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DIRECT USE OF GEOTHERMAL ENERGY

John W. Lund

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FOREWORD

The UNU Geothermal Training Programme provides specialized training for geothermal engineers and scientists from the developing countries. This specialized training is carried out within a framework of eight lines of study: geological exploration, geophysical exploration, borehole geology, borehole geophysics, drilling engineering, reservoir engineering, fluid chemistry and geothermal utilization. The students specialize in one of the above subjects. In some years there are several students specializing in the same line of study. When this happens, a Special Lecture Course is arranged. In 1984 and 1986, a Special Lecture Course was held in Reservoir Engineering with logging and production engineering materials also being presented.

Several students specialized in geothermal utilization during the 1987 session of the UNU Geothermal Training Programme. For that reason, a four weeks Direct Uses Special Course was arranged. The main topics and lecturers were as follows: "Thermal and Transport Processes," Dr. Oddur B. Björnsson, Fjarhitun Consulting Engineers, Ltd.; "District Heating," Prof. Thorbjörn Karlsson, University of Iceland; "Agriculture, Aquaculture and Processing," Dr. John W. Lund, Oregon Institute of Technology; "Drying Processes," Mr. Sigurjón Arason, Mr. Gudmundur Thoroddsson and Mr. Hannes Árnason, Fishing Research Institute.

An important function of the United Nations University and its associated institutions, is the dissemination of knowledge to developing countries. Therefore, the UNU Geothermal Training Programme has always put an emphasis on publishing the technical reports of its students, the written-up lectures of the annually invited lecturer, and special reports of relevance to the teachning of geothermal engineering and sciences. These reports have been distributed to individuals, geothermal companies and institutions world-wide, and are available from the UNU Geothermal Training Programme upon request. The present report was written by Dr. John W. Lund in connection with his participation in the Direct Uses Special Course in 1987. The report is divided into five chapters or sections, representing the material which covered each of the five days he lectured. Dr. John W. Lund and his colleagues at the Geo-Heat Center at the Oregon Institute of Technology, Klamath Falls, Oregon, the United States, are well known for their work on direct uses of geothermal energy. The UNU Geothermal Training Programme thanks Dr. Lund for preparing the written-up lectures published in this report.

Dr. Jón-Steinar Gudmundsson
Director
UNU Geothermal Training Programme

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EXPERIENCE IN THE UNITED STATES

1. INTRODUCTION

Direct heat utilization of geothermal energy in the USA occurs mainly in the western states, a region of recent tectonics and young volcanics. However, limited geothermal resources exist in the central and eastern United States. A radiogenic form is found along the east coast in high thermal conductivity crystalline rock with percentages of uranium and thorium sufficient to increase the crustal heat flow and thermal gradients. Geothermal resources in the Gulf Coast area consist of deeply buried high-temperature geopressured zones. In the central states, geothermal resources are low-temperature waters heated by deep circulation in sedimentary basins. Linear belts of warm springs occur in the Appalachian Mountains and south-central states near buried thrust faults formed by the collision of the Euro-Asian and North American crustal plates in Late Paleozoic time (Muffler, 1979).

Around the turn of the century in the United States, geothermal water was used primarily for bathing and in therapy (balneology). At the same time, small district heating projects began in Boise and Ketchum, Idaho. Around 1920, when inexpensive natural gas was available to heat baths and pools, geothermal use, as well as geothermal district heating, declined (Reed, 1983).

The 1973 oil crisis and high fuel prices revived interest in geothermal energy in the United States. Governmental incentives accelerated the growth of direct utilization of geothermal energy as illustrated by the rapid rise in the project curve in Figure I (Kenkeremath, et al., 1985, and

Lienau, 1986). These incentives were mainly provided by the U.S. Department of Energy (DOE) as financial and technical assistance programs. In 1978, engineering and economic feasibility studies for direct use applications were funded under the Geothermal Program Research and Development Announcement (PRDA). Also, the Program Opportunity Notice (PON) cost-shared 23 demonstration direct use projects with municipalities, private companies, and other organizations. These projects, all located in the West, included five district heating systems, five institutional heating systems (schools, hospitals and a prison), two agri-business projects, and one industrial project. All but six of these projects still operate (Lunis, 1986). Another program, the State-Coupled Low-Temperature Geothermal Resource Assessment, evaluated low- and moderate-temperature reservoirs of 16 states. The DOE has also issued loan guarantees to three direct use projects under the Geothermal Loan Guaranty Program.

The Federal Government and a number of states provided research centers and academic institutions with funding for engineering, geologic and economic technical assistance, as well as information dissemination for direct use projects, e.g., EG&G Idaho, Inc., John Hopkins University and Oregon Institute of Technology. The University of Utah Research Institute and University of California, Lawrence Berkeley Laboratory, provided resource information and reservoir engineering assistance. For example, from 1984-86, the Geo-Heat Center at Oregon Institute of Technology answered

88 direct use requests in 10 states, over 70 of which have resulted in projects that either have been completed or are in some stage of development (Lienau and Culver, 1987).

During the late 1970's tax credits from the Federal Government and several western states were additional incentives. These tax credits applied to residential and business use and conversion to geothermal energy for space and domestic water heating.

Today, 14 states have significant direct use projects. Projects in the United States are shown in Figure II. A total of 216 are operational, with 6 under construction and 21 planned. The operational projects account for over 2100 TJ/yr (233 MWt-peak). If the under-construction and planned projects are included, the projected energy use will double (Kenkeremath, et al., 1985, and Lienau and Culver, 1987). These figures are based on the energy consumed (beneficial heat) using the actual discharge temperature. Not included are an estimated 10,000 TJ/yr (400 MWt-peak) for enhanced oil recovery in the Williston Basin of Montana, North Dakota and Wyoming (Reed, 1983).

2. SUMMARY OF USE IN THE VARIOUS STATES

Table 1 shows the distribution of the annual energy use by state and that the greatest energy consumption is for space heating, 27.5% of the total. Space and district heating account for almost half (45.8%) of the annual use. The percentages of each use in Table 1 appear in Figure III.

TABLE 1

Estimated Geothermal Direct Heat Use in the United States

State	S	D	G	F	I	P	TOTAL
	Use in TJ/yr						
Alaska	4.2	0	1.0	0	0	4.2	9.4
Arkansas	7.4	0	0	0	0	7.4	14.8
California	81.5	42.9	57.3	102.9	31.0	5.3	320.9
Colorado	25.7	58.2	0	0	0	25.0	108.9
Hawaii	0	0	0	0	0.5	0	0.5
Idaho	29.3	167.4	153.9	310.4	3.6	10.5	675.1
Montana	57.0	0	25.3	0	0	7.4	89.7
Nevada	58.6	57.9	0	13.8	90.8	18.7	239.8
New Mexico	15.5	1.4	84.7	0	0	15.3	116.9
New York	5.3	0	0	0	0	0	5.3
Oregon	229.3	48.1	16.4	1.0	17.2	15.4	327.4
S. Dakota	8.8	10.2	9.8	0	0	15.8	44.6
Texas	10.5	0	0	5.3	0	0	15.8
Utah	19.3	0	71.2	0	0	3.2	93.7
Washington	16.8	5.3	0	0	0	2.1	24.2
Wyoming	12.0	0	12.0	9.9	0	0.5	34.4
Others*	5.0	0	0	0	0	10.0	15.0
TOTAL	586.2	391.4	431.6	443.3	143.1	140.8	2136.4
MWt(peak)	96	50	34	26	9	18	233
Ave.Load Fac.	19%	25%	40%	54%	50%	25%	29%

*This includes minor hot spring use in Georgia, Florida, North Carolina, Pennsylvania, Virginia, and West Virginia.

KEY: S = Space Heating and Domestic Hot Water
D = District Heating
G = Greenhouses
F = Fish Farming
P = Pools and Spas
I = Industrial Processing

The largest space heating application is in Klamath Falls, Oregon, where over 400 homes are heated with downhole heat exchangers; the largest district heating project is in downtown Boise, Idaho; the largest greenhouse operation is Burgett's Geothermal Greenhouses in Animas, New Mexico; the largest fish farming operation is Leo Ray's in Buhl, Idaho; the largest industrial processing operation is the vegetable dehydration plant at Brady Hot Springs, Nevada; and the largest pool and resort use is in Glenwood Springs, Colorado. Idaho is the state with the highest annual energy use, more than double the next largest states, Oregon and California. The greatest growth has occurred in California with strong support from the California Energy Commission Technical Assistance Program. The load factor on various projects ranges from 9% in southern California to 80% in the northern states, with 29% the average. The larger district heating projects carry an average load factor of 25%.

3. SPECIFIC PROJECTS

(a) Space and District Heating

Space, district, and domestic water heating are the most common geothermal energy uses in the United States. Even though the largest single district heating project is in Boise, Idaho, the largest concentrated heating use is in Klamath Falls, Oregon. The five highest concentrated uses are listed below:

Location	Annual Use in TJ (MWt)	Load Factor
Klamath Falls, Oregon	277.1 (35)	25.2%
Boise, Idaho	194.1 (23)	26.3%
Susanville/Litchfield, Calif.	92.3 (12)	25.2%
Pagosa Springs, Colorado	58.2 (7)	25.0%
Reno, Nevada	51.4 (6)	27.9%

Other district heating projects include San Bernardino and Ft. Bidwell, California; Elko, Nevada; Jemez Springs, New Mexico; Philip, South Dakota; and Ephrata, Washington.

Klamath Falls has used geothermal well water since the turn of the century. In about 1930, the first downhole heat exchanger (locally called a coil) was installed. Today, the heat exchanger coil consists of two strings of pipe, one for space heating and the other for domestic water heating, connected at the bottom by a reverse bend. Water is circulated through a closed system for heating and an open system for domestic hot water (Figure IV). Thus, the water resource is conserved; however, this heating system generally utilizes one well for one home, and is somewhat expensive. Wells are typically 30- to 200-m deep and encounter water from 70^{o} to 100^{o}C. Over 500 homes are heated in this way (Lund, 1982).

Construction of a district heating system for the downtown business area began in 1979. Two wells provide up to 45 Kg/s of 103^{o}C water through a 1240-m steel pipeline to a central plate heat exchanger building. A secondary fiberglass reinforced plastic closed loop circulates 93^{o}C water to eleven government buildings. A second closed loop provides space heating for a residential area. Presently, the system is being repaired because factory-sealed joints of the fiberglass secondary loop have failed. With the district heating project, a recovery and reuse system utilizing waste water from seven wells is being constructed.

A third development in Klamath Falls is on the campus of the Oregon Institute of Technology where geothermal water provides both space heating and cooling (Figure V). Eleven buildings of 52,000 m^2 are heated by 88°C water. A 264-kW lithium bromide chiller provides base load cooling in five buildings. The annual cost of the geothermal heating system is one-tenth that of conventional fuels (Gudmundsson and Lund, 1985).

The Boise, Idaho, Warm Springs Water District heating project is the oldest in the country, begun in 1892. Originally serving 450 homes, now it provides service for about 250 homes and 14,000 m^2 of state office space. This system yields up to 125 kg/s of 77°C water through a 3.3-km pipeline.

The Boise City system includes four production wells, 12 km of pipeline and a river disposal system. The system heats 20 buildings at 77°C and discharges the waste water into the Boise River at 49°C. The system's peak flow rate is 120 kg/s. The Capitol Mall Project at the edge of the Boise central business district heats seven state government buildings, supplying 72°C water to 70,000 m^2 of office space through a tunnel system. The spent fluid is disposed of in an injection well. The existing natural gas steam heating system for the Mall is a backup, which also supplies additional heat on extremely cold days. Ninety percent of the annual heating load is met by the geothermal system (Lunis, 1986).

Lienau (1984) discusses other district heating projects.

Snow melting on roadways and bridge decks has been successful in Oregon, Wyoming, Colorado, and West Virginia. Both heat pipes buried in the ground and the circulation of geothermal water have been tried. In all locations, the installation is restricted to critical areas, such as bridge decks and ramps at hazardous locations (Lund, 1976, and Lee, et al., 1984).

Heat pumps are used in shallow, low-temperature wells in Portland, Oregon; Salt Lake City, Utah; Columbus, Ohio; and other states for space heating and cooling. No data are available on energy use; however, several thousands are estimated to be operating.

(b) Greenhouses

Approximately 20 hectars of greenhouses are heated geothermally in the United States. The largest single greenhouse operation is at Animas, in southwestern New Mexico where 4.0 hectars are used for raising cut roses. The five leading greenhouse locations are:

Location	Annual Use in TJ (MWt)	Load Factor	Area (ha)	Product
Animas, New Mexico	75.8 (6)	40.0%	4.4	Cut roses & bedding plants
Buhl, Idaho	63.0 (5)	40.0%	2.3	Potted & bedding plants
Sandy, Utah	47.1 (4)	25.0%	1.9	Cut roses
Wendel/ Susanville, Calif.	43.4 (3)	43.2%	1.5	Vegetables
Helena, Montana	25.0 (2)	45.0%	0.8	Cut roses

Animas, with a resource of up to 118°C, is located at 1300-m elevation. Three separate greenhouse facilities grow bedding plants and cut roses. The largest operation, 4.0 hectars in Burgett's Geothermal Greenhouses, grows cut roses using a forced air system. This operation has also experimented with a binary power generator and is investigating the use of a 88-kW refrigeration unit to condition the roses before shipment. Approximately 5,000 roses per day are cut at this facility which supplies a 1300-km service area. The 0.2-hectar Beall operation also grows roses experimentally, while the McCants operations of 0.2 hectars grows bedding plants (personal communications with all three owners).

Three separate greenhouse facilities are located near Buhl on the Snake River in southern Idaho. M&L Greenhouses ships local nurseries and florists over 130 varieties of bedding and potted plants. Two wells supply 44°C water to 7000 m^2 of space heated by a forced air system. Flint Greenhouses raises potted blooming plants such as poinsettia, lilies, and chrysanthemums. This greenhouse complex also uses a forced air system to heat 7000 m^2 with 71°C water. Flint Greenhouses use 44°C water to heat 8600 m^2, with a forced air system, but the air is blown under the growing tables. Water also circulates through small pipes in the seedling tables. Potted blooming plants, including 29 varieties of chrysanthemums, are raised (Street, 1985).

Utah Roses, 16 km south of Salt Lake City at Sandy, also produces cut roses for a national floral market. The 1200-m geothermal well replaces a natural gas and oil heating system costing $169,000 annually.

At Wendel, California, near Susanville, over thirty 9- by 38-m Quonset-design greenhouses contain cucumbers and tomatoes. The vegetables are grown hydroponically, with the heat supplied by forced air heaters. Production rates are about 680 kg of cucumbers and 358 kg of tomatoes per unit per week. Each greenhouse is covered by two layers of six-mil plastic sheeting. A small electric air blower inflates the area between the two layers maintaining an air space of about 15 cm, and resulting in heat savings of approximately 40% over conventional coverings. The savings over conventional fuel averages $11,100 per hectar per year.

High Country Roses in Helena is Montana's only year-around rose grower. Forty to fifty thousand rose bushes live in slightly under one hectar of greenhouses with another 1.5 hectars planned. Ninety km of small diameter pipe supplies water from a 65°C spring. The operation hopes to capture 75%-80% of the rose market in Montana.

(c) Fish Farming

The largest fish farming operation is located at Buhl in southern Idaho along the Snake River. The five leading concentrations of fish farms are:

Location	Annual Use in TJ (MWt)	Load Factor	Product
Buhl, Idaho	310.2 (12)	80%	Catfish
Mecca, Calif.	75.0 (10)	25%	Prawns
Wabuska, Nevada	13.8 (2)	25%	Catfish/ tropicals
Ft. Bidwell, Calif.	12.1 (1)	80%	Catfish
Paso Robles, Calif.	11.8 (1)	50%	Catfish

Fish Breeders of Idaho, Inc., near Buhl, has been raising channel catfish in high-density concrete raceways for over ten years. The water comes from artesian geothermal wells flowing at 380 kg/s at 32^{o}C. Cold water from springs and streams cools the water to 28^{o}C, the best production temperature. Normal stocking densities are from 80-160 kg/m^{3} of space. The maximum recommended inventory for commercial production is about 1.6-2.4 x 10^{5} kg/m^{3}/s. Yearly production is usually three to four times the carrying capacity. Oxygen and ammonia are the principal factors limiting production (Ray, 1979).

A very successful catfish raising operation exists in the Indian community at Fort Bidwell in northeastern California. Construction of the raceways and well cost \$100,000. Geothermal well water at 40^{o}C is mixed with cold water to produce 27^{o}C water which is then piped into 7.6-m x 2.4-m x 1.2-m raceways. Two sets of parallel raceways use 57-63 kg/s. A 0.3-m drop between raceways aerates the water. Twenty-eight-gram fish at 3,000 per raceway are initially stocked, producing 2,000 fish at 0.9 kg each in five months. The fish are sold live at the source for $3.09 per kg and delivered live to San Francisco where they wholesale for $4.41 per kg and retail for $6.60-$8.80 per kg. Production at Fort Bidwell costs approximately $1.32 per kg (personal communication with William Johnson of Klamath Falls).

Giant freshwater prawns (Macrobrachium rosenbergii) have been raised at Oregon Institute of Technology. Some work has also been done in trout culture and mosquito fish (Gambuzia affinis). The data from this work has demonstrated that a tropical crustacean can be grown in a cold climate (as low as $-7^{o}C$) when the water temperature is maintained at the optimal growing temperature of 27^{o}-$30^{o}C$. Initially two smaller outdoor ponds 1.2 m deep were used and later two 0.2-hectar ponds were built. A selected brood stock was held in a small spawning building where larvae were hatched in artificial saltwater and reared to the post-larva stage. Growth rates of 2 cm per month have consistently occurred (twice that obtained in tropical climates) with a maximum density of 900 cm^2 of surface area per animal. The plumbing system consisted of perforated diffuser pipes, control valves, sand filter and thermostats to maintain an optimum temperature.

(d) Industrial Processing

The largest documented industrial use of geothermal energy is for vegetable dehydration at Brady, Nevada. An undocumented use from the Madison aquifer in northeastern Wyoming, Montana and North Dakota (Williston Basin) is estimated to be quite large based on a report by the USGS (Reed, 1983). Only four significant operations are known in the United States.

Location	Annual Use in TJ (MWt)	Load Factor	Product
Williston Basin	10,000 (400)*	80%	Oil recovery
Brady, Nevada	90.8 (6)	50%	Onions dehydration
San Bernardino, Calif.	31.0 (1)	80%	Sewage treatment
Vale, Oregon	17.3 (2)	25%	Mushrooms growing

*25,000 TJ are reported in Reed (1983); however, this figure is based on a 10°C reference temperature. Actual use based on the beneficial heat is estimated to be 40% of this figure.

Geothermal Food Processors, Inc., owned by Gilroy Foods, operates a vegetable dehydration plant at Brady Hot Springs, approximately 80 km east of Reno, Nevada. The geothermal energy replaces about 3.3 million m^3 of natural gas a year. The facility, housed in a 12- by 183-meter building near the former site of the Brady Hot Springs health resort, uses 132°C geothermal fluid to warm the air for curing and drying vegetables such as onions, celery, and carrots. The 4-meter wide bed processes 4500 kg of fresh onions per hour, resulting in 800 kg of dried product. Using the local geothermal resource has allowed the facility to produce a superior dehydrated product. Color is generally excellent largely because "hot spots" are eliminated since the lower water temperature cannot scorch the onions. In addition, bacteria-free fluids in the washing stages help keep the overall bacterial count lower than that of other manufacturers.

San Bernardino, California, uses a 54°C resource for space heating and sewage digestion. At present, 14 buildings are heated and two sewage digestors are operating. Plans are to add 35 buildings to the system.

A 113°C artesion well at Vale in eastern Oregon heats an indoor farm raising white button mushrooms. Oregon Trail Mushroom Company produces 24 kg of mushrooms per m^2 in 40 growing rooms, or 2.3 million kg of the mushrooms annually. A computer controls the carbon dioxide levels in the growing rooms and varies the temperature from 18°-60°C, depending on the stage of growth. The mushrooms mature in eight-week "batches," with the crop from five growing rooms harvested each week. Hot water from the geothermal well is pumped into a closed loop system of heat exchangers providing heating and cooling. The geothermal water makes the process cost-effective.

Other industrial applications in the United States were milk pasteurization in Klamath Falls, Oregon; several alcohol distillation plants in Oregon, Nevada, and Idaho;

and ore processing in Montana and New Mexico. None of these is presently operating.

3. FUTURE DEVELOPMENTS

At least 22 proposed projects could add 1620 TJ annually (177 MWt-peak) to the total reported in Table 1. Future growth is expected to be greatest in district heating, where eight proposed projects will produce 1360 TJ annually (172 MWt-peak); the largest will be the Reno, Nevada project designed for heating casinos and hotels in the downtown area. This system will route water from the Steamboat Springs area south of town. An expanded San Bernardino district heating project will become one of the largest in the country. Future growth of all direct heat uses in the U.S. is estimated at 8% annually (Lienau, 1986).

Proposed direct use projects in Hawaii, Wyoming, and Nevada are innovative and intriguing.

Hawaii's Community Geothermal Technology Program, initiated in 1986, has implemented five projects. Funding will come from the U. S. Department of Energy, the County of Hawaii, and private sector donors. The program encourages commercial use of geothermal energy by-products (heat and silica) in nonelectrical applications. The projects involve (1) mixing silica with other local compounds to produce a Hawaiian glass used by participating local hot-glass artists, (2) using low-pressure geothermal steam in cloth dyeing processes (mainly silk), (3) using geothermal heat for a kiln in drying the local koa wood, (4) using secondary fluid from a heat exchanger to heat the roots of potted oriental palms, and (5) using geothermal steam to dry papaya plants (Transitions, 1986).

At Casper, Wyoming, 5.3 hectars of greenhouses are under construction to raise penicillin culture, other pharmaceutical products, and flowers. Biogenises International, a European firm, plans to use the Madison aquifer producing fluids of 61°C to heat fan coil units and pipe emitters.

Six km south of Carson City, Nevada, 113 hectars may be developed for lobster production. Water at 49°C will provide a 21°C pond temperature. Water at 30% salinity will raise 360,000 lobsters annually. Prawn raising is also being considered.

Federal and state funding will be limited; thus financial support for future projects will depend upon local government and private companies. Technical assistance and information dissemination will be available from organizations such as the Geo-Heat Center (Klamath Falls, Oregon) and the Geothermal Resources Council (Davis, California). The outlook for future growth looks good in the United States.

4. ACKNOWLEDGEMENTS

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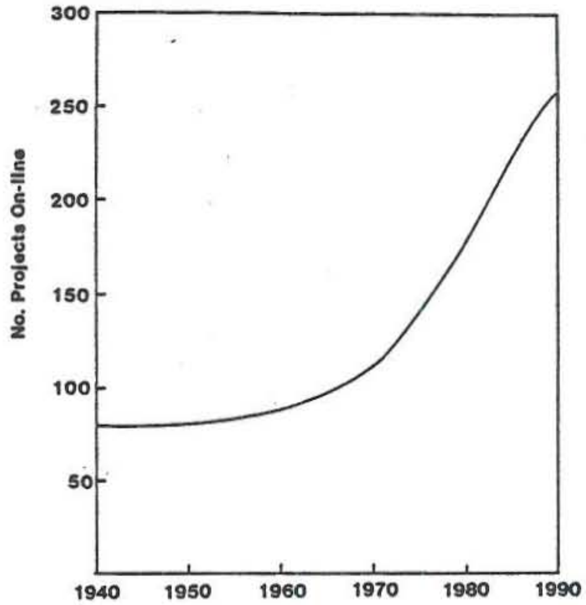

Figure I. Direct heat project activity in the United States.

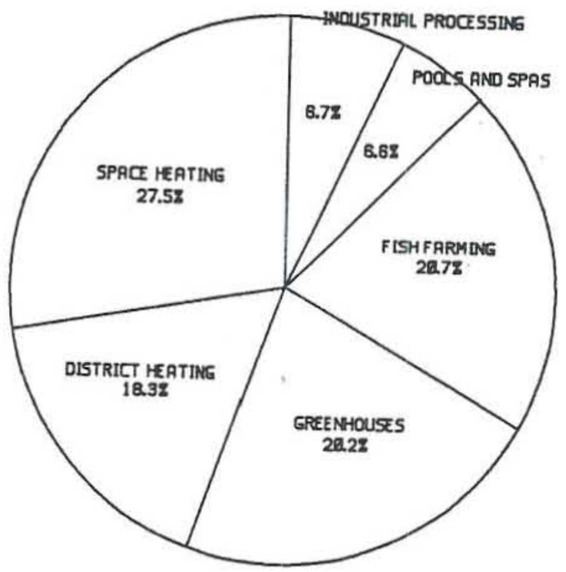

Figure III. Annual direct heat use in the United States (percentage). Total use = 2136 TJ.

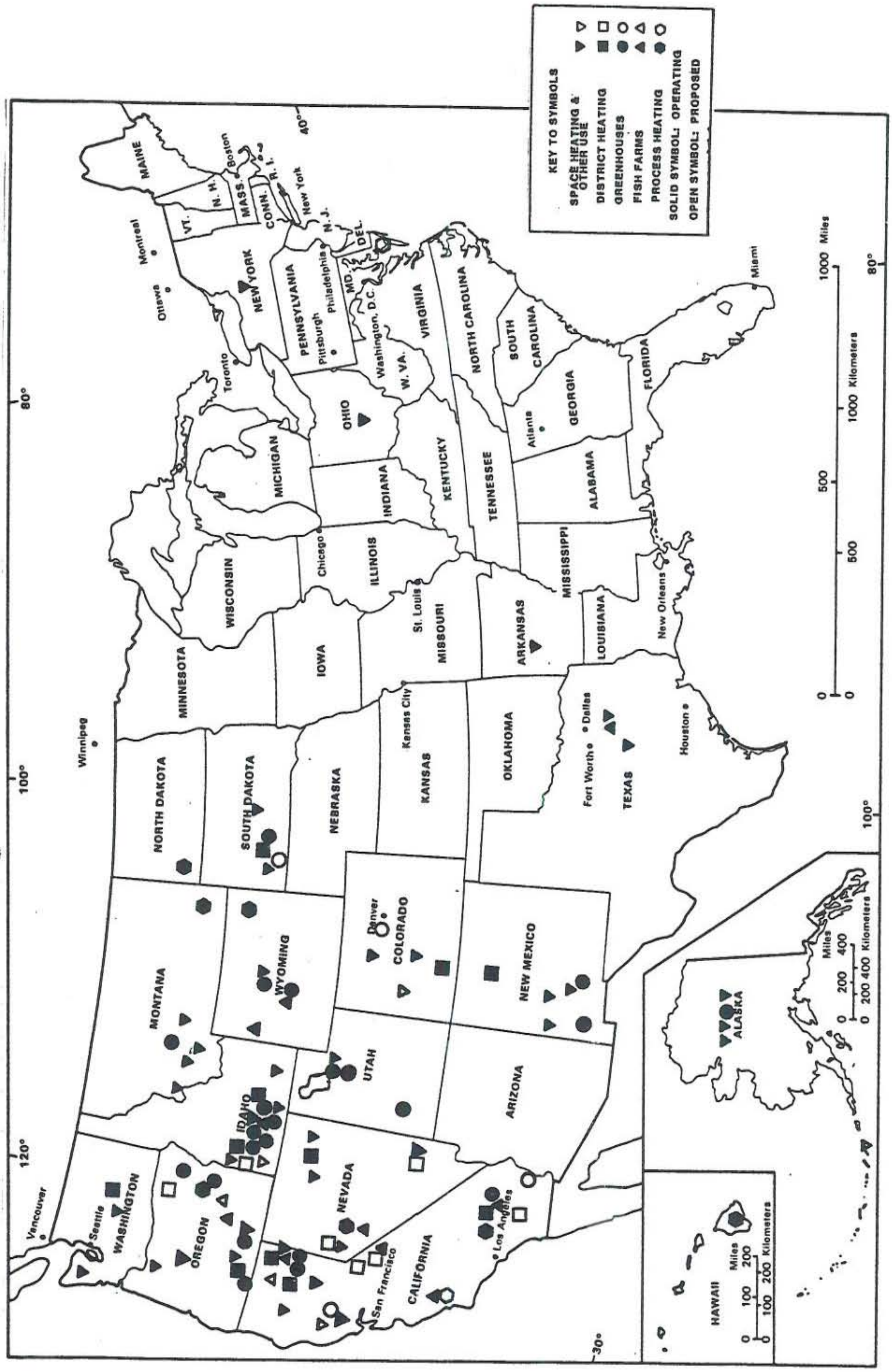

Figure II. Location of direct heat projects in the United States.

