will attempt herein to give our version of some of these rules from which initial comparisons of systems can be evaluated.

Experience throughout much of the western U.S. indicates that in most cases for residential estimates, the maximum heat loss of normal sized buildings will vary between 15 and 60 Btu/hr/ft^2 (1.7 x 10^3 to 6.8 x 10^3 kJ/hr/m^2 or 47 to 189 w/m^2) of floor area, depending upon the extent of insulation and design temperature difference.

Figure 5 illustrates this basic rule, where curve A relates to well insulated buildings, curve B is for a "normally" insulated building with R-19 ceilings, R-13 walls and double glazing, and curve C related to older homes with R-13 ceilings, single-glass and standard-frame construction with no wall insulation.

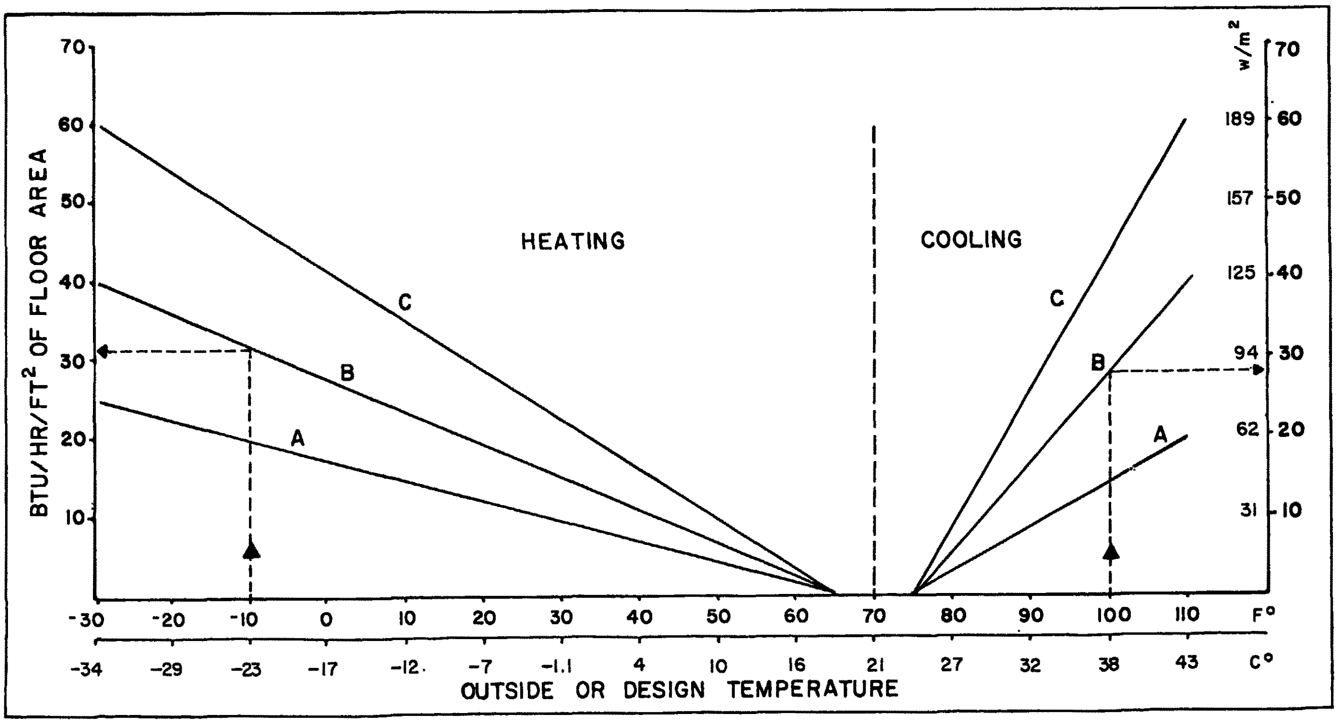

FIGURE 5. Design curves for heating and cooling loads.

Small commercial buildings will fall within the above parameters. For the larger and more complex commercial or industrial type of buildings, we recommend that a block load be calculated using the ASHRAE standards, even if it means estimating or "guesstimating" what the construction may be. This involves estimating the heat loss through outside walls and roof, but not considering the differences in heat requirements of different areas within the "block." Annual heat load may be estimated by numerous methods. ASHRAE Degree Day Method[1] usually produces a high figure, ASHRAE Bin Method[1] is far more accurate but is a lengthy process. Several computer programs that are quite accurate but expensive are available for more detailed estimating and comparison purposes.

The delivered heat to a project should allow for miscellaneous losses and start up from a cold start. Normally a factor of 25% is added to the heat loss calculations to obtain the total heat loss or heat load (HL).

Assuming this heat loss will be offset by either primary or secondary water flow, then the water flow (w) required will be equal to:

$$W\ (\text{gpm}) = \frac{\text{HL (Btu/hr)}}{500 \times \Delta T\ (°\text{F})} \text{ or } W(\text{l/s}) = \frac{\text{HL (kJ/hr)}}{15{,}200 \times \Delta T(°\text{C})} = \frac{\text{HL (kw)}}{4.22\ \Delta T(°\text{C})}$$

where T (temperature differential) is the amount of heat extracted from the fluid flow in °F.

For a quick method of determining annual heat load for comparison to other heating methods or systems, we recommend the formula:

$$\text{Annual Heat Load} = \frac{\text{DD} \times \text{HL} \times 24}{\Delta T} = \text{Btu/yr (or kJ/yr or watts)}$$

where DD = Annual degree days[2] (day-°F)
HL = Heat Loss[1] (Btu/hr), and
ΔT = Difference between inside and outside temperatures (°F).

For more detailed heat-loss calculations, the following basic formula is used:

$$\text{HL} = \text{A} \cdot \text{U} \cdot \Delta T$$

where HL = heat loss in Btu/hr (or kJ/hr or watts)
A = surface area in ft^2 of wall, window, ceiling, etc.
U = thermal transmittance[3] in $\text{Btu/hr/ft}^2\text{/°F}$, and
ΔT = design-temperature difference between inside and outside in °F

At the present "state of the art," residential-cooling applications utilizing geothermal energy are best left to professional engineers and no rules of thumb are applicable. Commercial cooling units are available which can utilize 180-210°F (82-99°C) water. In general, hot-water flow requirements are significantly higher for cooling than for heating and cooling water or cooling towers are required. Unless the hot and cold water are readily available, cooling systems may not be economical.

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[1] Details of the Degree Day Method and the Bin Method may be found in the 1976 ASHRAE Systems Handbook, Chapter 43.

[2] Annual Degree Days--Obtainable from the local weather stations, ASHRAE 1976 System Handbook Chapter 43, or from National Oceanic and Atmosphere Administration, National Climatic Center, Asheville, NC 28801.

[3] Thermal-transmittance values for various materials can be found in ASHRAE.

New Installations

As noted earlier, the design of a new geothermal space-heating system is quite similar to the design of a conventional hydronic space-heating system except that the designer often has no control over the temperature of the water available, and the temperature is often lower than conventional systems. Additional economic considerations must be made for the well, pumping equipment, in most cases heat-exchange equipment and, in cases where the well is some distance from the buildings, the transmission piping. These additional items will be covered in detail later, but in general their cost can be reduced by maximizing the temperature differential across the heat-emitting units. The problem reduces to one of utilizing the temperature available and balancing water-supply costs against the cost of obtaining high ΔT in the geothermal water. Considerations specific to different systems are below.

Radiant panels (floor, ceiling wall). This system can utilize water at lower temperatures than any other except heat pumps (see Figure 4). In order to obtain the required heat output at low inlet temperatures, the panels must have close coil spacing, shallow pipe depth, small pipe sizes and high flow rates. Plastic pipe 1/2-inch or less (13 mm) in diameter can be utilized to reduce coil costs and prevent corrosion and scaling where temperature limits of the pipe are not exceeded: 125°F (52°C) for ABS, 150°F (66°C) for PVC and 212°F (100°C) for CPVC.

Baseboard convectors. Baseboard convectors, due to their low initial cost, are in most cases the most economical heating system for residential and small commercial applications. They find little application in larger spaces since heat output and air circulation are limited and cooling is difficult. In order to attain a large ΔT and associated low flow rates, 3/4-inch (19 mm) and smaller tube sizes are required to maintain flow velocities in the desirable turbulent regime. Large, closely spaced fins with the width dimension greater than the height dimension provide greater heat transfer than square fins. Where multiple rows are required to obtain the desired output and space is available, horizontal placement of the rows will provide nearly one and one-half times the heat output of vertical stacking of the rows.

Since the heat output decreases rapidly with decreasing temperatures, the possibility of using geothermal water directly and eliminating the temperature loss in a heat exchanger should be investigated. In many low-temperature waters, iron pipe will provide better corrosion resistance than copper. The cost and availability of special tube materials to resist corrosion peculiar to the resource should be investigated and cost analysis run.

Average water temperatures below 140°F (60°C) are difficult to utilize and present special engineering and architectural problems.

Forced-air systems. Forced-air systems are by far the most popular for residential applications and are used almost exclusively for larger commercial applications either with or without supplemental perimeter heat convectors or baseboard units.

Although large temperature drops are desired, the designer should not necessarily set a ΔT to be attained in the design, but rather attempt to obtain as low an exit water temperature as possible. Although water temperature differential of 100°F (38°C) can be obtained when 200°F (93°C) water is available, under some conditions a 40°F (22°C) drop may be difficult when only 120°F (49°C) water is available. Conversely with high make-up air requirements in cold temperatures, water temperature drops in excess of 40°F (22°C) with 120°F (49°C) inlet water may be readily obtained with 6- or 8-row multiple-pass reverse-flow coils.

In many cases, the fan coil units will be of special design in order to obtain the high ΔT. Another approach is to use somewhat standard design units in series to obtain an overall high ΔT with the units on the low-temperature end of special design for the lower entering water temperatures.

Some examples of the special considerations and their consequences are:

Desired parameter	Consequences
High ΔT water	1. Increased face area 2. Deep coils with high ΔP water 3. Serpentine paths with high ΔP water 4. Closer fin spacing with high ΔP air 5. "Stacked" coils with high ΔP air

where ΔP = change or drop in pressure

Low Inlet-Temperature Water	1. Increased surface area 2. Closer approach temperatures 3. Higher water-flow rates
Low Temperature Air Out	1. High air flow 2. Larger duct work 3. Higher ΔP air

High water- and air-pressure drops may require circulation pump and fan design differing from more conventional systems.

Figure 6 illustrates the approximate output rate for cast-iron radiators, finned tubes and fan coils.

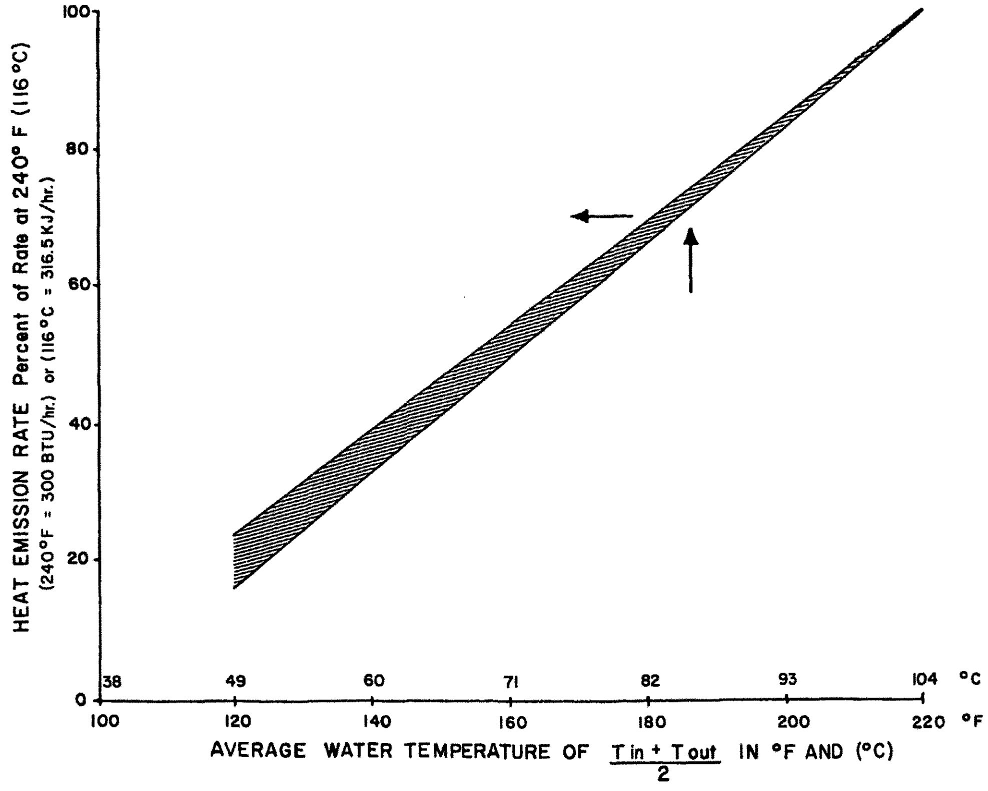

FIGURE 6. Approximate heat output rate of radiators, finned tubes and fan coils vs. water temperature.

Retrofit

In general, hot-water systems of any type are not usually difficult to retrofit if geothermal water above 180°F (82°C) is available. Most conventionally fueled systems operate at 180-210°F (82-99°C) and many have sufficient capacity to carry the heating load if water temperature is reduced 20-30°F (11-17°C).

The ability to carry the heating load at reduced temperature is due either to original over-design or to selection of standard-sized components of the nearest size larger than actual requirements. The older the system, the better are the chances of having over-capacity, since modern design information was not available, component selections were not as large and larger safety factors were usually applied. Systems with capacities of 150-175% of actual requirement are often encountered. A few observations and simple calculations (heat requirements vs. capacity) will usually indicate if sufficient capacity may be available and warrant further investigation.

One of the simplest and most straightforward methods of checking system capacity is to gradually reduce system-input temperature during the peak heating season until the geothermal temperature available is reached or desired space temperatures are not maintained. The usual result is that system "on" time is increased and temperatures are maintained. Since geothermal-system operating costs are usually low, the conversion would prove economical.

Forced-air systems. Systems utilizing hot water in fan-coil units are generally the easiest and least costly to retrofit. Most conventionally fueled systems are designed with simple one- or two-pass coils with air flow perpendicular to the coils and inlet-water temperatures of 180-200°F (82-93°C). Where similar geothermal temperatures are available there are no problems.

Most geothermal systems will require heat exchangers to prevent corrosion of the fan-coil tube. Even considering the 10°F (6°C) or so loss across the heat exchanger, new coil units in series with existing coils or new multipass coils will provide the required output with surprisingly low geothermal temperatures.

Where the available resource temperature is considerably lower, such things as increasing the duty time as noted above may not suffice and deeper coils, increased coil-face area, reduced fin spacing and increased air volume may be required. Each of these will affect other system parameters. For instance, deeper coils, closer fin spacing and increased air volume will increase the air-pressure drop across the coil and may require increased fan speed and/or increased fan-motor power. Fan speed can often be increased by simply changing fan-belt pulley ratios, but significant changes require increased motor horsepower. Increasing the coil-face area will aid in maintaining low air-pressure drops and can be achieved by mounting the coil at an angle to the air flow or duct axis or installing transition duct work to obtain a larger mounting space, as shown in Figure 7.

Increased air volume affects the entire duct system with increased velocities and possible attendant pressure and noise problems. Most systems will accept some increase in volume with some cases requiring changes in diffuser size to eliminate noise. Additional duct work may be added to increase the air-handling capacity and new outlets may be strategically located in areas requiring more heat or where they can supply several areas.

Electrical resistance duct-heating systems can be retrofit utilizing the considerations above.

The retrofit designer should remember that forced-air systems are the most complicated of the common systems and as such have the greatest number of variables. In most cases, this allows

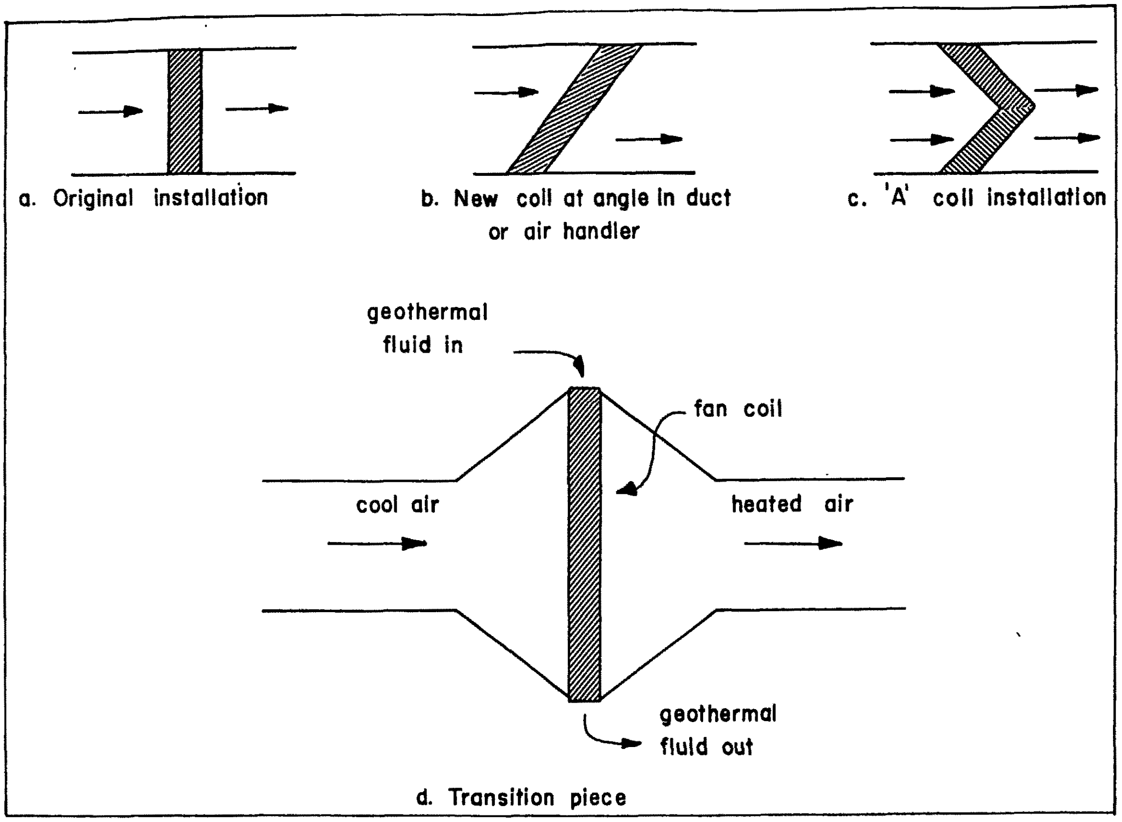

FIGURE 7. Simple methods to increase fan-coil face area.

more manipulation of the variables to attain the desired end results, but requires greater ingenuity and care in the design.

Hydronic systems. The common hydronic systems, baseboard or convector finned-tube units, radiators and radiant panels, have few variables one can change to accommodate lower inlet water temperatures, except to add radiation. Careful calculation of heat load and heating-unit output will ascertain the minimum permissible average temperature with existing radiation. (Better yet is the reduction of boiler outlet temperature as noted earlier.) Heat output of these units varies linearly though not directly with average water temperature as noted earlier in Figure 6. Lower inlet temperatures can be offset somewhat by increased flow rates, thereby reducing the temperature drop across the system. However, increased flows require increased pumping power, increase the possibility of water hammer, noise and, of course, require an adequate supply of water in direct-use applications. Proper control valves may alleviate the water-hammer problem, but noise can be eliminated only by maintaining flows below a critical velocity.

When retrofitting for lower temperatures, usually the most economical and desirable solution is to install new and/or increased radiation surface. Small tube sizes in new radiation will allow reduced water flow per radiation unit while maintaining nearly the same output allowing more radiation to be installed on existing piping systems.

Radiant panels (floor or ceiling) are the most difficult hydronic system in which to make large temperature changes since the expense of installing additional radiation of the same type is prohibitive. The retrofit designer must usually be satisfied with accepting the lower heat output of the panels and supplementing this with additional baseboard or other radiation or with supplemental forced air. In floor systems, the floor covering may be changed, i.e., from carpets to linoleum or tiles, but this is usually not acceptable.

Steam radiation. Steam systems utilizing convectors or radiators are probably the most difficult to retrofit. Water temperatures must be high to allow use of existing radiation (see Figure 6). Steam supply lines are usually adequate to supply hot water, but condensate lines (with steam traps removed) quite often are not. Inlet temperatures lower than 190°F (88°C) are usually impossible to utilize without extensive modifications unless the system was greatly over designed. The use of more efficient radiation devices in convection units with fans should be investigated to determine whether or not condensate lines will be adequate for required flows. Piping costs can sometimes be reduced by modification of the zoning arrangements allowing the use of some existing lines with additional new return piping to serve other zones. Accessibility of the piping system for modifications and additions often is an important consideration.

In all of the above types, the retrofit designer should not overlook the possibility of supplemental systems when available resource temperature will not permit the existing system to meet the demand. Often the supplemental units can be cascaded with the existing system thereby providing the required heat output with high temperature drops and efficient use of the resource.

Additional considerations

Importance of large temperature differential. In the early days of hydronic heating, it was commonplace to use a 20°F ΔT (11°C) for heat transfer from coils or radiation. This necessitated comparatively large pipe and pump sizes to circulate the amount of water required. In recent years, engineers have been using temperature differentials of 40°F, 60°F and 80°F (22°, 33° and 44°C), thus using considerably smaller pipes and pumps.

As an example, let us assume a system has a heating capacity of 500,000 Btu/hr (5×10^5 kJ/hr = 146 kw) capacity. At a ΔT of 20°F (11°C), this system would require 50 gpm (3 l/s). The same system on a ΔT of 60°F (33°C) would require a flow of only 16.6 gpm (1 l/s). Thus, in the case of the ΔT = 20°F (11°C), a 3" (76 mm) pipe would be required, whereas at a ΔT = 60°F (33°C), a 1-1/2 inch (38 mm) pipe would be required. This same reduction applies to pump sizing and all accessories. The economics of this are very evident in the piping system, but these savings are, of course, offset somewhat by higher costs of the heating units. Overall economics must be considered, but nearly always favor higher ΔT's.

These same principles are multiplied in geothermal heating and piping systems, since another basic principle enters into the thinking, i.e., if you pump 500 gpm (30 l/s) of 180°F (82°C) water out of a geothermal well and only use a ΔT of 20°F (11°C), you have only 5,000,000 Btu/hr (1.47 MW) of usable heat extracted; however, if that same water is returned to the injection well at 100°F (38°C), or a ΔT = 80°F (44°C), you have extracted a usable heat of 20,000,000 Btu/hr (5.86 MW). This represents a 400 percent increase in heat production with the same well, pumping and piping costs.

The increased ΔT may be obtained by several methods: increased coil size, multi-serpentine coils, cascading, or any other series-type flow.

Therefore, in any hot-water piping system, whether it is a primary geothermal water source, a secondary flow, or a system to a single coil, the larger the ΔT obtainable, the more significant will be the economic savings in the piping and pumping system.

Water quality considerations. In the design of a geothermal heating system, attention must be paid to the quality of the geothermal fluid. Many geothermal resources are high in total dissolved solids and most fluids contain hydrogen sulfide or other corrosive components.

Since the temperature of the geothermal fluid is decreased in a heating system, dissolved solids tend to precipitate out as scale. If the scale forms on a heat-transfer surface, such as the inside of a heater coil, the heater duty decreases due to increased resistance to heat transfer. As scale build-up continues, flow restriction becomes important, and pipes or tubes can plug.

One means of controlling scale is to use the geothermal resource to heat a secondary fluid which does not have a scaling problem. By heating the secondary fluid at the well area, scale buildup is localized. The heated secondary fluid is then circulated through the distribution systems, and reheated in a closed loop. Since the scale precipitates when the temperature decreases, most of the deposition from the geothermal fluid occurs inside the heat exchanger and chemical or mechanical cleaning of the exchanger is possible. In a system with a secondary heating loop such as this, it is possible to have a standby heat exchanger in parallel with the normal exchanger so that exchanger cleaning and maintenance does not force a system shutdown. Another advantage of a closed secondary heating loop is that anti-freeze and corrosion inhibitors can be added, thus protecting the distribution system and heaters.

