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SYSTEMS STUDY FOR THE USE OF GEOTHERMAL ENERGIES IN THE PACIFIC NORTHWEST

Final Report

Dr. Gunnar Bodvarsson, Dr. Larry Boersma , Dr. Richard Couch, Dr. Lorin Davis and Dr. Gordon Reistad

Oregon State University
Corvallis, Oregon 97331

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ABSTRACT

There are in the Pacific Northwest three geological provinces of basic interest as possible geothermal resource environments, viz., (1) the Snake River Plains and Columbia River Basin, (2) the Cascade Range and (3) Southeastern Oregon areas of Cenozoic volcanism. Several types of geothermal resources are possible in this region, but no high-temperature resources (above 200°C) have as yet been identified with certainty. The possibilities for low-to-medium temperature thermal water resources of great potential and extent appear, on the other hand, quite good. Moreover, modern resource stimulation techniques appear very well applicable to such resources in the region and will enhance the economic potential. An elementary theory of heat extraction from permeable horizons is available. Preliminary results indicate that low-to-medium temperature thermal waters can be economically produced from depths of up to 4 kilometers.

The second part of this work considers the prospective utilization of geothermal energy in the Pacific Northwest. Because no high-temperature resources have been identified in the region under consideration, electricity generation potential is not considered. It is shown that direct utilization of geothermal heat has a good potential because of two reasons: (1) there is a large need for heating at applicable temperatures and (2) meeting low-temperature needs with low-temperature resources decreases unnecessary wasting of the specific availability of high grade resources (fossil, nuclear, etc.).

Potential applications with temperature requirements in the range of 50 to 200°C are briefly examined. Promising applications for the Pacific Northwest are in the wood products industry, the pulp and paper industry, agricultural applications, space conditioning, and the food products industry. However, each of these areas require additional research to show the most practical methods and extend of use of geothermal energy.

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INTRODUCTION

The present report covers the results of a study entitled "Systems Study for the Use of Geothermal Energies in the Pacific Northwest" which has been carried out by Dr. Larry Boersma, Dr. Gunnar Bodvarsson, Dr. Richard Couch, Dr. Lorin Davis and Dr. Gordon Reistad, Oregon State University, at the request of the U.S. Atomic Energy Commission. The letter of assignment is dated June 17, 1974, and originates from the U.S. Atomic Energy Commission Richland Operations Office.

The study is intended as an initial effort to evaluate the geothermal energy potential in the Pacific Northwest and its potential applications to supply the energy requirements of future communities and industries in the region.

Due to the extremely low budget for this project ($10,000) none of the topics of this report can be covered in any detail. Only a brief examination of the subject matter has been carried out and main topics of future research identified.

PART I

GEOTHERMAL RESOURCES IN THE PACIFIC NORTHWEST

RESOURCE ENVIRONMENTS

The geologic record of the Pacific Northwest is characterized by evidence of very considerable volcanic activity from early Cenozoic to Holocene times. Several structural/physiographic provinces in this region are of particular interest as geothermal resource environments (Figure 1), among them:

1. The Snake River Plains and Columbia River Basin. These are largely flood-basalt fields occupying structural rifts or downwarps of large areal extent. Geothermal exploration has up to now concentrated on portions of the Snake River province (late Tertiary and Quaternary in age, about 150,000 km^2 in total area) which manifest hot spring activity. No hot springs are present in the Columbia River province (Miocene in age, about 220,000 km^2 in area), but the flood-basalts of both provinces appear to have sufficiently high geothermal gradients and horizontal permeability to make feasible stimulated production of thermal water from their lower sections. In this respect they appear to provide source conditions similar to the Reykjavik section of the Iceland basalt province.

2. The Cascade Range. Of primary interest here is the more or less linear belt of Quaternary Andesitic stratovolcanoes, most of which exhibit some thermal activity and have a record of Holocene eruptions. The distribution of hot springs is apparently influenced both by proximity to eruptive centers and by linear structural features. There is considerable evidence of magmatic injection at high crustal levels in association with the largest centers; depending on age and size, such zones may constitute significant reservoirs of thermal energy. Exploitation of geothermal resources in the Cascades is also expected to be quite dependent on environmental considerations.

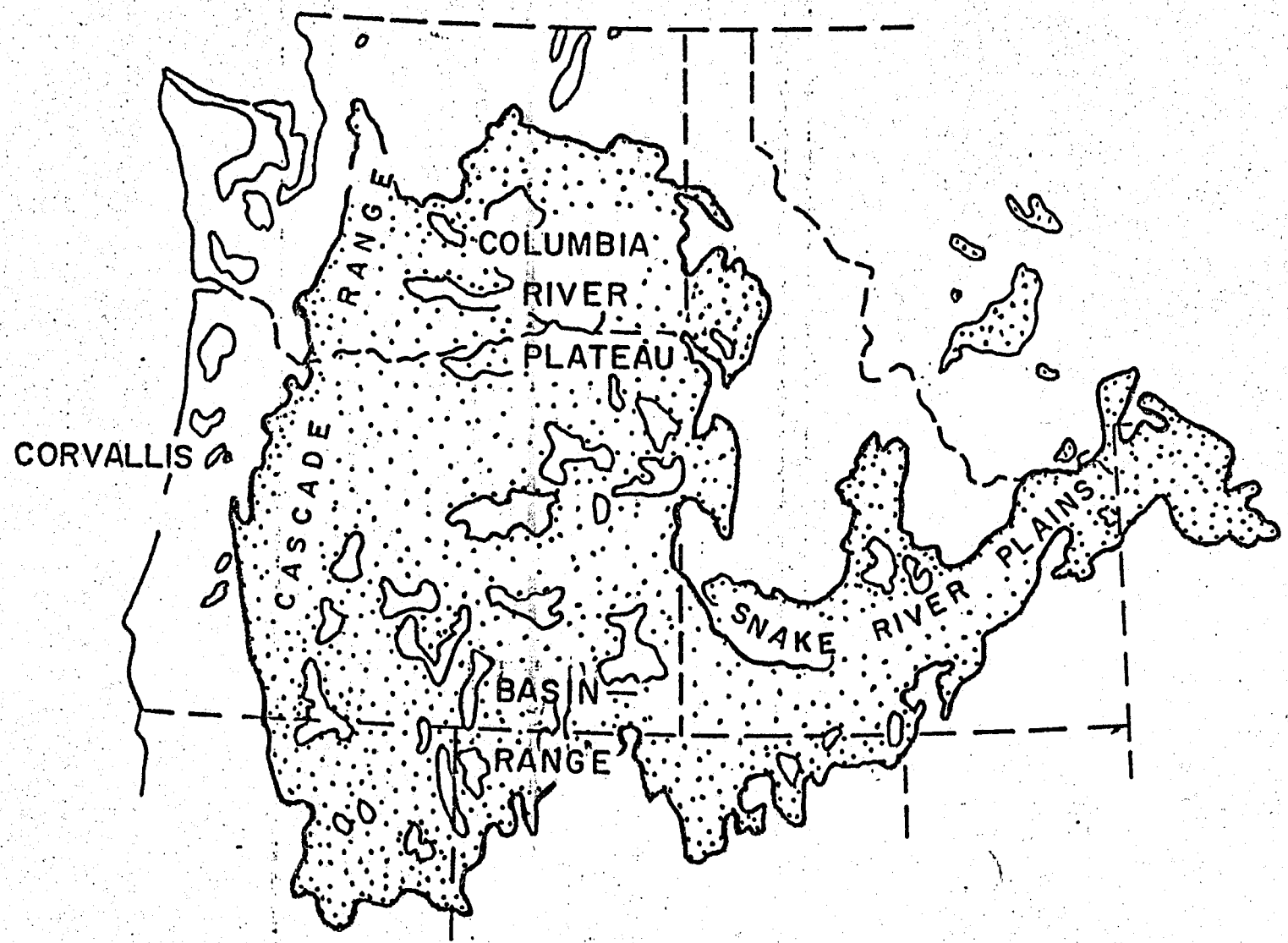


FIGURE 1 Map showing areas of Cenozoic volcanic rocks in the Pacific Northwest .

3. Southeastern Oregon. The structural style of this province is predominantly basin-range block faulting, but there are transitional structures on the province boundaries, and a broad median shear zone transgressive of other structures, as well as several large-scale eruptive-tectonic features. Of particular interest is the Brothers Fault zone in Oregon shown in Fig. 2, which has been described in a recent paper by Walker (1974). Almost all exposed rocks are volcanics and volcanoclastics of late Teritiary to Quaternary age, and numerous vents and hypabyssal intrusions of basaltic, silicic, and intermediate affinity can be identified. Flood-basalt sections and other lithologic zones of high lateral permeability are widespread. Surface leakage of hot fluids occurs along major tectonic elements, and has prompted geothermal exploration, including test drilling, in a number of specific localities.

EXPECTED GEOTHERMAL POTENTIAL AND RESOURCE TYPES

Not much data is available on the regional terrestrial heat flow in the Pacific Northwest. A compilation of recent results (Roy, et al., 1971) indicates the pattern shown in Fig. 3. There are indications that much of Eastern Oregon and Washington, the entire state of Idaho and the western part of Montana have a regional average heat flow above the global average of 1.5 HFU. This appears to be consistent with the extensive Cenozoic volcanism in the region.

Preliminary results as to prospective geothermal resource areas published by Godwin and others (1971) are shown in Fig. 4. The total estimated surface areainvolved is of the order of 50,000 square miles.

The following geothermal resource types can be expected within this area,

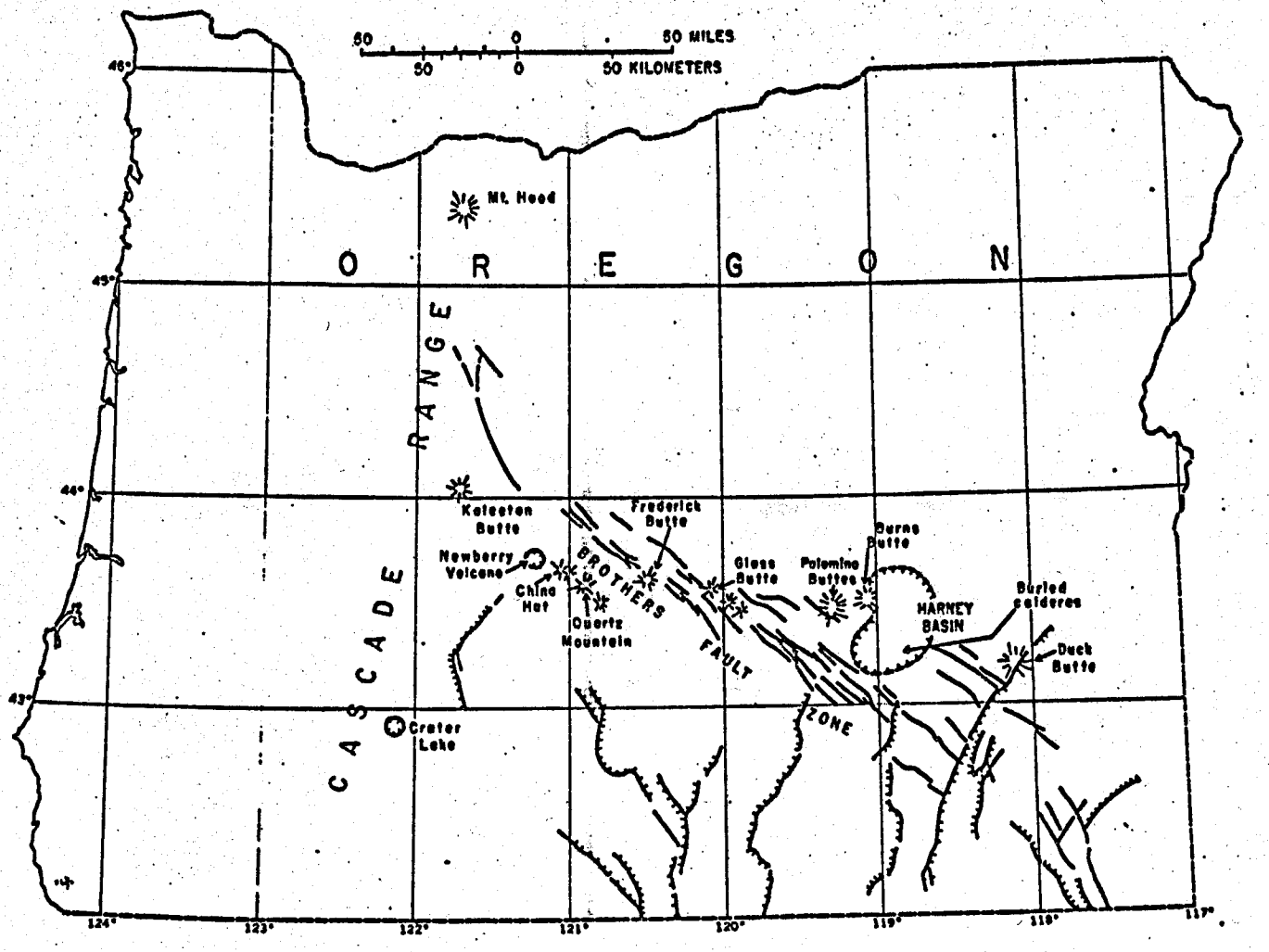


FIGURE 2 The Brothers Fault Zone (from Walker, 1974)