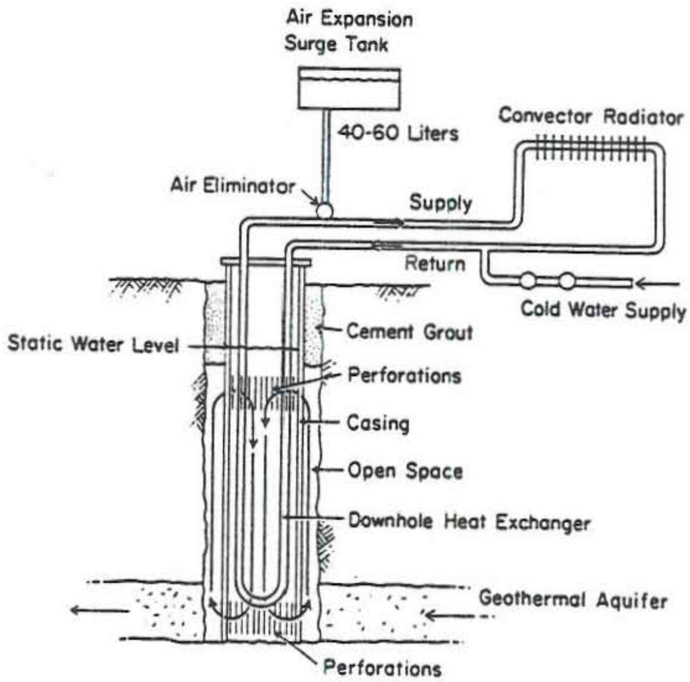

Figure IV. Downhole heat exchanger, Klamath Falls, Oregon.

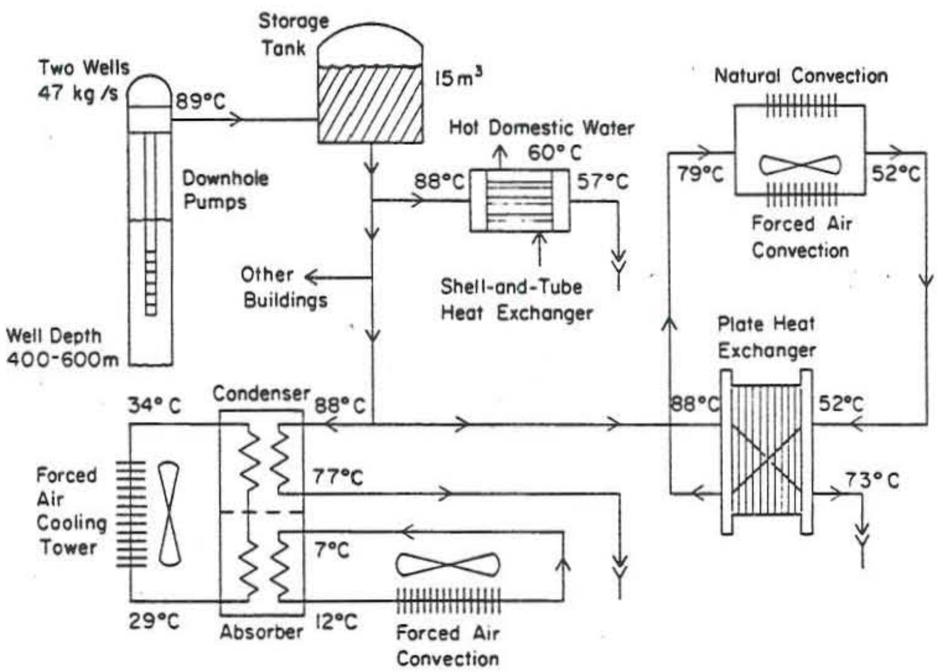

Figure V. Oregon Institute of Technology district heating and cooling.

DOWNHOLE HEAT EXCHANGER

1. INTRODUCTION (Lund, et al., 1975)

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).

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 I). 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.

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. Experience 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.

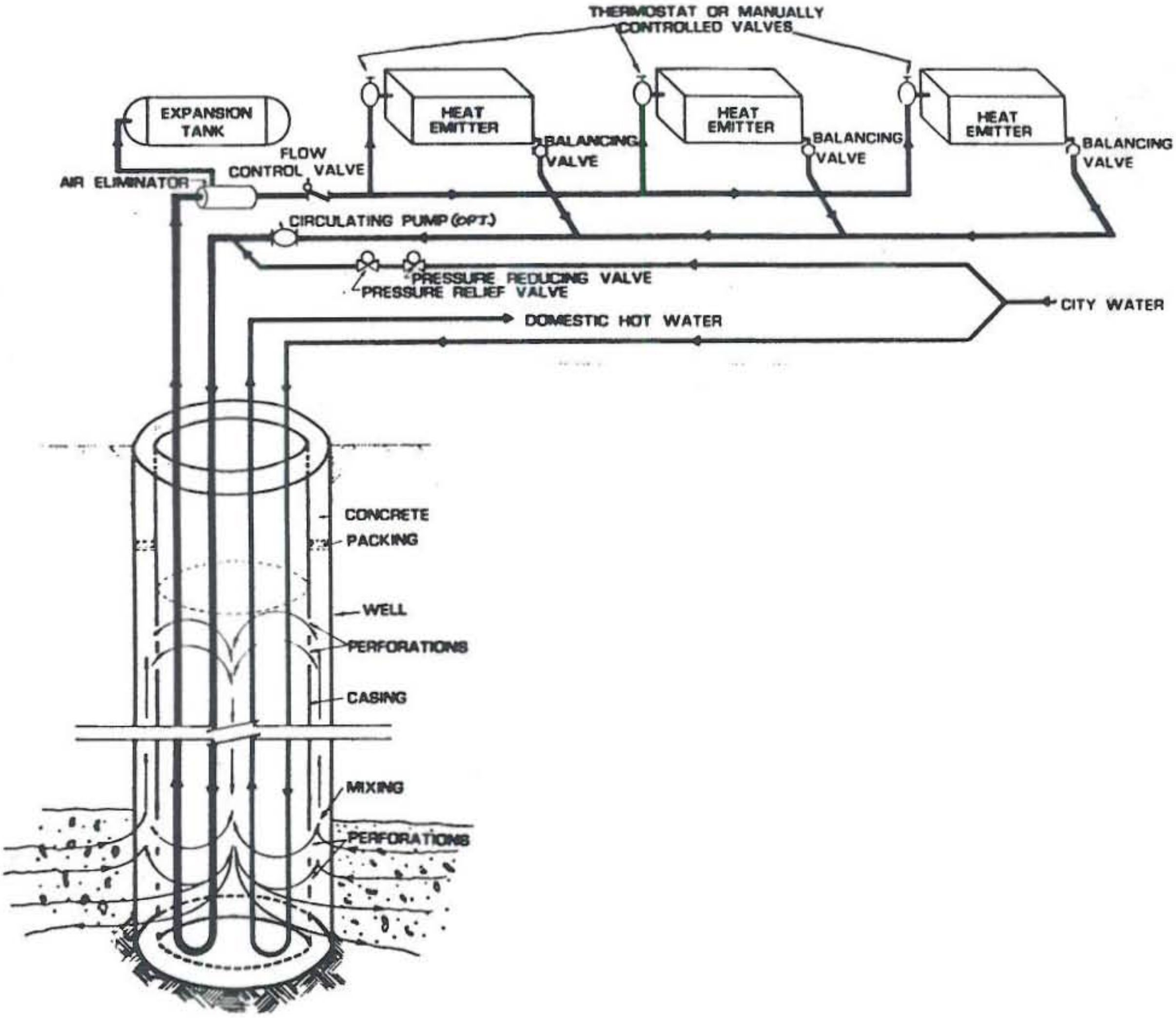

FIGURE I. Typical downhole heat exchanger system. (Klamath Falls, OR).

2. DESIGN AND CONSTRUCTION DETAILS (Culver, 1987)

DHE outputs range from supplying domestic hot water for a single family from a 40 foot, 140°F (12 m, 60°C) well at Jemenez Springs, New Mexico, to over 1 MWt at Ponderosa High School from a 560 foot, 202°F, 16 inch (170 m, 94°C, 40 cm) diameter well in Klamath Falls, Oregon. DHE's are also in use in New Zealand, Turkey, Hungary, Iceland, the USSR and others. A well producing 6 MWt has been reported in use in Turkey.

The wells in Klamath Falls are 10-or 12-inch (25- or 30-cm) diameter drilled 20 or more feet (6 m) into "live water" and an 8-inch (20-cm) casing is installed. A packer is placed around the casing below any cold water or unconsolidated rock, usually 20-50 feet (6-15 cm), and the well cemented from the packer to the surface. The casing is torch perforated (1/2 inch x 6 inch (1 x 15 cm)) in the live water area and just below the static water level. Perforated sections are usually 15-30 feet (4-9 m) long and the total cross sectional area of the perforations should be at least one and a half to two times the casing cross section. Since water levels fluctuate summer to winter the upper perforations should start below the lowest expected level. A 3/4 or 1 inch (2 or 2.5 cm) pipe is welded to the casing and extending from surface to below the packer permits sounding and temperature measurements in the annulus and is very useful in diagnosing well problems.

"Live water" is locally described as a hot water aquifer with sufficient flow and permeability to wash away the fines produced in a cable tool drilling operation or major lost circulation in rotary drilling.

The space heating DHE is usually 1 1/2 or 2 inch (4 or 5 cm) black iron pipe with a return U at the bottom. The domestic water DHE is 3/4 or 1 inch (2 or 2.5 cm) pipe. The return U usually has a 3-5 foot (1-2 m) section of pipe welded on the bottom to act as a trap for corrosion products

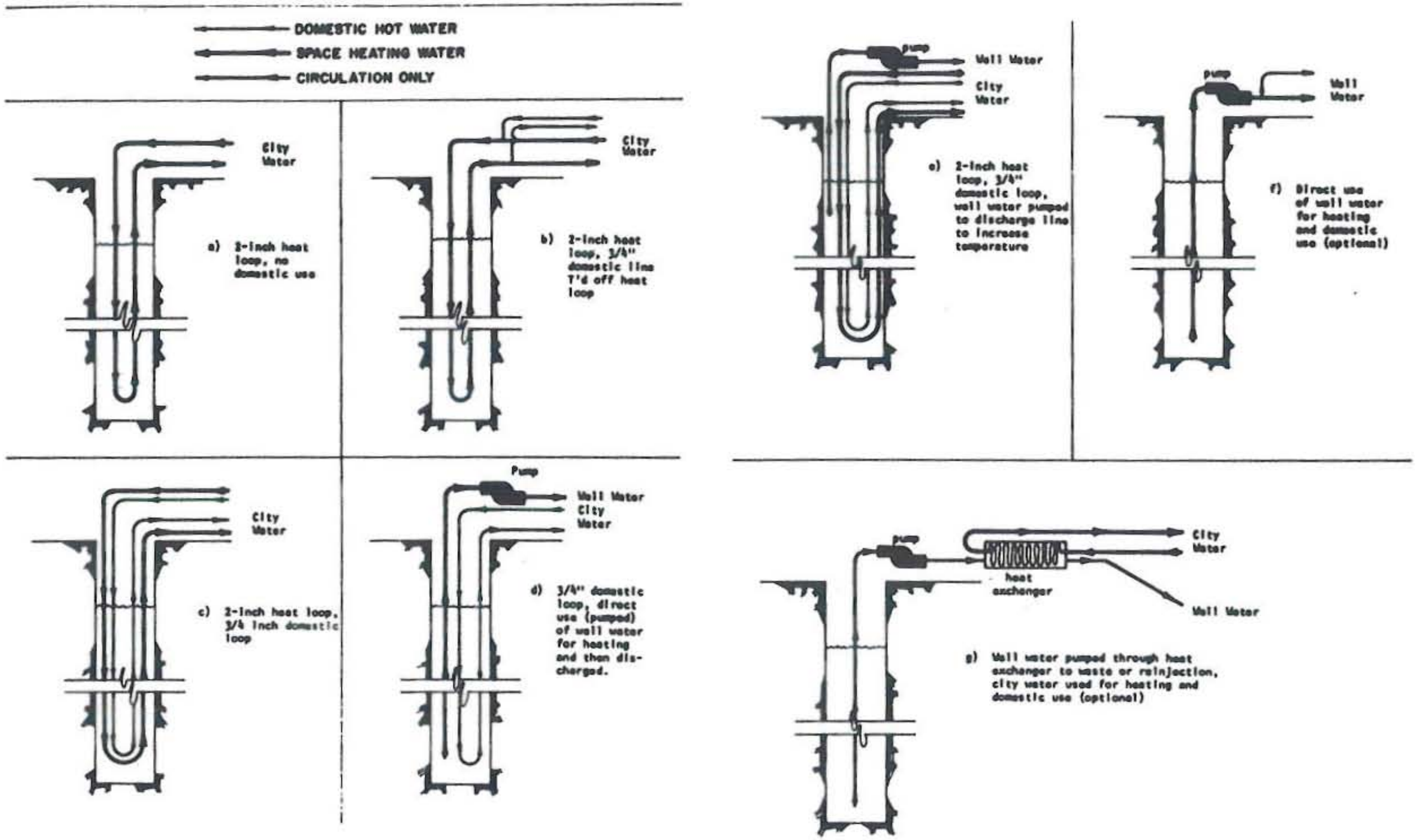

FIGURE II. Downhole heat exchanger systems (Klamath Falls).

that may fill the U preventing free circulation. Couplings should be malleable rather than cast to facilitate removal (Figure II).

Other DHE types in use are short multiple tubes with headers at each end and straight pipes extending to near the well bottom with coils of copper or steel pipe at the ends. In Reno, Nevada, many DHE wells are pumped by small submersible pumps to induce hot water to flow into the well. Systems for use with heat pumps circulate refrigerant in the DHE pipes. A 20-kWt, 16-foot (5-m) prototype heat pipe system was successfully tested at least several months in the Agnano geothermal field in southern Italy (Figures III and IV).

The first downhole heat exchanger, locally known as a coil, was installed in a geothermal well in Klamath Falls about 1930. The temperature of the well water and the predicted heat load determine the length of pipe required. Based on experience, local heating system contractors estimate approximately 1 ft of coil per 1500 Btu per hr (1.2×10^6 g cal/m) required as an average for the year. The "thermo-syphon" (or gravity feed in standard hot-water systems) process circulates the domestic water, picking up heat in the well and releasing the heat in the radiators. Circulation pumps are required in cooler wells or in larger systems to increase the flow rate. Thermo-syphon circulation will provide 3-5 psi (2000-3500 kg/m^2) pressure difference in the supply and return lines to circulate 15-25 gal/min (1-1.5 l/sec) with a 10^{o}-20^{o}F (5^{o}-11^{o}C) temperature change.

There are several older or cooler wells that are pumped directly into the storm sewers or canal. In most cases the well is pumped in order to increase the flow of geothermal waters and to raise the temperature of the well to a level locally considered satisfactory for use in space heating, about 140°F (60°C). In a few instances, mostly in the artesian area, well water is pumped directly through the heating system.

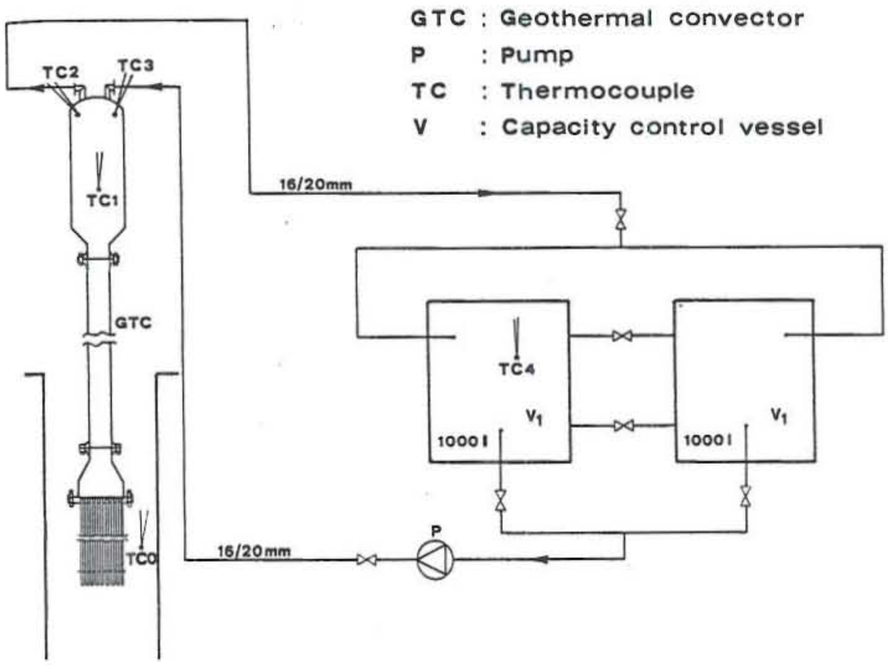

FIGURE III. Experimental loop in Agnano, Italy.

Considering life and replacement costs, materials should be selected to provide economical protection from corrosion. Attention must be given to the galvanic cell action between the ground water and well casing since the casing is an expensive replacement. Experience indicates that general corrosion is most severe at the air-water interface at the static water level and that stray electrical currents can cause extreme localized corrosion below the water. Insulated unions should be used at the wellhead to isolate the DHE from stray currents in the building and city water lines. Galvanized pipe is to be avoided since many geothermal waters leach zinc.

Considerable success has been realized with nonmetallic pipe, both fiberglass reinforced epoxy and polybutylene. Approximately 100,000 feet of fiberglass reportedly has been installed in Reno at bottom hole temperatures up to 325^{o}F (163^{o}C). The oldest installations have been in about 4-5 years--much too short a time to be evaluated. The only problem noted has been National Pipe Taper Threads (NPT) thread failure in some pipe that was attributed to poor quality resin. The manufacturer has warranted the pipe including labor costs.

Although the thermal conductivity for nonmetallic pipes is much lower, the overall heat transfer coefficient is a combination of the pipe thermal conductivity, film coefficients on both sides and coefficients of any scale or corrosion products on both sides. Since the nonmetallic pipe is smooth, does not corrode and scale does not stick to it, the overall heat transfer can be nearly as good.

Average DHE life is difficult to predict. For the 500 or so black iron DHE's installed in Klamath Falls average life has been estimated to be 14 years--however, in some instances, regular replacement in 3-5 years has been required. In other cases, installations have been in service over 30 years with no problems. Stray electrical currents, as noted above, have undoubtedly been a contributing factor in some early failures. Currents of several tens of milliamps have been measured. In others, examination of DHE's after removal, reveals long, deeply corroded lines along one side of a DHE. This may be due to continual thermal expansion and contraction while laying against the side of an unplumbed well. Constant movement would scrub off protective scale exposing clean surface for further corrosion.

Corrosion at the air-water interface is by far the most common cause of failure. Putting clean oil, preferably turbine oil (because of environmental acceptability) as is used in enclosed tube lineshaft pumps, or parafin in the well appears to help somewhat but is difficult to accurately evaluate.

For some reason, DHE wells are typically left open at the top. There appears to be no good reason they could not be sealed air tight. Once the initial charge of oxygen was used up in forming corrosion products, there would be no more available since there is essentially no dissolved oxygen in the water. Closed wells appear to extend the life of the DHE.

a. Convection Cells.

Although the interaction between the water in the well, water in the aquifer and the rock surrounding the well is poorly understood, it is known that the heat output can be significantly increased if a convection cell can be set up in the well. Also, there must be some degree of mixing, i.e., water from the aquifer continuously entering the well, mixing with the well water, and water leaving the well to the aquifer. There are two methods of inducing convection.

When a well is drilled in a competent formation and will stand open without casing, an undersized casing can be installed. If the casing is perforated just below the maximum static water level and near the bottom or at the hot aquifer level, a convection cell is induced and the well becomes very nearly isothermal between the perforations (Figures IV and V). Cold surface water and unstable formations near the surfaces are cemented off above a packer. If a DHE is then installed and heat extracted, a convection cell, flowing down inside the casing and up in the annulus between the well wall and casing, is induced. The driving force is the density difference between the water surrounding the DHE and water in the annulus. The more heat extracted, the higher the velocity. Velocities of 2 feet per second (0.6 m/s) have been measured with very high heat extraction rates, but the usual velocities are between 0.04 and 0.4 feet per second (0.01-0.1 m/s).

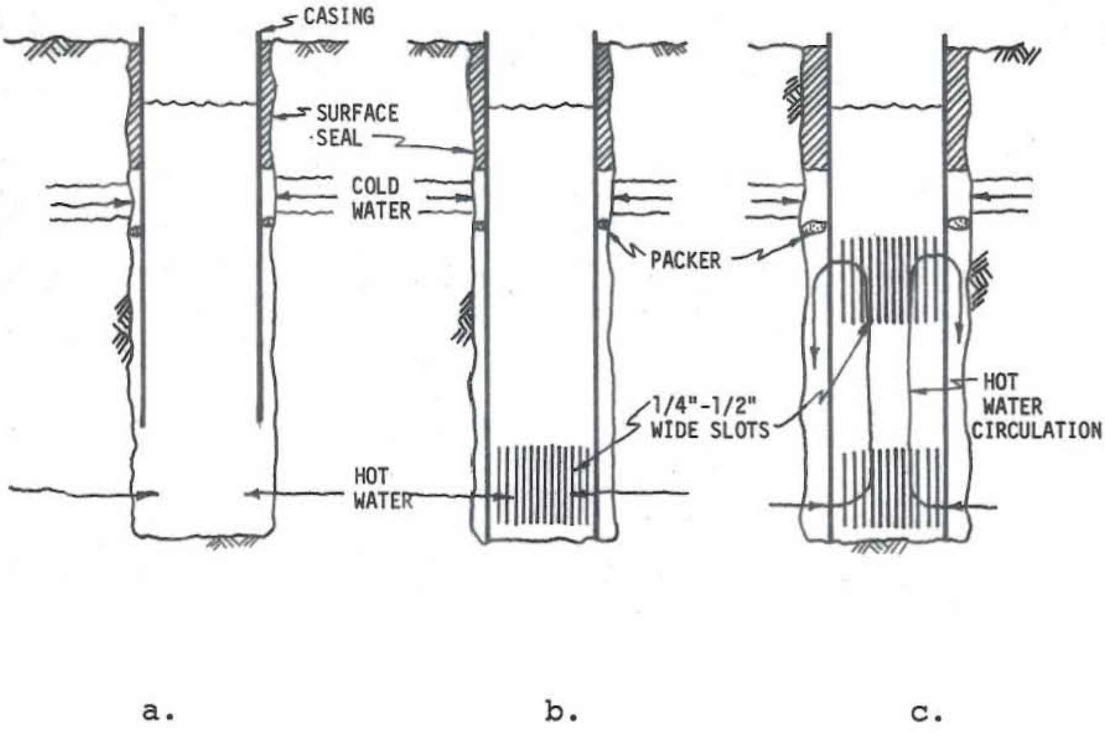

FIGURE IV. Well completion systems for downhole heat exchangers (type c preferred).

In Klamath Falls, it has been experimentally verified that when a well is drilled there is no flow in the well bore. When the undersized perforated casing is installed, a convection cell is set up flowing up the inside of the casing and down the annulus between casing and well wall. When a DHE is installed and heat is extracted, the convection cell reverses flowing down in the casing (around the DHE) and up the annulus. Similar circulation patterns were noted in New Zealand using convection promoters.

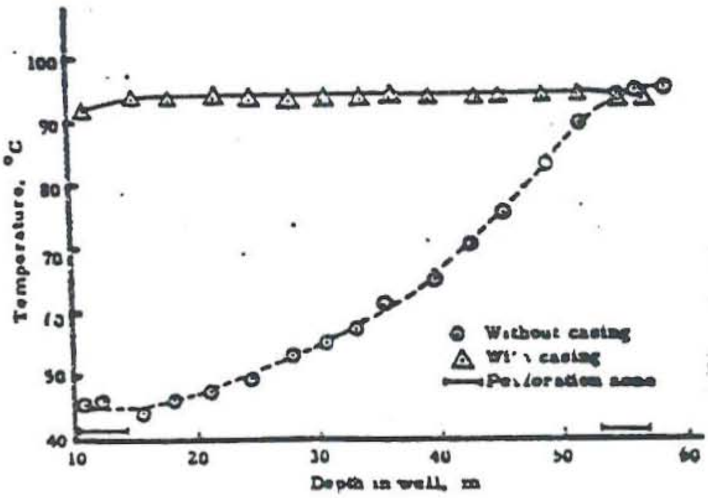

FIGURE V. Temperature vs. depth for a geothermal well (with and without perforations).

In New Zealand where wells do not stand open and several layers of cold water must be cased off, a system using a convection promoter pipe was developed (Figure VI). The convector pipe is simply a pipe open at both ends suspended in the well above the bottom and below the static water level. An alternate design sits on the bottom and has perforations at the bottom and below static water level. The DHE can be installed either in the convector or outside the convector, the latter being more economical since smaller convector pipe is used. Both lab and field tests indicate that the convection cell velocities are about the same in optimized designs and are similar to those measured in the undersized casing system.