In geothermal fluids that contain hydrogen sulfide or other corrosive components, it is important that the fluid does not contact susceptible materials. As an example, copper is readily attacked by sulfides, so the use of copper coils should be carefully studied if geothermal fluid is to be used directly. The use of a secondary heating loop can be beneficial because more expensive, corrosion-resistant materials can be limited to the well-area piping and heat exchangers.

There are many instances where geothermal fluids have been used directly in hydronic systems with little or no difficulty due to scaling or corrosion. To add a secondary heating loop or non-standard heating coil could be an unnecessary expense. Thus, the design of any system should be based on the particular quality of the geothermal source.

DISTRICT HEATING

District-heating systems are divided into three main components: the heat production unit, the distribution network and the consumer installations. The heating medium used in European systems is almost exclusively high-temperature (300°F, 149°C) to low-temperature (250-180°F, 121-82°C) hot-water systems. Swedish systems operate with high-temperature water requiring heat exchangers between the district and consumer. Denmark uses medium- to low-temperature hot water in the mains, providing the possibility of direct connection to the consumer installations, which simplifies system design. In the United States, steam is the most common medium used.

Why district heating?

A strong incentive for district heating is energy conservation and lower energy costs by using cheaper fuel and waste heat. Fuel economy is greater for district heating (for example, a home with an individual heating system operates at 50 to 70% efficiency compared to 80% in the case of district heating). Other incentives are improved air quality through improved discharges of fossil-fuel fired centralized plants; the concentration of the facility, allowing efficient use of fewer technical and supervisorial specialists; and fewer oil-transporting vehicles for fossil-fuel plants. Using geothermal energy as the energy source, a more efficient use of the resource can be realized.

Obstacles to district heating are: cost of distribution, distribution heat loss, the high cost of supplying one-family houses on lots over 5000 ft^2 (460 m^2), high initial capital investments and the many different types of heating systems in the United States. Natural gas is a severe competitor to district heating from an environmental and economic view; however, geothermal energy has proven competitive (Klamath Falls) where the resource is near the heating load.

Iceland has experienced great success in using geothermal energy for district heating with a savings of approximately 30% over using heating oil. Approximately 65% of the buildings in the country and 97% in Reykjavik are on district heating systems. Other European countries, such as Sweden and Denmark, are expanding district heating systems because of fuel economy.

Heating density

A very important economic factor is the heat density, i.e., the possible connected heat demand for district heating divided by the ground area. High heat density is required since the distribution network which transports the hot water to the buildings is expensive. Studies which have been done in the U.S. and Sweden have categorized areas according to the economy prospects of district heating as shown in Table 2 (Swedish District Heating Manual, 1978).

TABLE 2

Economy prospects of heat density for district heating

Peak Heat Density MBtu/hr acre MW/ha	Area	Category
>0.97	Downtown - high rise	Very favorable
0.97 - 0.70	Downtown - Multi-storied buildings	Favorable
0.70 - 0.28	City core - commercial bldg & multi-family apartment buildings	Possible
0.28 - 0.17	Residential - multi-family houses	Questionable
<0.17	One-family houses	Not possible

The economy of a district heating system can be improved by adding an industrial base or cooling loads to the system. This is illustrated in Figures 8 and 9 by comparing duration curves for thermal loads only (Figure 8) and combined winter thermal and summer air-conditioning. The latter is based on the assumption that the summer cooling load does not affect the pipe size.

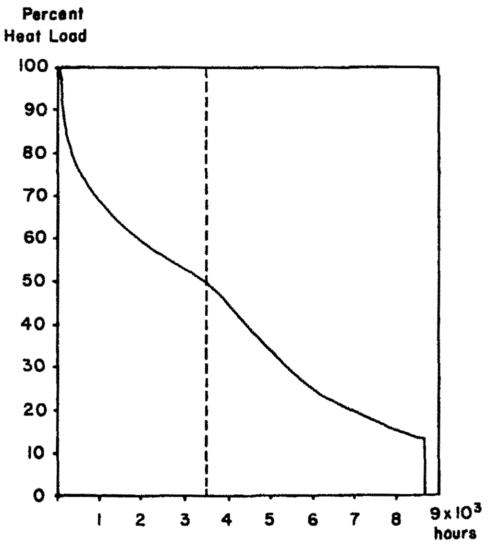

FIGURE 8. Thermal load duration curve.

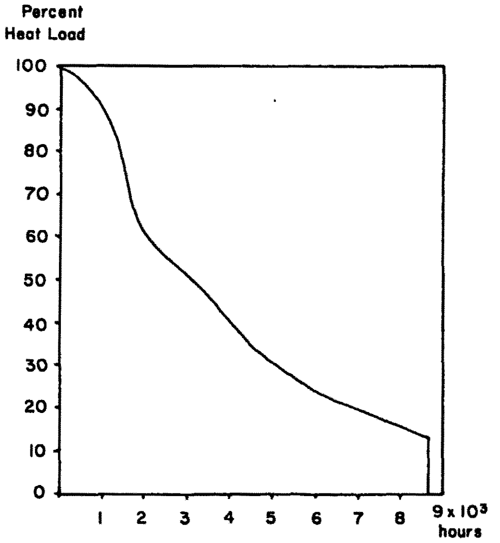

FIGURE 9. Thermal and air-conditioning load duration curve.

The area below the curve expresses the total heat consumption in a year. This is improved for the combined curve, Figure 9.

Low- vs. high-temperature systems

District heating is a matter of heat transportation which is accomplished by using low- temperature (250°F, 121 °C), high-temperature (300°F, 149°C) hot water or steam as the medium.

Low-temperature hot water in the mains provides the possibility of direct connection to the consumers. Direct connection means better efficiency, an increase in the permissible temperature differential at a given temperature, and a smaller amount of circulating hot water with smaller pipes and lower heat loss. System design is simplified, and without recirculation there is usually no need to incorporate internal pumps in space-heating installations, which leads to lower installation and operating costs.

High-temperature hot-water systems usually require the addition of heat exchangers and recirculation pumps in the consumers' buildings. Higher heat losses also result in the distribution network. Steam systems generally have a lower efficiency and a limited transport distance when compared to hot-water systems.

Auxiliary boilers and heat pumps

Geothermal energy can be used as a preheater in the case of a low-temperature resource. The geothermal fluid can be boosted to a higher temperature by fossil fuel, such as in the Reykjavik system, or to preheat a secondary fluid which is in turn peaked by fossil fuel. Capital costs are generally reduced by introducing an auxiliary boiler into large district-heating systems. Designed to meet the peak heat load a few days out of the year by increasing fluid temperature, this results in smaller pipes, pumps, heat exchangers and fewer wells.

Another possibility in the case of a low-temperature (140-160°F, 60-71°C) geothermal resource is to include heat pumps in addition to the auxiliary boilers. A system of this type installed in the Paris basin supplies heat to 10,000 apartments and is claimed to be economical (Ryback, 1979). Annual heat consumption from the contributions of different sources for geothermal alone and geothermal plus heat pumps is illustrated by the areas under the curves in Figure 10.

Geothermal district heating

The main emphasis in using low-temperature geothermal energy will be in space heating in the future. Large-scale district-heating projects will be undertaken (such as being developed in Boise and Klamath Falls). District heating will become more and more economical with further escalation in conventional fuels resulting in the development of resources farther from the heating load. Transmission distances of 30-60 miles (50-100 km) are being considered and proven on paper (Akureyri, Iceland), with 13 miles (21 km) presently a reality (Reykjavik, Iceland). Transmission temperature losses in the below 212°F (100°C) range are around 0.3°F/mi (0.1°C/km) for insulated pipe.

A geothermal district-heating system will generally have the same basic components as a conventional system. The production field, which includes wells, pumps and collection mains, replaces the boiler in a conventional system. All other components, such as piping, valves, controls and metering, etc., would be similar to a conventional system.

District-heating metering systems for the purpose of billing consumers can be based on quantity of water used (volume metering), quantity of heat used (energy metering) or specified apportionment factors (non-meter billing).

Water-volume meters in use in the district-heating sector use mechanical principles to measure water flow through a counter which registers the passing volume of water. This type of meter

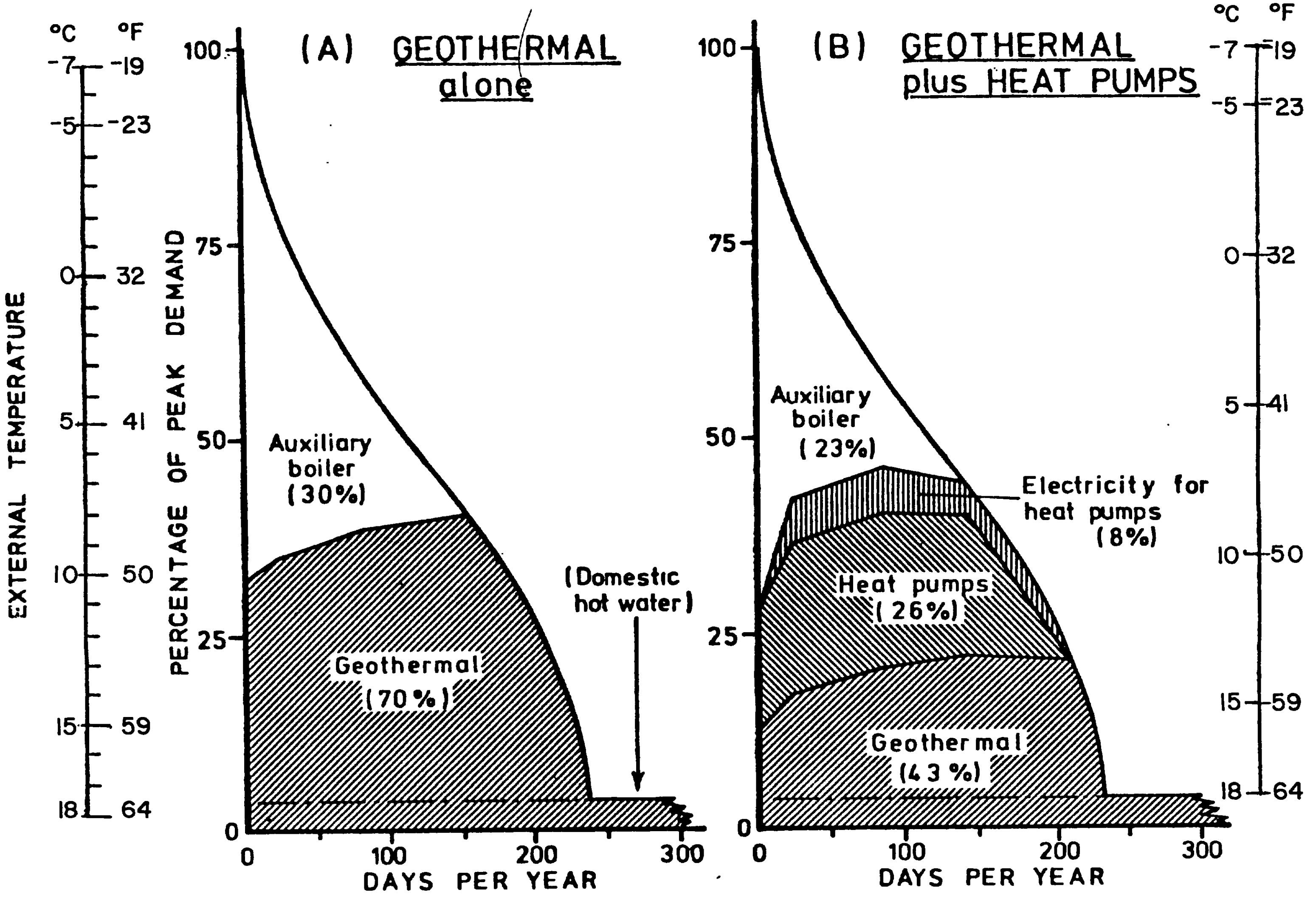

FIGURE 10. Meteorological conditions and corresponding contributions from different sources to total energy demand (Ryback, 1979).

contributes toward making consumers economy conscious in running their systems to achieve the greatest possible cooling of the district-heating water. Volume meters are relatively low cost for purchase and operation. The objection to volume metering is the variance in supply temperature to the consumer's installation.

There are two components in energy metering: quantity of flow and temperature differential across the system. Multiplication of these two values provides a measurement of the system's heat consumption. This method provides a favorable solution to heat measurement because consumers are billed on the basis of actual heat consumed. An objection to this type of metering has been the cost of purchase; however, Danish firms will be making available relatively low-cost energy meters.

Billing in proportion to the consumers installation, i.e., to the cubic volume or floor area, is a non-metering method used in some district-heating schemes. The advantage of this method is the savings in costs relating to the purchase, servicing and replacement of meters, as well as to meter reading, which is eliminated. This method is not suitable where there is a variation in insulation standards, mix of high- and low-density housing, or buildings of varying age.

A single-pipe (open-ended) distribution network with heat exchangers installed in each building and disposal of the geothermal fluid at the end of the consumer connections would be the most desirable type system. This makes the distribution network cheaper, as the cost of a single-pipe network is only about 70 percent of a two-pipe (closed-loop) system.

A two-pipe system involves a central heat exchanger, pumping and control facility. Depending on the location and characteristics of the resource, i.e., the necessity to recharge by means of injection wells, this may be the most desirable approach.

It is practical to divide the construction of the geothermal district-heating system into three main parts, which break down as follows:

Heat Production
1. Exploration and Assessment
2. Drilling and Well Completion
3. Collecting Mains

Transportation
1. Main Pumping Station
2. Supply Mains

Distribution System
1. Distribution Pumping Station
2. Street Mains
3. Service Branches
4. Consumer Connections

The cost of each part is variable. A specific example of geothermal costs is shown by two district-heating projects in Iceland (Reykjavik and Akureyri), where the proportions of costs are as follows:

Production	15 to 25 percent
Transportation	18 to 20 percent
Distribution System	58 to 66 percent

At present-day prices, the geothermal application will cost about the same or less than the corresponding annual fossil-fuel cost. Due to expected escalation of fossil-fuel prices, the costs of the geothermal system will decline. Most geothermal direct-use systems will pay for themselves in 5-10 years from savings in conventional fuel.

An example of the economical aspects of a district-heating system is illustrated in Chapter 5, Economics.

AGRICULTURAL AND INDUSTRIAL APPLICATIONS

Geothermal energy can be used in a wide variety of applications in the agricultural and industrial sectors. This section has the main objectives of (1) indicating potential applications, (2) illustrating how geothermal energy can be used in several specific areas, and (3) providing guidelines on the "application-resource interaction factors" that must be considered in agricultural and industrial applications of geothermal energy.

The material in this section has been prepared by several individuals working on various aspects of geothermal energy utilization. The material presented here is heavily influenced by their experiences and works as well as the many recently completed works in this area. No attempt is made to refer extensively to previous works. However, the main references are indicated as a selected bibliography of works in the utilization of geothermal energy.

Since the maximum resource temperature considered in this work is 300°F (149°C), the processes are also necessarily restricted to those with an application temperature of less than 300°F (149°C). Appendix I lists most of the industrial processes, their application temperature range and the annual energy use for the process type in the U.S.

Figure 11 graphically depicts the application temperature range for many of the processes from Appendix I as well as the agricultural applications not included in the standard and industrial classifications (SIC) groups and Appendix I.

Agricultural growth applications

Agricultural applications are particularly attractive because they require heating at the lower end of the temperature spectrum where there is an abundance of geothermal resources. This section considers the agricultural growth applications; the other agribusiness applications are classified as processing and are considered in the Industrial Section which follows.

The following agricultural growth applications, all of which have been extensively documented, are considered here:

- greenhousing
- animal husbandry
- aquaculture
- soil warming
- mushroom raising
- biogas generation

Greenhousing. Greenhousing is the raising of plants in a controlled environment to enhance yields. The greenhouse effect results from trapping of solar radiation and heat by using glass, plastic film or Fiberglas as environmental-control surfaces to enclose a growing area.

In addition to solar heating, other controllable heating and/or cooling must be applied to maintain temperatures for optimum plant growth. Environmental elements besides temperature that must be optimal or at least non-limiting in order to get the best yield of salable product dur-

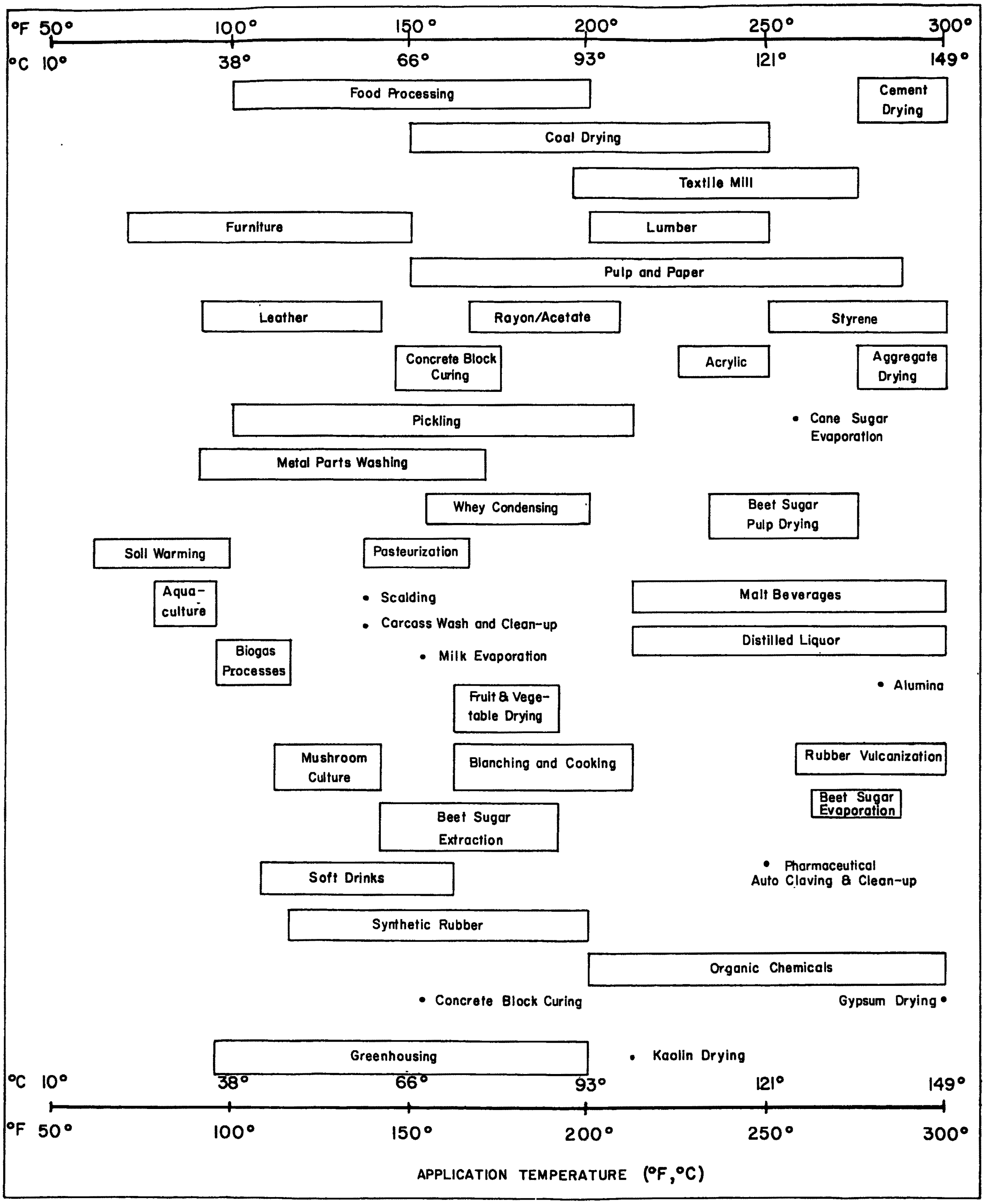

FIGURE 11. Application temperature range for some industrial processes and agricultural applications.

ing the desired marketing period are: level of plant nutrients in the growing media; carbon dioxide content in the air; humidity; soil or nutrient media aeration; plant spacing; plant variety; disease control; sunlight or artificial light supplement; and cultural practices, such as pruning, plant training and pollination (Johnson, 1979).

All commonly marketed vegetables, flowers, house plants and many tree seedlings are suitable for greenhousing. Greenhouse temperatures are a function of the crop; typical highest maintained temperatures range approximately from 65-80°F (18-27°C). Greenhouse heating can be accomplished by (1) circulation of air over finned-coil heat exchangers carrying hot water, (2) hot-water circulating pipes or ducts located in (or on) the floor, (3) finned units located along the walls and under benches, or (4) a combination of these methods. The heating fluid in these units can be as low as about 90°F (32°C). The air circulation method is more common and utilizes forced-air fincoil units similar to those discussed in the space-heating section. The heated air is often passed through perforated plastic tubes running the length of the greenhouse in order to maintain uniform heat distribution.

It should be noted that most crops require lower nighttime than daytime temperatures, with the consequent design benefit of having the lowest inside temperature when the coolest outside temperature occurs.

Animal husbandry. Environmentally controlled livestock raising provides significant advantages as compared to the typical practice of outdoor exposure to the elements. These advantages include: lower mortality (particularly during the critical first few weeks after birth), enhanced feed conversion (more weight gain per unit of feed), faster growth, better disease control, lower fat levels in the final meat product, improved quality byproducts (hides, for example), larger litter sizes for those species raised for multiple births, and relative ease of waste management. The level of thermal environmental control currently practiced ranges from floor heating for mostly open cattle finish-feed lots to totally enclosed raising of hogs and chickens. The totally ~~enclosed~~ systems utilize both space heating and floor-slab heating (at about 90°F, 32°C) to maintain about 70°F (21°C).

Aquaculture. Aquaculture is the cultivation and husbandry of freshwater and/or marine organisms under levels of control on the aquatic growth environment which are functions of the intensity of the aquacultural operation.

Fish farming is that portion of aquaculture which involves the rearing and harvesting of aquatic animals. Among farmable species are: common carp, Chinese carp, Indian carp, buffalo fish, paddle fish, catfish, pikes, perches, black bass, sunfish, tilapia, frogs, mullet, milkfish, eels, salmons, salmonids, smelt, sturgeon, shad, striped bass, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels and abalone (Bardack, 1972).

An emerging aquacultural industry is the cultivation of vegetable species adaptable for human and animal foods. Economics of harvesting and processing must be improved before such activity can become commercially viable. Crops adaptable to geothermally enhanced growth include: water hyacinth, duckweed, numerous algae species and kelp.

Heating can be accomplished using hot-water (90-110°F, 32-43°C) bearing pipes in the growth ponds or by direct addition of suitable quality hot water (70-90°F, 21-32°C) in order to maintain pond temperatures near 80°F (27°C).

Soil warming. Another agricultural application of geothermal water that shows some promise is that of increased production for certain crops through soil warming. From experimental work continuing at various sites throughout the world, it has been shown that certain root crops (vegetables typically thought of as "cool-weather" varieties) and certain rapid-growth tree species (such as the poplar) show enhanced growth and larger crop yields if the soil is maintained at approximately 70°F (21°C). As another secondary use or the last step in a cascading energy loop, the geothermal water can be piped through an underground grid system made up of one of the more inexpensive plastic pipe selections. By maintaining a pipe-run spacing of approximately three feet and an installed depth of two to three feet, crops can be planted and harvested almost directly over the top of pipes without damage to the installation. Polyethylene tubing available in continuous 1000-ft (300-m) or greater length rolls has shown to be an economical pipe material selection for this application.

Mushroom raising. Mushroom culture is the production of edible fungi under controlled conditions.

The most edible fungus naturally found in the United States is the Agaricus campestris. A horticultural adaptation of this species, Agaricus bisporus, has been developed as the commercially cultivated mushroom of this country.

The United States produced over 142 million pounds (64 million kg) of mushrooms for the fresh sales market and almost 168 million additional pounds (76 million kg) for processing during the 1974-1976 reporting period. This production is projected by the mushroom industry to reach 544 million pounds (247 million kg) in 1982-1984.

Heating applications in mushroom culture are: compost preparation (130-140°F, 54-60°C), spawning (similar to seed propagation for chlorophyll-type vegetation, 72-75°F, 22-24°C) and production (60°F, 16°C; Lambert, 1963). Heating requirements are met by exposed hot-water piping along the mushroom-house walls; cooling may be geothermally driven if the resource temperature is adequate. Typically this may be accomplished using small electrically powered compressor units.

