



**ORKUSTOFNUN**

NATIONAL ENERGY AUTHORITY  
GEOTHERMAL DIVISION

**UTLAN**

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**INSTITUT MIXTE  
DE RECHERCHES GÉOTHERMIQUES  
Christian Lacasse**

**NEW APPLICATIONS  
OF  
GEOTHERMAL ENERGY**

*útlán*

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**INSTITUT MIXTE  
DE RECHERCHES GÉOTHERMIQUES**



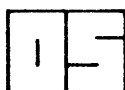
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AGENCE FRANÇAISE  
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**NEW APPLICATIONS  
OF  
GEOHERMAL ENERGY**

CHRISTIAN LACASSE



**ORKUSTOFNUN**  
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## FOREWORD

This study on the new applications of geothermal energy was financed both by the French Joint Institute for Geothermal Research I.M.R.G. (Institut Mixte de Recherches Géothermiques) including the Geological and Mining Research Bureau B.R.G.M. (Bureau de Recherches Géologiques et Minières) and the French Energy Agency A.F.M.E. (Agence Française pour la Maitrise de l'Energie), and by the National Energy Authority (ORKUSTOFNUN) in Iceland. It was limited due to the lack of literature on the subject . This report is not an exhaustive inventory of them . Every project of application is unique and differs by the features of the used fluids and by the desired utilization . It leaves aside the current use of geothermal energy in space-heating (district-heating and greenhouses) and in electric power generation .

Moreover, the use of the adjective "new" in defining a specific utilization of geothermal energy does not have the same meaning in an industrial country and in an underdeveloped country, although both have high geothermal potential .

This report explores the idea of cooling systems powered by geothermal energy (absorption-refrigeration, heat pump in reverse mode, Lysholm engine) .

It is my hope that this report will be an easily accessible and useful reference work for all those interested in geothermal energy utilization .

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## Introduction

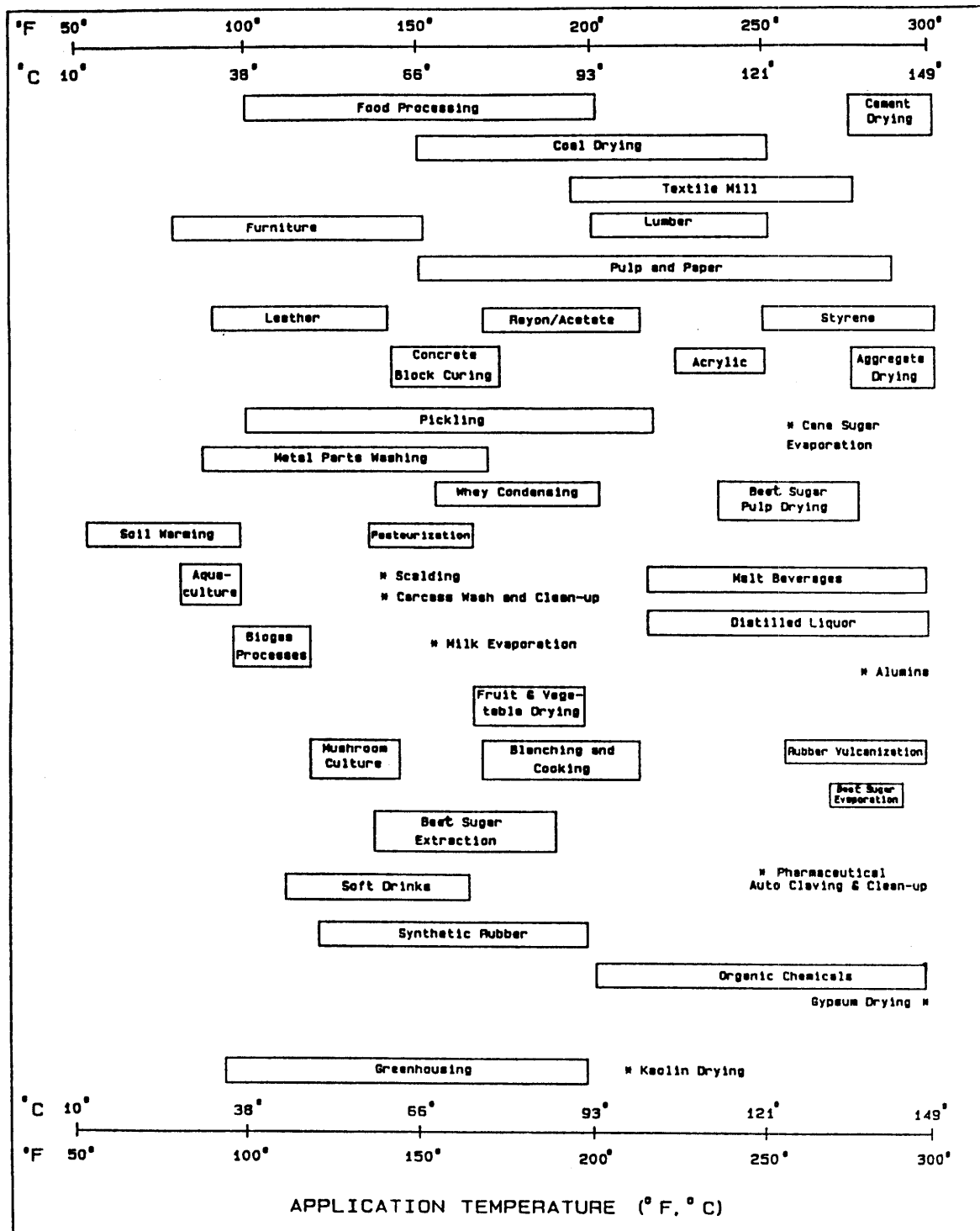
The use of geothermal energy of low to high enthalpy for direct applications has been growing extensively since the 1970's . The use of geothermal fluids is found in five main fields :

- district and space-heating
- spas and swimming-pools
- greenhouses
- aquaculture
- electric power generation

The following table (from B. Lindal, 1973) shows the temperature required for the utilization of geothermal heat :

Temperature (°C)			
s a t u r a t e d s t e a m  ↑ ↓  h o t w a t e r  ↓	200 :		
	190 :		
	180 :	- evaporation of highly concentrated solutions	c o n s t r u c t i o n a l
		- refrigeration by ammonia absorption	
		- digestion in paper pulp (Kraft)	
	170 :	- heavy water via hydrogen sulphide process	
		- drying of diatomaceous earth	
	160 :	- drying of fishmeal	
		- drying of timber	
	150 :	- alumina via Bayer's process	
	140 :	- drying farm products at high rates	
		- canning of food	
	130 :	- evaporation in sugar refining	
		- extraction of salts by evaporation and crystallization	
		- fresh water by distillation	
	120 :	- most multi-effect evaporation	
		- concentration of saline solution	
	110 :	- drying and curing of light aggregate cement slabs	
	100 :	- drying of organic materials, seaweeds, grass, vegetables, etc.	
		- washing and drying of wool	
90 :	- drying of stock fish		
	- intense de-icing operations		
80 :	- space-heating (buildings and greenhouses)		
70 :	- refrigeration (lower temperature limit)		
60 :	- animal husbandry		
	- greenhouses by combined space and hotbed heating		
50 :	- mushroom growing		
	- balneology		
40 :	- soil warming		
30 :	- swimming pools		
	- biodegradation		
	- fermentations		
	- warm water for year-round mining in cold climates		
	- de-icing		
20 :	- hatching of fish		
	- fish farming		

Table of the applicable temperature range for some industrial processes and agricultural applications (from P. J. Lienau, 1989) :



Many western countries and later eastern ones financed important programs for building geothermal plants within these main fields of application .

Today some of these countries see their program fulfilling their goal . For example, Iceland, with a population of 250000 inhabitants, is the most important user of geothermal energy per capita in the world (about 34.8 MWh per head), but has almost completed its developmental program for district-heating . Thus, in 1989, the exploited capacity of this country was around 8700 GWh/a of geothermal energy for direct use and around 2600 GWh/a for electric power generation .

82% of the Icelandic population enjoys this cheaper way of heating . That corresponds to almost 90% of the national space-heating market . The national gross energy consumption is covered by geothermal energy (32.2 %), hydroelectricity (37.3 %), oil (27.6%) and coal (2.9%), This country has to spread the use of geothermal energy to new sectors and especially to the industrial one .

Countries like the United States, Japan, New Zealand, Iceland, Mexico with important geothermal capacities finance R & D programs for new applications in geothermy (absorption-refrigeration, heat pumps, aquaculture, etc).

The evaluation of experimentally untested ideas for the application of geothermal resources should be supported beyond conceptual analyses through at least a phase of small-scale experiments . Such funds are available in several countries .

# 1 Absorption - Refrigeration

## 1.1 Introduction

The idea of using heat to produce cold sounds paradoxical at first but heat is energy and both are convertible . It is possible to power a refrigeration cycle with geothermal steam or hot water (or even both) with what is known as an absorption -refrigeration system .

Generally speaking there are two methods of cold production : absorption refrigeration and compressor refrigeration . The most important difference between them lies in the type of energy used.

A compressor plant is usually powered by an electric motor .

An absorption plant uses a thermal compressor which essentially consists of stationary heat transmission surfaces . Thermal power is supplied through heat to the boiler .

## 1.2 Principle

The refrigeration effect is produced through the use of two fluids and some quantity of heat input rather than electrical input as in the more familiar vapor compression cycle .

Both vapor compression and absorption refrigeration cycles accomplish the removal of heat through the evaporation of a refrigerant at a low pressure and the rejection of heat through the condensation of the refrigerant at a higher pressure (Figure 1) .

The method for creating the pressure difference and circulating the refrigerant is then the primary difference between the two cycles.

As we have seen before, the vapor compression cycle employs a mechanical compressor to create the pressure differences necessary to circulate the refrigerant (Figure 1) .

In the absorption system, a secondary fluid or absorbent is used to circulate the refrigerant . Because the temperature requirements for the cycle fall into the low- to moderate-temperature range, and there is significant potential for electrical energy savings, absorption would, at first glance, seem to be a good prospect for geothermal application .

Moreover, as the absorption plants mainly use thermal energy, it would be more attractive from an economical point of view in a case of cheap heat energy like geothermal steam .

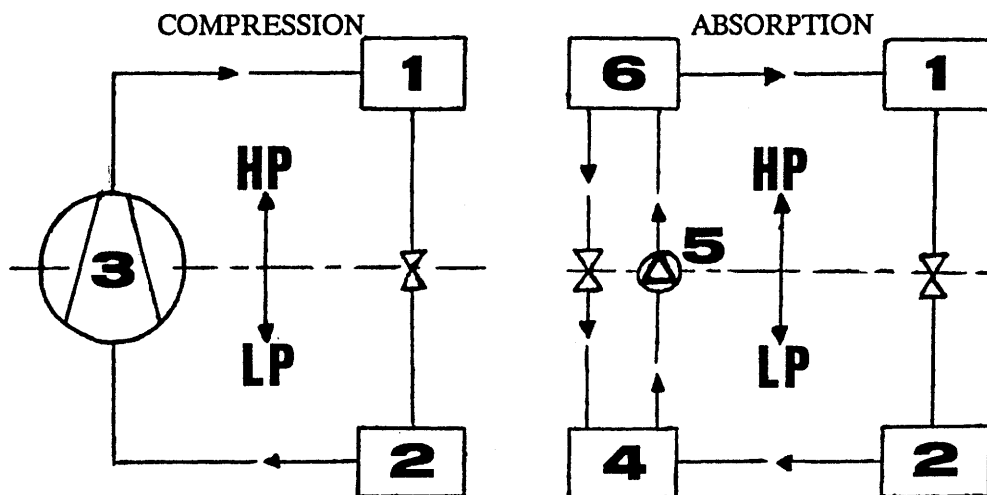


Figure 1 : comparison of compression-refrigeration systems with absorption-refrigeration systems

1. condenser 2. evaporator 3. compressor 4. absorber 5. solution pump 6. desorber  
HP. high pressure LP. low pressure

Absorption machines are commercially available today in two basic configurations .

For applications below 0°C, an ammonia/water cycle is employed with ammonia as the refrigerant and water as the absorbent (ammonia not being subject to freezing at these temperatures) .

For applications above 0°C (primarily air conditioning), the cycle uses lithium bromide as the absorbent and water as the refrigerant.

The following diagram (Figure 2), for the simple one-stage absorption plant, shows the heat source temperature as a function of the evaporating temperature required .

From it, a coefficient of performance (C.O.P) can be introduced by dividing the cooling output by the required heat (source energy) input (Figure 4) .

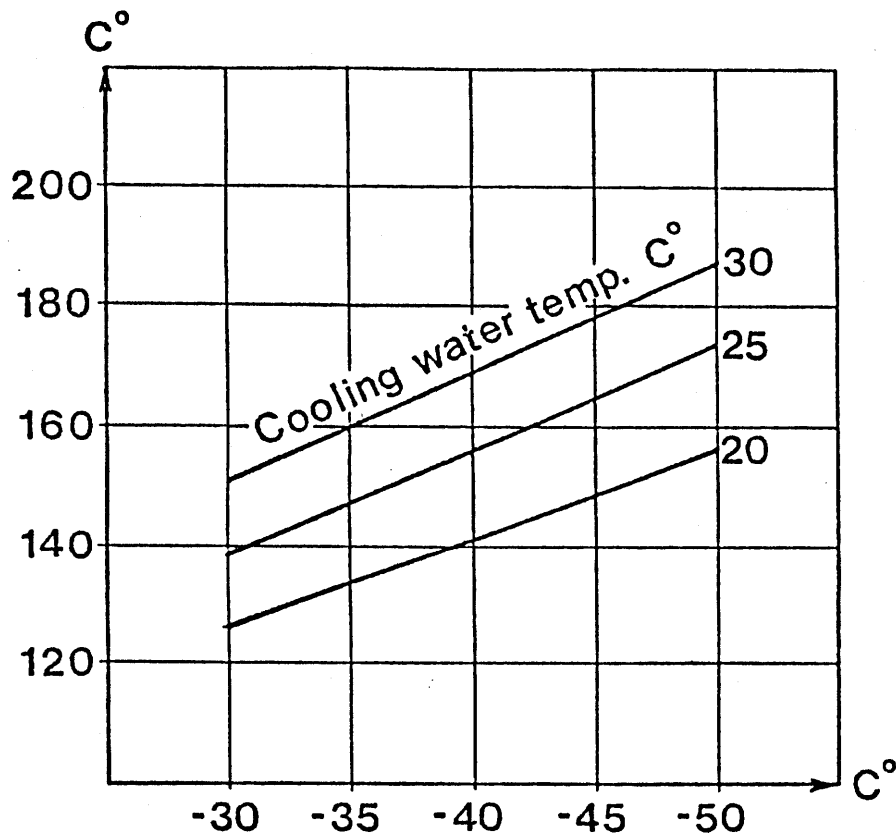


Figure 2 : heat input vs. evaporation temperature diagram for the simple one-stage absorption plant (Lorentzen, 1978)

### 1.3 Ammonia/water cycle machines

#### 1.3.1 Single stage absorption-refrigeration systems

The following diagram (Figure 3) shows the most commonly used geothermal refrigeration system in the configuration of a single-stage flow .

The geothermal well supplies steam (heating medium) to the rectifier (2) before being reinjected . The strong ammonia solution passes through a heat exchanger (4) into the generator (1) and the rectifier (2) in which it is separated into a weak solution and vapor . Ammonia vapor is driven out to the reflux condenser (3) for extracting residual traces of water.

Vapor liquifies into the condenser (6) under the prevailing high pressure, and drops into the receiver (7) . The refrigerating liquid arrives via an aftercooler (9) into the evaporator (10) where it reverts to a gaseous stage at low pressure and temperature, extracting then the required heat energy from the material to be cooled (cooling load) . The resulting vapor moves again via the aftercooler (9) into the absorber (5) . Ammonia vapor thus enriches the depleted ammonia solution (coming from the rectifier via the heat exchanger) in the absorber (5) to again form a strong solution in the liquid receiver (8) . Finally, the high ammonia content solution is pumped (11) back into the generator.