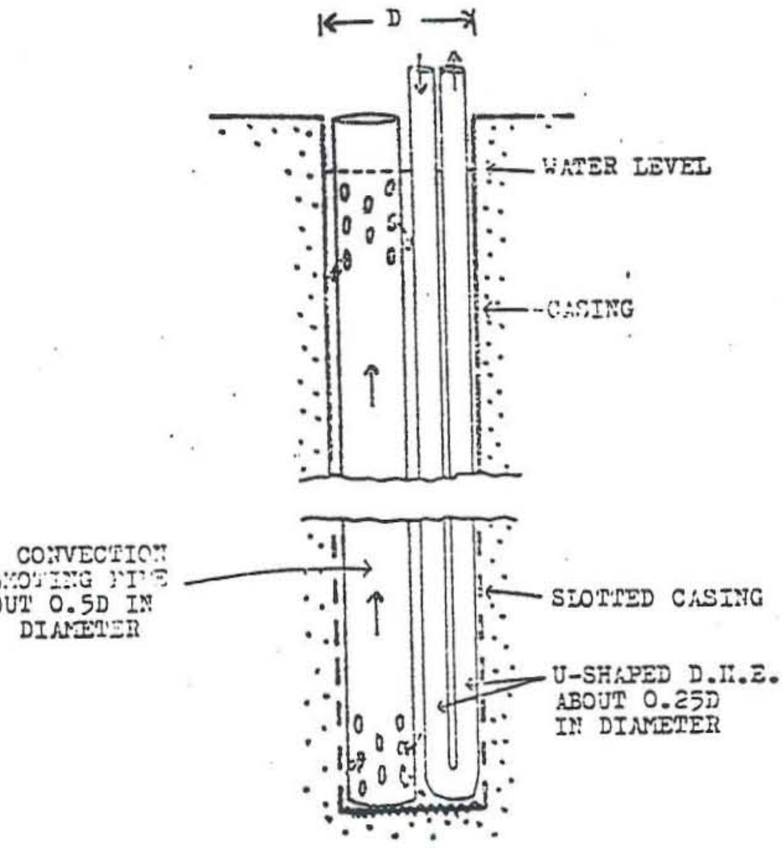

FIGURE VI. Convector promotion and DHE (New Zealand type).

Optimum conditions exist when frictional resistance due to wetted surfaces (hydraulic radius) is equal in both legs of the cell and DHE surface area providing maximum heat transfer. For the undersized casing and DHE inside the convector, this occurs when the casing or convector is 0.7 times the well diameter and 0.5 times the well diameter when the DHE is outside the convector. The full length U tube DHE is 0.25 times the well diameter in all cases. Partial length or multi-tube exchangers will have different ratios.

Maximum convection rates are obtained when the casing or convector pipe are insulated from each other. This maintains the temperature and density difference between the cell legs. Nonmetallic pipe is preferred. Although corrosion products help insulate the pipe, sealing does not normally occur to any great degree since the casing or convector are the same temperature as the water.

b. Design Considerations.

Downhole heat exchangers extract heat by two methods--extracting heat from water flowing through the aquifer and extracting stored heat from the rocks surrounding the well.

Once the DHE is extracting heat and a convection cell is established, a portion of the convecting water is new water entering the well--the same amount of cooled water leaves the well and enters the aquifer. The ratio of convecting water to new water has been termed the mixing ratio and is defined as:

$$Rm = 1 - \frac{m\ add}{m\ total}$$

where:

Rm = mixing ratio

m add = mass flow of new water

m total = total mass flow of convecting water

Note that a large number indicates a smaller proportion of new water in the convection cell.

Mixing ratios vary widely between wells in the same aquifer and apparently depend on aquifer permeability. Also, as more heat is extracted the mass flow rate in the convection cell increases but the mixing ratio appears to remain relatively constant up to some point, then increases with further DHE loading. This is interpreted as permeability allowing a "new" hot water to enter the well or, more probably, allowing "used" cool water to sink into the aquifer near the well bottom. At some combination of density difference and permeability the ability to conduct flow is exceeded and the well rapidly cools with increasing load.

The theoretical maximum steady state amount of heat that could be extracted from the aquifer would be when the mixing ratio equals zero. That is, when all the water makes a single pass through the convection cell and out the well bottom. Mixing ratios lower than 0.5 have never been measured and usually range from about 0.5-.94 indicating little mixing. The theoretical maximum steady state can be estimated if one knows the hydraulic conductivity and hydraulic gradient and assumes some temperature drop of the water.

If K is the hydraulic conductivity and $\Delta h/\Delta l$ is the hydraulic gradient, by Darcy's Law the specific velocity through the aquifer is given by:

$$v = K\ \Delta h/\Delta l$$

The mass flow through an area, A, perpendicular to the flow is therefore:

$$v\ A\ d = K\ A\ d\ \Delta h/\Delta l$$

where d is the density of water. The steady state heat flow can be found by:

$$Q = K\ A\ d\ c\ (T_0 - T_1)\ \Delta h/\Delta l$$

where:

- A = cross section of well in the aquifer or the perforated section
- d = density of water
- c = specific heat
- T_0 = aquifer temperature
- T_1 = temperature of water returning to the aquifer

Multiplying the above by Rm - 1, or about 0.5 to 0.06, one can determine the expected steady state DHE output.

The most important factor in the equation is K. This value can vary by many orders of magnitude--even in the same aquifer--depending on whether major fractures are intersected, drilling mud or debris partially clogs the aquifer, etc. The variation between aquifers can be even greater.

Based on short-term pump tests to determine hydraulic conductivity and an estimated 1% hydraulic gradient, the specific velocity in the Moana area of Reno is estimated at 1 to about 3 feet per year (0.3-1.0 m/yr). The hot aquifer is generally encountered in mixed or interbedded layer of fine sand and silt stone. In Klamath Falls, on the other hand, where the hot aquifer is in highly fractured basalt and coarse pumice, specific velocity is estimated at 20 to 150 feet per day

(6 to 46 m), perhaps higher in localized areas. Values of K in seven wells in Moana were estimated at 3 x 10^{-4} ft per second (1 x 10^{-7} meters per second). This implies a factor of 10 thousand to 10 million difference in the steady state output. Indeed differences by a factor of 100 have been measured, and some wells in Moana have been abandoned because they could not provide enough heat even for domestic hot water.

Many DHE wells in Moana are pumped to increase hot water flow into the well. Pumping rates for residential use is limited to 1800 gallons per day (6800 l/day) and the pump is thermostatically controlled. This is designed to switch on the pump if the DHE temperature drops below some predetermined level, usually about 120°F (49°C). This method permits use of a well that would not supply enough heat using a DHE alone, yet minimizes pumped fluid and pumping costs. It is, however, limited to temperatures at which an economical submersible or other pump can be used.

Unfortunately, at the present time, there is no good design procedure. Culver & Reistad (Culver 1978) presented a computer program that appears to predict DHE output to within 10%-15% if the mixing ratio is known. The problem is, there is no way of predicting mixing ratio except by experience in a specific aquifer and then probably only over a fairly wide range as noted above. The procedure was written in FORTRAN but has been converted to HP-85 BASIC by Pan (Pan 1983). The program enables optimum geometric parameters to be chosen to match a DHE to a load if one assumes a mixing ratio.

The program does not include a permeability variable nor does it take thermal storage into account. In wells with good permeability, thermal storage may not be a significant factor. Experience in Reno indicates that for low permeability wells, thermal storage is very important and that with low permeability a convection promoter can promote thermal storage and, thereby, increase non-steady state output.

Permeability can be rather accurately estimated using relatively simple Hvorslev plots used in well testing. Relating the permeability thus obtained to mixing ratios typical in other permeabilities could give an estimate of the mixing ratio one could use in the computer program. The problem is, there seems to be no middle ground data available, only very high and very low permeabilities, and precious little of that.

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GREENHOUSES

1. INTRODUCTION

A number of commercial crops can be raised in greenhouses, making geothermal resources in cold climates particularly attractive; however, growth can be optimized in warmer climates. These include vegetables, flowers (potted and cut), house plants, and tree seedlings. The optimum growth temperature of cucumbers, tomatoes, and lettuce is shown in Figure I on the following page (Barbier and Fanelli, 1977). Cucumbers grow best in the temperature range 77^{o}-86^{o}F (25^{o}-30^{o}C), tomatoes near 68^{o}F (20^{o}C), and lettuce at 59^{o}F (15^{o}C), and below. The growing time for cucumbers is usually 90 to 100 days, while the growing cycle for tomatoes is longer, in the range 9 to 12 months. The use of geothermal energy for heating can reduce operating costs (which can account for up to 35 percent of the product cost) and allows operation in colder climates where commercial greenhouses would not normally be economical. In addition, greenhouses can be suited to large quantities of relatively low-grade heat. Furthermore, better humidity control can be derived to prevent condensation (mildew), botritis, and other problems related to disease control (Schmitt, 1981).

2. EXAMPLES OF GEOTHERMALLY HEATED GREENHOUSES

There are numerous uses of geothermal energy for greenhouse heating throughout the world. In the USSR it is reported that over 6,200 acres (2,500 ha) of agricultural land are heated by geothermal of which 25 acres (10 ha) are

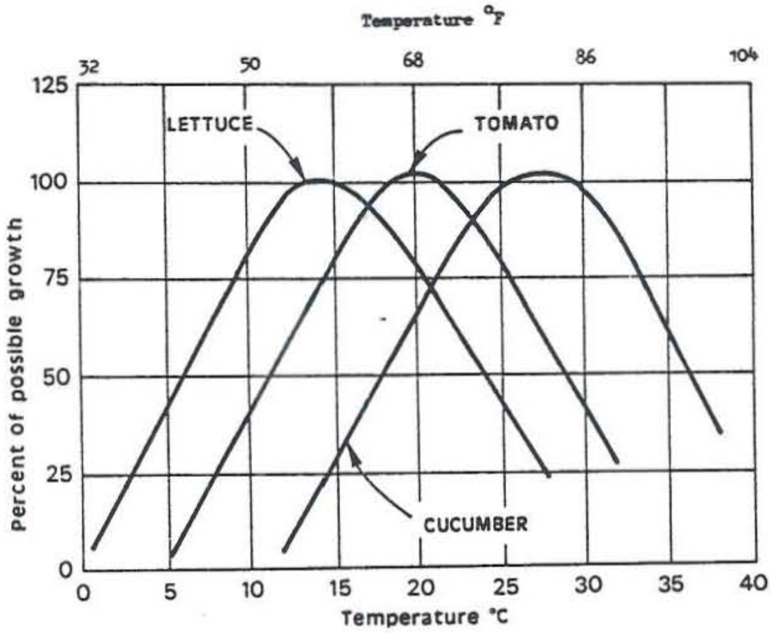

Figure I. Optimum growing temperature for selected agricultural products.

covered by greenhouses. In Hungary over 300 acres (120 ha) of greenhouses are heated geothermally. 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 the cost, much of the building structure pipe supporting system also acts as the supply and radiation systems for the geothermal fluid. Greenhouses cover about 20 acres (8.0 ha) in Japan where a variety of vegetables and flowers are grown. Individual greenhouses, operated by farmers and covering 3,200-16,000 ft^2 (300-100 m^6) use 158^o-212^oF (70^o-100^oC) geothermal water. Many large greenhouses totaling about one acre (0.4 ha), are operated as tropical gardens for sightseeing purposes. New Zealand has numerous greenhouses using geothermal hot water and steam. At the Land Survey Nursery in Taupo, greenhouses are heated by geothermal steam and soil is sterilized (pasteurized) at 140°F (60°C) to kill insects, fungus, worms, and some bacteria. In Iceland over 35 acres (14 ha) are heated, including a greenhouse, restaurant, and horticulture college at Hveragerdi. Everything from bananas, coffee beans, cacti, and tropical flowers to the standard tomatoes and cucumbers are grown in these greenhouses. Studies of the economic feasibility of greenhouses in Iceland have been based on theoretical 82-acres (33.5 hectace) facility, which would grow asparagus on 25 acres (10 ha), anthurium on 25 acres (10 ha), roses on 25 acres (10 ha), flower seedlings on 2 acres (1 ha), tomatoes on 2 acres (1 ha), lettuce on 2 acres (1 ha), and cucumbers on 1 acre (0.5 ha). Projected profit on the initial investment would amount to 11 percent before taxes, and the greenhouses would provide jobs for 250 persons (Hansen, 1981).

Numerous geothermally heated greenhouses exist in the U.S.; several examples are described as follows: In Salt Lake City, Utah, a 250,000-ft^2 (23,000-m^2) greenhouse is using 200 gpm (12.6 l/s) of 120°F (49°C) water for heating. Utah Roses, Inc., is producing cut roses for a national floral market. The 4,000-ft (1,200-m) geothermal well is replacing a natural gas/oil heating system. Fifteen miles (24 km) south of Klamath Falls, Oregon, on the Liskey ranch, approximately 50,000 ft^2 (4,600 m^2) of greenhouses were heated with 195°F (90°C) water from a 270-foot (82-m) deep well. One of the greenhouses consists of four 42-ft by 150-ft (13-m by 46-m) buildings connected to form one large complex. Initially, seedlings were raised for federal and private agencies. More recently, succulents and cacti were raised. All plants are grown in trays on raised tables, with the heat supplied by pipes under each table (Laskin, 1978). At Honey Lake, California, near Susanville, over thirty 30-ft by 124-ft (9-m by 38-m) Quonset-design greenhouses are used to raise cucumbers and tomatoes. The vegetables are raised by hydroponics, with the heat being supplied by forced air heaters. Production rates are about 1,500 pounds (680 kg) of cucumbers per unit per week and 850 pounds (358 kg) of tomatoes per unit per week. The cover of each greenhouse consists of two layers of six-mil sheeting (plastic). A small electric air blower continually inflates the area between the two layers and maintains an air space of about 6 inches (15 cm), resulting in heat savings of approximately 40 percent over conventional coverings. The savings, using geothermal heat as compared to conventional fuel, averages $4,500 per acre per year ($11,100/ha/yr) (Boren and Johnson, 1978). A similar analysis has been made for a greenhouse provided in La Grande, Oregon. The double 6-mil polyethylene covering required 45 percent less heating than single layer (Higbee and Ryan, 1981) (Figure II on following page).

One of the world's largest geothermally heated greenhouse operations is near Mt. Amiata, Italy. Approximately 54 acres (22 ha) of greenhouses are used to produce potted plants and flowers. Waste heat is supplied from a 15 MWe power plant.

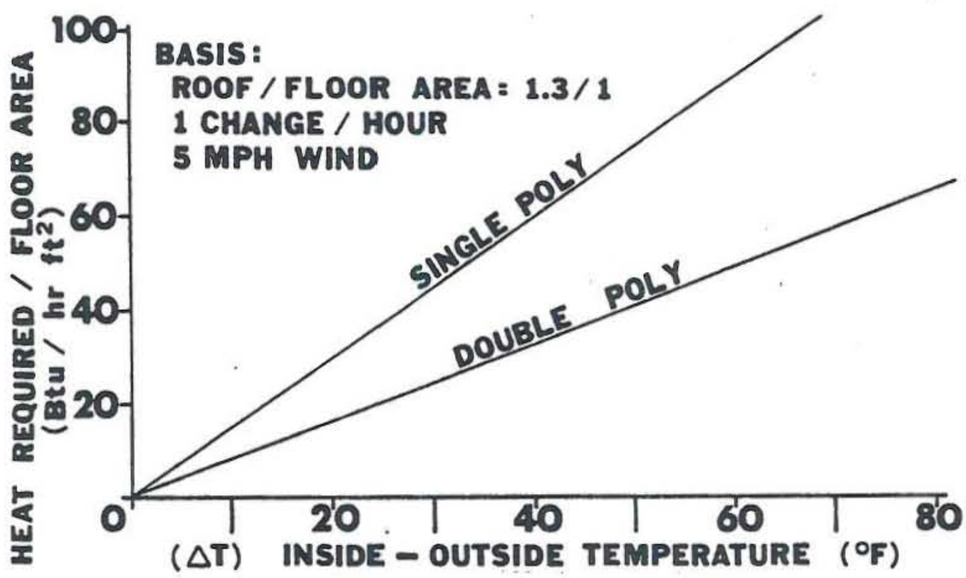

FIGURE II. Example of Heat Requirement for Greenhouses in La Grande, Oregon (Outside design temperature = $1^{o}F$ ($-17^{o}C$))

Approximately 50 acres (20 ha) of greenhouses are heated geothermally in the United States. The largest single greenhouse operation is at Animas, in southwestern New Mexico, where 4.0 hectars are used for raising cut roses. The five leading greenhouse locations are:

Location	Annual in TJ	Use (MWt)	Load Factor	Area acres (ha)	Product
Animas, NM	75.8	(6)	40.0%	10.8 (4.4)	Cut roses & bedding plants
Buhl, ID	63.0	(5)	40.0%	5.7 (2.3)	Potted & bedding plants
Sandy, UT	47.1	(4)	25.0%	4.7 (1.9)	Cut roses
Wendel/ Susanville, CA	43.4	(3)	43.2%	3.7 (1.5)	Vegetables
Helena, MT	25.0	(2)	45.0%	2.0 (0.8)	Cut roses

3. GENERAL DESIGN CRITERIA

Greenhouse heating can be accomplished by (1) circulation of air over finned-coil heat exchangers carrying hot water, often with the use of perforated plastic tubes running the length of the greenhouse in order to maintain uniform heat distribution, (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. A fifth approach is using hot water for surface heating. Surface-heated greenhouses were developed several decades ago in the USSR. The application of a flowing layer of warm water to the outside surface of the greenhouse can provide 80 percent to 90 percent of the energy needed. The flowing layers of warm water prevent snow and ice from accumulating.

The most efficient and economical greenhouse development consists of large structures covering one-half to a full acre (0.2 to 0.4 ha). A typical size would be 120 to 360 ft (36 by 110 m), constructed of fiberglass with furrow-connected gables. Heating would be from a combination of fan coils connected in series with a network of horizontal pipes installed on outside walls and under benches. A storage tank would be required to meet peak demand and for recirculation of the geothermal water to obtain the maximum temperature drop. Approximately 100 gpm (6.3 l/s) of 140^{o}-180^{o}F (60^{o}-82^{o}C) water will be required for peak heating. The average is much less. Fortunately, most crops require lower nighttime than daytime temperatures.

Greenhouse construction and outfitting will run from \$5 to \$10 per square foot (\$54 to \$108 per m^2).

4. GREENHOUSE CONSTRUCTION (Rafferty, 1985 & 1987)

a. Construction Materials

In order to make an evaluation of geothermal heating systems for greenhouses, it is first necessary to examine the different heating requirements imposed by various construction methods.

At one time, greenhouses were constructed exclusively of cypress wood frames and single glass panels. Recent years have seen substantial changes in construction techniques and materials. In general, construction may be considered to fall into one of the following four categories:

(1) glass
(2) plastic film
(3) fiberglass or similar rigid plastics
(4) combination of two and three

All of the above are generally constructed of steel or aluminum frames.

Glass greenhouses are the most expensive to construct due to both the cost of the glazing material and the requirement for a stronger framework to support the glass. In many cases, fiberglass panels are employed on the side and end walls of the structure. Building profile is generally of peaked design, with 36- and 42-foot (11-and 13-m) widths, and lengths in 20-foot increments (6-m) most common. This type of greenhouse is preferred by growers whose plants require superior light transmission qualities. In addition to offering the highest light quality, the glass greenhouse also has the poorest energy efficiency. Heating costs are high due to the poor insulating quality of single glazing and the high infiltration of cold air through the many "cracks" in the construction. This issue of high transmission loss has been addressed in recent years through the introduction of new, double glazing panels for glass houses. However, due to the expense of these panels and their effect upon light transmission, most glass greenhouses remain single layer.

Plastic film greenhouses are the newest variation in greenhouse construction techniques. This type of structure is almost always of the arched roof or "quonset-hut" design. The roof can come all the way down to the ground or can be fitted with side walls. The side walls, if employed, and end walls are generally of fiberglass construction. Maintenance requirements for the plastic film are high in that it generally requires replacement on three-year intervals or less, depending on the quality of the material. Most plastic film houses employ a double layer of film separated by air space. The air space is maintained by a small blower which pressurizes the volume between the layers. This "double poly" design is a very energy efficient approach to greenhouse design. It not only reduces transmission losses (losses through the walls and roof) by 30-40% (see Figure II), but also substantially reduces infiltration (in leakage of cold air). Although the plastic film tends to lose more heat than glass through radiation, the net effect is a reduction in heating requirements compared to glass construction. Infiltration is reduced because the "cracks" present in other types of construction are eliminated through the use of the continuous plastic film. As a result, there is less opportunity for the cold outside air to penetrate the structure. The superior energy efficiency on the film construction comes at the price of reduced light transmission, however. As a result, highly light sensitive crops cannot be grown in the double-poly greenhouse as successfully as in other constructions. These greenhouses are generally constructed in 30-foot (9-m) width with 100- and 150-foot (30-and 46-m) lengths.

Fiberglass greenhouses are similar in construction to the glass houses described above. They are generally of peaked roof design, but require less structural support as a result of the lower weight of the fiberglass. Heat loss of the fiberglass house is about the same as the glass house. Although the fiberglass material has a lower conductivity than glass, when considered in the overall building heat loss, this has little effect.

b. Heating Requirements

In order to select a heating system for a greenhouse, the first step is to determine the peak heating requirement for the structure. Heat loss for a greenhouse is composed of two components: (1) transmission loss through the walls and roof, and (2) infiltration and ventilation losses due to the heating of cold outside air.

To evaluate transmission loss, the first step is to calculate the surface area of the structure. This surface area should be subdivided into the various materials employed, i.e. square feet (square m) of double plastic, square feet (square m) of fiberglass, etc.

After determining the total surface area (SA) of the various construction materials, this value is then combined with a design temperature difference (DTD) and a heat loss factor (HLF) for each, to calculate the total transmission heat loss:

$$\text{Transmission Heat Loss} = (SA_1 \times DTD_1 \times HLF_1) + (SA_2 \times DTD_2 \times HLF_2)$$

The design temperature difference is a function of two values; design inside temperature and design outside temperature. The inside design value is simply the temperature to be maintained inside the space [usually in the 50^{o}-$65^{o}F$ (10^{o}-$18^{o}C$) range]. The design outdoor temperature is <u>not</u> the coldest outdoor temperature recorded at the site. It is generally considered to be a temperature which is valid for all but 22 hours per year during the heating season. Acceptable values for various locations are generally available from state energy offices or organizations such as American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE).

The final value in the transmission heat loss equation is the heat loss factor (HLF or U-factor). Acceptable values for various materials are shown in the following table.

Glazing Material HLF Values
(U-factor)

Glass	1.10	Single poly	1.15
Fiberglass	1.00	Double poly	.70

The heat loss factor is also influenced by wind speed. The above values are based upon a wind speed of 15 miles per hour (mph) (24 km/h). If other wind speeds are expected to occur at the design outside condition, then allowances should be made for this by adjusting the HLF according to the following table.

HLF Values (Btu/hr ft^2 °F) at Various Wind Velocities (MPH(km/h))

	0	5 (8)	10 (16)	20 (32)	25 (40)	30 (48)
Glass	.765	.951	1.040	1.140	1.160	1.180
Fiberglass	.695	.865	.949	1.034	1.058	1.078
Single poly	.810	1.000	1.090	1.190	1.210	1.230
Double poly	.535	.631	.675	.716	.728	.736

Conversion: x 4.88 kcal/h m^2 °C; x 20.43 kJ/h m^2 °C; x 5.675 Watts/m^2 °C

As mentioned previously, total heat loss is a function of two components: (1) transmission heat loss, (2) infiltration. For greenhouse design, infiltration is generally analyzed via the "air change" method. This method is based upon the number of times per hour that the air in the greenhouse is replaced by cold air leaking in from outside. The number of air changes which occurs is a function of wind speed, greenhouse construction, and inside and outside temperatures. The following table outlines general values for different types of greenhouse construction.

Air Change Data for Various Glazing Materials

	Air Changes/Hour (AC/H)
Single glass	2.5 to 3.5
Double glass	1 to 1.5
Fiberglass	2 to 3
Single poly	.5 to 1.0
Double poly	0 to .5
Single poly w/low fiberglass sides	1 to 1.5
Double poly w/low fiberglass sides	.5 to 1.0
Single poly w/high fiberglass sides	1.5 to 2.0
Double poly w/high fiberglass sides	1 to 1.5

As the number of air changes is related to the volume of the greenhouse, after selecting the appropriate figure from above, it is necessary to calculate the volume of the structure. Calculations do not include ventilation.

Heat loss due to infiltration

= AC/H x volume x DTD x 0.018 (in Btu/hr)

Where:

volume is in ft^2 and DTD is in ^{o}F, or

= AC/H x volume x DTD x 0.088 (in kg cal/hr)

= AC/H x volume x DTD x 0.102 (in kw)

Where:

volume is in m^2 and DTD is in ^oC.

Total greenhouse heating requirement

= transmission loss + infiltration loss

Note: The above is usually converted to energy loss/unit of floor area, as most greenhouse operators understand this relationship better.

This is the "peak" or design heating load for the greenhouse. The heating equipment selected for the structure would have to be capable of meeting this requirement.

c. Annual Heating Load

In many cases, the quantity of energy required to heat a greenhouse over an entire year is of interest. For a conventionally heated greenhouse, this figure would allow one to calculate annual fuel costs. In a geothermal application, the annual energy requirement would be related to pumping costs or heating expenses if energy is to be purchased from an outside entity. The annual energy determination is a complex one involving many repetitious heat loss and solar heat gain calculations. Actual heating requirements are influenced by the local climate, solar weather, set point temperatures and greenhouse construction.

5. GEOTHERMAL SOIL HEATING (Gudmundsson, 1983)

Soil heating for horticultural purposes uses geothermal water flowing in buried pipes and other conduits. This method is suitable where outside growing temperatures are marginal, and greenhouse construction is not economical.

The reasons for installing a soil heating system are threefold: (1) increase the total yield, (2) obtain produce earlier and, (3) grow new varieties. The commercial growers aim at lessening the risk of crop failure due to changeable weather conditions from year to year. An interesting facet of soil heating is the possiblity of growing varieties that keep better in storage. Vegetables are also very sensitive to soil temperature. As shown in Figure III, carrots grown above optimum temperature are short and plump, whereas those grown below optimum tend to be long and skinny, thus the temperature control becomes critical.

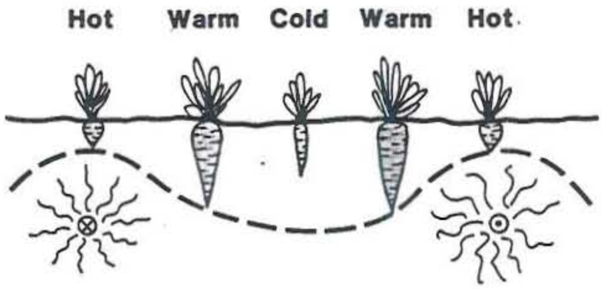

Figure III. Idealized effect of temperature on carrots.

Warm soil suitable for vegetable growing has been associated with hot springs and other geothermal features. Documented attempts at taking advantage of natural soil warming dates back to the middle 1950s in Iceland. One disadvantage with this method is the lack of temperature control.