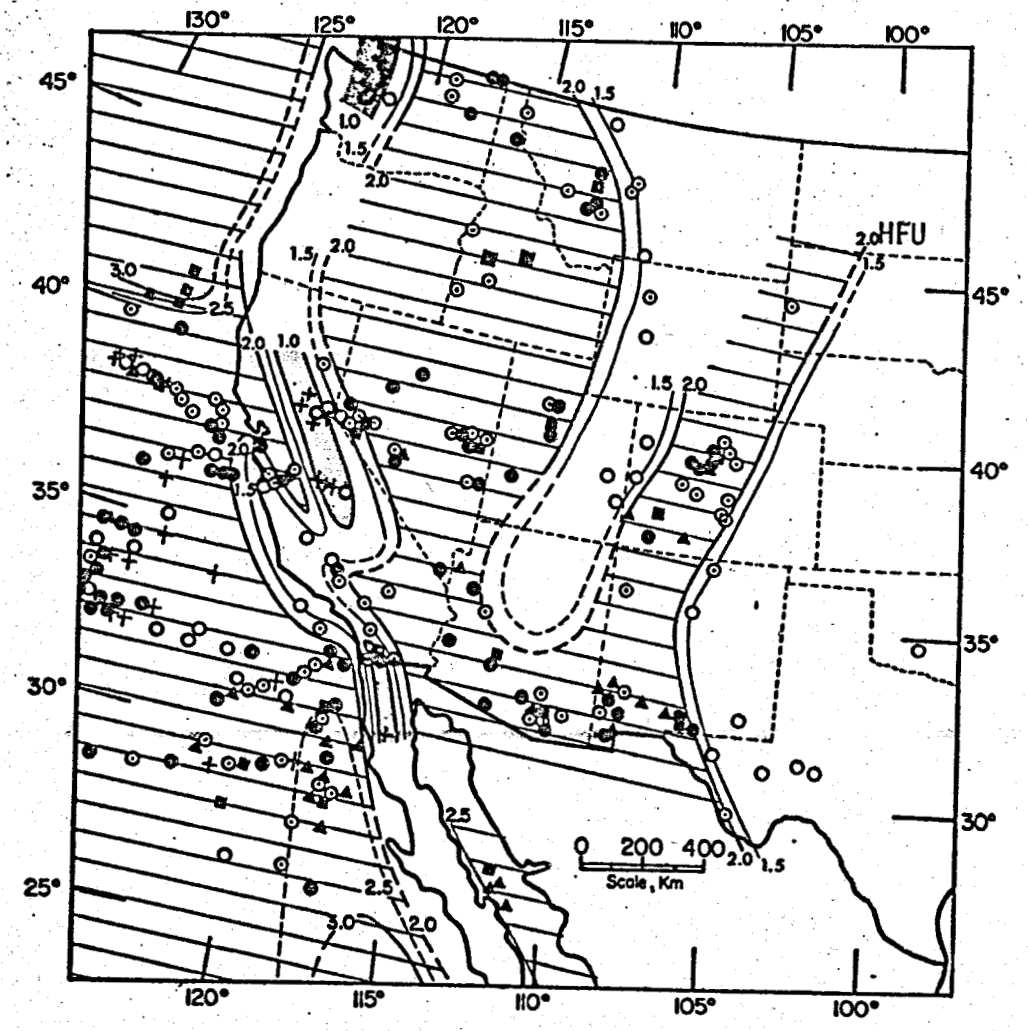


FIGURE 3 Heat flow in the western U.S. (from Roy, et. al., 1971)

HFU = Heat flow unit = 10^{-6} cal/cm^{2}sec

+ = 0 - 0.99 HFU

○ = 1.0 - 1.49

⊙ = 1.5 - 1.99

● = 2.0 - 2.49

▲ = 2.5 - 2.99

■ = > 3.0

Washington

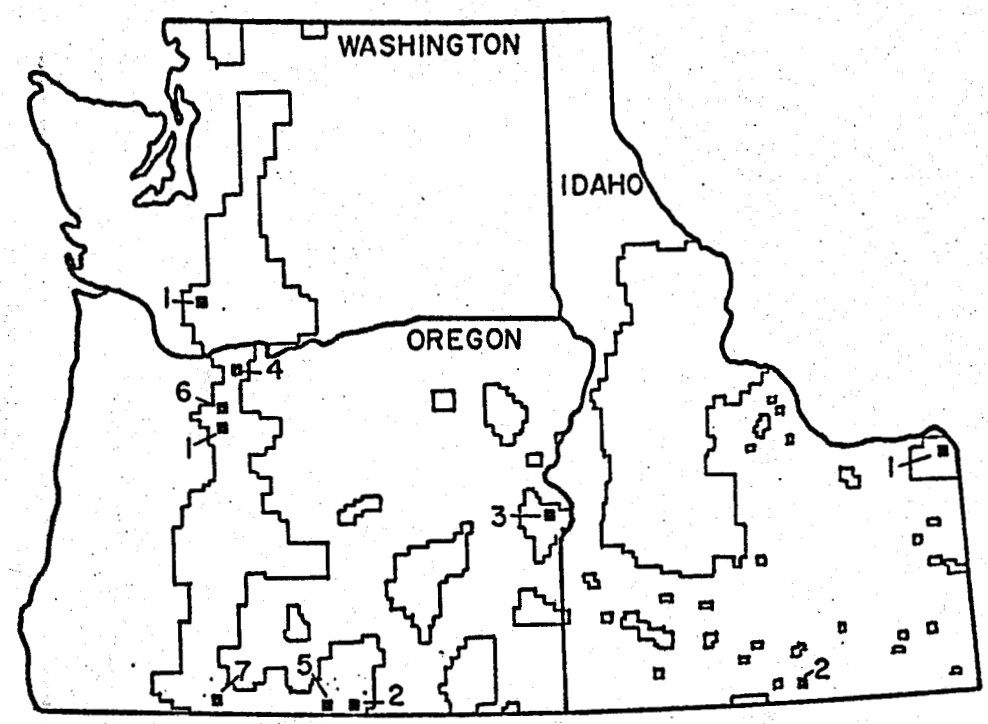
1 Mount St. Helens

Oregon

1 Breitenbush Hot Springs
2 Crump Geyser
3 Vale Hot Springs
4 Mount Hood
5 Lakeview
6 Carey Hot Springs
7 Klamath Falls

Idaho

1 Yellowstone
2 Frazier



■ Known Geothermal Resource Area

Prospective Geothermal Resource Area

Figure 4. Map of Washington, Oregon and Idaho showing lands classified for geothermal resources effective December 24, 1970 (from Godwin and others, 1971)

viz.,

(1) Low-to-medium temperature fluid phase resources embedded in layered volcanics of great horizontal extent. Temperatures from 50°C to 200°C can be expected.

(2) High-temperature resources of a more localized nature and closely associated with Holocene volcanism such as

(2.a) Fluid phase resources with temperature above 200°C.

(2.b) Dry steam resources with temperature of the order of 250°C.

(2.c) Dry hot rock resources with temperatures of several hundred degrees C.

The great extent of layered Cenozoic volcanics in the Pacific Northwest can be taken as an indication of the possibility for extensive geothermal resources of type (1) in the region. A further discussion of the mechanism of production of thermal water from such resources is therefore of particular interest, and will be given in the following section.

High-temperature geothermal resources of type (2) belong to the category which has been in the main focus of interest for a number of years. Since resources of this type have as yet to be identified in the Pacific Northwest, we will refrain from a further discussion and refer to the literature (for example, Kruger and Otte, 1973).

PRODUCTION OF LOW-TO-MEDIUM TEMPERATURE THERMAL WATERS FROM LAYERED VOLCANICS

Heat Extraction of Water Flowing Through a Flat Fracture of Infinitesimal Width in a Homogeneous Solid

Consider a half-space composed of a homogeneous impermeable solid with a density ρ, specific heat c, thermal conductivity k, thermal diffusivity $a = k/\rho c$ and having at time $t = 0$ a uniform temperature T_0. We will

assume that the physical properties of the solid and the fluid are temperature independent. Place a coordinate system such that the (y,z) plane coincides with the surface of the half-space with the x-axis placed vertically down into the solid. Let the surface be insulated and the half-space be permeated by a very narrow flat fracture coinciding with the (x,z) plane. The fracture is permeable to water but is assumed to have an infinitesimally small width. The model is shown in Figure 5.

Assume that starting at time $t = 0$ a specific mass flow of q units mass per unit length and time of a fluid is being injected into the fracture along the z axis. The fluid has zero inlet temperature and a specific heat σ. The resulting flow is parallel to the positive x-axis and is assumed constant in time and uniform in space. The present task is to derive the temperature $T(x,y,t)$ in the solid for $t > 0$. This problem is quite simple and assuming that the flow q is so large that $|\partial_x T| << |\partial_y T|$ the solution (Carslaw and Jaeger, 1959, Bodvarsson, 1969) is

$$T(x,y,t) = T_0 \mathrm{erf}[(\alpha x + |y|)/2\sqrt{at}], \quad x \geq 0, \quad t \geq 0 \tag{1}$$

where

$$\alpha = 2k/\sigma q \tag{2}$$

and

$$\mathrm{erf}(u) = (2/\sqrt{\pi}) \int_0^u \exp(-x^2)dx \tag{3}$$

The temperature of the fluid is consequently,

$$T_f = T(x,0,t) = T_0 \mathrm{erf}(kx/\sigma q\sqrt{at}) \tag{4}$$

Consider the situation at the distance x from the inlet. The temperature of the fluid there is given by equation (4) above. Moreover, during the time interval from $t = 0$ to t a total fluid mass of qt per unit length of the z-axis has passed by this location. This mass of fluid has absorbed heat from a fracture contact area of x units and $Q = qt/x$ is then the total mass of heated fluid produced per unit contact area. The term contact area refers to the area in the (x,z) plane and not to the rock surface area which is twice as large. Equation (4) can now be simplified,

$$r(t) = T(x,0,t)/T_0 = \mathrm{erf}(\beta\sqrt{t}/Q) \tag{5}$$

where $r(t)$ is the production temperature ratio at x and t, and

$$\beta = k/\sigma\sqrt{a} = \sqrt{\rho ck}/\sigma \tag{6}$$

It is convenient to introduce the concept of the half-time t_h for a given fluid mass Q. This is the time required for $r(t)$ to decrease to 1/2. Since $\mathrm{erf}(0.48) = 0.5$ we obtain on the basis of (5)

$$t_h = 0.23\, Q^2/\beta^2 \tag{7}$$

which can then be restated as

$$r(t) = \mathrm{erf}(0.48\sqrt{t_h/t}) \tag{8}$$

This is a useful relation independent of β and Q.