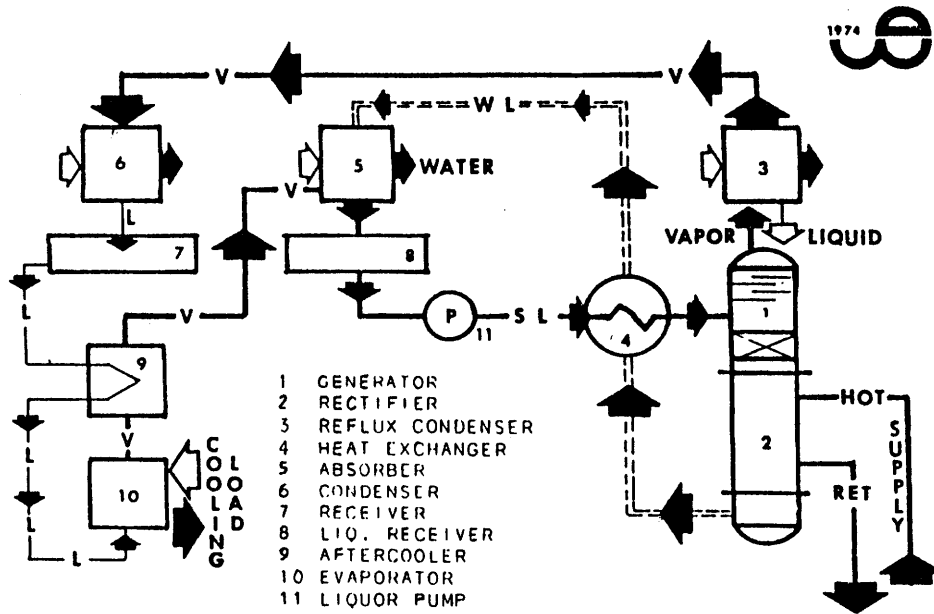


Figure 3 : basic single-stage flow diagram for minus 60°C geothermal refrigeration system proposal

A coefficient of performance (Figure 4) has been defined for this type of absorption equipment.

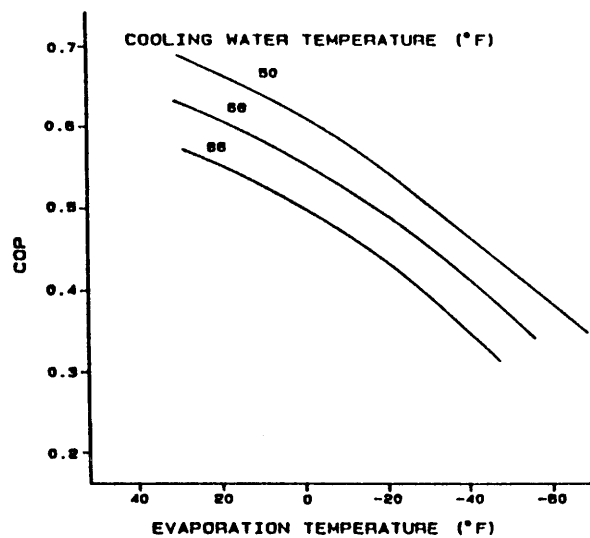


Figure 4 : the COP for an ammonia/water single-stage absorption equipment (Hirai, 1982)

### 1.3.2 Two stage absorption-refrigeration systems

Where under the available cooling-water condition the temperature of the heating medium does not suffice for bringing about the required low evaporation temperature in single-stage operation, a two-stage arrangement must be resorted to .

The most important advantage is that even very low evaporating temperatures can be sustained in two-stage systems with relatively low temperatures of the heating medium .

Such systems have one low-pressure and one high-pressure solution circuit, each consisting of an absorber, desorber, and a heat exchanger between .

The twice occurring desorption requires a greater heating capability than single desorption, however at a much lower heating temperature . The lesser quality of the heating medium is compensated for by a larger quantity of it . Where sensible heat is derived from it (as with waste gas), it can be cooled over a longer range, and thus be better exploited .

The lower the temperature demanded in the evaporator, and the warmer the cooling water, require a higher temperature of the heating medium, commensurate with an increase of the refrigerating effect .

Comparison table of the two absorption-refrigeration systems :

Evaporating temperature (1)	- 5		- 20		- 35		- 50	
Cooling-water temperature (1)	15	25	15	25	15	25	15	25
<b>Single-stage</b>								
Heat requirement (2)	1.7	1.9	2.0	2.4	2.6	3.1	3.6	4.4
Heating medium (3)	95	115	120	140	145	165	175	195
Cooling water requirement (4)	120	170	140	200	160	230	200	290
Power requirement at pump (5)	17	23	20	28	24	34	29	40
<b>Two-stage</b>								
Heat requirement (2)	2.9	3.1	3.3	3.6	3.8	4.2	4.5	5.1
Heating medium (3)	70	85	80	95	90	110	105	125
Cooling water requirement (4)	290	340	310	360	330	390	370	460
Power requirement at pump (5)	15	21	18	25	21	29	25	33

(1) : degree Centigrade

(2) : 1.000.000 kcal/h

(3) : lowest permissible temperature - Centigrade degree

(4) : cubic meter/h

(5) : kW

### 1.4 Lithium-bromide/water cycle machines

In these machines, the process occurs in two vessels or shells (Figure 5) .

The upper shell contains the generator and condenser, the lower shell, the absorber and evaporator .



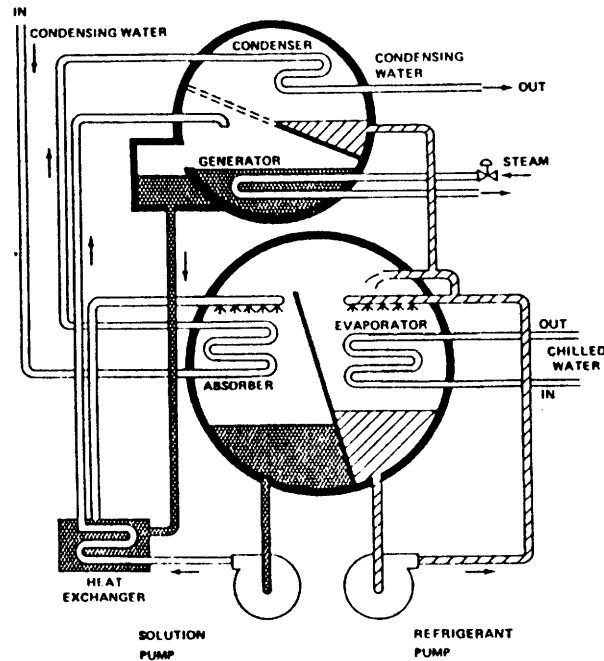


Figure 5 : diagram of two-shell lithium-bromide cycle water chiller (A.S.H.R.A.E. (\*), 1983)

(\* ) American Society of Heating, Refrigeration and Air Conditioning Engineers

Heat supplied in the generator section is added to a solution of  $\text{Li-Br}/\text{H}_2\text{O}$  . This heat causes the refrigerant, in this case water, to be boiled out of the solution in distillation process . The water vapor that results passes into the condenser section where a cooling medium is used to condense the vapor back to a liquid state . The water then flows down to the evaporator section where it passes over tubes containing the fluid to be cooled . By maintaining a very low pressure in the absorber-evaporator shell, the water boils at a very low temperature . This boiling causes the water to absorb heat from the medium to be cooled then passes into the absorber section where it is mixed with a  $\text{Li-Br}/\text{H}_2\text{O}$  solution that is very low in water content. This strong solution (strong in  $\text{Li-Br}$ ) tends to absorb the vapor from the evaporator section to form a weaker solution . This is the absorption process that gives the cycles its name . The weak solution is then pumped to the generator section to repeat the cycle .

Like the ammonia/water cycle machines a coefficient of performance can be introduced (Figure 6) .

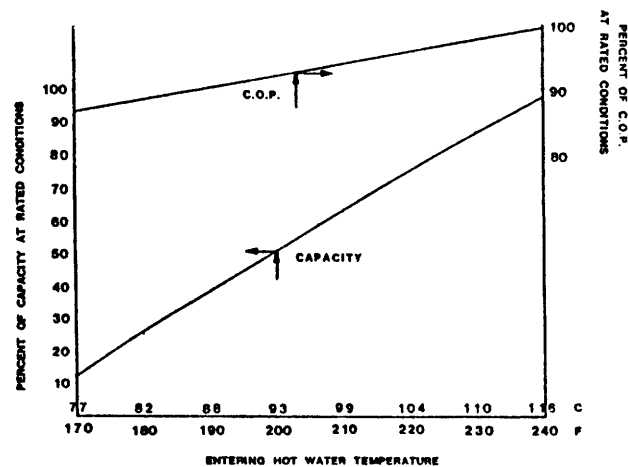


Figure 6 : the COP of a Lithium-Bromide single stage absorption chiller (Rafferty, 1983)

The lithium-bromide absorption chillers also present two types of machines : single stage units with generally 62-83 kPa steam (or equivalent hot water) entering the generator, 29°C cooling water and 6.7°C leaving chilled water (COP # 0.65 to 0.70); and two-stage units requiring higher temperatures (about 163°C) with significantly higher COP's .

However, temperature requirements for these are well into the power generation temperature range 177°C . As a result two-stage machines would probably not be appropriate for geothermal applications.

### **1.5 Benefits and disadvantages**

The absorption chillers are cheaper and more expensive than the electrical chillers concerning their operating cost and their initial investment respectively . Thus, with an equal cooling capacity, the electrical chiller costs are more important than the geothermal pumping costs .

But basing one's argument on this simple point of comparison would be risky in considering whether the utilization of an absorption chiller is profitable or not .

So many factors must be considered beforehand such as :

- the resource temperature
- the refrigeration capacity required
- the annual cooling load for space conditioning
- the pumping power if it's necessary
- the utility rates

### **1.6 Applications**

#### **1.6.1 China**

A research project has been undertaken by the Experiment Station for Geothermal Energy Utilization of Fuzhou City .

A set of experimental equipment was built up in January 1980 . This set uses a two-stage ammonia absorption refrigerate system supplied with geothermal water of 87°C and has been operated continuously and intermittently for seven months .

Test runs show that, by using geothermal water and cooling water respectively of 87°C and 25°C and at rates of 8.5 t/h and 58 t/h, an evaporation temperature of -24°C and a refrigerating capacity of 23363 Kcal/h can be obtained .

It can produce 4 tons of ice per day and, in addition, offers its refrigerating capacities to a cold storage area which is 50 m<sup>2</sup> in size with a below -12°C room temperature, and a vegetable freshness keeping storage container of same size .

The geothermal water drained off after refrigeration is then delivered to farmland for use in greenhouses and fishponds .

When the cooling water temperature is up to 32°C during the summer time, an evaporation temperature of -32°C can be obtained .

But the initial investment for this type of geothermal refrigeration system is higher than that for the compressor refrigerator of the same capacity . Conversely, its operating cost is lower .

#### **1.6.2 Denmark**

The Atlas Industrial Refrigeration Division produces and markets an absorption-refrigeration system called "OSCAR" (Oil heated -Self-Contained - Absorption - Refrigeration) useful for freeze-drying plants, ice cream plants, freezing tunnels, slice ice and block ice plants, frost stores, etc .

### **1.6.3 Iceland**

A large quantity of goods in the food industry (fish industry : 75% of the foreign export) is frozen . Until now the refrigeration systems in use in Iceland are solely conventional compressor systems . The National Energy Authority (Orkustofnun) is very interested in combining the geothermal energy in this country and the absorption-refrigeration technique to, possibly, lower the cost of freezing food in those areas that have access to geothermal energy .

The refrigeration industry in Iceland mainly consists of two processes, freezing with an evaporation temperature of  $-35^{\circ}\text{C}$ , and cooling and icemaking with an evaporation temperature of  $-10^{\circ}\text{C}$  .

The refrigerant is condensed with seawater or cold freshwater at a condensing temperature of  $20^{\circ}\text{C}$  . The capacity of the freezing systems is usually in the range of 100000 kcal/h to 500000 kcal/h, but the capacity of the cooling systems is, in most cases, less than 100000 kcal/h .

A feasibility investigation ("Notkun jarðvarma í frystiidnadi" / "Use of geothermal energy in refrigeration plants" (in Icelandic), University of Iceland, 93 pp., 1976) by Arni Ragnarsson has already proven the advantages of geothermal energy utilization in the refrigeration-absorption system for the freezing plants in Iceland but unfortunately has not been followed by any application until now .

### **1.6.4 Japan**

The Hitachi Company markets an absorption chiller using Li-Br solution as an absorbent and water as a refrigerant and low-pressure steam to produce refrigeration for air conditioning .

### **1.6.5 New Zealand**

The International Hotel at Rotorua is served by a plant that provides the whole building with all its heating and cooling requirements from a single geothermal bore - hot tap water for baths and washing, central heating in winter and air conditioning in summer . The climatic range to be contended with is from  $-4^{\circ}\text{C}$  to  $+30^{\circ}\text{C}$  . The maximum heating load is 0.5 Gcal/h (about 585 kW thermal) while the lithium bromide absorption cooling unit requires an input of 0.575 Gcal/h (about 668 kW thermal), requiring 1.47 heat units per single heat unit of cooling .

The bore serving the whole of this complex produces water at  $150^{\circ}\text{C}$  . The heat is transferred in a heat-exchanger to fresh water close circuits which are heated to  $120^{\circ}\text{C}$  for the heating system and for the absorption unit .

### **1.6.6 Soviet Union**

Li-Br absorption machines with a capacity of 2.5 million kcal/h of "cold" - rather less than 3000 kW thermal - using geothermal heat are being mass-produced in the U.S.S.R., capable of two-way operation so as to provide heat in winter and cooling in summer .

### **1.6.7 United States of America**

An experimental 150 ton absorption chiller (lithium-bromide/water cycle) was installed on the Oregon Institute of Technology campus because of a geothermal heating system .

Design conditions called for 23 l/s of chilled water at  $7^{\circ}\text{C}$ , 38 l/s of  $88^{\circ}\text{C}$  geothermal fluid, and 79 l/s of  $29^{\circ}\text{C}$  cooling water.

This Research Center has also been involved in two feasibility studies which have examined the use of absorption-refrigeration for commercial applications .

Most of them involve process temperatures lower than  $0^{\circ}\text{C}$  (ammonia/water cycle machines) and many are lower than  $-18^{\circ}\text{C}$ .

The first one involved the use of a  $177^{\circ}\text{C}$  fluid for an ice making and cold storage facility . W.A. Hirai and Associates of Hilo, Hawaii, as subcontractors to the Geo-Heat Center, prepared a study of the use of effluent from the Puna HGP-A well . An American firm, Lewis Refrigeration, manufactures the equipment.

The second one examined for the Geo-Heat Center by Davy-Mc Kee Corporation concerns the use of absorption-refrigeration for cooling requirements in a malting facility . This study assumed a resource temperature of 88°C .

A new central heating and cooling system at the McNeese campus, California, uses a heat exchanger between brine at 110°C and potable water and a lithium-bromide absorption refrigeration system respectively for heating and cooling buildings .

Under the sponsorship of the Energy Research and Development Administration and the California Energy Resources Conservation and Development Commission, a preliminary design and implementation plant of a heating/cooling system from geothermal energy was realized at Desert Hot Springs, California .

This unit uses a geothermal heat source of 66-232°C to product cooling and heating water respectively at 4.4-27°C and 38-93°C .

## **2 Heat pumps**

### **2.1 Introduction**

The earth is a massive collector that absorbs and stores heat from the sun. Its temperature fluctuates very little throughout the year . And in most climates, the ground temperature is warmer than air temperatures during the winter and cooler than the air during the summer . Water has even more potential for absorbing and storing heat . Therefore, the thermal energy of the earth and the earth's ground and surface water can be used to heat and/or cool homes (Figure 7) in many ways . Note that ground water has a primary advantage over surface water because its temperature is more stable .