Biogas generation. The decomposition of organic matter in the absence of oxygen is called anaerobic fermentation and is the basis of biogas production. Anaerobic fermentation of organic products results in methane, carbon dioxide, hydrogen, traces of other gases and the production of some heat. The residue remaining is hygienic, rich in nutrients and high in nitrogen. Weed seeds and potentially damaging germs are killed by the absence of oxygen during the fermentation process rather than by the significantly higher heat generated by the aerobic (in the presence of oxygen) process.

The efficiency and rate of anaerobic fermentation are affected by temperature, relative concentration of carbon and nitrogen, pH and solids concentration.

The biogas-producing activities are optimal in temperatures ranging from 85-105°F (29-41°C), although digestion will occur from freezing to 156°F (69°C). Fermentation, however, is less stable in the higher of these two ranges and, consequently, biogas units are typically maintained in the lower optimal range (Singh, 1975).

The key equipment element in the biogas process is the enclosed biomass digestion tank. The temperature of such digesters is controlled by the addition of heat to maintain the desired 85-105°F (29-41°C) temperature range. This heating can be accomplished by circulating hot water through metal coils either inside the tank or in the tank walls; insulation is typically provided to minimize this heating requirement.

Temperature cascade considerations. Within the previously indicated temperature range suitable for agricultural-growth processes there is obvious potential for thermal cascading of the heat-bearing fluids. For example, an agricultural-growth complex might use the highest-temperature water (200°F, 93°C) for greenhouse-space heating, followed by mushroom-culture applications from 110-140°F (43-60°C), biogas-generation process heating using 90-110°F (32-43°C) fluids, and, at the low end of the temperature scale, aquacultural activities could utilize water below 90°F (32°C). Such cascades can provide significant economic advantages as compared to single-purpose applications; cascaded applications have been discussed extensively elsewhere (Fageleman, 1978; Longyear, 1976; Reistad, 1978 and Swink, 1971).

Existing facilities. All of the above-described agricultural-growth facilities exist--no new technology is required, just proper design. Geothermally heated greenhouses are reported in at least three states; geothermal aquaculture activities are in practice in three states; and animal husbandry (although no geothermal facility yet exists) in both feedlots and totally confined buildings is commonly practiced throughout the United States, particularly in the Midwest and East. Much of the commercial-scale mushroom-growing operations are in the eastern U.S.; however, new western facilities are in the planning, with one such facility to be constructed at Vale, Oregon, which will use low-temperature (below 240°F, 116°C) geothermal fluids to power heating, cooling and humidity requirements (Geothermal Resources Council Bulletin, vol. 8 no. 6, June 1979). Biogas generation is common at sewage treatment plants; however, up to half of the methane generated is needed for heating of the generator in winter, making the value of the geothermal application obvious. Soil warming, practiced on a small scale in the U.S., is an increasingly common practice in Europe.

Industrial and agricultural processing

Lindal (1973), Reistad (1975) and Howard (1975) survey industrial applications and the potential for geothermal use in a number of the industries. Here we consider the basic processes and several of the more recently considered applications.

Basic processes. In industrial applications, thermal energy in the temperature range being considered here (up to 300°F, 149°C) is used in the basic processes of:

- Preheating
- Washing
- Cooking, blanching, peeling
- Evaporating
- Sterilizing
- Distilling and separating
- Drying
- Refrigeration

Preheating. Geothermal energy can be effectively used to preheat boiler and other process-feed water in a wide range of industries. Many manufacturing industries utilize boilers distributing steam throughout the plants. For a variety of reasons, much of the condensate is not returned. This imposes a considerable load on the boiler for feed-water heating of incoming water at typically 50-60°F (10-16°C) up to the temperature at which it is introduced into the boiler, typically 200-300°F (93-149°C), depending on the system. The geothermal resource can often be used to offload the boiler of some or all of this preheating load.

A wide variety of industries use, for various processes, large quantities of feed water which can be preheated or heated geothermally to the use temperature. Some of these applications also use heat-reclaim methods which must be analyzed when evaluating the potential for geothermal use.

Washing. Large amounts of low-temperature energy (95-200°F, 35-93°C) is consumed in several industries for washing and clean-up. One principal consumer is food processing, with major uses in meat packing for scalding, carcass wash and clean-up (140°F, 60°C); in soft-drink container and returnable bottle washing (170°F, 77°C); in poultry dressing as well as canning and other food processes. Textile industry finishing plants are another large consumer of wash water at 200°F (93°C). Smaller amounts are used in plastics (190-200°F, 88-93°C) and leather (120°F, 49°C). Most of these are consumptive uses.

Sizable amounts of hot water and other hot fluids at temperatures under 200°F (93°C) are used in the several metal-fabricating industries (fabricated metal products, machinery and transportation equipment) for parts degreasing, bonderizing and washing processes. Most of these are non-consumptive uses with a 10-20°F (6-11°C) range in the fluid and reheating to the use temperature.

Peeling and blanching. Many food-processing operations require produce peeling. In the typical peeling operation, the produce is introduced into a hot bath (which may be caustic) and the skin or outer layer, after softening, is mechanically scrubbed or washed off. Peeling equipment is usually a continuous-flow type in which the steam or hot water is applied directly to the produce stream or indirectly by heating a produce bath. In most instances, produce contact time is short.

Blanching operations are similar to peeling. Produce is usually introduced into a blancher to inhibit enzyme action, provide produce coating, or for cooking. Blanching may be either a continuous or batch operation. Typical blanching fluids require closely controlled properties. Thus, it is unlikely that geothermal fluids could be used directly in blanchers and peelers because of the water quality. Geothermal fluids could, however, provide the energy through heat exchangers.

The temperature range for most of the peeling and blanching systems is 170-220°F (77-104°C). These heating requirements are readily adaptable to geothermal resources.

Evaporation and distillation. Evaporators and distillators are routinely found in many processing plants to aid in concentrating a product or separating products by distillation. Most frequently the evaporator will operate as a batch process in which a quantity of product is introduced and maintained at some given temperature for a period of time. The source temperature requirements vary with the product being evaporated. However, in a majority of agricultural processes, water is being driven off; and in these cases, operating temperatures of 180-250°F (82-121°C) are typical. In some circumstances, the evaporators operate at reduced pressures which decrease temperature needs and improve product quality. Evaporators are commonly found in sugar processing, mint distilling and organic liquor processes. Evaporators, depending upon temperature and flow-rate requirements, can be readily adapted to geothermal energy as the primary heat source. The energy can be transferred through secondary heat exchangers to the working fluids or, in some instances, used directly at the evaporator, depending upon existing plant designs or adaptations to new plant expansions (May, 1977).

Sterilizing. Sterilizers are used extensively in a wide range of industries and include applications such as equipment sterilization in the meat-packing and food-processing industries and sterilization for the canning and bottling industry. Most sterilizers operate at temperatures of 220-250°F (104-121°C) and would utilize geothermal energy with the use of heat exchangers to heat the potable sterilizer water. Many sterilizers operate in a continuous mode. Equipment washdown and sterilization, however, may occur periodically or at shift changes.

Drying. Many industries utilize heat at temperatures under 300°F (149°C) for evaporating water or to dry the product, material or part. The largest consumers are pulp and paper drying and textile product drying--mostly in the 200-300°F (93-149°C) range.

Other large consumers of energy for drying are in beet-pulp drying, malt-beverage and distilled-liquor grain drying and cement drying. Additional large energy consumers in the drying application area (discussed later in this report) are grain, lumber kiln, plywood and veneer drying. Smaller consuming industries having drying applications include coal, sugar, furniture, rubber, leather, copper concentrate, potash, soybean meal, tobacco, pharmaceutical tablet and capsule, explosives and paving-aggregate drying.

Refrigeration. Cooling can be accomplished from geothermal energy through lithium-bromide and ammonia absorption refrigeration systems.[4]

The lithium-bromide system is the most common because it has water as the refrigerant; however, it is limited to cooling above the freezing point of water and has as its major application the delivery of chilled water for comfort or process cooling and dehumidification. These units may be either one- or two-stage. The two-stage units require higher temperatures (about 325°F, 163°C) but also have a higher COP (cooling output/source energy input), being about 1 to 1.1. The singlestage units are currently receiving substantial research emphasis in regard to use with solar energy and can be driven with hot water at temperatures somewhat below 190°F (88°C) and will typically have a COP of 0.65.

For geothermally driven refrigeration at temperatures below the freezing point of water, the ammonia absorption system must be considered. These can operate down to about -40°F (-40°C) evaporator temperature. However, these systems are normally only applied in very large tonnage capacities (100 tons and above) and have seen limited use. For the lower temperature refrigeration, the driving temperature must be at or above about 250°F (121°C) for a reasonable performance.

Specific applications

Food processing, crop drying and the forest-related industries have been extensively studied in regard to the use of geothermal energy. Examples of applications in these industries are presented below to show designs of using the geothermal energy and to indicate in an approximate manner how it might be used in other processes.

Food processing.

1. Vegetable and fruit dehydration (see Arnold, 1978; Lienau, 1978; Gordon, 1978 and Geothermal Resources Council Bulletin, vol. 7, no. 5, Nov.-Dec. 1978).

   Vegetable and fruit dehydration involves the use of a continuous operation, belt conveyor or batch process using fairly low-temperature hot air from 100-220°F (38-104°C). The heat historically has been generated from steam coils and natural gas, but can be provided by geothermal energy. Typical continuous operation processing plants will handle 10,000 pounds (4500 kg) of raw product per hour (single line), reducing the moisture from around 83 percent to 4 percent, depending upon the product.

   A crop currently being dehydrated with geothermal energy is onions. A similar dehydration process could be applied to fruits and other vegetables. Figure 12 illustrates a typical conveyor dryer for drying vegetables and which is the type presently being used for onions. High-powered blowers and exhaust fans move the air through water coils which contain either the geothermal fluid or a water in a secondary loop heated from geothermal energy and through the beds of onions on the dryer conveyor, to evaporate the necessary tons of water removed from the product each hour. Close air volume and pressure control must be maintained in all parts of this drying stage as the air moves up and down through the bed to obtain product drying uniformity. Automatic temperature controllers control the continuous operation.

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[4] Recent work has been devoted to developing other types of systems (Harris, 1977).

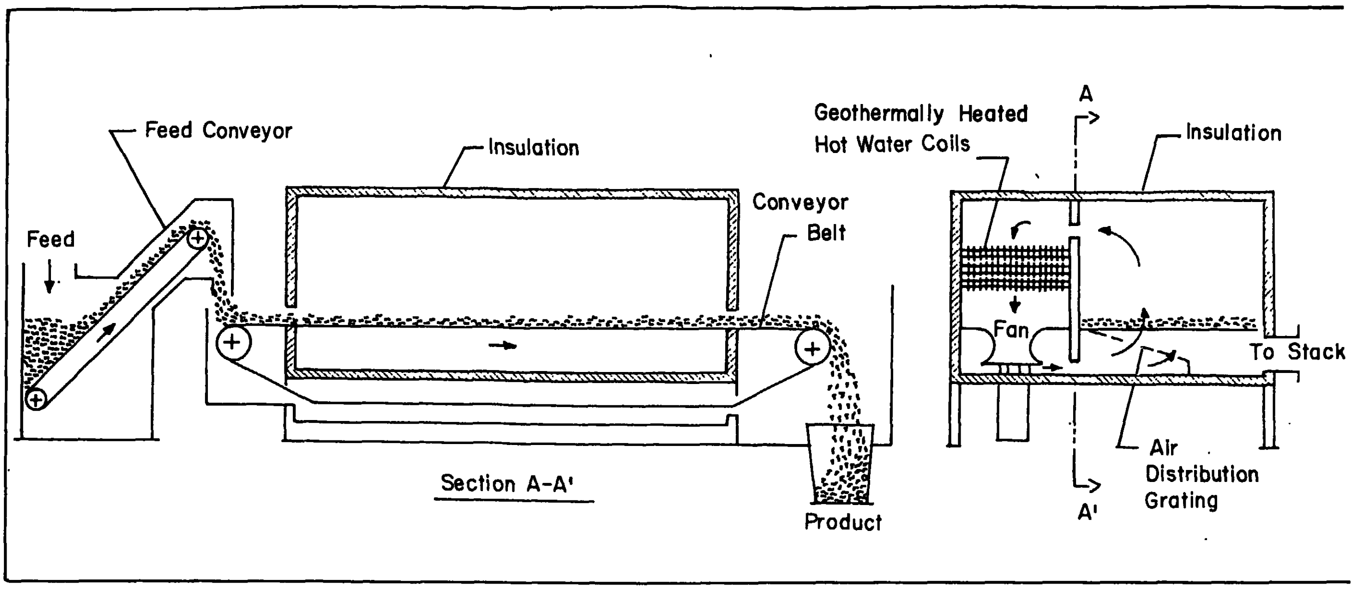

FIGURE 12. Schematic of conveyor dryer for vegetable drying.

At the proper point in the drying process, the onions are automatically transferred to the second stage of drying where, under reduced temperature conditions and deeper bed loadings (approximately 12 inches, 30 cm), the difficult-to-remove diffused water is slowly withdrawn.

Moderating temperatures and air flows are used to maintain close product temperature control as a steady evaporation of water is reduced from each onion slice and the evaporative cooling effect can no longer be counted on to maintain the low product temperature required for maximum product quality.

After drying, the onions are passed over a long stainless steel vibrating conveyor that gently carries them to the milling area. In the mill, skin is removed by aspirators from the onion pieces. The onions are then sliced, large chopped, chopped, ground, granulated and powdered.

2. Sugar-beet processing (see Vorum, 1978; Hornburg, 1975 and Pearson, 1977).

The first two stages of beet processing are preparation and slicing. Preparation is the stage between harvesting and slicing operations. It includes: receiving at the factory site; dirt and trash removal; short-term storage; beet-flow control; final trash removal and final cleaning; and elevating to the factory slicers. These stages do not use thermal energy.

Following the slicing operation (Figure 13), there are a number of processes that require thermal energy. The processes may be conveniently separated into five stages: a) diffusion; b) juice purification; c) evaporation; d) crystallization; and e) pulp-drying molasses (Lienau, 1978).

a) Diffusion

The diffusers separate the pulp and raw juice from the long thin strips (cossettes) of sliced beets. To start the process, makeup water enters and perco-

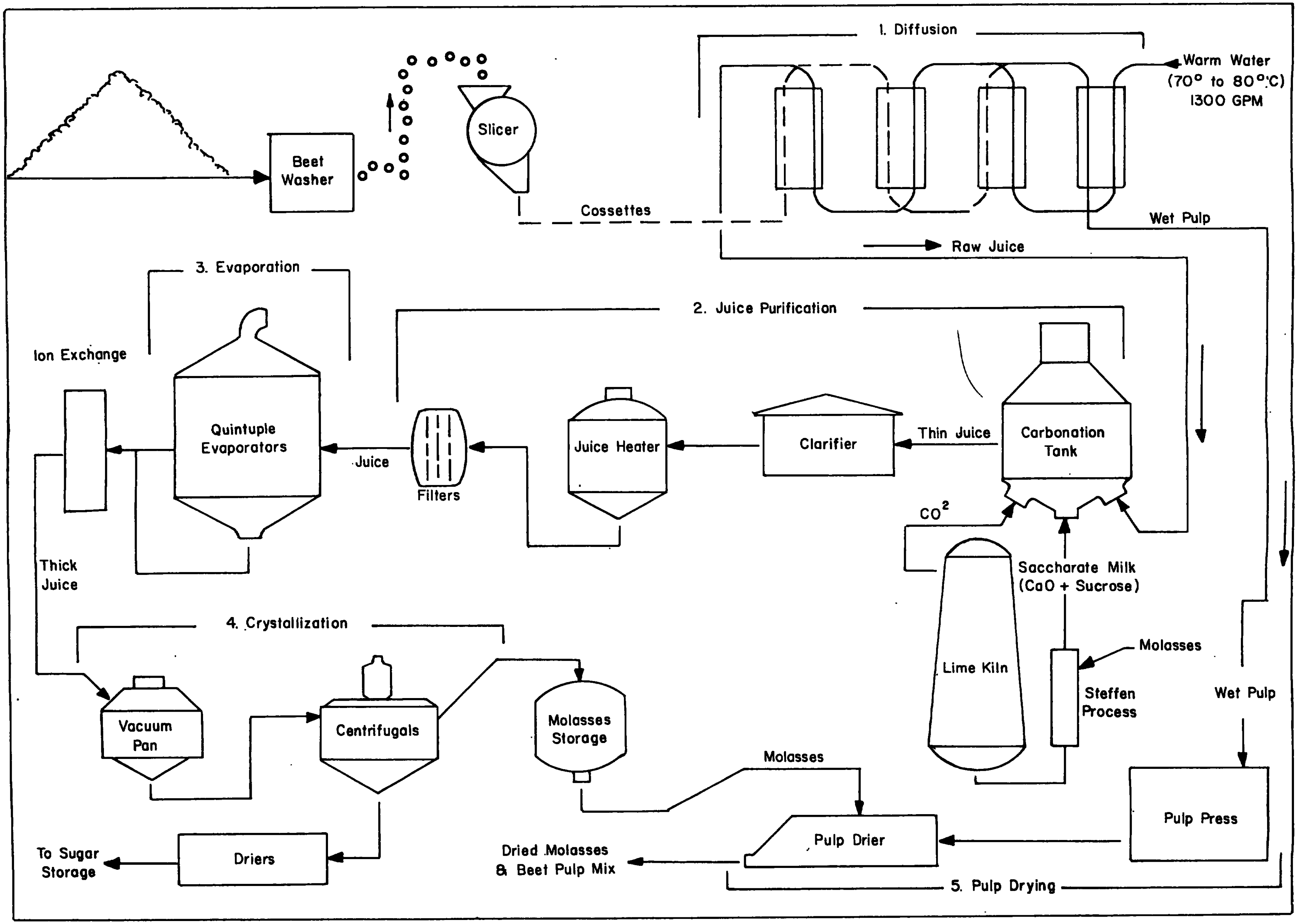

FIGURE 13. Processing stages for sugar production from sugar beets--composite flow sheet.

lates by gravity through the cossette mass, leaching out sugar as it proceeds counter-current to the cossettes. The temperature is raised to between 158-176°F (70-80°C) for better extraction. The rate of diffusion increases directly with temperature.

The sugar-depleted cossettes leaving the diffuser are known as pulp and are transferred to the pulp press and dryer. Sugar-enriched juice is next introduced to the juice-purification process. The diffusion juice contains between 10 and 15 percent sugar, which is about 98 percent of the sugar in the beets when sliced.

b) Juice purification

It is necessary to purify the juice since it contains nonsugar impurities. The nonsugar impurities in both true and colloidal solution make it very difficult to concentrate the diffusion juice or to crystallize pure sugar from it. Impurities are removed by introducing lime in the form of a slurry of calcium saccharates. Thermal energy is used preparatory to and during purification to heat juice from 148-194°F (64-90°C) and to provide the thermal energy used at lime kilns to produce CaO and CO_2.

The juice is heated to 240°F (116°C) and transported to the evaporators.

c) Evaporation

Heating is required to evaporate water from the beet juices. Water evaporated from the beet juices in the first-effect evaporator leaves a vapor which is subsequently used in succeeding evaporator stages and other processes in the plant. Thus, each evaporator effect acts as a condenser for the preceding effect. Each succeeding vapor pressure, and of course temperature, is proportionately lower with the lowest vapor pressure in the last effect under control of the barometric condenser.

One pound of steam admitted to the first-effect steam chest evaporates approximately one pound of water from the juice in the effect. One pound of the first vapor thus formed, when admitted to the second-effect steam chest, will evaporate one pound of water from the juice in the second effect. Consequently, one pound of steam admitted to the first-effect evaporator will evaporate approximately five pounds of water in a quintuple-effect evaporator. Evaporation comes from two sources: juice "flash" and condensation of steam or vapor in the chest.

In a conventional system, high-pressure steam from the boilers at 255 psia (1760 kPa) is expanded to exhaust steam pressure, either through turbines or reducing valves, and is used in the first-effect evaporator only. All other factory heating uses vapor from secondary evaporators.

By evaporation, the percentage of dissolved solids in the juice is raised from 10 to 15 percent to 50 to 65 percent and the outflow is called thick juice.

d) Crystallization

Sugar is crystallized by pan boiling in the vacuum pans. The boiling takes place at low pressure and thus low temperature in order to avoid caramelization.

When crystals are of the desired size and number, they are discharged from the vacuum pan into the mixer, which slowly agitates the mass. From the mixer, the mass of crystals is fed to the centrifuge. The liquid surrounding the crystals is centrifuged or spun off and leaves the basket through the perforations.

Following one or two brief washes with pure hot water, the wet white sugar crystals are discharged from the centrifugal basket and are sent to the dryer or granulator and the cooler. Hot, filtered air is passed through the granulator and cool, filtered air is passed through the cooler. The granulated sugar is then screened and either sacked immediately or stored in bulk bins.

e) Pulp drying

After the pulp leaves the diffusion process, it starts the pulp drying process. First, it enters the pulp press where much of the moisture is mechanically removed. It then enters the dryer where it is thermally dried and mixed with molasses, resulting in the dried molasses and beet-pulp product.

Presently, large quantities of low-pressure steam are used in the sugar processing industry. Many of the processes could be adapted to geothermal energy depending upon the resource temperature. The processes of diffusion and drying would utilize lower-temperature water, while 250°F (121°C) and above water could be used in the evaporation phases.

3. Potato processing (see Lienau, 1978).

Many of the processing methods used by potato processors can utilize energy supplied by 300°F (149°C) or lower geothermal fluids. Typically, however, a few of the operations, notably the frying operation, will require higher temperatures than can be provided by a majority of the geothermal resources.

Usually in a potato-processing plant there are potato-product lines and several by-product lines. Figure 14 illustrates a french-fried potato-processing line. Potatoes for processing are conveyed to a battery of scrubbers and then moved into a preheater, which warms the potatoes and softens the peel, making it easier to remove the skin. The potatoes are then chemically peeled by a 15 percent lye solution maintained at a temperature of 140-175°F (60-79°C).

Upon leaving the chemical peeler, the potatoes are conveyed to a battery of scrubbers, where the peeling is removed. After the scrubbers, the peeled potatoes are subjected to another washing process and then conveyed to the trim tables by pumping. The peeling removed by the scrubbers is pumped to a holding tank and sold as cattle feed following neutralization of the lye residue.

After the potatoes are trimmed for defects, the product is conveyed to cutter areas. Shakers sort the product. The properly trimmed and sized product is then carried by gravity to the blanching system.

After blanching, the potatoes are dewatered and fed through a sugar drag, which adds a slight amount of dextrose to the surface of the potato, imparting a golden color when the potatoes are fried. They then pass through a dryer which removes the surface moisture prior to a two-stage frying process. The first stage cooks the product more completely, while the second stage gives it the golden color. The oil in the fryers is heated to 375°F (191°C) by heat exchangers receiving high-pressure steam at 275 psig (1895 kPa).