The average temperature of the fluid mass Q is

$$T_{av}(t) = (T_0/t)\int_0^t r(\tau)d\tau = (T_0/t)\int_0^t \mathrm{erf}(\beta x/q\sqrt{\tau})d\tau \tag{9}$$

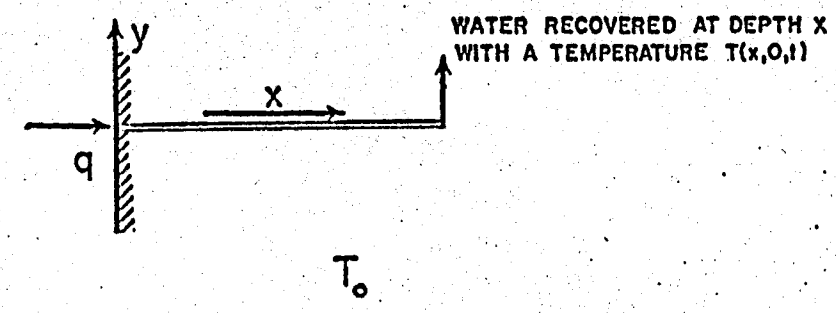


Figure 5 Sketch of the single-fracture system

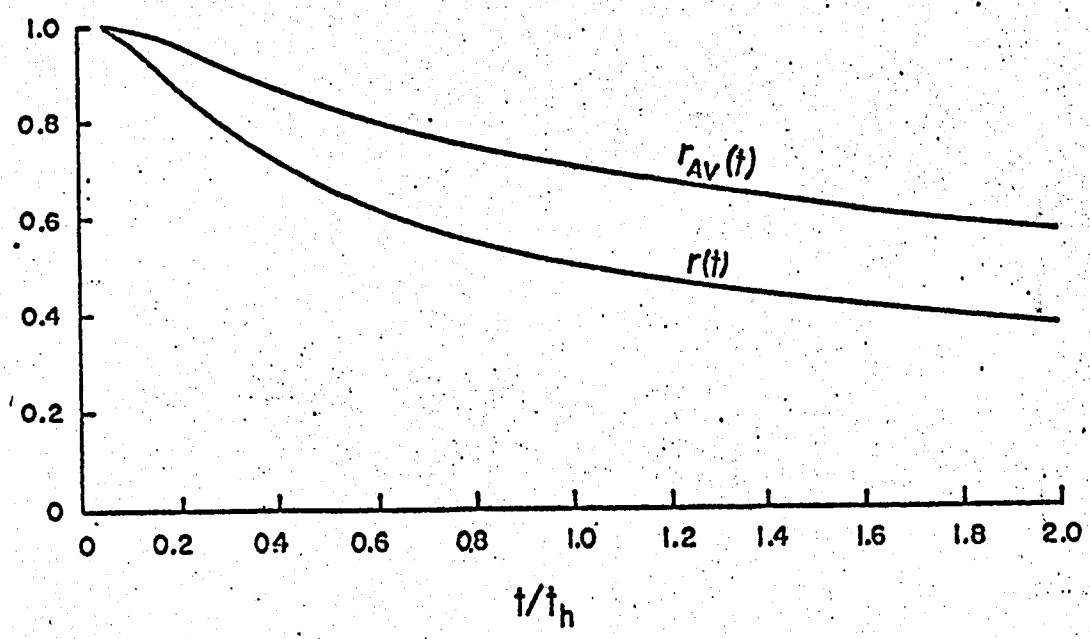


Figure 6 Production temperature ratios as functions of operation time/half time

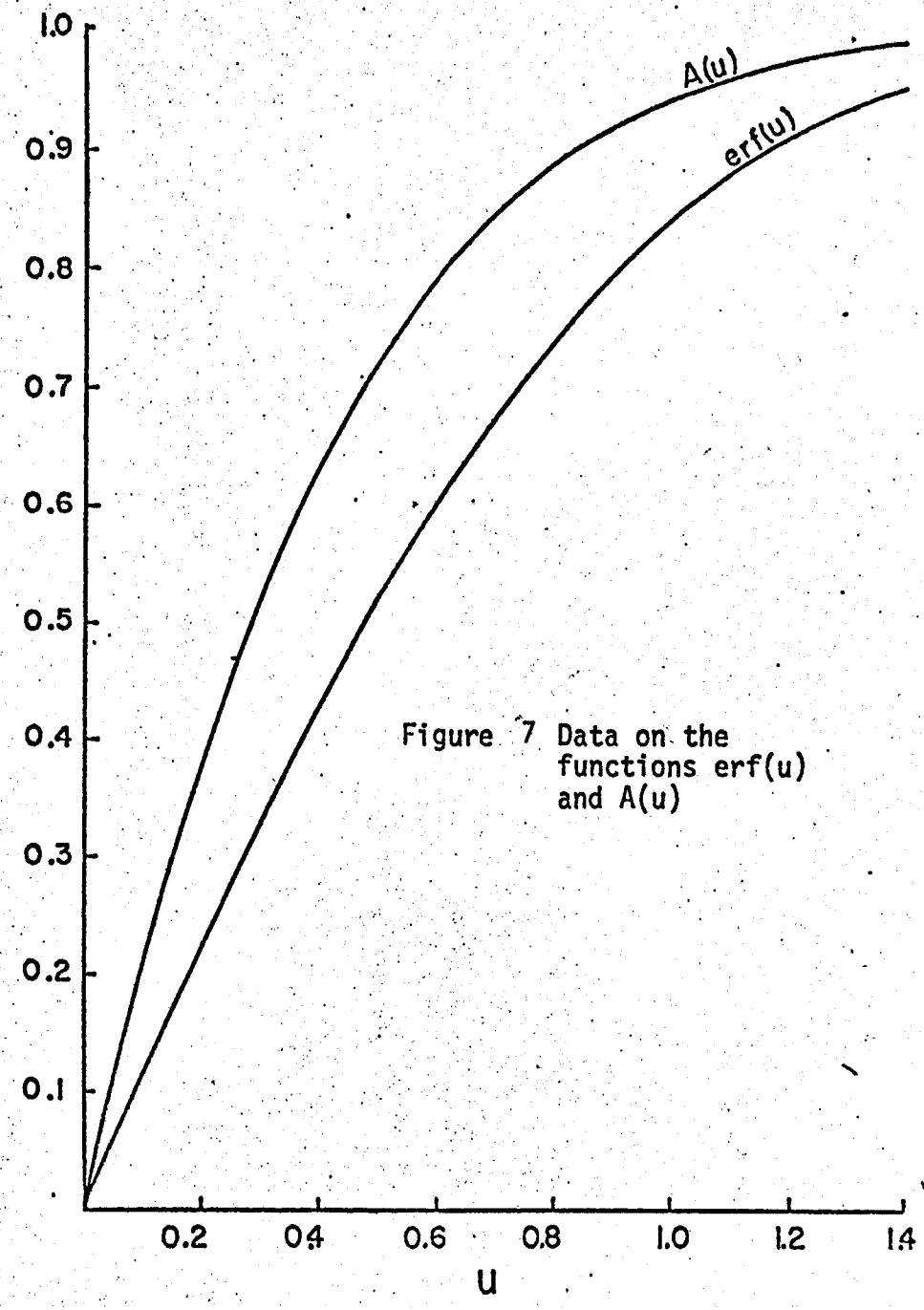


Figure 7 Data on the functions erf(u) and A(u)

which can be written

$$T_{av}(t) = T_o A(\beta \sqrt{t}/Q) \tag{10}$$

where the function $A(u)$ is defined

$$A(u) = 2u^2 \int_u^\infty (1/x^3)\mathrm{erf}(x)dx \tag{11}$$

With the help of t_h and $r_{av}(t) = T_{av}/T_o$ equation (10) can be modified in the same manner as (8) above,

$$r_{av}(t) = T_{av}/T_o = A(0.48\sqrt{t_h/t}) \tag{12}$$

Pertinent values of the functions $\mathrm{erf}(u)$ and $A(u)$ are given in Figure 7.

Equations (5), (8), (10), and (12) are our principal results. Equation (5) determines the fluid mass Q which can be produced per unit fracture area during a given time t and at a fixed end temperature ratio $r(t)$. Equations (8) and (12) furnish general relations for $r(t)$ and $r_{av}(t)$.

Common rock materials are quite uniform with respect to thermal properties. The values, $k = 2.1$ w/m,°C and $a = 10^{-6} m^2/sec$ can be assumed to be fairly representative values for most types of rocks. In practically all cases the heat carrying fluid is pure water and hence $\sigma = 4.2 \times 10^3$ jl/kg,°C giving $\beta = 0.5$ as a representative average value. Applying these values in the above equations, we can derive numerical data of practical relevance. The production temperature ratios $r(t)$ and $r_{av}(t)$ are shown in Figure 6 as functions of t/t_h. Figure 8 shows the specific production Q obtained during a given time interval from $t = 0$ to $t = t_o$ as a function of t_o and $r(t_o)$. Moreover, Figure 9 shows Q as a function

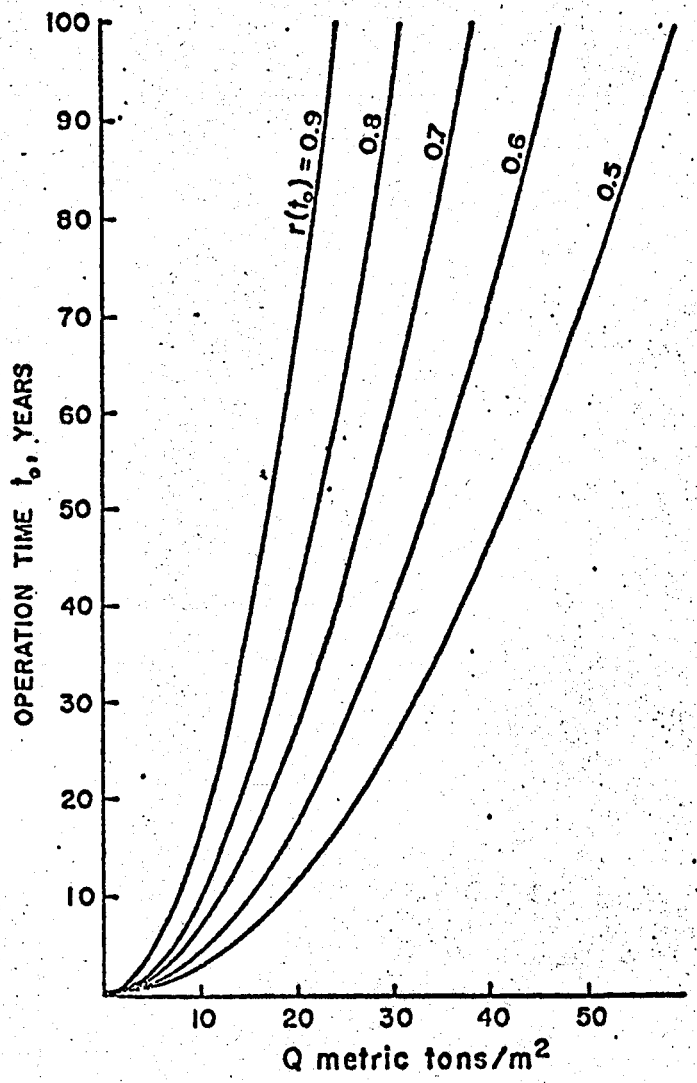


Figure 8 Specific production of thermal water as a function of operation time and end temperature ratio.