Moreover, when geothermal resource temperatures fall below the 38 to 49°C range, it is frequently impractical to use the fluid directly for most applications .

Under these conditions, the water-source heat pump can provide the necessary temperature boost to concentrate the heat from a very low temperature resource .

### **2.2 Principle**

Three systems must work together to get the most benefit from heating and cooling with thermal energy in the ground and water :

- the earth-coupled system
- the heat transfer system
- the heating and cooling distribution system

Heat pumps coupled with earth coils or water-coupled systems are used to extract heat from the water (or brine or antifreeze) that is circulated through these systems .

They are called water-source heat pumps because they draw heat from the water (or other liquid) circulating through the coils or pipes .

If water-source heat pumps distribute the heat with water passing through radiators (a hydronic system), they are referred to as water-to-water heat pumps .

If, on the other hand, the heat pumps use a forced-air system to heat the home, they are called water-to-air heat pumps . These are the most common type of residential, water-source heat pumps .

Some heat pumps are used just for heating, but many heat pumps have a reverse valve so they can be switched to cooling .

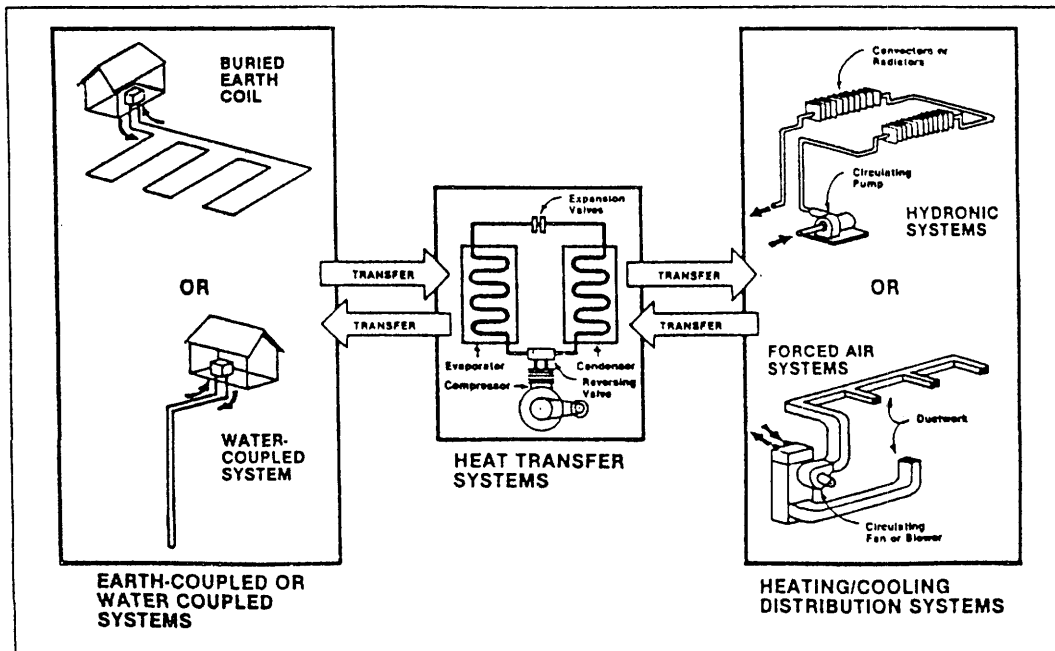


Figure 7 : how earth-coupled and water-coupled systems can be used to heat and cool homes (N.C.A.T. (\*), 1988)

(\*) The National Center for Appropriate Technology - U.S. Department of Energy

### 2.2.1 Heating system

Instead of simply moving a fluid at a given temperature from place to place, heat pumps use a mechanical process to increase the temperature of the fluid . This can happen because heat pumps use refrigerants which boil at low temperatures . The gas produced by boiling a refrigerant can be compressed, and compression increases the temperature of the gas . This heat is released when the gas condenses . When heat pumps are used for heating (Figure 8), water from earth coil or water-coupled systems flows alongside the refrigerant tube in the evaporator . Here, the liquid refrigerant absorbs heat from water, boils, and changes into a gas . This gas is squeezed by the compressor, and the temperature is raised as a result . This high-temperature, high-pressure gas is then pumped to the condenser where it gives up heat when a fan blows air across the condenser coils . As it loses heat, the gas changes back into a hot liquid .

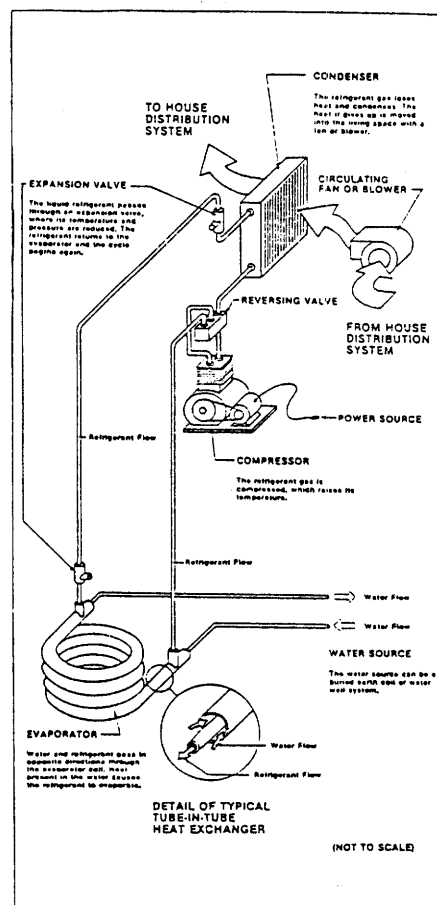


Figure 8 : typical water-source heat pump in the heating mode (N.C.A.T., 1988)

Then it passes through an expansion valve that further reduces temperature and pressure . The low-temperature, low-pressure liquid is pumped back to the evaporator, and the process begins again .

Heating systems are evaluated by comparing the amount of energy delivered (i.e., heat) with the amount of energy consumed to deliver that energy .

This is known as the coefficient of performance or COP (Figures 9 and 10) .

Water-source heat pumps normally have a COP of at least 3; that means it delivers three times more energy than it consumes .

### **2.2.2 Cooling system**

If a heat pump is equipped with a reverse valve, the process can be switched to operate in reverse for cooling (air conditioners) .

Thus, working on the same principle it extracts heat from a hot space (the source) and dumps it outside (the sink) .

The condenser functions as an evaporator, and the evaporator becomes a condenser . Heat from the living space is pulled across the condenser coils, and the liquid refrigerant evaporates. The compressor pumps the heated gas to the evaporator, heat flows from the refrigerant to the colder water, and the refrigerant condenses .

Then the warmed water is pumped from the heat pump and through the earth coil or water-coupled system where the water gives up its heat .

Cooling efficiency is normally measured in terms of the energy efficiency ratio (EER) .

The EER is similar to COP, but it is calculated using different units of measure . With EER's, higher ratings are better .

On the market, equipment is in two basic configurations, reciprocating and centrifugal .

Centrifugal machines are used for the largest applications, and reciprocating equipment for smaller ones .

## **2.3 Reciprocating**

Reciprocating compressor heat pumps are available as standard units in sizes generally below 879 kW heating output (McQuay, 1986) .

This equipment employs a one, four, six, or eight cylinder compressor on smaller equipment and multiple four or six cylinder compressors on larger units (Carrier, 1984) .

The refrigerant employed (R-22, R-500, R-12, R-114) is a function of the temperatures between which the machine is working .

Both evaporators and condensers are of the shell and tube type with water generally on the tube side .

Reciprocating machines generally do not include a separate liquid sub-cooling heat exchanger, though sub-cooling is addressed in condenser circuitry (Carrier, 1987) .

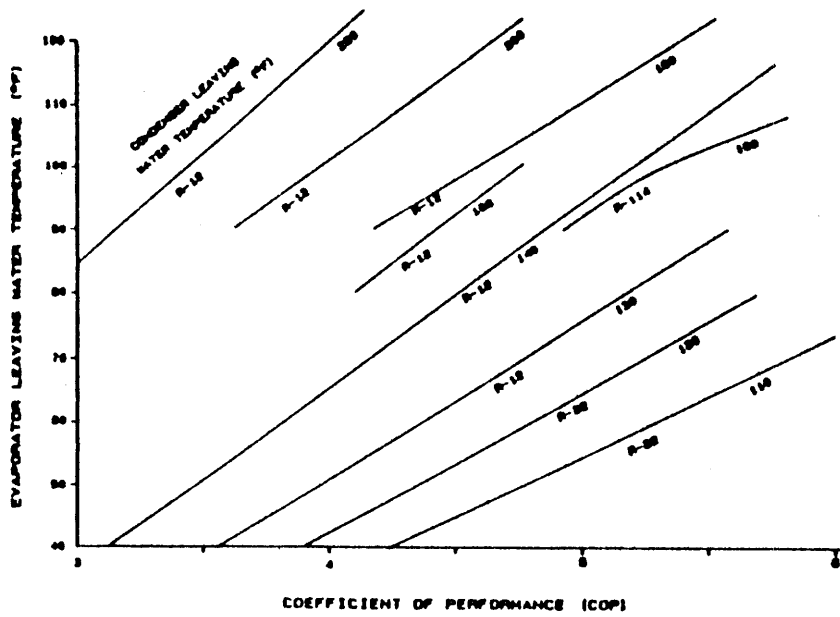


Figure 9 : performance of reciprocating heat pumps (McQuay, 1986 and Carrier, 1987)

### 2.4 Centrifugal

Centrifugal heat pumps are available in capacities ranging from 293 to 7325 kW in a single unit (McQuay, 1983) . The equipment features a single or dual one stage compressor, depending upon the size .

Construction of the balance of the machine is similar to that of the reciprocating machine with the exception that the source water in the evaporator flows through the tubes, rather than the shell as in reciprocating equipment .

This configuration permits the use of alternate tube construction materials to accomodate (without the use of a heat exchanger loop) aggressive fluids in certain applications .

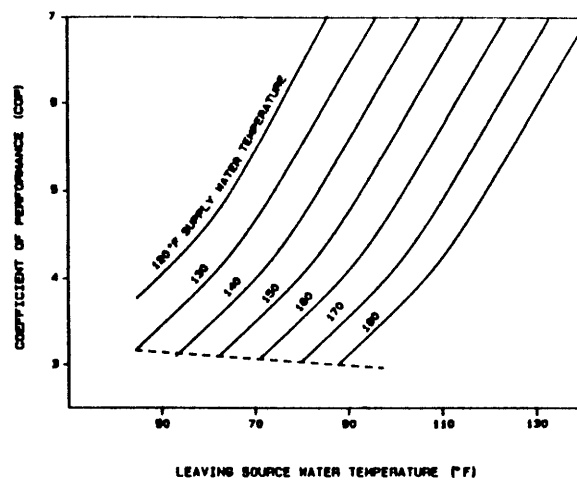


Figure 10 : performance of centrifugal heat pumps (McQuay, 1983)

## 2.5 Benefits and disadvantages

The geothermal heat pumps present many benefits from the point of view of their operating costs, energy savings (Figure 11) and the environment .

Thus, a typical residential geothermal heat pump shaves about 1-2 kW and 5-10 kW from the summer and winter peak loads, respectively .

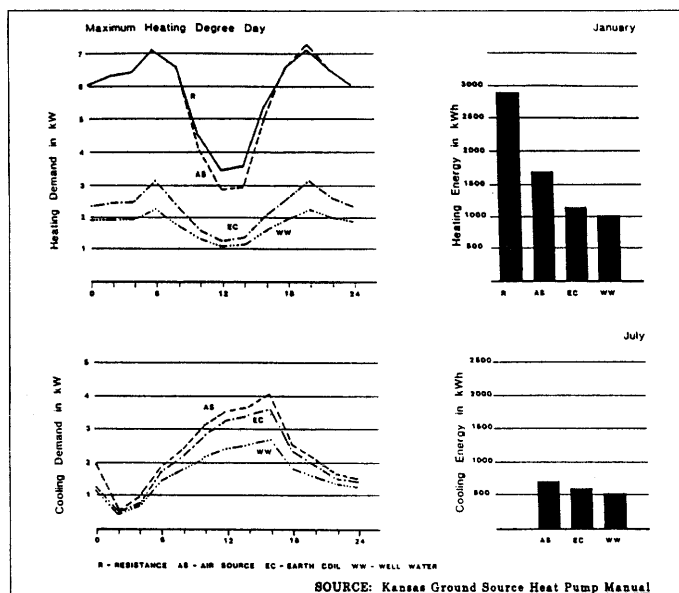


Figure 11 : representation of heat pump demand and energy consumption (Pratsch, 1990)

A geothermal heat pump's annual energy consumption is 30% less than that of an air-source heat pump and 50% less than electric resistance heating systems, significantly reducing pollutants emitted at the source of the power generation .

At equal source temperatures, the coefficient of performance of water-source heat pumps is higher than that of air-source heat pumps .

Moreover, geothermal heat pumps use about 25% of the refrigerant (HCFC-22) required by air-source heat pumps . Geothermal heat pumps have a simpler design, are sealed at the factory like a refrigerator, and do not require flushing with HCFC-22 during installation or servicing, as do air-source heat pumps and central air conditioners . But above all, HCFC-22 is much less damaging than the refrigerant (CFC-11) and is part of the solution to the CFC problem .

The disadvantages lie in the higher initial capital cost of heat pumps compared to the average residential heating/cooling systems .

Moreover, geothermal heat pumps can only be used where geothermal resources exist because the resource cannot be transported or held in storage .

## 2.6 Applications

### 2.6.1 Denmark

The Risoe National Laboratory of Roskilde has conducted a large investigation on the applicability of absorption cooling in the Danish energy system .



### **2.6.2 Japan**

The Hitachi Company markets absorption heat pumps with multi-stage absorber and multi-stage regenerator, air-to-water heat pump chillers and self-contained air-to-air heat pump air conditioners with reversible cycle cooling and heating control devices .

The Department of Mechanical Engineering (University of Sapporo) has conducted a large research program in cooperation with the System Planning Department of Helsinki (Finland) on wasted heat recovery and temperature upgrading by absorption heat pumps .

### **2.6.3 Sweden**

The Swedish Council for Building Research has tested out with an absorption heat pump in Trollhaettan .

The Department of Heat and Power Engineering (University of Lund) has designed an absorption heat pump at Ystad .

A technical and economical study on energy recovery by use of flue gas cooler in combination with an absorption heat pump was conducted by Studsvik Energiteknik (Nykoeping).

### **2.6.4 United States of America**

The most well known heat pump system applied in the U.S. is the Commonwealth Building in downtown Portland, in Oregon .

A central chiller/heat pump was connected to the building heating and cooling loops . Heating requirements were supplied by the condenser loop and cooling requirements by the evaporator loop. Two groundwater wells, one slightly warmer than the other, were directly connected to the heating and cooling loops .The warmer well was connected to the evaporator loop .

During the cooling season, excess heat was rejected to the condenser loop and carried away by a modulated flow from the cool well through the loop to the warmer well .

During the heating season, a similar arrangement from the warmer well through the loop to the cooler well was employed .

This system constituted the earliest known practical application of seasonal energy storage (Knipe, 1987) .

A large tonnage groundwater heat pump system installed in the Yakima (Washington) County Jail was designed in a similar fashion to Kroeker's early system .

But these two applications have quickly realised a severe corrosion problem with the system piping . Subsequently, the original design (Kroeker, 1948) was revised (Knipe, 1985) and isolation heat exchangers were added; the system has operated satisfactorily since .

In Klamath Falls, Oregon, there is a motel in which each bedroom is provided with its own individual heat pump, reversible for cooling in the summer .