The first soil heating system using geothermal fluids was built in Iceland in the late 1880s. About 16,000 square feet (1500 square meters) were heated by flowing geothermal water in closed conduits buried in the soil. Fludir in southern Iceland is a community developed around an active geothermal area of many hot springs. The main source of income for the community is horticultural activities, mainly for vegetable growing. Both natural ground heating and installed heating pipes are used in the community. The latter method originally used pipes that allow seepage into the soil. More recently 1.2-inch (4.0-cm) plastic pipes in a closed system have been used. Geothermal water at 200°F (93°C) flows by gravity into U-pipes approximately 6 feet (2 m) apart and buried 2.5 feet (0.75 m) deep. The discharge temperature of the water is around 104°F (40°C). The thermal load is about 9.5 Btu/hr/square foot (30 W/square meter). The optimum soil temperature appears to be around 68°-86°F (20°-30°C) for common vegetables. A typical system is shown in Figure IV.

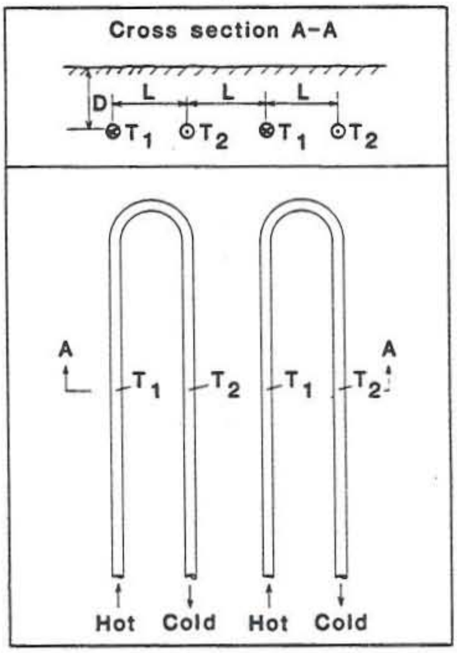

Figure IV. Layout of a typical soil heating system.

6. DESIGN CORRELATIONS

It was recognized that design methods were required to aid in the development of geothermal soil heating systems in Iceland. Jonsson et al. (1982) have reported the main correlations that resulted from that work. The thermal problem was solved numerically for the geometry shown in Figure IV. The system was assumed steady state and two-dimensional; soil thermal conductivity and surface heat transfer coefficient were taken as constants.

It was determined convenient to use dimensionless parameters when deriving the design correlations; see nomenclature. The dimensionless heat flux from a U-pipe was found to depend on three other dimensionless parameters:

$$q^* = \frac{q^D}{k(T_1 - T_\infty)} = f(Bi, \frac{L}{D}, \theta_2)$$

A range of typical values was determined for each of the parameters based on previous experimental work. These typical values were then used to solve the governing heat transfer equation numerically. The next step was to obtain correlations of practical use for those designing geothermal soil heating systems.

A cross-correlation scheme was devised for this purpose. It was discovered that the dimensionless heat flux and mean temperature (at a given depth) were proportioned to $(1 + \theta_2)$. It was more difficult to find a suitable function to express q* in terms of Bi and L/D because it was not possible to separate them as independent parameters.

Therefore, the product (a + bL/D) ln (1 + Bi) and a second degree polynomial in D/L were used. The best fit resulted in the correlation:

$$q^* = (1 + \theta_2)[(1 + 0.2\,\frac{L}{D})\ \ln\,(1 + Bi)]^{0.2}$$

$$[0.056 + 0.483\,\frac{D}{L} - 0.215\,(\frac{D^2}{L})]$$

When this correlation was compared to the numerical results, the maximum error was 2.4% while 75% of the values were within a 1% error band. The correlation can be used with reasonable accuracy if the dimensionless parameters are in the following (typical) ranges:

$$0 \le \theta_2 \le 1$$

$$1.2 \le \frac{L}{D} \le 4$$

$$2.5 \le Bi \le 10$$

The soil temperature was expressed in terms of a mean dimensionless temperature θ_m. It refers to a given depth and requires one more parameter than does the dimensionless heat flux; the depth ratio x/D. The mean dimensionless temperature was found to be linear in x/D with Bi affecting the slope. Using the dummy variable $z = (\ln Bi)^{-0.2}$ the following correlation was obtained:

$$\theta_m = (1 + \theta_2)\ z\ [3z - 2.4 + (7.2 - 6z)\frac{x}{D}]$$

$$[0.056 + 0.275\,\frac{D}{L} - 0.125\,(\frac{D}{L})^2]$$

When compared to the numerical results, the maximum error was 5%. The correlation can be used for the same range of parameters as shown above in addition to the following:

$$0.0 \leq \frac{X}{D} \leq 0.8$$

To evaluate the total heat flux for a soil heating system, it becomes necessary to consider the third dimension along the pipes. It appears reasonable to assume the water temperature decreases linearily in the pipes from inlet to outlet. This means that at any cross section perpendicular to the pipes, the sum of $T_1 + T_2 = T_{in} + T_{out}$. Therefore, for the geometry shown in Figure IV using U-pipes, the heat flux and mean temperature are independent of the third or axial dimension. It means that only the inlet and outlet water temperatures have to be known to calculate the heat flux and mean temperature.

It may be useful to show by example how the correlations given above can be used in practical situations. Suppose there is a vegetable field 100 m long and 26 m wide (330 x 85 ft) to be heated using a 70^oC (158^oF) geothermal water. The desired soil temperature at 20-30 cm (8-12 inches) depth is assumed to be 20^o-25^oC (68^o-77^oF). If the mean air temperature is taken as 10^oC (50^oF) and the water discharge temperature $T_{out} = 30^oC$ (86^oF), the dimensionless temperature $\Theta_2 = (30-10)/(70-10) = 0.33$. By trial and error the required depth and spacing can be found. If the pipe depth is taken as 50 cm (20 inches) and the spacing as 130 cm (51 inches), then L/D = 2.6 and 10 U-pipes are needed in the field. Taking the soil effective thermal conductivity

$k = 1$ W/m ^{o}C and the surface heat transfer coefficient $h = 10$ W/m^2 ^{o}C, the Biot number becomes Bi = 5.

The dimensionless heat flux is calculated $q^* = 0.34$ and the heat flux $q^2 = 41$ W/m^2. Since the area of the field is 2600 m^2 (28,000 ft^2), the total thermal power becomes 107 kW and the water requirement 0.64 kg/s (l/s) (10 gpm) since it is cooled from 70^{o}C to 30^{o}C. The dimensionless mean temperatures at 20 cm and 30 cm depths (corresponding x/D are 20/50 and 30/50) give soil temperatures of 21^{o}C and 24^{o}C (70^{o} and 75^{o}F) respectively. These temperatures are conveniently within the specified range of 20^{o}-25^{o}C for optimum field conditions.

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AQUACULTURE

1. INTRODUCTION

Aquaculture involves the raising of freshwater or marine organisms in a controlled environment to enhance production rates. The principal species that are typically raised are aquatic animals such as carp, catfish, bass, tilapia, frogs, mullet, eels, salmon, sturgeon, shrimp, lobster, crayfish, crabs, oysters, clams, scallops, mussels, and abalone.

The use of geothermal energy for aquaculture rather than water dependent upon the sun for its heat has demonstrated that more fish can be produced in a shorter period of time. When the water temperature is below the optimal range, the fish loses its ability to feed because the basic body metabolism is affected (Johnson, 1981). Thus a good geothermal supply, due to its constant temperature, can "out-perform" a natural mild climate.

Ambient temperature is generally more important for aquatic species than land animals. This suggests that the potential use of geothermal energy for aquaculture may be greater than for animal husbandry, such as pig and chicken rearing. Figure I shows the growth trends for a few land and aquatic species (Barbier and Fanelli, 1977). Land animals grow best in a wide temperature range, from just under 50°F (10°C) and up to about 68°F (20°C). Aquatic species such as shrimp and catfish have a narrower range of optimum production at a higher temperature, approaching 86°F

(30°C). Trout and salmon, however, have a lower optimum temperature no higher than 59°F (15°C).

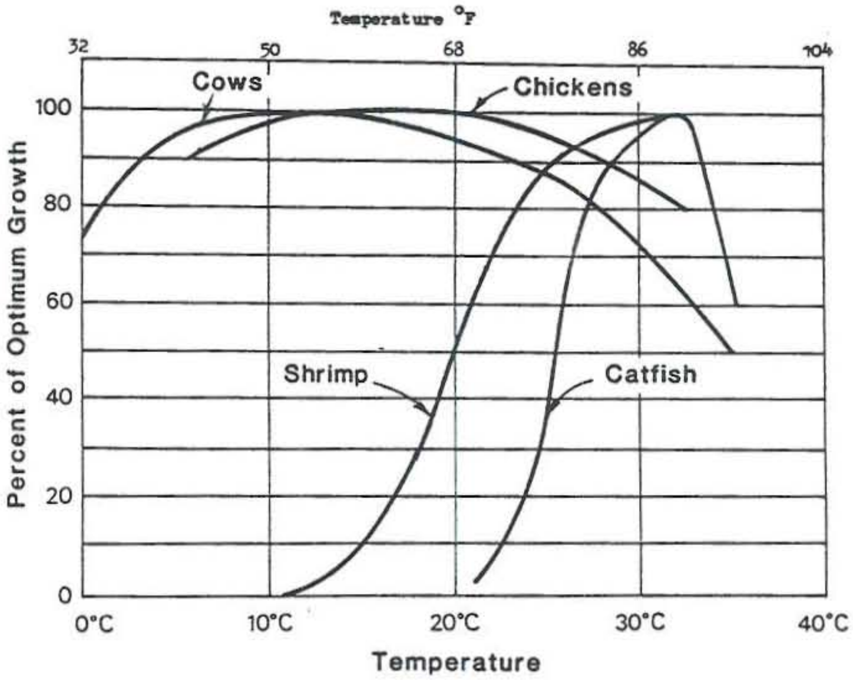

FIGURE I. Optimum growing temperatures for selected animal and aquatic species.

2. EXAMPLES OF GEOTHERMAL PROJECTS

Fish breeding is a successful business in Japan where carp and eels are bred and raised. The eels are the most profitable and are raised in 10-in (25-cm) diameter by 3-ft (6-m) long 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 3.5 to 5 oz (100 to 150 grams), with a total annual production of 8,400 lbs (3,800 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 1974). Icelandic fish hatcheries raise 610,000 salmon and trout fingerlings annually in geothermal water. A total of 10 fish hatcheries existed around the country--a new and fast-growing industry (Hansen, 1981).

In the U.S., aquaculture projects using geothermal water exist in Idaho, Oregon, and California. Fish Breeders of Idaho, Inc., located near Buhl, has been raising channel catfish in high-density concrete raceways for over ten years. The water is supplied by artesian geothermal wells flowing at 6,000 gpm (380 l/s) at 90^{o}F (32^{o}C). Cold water from springs and streams is used to cool the hot water to 80^{o}-85^{o}F (27^{o}-29^{o}C) for the best production temperature. Normal stocking densities are from 50 to 10 pounds of fish per cubic foot of space (80 to 160 kg/m^3). The maximum recommended inventory for commercial production is about 10,000 to 15,000 pounds per second foot of water (1.6 to 2.4×10^5 kg/m^3/s). Yearly production will usually be three to four times the carrying capacity. Oxygen and ammonia are the principal factors limiting production (Ray, 1979).

Giant freshwater prawns (Macrobrachium rosenbergii) have been raised at Oregon Institute of Technology since 1975. Some work has also been done in trout culture and mosquito fish (Gambuzia affinis). This work has provided data demonstrating that a tropical crustacean can be grown in a cold climate (as low as -20^{o}F or -7^{o}C) where the water temperature is maintained at the optimal growing temperature for this species of 81°-86°F (27°-30°C). Initially, two smaller outdoor ponds 4 ft (1.2 m) deep were used, and more recently 2 half-acre (0.2 ha) were built. A selected brood stock is held in a small spawning building where larvae are hatched in artificial saltwater and reared to the post-larva stage which make the facility self-supporting. Growth rates of 7/8 in (2 cm) per month have been maintained (twice that obtained in tropical climates) with a 1 ft^2 (900 cm^2) of surface area per animal maximum density. The plumbing system of the ponds consists of perforated diffuser pipes, control valves and thermostats to maintain an optimum temperature of the pond. This provides an even distribution of geothermal energy throughout the pond (Johnson, 1978 and 1981; Smith, 1981).

A very successful catfish raising operation has been started by the Indian community at Fort Bidwell in northeastern California. Geothermal well water at 105°F (40°C) is mixed with cold water to produce 80°F (27°C) water which is then piped into 25-ft long by 8-ft wide by 4-ft deep (7.6-m x 2.4-m x 1.2-m) raceways. Two sets of parallel raceways use 900-1,000 gpm (57 to 63 l/s). A one-foot drop between raceways is used to aerate the water. One ounce (28 g) fish at 3,000 per raceway are initially stocked, producing a surviving 2,000 fish at 2 pounds (0.9 kg) each in five months. Construction of the raceways and well cost $100,000. The fish are sold live at the source for $1.40 per pound ($3.09/kg) and delivered live to San Francisco where they wholesale for $2 per pound ($4.41/kg) and retail for $3 to $4 per pound ($6.60 to $8.80 per kg). Production cost at Fort Bidwell is approximately $.60 per pound ($1.32/kg) (personal communication with William Johnson).

A summary of the leading concentrations of fish farms in the United States are:

Location	Annual Use in TJ (MWt)	Load Factor	Product
Buhl, ID	310.2 (12)	80%	Catfish
Mecca, CA	75.0 (10)	25%	Prawns
Wabushka, NV	13.8 (2)	25%	Catfish/ Tropicals
Ft. Bidwell, CA	12.1 (1)	80%	Catfish
Paso Robles, CA	11.8 (1)	50%	Catfish

3. GENERAL DESIGN CONSIDERATIONS

Aquaculture ponds are best constructed with 1/4-acre (0.1-ha) of surface area. A size of 50 ft by 200 ft (15 by 61 m) is ideal for harvesting. A minimum-sized commercial operation should have 7 to 10 acres (3 to 4 ha) under development (water surface area), or about 30 to 40 ponds. The maximum surface area that should be considered for a single pond is one-half an acre (0.2 ha).

The most important items to consider are quality of the water and disease. If geothermal water is to be used directly, evaluation of heavy metals such as fluorides, chlorides, etc., must be undertaken to determine if the fish or prawns can survive. A small test program is often a wise first step. An aeration pond preceding the stocked ponds will often solve the chemical problem.

Crops that are a good candidate for aquaculture are:

Specie	Growth Period	Water Temperature
Tropical Fish	2-3 months	74^{o}-90^{o}F (23^{o}-27^{o}C)
Catfish	4-6 months	80^{o}-85^{o}F (27^{o}-29^{o}C)
Trout	4-6 months	55^{o}-65^{o}F (13^{o}-18^{o}C)
Prawns	6-9 months	81^{o}-86^{o}F (27^{o}-30^{o}C)

A more detailed list of species and temperature requirements are listed in Table 1.

Tropical fish (goldfish) are generally the easiest to raise and have a low investment and high yield. Smaller ponds can also be used. An average of 150,000 fish per year can be raised from one acre (0.4 ha), requiring the lowest temperature water; thus, they can better use low-temperature resources of cascaded water. Freshwater prawns generally have a high market value, with marketable sizes being 16 to 20 tails to the pound (0.4 kg). Channel catfish are also popular, especially as fillets. Production rates depend upon water quality and flow rates.

Ponds require geothermal water of 100^{o} to 150^{o}F (38^{o} to 66^{o}C) and a peak flow of 300 gpm (19 l/s) for one acre (0.4 ha) of uncovered surface area in colder climates. The long axis of the pond should be constructed perpendicular to prevailing winds to minimize wave action and temperature loss. The ponds are normally constructed of excavated earth and lined with plastic where necessary to prevent seepage loss. Temperature loss can be reduced, thus reducing the required geothermal flow, by covering the pond with a plastic bubble. Construction cost, exclusive of geothermal wells and pipelines, will run $30,000-$50,000 per acre ($75,000-$125,000 per hectar).

TABLE 1.
Temperature Requirements and Growth Periods for Selected Aquaculture Species

Species	Tolerable Extremes		Optimum Growth		Growth Period to Market Size(months)
	°F	°C	°F	°C	
Oysters	32- 97	(0-36)	76-78	(24-26)	24
Lobsters	32- 88	(0-31)	72-75	(22-24)	24
Penaeid Shrimp					
Kuruma	40-?	(4-?)	77-87	(25-31)	6-8
Pink	52-104	(11-40)	75-85	(22-29)	6-8
Salmon (Pacific)	40- 77	(4-25)	59	(15)	6-12
Freshwater Prawns	75- 90	(24-32)	83-87	(28-31)	6-12
Catfish	35- 95	(17-35)	82-87	(28-31)	6
Eels	32- 97	(0-36)	73-86	(23-30)	12-24
Tilapia	47-106	(8-41)	72-86	(22-30)	-
Carp	40-100	(4-38)	68-90	(20-32)	-
Trout	32- 89	(0-32)	63	(17)	6-8
Yellow Perch	32- 86	(0-30)	72-82	(22-28)	10
Striped Bass	?- 86	(?-30)	61-66	(16-19)	6-8

4. SPECIFIC DESIGN CONSIDERATIONS (Rafferty, 1986)

A non-covered body of water, exposed to the elements, exchanges heat with the atmosphere via four mechanisms: evaporation, convection, radiation and conduction. Each of these is influenced by different parameters and will be discussed separately in the paragraphs below.

a. Evaporative Loss

Evaporation is generally the largest component of the total heat loss from the pond. When water is evaporated from the surface of the pond, the heat is taken from the remaining water. As a result, as each pound of water evaporates from the surface, 1000 Btu (478 KJ/Kg) is lost with the escaping vapor. Losses can occur by evaporation even when the water temperature is at or below the surrounding air temperature. This is because water evaporates from the surface of the pond at the wet bulb temperature. At 100% relative humidity, the wet bulb temperature is the same as the dry bulb temperature (dry bulb is the temperature which is given by a standard thermometer). At anything less than 100% relative humidity, the wet bulb temperature is less than the dry bulb temperature and, as a result, evaporation loss can occur below the air temperature.

The rate at which evaporation occurs is a function of air velocity and the pressure difference between the pond water and the water vapor in the air (vapor pressure difference). In simple terms, as the temperature of the pond water is increased or the relative humidity of the air is decreased, evaporation rate increases. The equation which describes the rate of evaporation (of a 150-ft or 50-m long pond) is shown below (Eckert, 1959) (see Addendum for SI conversions):

$$Wp = \frac{(0.135v)/0.018}{85.74 \times (Ts + 460^{o})}(Pw - Pa) \times 144 \times A \quad ...[1]$$

Where:

Wp = Rate of evaporation in lbm/hour
A = Pond surface area in ft^2
v = Air velocity in ft/sec
Pw = Saturation vapor pressure of the pond water in psia
Pa = Saturation pressure air dew point in psia
Ts = Surface temperature ^{o}F

For enclosed ponds or indoor swimming pools, this equation can be reduced to (ASHRAE, 1978):

$$Wp = 0.204 \times A \times (Pw - Pa) \quad ...[2]$$

Where:

Wp = Rate of evaporation in lbm/hour
A = Pond area in ft^2
Pw = Saturation pressure of the pond water (psia)
Pa = Saturation pressure at air dew point (psia)

Following are some common values for v, Pw and Pa:

For v:
@ 5 mph wind, v = 7.33 ft/sec (8 Km/hr, 2.23 m/s)
@ 10 mph wind, v = 14.7 ft/sec (16 Km/hr, 4.47 m/s)
@ 15 mph wind, v = 22 ft/sec (24 Km/hr, 6.70 m/s)

For Pw:
@ $60^{o}F$ water Pw = 0.256 psia ($15.6^{o}C$, 0.0180 Kg/cm^2)
@ $70^{o}F$ water Pw = 0.363 psia ($21.1^{o}C$, 0.0255 Kg/cm^2)
@ $80^{o}F$ water Pw = 0.507 psia ($26.7^{o}C$, 0.0356 Kg/cm^2)
@ $90^{o}F$ water Pw = 0.698 psia ($32.2^{o}C$, 0.0491 Kg/cm^2)

For Pa: For outdoor locations with a design dry bulb air temperature of below $30^{o}F$, Pa can be taken as 0.074 psia (0.0052 Kg/cm^2)

For indoor locations with a design of approximately $75^{o}F$ and 50% relative humidity, Pa can be taken as 0.211 psia (0.0148 Kg/cm^2)

To obtain the heat loss in Btu/hour simply multiply the lbm/hour loss by the value of 1050 Btu/lbm (583 Kg-cal/kg).

$$Q_{EV} = Wp \times 1050 \qquad \ldots[3]$$

This is the peak or design heat loss. It is important to note that the example values given above are for the design (worst) case. At higher outdoor air temperatures and different relative humidities this value would be less. As mentioned earlier, the rate of evaporation loss is influenced by the vapor pressure difference between the pond water and the water vapor in the air. Figure III illustrates the effect of increased pond water temperature on vapor pressure (Pw). It is obvious that reduced water temperature would reduce the vapor pressure difference and hence the rate of evaporation.

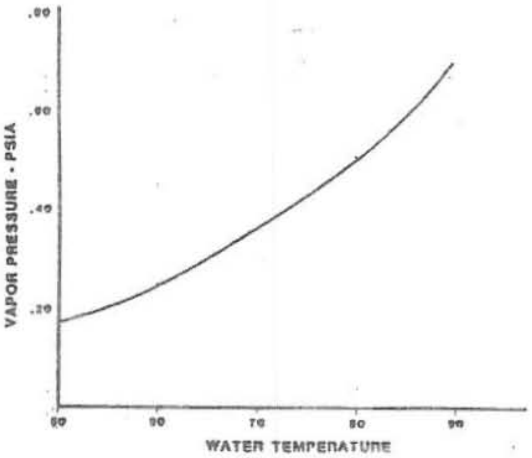

FIGURE III. Plot of Pond Water Vapor Pressure vs. Temperature

b. Convective Loss

The next major mechanism of loss from the pond surface is that of convection. This is the mode associated with the heat losses to cold air passing over the pond surface. The two most important influences on the magnitude of convective heat loss are wind velocity and temperature difference between the pond surface and the air. This is evidenced in the following equation (Wolf, 1983):

$$Q_{CV} = (0.135v) \times A \times (tw - ta) \qquad \text{...[4]}$$

Where:

Q_{CV} = Convection heat loss in Btu/hour
v = Air velocity in ft/sec
A = Pond area in ft^2
tw = Water temperature ^{o}F
ta = Air temperature ^{o}F

For an indoor pool this equation would be (Lauer, -)

$$Q_{CV} = 0.38\ (tw - ta)^{0.25} \times A \times (tw - ta) \qquad \text{...[5]}$$

Figure IV illustrates the importance of air velocity on convective heat loss. The shape of this curve would also be similar for evaporation loss.

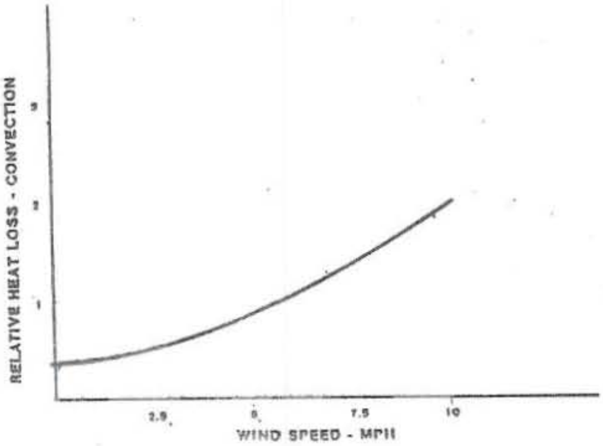

FIGURE IV. Plot of Relative Convective Heat Loss vs. Wind Speed

c. Radiant Loss

Radiant heat loss, the third largest component of the total heat loss, is dependent primarily on the temperature difference between the pond surface temperature and the surrounding air temperature. Under normal circumstances, radiant heat exchange is assumed to occur between solid bodies with little or no gain to the air in between the bodies. However, due to the evaporative losses near the pond surface, the air tends to contain a large quantity of water vapor. When this is the case, the pond surface radiates to the water vapor in the air, which is assumed to be at the temperature of the air itself. The equation which describes this process is as follows (Stoever, 1941):

$$Q_{RD} = 0.174 \times 10^{-8} \times 0.93 \left((460 + tw)^4 - (460 + ta)^4\right) \times A \qquad \ldots[6]$$

Where:

Q_{RD} = Radiant heat loss in Btu/hour
tw = Pond water temperature ^{o}F
ta = Air temperature ^{o}F
A = Pond surface area in ft^2

d. Conductive Loss

The final mode of heat loss is that of conduction. This is the loss associated with the walls of the pond. Of the four losses, conduction is by far the smallest and in many calculations is simply omitted. The method on the following page (ASHRAE, 1985) is valid for a pond depth of 3 ft to 5 ft (1 to 2 m).

$$Q_{CD} = (((L + W) \times 2 \times 1) + (L \times W \times 0.02))(tw - (ta + 15)) \quad ...[7]$$

Where:

Q_{CD} = Conductive heat loss in Btu/hour
L = Length of pond in ft
W = Width of pond in ft
tw = Design water temperature ^{o}F
ta = Design outside air temperature ^{o}F

e. Summary

$$Q_{TOTAL} = Q_{EV} + Q_{CV} Q_{RD} + Q_{RD}$$

It must be noted that these losses are the peak or maximum heat loss. At any given time during the year, other than the design case, the heat loss would be less than this value. The annual heating requirement cannot be determined from simply multiplying the peak heating requirement by 8760 hours/year. Because of the need for consideration of varying temperature, wind, humidity and solar heat gain, methods for calculating the annual heating requirement are beyond the scope of this article.

f. Surface Cover

As mentioned earlier, heat losses from the pond surface are most heavily influenced by wind velocity and the temperature difference between the pond and the surrounding air. Any method which can be employed to reduce either of these values would substantially reduce heating requirements.

For outdoor pools a floating cover is an excellent example. The use of a 1/2 in. (1.2 cm) floating foam cover (on the pool surface) would reduce the peak loss. This reduction is in large measure, a result of the floating type cover. Unfortunately, a floating cover is generally not considered practical for commercial aquaculture applications.

g. Pond Enclosure

A pond enclosure is another, though much more expensive, option for reducing heat loss. The advantages provided by an enclosure depend to a large extent upon the construction techniques employed (covering material, degree of enclosure, pressure or absence of ventilation). The variety of construction methods and materials available are too numerous to cover here. The basic advantages of an enclosure are reduced air velocity, reduced temperature difference between the pond and surrounding air, and reduced vapor pressure difference between the pond water and air (increased relative humidity). These effects reduce the losses associated with evaporation, convection and radiation.

h. Thermal Mass

One final method for reducing peak heating requirements for pond or pool heating lies in the use of the large thermal mass supplied by the water itself. Water is an excellent heat storage medium. This stored heating capacity can be used to reduce the peak heating requirements on the heating system.

As a result, the pond will cool by several degrees during the night. The heating system would then bring the pond back up to the temperature during the day when higher temperatures and solar gain would reduce heating requirements.