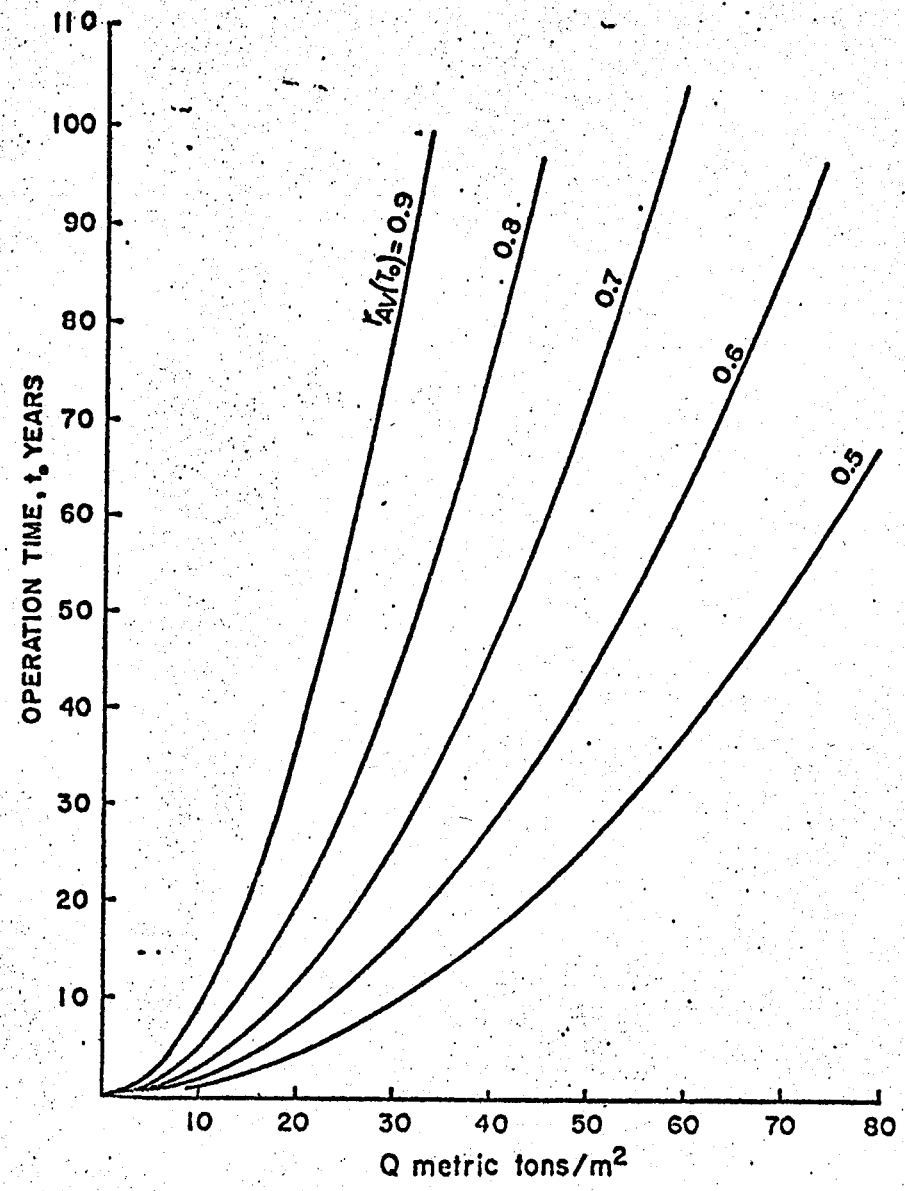


Figure 9 Specific production of thermal water as a function of operation time and average temperature ratio.

of t_o and $r_{av}(t_o)$.

The above results, which have been obtained for a single fracture model, can also be applied to the case of many fractures provided the distance between the individual fractures is sufficiently large to prevent thermal interaction. Considering the case of parallel equidistant fractures with a distance d, equation (4) shows that interaction is practically negligible if $d>3\sqrt{at_o}$. Assuming, for example, that t_o = 100 years, we find that d>170 m.

It is of interest to note that the argument of the error-function in equation (4) is $\beta x/q\sqrt{t}$. Hence, the time required at a given position x to attain a fixed fluid temperature T_f is proportional to $1/q^2$. The temperature development depends on the square of the specific flow. For example, the half-time for the specific flow of 2q is $t_h/4$. This is a characteristic of the present model resulting from the conductive transport of heat through the rock.

Application to the Cenozoic Volcanics of the Pacific Northwest

The above model has been applied by Bodvarsson (1962) to estimate the potential of geothermal areas in Iceland. Similar considerations apply to the Cenozoic volcanics of the Pacific Northwest. To obtain an order of magnitude measure of the heat which can possibly be extracted from such formations the following considerations are useful.

Assuming a temperature gradient of 50°C km we find that the temperature at the depth of 2 kilometers will be about 110°C. Moreover, assuming a production period of 100 years and an end temperature of 90°C, Figure 8 indicates that each square meter of contact area can produce about 25 metric tons of thermal water which has an average temperature of about 100°C. Consider a total area of 10,000 square kilometers of open lava-bed contacts at the depth of around 2 kilometers. The 100 year productivity is then 2.5×10^{11}

metric tons of water at around 100°C. Utilizing a temperature differential of 50°C the heat content of this water is equivalent to the effective enthalpy of about 1.5×10^9 metric tons or 10^{10} barrels of petroleum. Obviously, layered rocks of sufficient horizontal extent and permeability and located in a region of moderately high temperature gradients can be sources of a very large amount of heat which is applicable for space and many types of industrial and agricultural heating.

The above estimate was obtained on the basis of a total contact area of 10,000 square kilometers at a depth of around 2 kilometers. Taking into consideration that there are in the Pacific Northwest 200,000 to 300,000 square kilometers of thick layered Cenozoic volcanics, it appears quite reasonable to expect that the total available contact area at favorable depths may be much in excess of 10,000 square kilometers. The actual possibilities can only be revealed by exploration and drilling in the region.

The economics of the type (1) resources discussed above is a matter of considerable interest, in particular, the economic limits to the depth from which low-to-medium temperature thermal waters can be produced. Based on actual field experience obtained in Iceland, where thermal waters are currently being produced from layered volcanics, estimates of economical depth limits for the production of thermal waters at three different well-head temperatures are given in Table 1. These results are to be regarded as rough order of magnitude estimates which will, as matter of course, depend to a considerable extent on local conditions. They indicate, however, quite clearly that thermal waters for direct non-electrical uses can be produced economically from considerable depth provided there is sufficient local market for the heat.

Table 1

ECONOMICAL DEPTH LIMITS FOR THERMAL WATER RESOURCES TO BE USED FOR NON-ELECTRICAL PURPOSES SUCH AS SPACE, INDUSTRIAL AND AGRICULTURAL HEATING.

				Units
Average Source Temperature	100	150	200	°C
Expected Maximum Flow of pumped boreholes	25	25	25	kg/sec
Annual load (4,400 hours)	0.50	0.50	0.50	
Annual flow/borehole	400,000	400,000	400,000	tons/year
Value of thermal water	0.35	0.60	1.00	$/metric ton
Annual revenue/borehole	140,000	240,000	400,000	$/year
Operation costs of boreholes	20	22	25	%/year
Acceptable drilling costs	700,000	1,100,000	1,600,000	$/hole
Dry hole ratio	1/2	1/2	1/2	
Cost of drilling	120	160	200	$/meter
Economic maximum depth of production	2,900	3,400	4,000	meters
Minimum temperature gradient	31	41	48	°C/km

The value of the thermal water refers to the value at borehole and is based on a cost of heating oil of $100/metric ton = 0.35 cents/gal, less a transportation cost of 50%.

RESEARCH NEEDED TO PROMOTE THE DEVELOPMENT OF GEOTHERMAL RESOURCES IN THE PACIFIC NORTHWEST

The basic research needed to promote the development of optimum methods of exploring, assessing and utilizing geothermal resources in the Pacific Northwest can be itemized as concentrating on the topics given in Table 2.

Exploration and Assessment Techniques

Column (I) of Table 2 includes the geophysical exploration methods which are applicable for geothermal exploration and assessment work in the Pacific Northwest. The methods listed in rows (a) to (c) are of main interest and can be regarded as principal tools for future exploration work in the region. The methods listed in row (d) are of a more uncertain nature and the methods listed under (e) are to be regarded as supplementary to the principal methods in rows (a) to (c).

Research in the field of geothermal gradient and terrestrial heat flow mapping should concentrate on the development of more economical and faster methods of data aquisition, that is, the use of very shallow boreholes drilled by light equipment.

Research in the field of D.C. or ULF conduction and telluric current methods should concentrate on the development of better field procedures and improved interpretation and modeling techniques. Presently available instrumentation can be regarded as largely adequate whereas current interpretation techniques are inadequate and unable to extract all the information contained in the field data.

Further experimentation with the microearthquake and seismic noise methods is needed.

TABLE 2

GEOTHERMAL RESEARCH TOPICS IN THE PACIFIC NORTHWEST

(I) Exploration and assessment techniques	(II) Resource physics and production mechanics	(III) Utilization of geothermal energy
(a) Temperature gradient and heat flow methods	(a) Hydrology of the Cenozoic volcanics of the Pacific NW	(a) Generation of electrical power
(b) D.C. or ULF electrical conduction methods	(b) Natural convective circulation within the Cenozoic volcanics	(b) Space heating
(c) Natural field telluric and magneto-telluric methods	(c) Heat extraction by flowing water	(c) Refrigeration and air conditioning
(d) Microearthquake and seismic noise methods	(d) Drilling and production techniques	(d) Heating in industry and agriculture
(e) Structural methods such as gravity, magnetic and seismic methods	(e) Resource stimulation techniques	(e) Special problems: water treatment, scaling, fouling, heat exchangers, optimization
(f) Special assessment techniques	(f) Reinjection and disposal of thermal effluents	

The assessment of geothermal resources includes investigations of base temperature, resource volume, resource permeability, chemical quality of resource fluids and economical depth limits for production boreholes. The basic relevant data are provided by the geological and geophysical field work as well as the economical structure of the region (Bodvarsson, 1970).

Resource Physics and Production Mechanism

Little data is available on the general hydrology of the Cenozoic volcanics of the Pacific Northwest. In particular, little is known about the possibilities for large scale natural convective circulation systems in the layered volcanics. These topics are of principal interest for the development of geothermal resources in the region. Moreover, further research on the modes and rate of heat transfer between the country rock and the percolating resource fluids is a matter of great interest.

There is little doubt that the artificial stimulation of geothermal energy production will be a technique of great commercial interest in the future. Stimulation can be achieved by the pumping of water through natural or artificial openings in the hot rock. The layered volcanics of the Pacific Northwest appear to provide a very suitable setting for resource stimulation (Bodvarsson, 1974). The problems involved in the disposal of geothermal effluents by reinjection are also of great commercial interest.

In general, drilling costs and completion constitute a very substantial part of the total costs of developing geothermal resources. It is therefore of great importance to develop the optimal drilling and completion techniques in the various geological environments. The layered volcanics of the Pacific Northwest provide a special setting which requires research on optimal techniques.

PART II

PROSPECTIVE UTILIZATION OF GEOTHERMAL ENERGY IN THE PACIFIC NORTHWEST

GENERATION OF ELECTRICAL POWER

Electrical power is preferably generated from high-temperature resources, that is, at base temperatures of 180°C or more. Although from the technological point of view, power generation is feasible at much lower resource temperatures, the required throughflow of geothermal and condensor cooling fluids per unit power generated increases very rapidly with decreasing resource temperatures and there is therefore a definite economic lower limit to the resource temperature. Many aspects of the generation of electrical power on the basis of geothermal energy have been discussed at length elsewhere and will therefore not be dealt with here (Armstead, 1973).

No high-temperature resources have as yet been identified with certainty in the Pacific Northwest. With the exception of the discussion in Part I and a few general remarks to follow in the next section, a further discussion of the possibilities in this respect therefore appear premature and will not be taken up in this brief report.

POTENTIAL ROLE OF GEOTHERMAL ENERGY IN THE OVERALL ECONOMY

As compared with heat obtained by the combustion of conventional fossil fuels, geothermal energy resources are characterized by a much lower temperature level, and therefore a lower thermodynamic quality. Temperatures of the order of 1,500°C or more are easily attainable by combustion whereas the highest known temperatures of workable geothermal resources are of the order of 350°C.

With regard to the discussion to follow, it is useful to introduce the concept of the thermodynamic grade of a resource of heat. Let the grade be defined as the ratio of the theoretically available mechanical energy to the available enthaply of the resource material. Hence, for fossil fuel the grade is near unity while for geothermal resources it ranges from 0.1 to 0.3 for base temperatures of 100°C and 300°C respectively.

An examination of the usually presented energy flow diagrams from the viewpoint of specific availability (exergy) is instructive since it reveals that geothermal energy with its characteristically low grade may be able to improve the energy utilization picture in the United States.