In Oreana, Illinois, a 267 m<sup>2</sup> , two-story, four-bedroom house with basement had a ground water heat pump installed that used 12°C ground water .

In Northwood, North Dakota, an average house (110 m<sup>2</sup> ) required 41 million kJ of energy from ground water for space heating during the 1981 calendar year .

Public Service of Indiana (PSI) has reduced the cost of geothermal loops by about 30% through mass installation of earth loops during new subdivision construction . PSI named the product System GT, Geothermal Heating, Cooling, and Water Heating, and provided the earth loops free to participating developers . As a result, about 10% of the new homes in PSI's service area now have geothermal heat pumps . Recent marketing surveys show that 47% of customers in PSI's service area are aware of the geothermal alternative .

Neighboring utilities in Michigan, Kentucky and Illinois, who benefit from PSI's marketing, are also starting similar programs .

Air Conditioning and Refrigeration News reports that about 130000 water-source heat pumps were manufactured in the United States in 1989, including about 25000 geothermal heat pumps. The part of heat pumps in the direct use of geothermal energy (Figure 12) has been almost tripled over the last five years .

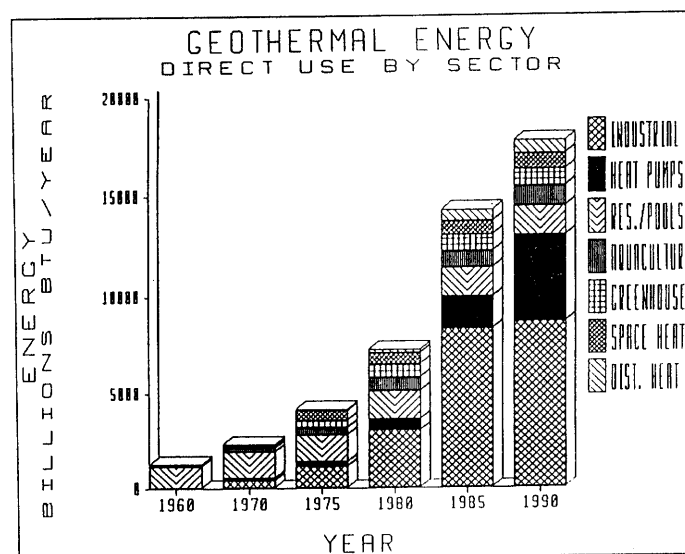


Figure 12 : geothermal energy : direct-use by sector (Lund, 1988)

### 3 The Lysholm Engine

The Lysholm Engine invented in 1934 by the Swede Alf Lysholm is a screw compressor that was primarily designed for gas compression . Since the 1950's, it was introduced to the refrigerant industry for compressing refrigerant vapors .

Now it is used in some package refrigeration units operated with geothermal fluids .

Thus, the coupling of two helical rotary screw expanders, one being used as a screw type compressor, and the other one as a prime mover, can be utilized as a portable refrigerant unit, capable of being operated with the total flow of a geothermal well of an intermediate to high temperature water geothermal system .

## 4 Aquaculture

### 4.1 Introduction

Future supply of proteins for human consumption are more and more dependent on the development of aquaculture, particularly in regions characterized by limited use of meat, milk and derivatives .

Moreover, it replaces traditional fishing that has reached near saturation and its production can be planned in advance according to market conditions .

Also, this activity is very attractive for geothermal applications because it requires heating at the lower end of the temperature range (Figure 13) where there is an abundance of geothermal resources .

Use of waste heat or the cascading of geothermal energy from power plants or other high-temperature uses also have excellent possibilities .

The use in aquaculture of geothermal fluids is rapidly expanding, particularly in the United-States, Comecon countries, Japan and Iceland .

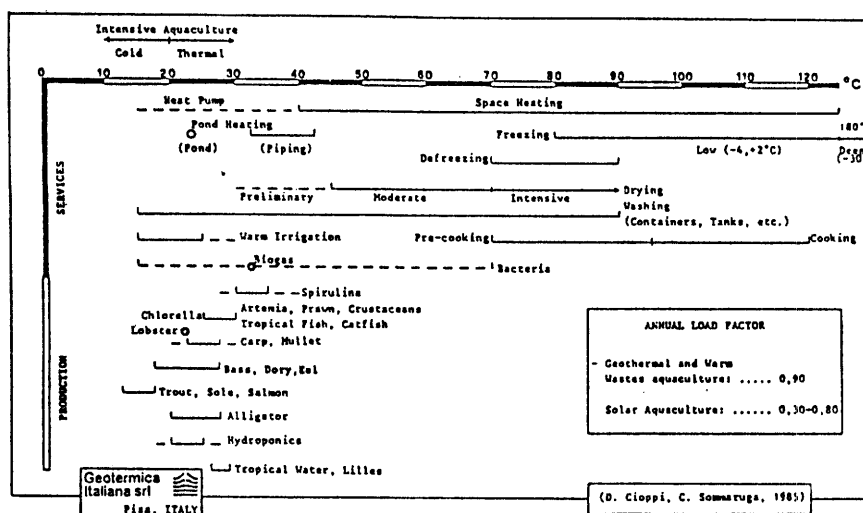


Figure 13 : fluid temperature ranges by geothermal aquaculture farms (Cioppi and Sommaruga, 1985)

### 4.2 Concept of biomass

Particularly interesting is intensive aquaculture, which can be made with the use of hot waters (thermal aquaculture) .

Thus, both in aquaculture and in greenhouses, a direct relationship exists between produced biomass (respectively fish and vegetables) and temperature (Figure 14), each type of biomass having its optimal temperature .

Thermal aquaculture may double fish growth with respect to the average values of natural waters, being, moreover, independent from seasonal cycles .

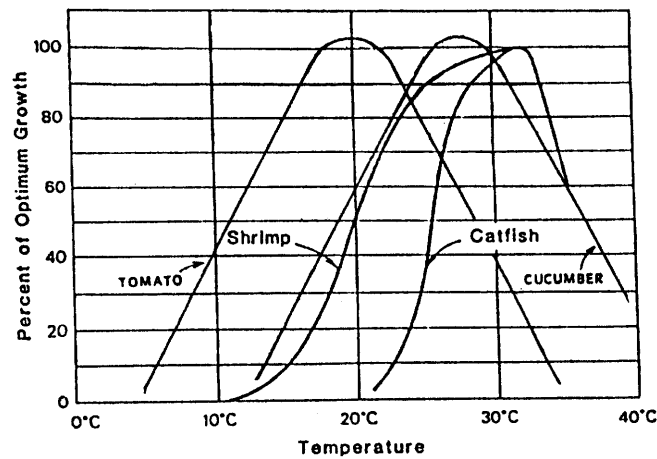


Figure 14 : optimum growing temperature for selected aquatic species and agricultural products (Lund, 1985)

Table of some aquaculture crops :

Specie	Growth period (*)	Water temperature
Oyster	24 months	24.4-25.6 °C
Lobster	24 months	22.2-23.9 °C
Pink shrimp	6-8 months	23.9-29.4 °C
Prawn	6-9 months	27.2-30.0 °C
Tropical fish	2-3 months	23.3-32.2 °C
Catfish	4-6 months	18.3-23.4 °C
Salmon (Pac.)	6-12 months	15.0 °C
Trout	4-6 months	12.8-18.3 °C
Carp	12-24 months	20.0-32.2 °C
Yellow perch	10 months	22.2-27.8 °C
Striped bass	6-8 months	16.1-18.9 °C

(\*) : Growth period to market size

#### 4.3 Characteristics and technology

Intensive thermal aquaculture requires :

- availability of large amounts of cold water (to be heated) and/or of natural hot water because of the frequent recyclings
- systems for the treatment, purification and recycling of waters
- pumping systems
- very low cost of the water and of the heating process

Geothermal fluids can, therefore, be quite advantageously used for intensive aquaculture, as they are constant throughout the year and their temperature optimal .

In many cases natural hot waters contain salts, even in large quantities, and other substances ( $H_2BO_3$ ,  $NH_3$ ,  $H_2S$ ,  $CO_2$ , As, Hg, etc) . When the chemical treatment of these waters is uneconomical sufficient amounts of fresh or suitably saline waters, could be heated using the polluting geothermal fluids .

The heating of cold waters with geothermal fluids can be obtained through :

- heat exchangers, placed outside the ponds
- radiators, submerged in the ponds
- submerged pipes

In case available temperatures are not sufficient, some increase in temperature could be obtained with passive solar systems (greenhouses, tunnels, etc) .

If, on the contrary, the temperature of geothermal waters is too high, they will have to be cooled through mixing or heat exchange with sufficient quantities of cold water .

#### 4.4 Pond heat loss

In order to determine the heat loss of the ponds, it is necessary to first select the temperature at which the water must be maintained .

A non-covered pond, exposed to the elements, exchanges heat with the atmosphere by way of four mechanisms : (a) evaporation, (b) convection, (c) radiation, and (d) conduction .

##### 4.4.1 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 . The quantity of heat required to evaporate water varies with the temperature and the atmospheric pressure .

Moreover, losses can occur through 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 .

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 increases .

The following figure (Figure 15) illustrates the effect of increased pond water temperature on vapor pressure difference and, hence, the rate of evaporation .

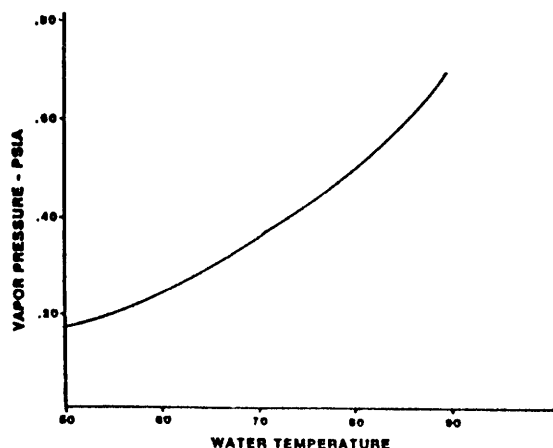


Figure 15 : plot of pond water vapor pressure vs. temperature (Rafferty, 1986)

#### 4.4.2 Convective loss

The convective loss is the mode associated with 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 (Figure 16) and the air temperature .

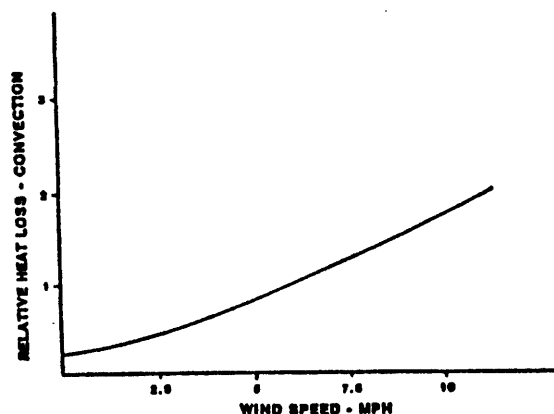


Figure 16 : plot of relative convective heat loss vs. wind speed (Rafferty, 1986)

#### 4.4.3 Radiant loss

The radiant loss is primarily dependent on the temperature difference between the pond surface temperature and the surrounding air temperature .

Due to evaporation 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 .

#### 4.4.4 Conductive loss

The conductive loss is the loss associated with the walls of the pond . Of the four losses, it is by far the smallest .

To give an example, for a 46 m<sup>2</sup> pond, the maximum evaporation, convection, radiation and conduction heat losses are respectively 46%, 38%, 13% and 3% .

#### 4.5 Benefits and disadvantages

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 basic body metabolism is affected (Johnson, 1981) .

Thus a good geothermal supply, due to its constant temperature, can "out-perform" a natural mild climate .

The most important items to consider are the 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 .

## **4.6 Applications**

### **4.6.1 China**

There are numerous breeding farms of carp (4 species) and tropical fish at Jiexi (Guandong), Fuznou Hubei (2000 m<sup>2</sup> of protected ponds), Yingshan, Chanjiang, etc .  
China has the world's oldest tradition of classic aquaculture .

In 1974, the Jiexi fishing ground of the Guangdong Province used hot spring fishponds to start an experimental breeding of four main carps . Further, they discovered that a proper temperature of pond water (20-30°C) would cause the fish to absorb more food, accelerating their growth . In the winter of 1979, as the climate of Guangdong Province was persistently microthermal (below 7°C), cloudy and drizzly, quantities of dace perished, while the Jiexi hot spring fishing ground was successful in holding the immature fishes and providing different places with volumes of fry .

In cooperating with other organizations, the Yingshan County Scientific Experiment Station and the Chanjiang Institute of Aquatic Products of the Hubei Province have been successful in using the geothermal water for carrying out the Zanzibar tilapia breeding, sex reversal and hybridization experiments, as well as those on production scale .

Through the sex reversal experiment, they have obtained 100% all-male fish . These experimental all-male fish, being rapid in growth and 40.4% higher in productivity than the natural colonial fish, are now being propagated .

In a few years, they have gathered about 1.5 million fry and provided other parts of the country with improved varieties . The aquatics breeding base of the Fuznou City, by utilizing the geothermal water for breeding the African crucian carp, enables the fry to safely pass the winter and provides different regions with a total of two million fry per year . In 1980, the Research Institute of Aquatics of the Hubei Province constructed a 2000 m<sup>2</sup> geothermal fishpond with a plastic roof for breeding eel . This pond can supply 80 tons of immature eel and fry .

Now the fishing pools cover an area of about 1.6 Mm<sup>2</sup> in 17 provinces and cities .

### **4.6.2 France**

Production is mostly oriented toward fry, and the breeding of mullet, dory and bass (high quality fish) at Balarne-les-Bains, and at Corbieres, Languedoc, etc .

### **4.6.3 Hungary**

Several breeding farms of carps use thermal spring waters and wastes of geothermal wells near Hortorgarbaghy Svarbas .

### **4.6.4 Iceland**

Fish-farming (trout and salmon) have been a fast growing industry in Iceland . Fish farms number almost 130 that represents around 100 Gwh/a .

Geothermal heat is commonly used together with fresh water and/or seawater to provide the optimum conditions for smolt rearing and rearing of fish for export .

### **4.6.5 Italy**

Several projects, now under study, will soon be implemented, especially in Tuscany . Existing activities include an aquaculture plant in Latisana (Friculi) which uses 35°C waters, and a fry farm in Santa Liberata/Orbetello (Tuscany) with 25°C waters .

#### **4.6.6 Japan**

Aquaculture farms have reached 38 MW in 1984 (10.2 MWt in 1975), equal to 40% of the installed capacity of geothermal direct uses.

Three crocodile farms exist in Beppu, Atagawa (2000 l/min at 105°C) and Nagashima for purely sightseeing purposes and fish breeding in Shikabe (70 l/min at 70°C) and other localities (the eels being the most profitable) .

In these fish farms water in the pipes is held at 23°C by mixing hot spring water with river water .

The total thermal power associated with these animal husbandry operations amounts to 10.9 MW, 14.9 MW and 17.4 MW for 40°C, 15°C and 0°C respectively .

#### **4.6.7 Mexico**

Experimental farms for lobster breeding using effluents of Cerro Prieto geothermal field (Baja California) are presently being tested .

#### **4.6.8 Soviet Union**

In the geothermal region of Kamchatka there are 30 ha of ponds for carp breeding and intergrated aquaculture/agriculture systems.

#### **4.6.9 United States of America**

There are at least 14 aquaculture farms, the main ones are the bluegill and catfish farm of Cedarville, California, catfish and carps of Raft River, Idaho, a giant malaysian prawn research facility at Klamath Falls, Oregon, and catfish and shrimps at Paso Robles, California and Corsicana, Texas : spring water temperature is around 50°C and waters are used in integrated chains (fish -greenhouses - irrigation) . Aquaculture is being developed mostly for sport fishing.

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 380 l/s at 32°C . Cold water from springs and streams is used to cool the hot water to 27-29°C for the best production.