The degree to which thermal storage can be incorporated into the heating system design is a complex issue of environmental factors, pond characteristics, and the species being raised. Some species, such as prawns, are particularly sensitive to temperature fluctuations (Johnson, 1978).

i. Flow Requirements

The rate of flow required to meet the peak heating demand of a particular pond is a function of the temperature difference between the pond water and the resource temperature. The following equation can be used to determine the flow requirement.

Where:

$$GPM = Q_{tot}/(500 \times (tr - tw)) \qquad ...[8]$$

Where:

GPM = Resource flow requirements in gallons per minute

Q_{tot} = Total calculated pond heat loss

$= Q_{EV} + Q_{CV} + Q_{RD} + Q_{CD}$

tw = Pond temperature in ^{o}F

tr = Resource temperature in ^{o}F

Again, the point is made that this is the peak requirement. The required flow at any other time would be at a smaller value. This approach is valid for aquaculture projects and resource temperatures up to levels which would prove harmful if supplied directly to the pond. Above this temperature (which varies according to species), the heating water would have to be mixed with cooler water to reduce its temperature. Two methods are possible for mixing. If a sufficient supply of cold water is available, the hot water could be mixed with the cold water prior to introduction in the pond. A second approach, which would apply in the absence of cold water, would be to recirculate pond water for mixing purposes. The recirculation could be combined with an aeration scheme to increase its beneficial effect. In both cases, the quantity of cold or recirculated water could be determined by the following formula:

$$GPM = \frac{GPM_h(T_h - T_m)}{(T_m - T_c)} \qquad \ldots[9]$$

Where:

GPM_c = Required cold flow rate gpm
GPM_h = Hot water flow rate gpm
T_h = Temperature of hot water ^oF
T_c = Temperature of cold water ^oF
T_m = Temperature of desired mixed water ^oF

The above methods are presented to provide an introduction to the subject of heat losses from ponds. The equations provided are simplifications of very complex relationships and should be employed only for initial calculations. In addition, losses which can occur from various aeration schemes and other activities have not been addressed. It is strongly recommended that a competent engineer be enlisted for final design purposes.

ADDENDUM (SI Units)

Equation [1] reduces to:

$$Wp = \frac{12.6v\ (Pw - Pa)\ A}{(Ts + 460)}$$

In SI units the equation is:

$$Wp = \frac{1593.4v\ (Pw - Pa)\ A}{(Ts + 273)} \qquad \text{...[1a]}$$

Where:

Wp is in kg/hr (l/hr)
v is in m/sec
Pw and Pa are in kg/cm^2
A is in m^2, and
Ts is in ^oC

Equation [2] converts to SI units:

$$Wp = 14.16 \times A \times (Pw - Pa) \qquad \text{...[2a]}$$

Where:

Wp is in kg/hr (l/hr)
A is in m^2, and
Pw and Pa are in kg/cm^2

Equation [3] converts to SI units:

$$Q_{EV} = Wp \times 583 \qquad \text{...[3a]}$$

Where:

Q_{EV} is in kg-cal/hr, and
Wp is in kg/hr, or

$$Q_{EV} = Wp \times 677 \qquad \text{...[3b]}$$

Where:

Q_{EV} is in watts

Equation [4] converts to SI units:

$$Q_{CV} = 2.16v \times A \times (tw - ta) \qquad \text{...[4a]}$$

Where:

Q_{CV} is in kg-cal/hr
v is in m/s
A is in m^2, and
tw, ta are in ^oC, or

$$Q_{CV} = 2.51v \times A \times (tw - ta) \qquad ...[4b]$$

Where:

Q_{CV} is in watts

Equation [5] converts to SI units:

$$Q_{CV} = 2.15\ (tw - ta)^{1.25} \times A \qquad ...[5a]$$

Where:

Q_{CV} is in kg-cal/hr
tw, ta are in ^{o}C, and
A is in m^2, or

$$Q_{CV} = 2.50\ (tw - ta)^{1.25} \times A \qquad ...[5b]$$

Where:

Q_{CV} is in watts

Equation [6] reduces to:

$$Q_{RD} = 0.162 \times 10^{-8}((460 + tw)^4 - (460 + ta)^4) \times A$$

In SI units the equation is:

$$Q_{RD} = 4.611 \times 10^{-8}((273 + tw)^4 - (273 + ta)^4) \times A \qquad ...[6a]$$

Where:

Q_{RD} is in kg-cal/hr
tw, ta are in ^{o}C, and
A is in m^2, or

$$Q_{RD} = 5.358 \times 10^{-8}((273 + tw)^4 - (273 + ta)^4) \times A \qquad ....[6b]$$

Where:

Q_{RD} is in watts

Equation [7] converts to SI units:

$$Q_{CD} = 0.454\ (((L + W) \times 6.56) + (L \times W \times 0.215))(tw - ta - 8.33) \qquad ...[7a]$$

Where:

Q_{CD} is in kg-cal/hr
L, W are in m, and
tw, ta are in ^{o}C, or

$$Q_{CD} = 0.528\ (((L + W) \times 6.56) + (L \times W \times 0.215))(tw - ta - 8.33) \qquad ...[7b]$$

Where:

Q_{CD} is in watts

Equation [8] converts to SI units:

$$kg/s = Q_{tot}/(3600 \times (tr - tw)) \qquad \text{...[8a]}$$

Where:

Q_{tot} is in kg-cal/hr, and
tr, tw are in ^{o}C, or

$$kg/s = Q_{tot}/(4183 \times (tr - tw)) \qquad \text{...[8b]}$$

Where:

Q_{tot} is in watts

Equation [9] converts to SI units:

$$(kg/s)_c = \frac{(kg/s)_h \, (T_h - Tm)}{Tm - Tc} \qquad \text{...[9a]}$$

Where:

$(kg/s)_c$ is in kg per second (cold)
$(kg/s)_h$ is in kg per second (hot) and,
T_h, Tm, Tc are in ^{o}C

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INDUSTRIAL APPLICATIONS

1. INTRODUCTION

Industrial uses of geothermal energy can involve many applications over a wide range of temperatures. Categories of energy uses include process steam, direct heat and electricity generation. Geothermal energy can contribute substantially to these industrial needs, as illustrated by the Tasman pulp and paper plant in New Zealand where geothermal steam provides 55 percent of the energy for all three categories listed. The most important consideration is matching the temperature of an available geothermal resource with a compatible industrial process. In some situations, low-temperature resources can be boosted through heat pumps and temperature amplifier to satisfy higher temperature demands.

Potential industrial applications of geothermal energy include process heating, evaporation, drying, distillation, refrigeration (absorption), sterilization, washing, de-icing (mining operations), salt and chemical extraction. A summary of some of the various uses is shown in Figure 1 (Lindal, 1973).

While there are many potential industrial uses of geothermal energy, the number of worldwide applications is relatively small. They do, however, represent a fairly wide range of uses, from fish, grain, mineral and timber drying, to pulp and paper processing, and to chemical recovery. The oldest known use of geothermal energy for industrial processing is in Italy. This early industrial application included the use by the Etruscans of boric acid deposited by the steam and hot water at Larderello, 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. Originally the boric acid was obtained by boiling off the geothermal water using firewood as a heat source. From 1827 onwards, geothermal steam was used as the energy source. With increase in production, growth in trade, and refinement of the process, a wide range of boron and ammonium compounds were produced in the early 1900s. This process continued until World War II, where a total of 6,500 tons had been produced. After the war, the plant was put into operation again, only this time the raw product was imported from Turkey, and geothermal steam used as the drying source. Approximately 30 tons of steam per hour are used in the process.

Other well-known examples of industrial uses of geothermal energy are in New Zealand. At Kawerau, the Tasman Pulp and Paper Company uses high-temperature steam for timber drying, black liquor evaporation, pulp and paper drying and electric power generation. Approximately 345,000 tons of newsprint, 160,000 tons of kraft pulp and 190,000 m^3 of timber are produced annually. Six wells are presently being used to provide 180 tons/hr of steam (100-125 MW_t). One of the largest wells in the world is located here, estimated to produce over 25 MW of thermal energy (170 tons/hr). The total investment cost for geothermal is $6.8 million, the majority of which is for well development. This amounts to approximately $70 per kW_t 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.

In the vicinity of the Broadlands field of New Zealand are several unique applications of geothermal energy. At the Lands Survey Nursery in Taupo, greenhouses are heated by geothermal steam, and soil is sterilized (pasteurized) at 60°C to kill insects, fungus, worms and some bacteria. At Lake Rotokaua, an estimated 20 million tons of sulfur lie within 60 meters of the surface having a purity of up to 80 percent. Originally, the sulfur was extracted by the Frasch process using geothermal steam injected in 4 bore holes. Presently, they are strip mining the low grade surface deposits and using geothermal steam to extract the sulfur. The sulfur is then combined with cold water in a slurry and shipped by tanker truck for use in fertilizer production. At Broadlands, a cooperative of 12 farms have joined together to construct a geothermal alfalfa (lucerne) dehydration plant. The plant uses 135°C steam in a large forced air heat exchanger for drying. The drier is a simple fixed bed, double pass drier, discharging into a hammermill and pellet press for the final product. The plant produces one ton of compressed pellets per hour from five tons of fresh alfalfa. The annual production is from 1,000 to 1,500 tons, with a production of 10,000 tons possible.

In northern Iceland a diatomaceous earth drying plant uses high-temperature steam to remove about 80 percent of the moisture from a diatomaceous slurry dredged from nearby Lake Myvatn. Hot water keeps the beneficiated diatomite slurry reservoir from freezing during operation in winter. Steam is used for keeping the slurry tank from freezing, for space- and fuel-oil heating and, for the most part, in drying the diatomite slurry in steam tubes. Figure 2 illustrates the flow diagram of the diatomaceous drying process (Howard, 1975). In addition, Iceland has developed several experimental projects for the drying of wool, fish, seaweed, hay and other grains.

Other industrial uses occur in Hungary, Japan, the Philippines, and China. The U.S. industrial uses will be described in detail later in this paper.

2. APPLICATIONS AND POTENTIAL USES

Direct utilization of geothermal energy for 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 design 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.

Industrial processing typically requires the highest temperatures, using both steam and superheated water. Temperatures up to 150^{o}C are normally desired; however, lower temperatures can be used in some cases, especially for drying of various agricultural products. Some experimental work is being performed with grain, hay, tobacco and paprika drying. In these cases, hot water supplies heat to forced-air heat exchangers and 49^{o}-60^{o}C air is blown over the product to be dried (Lienau/Boldizar, 1974). A graphic representation of application temperatures is shown in Figure 3. Figure 4 gives the percentage of various process heat requirements met by various temperature ranges (Lund, 1980).

Reports by Lindal (1973), Reistad (1975) and Howard (1975) survey industrial applications and the potential for geothermal use in a number of the industries. The following is an outline of the basic processes and several of the more recently considered applications.

a. Basic Processes

In industrial applications, thermal energy in the temperature range being considered here (up to 150°C) is used in the basic processes of:

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

b. 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 10°-16°C up to the temperature at which it is introduced into the boiler, typically 90°-150°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.

c. Washing

Large amounts of low-temperature energy (35^{o}-$90^{o}C$) 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 ($60^{o}C$); in soft-drink container and returnable bottle washing ($77^{o}C$); in poultry dressing as well as canning and other food processes. Textile industry finishing plants are another large consumer of wash water at $90^{o}C$. Smaller amounts are used in plastics (88^{o}-$93^{o}C$) and leather ($50^{o}C$). Most of these are consumptive uses.

Sizable amounts of hot water and other hot fluids at temperatures under $90^{o}C$ 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 nonconsumptive uses with a 6^{o}-$14^{o}C$ range in the fluid and reheating to the use temperature.

d. 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 77^{o}-104^{o}C. These heating requirements are readily adaptable to geothermal resources.

e. 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 80^{o}-120^{o}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.

f. <u>Sterilizing</u>

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 105^{o}-$120^{o}C$ 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.

g. <u>Drying</u>

Many industries utilize heat at temperatures under $150^{o}C$ 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 90^{o}-$150^{o}C$ 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. Additional details are presented in Section 7.

h. Refrigeration

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

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 163^{o}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 90^{o}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^{o}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 120°C for a reasonable performance.

3. DETAILS OF SELECTED INDUSTRIAL APPLICATIONS

Three different industrial applications of geothermal energy will be described in detail. The three are vegetable dehydration, milk pasteurization and grain drying. All of these processes are presently in operation in the world using geothermal energy: two in the U.S. and one in New Zealand. Several design modifications are proposed to conventional facilities to utilize low-temperature geothermal resources.

a. Vegetable Dehydration

Various vegetable products such as onions, tomatoes, carrots, peas, potatoes and fruits such as apples can be considered for dehydration. Their dehydration temperature is around 100°C as seen in Figure 5. Potato processing requires higher temperatures. Vegetable and fruit dehydration involves the use of a continuous operation, belt conveyor or batch process using fairly low-temperature hot air from 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 4,500 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 6 illustrates a typical conveyer 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 vegetables 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. As an example of this type of process, onion dehydration will be discussed in detail.

(1) <u>Onion Dehydration</u>

(a) <u>General Description</u>. All onions for processing are grown from specific varieties best suited for dehydration. Specific strains of the Creole Onion, Southport Globe Onion, and the Hybrid Southport Globe were developed by the dehydration industry. They are white in color and possess a higher solid content which yields a more flavorful and pungent onion.

Onion dehydration involves the use of a continuous operation, belt conveyor using fairly low-temperature hot air from 37^{o} to 104^{o}C. The heat originally was generated from steam coils, but now natural gas is more popular. Typical processing plants will handle

4,500 kg of raw product per hour (single line), reducing the moisture from around 83 percent to 4 percent (680 to 820 kg finished product). These plants produce 2.3 million kg of dry product per year using from 35 to 45 x 10^3 kilojoules (kJ) per dry kg produced (+ 14 x 10^3 kJ of electrical energy), or 9.3 x 10^3 kJ per kg of water evaporated.

An example of one type of processing equipment, the Proctor dehydrator, is a single-line unit 65 meters long and 3.8 meters wide requiring 2,450 m^3 of air per minute and up to 42 x 10^6 kJ per hour. Due to the moisture removal, the air can in some cases only be used once, and thus is exhausted. Special silica gel--Bryair, desiccation units are required in the final stage. Approximately $200,000 in fuel are thus used for a single-line dryer in a year's operation (180 days).

(b). Processing Steps. Onion dehydration using a continuous conveyor dryer involves the following basic steps: 1) harvesting, 2) transporting to the plant, 3) curing, 4) washing, 5) slicing, 6) dehydration in four stages, 7) milling, and 8) packaging. Each of these steps is discussed in detail for a Proctor (Proctor and Schwartz, Inc. of

Philadelphia) dehydrator. A cross-sectional diagram of a typical dryer is shown in Figure 6.

Harvesting is accomplished mechanically by specialized equipment that is designed and fabricated by the processing industry. Harvesting is accomplished by a small crew of 20 to 30 people used to inspect the onions and to operate the equipment. The onions are topped, dug, inspected, and loaded into bulk trucks holding about 22,700 kg each.

The trucks loaded with onions are taken directly to the plant. They are loaded into large curing bins where excess moisture is removed by passing large volumes of heated air (38°C) through the onions. Curing conditions the onions so that peeling and processing can be accomplished successfully.

After curing for 48 to 72 hours, the onions are passed into the processing line. The earlier method of scooping up the onions with a tractor has been replaced with an automatic conveyor system that gently carries them to the preparation line. Machines automatically remove any tops that may remain attached to the onions. They are then inspected, washed in a high-pressure washer, soaked in a stainless steel tank to remove sediment, washed again in a high-pressure washer, and re-soaked in a bath of highly chlorinated water in order to reduce bacteria to the lowest possible level. The onions are then reinspected and placed in stainless steel surge tanks. Two large stainless steel tanks are used so that one can be washed as the other is being used. The onions are fed out of the surge tanks into the slicers. Razor-sharp rotating knives cut the onions into uniform slices, which are then passed to the dryer.

From the slicers a continuous and uniform flow of onions is conveyed to the wiper feed that carries the sliced product laterally across the open feed end extension. Here the onions are carefully transferred to the dryer conveyor for the first stage of drying. This is the most critical stage, where, under high-volume air flow conditions and with moderately high temperatures, the bulk of the water is rapidly removed from the onion. The moisture content of the onions is reduced from an initial 83 percent to 25 percent. This is called the "A" stage, where onion loading depth is approximately 10 cm.

Absolute uniformity and controlled depth of loading on the dryers is necessary to prevent "pinking," an enzymatic discoloration that can take place in the onion slice if proper drying conditions are not maintained.

The pure white color of the discharged product from this drying stage is a test of the high quality of the product. Normal drying temperature for stage "A" is around 104^{o}C; however, temperatures as low as 82^{o}C can be used. The lower temperature will increase the processing time; however, the quality will be improved.

High-powered blowers and exhaust fans move the air over natural gas burners, 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 and a long list of safety devices control the continuous operation.

At the proper point in the drying process, the onions are automatically transferred to the second stage ("B" stage) of drying where, under reduced temperature conditions and deeper bed loadings (approximately 30 cm), the difficult-to-remove diffused water is slowly withdrawn. Here, moisture content is reduced to 10 percent. At the special transfer zone, the onions are gently handled by rotary devices that assure full removal from the first-stage dryer and separation removal of clumps for uniform second-stage loading.

The second stage of drying transfers to the third stage ("C" stage) with even deeper loading (approximately 75 to 100 cm deep), as the deeply diffused water becomes even more difficult to remove. 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 leaving the "C" stage, moisture content is down to 6 percent.

A special unloader takes the now nearly dry onions off the third-stage conveyor, transferring them to the elevating conveyor for the fourth and final stage of dehydration. Here, conveyor loading depths up to 1.8 meters are used for final moisture reduction and equilibration. Dehumidified air from a two-stage desiccation unit is counterflowed through this deep layer to bring the finished onions to the point (about 4 percent moisture) where milling can best be accomplished and shelf life maintained.

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 milled into sliced, large chopped, chopped, ground, granulated and powdered onions.

(c) Power Production and Energy Requirements. The energy requirements for the operation of a dryer will vary due to difference in outside temperature, dryer loading, and requirement for the final moisture content of the product. A single-line Proctor dryer handling 4,500 kg of raw product per hour (680 to 820 kg finished) will require about 5.3×10^8 kJ/day, or for an average season of 150 days, 8.0×10^{10} kJ/season, using approximately 35×10^3 kJ per kg of dry product.

The energy is provided by natural gas; air is passed directly through the gas flame in stages A and B, and over steam coils in stages C and D. The steam coils are necessary to prevent turning of the onions in the last two stages.

In addition to the heating requirements, electrical energy is needed for the draft and recirculation fans and small amounts for controls and driving the bed motors. Total electric power required for motors is from 500 to 600 horsepower, or about 1 x 10^4 kWh/day, or 2 x 10^6 kWh/season. This amounts to 2 x 10^3 kJ per kg of finished product and increases to about 14 x 10^3 kJ per kg when all electrical requirements are considered.

The details of each stage of a typical process are shown in Table I.

In general, four stages (A through D) are preferred; however, if the ambient air humidity is below about 10 percent, stage D can be eliminated. Also temperature and number of compartments in each stage may vary.

Stage D, supplying desiccated air with a Bryair unit, reduces the moisture content of the product to a point below that of the ambient air. The unit is divided into two sides: the process side, which supplies desiccated air to the dryer after it has been passed through silica gel beds; and the reactor side in which heated air is passed over the silica gel beds in order to remove the moisture which had been absorbed in the process side.

The process air is drawn in from the outside under ambient conditions of temperature and humidity, passed through a filter and a cooling coil, and then is circulated through the dry silica gel beds where some of the moisture is absorbed. The process air then is drawn out by a fan and directed to the D2 stage of the dryer. This process air leaves the Bryair unit at a temperature of about 50°C with a moisture content of about 4 grams per kilogram.

On the reactor side, ambient air is drawn into the intake and passed over a gas burner which heats the air to about 120°C, after which the air is circulated through the silica gel beds so that the moisture which had been absorbed in the process side is removed.

A suction fan on the discharge side then exhausts the moisture-laden reactor air to the atmosphere at temperatures of from 66° to 107°C. A slight pressure differential is maintained between the process and reactor sides so that air is prevented from leaking to the process side from the reactor side.

In summary, total energy requirements are as follows: Single-line Proctor dehydrator approximately 64 meters long by 3.8 meters wide; average input 4,500 kg wet product (15-20 percent solids) producing 680 to 820 kg dry product (95-96 percent solids) per hour requires 2.3 kJ/hr of heat energy or 1.0×10^{11} kJ/season (180 days).

A specific example of a Proctor dehydrator is detailed in Table II, and Figures 7 and 8. The total energy requirements, using natural gas as a fuel, varies from 22 to 27 x 10^6 kJ/hr depending upon the abmient air varying from 18^{o} to $4^{o}C$. Air flows depend upon temperature and amount of recirculated air--which could only be estimated.

(d) Geothermal Applications. Using the specific example detailed in Table II and Figures 7 and 8, a design was made to convert the Proctor dehydrator to geothermal energy. Using an $11^{o}C$ minimum approach temperature between the geothermal water an process air, a well with $110^{o}C$ water is required.

The first-stage air temperature can be as low as $82^{o}C$; however, temperatures above $93^{o}C$ are desirable, as indicated by people in the industry.

Figure 9 indicates Design I using $110^{o}C$ water. The line has to be split between compartments A-1 and A-2, since both require $99^{o}C$ air temperature. A total of 57 l/s (liters/second) is required. Two wells can probably supply this volume, as 31 to 38 l/s have been pumped from existing wells in the U.S. The Bryair desiccator requires $149^{o}C$ on the reactor side, thus only half of the $1.1x10^{6}$ kJ/hr energy requirements can be met geothermally. Geothermal heat will be used for preheating to $79^{o}C$, with natural gas or propane used to boost the air to $149^{o}C$. The waste water from the Bryair preheater has a temperature of 89°C, thus this could be used for space heating, greenhouses or other low-temperature energy needs. The waste water would be returned by an injection well.

Design I considers the ambient air to be 4°C (worst conditions), while Design II considers an 18°C air temperature. This will reduce the required flow to 48 l/s, however, still requiring two production wells.

Design III uses 104°C geothermal water and 93°C air temperature for compartment A-1. This requires 61 l/s, or again two wells.

In compartments A-1, A-2, A-3, and A-4, four finned air-water heat exchangers in parallel would be required to satisfy the energy requirement and water velocity flows. The remaining stages would require from one to two heat exchangers in each compartment, depending upon the energy requirements.

The details of the flow patterns for Designs I, II and III are shown in Figures 9, 10 and 11.

If lower-temperature geothermal waters were encountered (below 93°C), then not all of the energy could be supplied to Stage A geothermally. Geothermal water would then be used as a preheater, with natural gas providing the energy for the final temperature rise. A design of this type for compartment A-1 was considered in the Trident Report (1977) for the Solar Division of ERDA.

(e) Case History of an Existing Plant (See: GRC, 1978; Rodzianko, 1979.) The first U.S. vegetable dehydration plant to utilize geothermal energy is located at Brady Hot Springs, approximately 80 kilometers east of Reno, Nevada (Figure 12). The Geothermal Food Processors, Inc. (GFP) facility, housed in a 12- by 183-meter building near the former site of the Brady Hot Springs health resort, uses 132°C geothermal fluid from a well located about 300 meters south of the plant to warm the air used to cure and dry vegetables such as onions, celery and carrots. The geothermal energy replaces about 3.3×10^6 m^3 of natural gas a year which otherwise would have been needed and would have cost an estimated $235,000 per year.

The original concept motivating the formation of Geothermal Food Processors, Inc. was the ability of the geothermal energy source to deplace the use of natural gas in the dehydration process.

The steps involved in the production and processing of onions for dehydration at Brady Hot Springs are as follows:

- Seed development
- Growing
- Harvesting and delivery
- Curing
- Washing and preparation
- Slicing
- Dehydration
- Milling
- Quality control and final packaging

It can be seen in these steps that fluids and/or heat can be used at the curing, washing (wet preparation), and dehydrating stages of the process. The hot water was originally expected to supply heat for the dehydration process alone, but the advantages of using geothermal water in the wet preparation phase have become clearly evident. Because of the oxygen-free and essentially bacteria-free nature of the fluid, use of the water during the wash helps to maintain the low bacterial count (below industry standards) of the GFP product.

Although the plant is capable of processing 14 $\times 10^6$ kg of raw onions per year, initial production will run between 7 and 8 $\times 10^6$ kg. In a normal year, onion processing will start about May 15 and continue to November 1. After a short conversion period, the plant will process celery from November 15 to January 15 followed by a run of carrots from

March 1 to April 15. It is possible that sometime in the future, the plant will process potatoes as well.

Geothermal fluid is pumped from the well through an insulated pipeline 400 meters long to a heat exchanger, which transfers the heat in the geothermal fluid to air, which is then used in the dryer. From this point on, the technology associated with the plant is conventional and common to the food industry. The onions are fed into a series of drying plenums where air, warmed by geothermal energy, is passed through them to provide initial drying and curing of the skins. They then proceed through topping, coring, washing and dicing operations to a 3-stage, 58-meter dryer which also uses the geothermally heated air, and finally through sizing and packing operations. Approximately 75 persons are employed in the operation of the plant.

It appears that, because of the use of the local geothermal resource, GFP has been able to produce a superior dehydrated product. Color is generally excellent in large part because of "hot spots" resulting from the heat of the burning natural gas improperly adjusted are eliminated since the lower temperature of the geothermal fluid cannot scorch it. In addition, bacteria-free fluids in the washing stages help keep the overall bacterial count low as compared with other manufacturers.

b. <u>Milk Pasteurization</u>

(See Lund, 1976; GRC, 1979.)

Medo-Bel Creamery, in Klamath Falls, Oregon, is the only creamery known to use geothermal heat in the milk pasteurization process (Figure 13). The geothermal well located at the corner of Spring and Esplanade Streets was first drilled in 1945 by the Lost River Dairy. The well was designed by a New York engineering firm to insure maximum heat at the well head with a minimum of pumping time.

A 233-meter deep well was cased to 109 meters with 20-cm diameter casing and to 149 m with 15-cm diameter casing. The original well had an artesian flow of around 119 l/s at the surface of 82^{o}C water. Based on a recent profile (1974) the well water varies from 80^{o}C at the surface to 98^{o}C at a depth of 137 meters, with the artesian surface at one meter below the ground level. The geothermal hot water is pumped directly from the well to the building approximately 15 m away through an overhead line. This overhead line allows easy maintenance and prevents freezing during cold weather since it is self-draining.

Rather than using downhole heat exchangers as is common in Klamath Falls, the water is used directly in air handing units in each room and in the plate-type pasteurizing heat exchanger (Figure 14). The used hot water is then emptied into the storm sewer where it is later used by industry in the south end of the town.