The usually presented energy flow type diagram for the U.S. is shown in Figure 10 for 1970. Figure 11 shows the flow of specific availability in the U.S. in 1970 (Reistad, 1974). The two diagrams are drawn on the same format to illustrate the difference between energy and specific availability flows. The energy flow diagram illustrates that for every unit of energy that is utilized approximately one unit of energy is wasted. The specific availability flow diagram shows a much bleaker picture of our technology -- for each unit of available energy consumed in end uses, greater than three units of available energy is wasted. Moreover, Figure 11 reveals that our level of technology in energy conversion and utilization is roughly one-half of that indicated by the usual energy "picture" as shown in Figure 10. The main reason the specific availability performance is so poor is that current methods of meeting the low-grade heating requirements in the industrial and household and commercial sectors are grossly impractical.

When considering which segment of our economy is most in need of improvement, magnitude of waste may be a good indication. The energy flow diagram indicates that the electrical generation and transmission sector and the

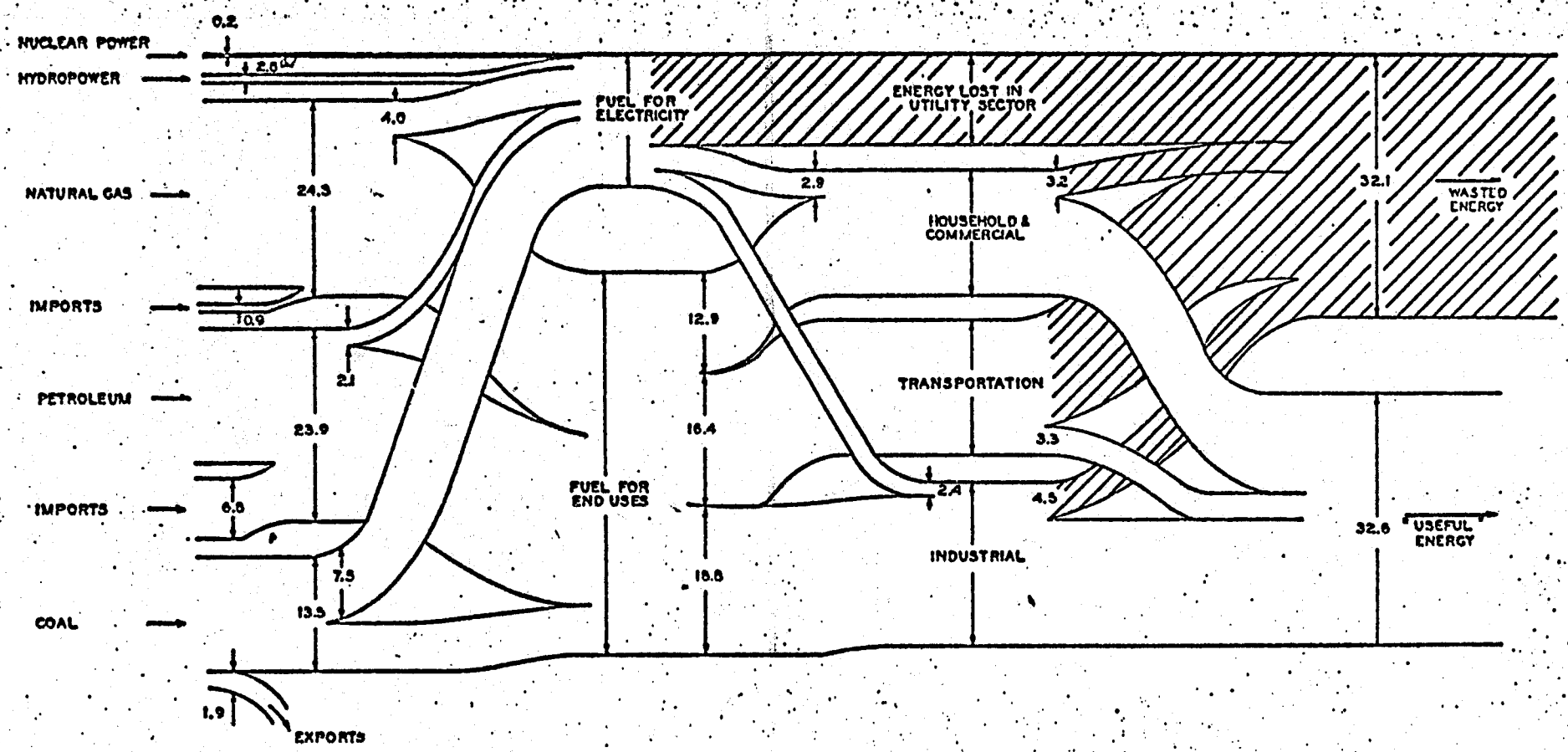


Figure 10 Flow of energy in the U.S. (Reistad, 1974). All values reported are 10^{15}Btu[$1.055(10^{18})$J]. The energy value for hydropower is reported in the usual manner of coal equivalent.

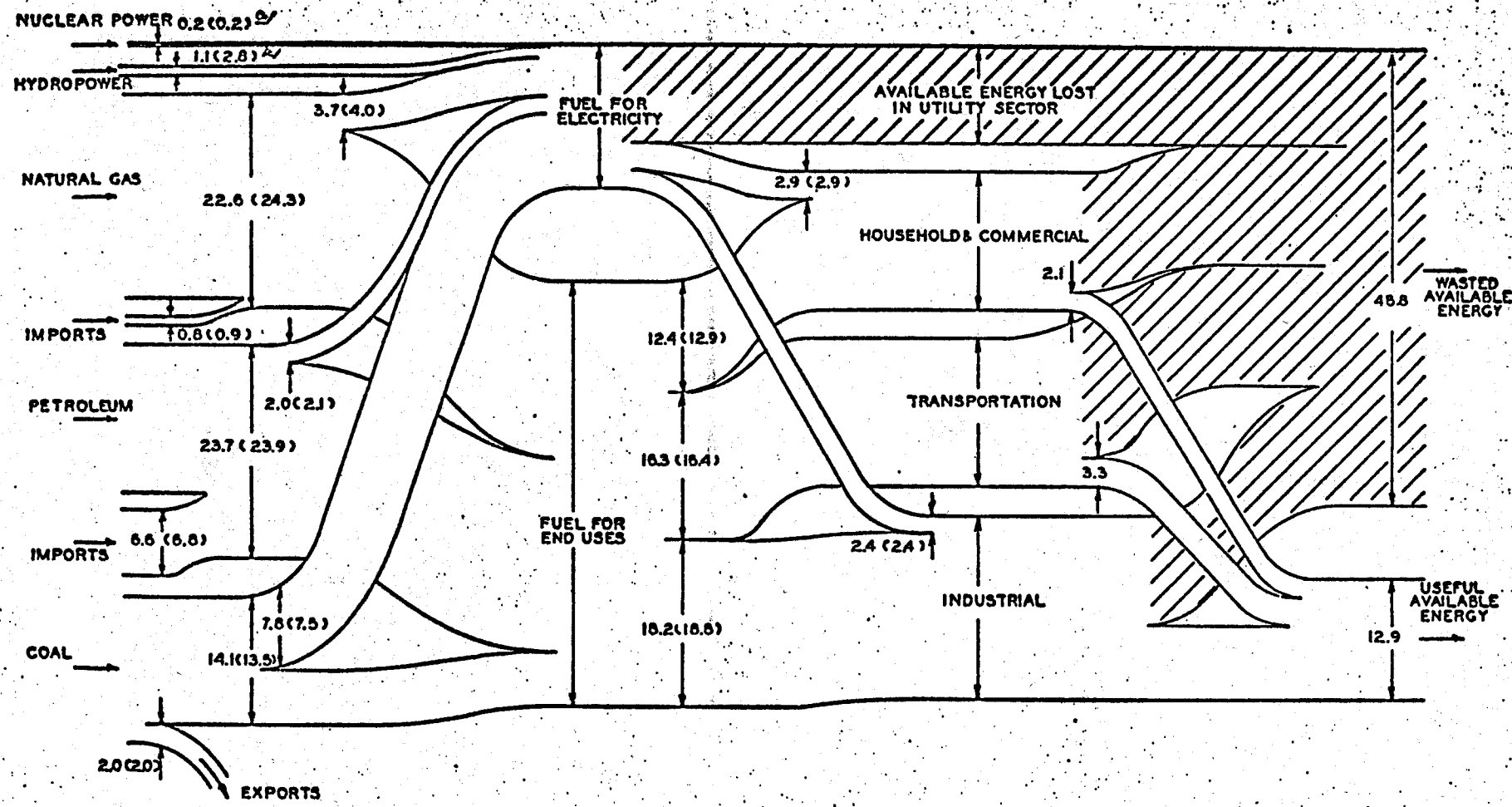


Figure 11 Flow of available energy in the U.S. (All values reported are 10^{15}Btu[1.055 (10^{18})J].

a/ All values in ( ) are energy, other values reported are available energy.

b/ The energy value for hydropower is reported in the usual manner of coal equivalent; actual energy is 1.12 x 10^{15} Btu.

transportation sector were the largest contributors to the wasting of energy, and that both were substantially less efficient than either the industrial or household and commerical segments. Figure 11, on the other hand, shows each of the four segments of our economy contributing roughly equal shares to the waste of specific availability. Here, the transportation and household and commercial categories are indicated as the least efficient (effective) with effectiveness values roughly half that for electrical generation and industrial. The specific availability flow diagram thus indicates that the household and commercial category, that can most easily be converted to geothermal energy, is a prime area for significantly improving the available energy use in our economy.

Although the thermodynamics above is very helpful to indicate the proper direction to look for improvement, the final test is economics and practicability. Investigations of the economics, the specific flow requirements, and experience with geothermal systems indicate that electrical generation from geothermal resources is quite often uneconomic when the resource temperature is at or below 200°C.

An investigation of the temperature required for energy in the U.S. national economy indicated that greater than 40% of the total energy requirements in the U.S. could be met by heating at a maximum of 200°C (Reistad, 1975). This amount represents greater than 60% of the total if transportation and non-energy uses of fuels are not considered.

Thus, the total potential direct application of geothermal energy is very significant on a national scale.

USE OF GEOTHERMAL RESOURCES IN DIRECT APPLICATIONS

With the exception of recent research on utilization of warm water rejected from power plants, research on applications of heating in the temperature range of 30 to 200°C has not been carried out on a significant scale. The main reasons are (1) energy has, until now, been moderately cheap and easy to get; and (2) the high temperatures available from the high grade sources of energy, such as fossil fuels, have permitted convenient systems by trading irreversibilities of heat transfer through large temperature differences to minimize system design effort and cost. Research on meeting these requirements in an efficient manner is now necessary because (1) not only is energy becoming very costly, but it may be difficult to get in certain forms at any price and (2) if geothermal energy is to meet these requirements, the available resource temperatures are too close to the required application temperatures to allow trading inefficient system design against design effort.

The recent research on utilization of warm waters from power plants has, for the most part, been restricted to investigating the use of waters in the temperature range of about 30 to 50°C. The geothermal resources appear to have the greatest potential in direct applications when they exist at temperatures below about 200°C, since above this temperature, electrical power generation is usually economical. For purposes here, then the direct applications of geothermal energy can be broken into two classifications:

1. Applications previously investigated as uses of warm water in the temperature range of 30 to 50°C.
2. Applications that can utilize waters in the temperature range of 50 to 200°C.

The following material will treat each of these classifications. It should be noted, however, that applications that have been investigated as part of warm water utilization studies may benefit markedly from higher temperatures and thus may require additional investigation in this new setting.

1. Applications Previously Investigated As Users Of Warm Water In The Temperature Range Of 30 To 50°C.

Applications that have been investigated as part of warm water utilization studies are:

A. Agricultural Applications
   - --Greenhouses
   - --Algal basins
   - --Aquaculture basins
   - --Open field soil warming

B. Urban Applications
   - --Space conditioning
   - --Water heating
   - --Miscellaneous uses
     - -snow melting
     - -recreational pool heating
     - -sewage treatment

These two major classifications and their potential for geothermal energy use will now be considered.