An experiment to breed giant fresh water prawns, raised at Oregon Institute of Technology since 1975, has provided data demonstrating that a tropical crustacean can be grown in a cold climate (as low as -7°C) where the water temperature is maintained at the optimal growing temperature for this species of 27-30°C .

Thus, growth rates of 2 cm per month (in the post-larva stage) have been maintained (twice that obtained in tropical climates) with a maximum density of 900 cm<sup>2</sup> of surface area per animal .

A very successful catfish raising operation has been started by the Indian community at Fort Bidwell in northeastern California.

Geothermal well water at 41°C is mixed with cold water to produce 27°C water .

#### **4.6.10 Zimbabwe**

The only aquaculture farm in Africa is near Victoria Falls, where for 20 years crocodile breeding has taken place using 25°C geothermal waters (external temperature : 0-15°C) .



## **5 Forest and agriculture products processing**

### **5.1 Introduction**

Significant amounts of energy are consumed annually for forest and agriculture product development especially for making paper, drying lumber, and dehydrating and drying fruits, vegetables and grains .

Some specific stages of each of these different processes require a big quantity of steam generally supplied by gas or fuel boilers .

Geothermal energy could find new applications in these industrial techniques of organic matter transformation .

### **5.2 Pulp, paper, and wood processing**

The pulp process utilized is the Kraft, or sulfate method represented by six main steps to obtain paper from raw wood (Figure 17) :

#### **- Debarking and chipping**

The wood to be pulped is first debarked in the barker . The bark is used as fuel to produce process steam . Once debarked, the wood is chipped to specific size, which aids in packing chips in the digester . The correct ratio of chips to liquor must be maintained between 2.5 and 3.5 kg / 1 kg of wood.

#### **- Cooking and digesting**

The cooking liquor contains essentially sodium sulfide and caustic soda . The liquor, as it is received from the recovery system, is too concentrated for proper digesting results; therefore, it has to be diluted . The dilution is accomplished using the weak black liquor to keep water addition to a minimum . The digester charge is then heated either through the addition of live steam to the bottom of the digester or indirectly with steam . The time required for cooking the wood varies, depending on the use of the pulp . The maximum cooking temperature is between 168 and 175°C (steam pressure is 655 and 793 kPa, respectively).

At the completion of cooking, the pressure within the digester is allowed to decrease to approximately 552 kPa . The pulp is then expelled by opening a quick opening valve at the bottom of the digester . The pulp then flows to the flash tank . The flash tank is arranged with a special vapor outlet . Heat is sometimes recovered from this vapor .

#### **- Screening and washing**

The pulp is then screened to remove small pieces of uncooked wood .

Following screening, the pulp is washed to remove the cooking liquors . It is economically important to remove as much of the liquor as possible . The pulp washing is carried out in rotary vacuum washers . This process is so efficient that between 98 and 99% of the cooking chemicals are washed from the pulp . Hot water is used for washing . The pulp leaving the washer is of relatively high consistency . The weak black liquor washed from the pulp is first concentrated in multiple effect evaporators and then further concentrated in direct contact evaporators .

#### **- Bleaching and washing**

The bleaching of pulp is carried out in from one to five or more stages . The basic steps in the bleaching process are :

- . mix the chemicals in the proper ratios with the pulp
- . raise the pulp temperature to the required level
- . maintain the mix at this temperature for a specific period

. wash residual chemicals from the pulp  
 Chlorine dioxide is almost always used as the bleaching chemical .

- Beating and refining

The purpose of beating and refining is to change the physical form of the fibers in the pulp. The process is related to grinding . It is carried out in a number of different ways depending on the fibers desired . The overall objective is to maximize bonding strength .

- Pressing and drying

Paper is made by depositing a dilute water suspension of pulp on a fine screen, which permits the water to drain through but which retains the fiber layer . This layer is then removed from the screen, pressed, and dried .

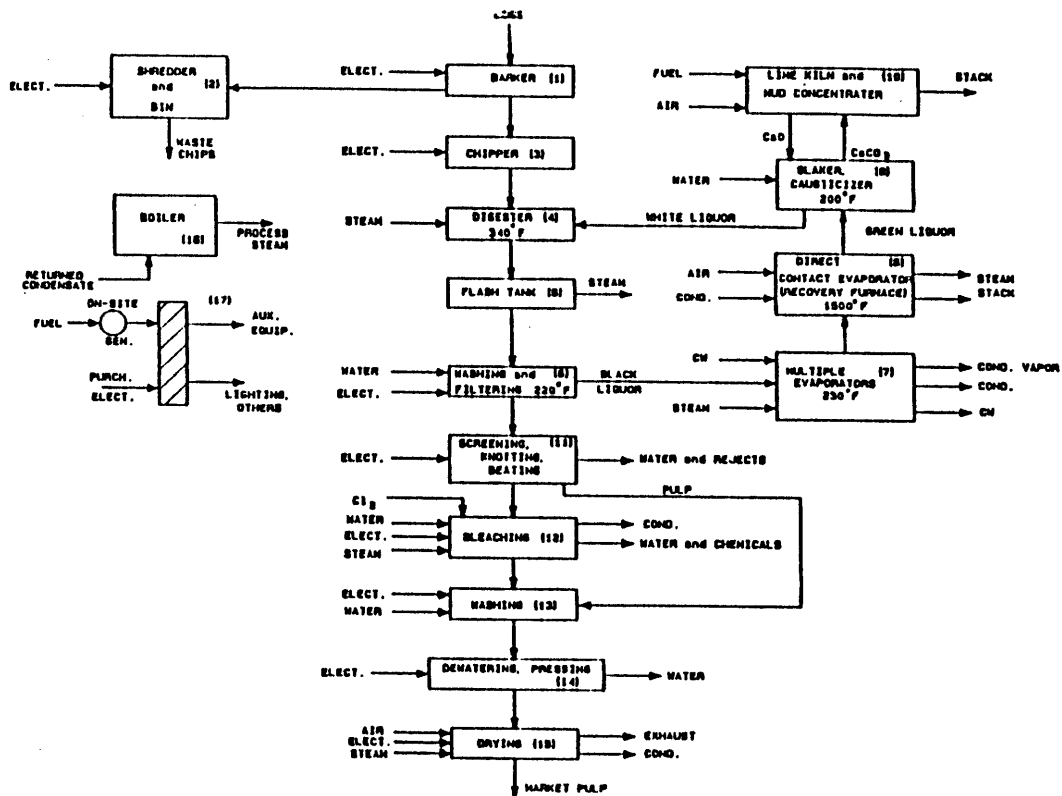


Figure 17 : Kraft process (Lienau, 1989)

Most of the process heat requirements are in the range of 121 to 177°C and the heating is accomplished by way of steam in shell and tube heat exchangers .

Geothermal fluids could partly accomplish water heating and heating of air for paper drying . Two wash water heaters are used, one using geothermal fluid at 100°C and the other using steam at 172 kPa to heat the water to the final temperature of 99°C . Also, an air dryer is used to preheat the air in the drying section . This section would also be designed to use steam at 172 kPa .

5.3 Timber and lumber drying

The two basic purposes of lumber drying are to set the sap and to prevent warping . The sap sets at 57 to 60°C . Warping is prevented by establishing uniform moisture content throughout the thickness . For information, lumber left to dry under ambient conditions loses

its moisture from exposed surfaces at a faster rate than internally . This differential drying rate sets up stresses that cause warping .

In the kiln drying process (Figure 18), the evaporation rate must be carefully controlled to prevent these stresses . The allowable drying rates vary from species to species and decrease with thicker cut sizes . Kiln drying is usually carried out as a batch process . The kiln is a box-shaped room with loading doors at one end . It has insulated walls and ceiling and has fans to recirculate the air at high velocity through the lumber . The sawed lumber is spaced and stacked to assist the free air movement and is loaded by large fork lifts or preheated to a temperature consistent with the drying schedule; air enters the kiln where it recirculates through the stacked lumber and picks up moisture . Exhaust fans draw the moist air from the kiln and discharge it to the atmosphere . The rates of flow and temperature are adjusted so that the temperature and the humidity in the kiln will retard the drying rate sufficiently to prevent warping . During the drying cycle, the lumber loses a large portion of its weight from the evaporation of water, 50 to 60% for many species .

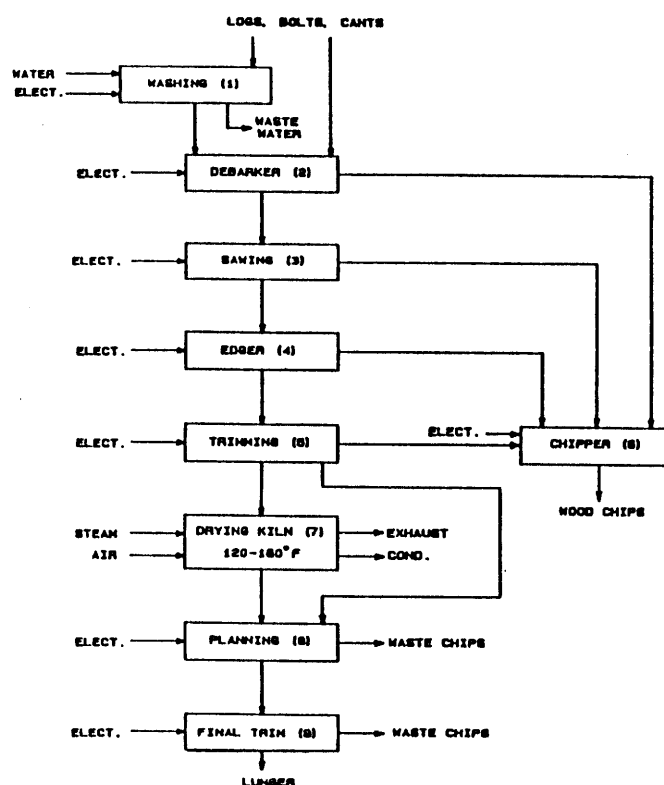


Figure 18 : lumber drying process flow (Lienau, 1989)

Geothermal energy could be adapted to kiln drying by passing air over finned heat exchanger tubes carrying hot water .

The required temperature of the fluid depends on the specie and the sawed size of the lumber and generally is in the range of 79 to 90°C .

#### 5.4 Vegetable and fruit dehydration

Vegetable and fruit dehydration involves the use of a tunnel dryer, or a continuous conveyor dryer using fairly low temperature hot air from 38 to 104°C .

A tunnel dryer is an enclosed, insulated housing in which the products to be dried are placed upon tiers of trays or stacked in piles in the case of large objects .

Heat transfer may be direct from gases to products by circulation of large volumes of gas, or

indirectly by the use of heated shelves or radiator coils .

The vegetable dehydration process flow (Figure 19) is as complex as for lumber drying . It takes into account the internal diffusion of heat or moisture .

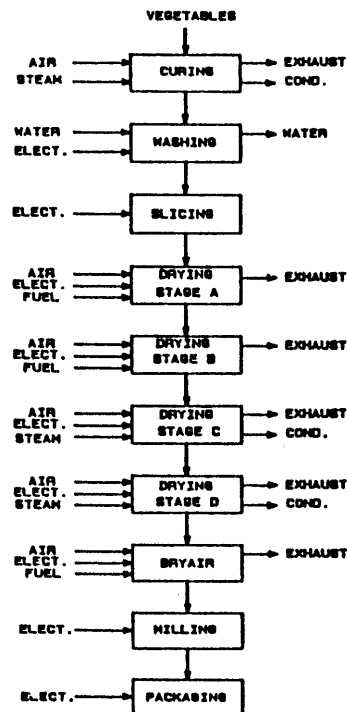


Figure 19 : vegetable dehydration process flow (Lienau, 1989)

The energy is usually 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 eliminate the turning of the product 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 the driving of the beds' motors .

Geothermal fluid could be used to supply the require energy in stages C and D .

Using a  $-7^{\circ}\text{C}$  minimum approach temperature between the geothermal fluid and process air, a well with  $110^{\circ}\text{C}$  fluid is required .

The first-stage air temperature can be as low as  $82^{\circ}\text{C}$ ; however, temperatures  $>93^{\circ}\text{C}$  are desirable .

### 5.5 Grain drying

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  $38$  to  $82^{\circ}\text{C}$ . Most farm crops must be dried to, and maintained at, a moisture content of  $12$  to  $13\%$  wet basis, depending on the specific crop, storage temperature, and length of storage . Mold growth and spoilage are functions of elapsed storage time, temperature, and moisture content above critical values . Grain to be sold through commercial markets is priced according to a specific moisture content, with discounts for moisture levels above a specified value .

The grain dryer is typically a deep bed dryer, consisting of :

- . a fan to move the air through the product
- . a controlled heater to increase the ambient air temperature to the desired level

. a container to uniformly distribute the drying air through the product  
The exhaust air is vented to the atmosphere .

## **5.6 Applications**

### **5.6.1 Iceland**

A seaweed-drying plant at Reykhólar in Western Iceland has used hot water for drying its product which is exported to pharmaceutical firms .

### **5.6.2 Japan**

In Yuzawa the facility for drying timber consists of a vacuum dryer and a bark boiler using hot water with 93°C inlet and 80°C outlet temperatures and with a 47.6 ton/h flow rate (Horii, 1985).

### **5.6.3 New Zealand**

A joint wood and paper processing and power generation plant used the Kraft process in Kawerau . Geothermal energy is delivered to mills by 1.15 ton/h of 1620 and 793 kPa steam, which are obtained by flashing the wet steam (1270 ton/h) at a central flash plant (Wilson, 1974) .

The Broadlands Lucerne Company's geothermal dryer has a capacity for drying about 2300 kg/h of alfalfa, producing pellets for 165 d/y . A separator is used to deliver steam (27 ton/h of steam at 113°C) to steam coils heating air to 124°C (Freeston, 1980) .

### **5.6.4 Taiwan**

In Tatun a timber drying plant with a kiln's capacity of 40 cubic meters can produce 240 cubic meters of kiln dried lumber per month using 60°C hot water in the kiln with a flow rate of 0.5 ton/h (Chin, 1976) .

### **5.6.5 United States of America**

In Brady Hot Springs (Nevada) Geothermal Food Processors produce dried onions using hot water coils (47 l/s of hot water at 154 °C) from a 50 to 5% moisture content using a continuous through-circulation conveyor dryer . Production rate is 4500 kg/h of fresh onions, resulting in 800 kg/h of dried product for 6 months per year (Guillen, 1987) .

The firm of Papaya Products of Hawaii has been marketing products, such as papaya powder, through natural food outlets in the continental U.S. . The objective of the project was to investigate whether geothermal heat could be used for fruit drying and, if technically possible, whether the process could be placed on a viable commercial basis . The conclusions reached by the investigators were positive on both counts .

Steam from the geothermal well entered a series of coiled pipes installed in the upper part of the drying cabinet in which pineapples, bananas and papayas are dried by air heated at approximately 49°C .

The main difficulty encountered by the fruit drying project was the inability to adequately control the input hot air .

## 6 Biomass development

### 6.1 Introduction

After the two oil crises of 1973 and 1979, O.E.C.D. countries have become increasingly aware of the problems underlying the energy situation and have progressively introduced policies aimed at more efficient energy use and the exploitation of energy sources which can be substituted for oil .

Among these sources, biomass seems one of the most interesting because it is in principle renewable and to a large extent the techniques for converting it to energy are known .

But an important oil price drop followed these two oil crises and most of the R & D programs in the biomass utilizations field were stopped . So the recent Persian Gulf crisis could bring a new interest in biomass development .

In this new international context the utilization of geothermal energy for biomass development must be considered, especially in the countries with a wide range of agricultural crops and trees which have a potential for energy farming such as Brazil and New Zealand .

Lastly, a real hope has appeared in the biotechnology field with the experimental isolation of microorganisms from geothermal hot springs and with their feasible industrial production and their marketing in the future .