The pasteurization process involves pumping up to 6 l/s into the building and through a short-time pasteurizer (Cherry Burrell plate heat exchanger of stainless steel construction). The geothermal water is pumped from the well at 87°C and passes through the heat exchanger where the milk is heated to a minimum temperature of 77°C for 15 seconds. If the milk temperature should drop below 74°C, the short-time pasteurizer automatically recirculates the milk until the required exposure is obtained. The milk then goes to the homogenizer at 77°C back to the short-time pasteurizer to cool by chill water to 3°C where the milk goes into the cartons with no chance of cook on. This insures both flavor and longer shelf life. As an added bonus, the outgoing heated milk is cooled somewhat by passing it by the incoming cold milk and the cold milk is in turn heated slightly by the outgoing milk. Milk is processed at a rate of 0.8 l/s, and a total of 225,000 kg are processed each month.

Some steam is necessary in the process to operate equipment, thus geothermal water is heated by natural gas to obtain the required temperature. Geothermal hot water is also used for other types of cleaning.

In addition to the milk pasteurizing, some batch pasteurizing of ice cream mix is carried out by geothermal heat. A 950-liter storage tank is used to mix geothermal hot water and process steam to a temperature of 121°C. This heat is then used to pasteurize the ice cream mix at 63°C for 30 minutes. This method is the original pasteurizing method used at the creamery.

The geothermal water has slightly over 800 ppm (mg/l) dissolved solids of which approximately half are sulfate, a quarter sodium and a tenth silica. The pH of the water is 8.8. Minimum corrosion is evident in the well, requiring the jet pump to be replaced only once in the 30-year period (1974). The original pump was rated at one hp and the new pump is rated at 7-1/2 hp. The corrosion has also been minimum in the area heaters and does not affect the stainless steel plate heat exchanger. Corrosion has been substantial in the pipelines.

The annual operational cost of the system is negligible. However, the savings amounts to approximately $1,000 per month as compared to conventional energy costs. Geothermal hot water is also used to heat the 2,800 m^2 building, which amounts to a substantial savings during the winter months.

c. 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 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 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 82°-121°C. Figure 15 shows schematics of such an alfalfa-drying plant. The chopped field-wilted material is fed to a dryer where heated air 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 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 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 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 30-50 m^3 of air per minute are required per cubic meter of green malt in the kiln. If the drying rate is too rapid, the grain will shrink and crack and suffer general physical damage.

A detailed description of alfalfa dehydration is discussed in the following section.

6. ALFALFA DEHYDRATION

a. General Description.

Two basic products are made from the dehydrated alfalfa: pellets and cubes. The cubes are about 4 cm x 4 cm x 8 cm long. Cube production generally only requires field (sun) drying to about 17 to 19 percent moisture. During production the cubes generate heat and must be cooled at the end of the production cycle. When used as feed, the cubes do not require the addition of roughage. The pellets are about 0.5 cm in diameter by 1-2 cm long and they require significant quantities of heat for dehydration at a plant. They require about 1×10^7 kJ per ton of dried product or 2×10^6 kJ per ton of wet product in the process. When used as feed, the addition of roughage is necessary--costing about the same as the pellets.

Two different types of dehydration plants are known. The first, a rotary flame furnace used in the United States, requires temperatures up to 1000°C, and the other, used in New Zealand, is a forced-air system using a multi-layer conveyor belt with temperatures up to 120°C. In both cases, it takes about 4,500 kg of wet alfalfa to produce 900 kg of finished product.

(1) California High Temperature Plant. A large alfalfa dehydration plant in the Sacramento Valley of California will produce 10,000 to 30,000 tons of finished pellets per year consisting of both alfalfa and brewers grain waste from a nearby brewery. The pellets are -0.5 cm in diameter by 2 cm long produced from alfalfa at an initial moisture content of 77-82 percent and with a final moisture content of 10 percent.

A Sterns-Rogers single-pass rotary dryer is used, evaporating 27,000 to 30,000 kg of dry product per hour with a 100 million kJ/hr natural gas burner. Thus, this requires about 37 x 10^3 kJ per kg of dry product.

The main advantage of this process over sun curing is that more vitamin A and xanthrophyll (a yellow pigment present in the normal chlorophyll mixture of green plants) is retained. The latter is important in chicken and egg coloring. The xanthrophyll is retained better by high heat and rapid dehydration.

(2) New Zealand Low-Temperature Plant. The system used in New Zealand at Broadlands is the result of a cooperative of 12 farms in the area, formed in 1973. Over a three-year trial period the system has proved successful and up to May, 1977, some 3,000 tons of dried alfalfa pellets have been produced.

In general, theothermal steam from a deep well bore in the Broadlands geothermal field is used. The steam if produced via a separator and used in a heat exchanger system to produce a hot air stream of approximately 135°C. The plant uses 7,200 kg of steam per ton of pellets. A simple fixed bed, double-pass dryer is used. This dryer is made by the company and the system is unique. A continuous operation extracts approximately 3,600 kg of moisture per hour giving approximately one ton per hour of dried alfalfa per drying unit. A larger 1-1/2 ton per hour unit is at present being developed. The system can be used for all types of green feed and grains and should also be suitable for wood chips, etc. The alfalfa pellets produced are of high quality, strong green in color and exceed international specifications for alfalfa products. They are completely free of any type of contaminant, the material being dried in hot fresh air at all stages.

The alfalfa (lucerne) grown by farmers in the area surrounding the plant is chaffed and blown directly into trucks and delivered to and loaded onto the dryer elevator at moistures ranging between 70 and 85 percent. The drying cycle takes approximately 1/2 hour and the dried materials being auger discharged into a hammer mill. It is then transported to the pellet press where it is compressed into pellets for storage and transport. Labor in the plant is minimal, two men being able to operate the entire process excluding harvesting. A plant to produce 3 tons of pellets per hour would cost $500,000 and would require 1,200 hectares of alfalfa to keep the plant working at full capacity. Working 4,000 production hours per year would produce 10,000 tons of pellets.

(3) Boardman, Oregon, Low-Temperature Plant.

A new method of dehydration has been used in the Boardman area in northern Oregon. This involves wilting the product in the field to remove about 25 percent moisture. The balance of the moisture is then removed by dehydration at the plant in order to retain as much of the nutrient value (vitamin A) as possible. This process requires temperatures from 80^{o} to 120^{o}C.

There are several reasons for fuel drying on the final product instead of complete sun wilting.

Fuel drying produces a harder and heavier pellet, and retains a greater percentage of the vitamin A and xanthrophyll.

Ideally, 100,000 to 125,000 international units of vitamin A and xanthrophyll are needed; however, this can only be achieved by complete fuel drying as described in the California plant. By field wilting and then some fuel drying, they can retain a minimum of 17 percent protein and an average of 55,000 international units of vitamin A (xanthrophyll is assumed to be at about the same level as vitamin A). In addition, a bright green color is maintained that appears to improve the salability of the product.

The domestic market uses pellets for a feed mix. The main advantage with the process at Boardman is:

(a) Low fuel and temperature requirements.
(b) High field moisture loss.
(c) A final product with a bright green color.
(d) An average of 55,000 international units of vitamin A (xanthrophyll assumed to be at the same level).
(e) A minimum of 17 percent protein.

A plant of this type will produce 80 to 110 tons of pellets per eight-hour shift (ten tons per hour average--16 to 17 tons maximum). The alfalfa is purchased (or costs the company) at $45 to $55 per ton standing (at 12 percent moisture), and costs an additional $20 per ton to harvest and pellet. Of the total cost $2.50 is due to the actual drying or about 23 liters of fuel oil per ton of alfalfa (at $.40 per gallon). This fuel usage can range from 19 to 113 liters per ton depending upon the moisture content and the ambient conditions. The total cost of pellets is $65 to $75 per ton, of which about $5 per ton is the margin of profit. Thus any fuel savings by converting to geothermal would have a significant percentage effect on the margin of profit.

The main disadvantage with this process is that it does not produce any roughage or fiber. Cubing will provide the necessary fiber, otherwise the pellets must be combined with roughage for domestic use. Cost of the construction of a pellet plant today is around $1 million, whereas a stationary cubing plant would cost $200,000 and a field cubing plant about $50,000.

b. Processing Steps.

The processing steps for the plant as described for the Boardman area are somewhat unique in the West, as it involves field wilting and a final dehydration in a rotary drum dryer. This process is also being attempted in the Midwest of the United States. Approximately 25,000 to 30,000 tons of alfalfa pellets (at 8 to 15 percent moisture) can be produced each year at 20 tons per hectare (at 8 percent moisture). This assumes four to five cuttings per year. It should be pointed out that the Boardman area has extremely dry and hot summers with little or no rain, thus making field wilting practical.

The process starts with cutting and chopping the alfalfa in the field at about 70 percent initial moisture. The chopped material is then allowed to sun wilt for 24 to 48 hours to a 15 to 25 percent moisture content. This can easily be accomplished in the Boardman area due to available sun and low rainfall (if any) during the season. The Midwest is only able to wilt to about 60 percent moisture. This short field wilting time also prevents minimal damage to the next crop, as the cut material is removed before the new shoots sprout and are crushed by equipment. The field wilted material is then trucked to the plant (generally a short distance as they cannot afford to haul "water"), and stockpiled for no more than a couple of days. The chopped material is then belt-fed to a triple-pass rotary drum dryer. This dryer initially used natural gas for fuel, but this has been cut off so they now use fuel oil. The alfalfa is dried at a temperature below 120^{o}C, as any temperature over 200^{o}C will over-dry the product. The actual drying temperature depends upon the ambient conditions and moisture content of the alfalfa. The final pellets are checked for firmness, color, etc., as a means of adjusting the plant. Drying temperatures can go as low as 80^{o}C, and on some warm days the outside air can produce temperatures of 65^{o}-70^{o}C without fuel. The material is moved through the dryer by a suction fan capable of producing 1,400 m^3 per minute (25 percent of this air is recycled). The retention time is about 15 to 20 minutes.

From the dryer, the alfalfa is fed to the hammermill and the pellet meal bin. The latter is the surge point in the system. Here the material is conditioned with 8 kg per ton of 2,450 g/cm^2 production steam and then fed to the pellet mill pressure extruder. The steam helps in providing a uniform product and makes it easier to extrude the alfalfa through the 0.5 cm diameter holes in the circular steel plates. The material is then cooled and the fines removed in a scalper. Finally, the product is weighed on batch scales, packaged and stored.

c. Geothermal Conversion

A low-temperature geothermal energy conversion design was made for the Boardman-type plant, as not enough details were available for the New Zealand-type. However, since the temperatures for both are similar, a design for the New Zealand-type using geothermal water instead of steam is possible.

Using a 93^{o}C air drying temperature for the triple-pass dryer would require at least 104^{o}C geothermal water.

Assuming a combination of ambient air and 25 percent recycle air at 24^{o}C and 1,400 m^3 per minute, 7.2 x 10^6 kJ/hr would be required.

If only 93^{o}C water were available, then 82^{o}C air could be used requiring 6.6 x 10^6 kJ/hr.

The following combinations of flow rates and temperatures could be used to provide the necessary energy.

T_1 (Geothermal water incoming °C)	F_1 (Geothermal water flow l/s)	T_2 (Waste geothermal water temp. °C)
104°	31	89°
104°	19	79°
93°	31	79°
93°	19	70°

One could then provide the required flow, with one injection well for the waste water. The assumed layout of the plant and wells are shown in Figure 16. Due to the high energy requirements and flow rates, a four-pass fixed water-to-air heat exchanger would be required.

6. 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.

a. <u>Retrofit vs. New Installations</u>.

In many of the large and complex industrial operations, most of the potential application 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 agri-business 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.

b. <u>Applicability of Heat Pump</u>.

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 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 44°-50°C (the smaller the lift, the better the feasibility) and (2) auxiliary energy, usually in the form of electricity, is required.

c. 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.

7. DRYING DETAILS (Lineau, 1987)

a. Drying Equipment.

(1) Classification of Dryers

The two most useful classifications for drying equipment are based on (1) the method of transferring heat to the wet solids or (2) the handling characteristics and physical properties of the wet material. The first method of classification reveals differences in dryer design and operation, while the second method is most useful in the selection of a group of dryers for preliminary consideration in a given drying problem.

A classification chart of drying equipment on the basis of heat transfer is shown in Figure 17.

Direct Dryers. The general operating characteristics of direct dryers are these:

(a) Direct contacting of hot gases with the solids is employed for solids heating and vapor removal.

(b) At gas temperatures below the boiling point, the vapor content of gas influences the rate of drying and the final moisture content of the solid. With gas temperatures above the boiling point throughout, the vapor content of the gas has only a slight retarding effect of the drying rate and final moisture content.

(c) For low-temperature drying, dehumidification of the drying air may be required when atmospheric humidities are excessively high.

(d) A direct dryer requires more heat per pound of water evaporated, the lower the final moisture content.

(e) Efficiency increases with an increase in the inlet-gas temperature for a constant exhaust temperature.

Indirect Dryers. Indirect dryers differ from direct dryers with respect to heat transfer and vapor removal.

(a) Heat is transferred to the wet material by conduction through a solid retaining wall, usually metallic.

(b) Indirect dryers are suited to drying under reduced pressures and inert atmospheres to permit the recovery of solvents and to prevent the occurrence of oxidation of easily decomposed materials.

(c) Indirect dryers using condensing fluids as the heating medium are generally economical from the standpoint of heat consumption, since they furnish heat only in accordance with the demand made by the material being dried.

(2) Selection of Drying Equipment

(a) Initial Selection. Preliminary selection can be made with the aid of Table 3, which classifies the various types of dryers on the basis of the materials handled.

(b) Initital Comparison. The dryers so selected should be valuated, approximately, from available cost and performance data.

(c) Drying Tests. Drying tests should be conducted in those dryers still under consideration. These tests will determine the optimum operating conditions and the product characteristics and will form the basis for firm quotations from equipment vendors. Manufacturers of drying equipment are usually prepared to perform the required tests on dryers simulating their equipment. Once a given type and size of dryer is installed, the product characteristics and drying capacity can be changed only with relatively narrow limits.

(d) Final Selection. From the results of the drying tests and quotations, the final selection of the most suitable dryer can be made. Important factors to consider are:

1) Properties of the material being handled.
2) Drying characteristics of the material.
3) Flow of material to and from the dryer.
4) Product qualities.
5) Recovery problems.
6) Facilities available at site of proposed installation.

(3) Batch Trays and Compartments

Description. A tray or compartment dryer is an enclosed, insulated housing in which solids are placed upon tiers of trays in the case of particulate solids, or stacked in piles or upon shelves in the case of large objects (Figure 18). Heat transfer may be direct from gas to solids by circulation of large volumes of hot gas, or indirect by use of heated shelves or radiator coils. Compartment units are employed for heating and drying of lumber, sheet materials and all forms of particulate solids.

Because of the high labor requirements usually associated with loading or unloading the compartments, they are rarely used except in the following cases:

a) A long heating cycle is necessary because the size of the solid objects or permissible heating termperature requires a long hold-up for internal diffusion of heat or moisture.
b) The quantity of material to be processed does not justify investment in more expensive, continuous equipment.

Satisfactory operation of tray-type dryers depends on maintaining a constant temperature and a uniform air velocity of 61-610 m/min (200 to 2000 ft/min) over all the material being dried. Non uniform air flow is one of the most serious problems in the operation of tray driers.

Trays may be square or rectangular, with 1.2 to 2.4 m^2/tray (4 to 8 sq. ft/tray), and may be fabricated from any material compatible with corrosion and temperature conditions. When the trays are stacked in the truck, there should be a clearance of not less than 3.8 cm (1.5 in.) between the material in one tray and the bottom of the tray immediately above. Metal trays are preferable to non-metallic trays, since they conduct heat more readily. Tray loadings range usually from 1.3 to 10 cm (0.5 to 4.0 in.) deep. Steam is the usual heating medium and a standard heater arrangement consists of a main heater before the circulating fan.

Air is circulated by propeller or centrifugal fans; the fan is usually mounted within or directly above the dryer. Total pressure drop through the trays, heaters, and ductwork is usually in the range of 2.5 to 5.0 cm (1 to 2 in.) of water. Air recirculation is generally in the order of 80 to 95 percent, except during the initial drying stage of rapid evaporation. In most installations, air is exhausted by a separate small exhaust fan with a damper to control air-recirculation rates.

(4) Continuous Tunnels

Schematic diagrams of three typical tunnel arrangements are shown in Figure 19. Continuous through-circulation dryers operate on the principle of blowing hot air through a permeable bed of wet material passing continuously through the dryer. Drying rates are high because of the large area of contact and short distance of travel for the internal moisture.

The most widely used type is the horizontal conveying-screen dryer in which wet material is conveyed as a layer, 2.5 to 15 cm (1 to 6 in.) deep, on a horizontal mesh screen or perforated apron, while heated air is blown either upward or downward through the bed of material. This dryer consists usually of a number of individual sections, complete with fan and heating coils, arranged in series to form a housing or tunnel through which the conveying screen travels. The air circulates through the wet material and is reheated before re-entering the bed. Usually hot gases are circulated upward at the wet end and downward towards the dry end. A portion of the air is exhausted continuously by one or two exhaust fans, which handle air from several sections. Since each section can be operated independently, extremely flexible operation is possible, with high temperatures usually at the wet end, followed by lower temperatures at final conditioning. The maximum pressure drop that can be taken through the bed of solids without developing leaks or air bypassing is roughly 5.0 cm (2.0 in.) of water.

Steam-heated air is the usual heat-transfer medium used in these dryers, although combustion gases may be used. Temperatures above 315°C (600°F) are not usually feasible because of problems of lubricating the conveyor, chain and roller drives. Recirculation of air is in the range of 60 to 90 percent. Conveyors may be made of wire-mesh or perforated-steel plate. The minimum practical screen opening size is about 30 mesh.

(5) Rotary Dryers

A rotary dryer consists of a cylinder, rotated on bearings and inclined to the horizontal. The dryer is sloped so that the material gradually flows along the length of the shell.

The rotary dryer is one of the most widely used forms of continuous dryer. It is suitable for drying a wide range of materials rapidly and at a low unit cost when quantities are large. Rotary dryers are quite suitable for heat-sensitive materials provided that the restriction of drying temperature does not result in any excessive drying time. The tumbling action is beneficial within limits for all products since any semi permeable crust on the surface on the particles (case hardened) is disrupted, thus allowing easier escape of moisture from their inside.

Rotary dryers can be classified primarily as direct, indirect, and indirect-direct. The terms refer to the method of heat transfer, being direct when heat is added to or removed from the solids by direct exchange between flowing gas and solids. Indirect being when the heating medium is separated from physical contact with the solids by a metal wall or tube. Indirect-direct is a combination, and there are a number of other special types. Only totally indirect will be discussed here, since they are applicable to using geothermal steam.

<u>The Indirect Dryer</u>. In the case of direct dryers continuous rows of lifters are used to pick up the material and it then cascades through the air stream. For the indirect dryer, lifters are replaced by tubes containing steam or hot water. In small machines there is one row of tubes, but in most sizes two rows are employed, the inner row being of smaller diameter than the outer

(see Figure 20). The feed is heated by direct contact with the tubes over which it flows in a thin layer. Air is drawn through the dryer in sufficient quantity to remove the water vapor. The air leaves the dryer almost saturated so that the quantity required is usually much less than in a direct rotary dryer. The air velocity is usually about 0.3 m/s (1.0 ft/s).

The heating steam is introduced into the tubes, and condensate is removed, through a rotary gland at the solid discharge end of the dryer. The dry solid is discharged through ports in the shell, which have dams to maintain a sufficient depth of bed. Because of the low heat losses in the exit air stream the efficiency is high. It is suitable for heat-sensitive materials as the maximum temperature can be accurately controlled by control of the temperature of the heating medium. It is not suitable for any materials that cake strongly on the heating tubes.

Steam is admitted to the tubes through a revolving steam joint into the steam side of the manifold (Fig. 21). Steam manifolds for pressures of up to 10.5 kg/cm^2 (150 psig) are of cast iron. The tubes are fastened rigidly to the manifold face plate and are supported in a close-fitting annular plate at the other end to permit expansion. Packing on the steam neck is normally graphite-asbestos.

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Table 1
STAGES OF ONION DEHYDRATION

Stage	Size (length) (m)	Motor Output (hp)	Air Temperature °C	Air Volume m^3/min*	Depth of Onions (cm)	Moisture Content (%)
Curing bins	30 x 30	--	38	variable	variable	
Transfer						80-85
A (4 compartments)	22	400	88-104	6,500	10	
Transfer						20-25
B (2 compartments)	7.6	90	68-77	1,700	30	
Transfer						12-16
C (2 compartments)	7.6	70	57	2,000	75-100	
Transfer						6-8
D (2 compartments)	7.6	40	49	5,700	150-180	
Transfer						4-5

*Some air may be recirculated depending upon moisture content.

Table 2
ONION DEHYDRATION

Stage	Air Temperature	Heat Supply	Approximate Heat Exchanger Opening Size	Estimated Air Flow (m^3/hr)	Estimated* kJ/hr x 10^6
A1	99°C	gas burners	3.3 x 0.9 = 3.0 m^2	820	5.3
A2	99°C	gas burners	4.3 x 0.9 = 3.9 m^2	820	6.2
A3	88°C	gas burners	4.0 x 0.9 = 3.6 m^2	1,160	3.8
A4	88°C	gas burners	4.6 x 0.9 = 4.1 m^2	1,160	5.2
B1	71°C	gas burners	4.3 x 0.9 = 3.9 m^2	480	3.8
B2	63°C	steam coils	3.3 x 0.9 = 3.0 m^2	540	1.1
C	54°C	steam coils	4.6 x 0.9 = 4.1 m^2	570	0.4
D	49°C	steam coils	8.8 x 0.9 = 7.9 m^2	300	0.6
Bryair	149°C	gas burners	2.3 m^2	180	1.1
				TOTAL:	27.5 x 10^6

*Assuming ambient at 4°C; total = 22 x 10^6 kJ/hr at 18°C ambient.

Table 3 Classification of Commercial Dryers Based on Materials Handled

Type of dryer	Liquids	Slurries	Pastes and sludges	Free-flowing powders	Granular, crystalline, or fibrous solids	Large solids, special forms and shapes	Continuous sheets	Discontinuous sheets
	True and colloidal solutions; emulsions. Examples: inorganic salt solutions, extracts, milk, blood, waste liquors, rubber latex, etc.	Pumpable suspensions. Examples: pigment slurries, soap and detergents, calcium carbonate, bentonite, clay slip, lead concentrates, etc.	Examples: filter-press cakes, sedimentation sludges, centrifuged solids, starch, etc.	100 mesh or less. Relatively free flowing in wet state. Dusty when dry. Examples: centrifuged precipitates, pigments, clay, cement.	Larger than 100 mesh. Examples: rayon staple, salt crystals, sand, ores, potato strips, synthetic rubber.	Examples: pottery, brick, rayon cakes, shotgun shells, hats, painted objects, rayon skeins, lumber.	Examples: paper, impregnated fabrics, cloth, cellophane, plastic sheets.	Examples: veneer, wallboard, photograph prints, leather, foam rubber sheets.
Tray and compartment. Direct type, batch operation	Not applicable	For very small batch production. Laboratory drying	Suited to batch operation. At large capacities, investment and operating costs are high. Long drying times	Dusting may be a problem. See comments under Pastes and Sludges	Suited to batch operation. At large capacities, investment and operating costs are high. Long drying times	See comments under Granular solids	Not applicable	See comments under Granular solids
Batch through-circulation. Direct type, batch operation	Not applicable	Not applicable	Suitable only if material can be preformed. Suited to batch operation. Shorter drying time than tray dryers	Not applicable	Usually not suited for materials smaller than 30 mesh. Suited to small capacities and batch operation	Primarily useful for small objects	Not applicable	Not applicable
Tunnel. Continuous Tray. Direct type, continuous operation	Not applicable	Not applicable	Suitable for small and large-scale production.	See comments under Pastes and Sludges. Vertical-turbo applicable	Essentially large-scale, semicontinuous tray drying.	Suited to a wide variety of shapes and forms. Operation can be made continuous. Widely used	Not applicable	Suited for leather, wallboard, veneer.
Continuous through-circulation. Direct type, continuous operation	Not applicable	Only crystal filter dryer may be suited	Suitable for materials that can be preformed. Will handle large capacities. Roto-louvre requires dry-product recirculation	Not generally applicable, except Roto-louvre in certain cases	Usually not suited for materials smaller than 30 mesh. Material does not tumble, except in Roto-louvre dryer. Latter operates at higher temperatures	Suited to smaller objects that can be loaded on each other. Can be used to convey materials through heated zones. Roto-louvre not suited.	Not applicable	Special designs are required. Suited to veneers. Roto-louvre not applicable
Direct rotary. Direct type, continuous operation	Applicable with dry-product recirculation	Applicable with dry-product recirculation	Suitable only if product does not stick to walls and does not dust. Recirculation of product may prevent sticking	Suitable for most materials and capacities, provided that dusting is not too severe	Suitable for most materials at most capacities. Dusting or crystal abrasion will limit its use	Not applicable	Not applicable	Not applicable
Pneumatic conveying. Direct type, continuous operation	See comments under Slurries	Can be used only if product is recirculated to make feed suitable for handling	Usually requires recirculation of dry product to make suitable feed. Well suited to high capacities. Disintegration usually required	Suitable for materials that are easily suspended in a gas stream and lose moisture readily. Well suited to high capacities	Suitable for materials that are easily suspended in a gas stream. Well suited to high capacities. Product may suffer physical degradation	Not applicable	Not applicable	Not applicable
Spray. Direct type, continuous operation	Suited for large capacities. Product is usually powdery, spherical, and free-flowing. High temperatures can be used with heat-sensitive materials. Product may have low bulk density	See comments under Liquids. Pressure-nozzle atomizers subject to erosion	Requires special pumping equipment to feed the atomizer. See comments under Liquids	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Continuous sheeting. Direct type, continuous operation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	Different types are available for different requirements. Suitable for drying without contacting hot surfaces	Not applicable

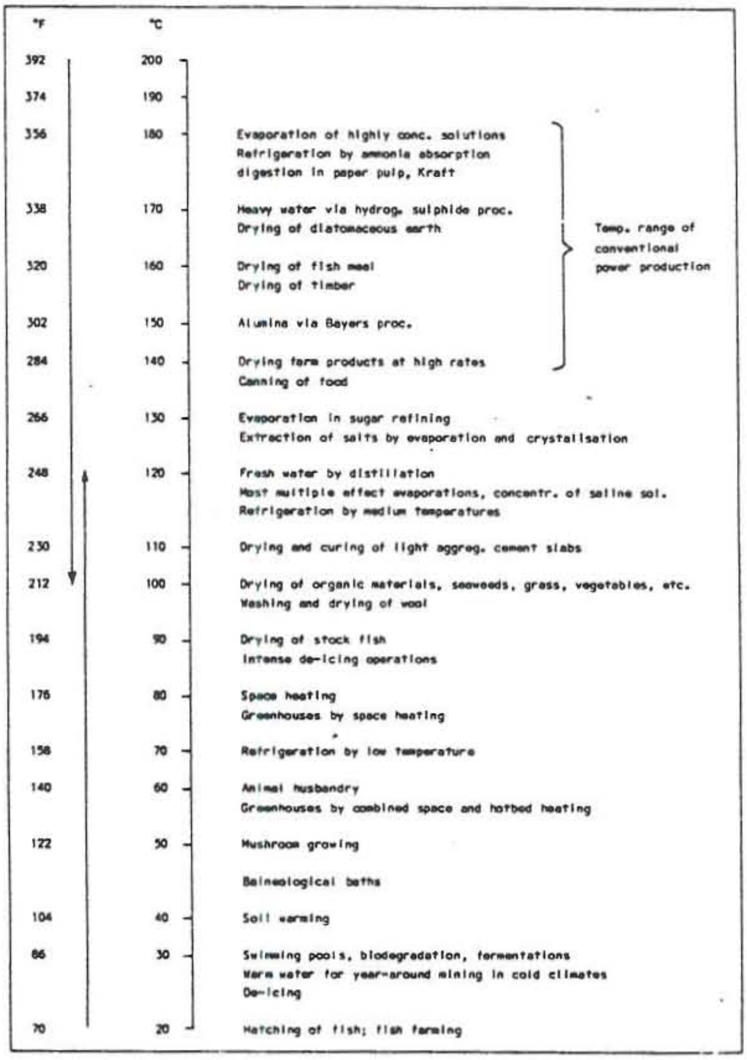


Figure 1. The approximate temperature required for various geothermal uses.