Agricultural Applications

Energy and Food Production: Of equal importance to energy supply problems and inextricably tied to them are the problems of supplying an adequate diet to all inhabitants of the earth at a reasonable cost. The efficiency of food production has steadily increased by the use of better equipment, manufactured fertilizers, and the introduction of high yielding plant varieties. However, these developments have made modern agriculture strongly dependent on the availability of low cost energy.

The impact of energy shortages on food production is not only the availability of energy but also the price. Increased costs will have a significant impact on the cost of food in all parts of the world. As the price of fuel increases it will be less available to countries without foreign exchange reserves. This has already occurred during the past year. Grain production was reduced in several countries because fertilizers were not available in sufficient quantity. In the United States the cost of nitrogenous fertilizers rose from about $70 to about $300 per ton during 1972-75 period, as a result of increased energy costs.

The amount of energy consumed in agriculture related activities is small although significant (Table 3). Several attempts have been made recently to quantify energy flows in agriculture. Table 4 shows the total annual per capita energy consumption for food related activities in the United States for the year 1963 (Hirst, 1974). The energy required on the farm was only a small part of total energy needs in 1963. Forty-seven percent of the total energy requirement was used for processing. Thirty-one percent of the total requirement was used for food processing in the home.

A similar analysis was made for Australia (Anonymous, 1974). Results (Table 5) show a lower rate of energy consumption (6.1 vs 8.2 million Kcal/person/year) and a different distribution of use. About the same percentage

Table 3. Energy inputs for several uses in percent of total U.S. consumption (Heichel, 1974).

Category	Percent of total U.S. consumption
Transportation	25
Space heating	18
Iron and steel	5.7
Petroleum refining	4.8
Agriculture	3.5
Paper	2.2
Petrochemical feedstock	2.1
Aluminum	1.2
Ammonia	0.8
Glass	0.3

Table 4. Total annual per capita energy consumption for food related activities in the U.S. for 1963 (Hirst, 1974).

Category	Annual Consumption	Percent of total	
		Food related energy uses	All energy uses
	10^6Kcal/person	%	%
Farm production	0.30	4	.9
Processing			
Transportation	1.16	14	3.1
In plant	2.67	33	7.3
Distribution			
Transportation	0.23	3	0.7
Trade	1.31	16	3.5
Home preparation	2.49	31	6.8
Total	8.16	100	22.3

Table 5. Total annual per capita energy consumption for food related activities in Australia for 1974 (Anonymous, 1974).

Category	Total annual consumption	Annual consumption per person	Percent of total
	10^{12}Kcal/year	10^{6}Kcal/person	%
Farm production			
Fuel and electricity	13.1	1.1	18
Fertilizers	4.5	0.4	6
Other	3.2	0.3	4
Processing			
Transportation	1.8	0.2	2
In plant	20.2	1.7	27
Distribution			
Transportation	1.8	0.2	3
Trade	7.9	0.7	11
Home preparation			
Refrigeration	11.0	0.9	15
Cooling	10.0	0.8	14
Total	73.5	6.1	100

Table 6. Ratio of the energy required for food production to the food energy content for major food groups (Hirst, 1974).

Food category	Ratio
Sugar, fats, oils	2.6
Flour and cereals	4.0
Fresh vegetables	5.0
Dairy products	7.6
Meat and poultry	9.8
Eggs	10.0
Fresh fruits	10.2
Fish	15.0
Processed fruits and vegetables	16.0
Average	6.4

was used for home preparation, but the Australian study showed a higher percentage for processing and distribution. The differences are in part due to different types of agriculture in the two countries.

The energy efficiency of farming can be estimated by comparing the energy required to raise food with the energy content of the food produced. Table 6, based on a graph presented by Hirst (1974) indicates that the average return on a unit of energy invested in food production was about 16 percent. The efficiency ranged from about 43 percent for high energy content products to 6 percent for low energy products which require much energy for storage and processing.

Land and Food Production: Agricultural productivity has increased throughout the past decade and this is indeed fortunate as the demand for food has similarly increased due to population increases and increased levels of affluence. Based on an exponentially increasing population and a gradually decreasing amount of land available for crop production, one publication (Meadows *et al.*, 1972) predicts that by about the year 2000 the amount of arable land available will be just sufficient to feed the world population (Figure 12). Although man now only farms about half of the earth's 3.2 billion hectare which can potentially be cultivated, there is a definite limit to the available area and some of the best farmland is lost each year to agricultural production by the construction of roads, urban development, airports, and shopping centers. In the United States about 0.5 million hecatre of fertile lands are lost each year. The estimates shown in Figure 12 are global estimates assuming that agricultural productivity remains at its 1970 level. Bringing new land into production is often limited by water resources and may be limited by energy resources in the near future. The use of geothermal energy has potential to alleviate both restrictions.

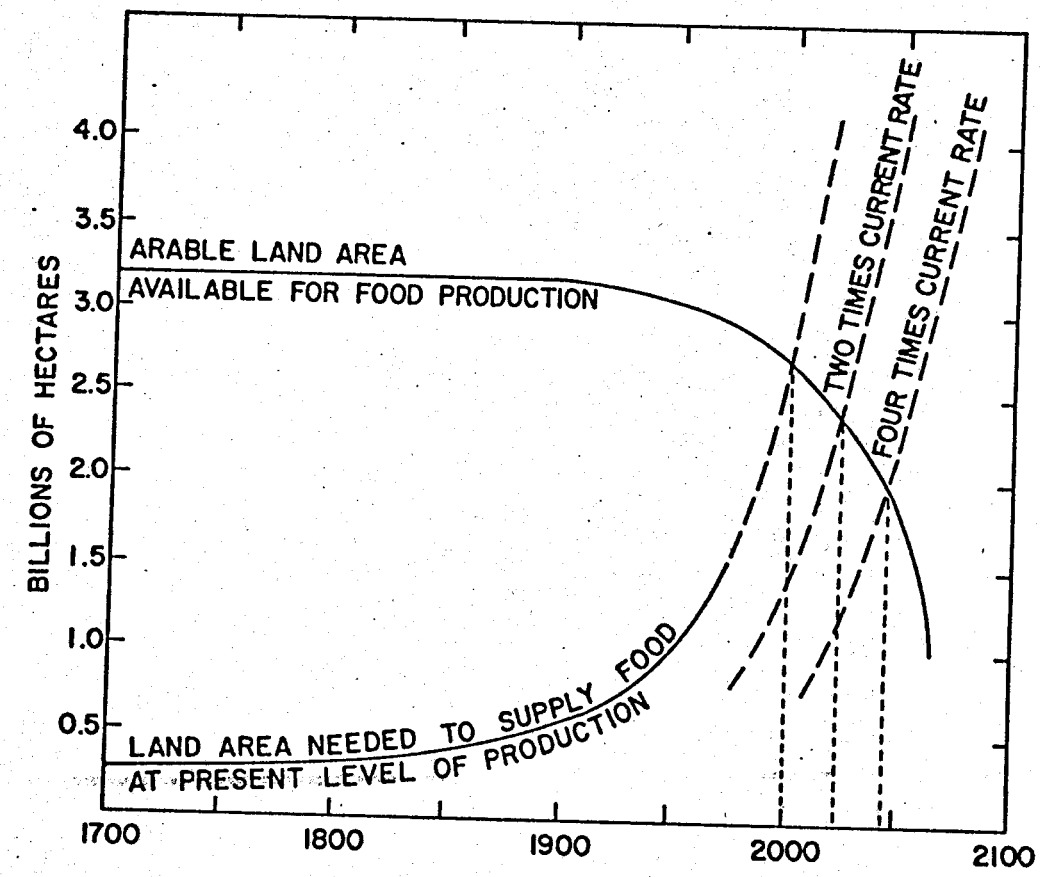


Figure 12 Land area needed to supply a basic food ration to the world population at current yield levels and two and four times current yield levels. Also shown is the land area available for food production assuming a loss of agricultural land to non-agricultural uses.

Water Supply Problems: Withdrawals for cooling of thermal electric power plants is by far the largest category of water use in industry. Much concern has been expressed recently as to whether water supplies will be sufficient to support the accelerated energy development projected. Figure 13 shows that the rate of water withdrawn for thermal electric power production exceeded withdrawals for irrigation by 1965, when it became the leading class of water withdrawal in the United States. However, the rate of water withdrawal shown is based on once-through cooling and thus does not represent a consumptive use as is the case with irrigation. The use of geothermal energy for desalination of brackish water may well be one of the most productive applications.

Potential For Geothermal Energy Use: Because a wide range of temperatures could be obtained, geothermal energy can be applied at many stages in the food producing chain of events. According to Tables 4 and 5 the most productive applications would be the processing sector and in the home preparation sector. Application in the latter category would mean processing for immediate home-use involving less preparation. However, most of the analysis in development of uses for alternate energy sources such as geothermal energy to date has been in the area of "On Farm Production". Proposed applications include heating and cooling of greenhouses, heating and cooling of open air basins for single cell protein production or fish production, open field soil warming.

Greenhouses: Heating and cooling of the greenhouse airspace with waste heat can be accomplished by several techniques. Most promising are: (i) the Oak Ridge System which uses a wet pad in combination with a finned-tube heat exchanger for heating and cooling, (ii) the Oregon State University system which uses a more compact finned-tube heat exchanger for heating and a conventional evaporative cooler or ventilator for cooling, and (iii) the Oregon State University soil warming system. The Oak Ridge system has the disadvantages

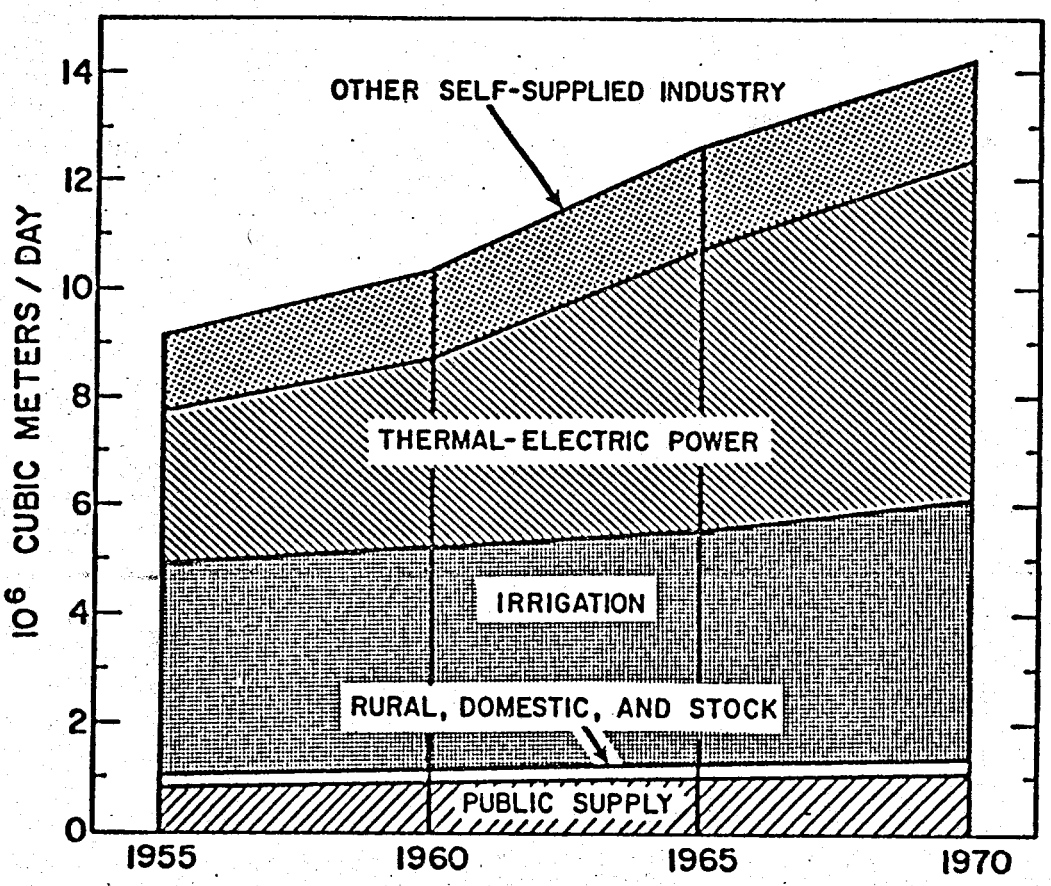


Figure 13 Rates of water withdrawals for several uses (Davis and Wood, 1974). The rate of withdrawals shown for power generation is based on once-through cooling and is a non-consumptive use.

of high humidity, large heat exchangers, and a continual exposure of the condenser cooling water to greenhouse or outside air. The OSU system eliminates these problems. In some situations soil warming may be used as the sole heat source. Plants grow well at cooler air temperatures with the roots maintained warm. The soil warming system, however, cannot be expected to appreciably increase the greenhouse air temperature (Boersma and Rykbost, 1975). Therefore an auxiliary heating system should be available to warm the greenhouse airspace during periods of unacceptably low night temperatures.