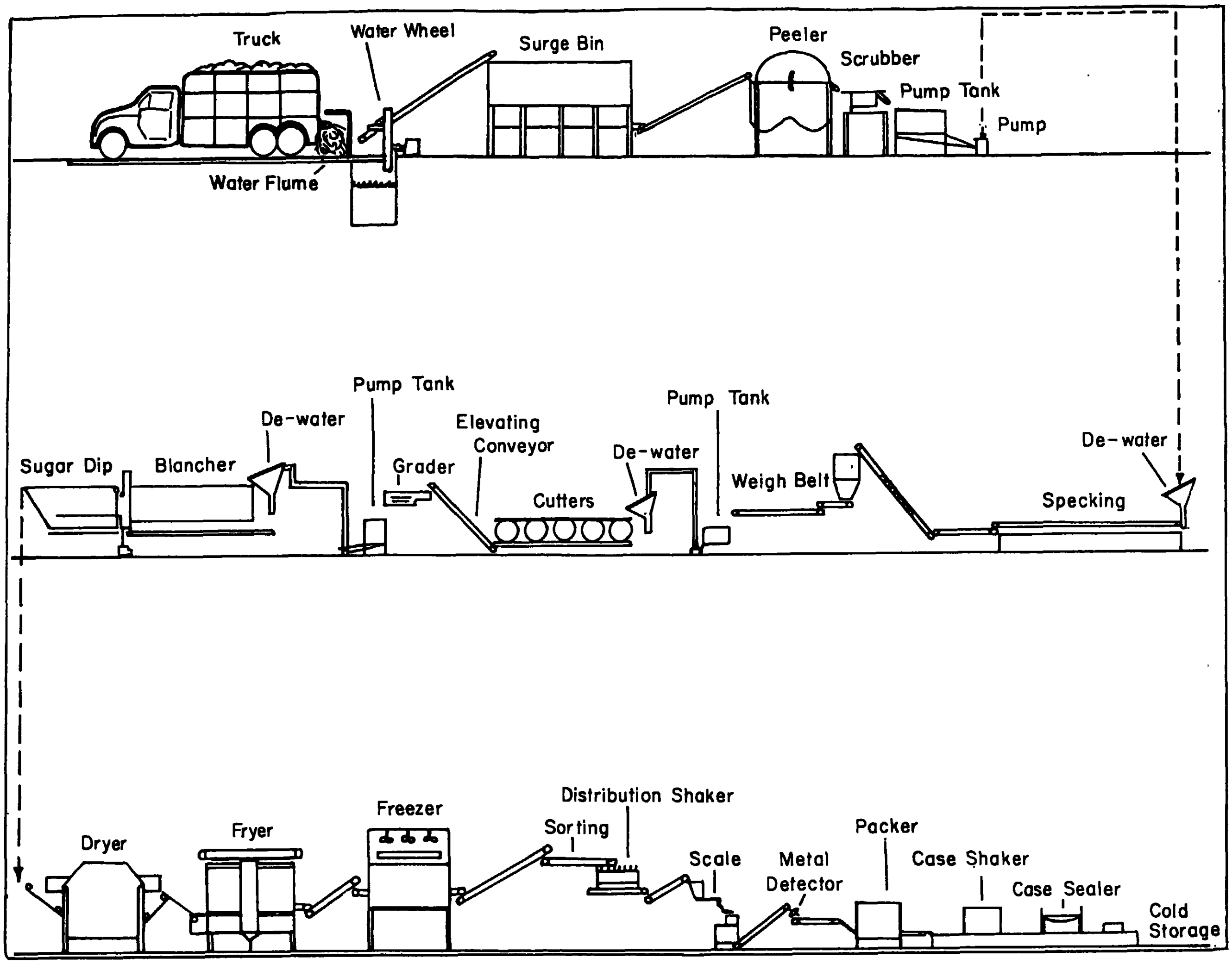

FIGURE 14. Potato-processing schematic.

For systems that would use geothermal energy, the energy would probably be supplied to the process via intermediate heat exchangers. To avoid any possible contamination of the product by the geothermal fluid, or the need for treatment of the fluid, the geothermal fluid passing through these exchangers will transfer energy to a secondary fluid, usually water, which delivers the energy to the process. The secondary fluid, circulating in a closed system, then returns to the intermediate heat exchanger to be reheated. For a geothermal fluid at 250-300°F (121-149°C), all of the thermal energy needs of the potato-processing plants could be met except for the heating of the fryers.

4. Slaughter operations.

Applications of hot water in slaughter operations are numerous and include: water at about 180°F (82°C) for required plant sanitation; heated water (140°F, 60°C) for washing of carcass shrouds and work clothing; heated soak tanks for hog dehairing; circulation of hot water through coils in waste tanks to prevent coagulation of fats, employee hot-water requirements and absorption refrigeration for many cooling requirements.

Crop drying.

1. Alfalfa dehydration (see Lienau, 1978 and Gordon, 1978).

   Two different types of dehydration plants have been used for some time. The first, using conventional fuels, is a rotary-flame furnace and is common in the United States. It requires temperatures up to about 1800°F (1000°C). The other is used in New Zealand and operates on geothermal steam. It is a forced-air system using a multi-layer conveyor belt with temperatures up to about 275°F (135°C). In addition, a newer method has been used in the last few years. It involves field wilting to reduce the moisture content, with the remainder of the moisture to be removed in the dehydration plant. This process requires temperatures of about 180-250°F (82-121°C). Figures 15 and 16 show schematics of such an alfalfa-drying plant being geothermally driven. The chopped field-wilted material is fed to a dryer where air, heated by the geothermal fluid, contacts it and removes the moisture. The exact drying temperature depends upon the ambient conditions and moisture content of the alfalfa. The final pellets are checked for firmness, color, etc. and the plant adjusted accordingly. Dryer temperatures can be as low as 180°F (82°C).

2. Grain drying and barley malting (see Arnold, 1978; Lienau, 1978; Gordon, 1978 and Vorum, 1978.)

   Significant amounts of energy are consumed annually for grain drying and barley malting. These processes can be easily adapted to geothermal energy in the temperature range of 100-180°F (38-82°C).

   The kiln or grain dryer typically is a large vertical vessel with the grain entering at the top. Hot air is forced up through the grain, extracting the moisture before being exhausted.

   The two important variables in the drying operation are the air-mass flow rate and the temperature at the inlet to the dryer. To maintain the fuel requirements at the lowest

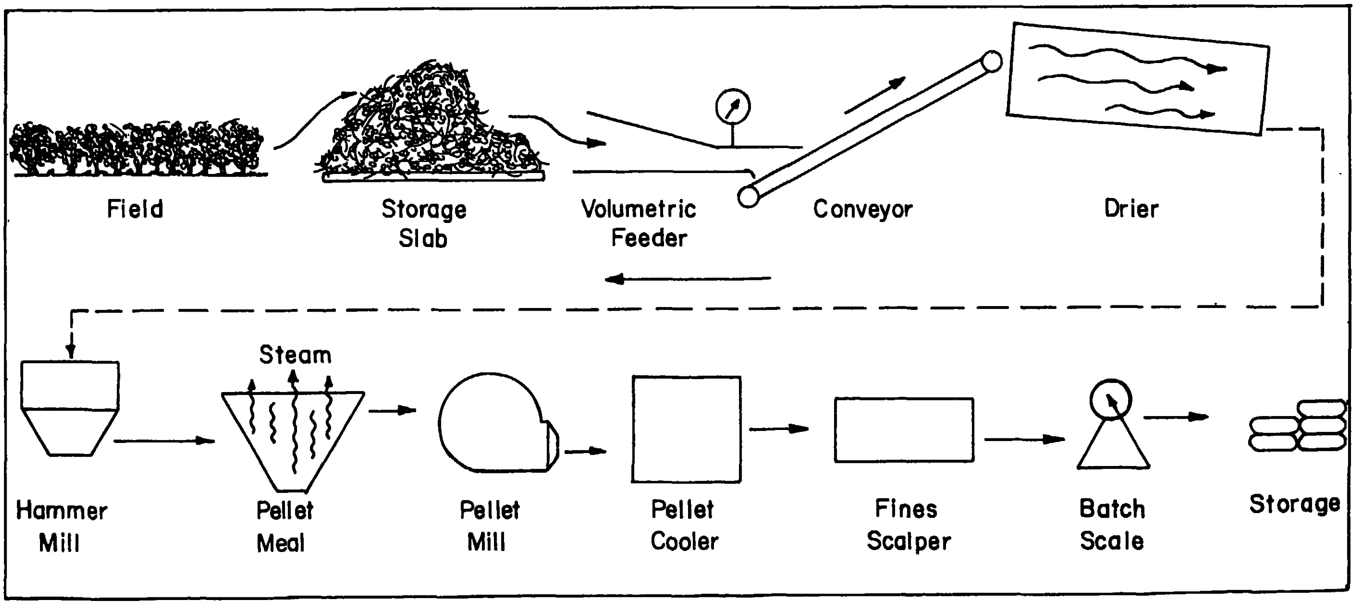

FIGURE 15. Schematic of alfalfa-drying and pelletizing process.

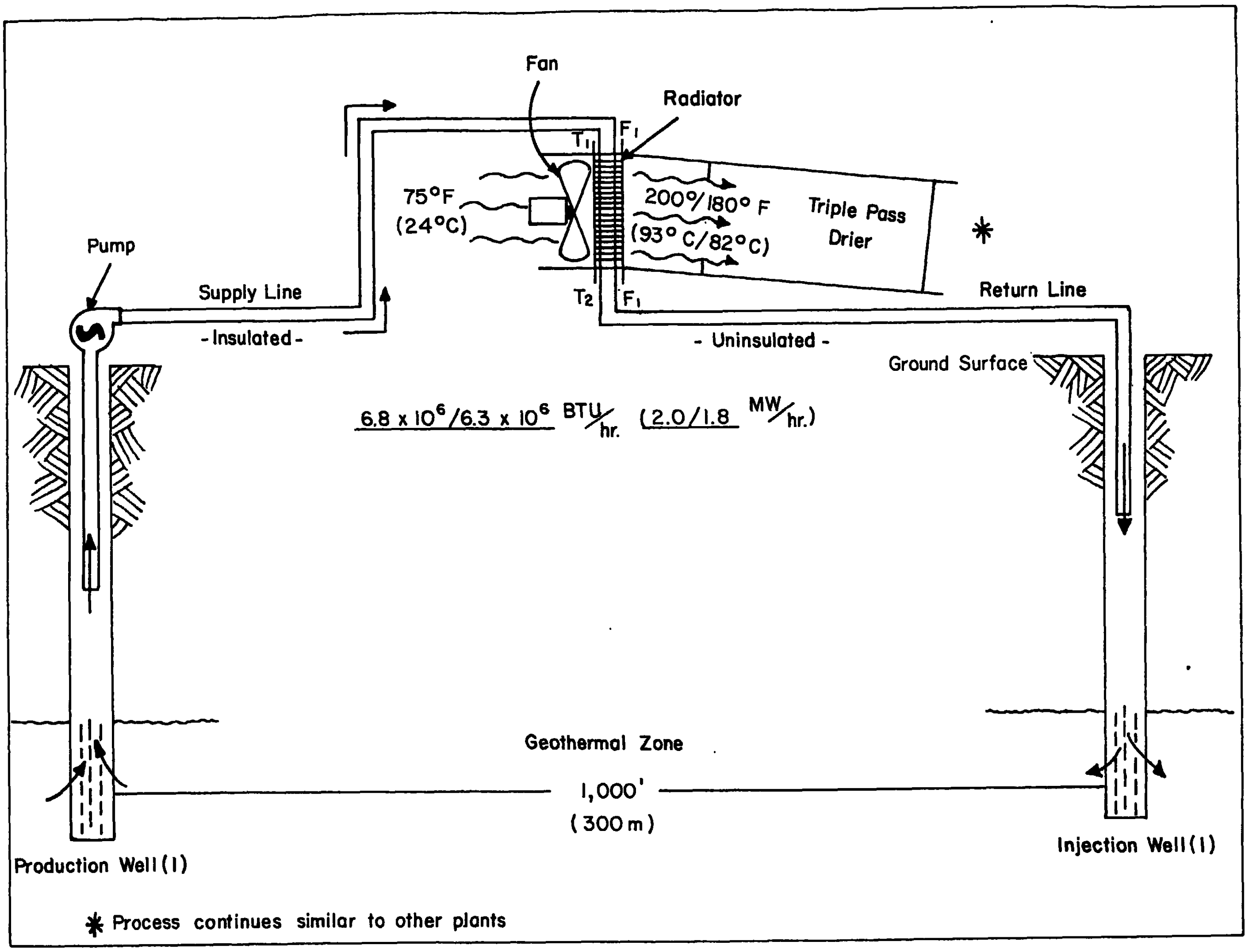

FIGURE 16. Alfalfa-drying plant and well layout.

possible level, the air-flow rate should be minimized because the air is exhausted. However, two factors impose a practical lower limit on air flow: the rate must be high enough to provide uniform and sufficient contact between air and grain or malt across the entire bed, and the rate must also be high enough so that moist air leaving the bed is somewhat less than saturated with water. As a general rule, about 40-60 cubic feet (1.1 to 1.7 m^3) of air per minute are required per bushel of green malt in the kiln. If the drying rate is too rapid, the grain will shrink and crack and suffer general physical damage.

Forest Industries.

1. Kiln drying of lumber (see Reistad, 1978 and VTN-CSL, 1977).

Most upper-grade lumber in the western United States is dried in batch kilns. In small saw mills where drying kilns are heated by steam from conventional oil-fired boilers, substitution of geothermal energy for the heating energy source can achieve substantial energy cost savings. In larger, well-integrated mills, all energy from operations can be provided by burning sawdust and other wood waste-products. If a market develops for the waste-products or if the energy can be more economically applied elsewhere, the geothermal source may also become economical in integrated plants. It is evident that such a by-product market is developing.

The batch kiln is a box-shaped space with loading doors at the ends. The sawed lumber is spaced and stacked to allow for free air movement around the individual pieces and loaded into the kiln on specialized handling trucks. When the kiln is fully loaded, the doors are closed and the heating cycle started. The kiln has insulated walls and ceiling and has fans to circulate warm air over the lumber, exhaust moist air and draw in fresh air.

Drying is done for two main purposes: to set the sap and prevent warping. The sap sets at 135-140°F (57-60°C) and warping is prevented by establishing a uniform moisture content throughout the lumber piece, which can only be accomplished by carefully controlled drying schedules. The allowable drying rates vary from species to species and decrease with thicker pieces. Table 3 illustrates a typical drying schedule.

TABLE 3

Typical kiln drying schedules

Ponderosa pine	Dry Bulb		Wet Bulb		Time	E.M.C.(%)
	°F	°C	°F	°C		
4" x 4" (10 x 10 cm) All Heart Common Sort (fast on well sorted stock)	160	71	130	54	Approx 21 hrs	5.8
	No conditioning					
4" x 4" (10 x 10 cm) All Heart RW (Conservative) Common	150	66	130	54	Up to setting	8.0
	150	66	125	52	to 12 hrs	6.9
	160	71	130	54	12 hrs till dry (24-28 hrs)	5.8
	No conditioning					
4" x 4" (10 x 10 cm) Half & Half Common (mostly 8", 20 cm)	160	71	140	60	40-50 hrs	8.0
	No conditioning					
Shop & Select 4" x 12" (10 x 30 cm)	115	46	108	42	First day	14.1
	120	49	110	43	Second day	12.1
	125	52	115	46	Third day	12.1
	130	54	120	49	Fourth day	12.1
	140	60	130	54	5th - 10th	11.9
	145	63	130	54	10th - 12th	9.5
	150	66	135	57	15th - 18th	9.5
	155	68	140	60	18th - 22nd	9.4
	160	71	140	60		7.9
	Cool					
	180	82	170	77	Approx 24 hrs Equalizing & Conditioning	11.1

E.M.C. = Equilibrium Moisture Content

Originally from kiln-drying Western Softwoods, Moore Dry Kiln Company, Oregon; adapted here from VTN-CSL, 1977.

The difference in using geothermal hot water (180°F, 82°C) as an energy source as compared to a conventional steam-heated dry-kiln primarily would be in the selection of heat exchangers and fans, the absence of a boiler, and the presence of added piping and a circulation pump for the geothermal fluid. Evident from Table 3, geothermal fluids at a temperature somewhat greater than 160-180°F (71-82°C) would be required to meet the entire drying schedule for Ponderosa pine. VTN-CSL (1977) reports that the geothermal fluid must be 20-40°F (11-22°C) above the operating temperature for economic operation, although where geothermal fluid of insufficient temperature is available, the heating can be supplemented by conventional fuels during the final high-temperature portions of the drying schedules.

Analyses comparing geothermal-heated lumber kilns with gas or oil-fired systems have been carried out for the Klamath Falls, Oregon, area (Reistad, 1978) and the Modoc County, California. area (VTN-CSL, 1977) which indicate substantial economic advantage of the geothermal systems in these two areas.

2. Material drying in plywood and particleboard mills.

   In plywood mills, the main thermal-energy use is for the drying of veneer, while in particleboard mills, it is the drying of the particulate material used to make the particleboard. Because the wood in these instances is much smaller than the dimensional lumber mentioned above, it is typically dried at much higher temperatures, about 350-400°F (177-204°C) for veneer drying and 350°F (177°C) and higher for the particulate material. To be adapted for geothermal use, the drying operation would have to be redesigned to lower inlet air temperatures or else the geothermal energy could just be used for preheating the inlet air. The redesign presents no particular problem and could be readily accomplished for a particulate system.

3. Pulp and paper processing (Hornburg, 1975 and 1978).

   The pulp and paper industry has good potential for use of geothermal energy at temperatures at and beyond the upper end of the range considered here. In New Zealand, the Tasman pulp and paper plant uses 120 psia (827 kPa, 341°F, 172°C) wet-saturated steam produced from a number of boreholes to provide much of the thermal energy requirements and some of the electricity requirements of a large pulp, paper and lumber operation.

   Table 4 lists the process-heating needs of a conventional 1000-ton/day (907 t/d) pulp and paper mill based on the Kraft method.

TABLE 4

Process heat needed for a certain 1000-ton-per-day (907 t/d) pulp and paper mill (Kraft Process) of conventional energy system design.

Use	1000's of Btu/hr (907 t/d)	Steam - # Hr 25 psia (172 kPa)	Steam - # Hr 135 psia (930 kPa)
Wash-Water Heating	248,100 (72.7 MW)	247,654	0
Evaporators	114,800 (33.6 MW)	114,594	0
Miscellaneous, L.P.	2,957 (0.9 MW)	2,952	0
Black Liquor Heating	5,372 (1.6 MW)		5,630
Digester	153,346 (44.9 MW)		160,734
Dryer	317,731 (93.1 MW)		333,016
Miscellaneous, H.P.	66,768 (19.6 MW)		69,980
Totals	909,074 (266.4 MW)	365,200 (165,600 kg)	569,360 (258,250 kg)

In addition to this process steam, 29.8 MW of electricity is needed for plant operation.

For geothermal resources at temperatures less than 300°F (149°C), the major impact comes in replacing the low-pressure steam use in the wash-water heating, evaporators and miscellaneous processing. Hornburg (1978) presents a design for the use of a 250°F (121°C) resource in the pulp and paper industry. That work indicates that the simplest and most efficient method of using geothermal energy is by direct exchange to a process fluid. Specifically, it was found that this was possible by heating the wash water and preheating the air for the paper dryers, amounting to 220 million Btu/hr (2.32×10^6 kJ = 64 MWt) for the 1000-ton/day plant (24% of total thermal requirements). Some potential for flashing of the geothermal resource and subsequent upgrading of the vapor phase to be used in some of the other processes in this industry is also shown.

Special considerations

In addition to the aspects discussed above, process-heating applications involve several additional factors that can seriously impact the design and feasibility of using the geothermal resource. This section considers a number of these factors.

Retrofit vs. new installations. In many of the large and complex industrial operations, most of the potential applications in the very near future will be of a retrofit type. For these, the geothermal system design will be largely the supply of the hot fluid to the system or building boundary, and extensive internal equipment modifications will be essentially absent for several reasons: expense, process disruption and the noted agribusiness practice of maintaining proprietary process secrecy.

New facilities offer the advantage of much greater potential geothermal heat applications: base loading levels can be established; equipment designs can be modified to accommodate the hot fluids (heat transfer surfaces, for example could be enlarged to provide the same amount of heat from hot liquids as compared to, say, high-pressure steam); and all suitable plant aspects can be designed in view of the rapidly deteriorating fossil-fuel situation.

Applicability of heat pump. In a number of instances, the situation may arise where the geothermal fluid temperature is lower than the required application temperature and/or the flow rate of geothermal fluid is not sufficient to directly meet the needs of the application. In such circumstances, the use of a heat pump to allow additional energy to be extracted from the geothermal fluid (lowering the disposal temperature) and raise the thermal-energy output temperature may be desirable. At the present time, units are commercially available with output temperatures up to about 230°F (110°C). A combination of heat pump and heat exchanger(s) may prove beneficial, in various situations, to obtain a greater energy extraction (larger temperature drop) from the geothermal resource. The economic feasibility of such installations varies with the specifics of the resource and the application. However, two major considerations are that (1) the temperature lift of the heat pump (for a COP $\leq$ about 3) should be less than about 80-90°F (44-50°C; the smaller the lift, the better the feasibility) and (2) auxiliary energy, usually in the form of electricity, is required.

Direct and indirect application of geothermal fluids in processing. Several factors should be considered by the designer in using a geothermal fluid directly in a process stream. In most instances, use of the geothermal fluid directly will result in the elimination of additional heat exchangers, pumping and piping. However, the economic savings may be overshadowed by consideration for peaking, product contamination and environmental concerns.

Direct use may not be practical in many cases. If the process has or is required to have a standby or peaking capability provided by an auxiliary boiler, it may not permit use of the geothermal fluid in the boiler as feedwater. In cases where the process loop has special water treatment requirements, introduction of geothermal water complicates such treatment and may prove uneconomical.

Product contamination and environmental factors must be considered in the cases where geothermal fluids come in contact with the product. Present EPA guidelines will not permit injection disposal of geothermal fluids which are chemically altered.

PRODUCTION AND INJECTION EQUIPMENT

Wellhead pumps

There are a variety of methods of providing geothermal fluid to an above-ground system. Artesian wells provide surface water naturally and some non-artesian wells can be induced to flow without pumping. However, wellhead pumps are necessary for non-flowing wells and can be desirable for wells that are self-flowing.

A mechanism by which a non-artesian well can be induced to flow is to reduce the density of the column of liquid in the well. For instance, if the liquid is mixed with a gas, the combined fluid density may be low enough that the downhole pressure is sufficient to force the fluid to the surface. If the geothermal source is hot enough and the downhole conditions allow the liquid to partially flash to steam, the reservoir maintains the low-density liquid-vapor mixture in the well. Under these circumstances, a well will continue flowing until the resource cools down or the well is capped.

When a reservoir flows by partial flashing to steam, the downhole fluid cools due to the latent heat of vaporization of the steam. If dissolved solids are at or near saturation in the reservoir, downhole depositions can form on casing walls and restrict well flow. In addition, these scale deposits can be harder material than the reservoir formation itself, so reaming out a plugged casing can be expensive.

An important advantage to pumping a self-flowing well is that pressure on the liquid is maintained, so downhole flashing and scaling are minimized. Also, by not allowing the fluid to flash, the pump discharge temperature can be much higher than the surface temperature of a self-flowing well. This is an important consideration when high-temperature geothermal applications are desired.

Vertical turbine pumps

Vertical turbine pumps have been used for many years in domestic and irrigation-water supply applications and have been successfully used in geothermal wells. Vertical turbine pumps increase fluid pressure by the centrifugal force imparted on a liquid by a shaft-driven impeller. In order to achieve the high pressure required in some geothermal service, these pumps frequently contain more than one stage arranged in series. Although the flow through each stage is the same, each stage of the pump successively increases the liquid pressure. An above-ground motor rotates a shaft that extends the length of the pump column to drive the impellers.

A sketch of a vertical turbine pump appears in Figure 17. As shown, the pump suction is at the bottom of the bowl assembly. The fluid progresses upward through each stage and exits in the annulus between the column pipe and the shaft-enclosing tube. At the top of the well, the fluid leaves the column pipe through the discharge head and enters the service piping.