### 6.2 Alcohol production

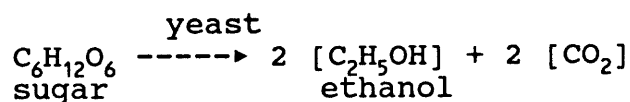
Alcohol production (ethanol) from wood (or beet) can be summed up in three stages (Figure 20) :

#### - hydrolysis

Wood contains little sugar and, therefore, the sugar required for the fermentation process must be derived from the cellulose present in the wood . This is called hydrolysis and can be achieved by a number of methods . The method which seems to be economically and technically the most successful is by percolating dilute sulphuric acid (0.5%) at high temperature (150-200°C) through the wood chips .

#### - fermentation

The solution containing the fermentable sugars (hexoses) enters a fermentation vessel where it is introduced to yeast cells which act as catalyst for the reaction . The temperature must be maintained at about 30°C, the reaction being exothermic . The chemical equation describing the reaction is :



#### - distillation

After the fermentation is complete, the beer containing 5-15% ethanol is distilled . This process separates the ethanol from the water and byproducts by boiling off the ethanol at just below 100°C .

The ethanol produced is 95% pure, the other 5% being water (an azeotropic mixture) .

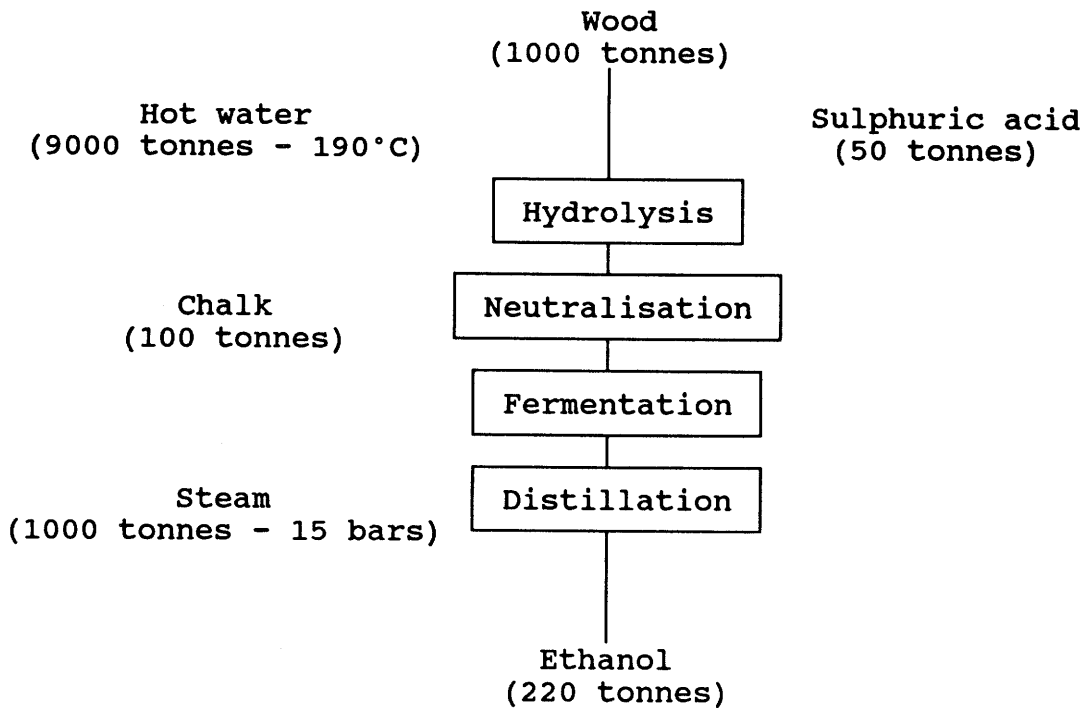


Figure 20 : schematic diagram of the wood ethanol process (Bottomley, 1980)

From a technical viewpoint, geothermal heat has large scale uses in the preheating, hydrolysis, and distillation stages . It is possible that heat exchangers would not be necessary as direct use of geothermal fluid could be viable . However, the financial advantages are not conclusive .

### 6.3 Biogas generation

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

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

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

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

## **6.4 Biotechnology**

A joint research project supervised by the Institute of Biology and the Technological Institute of Iceland could be also classified as biomass production, especially in the biotechnology field, from geothermal energy .

Icelandic biologists have been producing thermophilic cyanobacteria or bluegreen algae in artificial hot springs . The purpose of that is to isolate and purify a special blue pigment from these organisms and enzymes .

The use of geothermal heat in these projects have mainly to do with the isolation of the organisms . In fact they use just the extensive geothermal areas in Iceland to find and select different organisms with different properties . Once they have got these microorganisms growing in the laboratory, they don't need the geothermal energy anymore .

## **6.5 Applications**

### **6.5.1 Iceland**

This country is conducting a pilot research project in the biotechnology field (see the previous chapter) .

### **6.5.2 New Zealand**

This country expressed its interest in this application field with the recent completion of a whey-ethanol plant at Reporoa, the operation of a pilot wood-ethanol plant in Rotorua, and a recently completed feasibility study for producing ethanol from sugar beet .

Some regions in the north island, such as Waimangu and Broadlands in the Taupo volcanic zone, are suitable for forestry farming, in particular, radiata pine and are in or adjacent to geothermal fields .

### **6.5.3 United States of America**

As has been described before the biomass-ethanol process is very energy intensive with large hot water and steam quantities being required . There has been some investigation in the U.S.A. into the possible use of geothermal fluid, thereby making the process more economically attractive .

## **7 Food processing**

### **7.1 Introduction**

Numerous food processes require hot water and steam in the processing line .

It would be tedious to make an inventory of all of them . Only the main and the most common applications are described here .

### **7.2 Washing**

Large amounts of low-temperature energy (35-93°C) is consumed in food processing, with major uses in meat packing for scalding, carcass wash and clean-up (60°C); in soft-drink container and returnable bottle washing (77°C); in poultry dressing as well as canning and other food processes.

### **7.3 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 energy through heat exchangers .

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

#### **7.4 Sterilizing**

Sterilizers are used extensively in a wide range of industries and include applications such as equipment sterilization in the meat-packing and food-processing industries and sterilization for the canning and bottling industry . Most sterilizers operate at temperature of 104-121°C and could 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 .

#### **7.5 Sugar-beet processing**

The first two stages of beet processing are preparation and slicing . Preparation is the stage between harvesting and slicing operations . Following the slicing operation, there are a number of processes that require thermal energy . These processes may be conveniently separated into five stages (Figure 21) :

##### **- diffusion**

The diffusers separate the pulp and raw juice from the long thin strips (cosettes) of sliced beets . To start the process, water enters and percolates by gravity through the cosette mass, leaching out sugar as it proceeds counter-current to the cosettes . The temperature is raised to between 70-80°C for better extraction . The rate of diffusion increases directly with temperature .

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

##### **- juice purification**

It is necessary to purify the juice since it contains nonsugar impurities . The nonsugar impurities in both true and colloidal solution make it very difficult to concentrate the diffusion juice or to crystallize pure sugar from it . Impurities are removed by introducing lime in the form of a slurry of calcium saccharates . Thermal energy is used preparatory to and during purification to heat juice from 64-90°C and to provide the thermal energy used at lime kilns to produce CaO and CO<sub>2</sub> .

The juice is heated to 116°C and transported to the evaporators .

##### **- evaporation**

Heating is required to evaporate water from the beet juices . Water evaporated from the beet juices in the first-effect evaporator leaves a vapor which is subsequently used in successive

evaporator stages and other processes in the plant . Thus, each evaporator effect acts as a condenser for the preceding effect . Each succeeding vapor pressure, and of course temperature, is proportionately lower with the lowest vapor pressure in the last effect under control of the barometric condenser .

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

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

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

#### - crystallization

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

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

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

#### - pulp drying

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

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



energy to the process . The secondary fluid, circulating in a closed system, then returns to the intermediate heat exchanger to be reheated . For a geothermal fluid at 121-149°C, all of the thermal energy needs of the potato-processing plants could be met except for the heating of the fryers .

### **7.7 Hatching and drying**

Geothermal hot water and steam are used especially in Iceland some fish factories to hatch and dry fish .

### **7.8 Slaughter operations**

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

## **8 Distillation : production of fresh water**

### **8.1 Introduction**

With the increasing rates of population growth and of water consumption per head rising living standards and increased industrialization, the supply of adequate quantities of fresh water become a matter of growing urgency in many parts of the world .

Suitable sites for rainwater catchment reservoirs are becoming more difficult to locate in highly populated countries like the United Kingdom . Other densely populated areas like California can at present rely to a limited extent on long distance transportation of water from remote catchments . Newly found prosperity from oil wealth has led to great population growth in almost totally arid areas in the Middle East . Recourse is becoming increasingly necessary to the desalination of sea and brackish waters .

Desalination requires heat of moderate grade (120°C) so that hyperthermal fields would be more or less necessary for efficient geothermal desalination .

The chances of the coexistence of a hyperthermal field and an arid, but highly populated, area are not great, but such places could well be found in California, Mexico, North Africa, the Canary Islands, Greece and perhaps in parts of the Middle East. Moreover, if and when we ever succeed in creating artificial thermal fields in semi-thermal or even non-thermal areas, the opportunities for geothermal desalination will become very great indeed .

### **8.2 Principle and applications**

#### **8.2.1 Mexico**

As the geothermal area of Cerro Prieto being located in one of the driest and saline zones of the Mexican Republic, the construction of the geothermoelectric plant presented the problem of fresh water supply for the preparation of concrete and mortars, because the available water in the area has a salinity content between 2000 to 3000 ppm of sodium chloride .

For this reason and because external supply was very expensive, the engineers decided to use part of the steam produced by a geothermal well for the condensate, and they designed a small condensation plant able to supply the flow of 0.7 liters per second needed for the construction of the geothermoelectric plant .

They planned to use this flow to supply the needs of drinkable water consumption for the personnel and to replace the water loss in the cooling circuit of the geothermoelectric plant . The success obtained in this pilot plant presents very favorable prospects for its scale-up .

The condensation plant is fundamentally composed of two evaporative condensers, a cooling tower and an aeration tower .

- Condensers : the use of standard shell and tube condensers, cooling by means of the available water (3000-4000 ppm total solids) presented the problem of great and swiftly forming scaling. To solve it, the engineers decided to design evaporative condensers . By running cooling water through the uncovered tubes, they achieved a simple and effective scale control .

- Cooling tower : the engineers disposed of the waste water in a neighbouring drainage channel. This water was recirculated in a counterflow mechanically induced draft cooling tower, specially made for this purpose . The water loss by evaporation and dragging are supplied by the water of the above-mentioned channel.

In this type of equipment, the problem of scale formation by the salt content in the cooling water is easily detected by visual inspection, proceeding if necessary, to manual cleaning by the use of a tube scraper; inside the tubes the problem is small because the separated condensed steam carries very few scaling contaminants .

- Aeration tower : the water obtained by condensation of the geothermal steam is pumped to an aeration tower for the stripping-off of the dissolved CO<sub>2</sub> and H<sub>2</sub>S gases and then is pumped to the storage tank .

It is important to mention that this pilot plant is only moved by the geothermal steam, and for this reason its control is very simple depending only on the control of the regulation valve of the steam fed to the system . It avoids the use of multiple controls and allows a saving of energy and fuel consumption .

### **8.2.2 United States of America**

The Imperial Valley occupies a part of the delta of the Colorado river along the Mexican border in the desert country of southern California . the fertile silt of this area, when provided with water by irrigation, makes it one of the world's richest agricultural areas . Lately, however, there has been concern about further development of this area because of the constraints imposed by the water supply .

Within recent years, increasing attention has been directed toward the Imperial Valley because of large reservoirs of hot water underlying the area . This resource has been known, but little effort has been devoted to its development until the last few years . As the result of action by several individuals (from the Institute of Geophysics, University of California at Riverside) with a great deal of vision and imagination, a coordinated effort is now beginning for a thorough appraisal of this resource .

The conclusion of this study was that the geothermal waters of the Imperial Valley constitute an enormous potential, but it also recognizes that some problems of large magnitude must be solved if the asset can be made to pay . One of these, perhaps the most critical, is the problem of brine disposal . The only market evident for very large quantities of geothermal brine is for saline water conversion .

Thus, it became rather logical for the desalination concept to be joined with the idea of geothermal energy development .

Two important problems occur in this type of plant coupling desalination and geothermal energy development .

The first one is the heat rejection . Normal desalting plants obtain cold feed, purchase heat for its conversion and discharge both waste heat and brine effluent to the sea . In the Imperial

Valley, feed will be brought in at an estimated 205°C; waste heat must be rejected to the atmosphere, and the waste brine must be evaporated to dryness or reinjected into the earth . The second one is of chemical nature . From some analyses of geothermal water from a Mexican field just south of the area under consideration, it seems certain that hydrogen sulfide and carbon dioxide will be present in appreciable quantities . These gases represent potential by-products . Elemental sulfur or sulfuric acid can be made from H<sub>2</sub>S, and it is possible to recover CO<sub>2</sub> for commercial use if the quantity is sufficient . Silica in the brine must be reckoned with in the wells as well as in the plant . Flashing of brine in the well will produce a scale which must be removed periodically . Steps will be necessary to prevent the formation of silica scale on heat transfer tubing . A number of alternatives are available for this treatment, possibly with sulfuric acid made from H<sub>2</sub>S .

### **8.3 Benefits and disadvantages**

Desalination is a heat-intensive process that can most effectively be achieved by means of multiple-effect or flash evaporators .

Since a high performance ratio plant costs much in capital but little in heat, and vice versa, it follows that where heat is expensive a very high performance plant can be justified, but where heat is cheap a lower performance ratio is economically acceptable .

Geothermal heat is generally very cheap, so that distillation plants of low capital cost could be used in conjunction with it.

It is conceivable that we shall one day succeed in distilling sea or brackish water economically, not merely for drinking purposes but also for irrigation - a feat that has not yet been achieved.

## **9 Mineral extraction**

### **9.1 Introduction**

Some of the geothermal areas are located by the sea or close to an oil reservoir . In the first case, geothermal plants could use hot water or steam to produce both fresh water by distillation (see chapter 8) and salt by evaporation directly from sea water . In the second case, the resulting geothermal fluids are brines by infiltration . Thus the production of salt (potassium, calcium and magnesium chlorides) could also be considered .

### **9.2 Principle and applications**

#### **9.2.1 From sea-water**

##### **9.2.1.1 Iceland**

The most extensive technical work undertaken regarding the Sea Chemicals Complex so far has been the manufacture of magnesium with the aid of geothermal energy in the Reykjanes Peninsula . The only source of magnesium would be sea water .

In principle the process adopted initially follows conventional routes . Magnesium would be precipitated out of sea water with lime, and magnesium hydroxide would be produced . In lime manufacture, which is an essential part of this scheme, fossil fuel cannot be replaced by geothermal steam due to the high temperatures required, but the steam may be helpful in increasing the carbon dioxide concentration in the recovered stack gas .

As in the overall flow diagram (Figure 22), the carbon dioxide recovered from the lime kiln and the magnesium hydroxide would be used for the production of magnesium bicarbonate . The process would then continue with the production of magnesium chloride and sodium bicarbonate

out of the magnesium bicarbonate by the introduction of sodium chloride .