The economic potential of using waste heat from power plants to control air temperatures in commercial greenhouses has been evaluated by comparing total discounted costs of the waste heat system to that of a conventional gas-fired forced-air system (Boersma et al., 1974). Based on U.S. Federal Power Commission's projections through 1990, the annual costs were calculated for the time period of 1976 through 2005 for the Portland, Oregon climate which is characterized by mild winters and cool summers. Table 7 shows the value of the waste heat in dollars per Kcal for conditions where the two systems would cost the same to own and operate. The value of the waste heat per million Kcal is estimated at $0.63 in 1976 increasing to $6.01 in 2005. The indicated values would be changed by selecting a different projection. According to this analysis users of the heat exhanger system could pay a substantial fee for warm water.

Algal Basins: Algae grow in water contained in basins. They can be cultured throughout the year, while field crops only grow during the summer months. This accounts for about a four fold increase in dry matter production over conventional agronomic crops. Algal cells can be harvested without leaving parts behind while plant roots, stems, and leaves of most agronomic crops are left in the field. This accounts for about a two fold difference in dry matter

Table 7. Annual heating costs for a 30 x 60 meters greenhouse using (i) gas-fired forced-draft or (ii) a waste-heat heat-exchanger system to maintain a minimum temperature of 15 degrees Celsius in a Portland, Oregon climate (Boersma *et al.*, 1974)

Year	Gas system costs			Waste heat system costs		Value of waste heat
	Depreciation interest, maintenance and taxes	Gas	Total	Depreciation interest, Maintenance and taxes	Equivalent energy value	
						$/10^6$ Kcal
1976	2,395	8,131	10,526	3,555	6,971	2.49
1980	2.495	10,854	13,313	3,612	9,701	3.46
1986	3,038	16,822	19,860	3,722	16,138	5.76
1990	3,148	22,492	25,640	3,815	21,825	7.79
1996	3,595	34,838	38,433	3,992	34,441	12.30
2000	3,800	46,588	50,388	4,143	46,245	16.52
2005	4,116	67,028	71,144	4,378	66,766	23.85

production. The protein content of algae is about three times higher than that of soybeans. These three factors combine for the better than 25 fold higher rate of protein production per acre by algae over soybeans.

Low temperatures prevent algae from using available light energy efficiently. The growth rate of algal cells is controlled by a light dependent process and a light independent process. The light dependent process uses light energy to produce a chemical compound which is subsequently converted to protein by the light independent process. The rate at which the initial compound can be produced is controlled by the rate of its conversion to protein, which is controlled by the culture temperature. The rate is low at cool temperatures and high at warm temperatures. For example, for some algal species, the rate of cell doublings, which is a measure of growth rate, is two per day at 25 degrees Celsius but nine per day at 35 degrees Celsius. Consequently the advantages of growing the algae in heated basins merits evalutaion.

Information to make an economic analysis of heating algal basins is not available. Therefore, any attempt to make such an analysis must be based on best estimates. Such an estimate has been made by Boersma et al. (1974) with the following conclusion:

> Protein production could be economically feasible with a heated system but probably would not be economically feasible with an unheated system.

Aquaculture: Several studies have indicated the possibility of growing fish in heated basins. Young salmon and shrimp grow almost twice as fast in heated sea water as they do at ambient temperatures (Figure 14). Some fresh water fish, such as catfish, grow much faster in heated water than at ambient temperatures. The two systems found to be most promising for temperature control are open systems in which fish grow in the condenser cooling water and closed

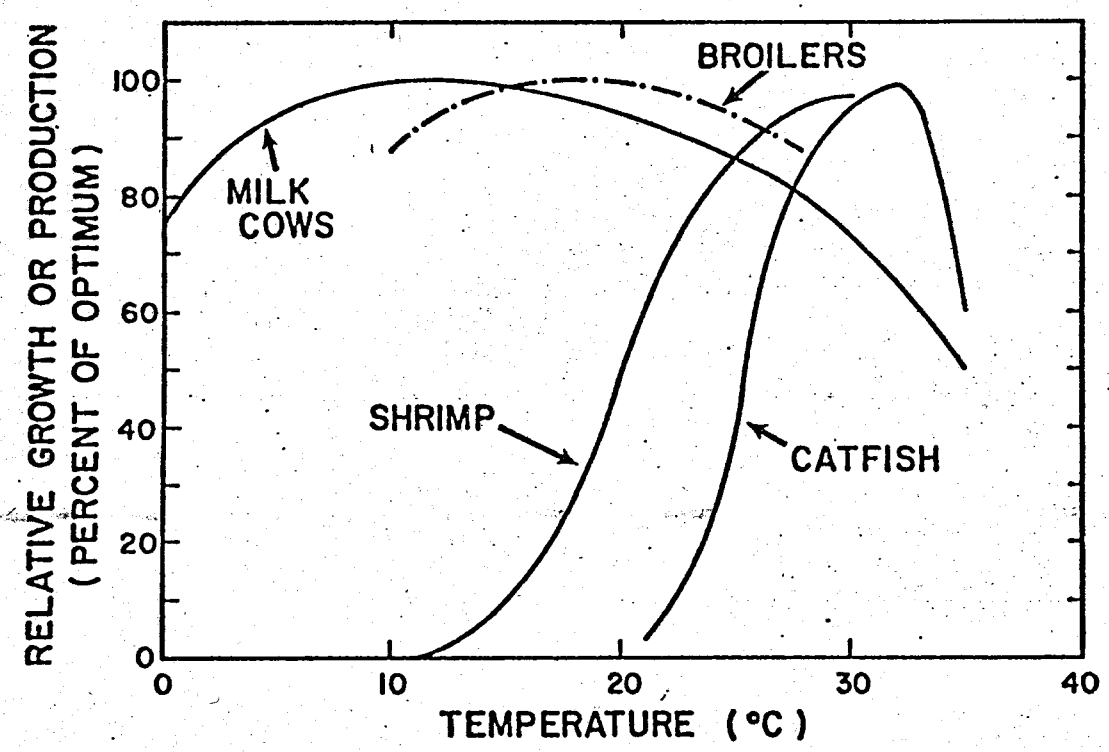


Figure 14 The growth rate of shrimp, catfish, broilers and milk producing cows as a function of temperature (Beall, 1970).

systems in which the basin water is circulated through a heat exchanger where it is heated by the condenser cooling water. Several observations can be made which are considered to be important, (i) this application of waste heat has been shown to have great economic potential for certain species of fish. These are mostly freshwater species although potential for saltwater species and shellfish also exist, (ii) a problem of potential markets for the freshwater fish species exists. Probably the best market would be the use for protein-rich animal food. Fish meal produced in such basins could for example replace the protein derived from the anchovy fishery of Peru. The economic potential for such a scheme depends on the solution of production problems such as feeding techniques, waste control, and disease control, (iii) this application would be advantageous in an integrated system where the fish could be processed and consumed locally.

Soil Warming: Waste heat can be used to increase the soil temperature by circulating condenser cooling water through subsurface pipes. Effect on yield of maintaining a 30 Celsius temperature in pipes 100 cm deep and 180 cm apart is shown in Figure 15 (Rykbost et al., 1974). Analysis indicates that economic feasibility is generally limited to high value crops such as tomatoes or broccoli (Figure 16). The economic potential has, however, not been optimized at this time.

Urban Application

The requirement for low-grade heating in urban communities of the U.S. represents a significant fraction of the total energy requirement in the U.S. Consider 1968 data: space heating consumed 10,857 x 10^{12} Btu which could have been supplied at temperatures between 40 and 75°C; hot water heating consumed 2,389 x 10^{12} Btu which could have been satisfied at temperatures of

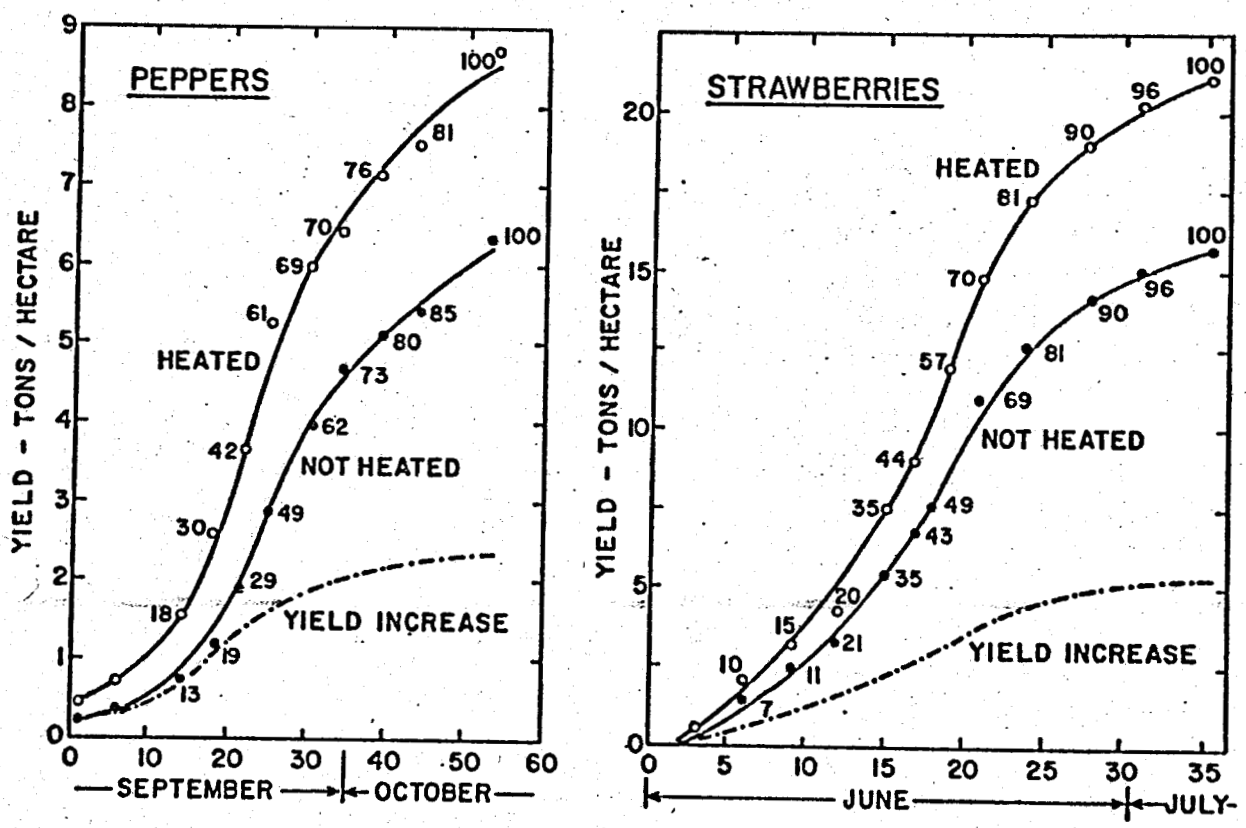


Figure 15 The yield of peppers and strawberries on heated and unheated plots (Rykbost et al., 1974).