The pump shown in Figure 18 is an enclosed lineshaft pump. Tubing bearings support the shaft at regular intervals (usually 5-7 feet, 1.5-2.1 m) and are lubricated by a fluid that is either pumped or gravity-fed through the tubing. Although oil has been successfully used for bearing lubrication in some geothermal applications, there has been little experience with oil lubrication for high-temperature (above 300°F, 149°C) geothermal pumps. In some high-temperature

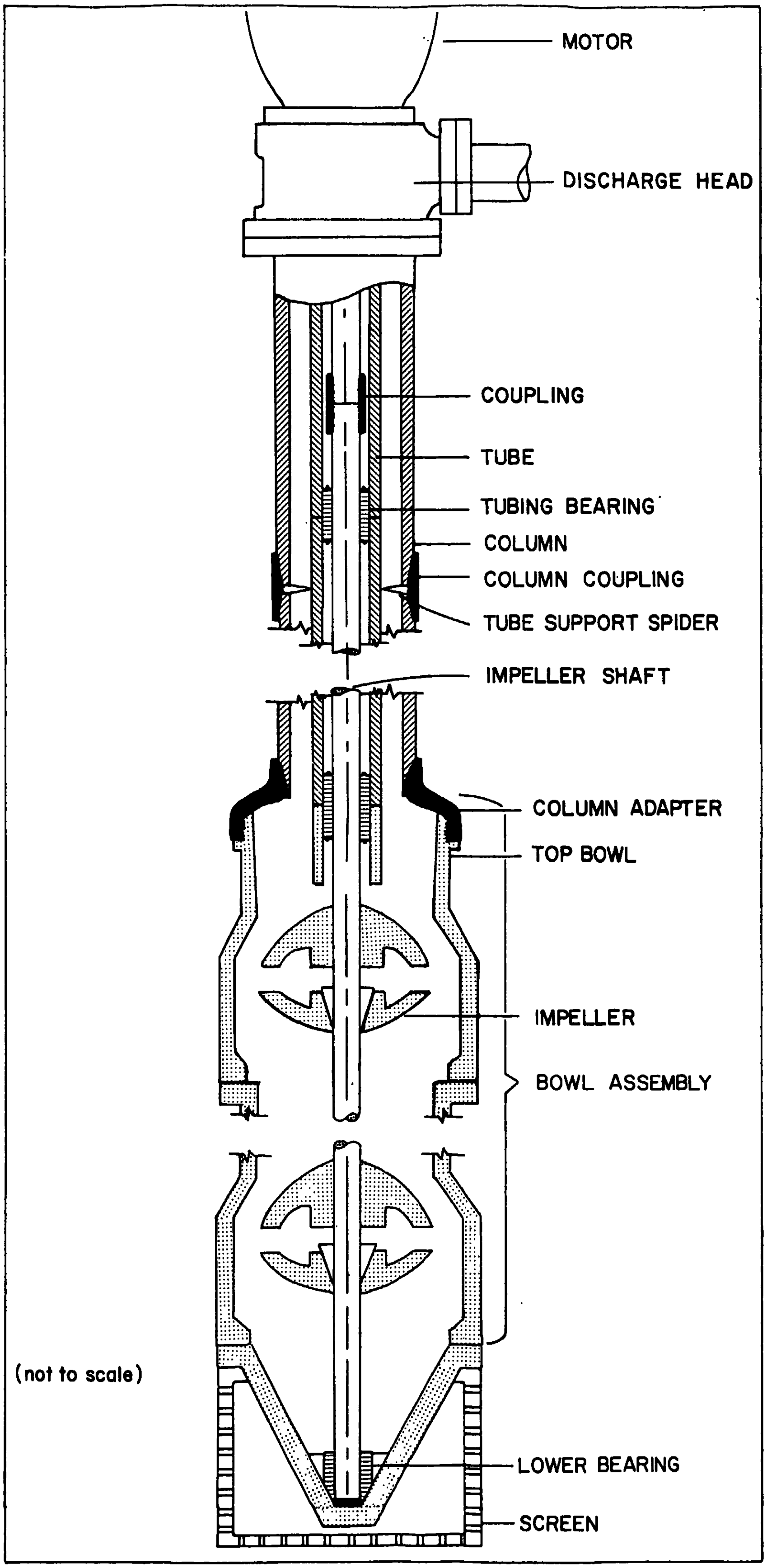

FIGURE 17.
Vertical turbine pump.

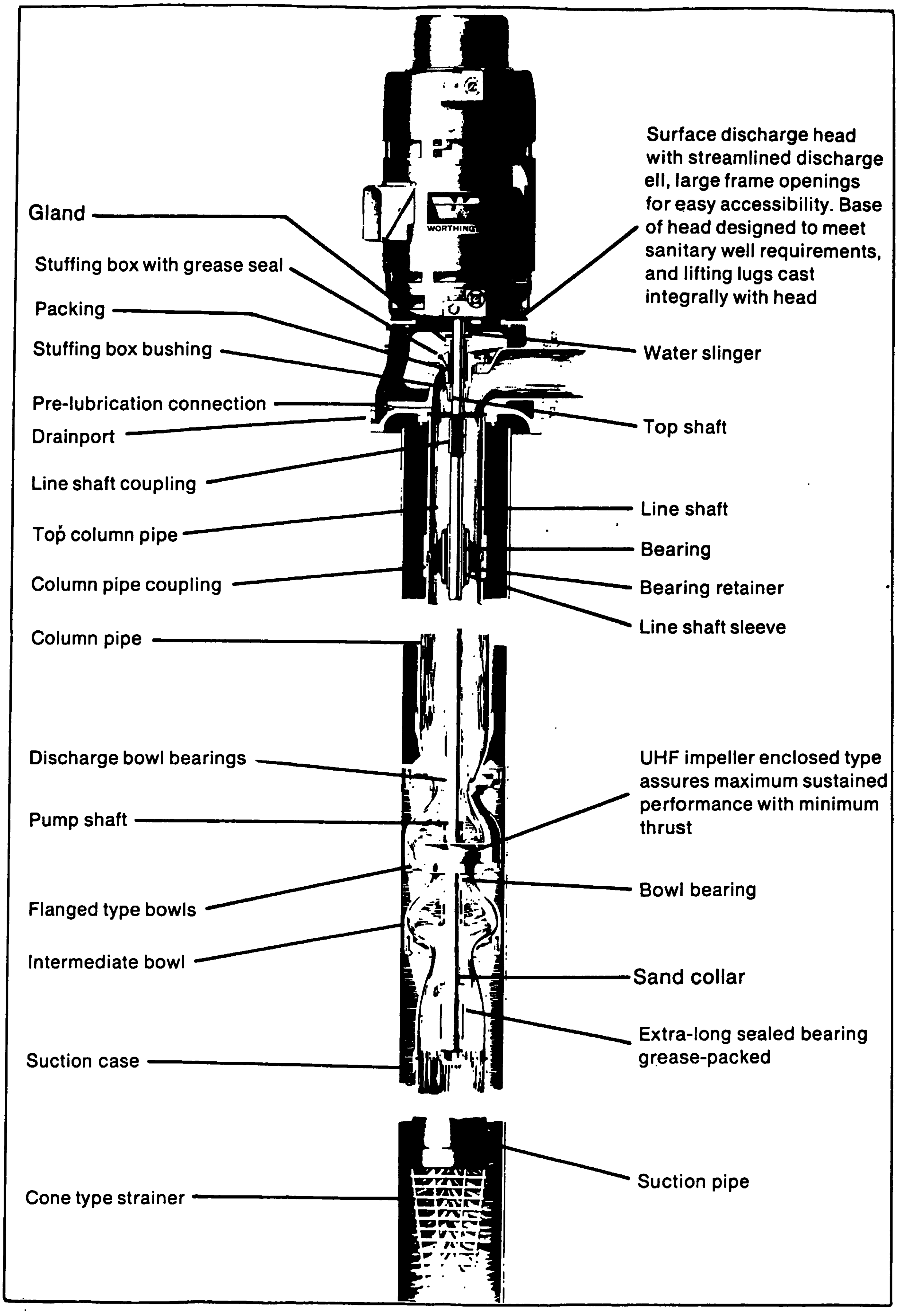

FIGURE 18. Enclosed lineshaft pump (source: Worthington).

vertical turbine pumps, water has been pumped through the tubing to lubricate the bearings. This water can be a filtered slip-stream from the pump discharge or fresh water from a separate supply. Problems have arisen from solids depositing on the bearings, but these problems can be avoided (at least partially) by using softened water for lubrication.

An alternative to the enclosed-lineshaft and lubricating-fluid system is an open-lineshaft system. With an open lineshaft, the bearings are supported from the column pipe and there is no tube. The shaft bearings are lubricated by the production fluid moving up the column. Open-lineshaft pumps have found much use in domestic water-supply pumps (because there is no lubricating oil to contaminate the water) but have not found great success in geothermal applications.

Maintenance of a vertical turbine pump depends greatly on the fluid being pumped. In low-temperature, low-solids content applications, these pumps can provide years of service without maintenance. In corrosive service, or where solids readily deposit on the metal surfaces, the pumps may operate less than a year before cleaning and repair are required.

A problem associated with pumping a hot fluid is that metals in the pump expand. Since the lineshaft is frequently a different material from the column and tube, the expansion rate will also be different. This differential expansion rate is magnified by the length of the pump, so allowance must be made to adjust the shaft after the pump has equilibrated at the pumping temperature.

One common technique to solve the differential-expansion problem is to make the shaft adjustable from the surface. When the pump is installed, the shaft is adjusted to center the impellers in the bowls. After the pump has been producing hot fluid, the impellers will no longer be centered due to differential expansion, so the shaft must be readjusted. After adjusting the shaft when the entire pump, column and shaft have reached temperature equilibrium, no more adjustments are required.

The pump-power requirement can be found by the following formulae, where bhp is the brake horsepower:

$$\text{bhp} = \frac{\text{gpm} \times \text{total head in feet}}{3960 \times \text{efficiency}} \times \text{specific gravity} = \frac{\text{l/s} \times \text{total head in meters}}{206{,}000 \times \text{efficiency}}$$

or

$$\text{bhp} = \frac{\text{gpm} \times \text{pressure difference in psi}}{1714 \times \text{efficiency}} = \frac{\text{l/s} \times \text{kPa}}{3944 \times \text{efficiency}}$$

Typical efficiencies for vertical-turbine pumps are 50 to 80 percent and can be found from the pump curve for any specific pump and its operating conditions.

Downhole pumps

The electrical submergible pump has been utilized successfully in the oil industry for more than 50 years. Its adaptation to geothermal applications has only occurred during the last 6-8 years, but this adaptation, in many respects, has been a natural extension of technical knowledge gained over the 50 years of oil-pumping service.

A submergible pumping system consists of three major components: the drive motor, protector section and the pump (Figure 19). Surface components consist typically of an electrical junction box, switchbox and transformers, as required.

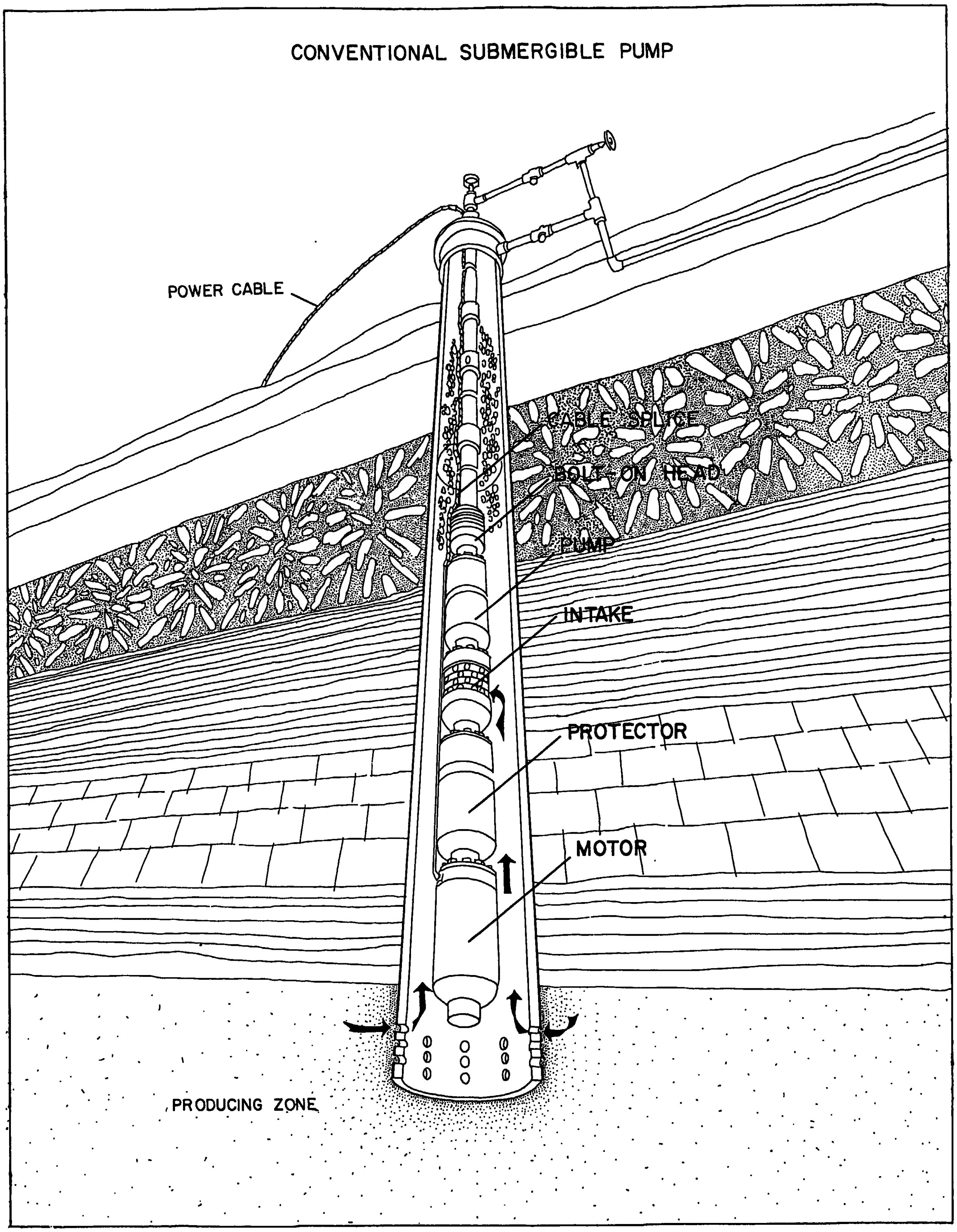

FIGURE 19. Conventional submergible pump (source: TRW REDA Pumps).

The motor section consists of a 3-phase, induction type which is oil filled for cooling and lubrication. A high-starting torque enables a full-load operating speed to be reached in a very short time period. Motor cooling is achieved through heat transfer to the well fluid moving by and such motors have been operated satisfactorily on well fluid temperatures in excess of 300°F (149°C). These motors are available in a wide range of diameters, horsepowers and voltages to accommodate a variety of applications.

The protector section is located between the pump and motor. Its primary function is to isolate the motor from the well fluid. The protector design allows for pressure equalization between the pump-intake pressure and the motor's internal pressure, permitting expansion or contraction of the motor oil due to thermal gradients. Mechanical seals provide protection against fluid migration along the pump shaft and a marine-type thrust bearing is included to absorb axial forces induced by the pump.

The pump section consists of a multistage centrifugal arrangement quite similar to the surface-driven turbine pumps described earlier under Vertical Turbine Pumps. Capacity ranges up to approximately 2000 gpm (126 l/s) and lifts up to 15,000 feet (4500 m). Due to hydraulic limitations combined with diameter limitations, the lift per stage is relatively low; however, as many as 500 stages have been used in the past to meet high head requirements. Through the use of corrosion-resistant materials, pump wear and corrosion are minimized and long-term predictable performance in all normally encountered fluids can be assured.

Advantages of the submergible pumping system are many and include:

1. The system can efficiently deliver the largest amount of horsepower at the pump of any pumping system in the small-diameter casing sizes associated with wells of any depth.
2. Conventional designs can be utilized in crooked drill holes or deviated wells.
3. Conventional designs are now capable of operating at temperatures to 300°F (149°C).
4. Well-surface requirements are minimized.
5. No costly foundation pads or housing structures are required.
6. Pump and motor noise is confined to the well bore.

A recent development in submergible pumps allows for a well completion that permits easy and safe removal of the pump without removing the discharge pipe. Figure 20 is an illustration of how this pump is suspended inside the discharge pipe and retrieved with the attached cable. Removal (through a stripper valve) does not involve the use of well-kill fluids to hold back well flow, as is the case for more conventional pump-service operations.

Circulation pumps

In any geothermal utilization scheme, once the geothermal-well pump has been selected, auxiliary circulation pumps can become a requirement. These pumps can be used to boost the pressure in the geothermal loop or to provide the pressure and flow in a secondary closed-loop system. Many excellent selections are available in this regard. Centrifugal pumps, selected on the basis of pressure, flow, temperature and corrosive considerations of the fluid being handled, become a straightforward engineering task. Hot-water circulating pumps have been used for many years and the state-of-the-art can be applied directly to geothermal applications.

PIPING SYSTEMS

This section refers only to that portion of piping transporting geothermal water. Piping in a closed-loop system carrying city or potable water, which may have been heated by geothermal

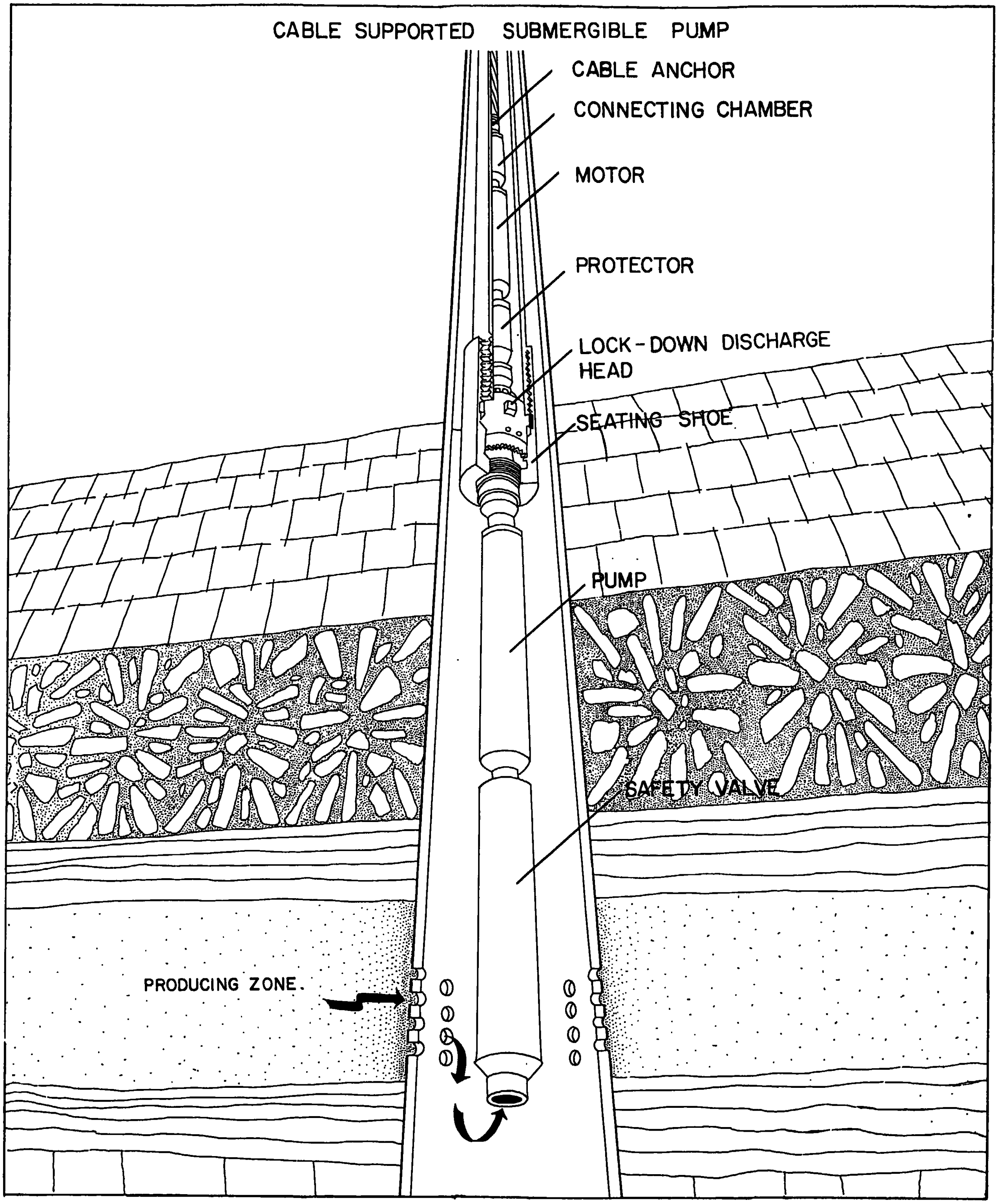

FIGURE 20. Cable-supported submergible pump (source: TRW REDA Pumps).

water, becomes a standard heating system, is well documented in ASHRAE guidebooks and is no different from what has been in common use.

Types of pipe

Metallic pipe. The most commonly used pipe is black steel, schedule 40, for pressures under 125 P.S.I. (860 kPa). Jointing of this pipe may be threaded, welded or with use of gland-type couplers (Victaulic or equal). In using gland-type fittings, it is very necessary to research the chemical and temperature range of the elastomeric gaskets to make sure they are compatible with the water.

Generally, it is advisable to keep the velocity on the high side to provide scouring and reduce chemical build up. Free oxygen in these systems will produce Fe_3O_4, therefore it is necessary to keep a tight system.

Other types of piping, such as copper, brass, stainless steel and the more exotic metals may be permissible under certain water conditions but should be used only as "last resort" due to their increased cost.

When buried in the ground, metallic piping should be well protected from exterior corrosion. Using magnesium anodes to offset the galvanic action of soils and ground water is often advisable, particularly in very moist soil or acid soils.

Nonmetallic pipe. Asbestos cement piping has been used for out-fall lines with good success; however, some waters will have a deteriorating reaction with the piping chemicals. On supply pipes or pressure pipes, there is the additional possibility of oxygen entering the water due to the porosity of the piping.

Polymer concrete pipes (mixtures of cement aggregate and various polymers) are presently under development. These pipes have been tested in various geothermal fluids and have been resistant to leaching, scaling and erosion. Testing is continuing and the pipes are commercially available, but at the present time there is no large commercial application experience.

There are many types of patented plastic pipes, such as PVC, CPVC, Fiberglas, polypropolene and other thermoplastic materials that have excellent chemical resistance, sealing, higher flow rates for a given size and a wide range of thermal expansion and temperature limitations. We advise a thorough study of their limitations[5] before using any of these pipes and recommend providing the manufacturers with chemical analysis of the water and receiving from them a written guarantee for its usage. These materials have been used in only limited applications to this time and there is little experience on which to base design and operations and maintenance costs.

Some Fiberglas-reinforced plastic (FRP) pipes meet rigid military specifications (MIL-P-28584) of up to 115 psig (800 kPa) at 300°F (149°C) and have been used for steam-condensate lines with good results. Maintenance costs over a 12-year period have been nil and the pipe shows no sign of deterioration. FRP in general will not carry live steam as the steam breaks down the plastic; seeping and ultimate failure may result.

Determining pipe parameters

Pipe sizing. Pipe size is determined by the temperature difference (ΔT) between the water entering and leaving a system. For best economy of the overall design, it is most advantageous

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[5] For example, temperature limits for various pipes are 125°F (52°C) ABS, 150°F (66°C) PVC and 212°F (100°C) CPVC.

to use the largest ΔT possible. Flow rates are determined from the heat output required by the system divided by the temperature differential as follows:

$$\text{Mass Flow Rate (lb/hr)} = \frac{\text{Heat output (Btu)}}{\Delta T}$$

Expressed in the commonly used gallon per minute (GPM), this formula becomes

$$\text{Flow rate (GPM)} = \frac{\text{Heat output required}}{\Delta T \times 8.33\ \text{lb/gal} \times 60\ \text{min/hr}} \quad \text{or} \quad \text{l/s} = \frac{\text{kJ/hr}}{15{,}200 \times \Delta T(^{\circ}\text{C})} = \frac{\text{KW}}{4.22\ \Delta T(^{\circ}\text{C})}$$

$$\text{(GPM)} = \frac{\text{Heat output required}}{\Delta T \times 500}$$

This would vary slightly due to the specific heat and density of the water at various temperatures. However, in the range of temperatures normally used, the above formulae are accepted.

Head loss. The second consideration is the head loss in a system. As the pipe size is decreased for a given water flow, the head loss will increase thus, increasing the pump motor size and the energy consumption. Head loss in a piping system is a function of the quantity (GPM), circulated and the friction loss in the pipe. Generally, a .75 ft/100 ft head loss to 2.5 ft/100 ft (0.75-2.5%) is desirable, the lower figure being used for smaller pipes. There are advantages to using the higher flow rates, such as scouring of the pipes and the ability to move entrained air through the systems.

In determining the total head loss in a piping system, one must know the total length of the system plus the equivalent length allowed for fittings and valves. The head loss in the piping system is equal to the total equivalent length times the friction loss per ft or per 100 ft. Tables for determining the friction-loss factors and resultant pipe sizes may be found in ASHRAE Handbook of Fundamentals, 1972 edition, Chapter 26. This reference also gives complete information for pipe sizing.

In addition to the water-friction loss in the piping system, one must also consider the head loss through the heat exchangers or coil system that the water passes through. These losses are usually quite significant and can be most easily obtained from manufacturers' catalogs or direct from the manufacturer of the equipment used.

Static losses in a system (that is, the loss to lift the water to the highest point of usage) must also be considered in determining the total head loss on a pump. Therefore, the total head loss is equal to H_f (Head Loss due to friction) plus H_e (Head Loss through equipment) plus H_s (Static Head Loss).

Static Head Loss is ignored in any closed-loop system since the total system is filled with water and the weight of the water rising in a system is offset by the weight of the water that is returning down in the system.

Design procedures. In any piping and utilization system, it is recommended that a preliminary layout be prepared and from this, preliminary pipe sizes, pressure drops, equipment sizing and pump selection be determined.