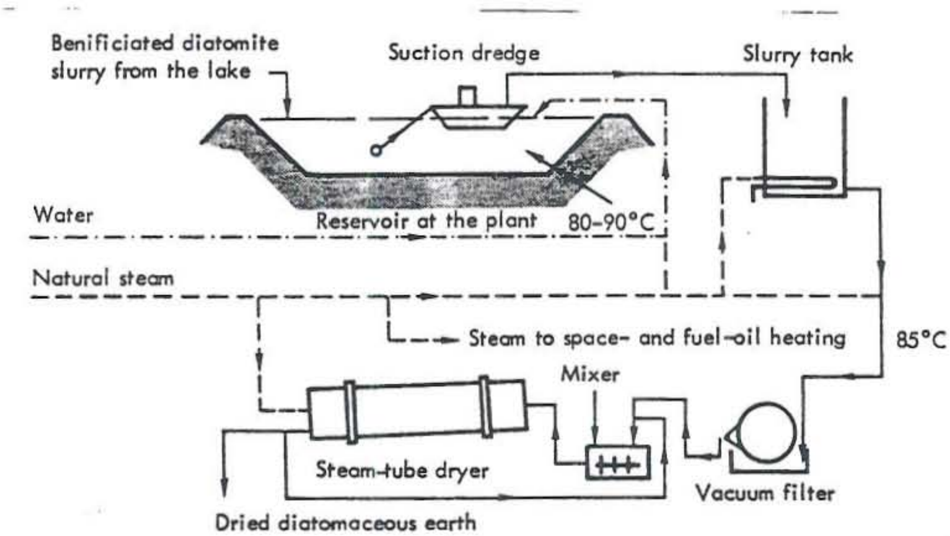


Figure 2. Myvatn, Iceland diatomaceous earth plant.

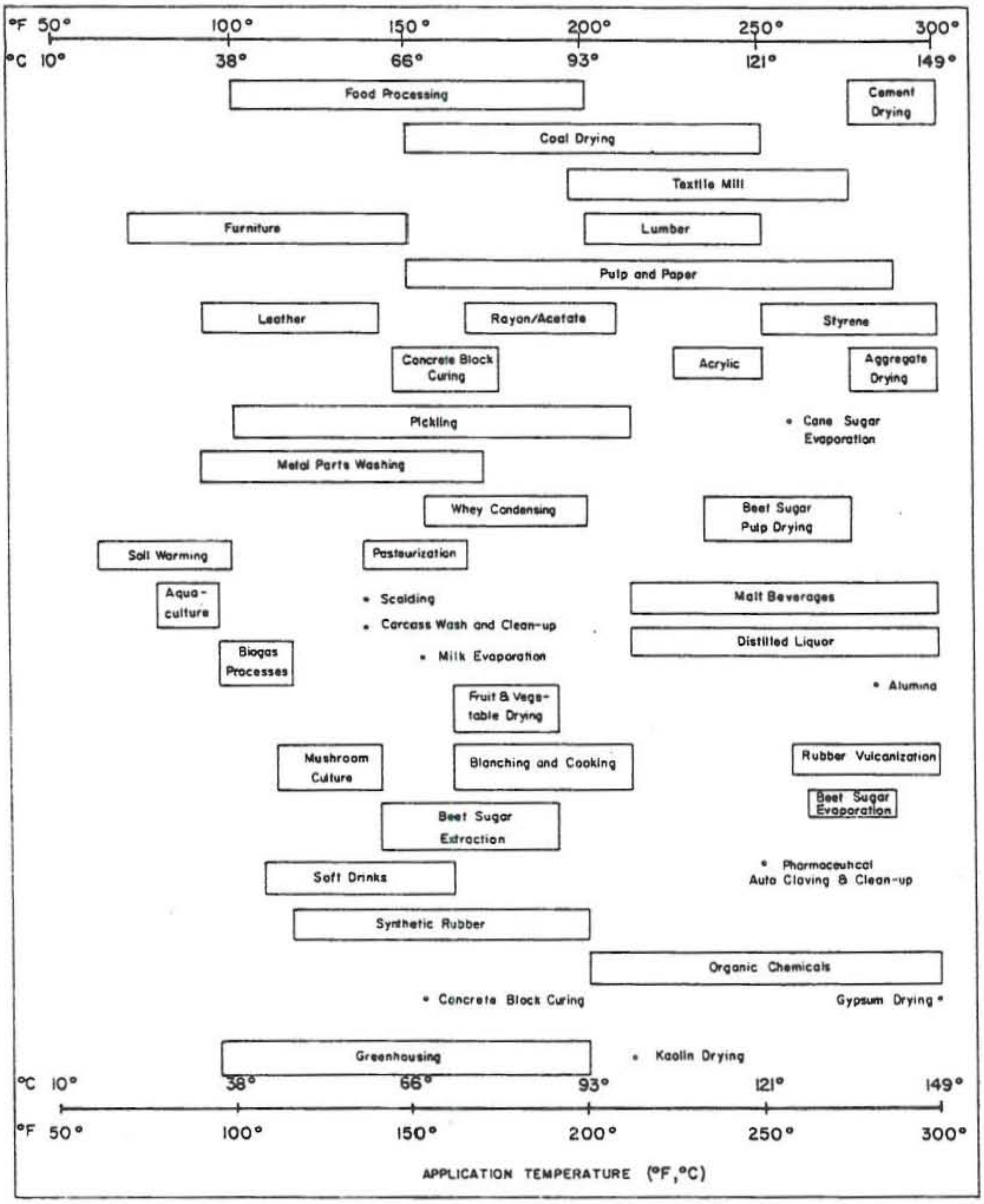


Figure 3. Application temperature range for some industrial processes and agricultural applications.

INDUSTRY	40°C-60°C	60°C-80°C	80°C-100°C	100°C-120°C	120°C-140°C	140°C-160°C	160°C-180°C	180°C-200°C	200°C	250°C
Meat packing	NA	99%	100%							
Prepared meats	NA	46.2%	61.5%	100%						
Natural cheese	23%	100%								
Fluid milk	NA	NA	100%							
Canned fruits and vegetables	NA	NA	22.7%	67.6%	100%					
Dehydrated fruits and vegetables	NA	100%								
Potato dehydration										
granules	NA	19.9%	40%	53%					100%	
flakes	NA	19.9%	40%	53%				100%		
Frozen fruits and vegetables	NA	NA	30%	100%						
Wet corn milling	21.5%			36.4%	46.6%		84.1%		100%	
Prepared feeds										
pellet conditioning	NA	NA	100%							
alfalfa drying	NA	NA	NA	NA	NA	NA	NA	NA	100%	
Beet sugar	NA	7.4%	22.4%		95.4%					100%
Soft drinks	60.9%	100%								
Sawmills and planing mills	NA	NA	NA	NA	NA	100%				
Alumina	NA	NA	NA	NA	76.2%					100%
Soaps	NA	NA	0.6%						100%	
Detergents	NA	NA	52.2%				99.9%		100%	
Concrete block										
low pressure	NA	100%								
autoclaving	NA	NA	NA	NA	NA	NA	NA	100%		
Ready mix	100%									

Figure 4. Industrial process heat requirements.

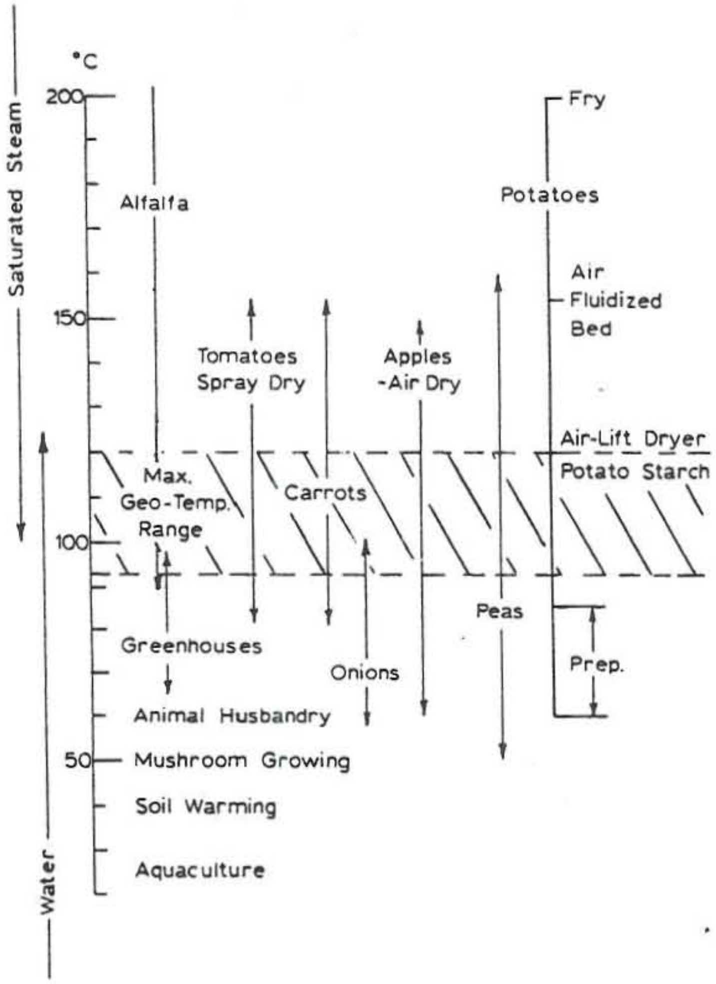


Figure 5. Process temperatures for potential vegetable products.

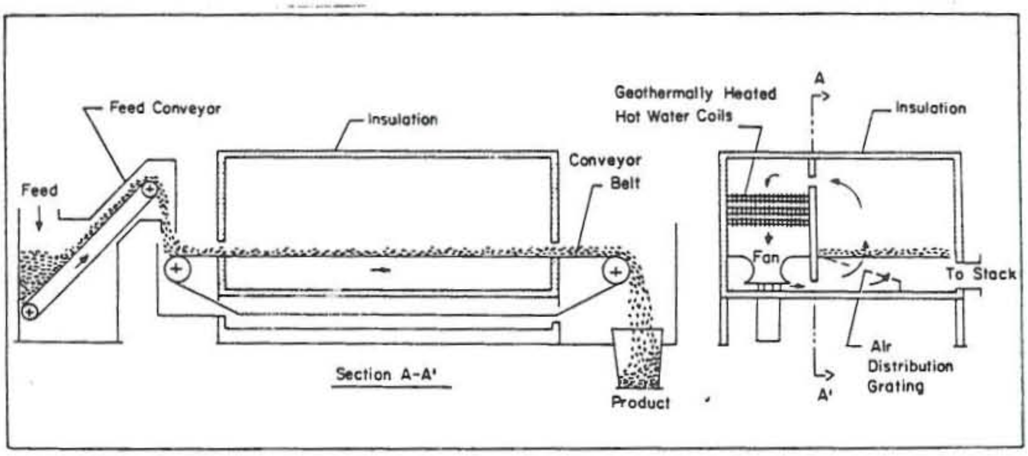


Figure 6. Schematic of conveyor dryer for vegetable drying.

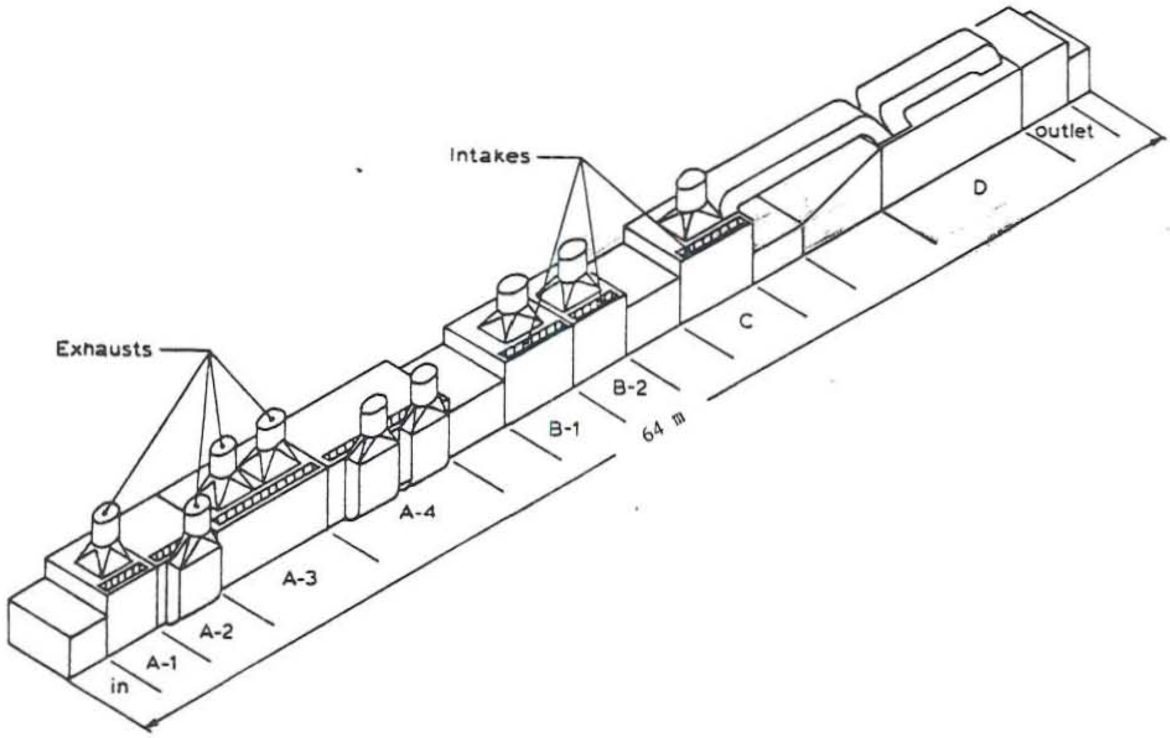
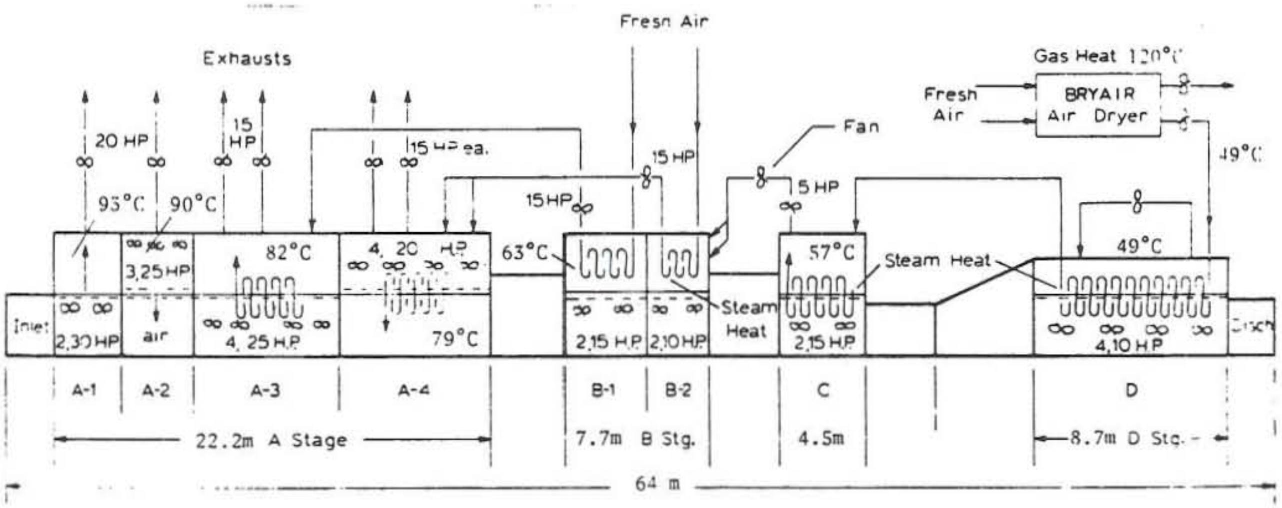


Figure 7. Single-line onion dehydrator.



$T_{amb.}$	Energy Into Air kJ/hr x 10^3							Bed Width 3.8 m		
18°C	4,490	5,170	3,340	4,430	2,950	830	400	230	260	940
4°C	5,320	6,160	3,890	5,160	3,720	1,040	440	310	280	970

Figure 8. Temperature and energy requirements for each compartment of a single-line onion dehydrator.

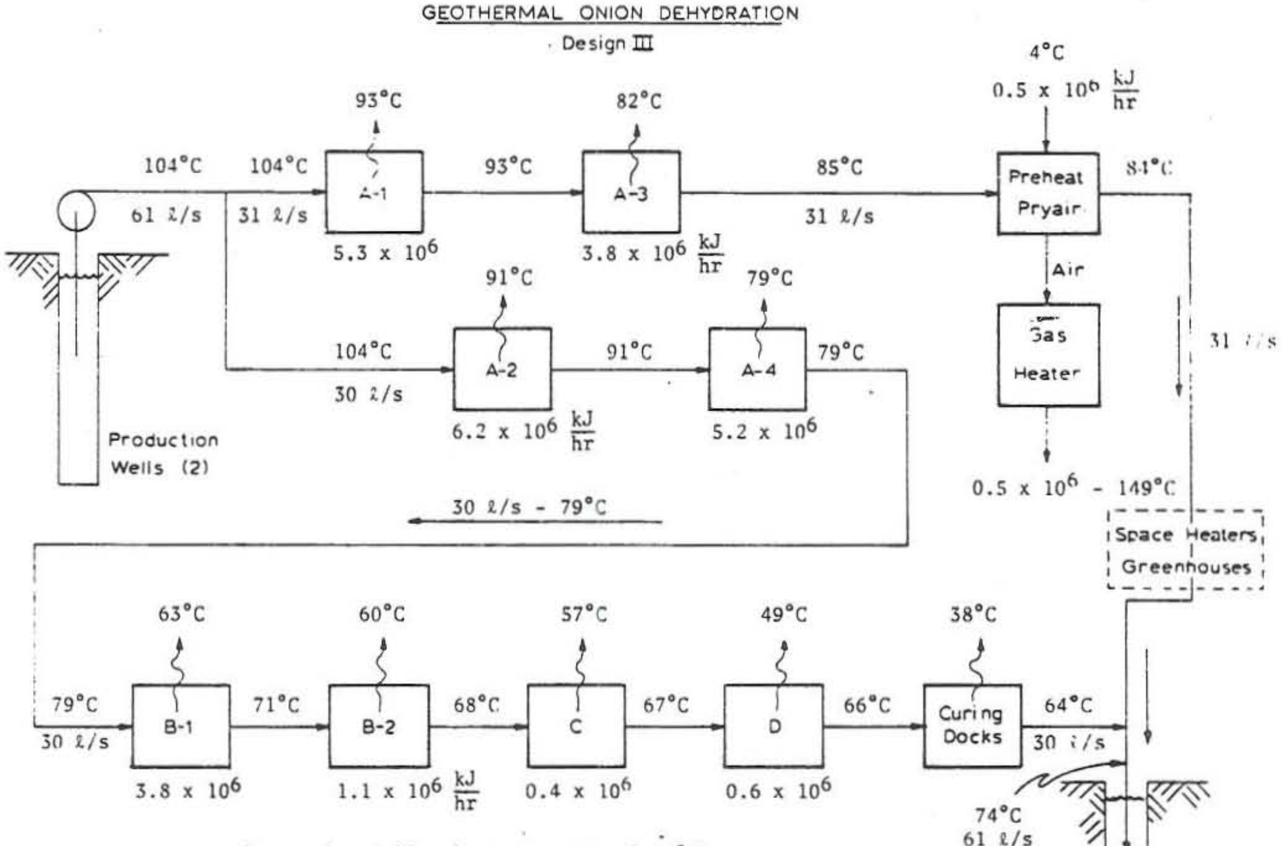


Figure 11. Design III--Single-line onion dehydrator using 104°C geothermal water and 4°C ambient air.

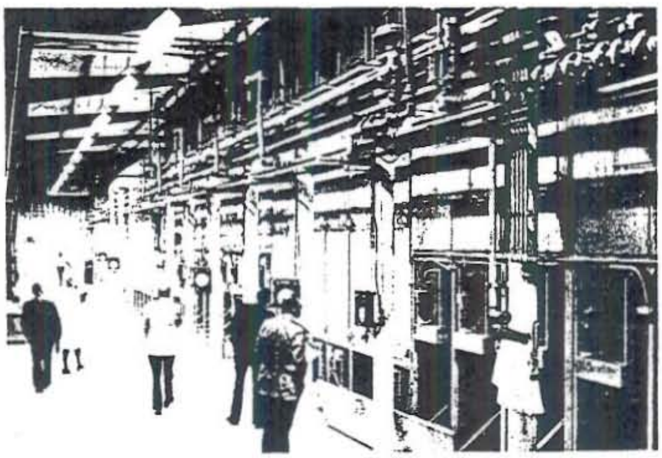


Figure 12. Geothermal Food Processors, Inc. plant's main dryer, built by Proctor, which operates on 100°C+ geothermal water.

Figure 13. Medo-Bel Creamery with well house and supply line in the left background.

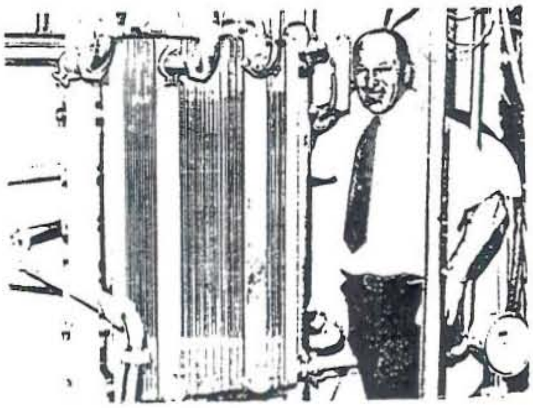


Figure 14. Owner, Elmer Belcastro, standing next to the plate heat exchanger (pasteurizer).

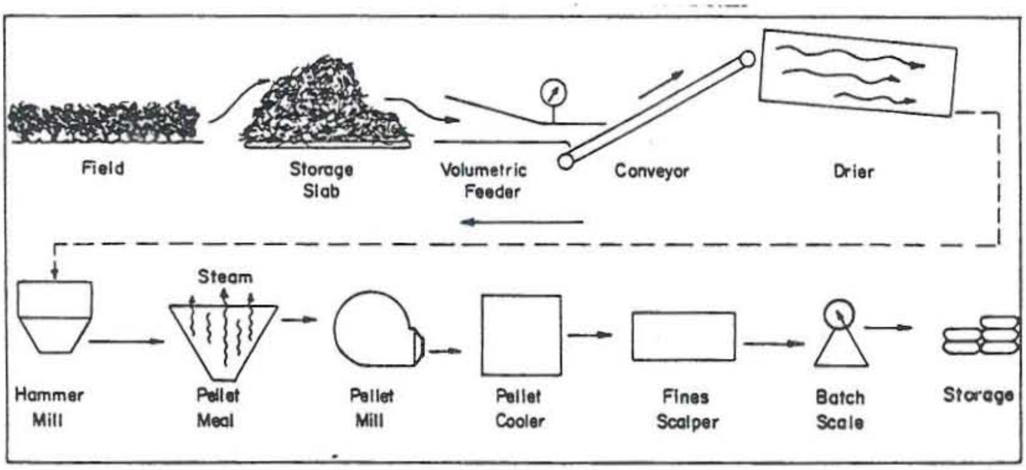


Figure 15. Schematic of alfalfa-drying and pelletizing process.

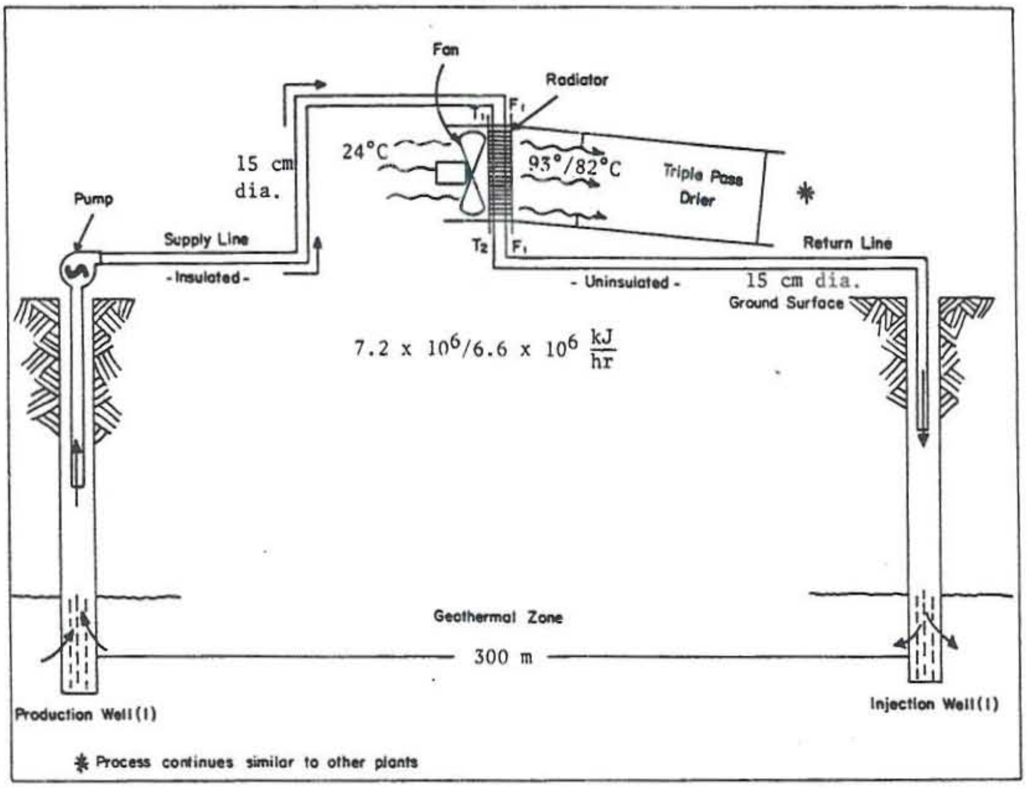


Figure 16. Geothermal alfalfa drying plant and well layout.