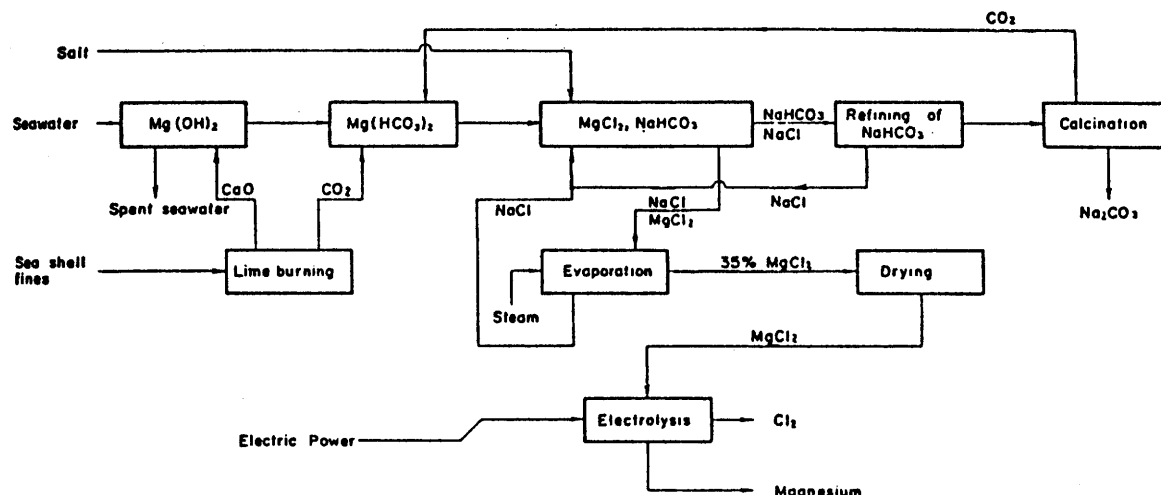


Figure 22 : the production of magnesium via the bicarbonate method (Lindal, 1975)

Two different intermediate processes have been considered for the conversion of magnesium bicarbonate and sodium chloride into magnesium chloride and sodium bicarbonate . One involves the use of ion exchange resins where the effluents are relatively pure solutions . The other involves the direct reaction of the components, where sodium bicarbonate may be precipitated out in solid form . In both cases, the components of the effluents are recovered. The process involves the production of commercial soda ash on one hand and a solution of magnesium chloride on the other, which may have a concentration of 10% or higher . The magnesium chloride solution (in view of electrolysis) would be concentrated in multiple effect evaporators by the use of geothermal steam to the point of 35%, or magnesium chloride hexahydrate could be crystallized out at a similar concentration .

### 9.2.1.2 Japan

The saltmaking industry in the Shikabe area, Hokkaido, use 200 floating shallow tanks of 91 cm x 182 cm made of zinc-steel plates in the open-air heating tank, and sea water is heated with hot water from the bottom of the tank . Sea water is poured into the first tank of the group, and transferred to the adjacent tank successively with the salt concentration increased, and finally the concentrated salt water sent to the other end of the tank is transferred to the roofed concentration tank .

On the other hand, the hot water and steam emitted from the well are led through the heating pipe provided in the concentration tank, and after heating and further concentration of the already concentrated salt water, led into the open-air tank group . In this open-air tank group, the hot water and steam flow in the direction opposite to the flow of sea water while heating the bottom of the sea water tank, and are finally released from the place of first sea water pouring tank . The salt water in the concentrating tank concentrated by heat to the appropriate specific gravity is further processed to remoisture after eliminating foreign matters, and becomes a refined product .

This saltmaking plant formerly produced about one ton of salt daily, totalling 300 tons annually, but the annual production at present has decreased to about 150 tons due to the attenuation of the steam well .

### 9.2.1.3 Mexico and United States of America

In these two countries the saltmaking could be combined with the production of fresh water (see chapter 8) .

## 9.2.2 From geothermal brine

### 9.2.2.1 Iceland

The Reykjanes, SW Iceland, salt plant calls for the recovery of common salt, potash, and calcium chloride concentration the same as sea water and a temperature of 270 to 290°C (Figure 23) .

Component	Reykjanes (well 8)
Temperature (°C)	270
pH/°C	6.25/270
SiO <sub>2</sub>	592
B	8.02
Na	9854
K	1391
Ca	1531
Mg	1.15
CO <sub>2</sub> (1)	1437
SO <sub>4</sub>	28.7
H <sub>2</sub> S (2)	31.5
Cl	18827
F	0.1
Dissolved solids	33653

Figure 23 : the chemical composition of reservoir fluid in the Reykjanes Peninsula, Iceland .

Chemical compositions are in ppm - (1) CO<sub>2</sub> total : H<sub>2</sub>CO<sub>3</sub> + HCO<sub>3</sub><sup>-</sup> + CO<sub>3</sub><sup>2-</sup> -

(2) H<sub>2</sub>S total : H<sub>2</sub>S + HS<sup>-</sup> + S<sup>2-</sup> - (Arnorrsson, 1974)

This brine will attain a higher mineral concentration by flashing at reduced pressure, and the salts may be produced separately with the aid of the same flash-off steam .

The basic method for the recovery of minerals from the geothermal brine involves the separation of the different components by evaporation and fractional crystallization . In 1971 a small pilot plant was operated in Reykjanes (Figure 24) for initial testing of the methods envisioned .



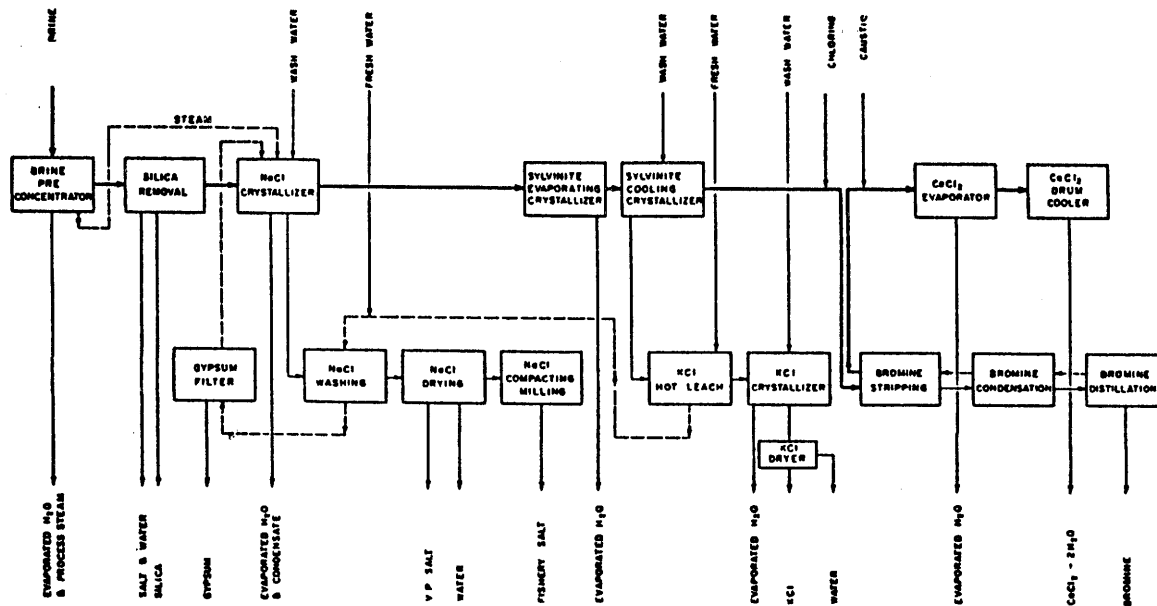


Figure 24 : process diagram, Reykjanes salt plant (Lindal, 1975)

The minerals contained in the brine will attain solid form in the following order : silica, sodium chloride, potassium chloride, calcium chloride . During the process, major quantities of water must be removed, and particularly before the fluid reaches saturation point with respect to sodium chloride .

Evaporation of the brine was tested in a small evaporator with forced circulation . The brine was fed directly, without any pretreatment or removal of silica .

The evaporator was made out of carbon steel, including the tubes in the heat exchanger . This was a single-stage construction, and the natural steam from this same drill hole was used as the source of heat for evaporation .

Scaling due to silica and even calcium sulfate was found . Yet, it proved possible to operate the evaporator at a constant and moderately high heat transfer rate . It was found that an admission of oxygen to the heating surface would affect heat transfer immediately by the adherence of more silica and a build-up of scale . It was also suspected that oxygen was responsible for some sulfate scaling in the beginning of the operation, due to the oxidation of sulfur components in the brine . By keeping oxygen entirely away, it is believed that a heat transfer coefficient of 2700 kcal/hr.°C.m<sup>2</sup> or higher may be maintained .

Corrosion was very modest in every case, and in the case of steel, it was an order of magnitude less than would be expected in ordinary sea water . When the brine has been concentrated in an evaporator of the type used here, the greatest part of the silica has already precipitated out and forms a rapidly settling slurry .

### 9.2.2.2 United States of America

In the Salton Sea area, California, a pilot plant extracts alkali and earth alkaline chlorides by atmospheric evaporation and crystallization with occasional geothermic heat exchange .

The effluent brine coming from the absorption units may contain a composition like this :

Al	450 ppm	Na	51000 ppm	Cs	20 ppm
Ca	40000	K	25000	Cl	185000
Mg	730	Li	300	I	22
Sr	750	Rb	169	Br	146
Ba	200				

The waste steam, still hot, is used to heat by exchange certain cycles of the cooled brine distributed from various ponds before they undergo crystallization (Figure 25) .

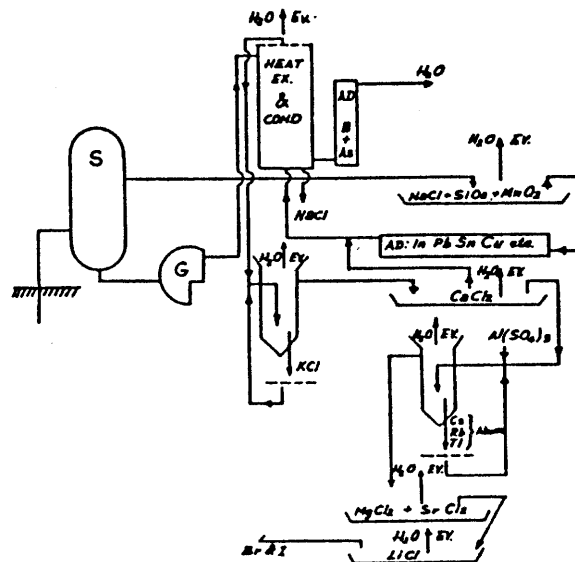


Figure 25 : extraction of alkali and earth alkaline chlorides by atmospheric evaporation and crystallization with geothermal heat exchange (Werner, 1970)

The brine from the separator will pass through a suitable pond system in which first NaCl, which is supersaturated, will precipitate; while passing through this Na pond the brine will cool to the ambient temperature of about +15°C (annual average in the Imperial Valley district) . The brine overflowing from the NaCl pond becomes enriched with KCl which possesses a lower solubility than CaCl<sub>2</sub> . Since the seasonal temperature changes in the valley during the year are quite small, the brine saturated in respect to KCl and probably close to CaCl<sub>2</sub> can be processed in ECCAH crystallizers and the effluent herefrom should be brought into a geothermally heated enricher basin in which the KCl is again brought to saturation . The effluent from here will combine with the overflow from the Na pond to upgrade the KCl value of the same . Dependent on the seasonal fluctuating evaporation and the short term temperature of the air, the Na pond effluent may flow directly to the enricher basin, will be heated there, and is then pumped into the crystallizer .

Because of the abundance of CaCl<sub>2</sub>, it will be possible that some CaCl<sub>2</sub> may precipitate with the crystallized KCl . The removal of CaCl<sub>2</sub> which is quite deliquescent with KCl mother liquor is no problem . The resulting effluent from the KCl crystallization flows by gravity into the Ca pond in which CaCl<sub>2</sub> may precipitate . A reverse flow into the Na pond is facilitated from time to time whenever temperature and KCl concentration are indicated .

MgCl<sub>2</sub> and SrCl<sub>2</sub> are present in similar primary quantities and whenever saturated the brine of the Ca pond should be conveyed above a certain temperature into the Mg pond where both salts, being very similar in their behaviour, may precipitate . Both salts can be conveniently

separated from each other since their solubilities, especially in the lower temperatures, are quite different .

Whenever saturation is reached to form Cs or Rb alum by the addition of  $\text{Al}(\text{SO}_4)_3$ , which may happen either before or after the Mg pond, both can be withdrawn from the entire system in alum crystallizers .

It can be expected that LiCl, because of the primarily small concentration, will reach saturation either in the Mg pond or in its own pond . Some  $\text{CaCl}_2$ , however, is expected to pass through to the Li pond and should be returned whenever saturated .

Bromide will accumulate in the Mg pond as  $\text{MgBr}_2$  and can be recovered by allowing the saturated liquid to pass a counterstream of chlorine gas (which is formed in sufficient quantities from the mercury cells) .

If iodine is present, this can be removed by treatment with a copper salt to form CuI, which precipitates .

### **9.3 Benefits and disadvantages**

In the salt processes the modern technique to separate chemical compounds by precipitation and crystallization, whenever concentration and temperatures are right, is still very new . This technique is slowly replacing the present day employed analytical precipitation techniques in which chemical reagents are added of any sort, hereby complicating given solutions and also multiplying some of the problems of recovery .

Because of the cheap waste heat available with geothermic brines, it seems that the mineral extraction can be accomplished in these cases more cheaply and more efficiently . Furthermore in some cases the value of the minerals often supercedes the values derived from the sale of power and will make the complete project viable .

## **10 Enhanced oil recovery**

### **10.1 Introduction**

Thermal enhanced oil recovery (TEOR) using geopressured-geothermal (GPGT) fluids is a unique concept for recovering heavy and medium oils that are bypassed during conventional production processes . The successful implementation of this technology would provide an environmentally clean and less expensive method of thermal recovery as opposed to the burning of crude oil or natural gas used widely by industry at the present time .

### **10.2 Principle and applications**

The basic principle of the TEOR method is that the lower the viscosity of the oil the better it flows into the producing well; and, by increasing the temperature of the oil reservoir the viscosity of the oil and the residual oil saturation can be lowered . The application of TEOR to high porosity reservoirs containing low gravity, high viscosity oils is now routine .

Negus-de Wys, showed the relationship of the temperature to viscosity for bitumens ( $<10^\circ\text{API}$  gravity), heavy oil (10 to  $20^\circ\text{API}$  gravity) and medium oil ( $>20$  to  $25^\circ\text{API}$  gravity) (Figure 26).

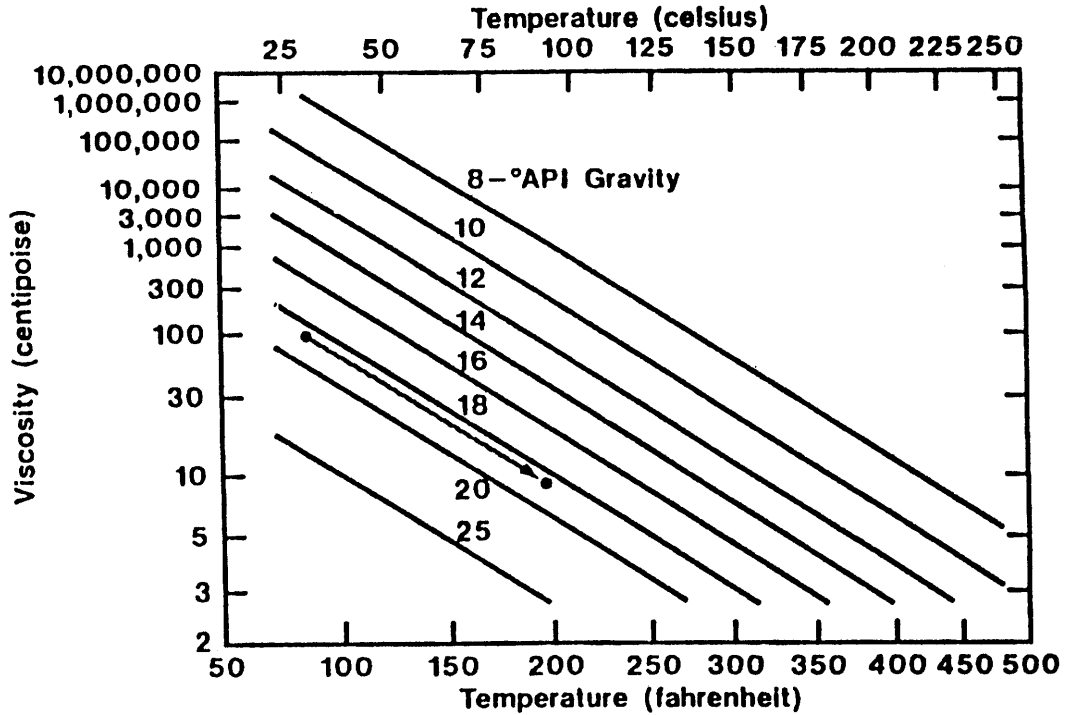


Figure 26 : oil viscosity as function of temperature and gravity  
 °API : gravity scale of the American Petroleum Institute (I.N.E.L. (\*), 1990)

(\* ) Idaho National Engineering Laboratory

Thermal recovery methods include steam stimulation, steam flooding (including hot water injection), in situ combustion, and electromagnetic heating (Figure 27) .