An overall examination of this preliminary design should then be affected and adjustments in pipe sizes and pump sizes may be made to determine the best first cost versus the operating cost of the system to obtain the optimum design.

Expansion allowances. Consideration must be given to the expansion and construction of piping due to temperature changes. This expansion must be taken up within the piping system either with offsets, pipe loops, expansion joints, special mechanical couplings, by utilizing the inherent flexibility of the piping in bending or by preheating. The method or devices selected will depend upon force limitations, available space, installed cost, serviceability, maintenance cost, length of life, etc. The amount of expansion within a given piping system depends on the temperature differential and the type of piping. The relation between these two for any given pipe material is available from most engineering handbooks or from manufacturers.

Where possible, we recommend utilizing the flexibility of the piping itself either by unrestricted movement of the pipe where it makes bends or by using offsets or pipe-loops. However, these methods are usually not satisfactory for a buried system.

Mechanical expansion joints are commonly used where space is a limiting factor; however, they must be accessible for maintenance.

Some piping systems use an elastomeric-gasketed type coupling, such as tapered joints with O-rings or those applied to grooved-end pipe to take up the expansion. However, these must be selected carefully to insure adequate expansion and to be able to operate within the pressure and temperature limitations of the elastomer selected.

Preheating of direct-bury piping for large central heating districts has been used in several countries in Europe. Insulated pipe is laid in trenches, preheated to a fixing temperature between the middle of the normal operating range and the middle of the total temperature difference (cold to high-operating) and back-filled at that fixing temperature. The system eliminates guides, anchors and expansion loops or compensators since they have already been "prestressed." A good bond between pipe, insulation and outer jacket (PVC, PEH, etc.) is required. The system is said to reduce installation cost by up to 20% and reduces system failures.

For a complete discussion on expansion in piping, we refer you to Chapter 14 of the 1976 ASHRAE Systems Handbook.

All expansion devices must be used in conjunction with anchors and guides to insure that the expansion occurs as designed and that the alignment of the piping is maintained in order to make the devices operate as designed.

Heat loss from piping system. The heat losses to be tolerated from a piping system will invariably be determined by the economic balance between first cost and operating cost. Also recent legislation and adoption of energy codes have dictated certain minimum insulation values for piping regardless of the type of heat source. Geothermal water is a natural resource, and although it may appear at this time that it is virtually an unlimited source of energy, it should not be wasted.

The thickness and type of insulation to be used on a system must be evaluated not only on cost but also on location of the piping and the temperatures involved. In an underground system, the resistance to moisture absorptivity and resistance to superimposed loads must be considered. Above-ground insulations must be evaluated for fire and smoke protection, from damage by personnel and from damage to thermal efficiencies.

Most of the criteria for proper installation of insulation can be obtained from the insulation manufacturers. ASHRAE, 1976 Systems Handbook, Chapter 14, gives a good comparison chart for evaluating the various types of insulation.

HEAT EXCHANGERS

The principal reason for having heat exchangers in geothermal systems is to confine the geothermal waters with their inherent impurities to locations where corrosion and/or scaling can either be controlled by materials selection or where cleaning or replacement will be relatively easy and economical. Thus, large and sometimes complicated piping and heat-emitter systems are protected from the harsher environment of the geothermal fluid. In some areas of relatively benign geothermal fluid, direct use in the system may be practical. Chemistry of the water and its effect on materials should be carefully checked.

It must be remembered that there will be a temperature differential between the primary and secondary fluids any time a heat exchanger is used. The smaller the differential (closer approach temperature), the more expensive the heat exchanger will be. Approach temperatures of less than 10°F (6°C) are often uneconomical but depend on the heat-exchanger type and particular application. In some cases, where well and piping costs are low, approach temperatures of 4-5°F (2-3°C) have proven economical.

The principal types of heat exchangers used in geothermal systems are the downhole heat exchanger; the shell-and-tube heat exchanger; the plate heat exchanger; the fluidized-bed heat exchanger; the direct-contact heat exchanger; and the plastic-tube heat exchanger.

Downhole heat exchanger

The downhole heat exchanger (DHE) eliminates the problem of disposal of geothermal fluid, since only heat is taken from the well. The exchanger consists of a system of pipes or tubes suspended in the well through which "clean" secondary water is pumped or allowed to circulate by natural convection. These systems offer substantial economic savings over surface heat exchangers where a single-well system is adequate (typically less than 0.8 MWe, with well depths up to about 500 ft [150 m]) and may be economical under certain conditions at well depths to 1500 ft (450 m; Figure 21).

Several designs have proven successful, but the most popular are a simple hairpin loop or multiple loops of iron pipe (similar to the tubes in a U-tube and shell exchanger) extending near the well bottom (Figure 22) and a spiral coil of copper tube suspended near the well bottom. An experimental design consisting of multiple small tubes with "headers" at each end suspended just below the water surface appears to offer economic and heating capacity advantages.

In order to obtain maximum output, the well must be designed to have an open annulus between the well bore and the casing and perforations above and below the heat-exchange surface. Natural convection circulates the water down inside the casing, through the lower perforations, up in the annulus and back inside the casing, through the upper perforations. If the design parameters of bore diameter, casing diameter, heat-exchanger length, tube diameter, number of loops, flow rate and inlet temperature are carefully selected, the velocity and mass flow of the natural convection cell in the well may approach those of a conventional shell-and-tube heat exchanger.

The interaction between the fluid in the aquifer and that in the well is not fully understood, but it appears that outputs are higher where there is a high degree of mixing indicating that somewhat permeable formations are preferred (Figure 23).

Considering life and replacement costs, materials should be selected to provide economical protection from corrosion. Attention must be given to the anodic-cathodic relationship between the exchanger and the casing since it is relatively expensive to replace the well casing. Experi-

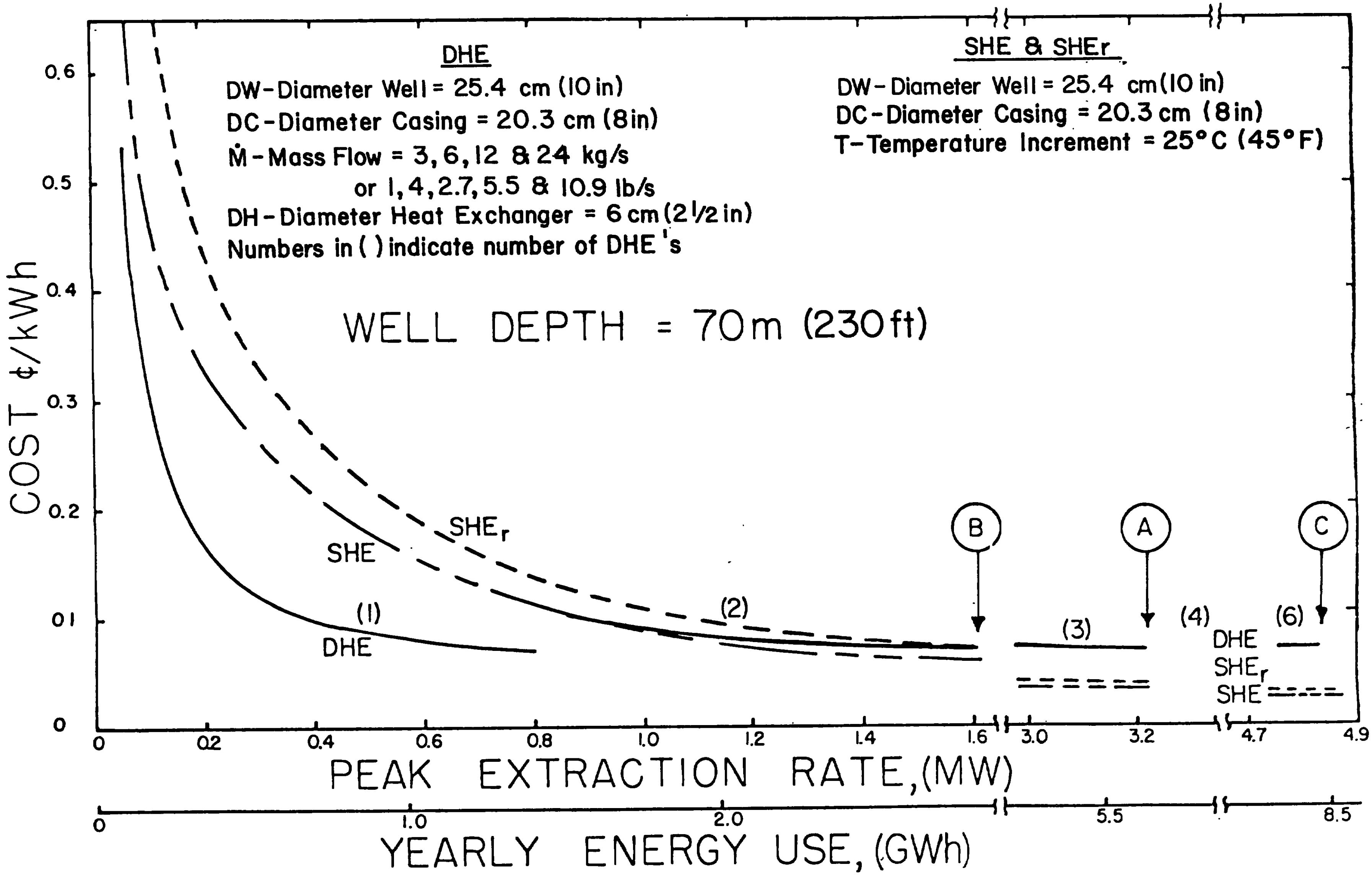

FIGURE 21. Unit energy costs for geothermal energy from downhole (DHE) and surface heat-exchange (SHE) systems for a well depth of 70 meters (230 ft). Points A, B and C indicate the limiting energy-extraction rates for the SHE and SHE_r (with reinjection) systems with well flows of 32 l/s (250 gpm) and 47 l/s (750 gpm) respectively at the temperature drop shown. (Note: 1¢/KW h = $2.93/million BTU = $2.78/GJ.),(GWh = Giga Watt hour)

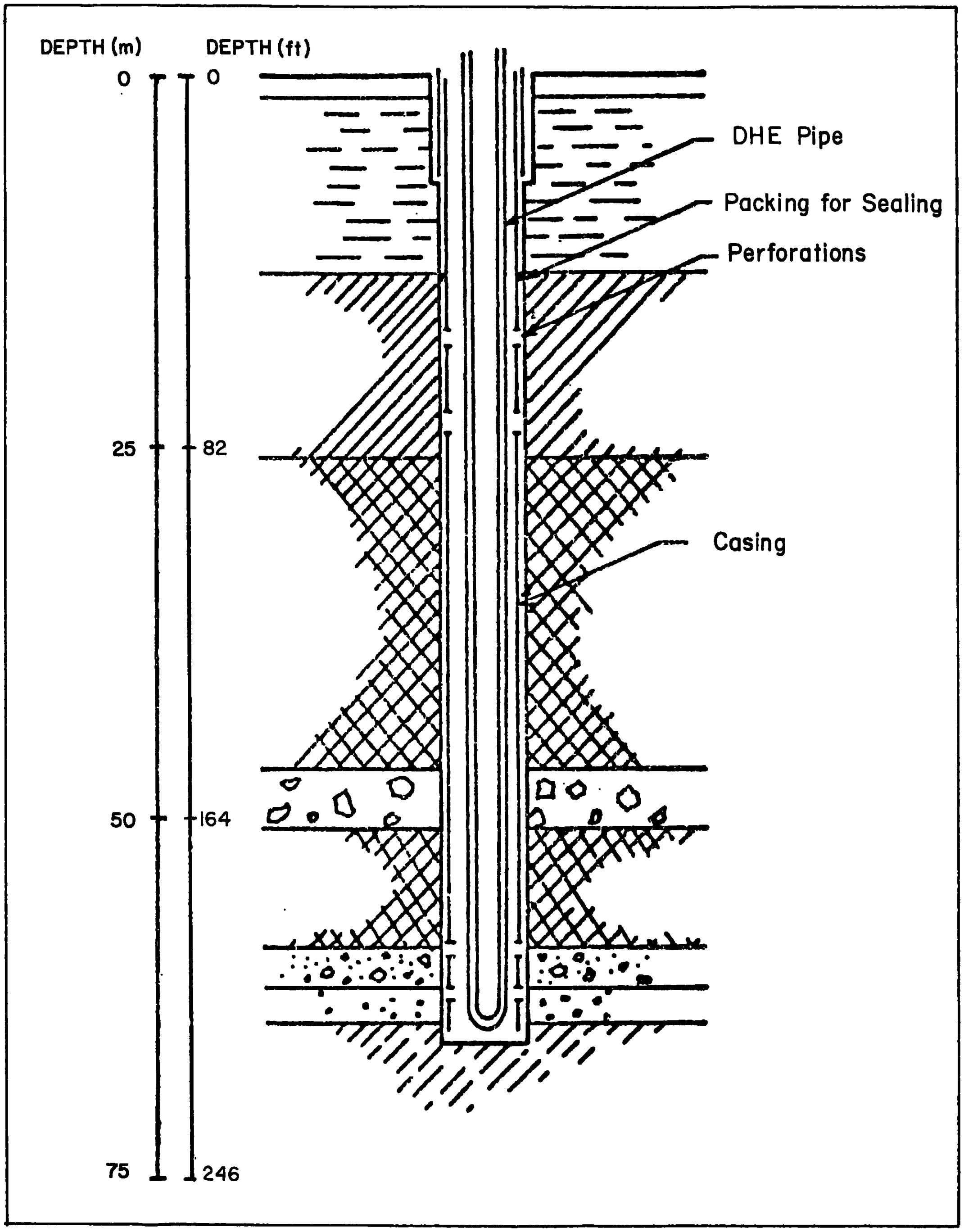

FIGURE 22. Typical downhole heat-exchanger installation.

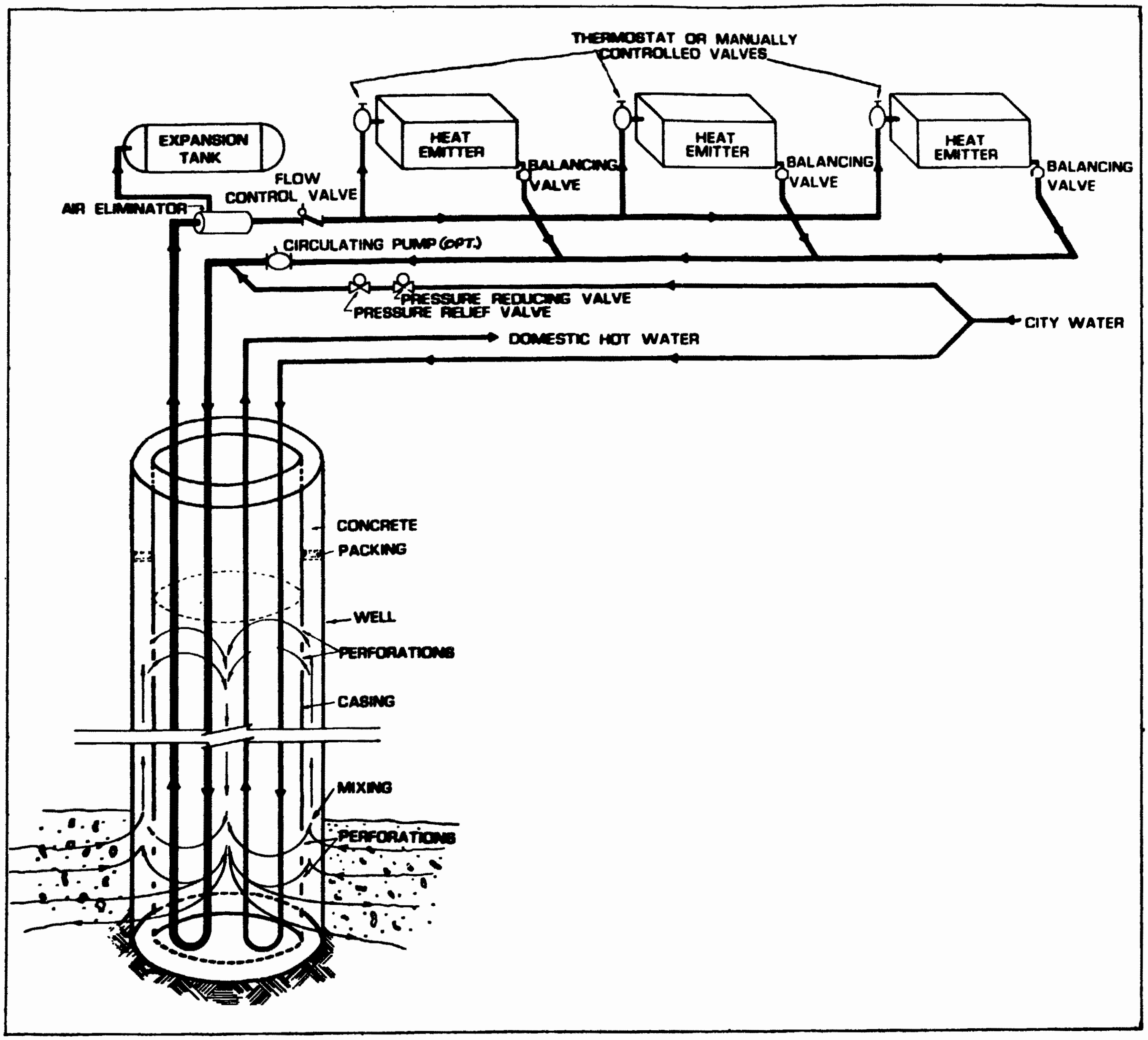

FIGURE 23. Typical hot-water distribution system using a downhole heat exchanger (Culver, 1978).

ence in the approximately 600 downhole exchangers in use indicates that corrosion is most severe at the air-water interface at static water level and that stray electrical currents can accelerate corrosion. Insulating unions should be used to isolate the exchanger from stray currents in building and city water lines.

Shell-and-tube heat exchangers

Conventional shell-and-tube heat exchangers may be utilized for geothermal applications with certain design considerations. Their application is well known and little will be said here. The shell-and-tube heat exchangers are placed above ground and can be either adjacent to the well head or at any place along the distribution system in the case of a large district-heating system.

This type of heat exchanger is readily available or may be custom-designed to meet the specific need. The shell-and-tube heat exchanger is just what the name implies, i.e., a series of tubes, normally carrying the geothermal water, surrounded by an enclosing shell, confining the secondary-system water around the tubes. The tubes in this type exchanger can be a "U"-tube configuration or a straight tube with removable heads at both ends to facilitate cleaning of the tubes. We recommend the straight-tube configuration strictly for ease of cleaning. Exchangers may be used in series to obtain higher ΔT, or for heating different secondary fluids.

Impurities in the well-water systems will determine the types of materials to be used in the heat exchangers. Less expensive exchangers are normally manufactured using mild steel for the shell and heads, with copper tubes. Stainless-steel shells and certain copper, bronze, silicon bronze or stainless-steel tubes and heads may be used for greater corrosion resistance. Further information may be found in the corrosion section of this report. In some cases, scaling can be a serious problem in shell and tube exchangers. The water can be chemically analyzed and the Langiller Saturation index applied to obtain information on the amount of scaling to be expected. Large fouling factors, up to 25% or more, may be required.

When mild steel shells and copper or silicon bronze tubes can be utilized, the shell-and-tube heat exchanger will generally be more economical than plate exchangers. However, for the same duty, the shell and tube exchangers will generally require more space.

Plate heat exchangers

Although relatively unknown, plate-type heat exchangers have been used predominantly in the food-processing industry, where corrosion resistance and cleanliness are necessary, and in certain other applications where very close approach temperatures are required (Figure 24).

The plate heat exchanger consists of a series of plates held in a frame by clamping rods. The primary and secondary fluids are usually passed through alternating passages between the plates in single-pass counter flow, although other flow paths can usually be arranged by simple external piping. Since the flow is pure counter-flow, Log Mean Temperature Difference (LMTD) correction factors approach unity and high turbulence is achieved, providing a very efficient exchange in a small volume. Stamping of the plates provides a variety of flow-path patterns and sizes.

The plate-type exchangers can be economically constructed of corrosion-resistant materials since the plate material is usually more economical than tube material. Materials readily available for geothermal use include stainless steels, titanium, brasses and hastelloy.

Specific advantages of plate heat exchangers over shell and tube exchangers for geothermal applications are:

1. More economical when materials other than mild steel are required.
2. Less floor space required.
3. Closer approach temperatures at reduced costs.
4. Easy disassembly for cleaning.
5. Easy to expand for increased heating loads by adding plates.
6. Series and/or parallel systems can be incorporated in one frame.

Disadvantages for some applications are:

1. Low-density fluids (vapors and gases) are difficult to handle economically.
2. Since gaskets between plates must be elastomeric, temperatures are limited to 500°F (260°C).

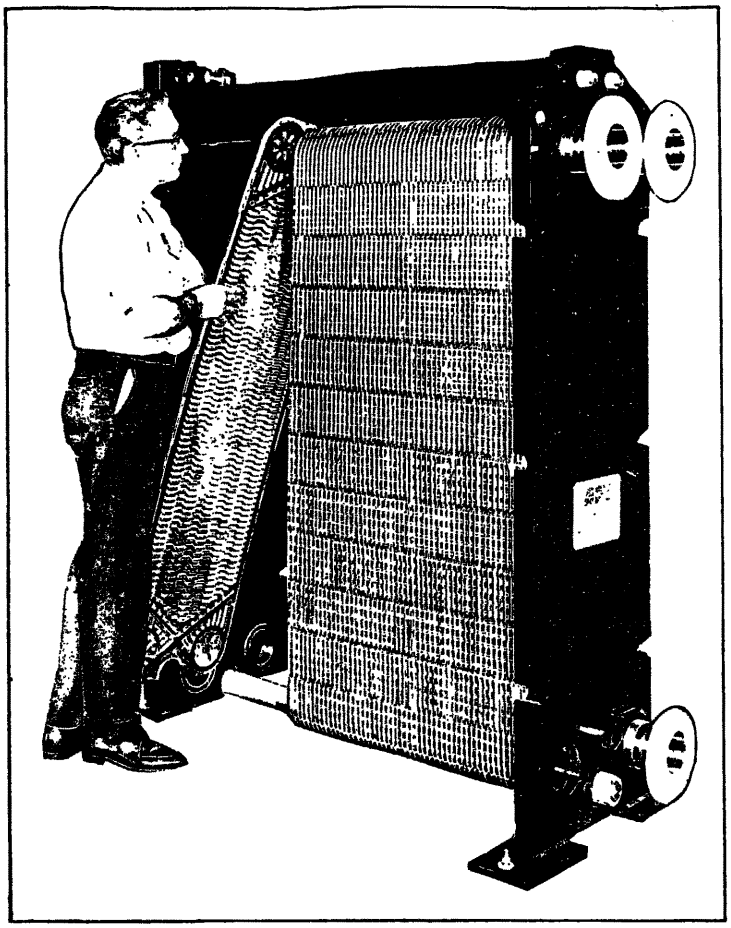

FIGURE 24. Plate heat exchanger (source: APV Co., Inc.).

We recommend investigating the use of plate-type exchangers for all applications unless the disadvantages noted above clearly eliminate their use. In the several instances where they are in use or use is proposed, plate exchangers have shown great economic advantages. The economy is particularly advantageous where low-temperature geothermal fluid requires close approach temperatures for economic sizing of other components. Systems presently in operation have economically achieved approach temperatures of 4°F (2°C) with geothermal fluid of about 130°F (54°C).

Direct-contact heat exchanger

This type of heat exchanger provides one of the most efficient and simplest means of transferring heat from hot geothermal water to another working fluid. Direct-contact exchangers have been used in petro-chemical applications for a number of years, usually in the exchange between a fluid and a gas (Figure 25).