Classification of dryers based on method of operation

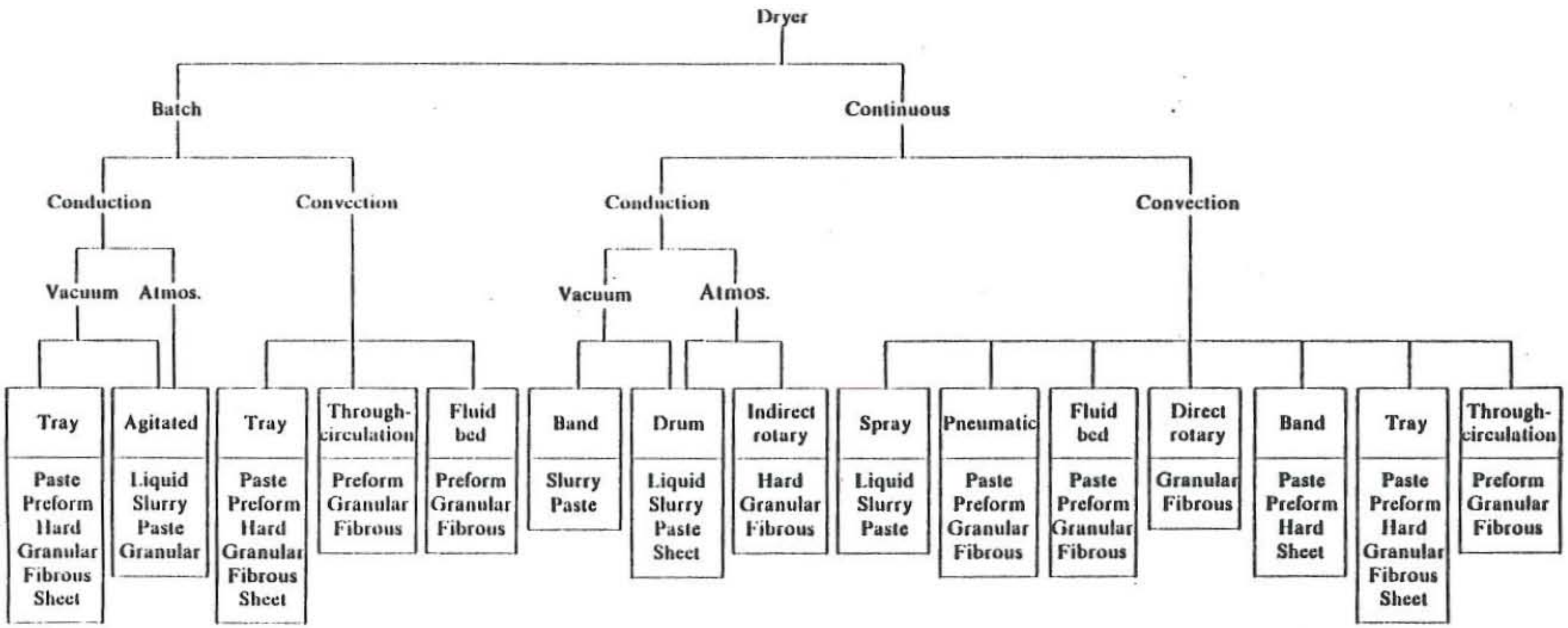
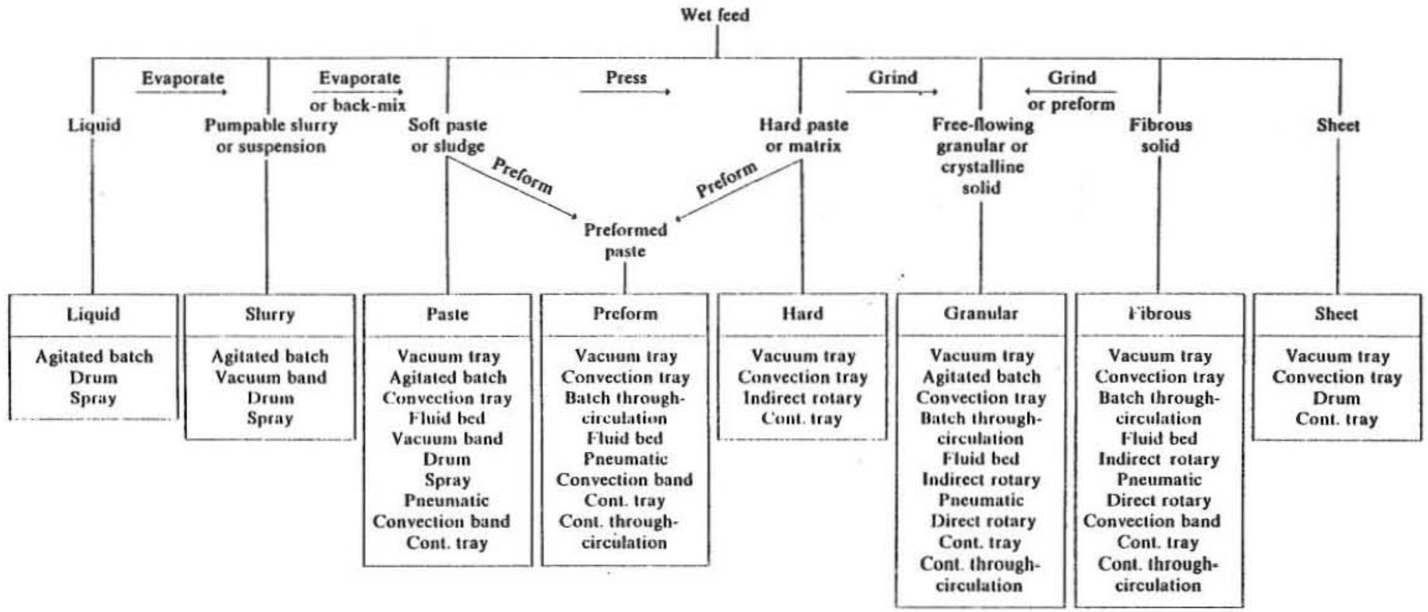
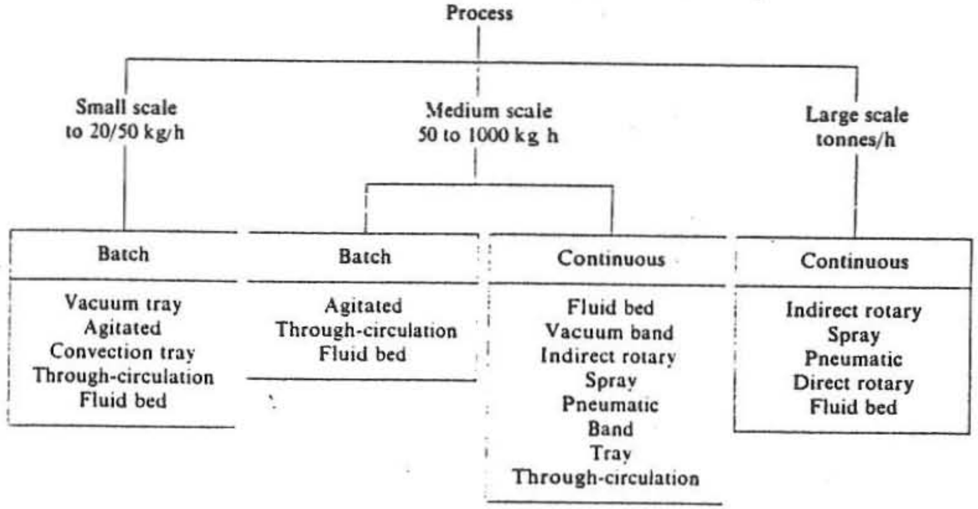


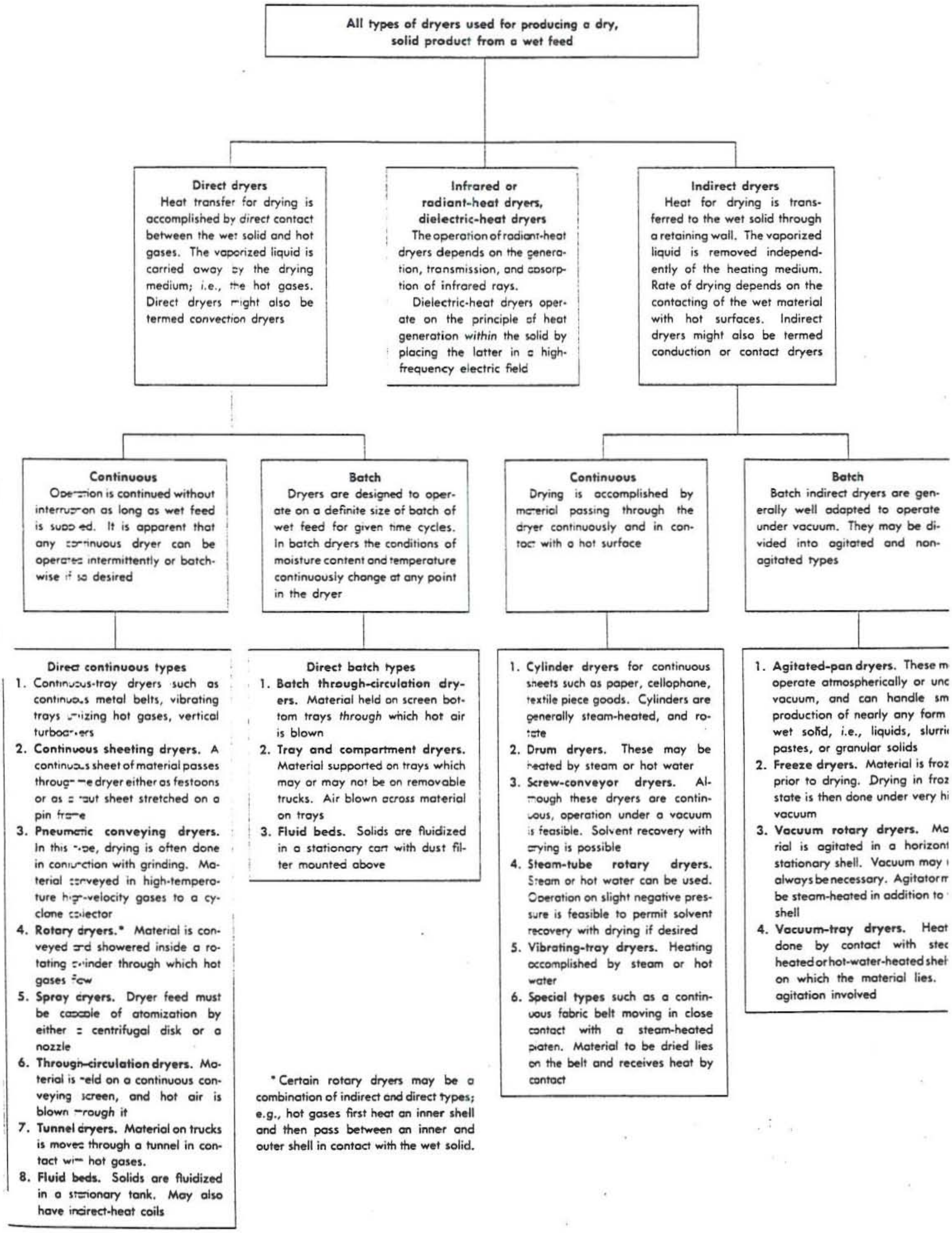
FIGURE 17

Classification of dryers based on physical form of feed

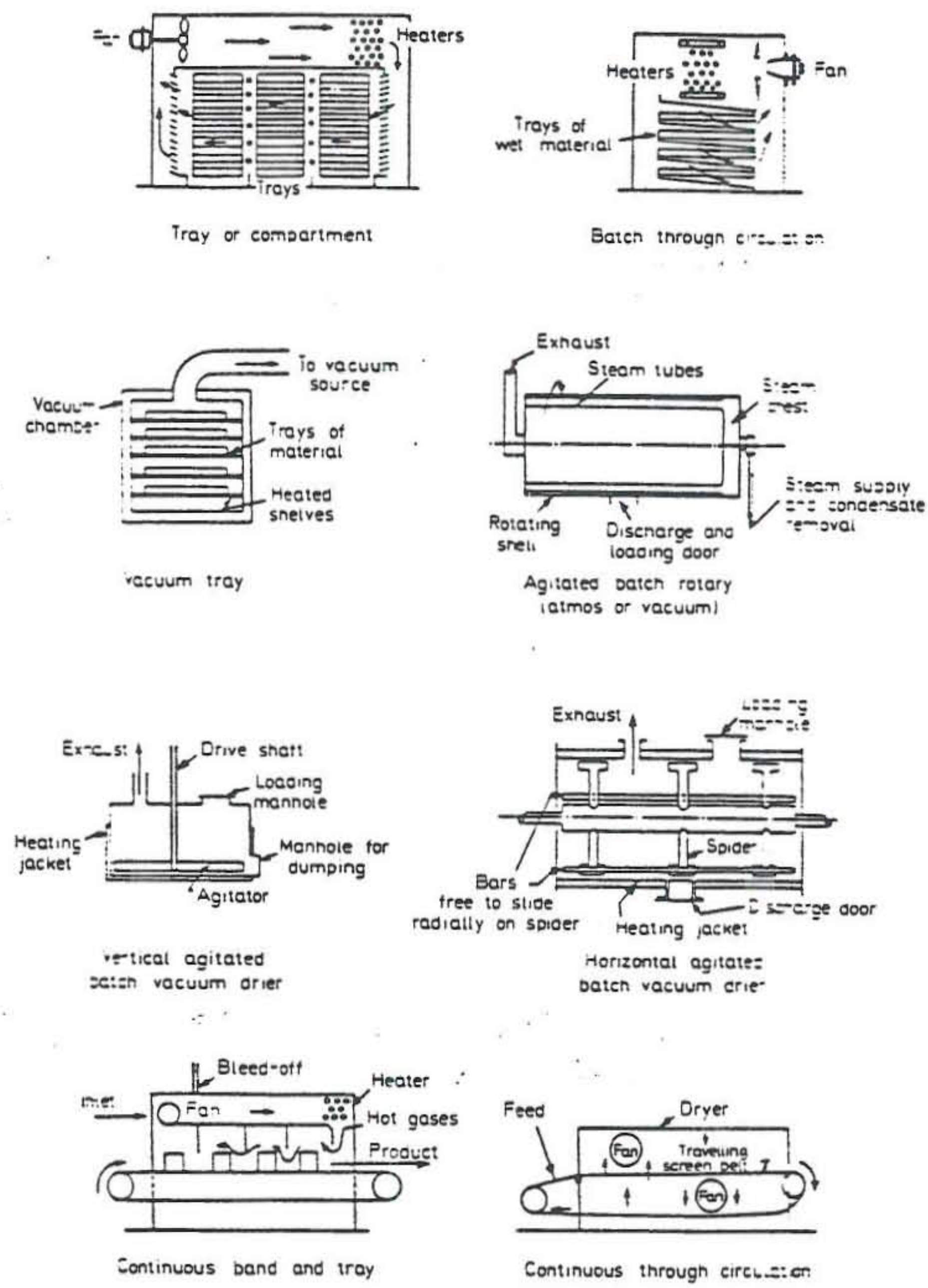


Classification of dryers by scale of production

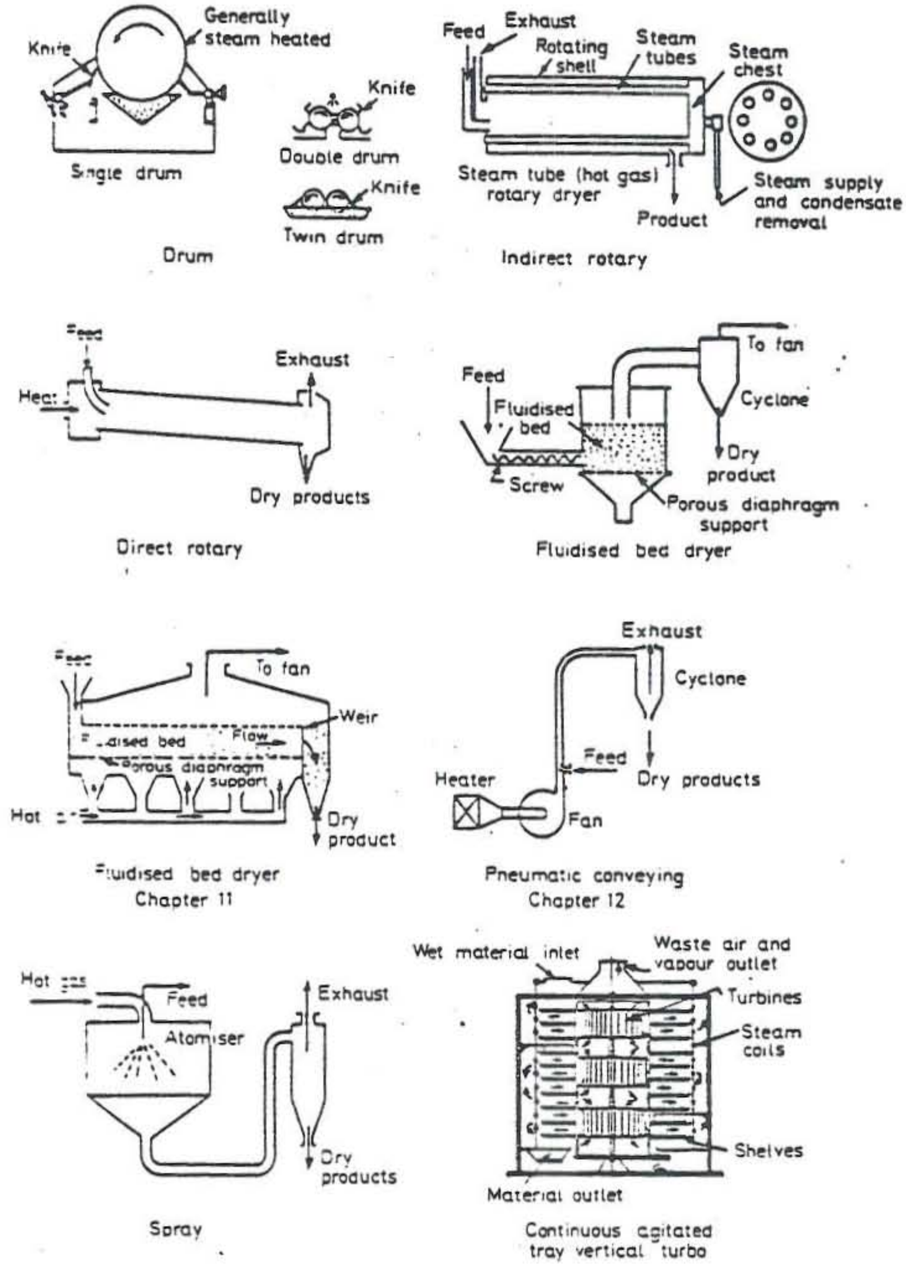




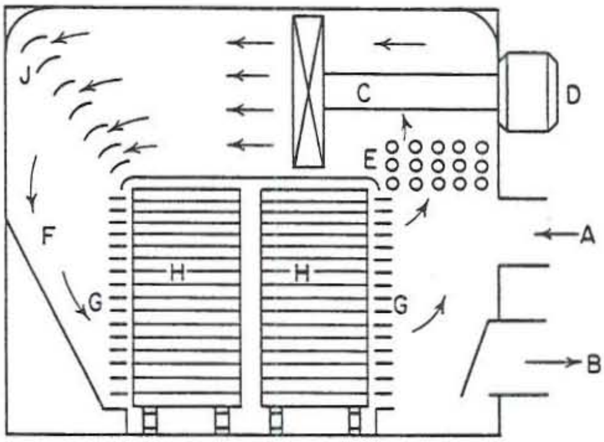
Classification of dryers, based on method of heat transfer. [Revised from: *Marshall, Heating, Piping, Air Conditioning*, 18, 71 (1946).]



Classification of dryers by method of operation

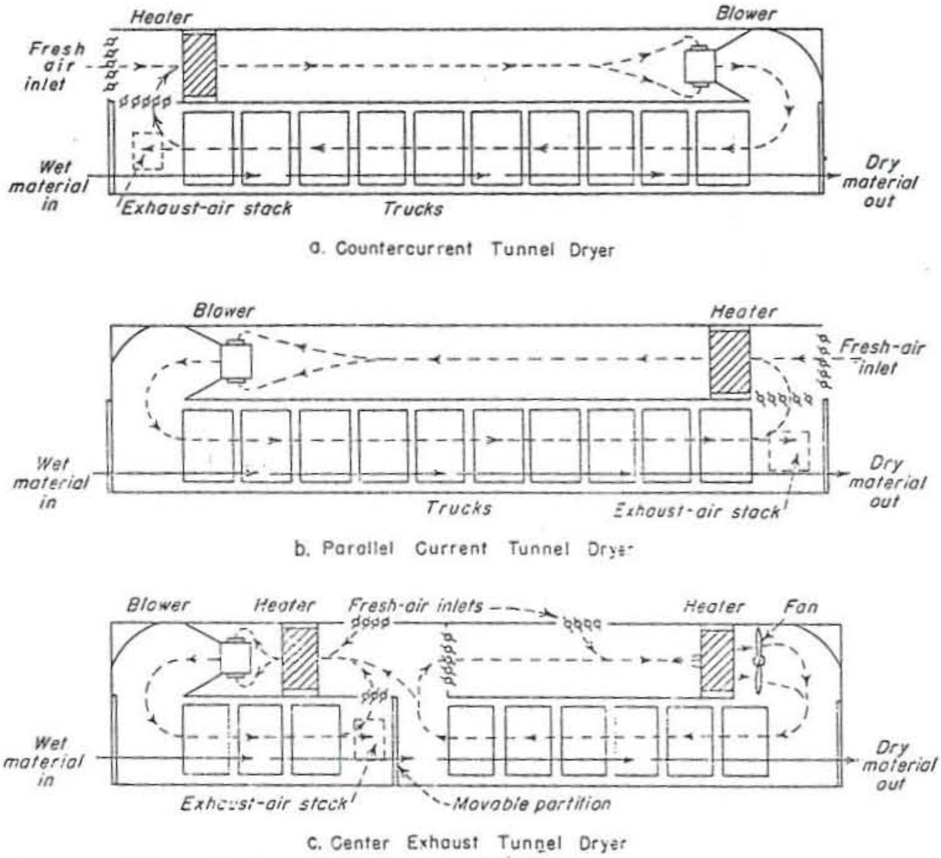


Classification of dryers by method of operation—continued

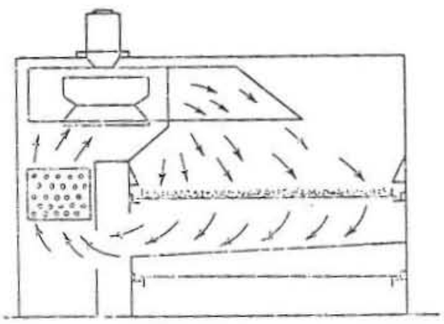


Double-truck dryer. (*A*) Air-inlet duct. (*B*) Air-exhaust duct with damper. (*C*) Adjustable-pitch fan 1 to 15 hp. (*D*) Fan motor. (*E*) Fin heaters. (*F*) Plenum chamber. (*G*) Adjustable air-blast nozzles. (*H*) Trucks and trays. (*J*) Turning vanes. (*National Drying Machinery Co.*)

FIGURE 18



Three types of tunnel dryers. [Van Arsdel, *Food Ind.*, 14 (10), 43 (1942).]



Section view of a continuous through-circulation conveyor dryer. (*Proctor and Schwartz, Inc.*)

FIGURE 19

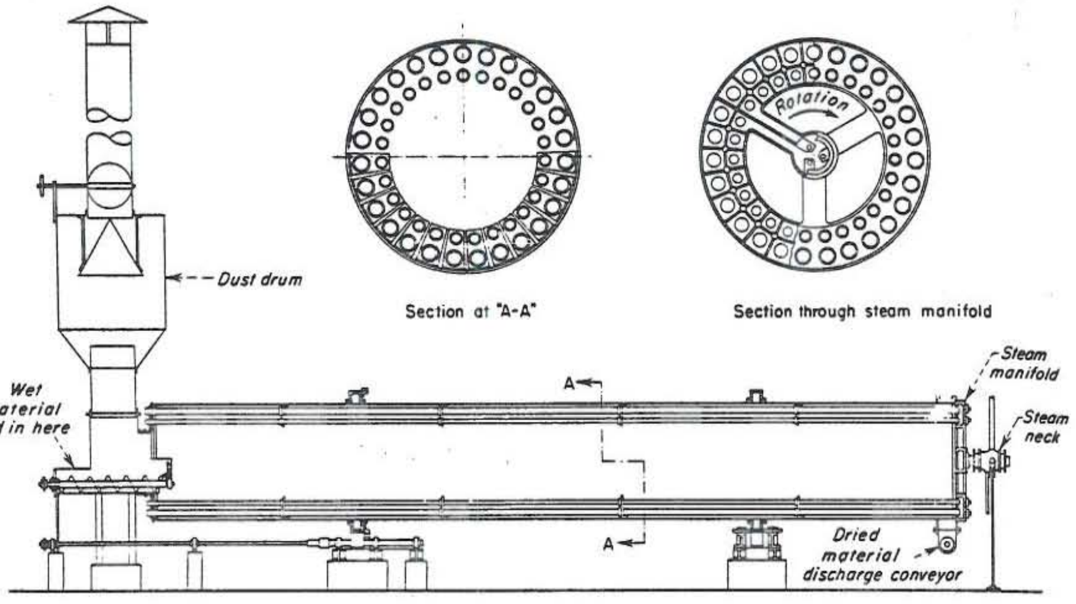


FIGURE 20 Steam-tube rotary dryer.

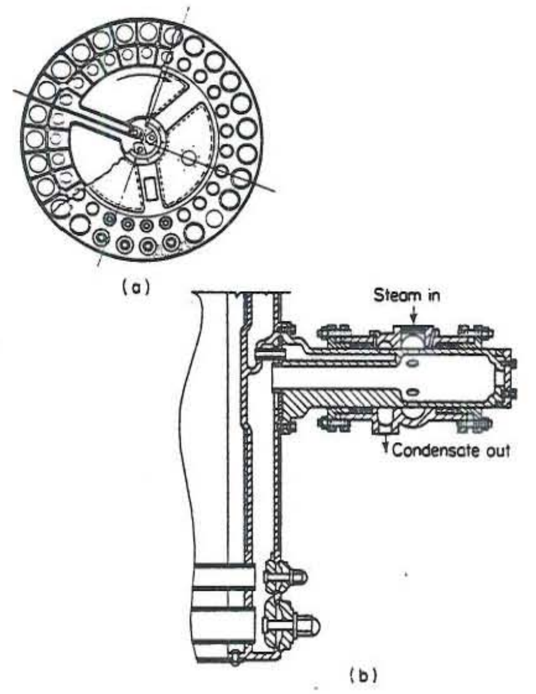


FIGURE 21 Rotary steam joint for a standard steam-tube dryer. (a) Section of cast steam manifold. (b) Section of manifold and steam joint.