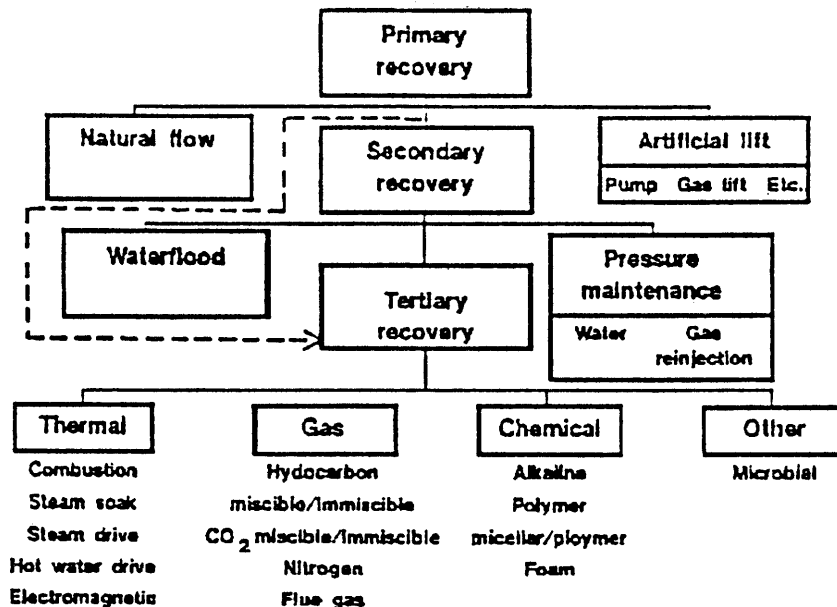


Figure 27 : oil recovery mechanisms .  
 EOR methods are on the bottom row (I.N.E.L. (\*), 1990)

(\* ) Idaho National Engineering Laboratory

In situ combustion and electromagnetic heating do not relate to the proposed methods for utilizing GPGT fluids . The steam methods do .

- Steam stimulation (cyclic steam injection, steam soak, or huff and puff) employs one well for both injection and production . Steam (about 1000 bbls/days) is injected into the reservoir and left to soak for 2 to 3 weeks . The well is then shut-in for a few days to allow heat dissipation, and then produced . The main effect is the reduction in the viscosity of the oil . The steam vapor is rapidly condensed to water and the product is oil and water .

- Steam flooding (steam drive) consists of continuously injecting steam into a central well to reduce the oil viscosity and drive the oil, gases, and water to surrounding production wells . Initially, the oil is displaced by steam drive and steam distillation (when heated the lighter fractions of the capillary trapped oil are distilled and become mobile) . Steamfloods are commonly used after steam stimulation has recovered the oil in the immediate area around the well bore . The actual agent in steam flooding is hot water since the steam is rapidly condensed. As the temperature reduces with distance from the well bore, the steam condenses to hot water and this causes thermal expansion of the fluids, reduction of viscosity and residual oil saturation, compression of the solution gas, and changes in relative permeability .

Combustion of the oil in the reservoir to create a steam bank often follows simple steam flooding . The steam, combustion gas, and evaporated hydrocarbons drive the reservoir oil, gas, and water into the producing well . Oxygen or air is injected to maintain combustion, and because no heat is lost the combination process can be used for deeper reservoirs than simple steam methods .

Present TEOR projects in the United States total 154, with 9 using hot water flooding . California, Alaska, Arkansas, Louisiana, Texas, and Wyoming are the major states from which considerable quantities of additional production is possible . Currently, no new hot water projects are planned for initiation in the United States in the immediate future, but 5 steam projects are planned for Kern County (California), Iberville Parish (Louisiana), and Hardin County (Texas) .

### **10.3 Benefits and disadvantages**

The TEOR method using GPGT fluids is similar to water flooding and thus the basic technology already exists . However, the major difference is the usually high total dissolved solids (TDS) present in GPGT waters . The exact effect of the brine on the target reservoir is uncertain but may have beneficial effects not only on viscosity and oil extraction but also on permeability and porosity . The operational and mechanical problems associated with piping the GPGT fluids into shallow reservoirs are also uncertain but can probably be readily overcome. The important point is that an enormous amount of additional domestic heavy and medium oil will be recovered if the concept works . GPGT fluids combine the temperatures, propulsion, and technology that would be comparatively clean environmentally .

## **Conclusion**

Geothermal fluids from both low and high temperature areas can lead towards various fields of application . Some of them (greenhousing, aquaculture, food processing, distillation) could partly resolve the growing problem of food and fresh water needs in the world . While the others (electric power generation, heat pumps, biomass development, minerals and oil recovery) could delay for later the second major problem interesting our planet which is the irreversible reduction of the raw material reserves .

But the feasibility and the viability of an implantment project depend on two major factors : the first one implies favourable natural conditions (presence of a geothermal reservoir with a consequent heat flow and a constant flow rate) whereas the second is linked to "favourable" economic climates (high prices of oil and electricity) and to particular policies .

On this last point, the concern to protect our environment against domestic pollution by the combustion of fossil fuels especially - the third major problem for next generations - must prevail in the search for a short-term "pay-back" of a geothermal plant .

Now geothermal energy has the main advantage to be almost non-polluting . Iceland, the most important country user of geothermal energy per capita in the world, hasn't it the most unspoiled landscapes and the purest air ?

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## Appendix 1

### Conversion factors

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The geothermal community is an international one; thus all units are given in the U.S. system with metric in parenthesis, i.e., 140°F (60°C). Every attempt was made to use the same number of significant figures in both systems. Thus, for example, 300°F would be converted to 149°C when used as an exact number (three significant figures), and to 150°C when used as an approximate number (two significant figures). In two cases, conversion to metric was not attempted: (a) in the detailed economics calculations of Chapter 5, as this would confuse the explanation of the engineering economics principles, and (b) in the details of the leasing information in Chapter 7, as this information is peculiar to the U.S.A.

The following English and SI (metric) relationships and abbreviations were used:

<u>English</u>	<u>International System (SI)</u>
1 pound mass (lb)	= 0.4536 kilograms (kg)
1 pound force (lbf)	= 4.448 newtons (N)
<sup>1</sup> 1 ton (short = 2,000 lb) (tn)	= 0.9072 tonne (metric = 1,000 kg) (t)
1 ounce (oz)	= 28.35 grams (g)
1 pound per square foot (psf)	= 0.04788 kilo Pascals (kPa) = 0.04788 kN/m <sup>2</sup>
1 pound per square inch (psi)	= 6.895 kilo Pascals (kPa)
1 mile (mi)	= 1.609 kilometer (km)
1 foot (ft)	= 0.3048 meters (m)
1 inch (in)	= 2.540 centimeters (cm)
1 gallon (gal)	= 3.785 liters (l)
1 gallon per minute (gpm)	= 0.06308 liter per second (l/s)
1 British thermal unit (Btu)	= 1055 Joules (J) = 1.055 kilo Joules (kJ)
British thermal unit per hour (Btu/hr)	= 0.2930 watts (w)
1 acre (A)	= 0.4047 hectares (ha) = 4047 square meters (m <sup>2</sup> )
<sup>2</sup> 1 degree Fahrenheit (°F)	= 1.8 x degree celcius (°C) + 32° 1°F/1000 ft = 1.823°C/km
1 barrel (petroleum)	= 42 gal (159 liters)

10<sup>-6</sup> = micro (μ)

10<sup>-3</sup> = milli (m)

10<sup>-2</sup> = centi (c)

10<sup>3</sup> = kilo (k)

10<sup>6</sup> = mega (M)

10<sup>9</sup> = giga (G)

<sup>1</sup> Since references to this unit were only approximate, the two terms were considered equal and some have not been converted in the text.

<sup>2</sup> If only a change in temperature is required, then  $\Delta^{\circ}\text{F} = 1.8 \times (\Delta^{\circ}\text{C})$ .

## Appendix 2

### Temperature-equivalent temperature readings for Fahrenheit and Centigrade scales

Formula: °F = °C (9/5) + 32  
°C = (°F - 32) 5/9

Fahren-heit Degr.	Centi-grade Degr.	Fahren-heit Degr.	Centi-grade Degr.	Fahren-heit Degr.	Centi-grade Degr.	Fahren-heit Degr.	Centi-grade Degr.	Fahren-heit Degr.	Centi-grade Degr.	Fahren-heit Degr.	Centi-grade Degr.	Fahren-heit Degr.	Centi-grade Degr.	Fahren-heit Degr.	Centi-grade Degr.
-40	-40	0	0	39	3.89	78	26	118	47.78	157	69.44	197	91.67	236	113.33
-39	-39.44	0	-17.78	39	4	79	26.11	118	48	158	70	197.60	92	237	113.89
-38	-38	1	-17.22	40	4.44	80	26.67	119	48.33	159	70.56	198	92.22	237.20	114
-38	-38.89	1.40	-17	41	5	80	27	120	48.89	159.80	71	199	92.78	238	114.44
-37	-38.33	2	-16.67	42	5.56	81	27.22	120.20	49	160	71.11	199.40	92	239	115
-36	-38	3	-16.11	42	6	82	27.78	121	49.44	161	71.67	200	93.33	240	115.56
-36	-37.78	3.20	-16	43	6.11	82	28	122	50	161.60	72	201	93.89	240.80	116
-35	-37.22	4	-15.56	44	6.67	83	28.33	123	50.56	162	72.22	201.20	94	241	116.11
-34	-37	5	-15	44	7	84	28.89	123.80	51	163	72.78	202	94.44	242	116.67
-34	-36.67	6	-14.44	45	7.22	84	29	124	51.11	163.40	73	203	95	242.60	117
-33	-36.11	6.80	-14	46	7.78	85	29.44	125	51.67	164	73.33	204	95.56	243	117.22
-32	-36	7	-13.89	46	8	86	30	125.60	52	165	73.89	204.80	96	244	117.78
-32	-35.56	8	-13.33	47	8.33	87	30.56	126	52.22	165.20	74	205	96.11	244.40	118
-31	-35	8.60	-13	48	8.89	87	31	127	52.78	166	74.44	206	96.67	245	118.33
-30	-34.44	9	-12.78	48	9	88	31.11	127.40	53	167	75	206.60	97	246	118.89
-29	-34	10	-12.22	49	9.44	89	31.67	128	53.33	168	75.56	207	97.22	246.20	119
-29	-33.89	10.40	-12	50	10	89	32	129	53.89	168.80	76	208	97.78	247	119.44
-28	-33.33	11	-11.67	51	10.56	90	32.22	129.20	54	169	76.11	208.40	98	248	120
-27	-33	12	-11.11	51	11	91	32.78	130	54.44	170	76.67	209	98.33	249	120.56
-27	-32.78	12.20	-11	52	11.11	91	33	131	55	170.60	77	210	98.89	249.80	121
-26	-32.22	13	-10.56	53	11.67	92	33.33	132	55.56	171	77.22	210.20	99	250	121.11
-25	-32	14	-10	53	12	93	33.89	132.80	56	172	77.78	211	99.44	251	121.67
-25	-31.67	15	-9.44	54	12.22	93	34	133	56.11	172.40	78	212	100	251.60	122
-24	-31.11	15.80	-9	55	12.78	94	34.44	134	56.67	173	78.33	213	100.56	252	122.22
-23	-31	16	-8.89	55	13	95	35	134.60	57	174	78.89	213.80	101	253	122.78
-23	-30.56	17	-8.33	56	13.33	96	35.56	135	57.22	174.20	79	214	101.11	253.40	123
-22	-30	17.60	-8	57	13.89	96	36	136	57.78	175	79.44	215	101.67	254	123.33
-21	-29.44	18	-7.78	57	14	97	36.11	136.40	58	176	80	215.60	102	255	123.89
-20	-29	19	-7.22	58	14.44	98	36.67	137	58.33	177	80.56	216	102.22	255.20	124
-20	-28.89	19.40	-7	59	15	98	37	138	58.89	177.80	81	217	102.78	256	124.44
-19	-28.33	20	-6.67	60	15.56	99	37.22	138.20	59	178	81.11	217.40	103	257	125
-18	-28	21	-6.11	60	16	100	37.78	139	59.44	179	81.67	218	103.33	258	125.56
-18	-27.78	21.20	-6	61	16.11	100	38	140	60	179.60	82	219	103.89	258.80	126
-17	-27.22	22	-5.56	62	16.67	101	38.33	141	60.56	180	82.22	219.20	104	259	126.11
-16	-27	23	-5	62	17	102	38.89	141.80	61	181	82.78	220	104.44	260	126.67
-16	-26.67	24	-4.44	63	17.22	102.20	39	142	61.11	181.40	83	221	105	260.60	127
-15	-26.11	24.80	-4	64	17.78	103	39.44	143	61.67	182	83.33	222	105.56	261	127.22
-14	-26	25	-3.89	64	18	104	40	143.60	62	183	83.89	222.80	106	262	127.78
-14	-25.56	26	-3.33	65	18.33	105	40.56	144	62.22	183.20	84	223	106.11	262.40	128
-13	-25	26.60	-3	66	18.89	105.80	41	145	62.78	184	84.44	224	106.67	263	128.33
-12	-24.44	27	-2.78	66	19	106	41.11	145.40	63	185	85	224.60	107	264	128.89
-11	-24	28	-2.22	67	19.44	107	41.67	146	63.33	186	85.56	225	107.22	264.20	129
-11	-23.89	28.40	-2	68	20	107.60	42	147	63.89	186.80	86	226	107.78	265	129.44
-10	-23.33	29	-1.67	69	20.56	108	42.22	147.20	64	187	86.11	226.40	108	266	130
-9	-23	30	-1.11	69	21	109	42.78	148	74.44	188	86.67	227	108.33	267	130.56
-9	-22.78	30.20	-1	70	21.11	109.40	43	149	65	188.60	87	228	108.89	267.80	131
-8	-22.22	31	-0.56	71	21.67	110	43.33	150	65.56	189	87.22	228.20	109	268	131.11
-7	-22	32	0	71	22	111	43.89	150.80	66	190	87.78	229	109.44	269	131.67
-7	-21.67	33	0.56	72	22.22	111.20	44	151	66.11	190.40	88	230	110	269.60	132
-6	-21.11	33.80	1	73	22.78	112	44.44	152	66.67	191	88.33	231	110.56	270	132.22
-5	-21	34	1.11	73	23	113	45	152.60	67	192	88.89	231.80	111	271	132.78
-4	-20.56	35	1.67	74	23.33	114	45.56	153	67.22	192.20	89	232	111.11	271.40	133
-4	-20	35.60	2	75	23.89	114.80	46	154	67.78	193	89.44	233	111.67	272	133.33
-3	-19.44	36	2.22	75	24	115	46	154.40	68	194	90	233.60	112	273	133.89
-2	-19	37	2.78	76	24.44	116	46.67	155	68.33	195	90.56	234	112.22	273.20	134
-2	-18.89	37.40	3	77	25	116.60	47	156	68.89	195.80	91	235	112.78	274	134.44
-1	-18.33	38	3.33	78	25.56	117	47.22	156.20	69	196	91.11	235.40	113	275	135







NEW APPLICATIONS OF GEOTHERMAL ENERGY

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