The basic exchanger consists primarily of a pressure vessel with its longitudinal axis vertical and piped such that the hot fluid and the fluid to be heated are introduced countercurrent to each other. Each fluid is usually directed through a nozzle arrangement to provide for efficient mixing and maximum contact between the two fluids. Once mixing and heat exchange has taken place, the two fluids are allowed to separate as a result of state or density changes. The working fluid carryover to the hot fluid is almost inevitable. Selection of the proper working fluid to minimize carryover is based on chemical and thermal characteristics. As an

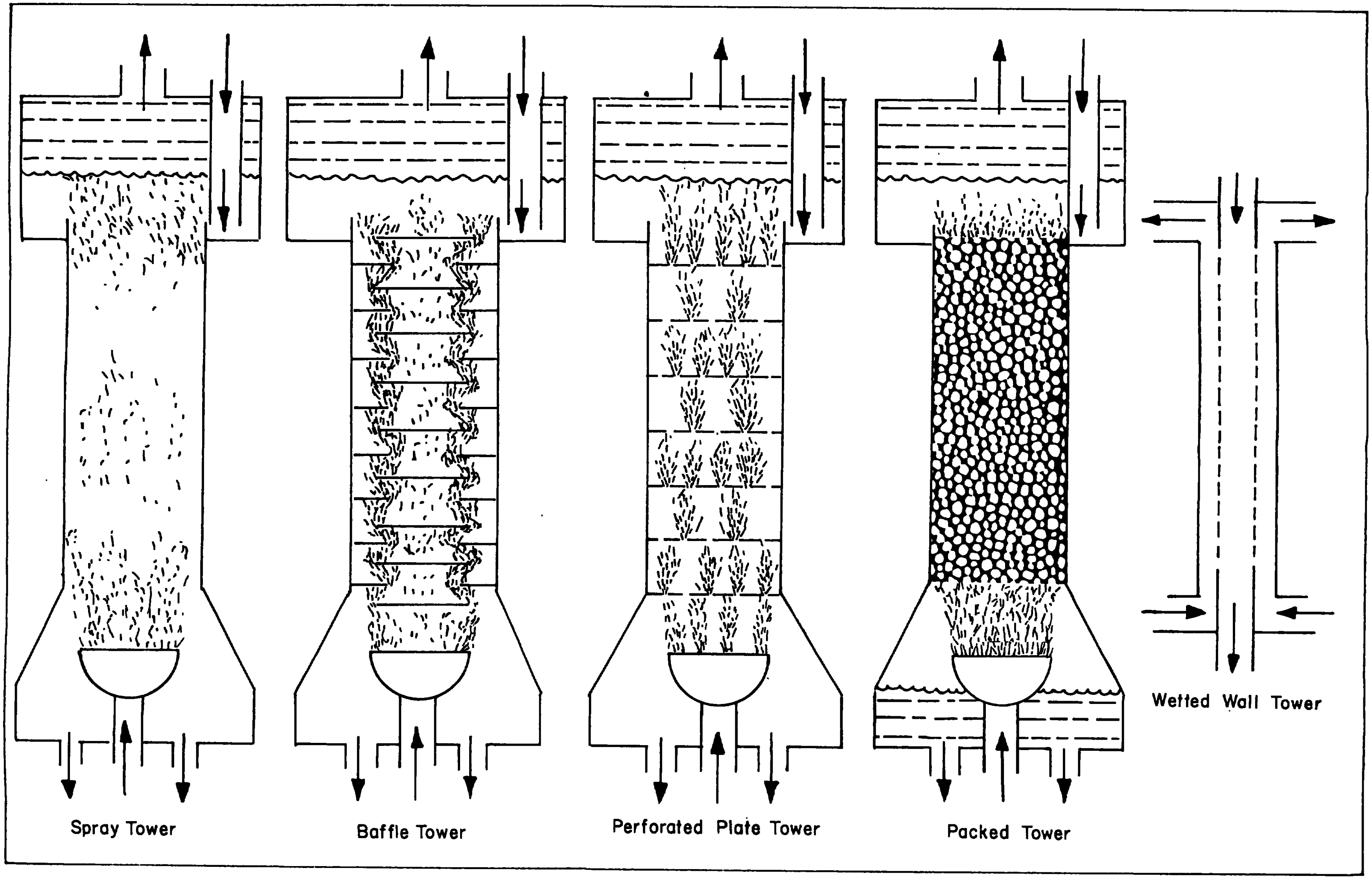

FIGURE 25. Schematic of various types of direct-contact counter-flow devices.

example, the flash point of the working fluid selected should be well below the temperature of the geothermal water to assure complete vaporization of the working fluid and thus good separation after being heated.

The advantages of this device for direct applications include simplicity of design and a small volume size required for rather large heat-transfer rates. Applications considered primarily to date have usually been in the electric-power generation areas, but the application should lend itself well to heat pumps or process use or perhaps a Rankine cycle engine.

Fluidized-bed heat exchanger

The fluidized-bed exchanger is similar to a shell-and-tube in design and overall appearance. The difference is that a medium (sand, ground walnut hulls or almost any granulated, uniformsize material) that can be made to behave like a fluid (with the introduction of pressurized air or any other fluid, for that matter) is maintained in the shell portion surrounding the tubes. This fluidized medium provides for a constant scrubbing action against the tubes, eliminating many fouling or scaling problems. It can also have a beneficial effect on the overall heat transfer through turbulent action around the individual tubes, increasing the contact time between hot and cold fluids (Figure 26).

For the geothermal water high in dissolved solids that have a potential for severe scaling, the fluidized bed exchanger becomes an excellent choice. Heat-transfer rates can be maximized without the maintenance concerns of fouled exchanger tubes. In the application described, geothermal water would be piped to the shell side of the exchanger through nozzles to fluidize a sand medium. The secondary water or fluid to be heated would circulate through the exchanger tubes.

Typical process applications for the fluidized bed exchanger may include many drying applications where the fluidized medium is actually the material being dried. The drying process can be accomplished in a batch-type arrangement or through a continuous flowing process where the medium is constantly carried over and expelled once it reaches a certain moisture content. In this application, geothermal water would be used in the tube side of the exchanger and the material to be dried, fluidized with pressurized air, would be introduced in the shell side.

Plastic-tube heat exchangers

Plastic-tube heat exchangers with an upper temperature limit of 122°F (50°C) are presently available from a Swedish manufacturer and higher temperature units are reportedly under investigation. The units are completely corrosion resistant to most geothermal waters and should not be susceptible to scaling. As might be expected, the units are larger than a comparable capacity typical U.S. fan-coil unit, but the corrosion- and scaling-resistance overcomes the disadvantage of size.

Current use of the plastic units has been in heat-recovery systems where heat from corrosive water is transferred to air and, conversely, where chemical-laden air is used to heat water. There are no metal components with bolts, manifolds, end plates and spacers made of plastic.

Use of highly cross-linked polyethylene tubes or other engineering plastics should permit construction of units able to withstand temperatures of above 200°F (93°C) and pressures of 150 psi (1030 kPa) with safety factors of 3, although no such units have been tested to date. There are no U.S. manufacturers producing either the highly cross-linked polyethylene or the plastic-tube exchangers.

A plastic-tube heat exchanger has been in use for several years in the Blue Baths in Rotorua, New Zealand. The exchanger consists of a loose bundle of 640 0.025-inch (0.64-mm) ID Teflon

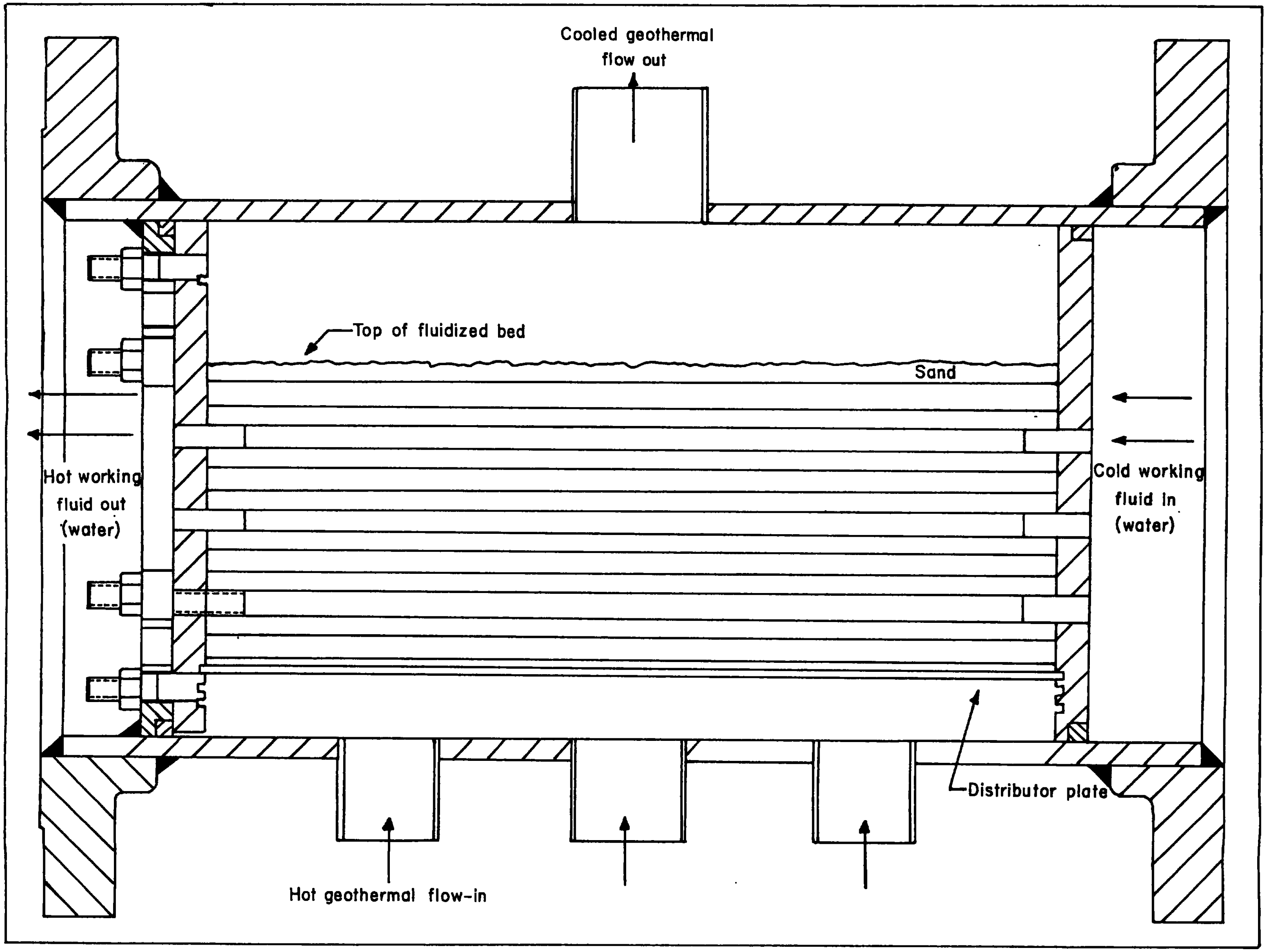

FIGURE 26. Horizontal arrangement of a liquid fluidized-bed heat exchanger.

tubes of suspended in a circulating bath of 200°F (93°C) geothermal water. Similar units are manufactured by DuPont.

CORROSION, SCALING AND MATERIALS SELECTION

Properly managed boiler water, steam or hot-water heating systems are free of the typical geothermal fluid components. These fluids are substantially less aggressive than geothermal fluids and have little tendency to form scales by deposition of dissolved solids. The chemical species present in geothermal fluids are the primary factors that result in corrosion and scaling when these fluids are used as heat sources.

Geothermal-fluid chemistry

Geothermal-fluid temperature and chemistry are so closely related that there is a general increase in total dissolved solids (herein referred to as salinity) as temperature increases. The chemical species found in the fluids are a function of the local, *in situ* geology. Certain important species are found to a greater or lesser extent in all geothermal fluids and are tabulated in Table 5. Hydrogen concentration, as expressed by pH, is a function of other species, e.g., carbon dioxide. Oxygen is not present in most geothermal reservoirs since oxygen and hydrogen sulfide do not coexist in significant amounts at equilibrium. The presence of significant concentrations of oxygen (>10 ppb) in the presence of hydrogen sulfide is usually an indication of leakage of air into the piping system or the mixing of very near surface water with the fluid (DeBerry, 1978).

TABLE 5

Dissolved major corrosion and scaling species in most geothermal fluids

Corrosion	Scaling	Character
Oxygen (in leakage)		Gas
Hydrogen Sulfide		Gas
Carbon Dioxide		Gas
Ammonia		Gas
Hydrogen		Ions
Sulphates		Solid
Chlorides		Solid
	Silicates	Solid
	Carbonates	Solid
	Sulfides	Solid
	Oxides	Solids

Hydrogen sulfide. Probably the most severe effect of H_2S is its attack on certain copper and nickel alloys. Copper, cupronickel and nickel copper alloys 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 to H_2SO_4 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 some 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 (in the low ppb range) amounts of oxygen.

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.

Transition metal ions. "Heavy" or transition metal ions might also be included as key species. Their action on most construction materials at low concentrations 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 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.

An important factor to be considered when evaluating a geothermal resource is the variability of the chemical characteristics of the fluids. The compositions of geothermal fluids vary considerably from field to field. There are significant differences between wells in a given reservoir resulting from localized variations in the geology. There are variations with time in a well due to changes in the flow patterns resulting from production of the reservoir.

Corrosion and scaling inhibitors

The volumes of fluid required for most geothermal-heating applications are typically too large for economical use of corrosion inhibitors. The EPA requirement for the removal of any chemical added to the fluid for corrosion control prior to disposal provides further incentive for alternate corrosion-control methods. These factors suggest that materials selection is the most economical means of corrosion control.

Unlike the requirement for removal of corrosion inhibitors, EPA regulations regarding scale-control chemicals are much more liberal. Scale-control chemicals fall into two general classes: those that modify surface characteristics and retard nucleation and those that change the chemical character of the deposited species.

These chemicals interfere with nucleation and growth mechanisms rather than altering the equilibrium solubility of the depositing mineral. Polysulfinates, polyacrolates and other low-molecular weight polymers are frequently used for scale control. One point should be borne in mind: corrosion scales frequently provide nucleation sites for mineral scale deposits.

Corrosion and materials selection

This section describes the forms and mechanisms of corrosive attack that can occur in geothermal-process liquid streams. These generalizations are especially useful when materials must be specified for conditions at which tests have not been done. If the corrosion rate of a material has been tested at the stream conditions of interest, this information is still useful. It explains the effects of fabrication practices, equipment configuration and operating stresses. It also identifies some additional ways materials can deteriorate.

Table 6 contains information about the performance of specific metals in liquid streams.

General guidelines

By taking appropriate precautions, carbon 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 carbon steels. The application of mild steels to geothermal environments requires that precautions be taken for aeration, flow rate, scaling, galvanic coupling, protection of exterior surfaces and steel specifications.

Aeration. Acceptable uniform corrosion rates of carbon steels in fluids containing <10,000 ppm chloride ion are due mainly to the reducing, oxygen-free nature of the fluids. The introduction of small quantities of oxygen can increase uniform corrosion by at least tenfold and initiate pitting and crevice corrosion.

The effect of oxygen on the corrosion of a mild steel is shown in Figure 27 for an otherwise nearly gas-free seawater stream. The same effect occurs in geothermal systems. The solubility of oxygen in saline fluids decreases with increasing temperature up to 212°F (100°C), at which point it increases again (Cramer, 1974). The electrochemical reaction rate increases with temperature.

Aeration damage during plant operation should be minimized by guarding against leaks in the lower-temperature vacuum sections of the plant. The highest potential for serious damage from aeration occurs due to inleakage during plant outages or layups. Stagnant conditions are conducive to crevice and pitting corrosion promoted by oxygen. Oxidation of ferrous ions and H_2S in the geothermal fluid can produce ferric ions and local acidity, which accelerate attack. Procedures for avoiding damage during shutdowns include draining and rinsing equipment and purging with an inert gas. Oxygen scavengers might be applicable, but possible side reactions with species in the specific fluid should be evaluated.

Flow rate. The best performance of carbon steels occurs when liquid flow rates are limited to 5-7 ft/sec (1.5-2.1 m/s). Localized, uncontrolled flashing in geothermal streams can cause high flow rates in the system. This action can produce bubbles of noncondensable gas which can cause impingement attack. Entrained solids in the stream can cause erosion-assisted corrosion. The relative hardness of particle and metal has little effect on this type of corrosion.

Failure of components, such as pipe ells, has occurred in fluids as diverse as those at Salton Sea and Raft River. These failures are probably caused by the flow conditions noted above.

TABLE 6

Forms and causes of corrosion for metals in liquid geothermal streams and ways to prevent attack.

Material	Major Forms of Corrosion	Main Environmental Factors	Limits and Precautions	Other Comments
Mild & Low Alloy Steels	uniform	pH	Rapid rate increase below pH 6	Air in-leakage is a major hazard; local flashing in pipes can cause very high flowrates and erosion/corrosion
		chloride	Rapid rate increase above 2% Cl^-	
		flow velocity	Limit flow to 5-7 fps (1.5-2.1 m/s)	Avoid direct impingement on steel
	pitting, crevice	temperature chloride	Susceptibility increases with increasing temperature and chloride concentration	Avoid mechanical crevices
		scale	Remove mill scale; avoid deposits	
	sulfide stress cracking	H_2S	Can occur at very low H_2S levels	Complex interactions
		yield strength (hardness)	Use low strength material wherever possible (Rc < 22 g YS < 100,000 psi)	
		temperature	Hazard greater at lower temperatures	
	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	In general, susceptibility increases with increasing concentration and temperature	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
		scale	Avoid scale deposits	
		stagnant or low flow	Avoid stagnant or low flow conditions	
		oxygen	O_2 greatly increases susceptibility	

(continued)

TABLE 6 (continued)

Forms and causes of corrosion for metals in liquid geothermal streams and ways to prevent attack.

Material	Major Forms of Corrosion	Main Environmental Factors	Limits and Precautions	Other Comments
	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^- > 5ppm; O_2 100 ppb; T > 140°F (60°C)	Hazard increases with increase in Cl^-, O_2, T; some alloys more resistant; protect exterior surfaces
	pitting, crevice	chloride temperature	See ferritics above	Resistance increases with Mo content; avoid mechanical crevices
		scale	Avoid scale deposits	
		stagnant or low flow	Avoid stagnation or low flow conditions	
		oxygen	O_2 greatly increases susceptibility	
	intergranular	chloride, temperature	Avoid by proper welding and heat treating procedures	
martensitic alloys	as above	as above	As above	
	sulfide stress cracking	H_2S, temperature, stress, hardness	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	Maximum temperature for resistance depends on chloride and pH	Several alloys have much better resistance than pure Ti. Precracked Ti may undergo stress corrosion cracking

(continued)

TABLE 6 (continued)

Forms and causes of corrosion for metals in liquid geothermal streams and ways to prevent attack.

Material	Major Forms of Corrosion	Main Environmental Factors	Limits and Precautions	Other Comments
	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
Copper Alloys	pitting, uniform, de-alloying	H_2S chloride, temperature, CO_2.	H_2S as low as 0.1 ppm can cause attack	Usefulness limited in H_2S environment
	stress corrosion cracking	ammonia, pH		
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 & tantulun				Resistant to low pH, not chloride solution
aluminum	pitting, crevice	Hg and Cu ions, pH, chloride, temperature, lack of oxygen	Poor results obtained in geothermal tests	May be useful as exterior siding and construction material

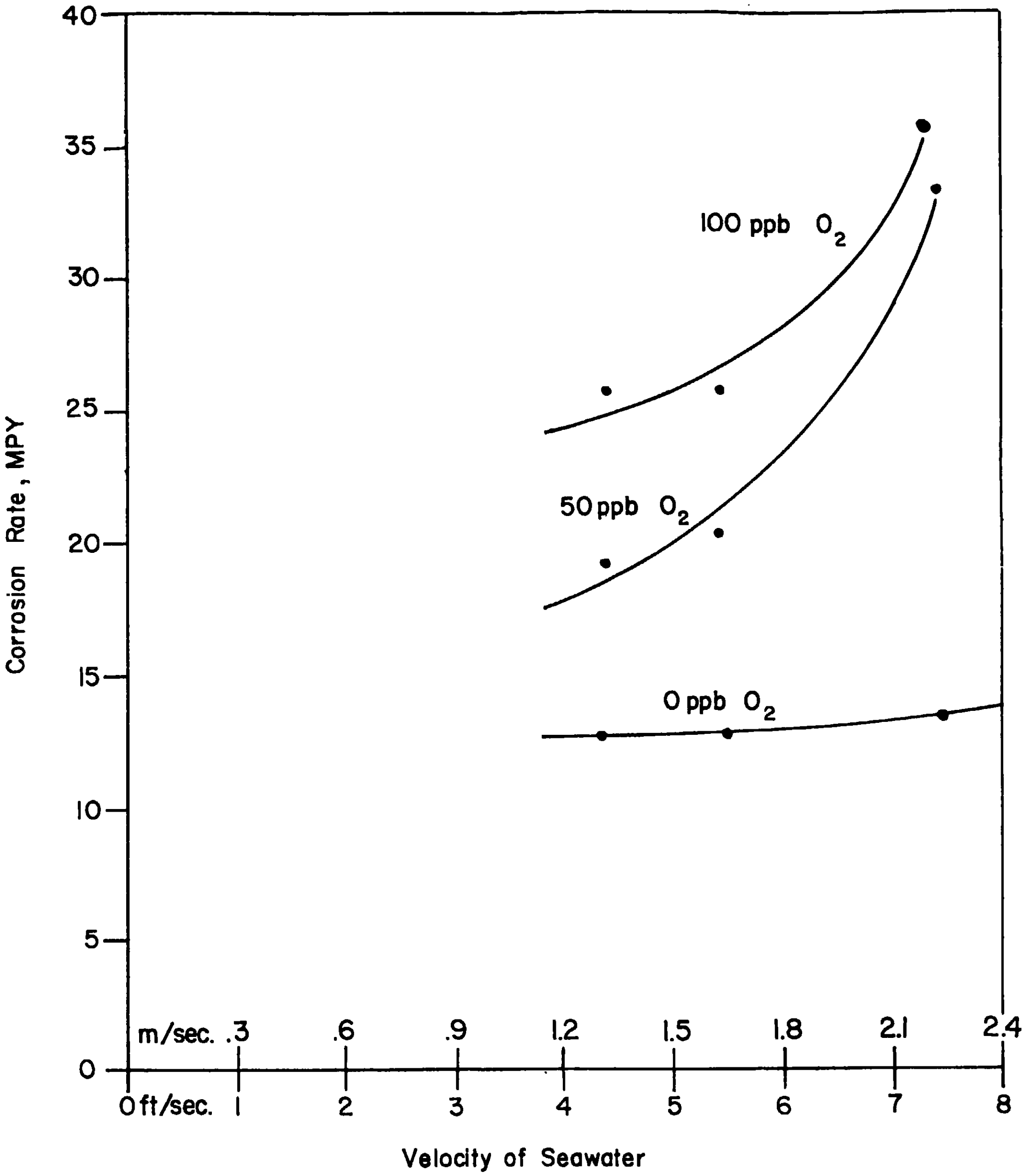

FIGURE 27. Effect of oxygen on uniform-corrosion rate of 1010 mild steel in 250°F (121°C) seawater (based on data presented in George, 1975).

Designs to avoid direct impingement on carbon steels and localized flashing should alleviate these types of failures. Providing liquid buffer zones may help. Pump impellers, especially for downhole applications, may be subject to severe cavitation damage. The CO_2 content of many geothermal fluids can cause an apparent vapor pressure that exceeds steam-table values by tens to hundreds of psi (100's to 1000's kPa). Caution in design and material selection is required.

Effects of high velocities are illustrated in Figure 28 for seawater at 250°F (121°C).

Scaling. Some mechanical protection against uniform corrosion may result from scales formed on steel by precipitation from geothermal fluids, but localized corrosion can also occur under the scales. Scales in geothermal systems are porous and prone to cracking by differential thermal expansion. The exposure of the base metal to a geothermal fluid can lead to local acid-

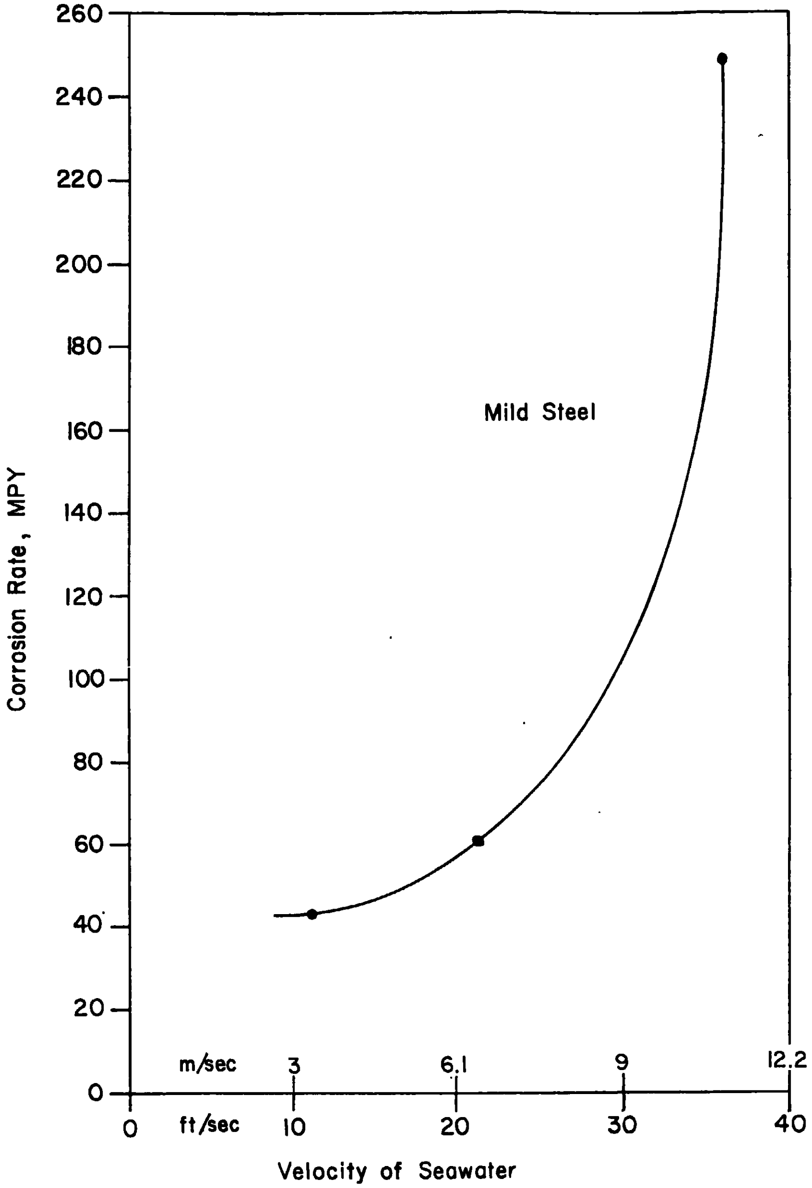

FIGURE 28. Weight-loss corrosion rates of mild steel in high-velocity, high-temperature oxygen-free seawater (based on data presented in George, 1975).

ity and high chloride concentration similar to conditions during crevice corrosion. Accelerated attack by H_2S is increased in acidic environments such as this.

Attack at small exposed areas can become more serious if the steel is galvanically coupled to a more noble metal. In extreme cases, this concentration of the corrosion-steel dissolution current can cause perforation of thick-walled steel components in a very short time.

Chemical cleaning solutions used to remove scale should be evaluated carefully since some types (such as inhibited HCl) accelerate corrosion of mild steel. Severe attack can occur if aggressive cleaning solution is trapped in or under incompletely removed scale.

Stainless steels. 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 successfully in geothermal environments, but care must be taken in their selection and application.

1. Aeration.

   Many stainless steels that could perform well in oxygen-free geothermal environments can be subject to severe pitting and crevice corrosion in the presence of small quantities (low ppb concentrations) of oxygen. Stress-corrosion cracking of commonly used austenitic stainless steels in high-temperature chloride solutions can occur minutes after introducing oxygen in ppm quantities or less. This failure is often catastrophic. Other alloys are more resistant. Pits, crevice attack or cracks initiated during upset or plant-outage conditions can continue to grow once normal operation is resumed. Special care should be taken during plant commissioning due to the likelihood of unstable conditions.

2. Flow rate.

   Stainless steels are more resistant to high velocities than plain and low-alloy steels. Continuous high-velocity flow is more desirable than low-flow rates or stagnant conditions. Under stagnant conditions, settling of entrained solids or spot deposition of loose scale can lead to crevice corrosion. Stagnant conditions should be avoided, and stainless components should be drained and rinsed during plant shutdown. Resistance to erosion-corrosion is more closely related to general corrosion resistance than hardness of the metal.

3. Scale.

   Local concentration cells can develop under porous or cracked scale on stainless steel and lead to crevice corrosion to which many stainless steels are susceptible. After an attack is initiated, local increases in acidity and chloride concentration cause intense corrosion.

4. Welding.

   Good welding procedures are important to the successful application of stainless steels. Physically poor welds may have crevices that are susceptible to crevice corrosion. Stress-corrosion cracking may initiate at pits close to poor welds. Sensitization of base metal during welding will cause rapid failure.

5. Exterior surfaces.

   Measures should be taken to protect the exterior of stainless-steel components that are exposed to air. Leaks and splashes of hot chloride solutions combined with the high oxygen content of air can subject these components to stress-corrosion cracking conditions. Flange leaks leading to conditions in which geothermal fluid concentrates and dries under insulation can be dangerous. Non-porous gaskets are required to guard against cracking at flanges.

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 geothermal facility (Geothermal Resources Council, 1976). 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 where their mechanical properties are desirable. Cupronickels will have limited usefulness in geothermal streams containing even trace (ppb) quantities of H_2S.

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. Aluminum alloys have also given poor results in geothermal-condensate cooling-water systems.

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. Even in this fluid, the performance of copper-nickel alloys (Monel 400, 70Cu/30Ni and 90Cu/10Ni) was very poor. De-alloying of some copper alloys was observed. However, some nickel-free brasses and bronzes gave acceptable performance (Miller, 1975).

Scaling

Scaling results from two sources: deposition of minerals from the fluid as a result of supersaturation and scales that result from accumulation of corrosion products. Either of these scales reduce the efficiency of the system by increasing the resistance to heat transfer and fluid flow. Such scales often promote localized corrosion.

Deposition of scales from solution. The minerals most frequently deposited from geothermal fluids are calcium carbonate (usually calcite) and silica. To a lesser extent, calcium sulfate (gypsum, anhydrite, selinite) may be deposited. Some geothermal wells carry high concentrations of heavy metals and sulfides; these fluids may yield sulfides of copper, lead, silver, etc., in addition to silica or carbonate scales.

Both calcium carbonate and calcium sulfate exhibit retrograde solubility (solubility is a strong function of pH and carbon dioxide concentration) and are related by several equilibria.

$$CO_2 + H_2O = H_2CO_3$$

$$CaCO_3 + H_2CO_3 = Ca(HCO_3)_2$$

$$H_2CO_3 = H^+ + HCO_3^-$$

$$HCO_3^- = H^+ + CO_3^{2-}$$

$$CaCO_3 = Ca^{2+} + CO_3^{2-}$$

Because the solubility of calcium carbonate increases with decreasing temperatures and is pH-dependent, no deposition will occur if the partial pressure of CO_2 is maintained at a level equal to downhole level.

As pH is decreased, the solubility of the calcite increases; however, many materials are degraded as hydrogen-ion concentrations increase. The presence of calcite scales frequently results in decreased corrosion by interfering with the diffusion of corrodants to the metallic surface. For this reason, calcite scales may be grown to controlled thickness as a general corrosion-control measure.

Calcium sulfate solubility is given by

$$CaSO_4 = Ca^{2+} + SO_4^{2-}$$

The solubility product constant is

$$Ksp = [Ca^{2+}] \quad [SO_4^{2-}]$$

When concentrations are expressed in mg/kg of fluid (ppm) the Ksp is reached at about 400,000. Geothermal fluids having a concentration product in this range or higher should be viewed as having a tendency towards calcium sulfate deposition.

The solubility of silica (SiO_2) is dependent on the form of the deposit. Amorphous silica has a much higher solubility than quartz, the familiar crystalline form. The usual assumption is that the geothermal fluid is in equilibrium with amorphous silica in above-ground environments and with quartz in the geological formation.

If the concentration of silica in the water is known, the temperature below which precipitation of amorphous silica can occur (from data in GRC, 1976) is given by

$$t = \frac{1531.98}{10.064 - \ln SiO_2} - 273.16$$

where

t = temperature °C

$\ln SiO_2$ = natural log of silica concentration in ppm.

If only the reservoir temperature is known, the amount of silica in the water assuming equilibrium with quartz is given by (Ellis and Mahon, 1977)

$$\ln SiO_2 = \frac{13.281 - 3531}{t + 273.16}$$

where

t and $\ln SiO_2$ are defined as above.

This value can also be substituted into the previous equation to find the temperature below which amorphous silica scaling is possible.

The rate of scale deposition is critically dependent upon the material being deposited. Silica deposition is very slow, often requiring several hours or days for equilibrium to be established. Calcite deposition is very rapid and its equilibria are achieved in short time periods, frequently milliseconds. Calcium sulfate deposition lies between these extremes.

Corrosion-product scales. Corrosion products may form a coherent scale on the substrate metal. In the case of plain carbon and low-alloy steels in geothermal fluids, the primary corrosion products are iron oxides, hydrous iron oxides, iron silicate and iron sulfides. The very low solubility of these in the fluid results in solid corrosion products. These oxides, silicates and sulfides tend to form and grow on the substrate metal. Other corrosion products, such as metal chlorides that form in pits and crevices, are more likely to leave the reaction site. Copper and copper-base alloys, including combinations of copper and nickel, tend to react with the sulfides in the geothermal fluids to form copper sulfides, nickel sulfides and copper-nickel sulfides. These sulfides tend to form on the metal. Zinc and aluminum in brasses form relatively soluble corrosion products and are not, typically, found in association with the sulfides.

Corrosion-product scales usually exhibit lower heat-transfer properties than the metals from which they are formed. These scales also are rougher than the substrate metal. Both of these factors result in lower efficiencies that require, for example, larger heat exchangers and pumps. However, these scales do form a barrier between the fluid and the metal and may provide some general corrosion protection to the metal. In some cases, the corrosion-product scales contain cracks and/or small holes that permit localized corrosion in the form of crevice corrosion and pitting. The corrosion scales cannot be relied on for corrosion protection.

Control of corrosion-product scales is best achieved through materials selection because of the limited economic and environmental applicability of corrosion inhibitors. Care must be exercised in materials selection because some metals depend on a stable corrosion-product film for general corrosion resistance. Aluminum is one such material. The stable aluminum oxide protects the relatively reactive aluminum metal from the aggressive water. Geothermal fluids are reducing and this may retard repair of damaged film sites on the aluminum, resulting in rapid localized corrosion of the metal. Reduceable metal ions, such as copper and mercury, may also cause rapid corrosion of aluminum. Desalination environments, on the other hand, are oxidizing, and aluminum finds application in this type of service.

Many consider seawater experience to be directly transferrable to geothermal situations. However, seawater is usually free of sulfides and, in near surface sources, nearly saturated with air. Copper/nickel alloys are used extensively in seawater applications and are frequently the materials of choice. The hydrogen sulfide present in geothermal fluids, however, rapidly degrades copper and copper alloys containing nickel. These two examples suggest that care must be exercised when using data from either seawater or desalination service for materials selection for geothermal environments. Subtle differences in geothermal-fluid chemistry frequently result in the use of a heat exchanger and a "clean" secondary fluid for many heating applications.

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Appendix A

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/Yr)
Group 10				
1. Copper Concentrate - 1021				
Drying	250*	(121)	1.7	(1.8)
Group 12				
2. Bituminous Coal - 1211				
Drying (including lignite)	150-250*	(66-104)	18.0	(19.0)
Group 14				
3. Potash - 1474				
Drying Filter Cake	250*	(121)	1.03	(1.09)
Group 20 - Food & Kindred Products				
4. Meat Packing - 2011 Sausages and Prepared Meats - 2013				
Scalding, Carcass Wash and Cleanup	140	(60)	43.7	(46.1)
Edible Rendering	200	(93)	0.52	(0.55)
Smoking/Cooking	155	(68)	1.16	(1.22)
5. Poultry Dressing - 2016				
Scalding	140	(60)	3.16	(3.33)
6. Natural Cheese - 2022				
Pasteurization	170	(77)	1.28	(1.35)
Starter Vat	135	(57)	0.02	(0.02)
Make Vat	105	(41)	0.47	(0.50)
Finish Vat	100	(38)	0.02	(0.02)
Whey Condensing	160-200	(71-93)	10.2	(10.8)
Process Cheese Blending	165	(74)	0.07	(0.07)
7. Condensed and Evaporated Milk - 2023				
Stabilization	200-212	(93-100)	2.93	(3.09)
Evaporation	160	(71)	5.20	(5.48)
Sterilization	250	(121)	0.54	(0.57)
8. Fluid Milk - 2026				
Pasteurization	162-170	(72-77)	1.44	(1.52)

Appendix A (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
9. Canned Specialties - 2032				
Beans				
Precook (Blanch)	180-212	(82-100)	0.40	(0.42)
Simmer Blend	170-212	(77-100)	0.24	(0.25)
Sauce Heating	190	(88)	0.20	(0.21)
Processing	250	(121)	0.38	(0.40)
10. Canned Fruits and Vegetables - 2033				
Blanching/Peeling	180-212	(82-100)	1.88	(1.98)
Pasteurization	200	(93)	0.15	(0.16)
Brine Syrup Heating	200	(93)	1.02	(1.08)
Commercial Sterilization	212-250	(100-121)	1.67	(1.76)
Sauce Concentration	212	(100)	0.44	(0.46)
11. Dehydrated Fruits and Vegetables - 2034				
Fruit & Vegetable Drying	165-185	(74-85)	5.84	(6.16)
Potatoes				
Peeling	212	(100)	0.33	(0.35)
Precook	160	(71)	0.47	(0.50)
Cook	212	(100)	0.47	(0.50)
12. Frozen Fruits and Vegetables - 2037				
Citrus Juice Concentration	190	(88)	1.33	(1.40)
Juice Pasteurization	200	(93)	0.27	(0.28)
Blanching	180-212	(82-100)	2.26	(2.38)
Cooking	170-212	(77-100)	1.41	(1.49)
13. Wet Corn Milling - 2046				
Starch Dryer	120*	(49)	3.03	(3.20)
Steepwater Heater	120	(49)	0.77	(0.81)
Sugar Hydrolysis	270	(132)	1.89	(1.99)
Sugar Evaporator	250	(121)	2.74	(2.89)
Sugar Dryer	120*	(49)	0.16	(0.17)
14. Prepared Feeds - 2048				
Pellet Conditioning	180-190	(82-88)	2.28	(2.40)
15. Bread and Baked Goods - 2051				
Proofing	100	(38)	0.84	(0.89)

Appendix A (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
16. Cane Sugar - 2062				
Mingler	125-165	(52-74)	0.59	(0.62)
Melter	185-195	(85-91)	3.30	(3.48)
Defecation	160-185	(71-85)	0.44	(0.46)
Granulator	110-130	(43-54)	0.44	(0.46)
Evaporator	265	(129)	26.39	(27.84)
17. Beet Sugar - 2063				
Extraction	140-185	(60-85)	4.63	(4.88)
Thin Juice Heating	185	(85)	3.08	(3.25)
Thin Syrup Heating	212	(100)	6.68	(7.05)
Evaporation	270-280*	(132-138)	30.8	(32.5)
Granulator	150-200	(66-93)	0.15	(0.16)
Pulp Dryer	230-280*	(110-138)	16.5	(17.4)
18. Soybean Oil Mills - 2075				
Bean Drying	160	(71)	4.05	(4.27)
Toaster Desolventizer	215	(102)	6.08	(6.41)
Meal Dryer	300*	(149)	4.36	(4.60)
Evaporator	225	(107)	1.62	(1.71)
Stripper	212	(100)	0.30	(0.32)
19. Shortening & Cooking Oil - 2079				
Oil Heater	160-180	(71-82)	0.72	(0.76)
Wash Water	160-180	(71-82)	0.12	(0.13)
Dryer Preheat	200-270	(93-132)	0.60	(0.63)
Cooking Oil Reheat	200	(93)	0.32	(0.34)
Hydrogenation Preheat	300	(149)	0.37	(0.39)
20. Malt Beverages - 2082				
Cooker	212	(100)	1.53	(1.61)
Water Heater	180	(82)	0.53	(0.56)
Mash Tub	170	(77)	0.60	(0.63)
Grain Dryer	300*	(149)	9.18	(9.68)
Brew Kettle	212	(100)	3.98	(4.20)
21. Distilled Liquor - 2085				
Cooking (Whiskey)	212	(100)	3.16	(3.33)
Cooking (Spirits)	320	(160)	6.27	(6.61)
Evaporation	250-290*	(121-143)	2.32	(2.45)
Dryer (Grain)	300	(149)	1.94	(2.05)
Distillation	230-250	(110-121)	7.69	(8.11)

Appendix A (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
22. Soft Drinks - 2086				
Bulk Container Washing	170	(77)	0.21	(0.22)
Returnable Bottle Washing	170	(77)	1.27	(1.34)
Nonreturnable Bottle Warming	75-85	(24-29)	0.43	(0.45)
Can Warming	75-85	(24-29)	0.52	(0.55)
Group 21 - Tobacco				
23. Cigarettes - 2111				
Drying	220*	(104)	0.43	(0.45)
Rehumidification	220*	(104)	0.43	(0.45)
24. Tobacco Stemming & Redrying - 2141				
Drying	220*	(104)	0.50	(0.26)
Group 22 - Textile Mill Products				
25. Finishing Plants, Cotton - 2261				
Washing	200	(100)	15.4	(16.2)
Dyeing	200	(100)	4.5	(4.7)
Drying	275	(135)	22.2	(23.4)
26. Finishing Plants, Synthetic - 2262				
Washing	200	(93)	35.9	(37.9)
Dyeing	212	(100)	15.2	
Drying & Heat Setting	<275	(135)	23.2	(24.5)
Group 24 - Lumber				
27. Sawmills & Planing Mills - 2421				
Kiln Drying of Lumber	200*	(100)	63.4	(66.9)
28. Plywood - 2435				
Plywood Drying	250	(121)	50.6	(53.4)
29. Veneer - 2436				
Veneer Drying	212	(100)	57.8	(61.0)

Appendix A (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
Group 25 - Furniture				
30. Wooden Furniture - 2511				
Makeup Air & Ventilation	70	(21)	5.7	(6.0)
Kiln Dryer & Drying Oven	150	(66)	3.8	(4.0)
31. Upholstered Furniture - 2512				
Makeup Air & Ventilation	70	(21)	1.4	(1.5)
Kiln Dryer & Drying Oven	150	(66)	0.9	(0.9)
Group 26 - Paper				
32. Pulp Mills - 2611 Paper Mills - 2621 Paperboard Mills - 2631 Building Paper - 2661				
Pulp Refining	150	(66)	175	(185)
Black Liquor Treatment	280	(138)	164	(173)
Pulp & Paper Drying	290	(143)	383	(404)
Group 28 - Chemical				
33. Cyclic Intermediates - 2865				
Styrene	250-300	(121-149)	35.0	(37.0)
Phenol	250	(121)	0.45	(0.47)
34. Alumina - 28195				
Digesting, Drying, Heating	280	(138)	113.2	(119.4)
35. Plastic Materials & Resins - 2821				
Polystyrene, suspension process				
Polymerizer Preheat	200-215	(93-102)	0.102	(0.107)
Heating Wash Water	190-200	(88-93)	0.067	(0.068)
36. Synthetic Rubber - 2822				
Cold SBR Latex Crumb				
Bulk Storage	80-100	(27-38)	0.179	(0.189)
Emulsification	80-100	(27-38)	0.086	(0.091)
Blowdown Vessels	130-145	(54-63)	0.865	(0.912)
Monomer Recovery by Flashing & Stripping	120-140	(49-60)	4.095	(4.319)

(continued on next page)

Appendix A (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
36. Synthetic Rubber - 2822 (continued)				
Dryer Air Temperature	150-200	(66-93)	3.663	(3.864)
Cold SBR, Oil-Carbon Black Masterbatch				
Dryer Air Temperature	150-200	(66-93)	0.506	(0.534)
Oil Emulsion Holding Tank	80-100	(27-38)	0.090	(0.095)
Cold SBR, Oil Masterbatch				
Dryer Air Temperature	150-200	(66-93)	1.09	(1.15)
Oil Emulsion Holding Tank	80-100	(27-38)	0.090	(0.095)
37. Cellulosic Man-made Fibers - 2823				
Acrylic	<250	(<121)	23.5	(24.8)
38. Noncellulosic Fibers - 2824				
Rayon	<212	(<100)	37.8	(39.9)
Acetate	<212	(<100)	37.6	(39.7)
39. Pharmaceutical Preparations - 2834				
Autoclaving & Cleanup	250	(121)	18.85	(19.88)
Tablet & Dry-Capsule Drying	250	(121)	1.00	(1.05)
Wet Capsule Formation	150	(66)	0.05	(0.05)
40. Soaps & Detergents - 2841				
Soaps				
Various Processes in Soap Manufacture	180	(82)	0.50	(0.53)
Detergents				
Various Low-Temperature Processes	180	(82)	0.36	(0.38)
41. Organic Chemicals, N.E.C. - 2869				
Ethanol	200-250	(93-121)	6.0	(6.0)
Isopropanol	200-300	(93-149)	11.0	(12.0)
Cumene	250	(121)	1.0	(1.0)
Vinyl Chloride Monomer	250-300	(121-149)	9.0	(9.0)
42. Urea - 2873215				
Low-Pressure Steam-Heated Stripper	290	(143)	0.89	(0.94)

Appendix A (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement °F	(°C)	Process Heat Used for Application 10^{12}BTU/Yr	(10^{12} KJ/YR)
43. Explosives - 2892				
Dope (Inert Ingredients)				
Drying	300	(149)	0.006	(0.006)
Wax Melting	200	(93)	0.118	(0.12)
Nitric Acid Concentrator	250	(121)	0.070	(0.07)
Sulfuric Acid Concentrator	200	(93)	0.027	(0.02)
Nitric Acid Plant	200	(93)	0.223	(0.23)
Blasting Cap Manufacture	200	(93)	0.016	(0.01)
Group 29 - Petroleum				
44. Petroleum Regining - 2911				
Alkylation	45-300	(7-149)	59	(62)
Butadiene	250-300	(121-149)	60	(63)
45. Paving Mixtures - 2951				
Aggregate Drying	275-300*	(135-149)	88.1	(92.9)
Group 30 - Rubber				
46. Tires & Inner Tubes - 3011				
Vulcanization	250-300	(121-149)	6.18	(6.52)
Group 31 - Leather				
47. Leather Tanning & Finishing - 3111				
Bating	90	(32)	0.094	(0.099)
Chrome Tanning	85-130	(29-54)	0.060	(0.063)
Retan, Dyeing, Fat Liquor	120-140	(49-60)	0.15	(0.16)
Wash	120	(49)	0.034	(0.036)
Drying	110*	(43)	2.05	(2.16)
Finish Drying	110*	(43)	0.13	(0.14)
Group 32 - Stone, Clay, Glass & Concrete Products				
48. Hydraulic Cement - 3241				
Drying	275-300*	(135-149)	8.0	(8.0)
49. Concrete Block - 3271				
Low-Pressure Curing	165*	(74)	12.29	(12.96)

Appendix A (continued)

Industrial Process Heat Requirements at Temperatures 300°F (149°C) and Below

Industry - SIC Group	Application Temperature Requirement		Process Heat Used for Application 10^{12}BTU/Yr (10^{12} KJ/YR)	
	°F	(°C)		
50. Ready-Mix Concrete - 3273				
Hot Water for Mixing Concrete	120-190	(49-88)	0.34	(0.36)
51. Gypsum - 3275				
Wallboard Drying	300	(149)	11.18	(11.79)
52. Treated Minerals - 3295				
Kaolin				
Drying	230*	(110)	12.7	(13.4)
Expanded Perlite				
Drying	160*	(71)	0.22	(0.23)
Barium				
Drying	230*	(110)	0.34	(0.36)
Group 33 - Primary Metals				
53. Ferrous Castings				
Gray Iron Foundries - 3321				
Malleable Iron Foundries - 3322				
Steel Foundries - 3323				
Pickling	100-212	(38-100)	151	(160)
Group 34 - Fabricated Metal Products				
54. Galvanizing - 3479				
Cleaning, Pickling	130-190	(54-88)	0.011	(0.012)
Group 36 - Electrical Machinery				
55. Motor & Generators - 3621				
Drying & Preheat	150	(66)	0.043	(0.045)
Baking	300	(149)	0.133	(0.140)
Group 37 - Transportation Equipment				
56. Motor Vehicles - 3711				
Baking-Prime & Paint Ovens	250-300	(121-149)	0.29	(0.31)

Note: SIC Groups 34, 35, 36, 37 utilize hot water for parts degreasing and washing in application temperatures of 80-180°F (27-82°C); total process heat used is not currently available.

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