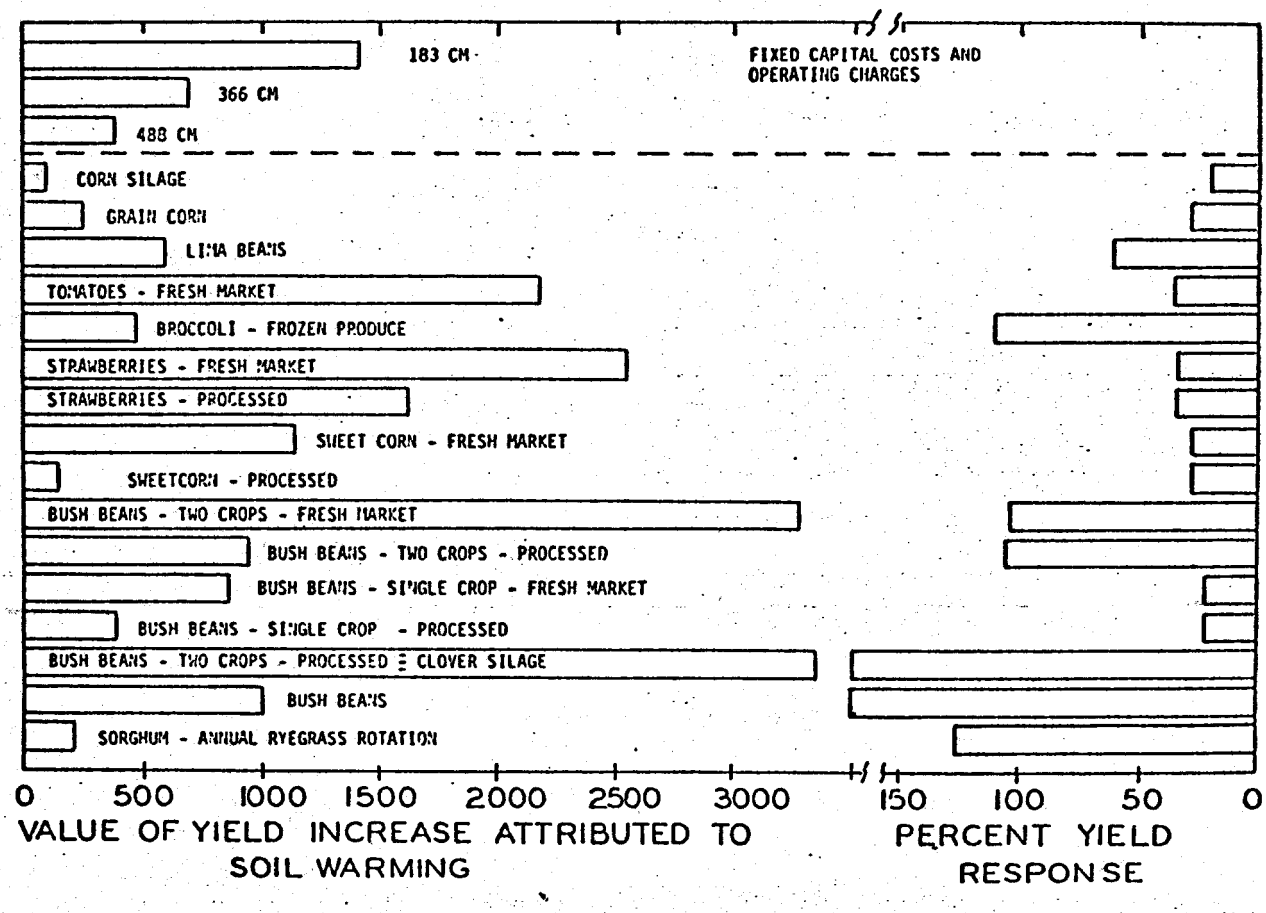

183 CM
366 CM
488 CM
FIXED CAPITAL COSTS AND OPERATING CHARGES
CORN SILAGE
GRAIN CORN
LIMA BEANS
TOMATOES - FRESH MARKET
BROCCOLI - FROZEN PRODUCE
STRAWBERRIES - FRESH MARKET
STRAWBERRIES - PROCESSED
SWEET CORN - FRESH MARKET
SWEETCORN - PROCESSED
BUSH BEANS - TWO CROPS - FRESH MARKET
BUSH BEANS - TWO CROPS - PROCESSED
BUSH BEANS - SINGLE CROP - FRESH MARKET
BUSH BEANS - SINGLE CROP - PROCESSED
BUSH BEANS - TWO CROPS - PROCESSED ≡ CLOVER SILAGE
BUSH BEANS
SORGHUM - ANNUAL RYEGRASS ROTATION
0 500 1000 1500 2000 2500 3000
VALUE OF YIELD INCREASE ATTRIBUTED TO SOIL WARMING
150 100 50 0
PERCENT YIELD RESPONSE

Figure 16

90°C; and air conditioning consumed 1,540 x 10^{12} Btu which could have been satisfied by absorption machines requiring heating at temperatures ranging from 110 to 200°C. As percentages of the total U.S. energy consumption for 1968, these become 18, 4 and 2½% respectively.

A large scale approach to meeting these urban requirements, such as "district heating systems", although presently popular in Europe, have not had much backing in the U.S. since before the 1950's. Interest in decreasing the thermal pollution from power plants has recently prompted modern studies regarding the feasibility of supplying the thermal energy requirements of urban communities by coupling the community to a steam-electric power plant. Miller et al. have considered a system that includes a district hot water distribution network. Reistad et al. (1974) have recently completed a study which shows that hot water (300°F) can be economically transported a distance of about 8.5 miles* to supply the needs of the downtown area and apartments for 129,000 inhabitants of a 200,000 population city. The study also showed for a heat-pump system which used warm water (90 - 115°F) from the power plant for a low-temperature source, the economical transporting distance was about one-fourth that for high temperature systems.

Geothermal energy has a good potential for supplying the thermal energy requirements of an urban community. Much of the total geothermal resource has temperatures that are high enough for either of the two systems mentioned above. Geothermal energy has an advantage over the system that requires coupling with power plants, because currently there is considerable resistance to locating either nuclear or fossil-fueled power plants close to urban communities. The argument can be made that geothermal resources probably don't exist

*The study was completed before the dramatic change in fuel prices which started with the oil embargo in the Fall of 1973.

where the large urban loads do. This is true to some extent, but there are two important counter agruments:

1) The possibility of using a low-temperature "geothermal resource" considerably broadens the amount of geothermal resources available and tremendously increases the likelihood of geothermal resources existing at economical depths below present urban areas.

2) If long time periods are considered, the existence of relatively cheap geothermal energy will create urban areas near known geothermal resources.

2. Applications That Can Utilize Waters In The Temperature Range Of 50 to 200°C.

The major applications that can utilize waters in the temperature range of 50 to 200°C, in addition to those listed above, are heating and refrigeration in the following industries:

A. Paper and Allied Products Industry

B. Lumber and Wood Products Industry

C. Chemical and Applied Products Industry

D. Food and Kindred Products Industry

E. Petroleum Industry

F. Other miscellaneous industries.

The energy consumption rate of these industries that are significant consumers in the state of Oregon are shown below (Penwell *et al.*, 1973).

	Oil Gal/Day	Gas Ft^3/Day	Electric kwh/Day	Total 10^{10} Btu/Day
Paper and Allied Products	167,438	77,255,342	6,259,696	12.18
Lumber and Wood Products	165,616	27,534,795	5,635,067	6.97
Chemicals and Allied Products	-------	12,183,288	1,180,282	1.62
Food and Kindred Products	23,278	5,860,548	979,701	1.24

Each of the above four categories of industries are quite important to the economy of Oregon and the Pacific Northwest. The potential for each of these to use geothermal energy will now be considered.

Paper And Allied Products Industry

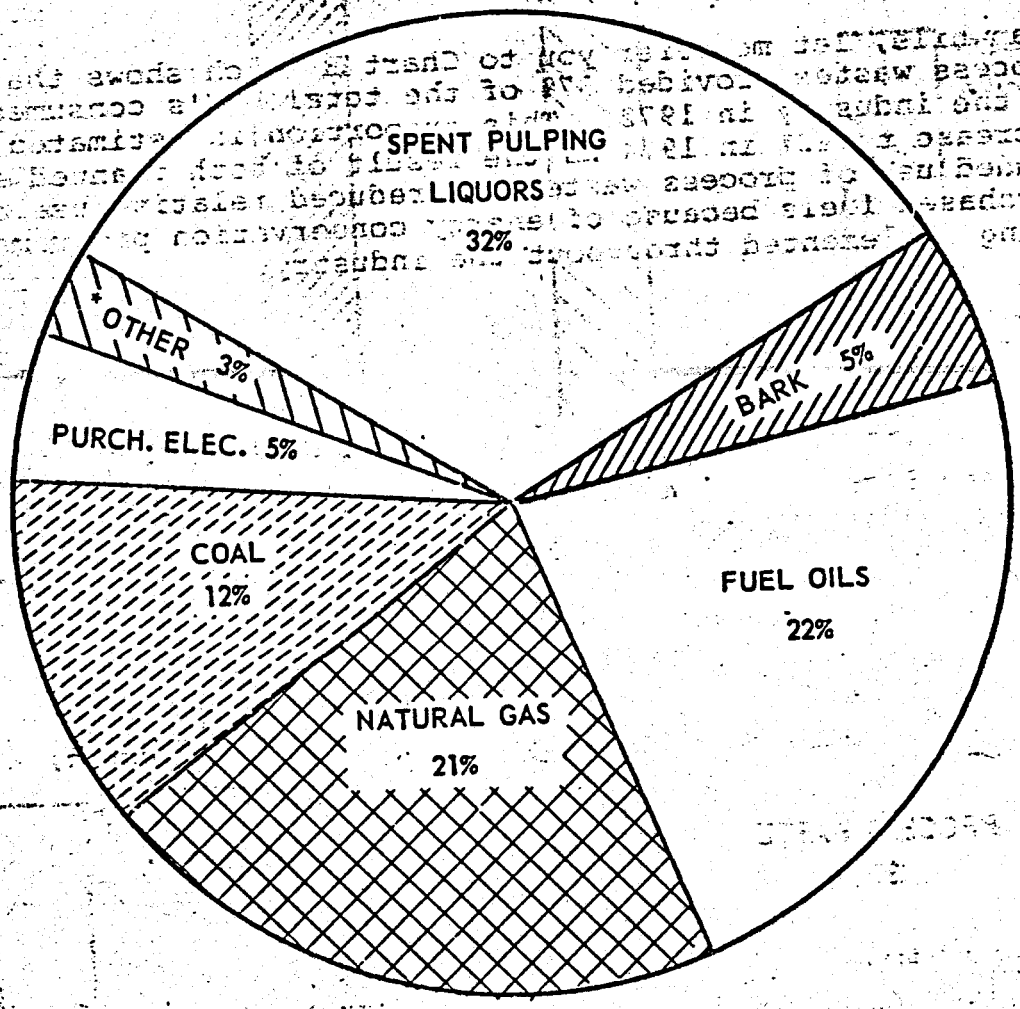
The paper and allied products industry is a prime candidate for direct application of the geothermal resources of the Pacific Northwest, because it consumes almost twice as much energy as the next largest consumer in Oregon, and a large portion of its energy consumption is for heating at temperatures below 200°C. Specifically, greater than 80% of the energy consumption in this industry is for process heating. Also, the substitution of geothermal energy into the pulp and paper industry could have significant national impact because the industry is the fourth (1972) largest manufacturing consumer of energy in the industrial sector, following Chemical and Allied Products, Primary Metals, and Petroleum and Coal Products and is the largest (1972) in fuel oil cost in the U.S.

Although the industry has the largest fuel oil cost of the manufacturing industries, the fuel oils only accounted for 22% of the total energy consumed in 1972. Figure 17 shows the split of the total energy usage in the U.S. Pulp and Paper Industry by fuel type. Note that about one-third of the total comes from bark and spent pulping liquors.

The principal current technology in use in the U.S. Pulp and Paper Industry is the kraft paper manufacturing process. A diagrammatic representation of the process is shown in Figure 18. Although the energy requirements of the various operations change with different paper types (the total energy requirements of the different products vary widely, ranging from 15 to 48 million Btu per ton), the requirements for bleached folding boxboard will be

The individual internal and external sources of energy in 1972, on an industry wide basis, are illustrated in Chart 4.

U. S. PULP & PAPER INDUSTRY'S SOURCES OF ENERGY BY FUEL TYPE 1972

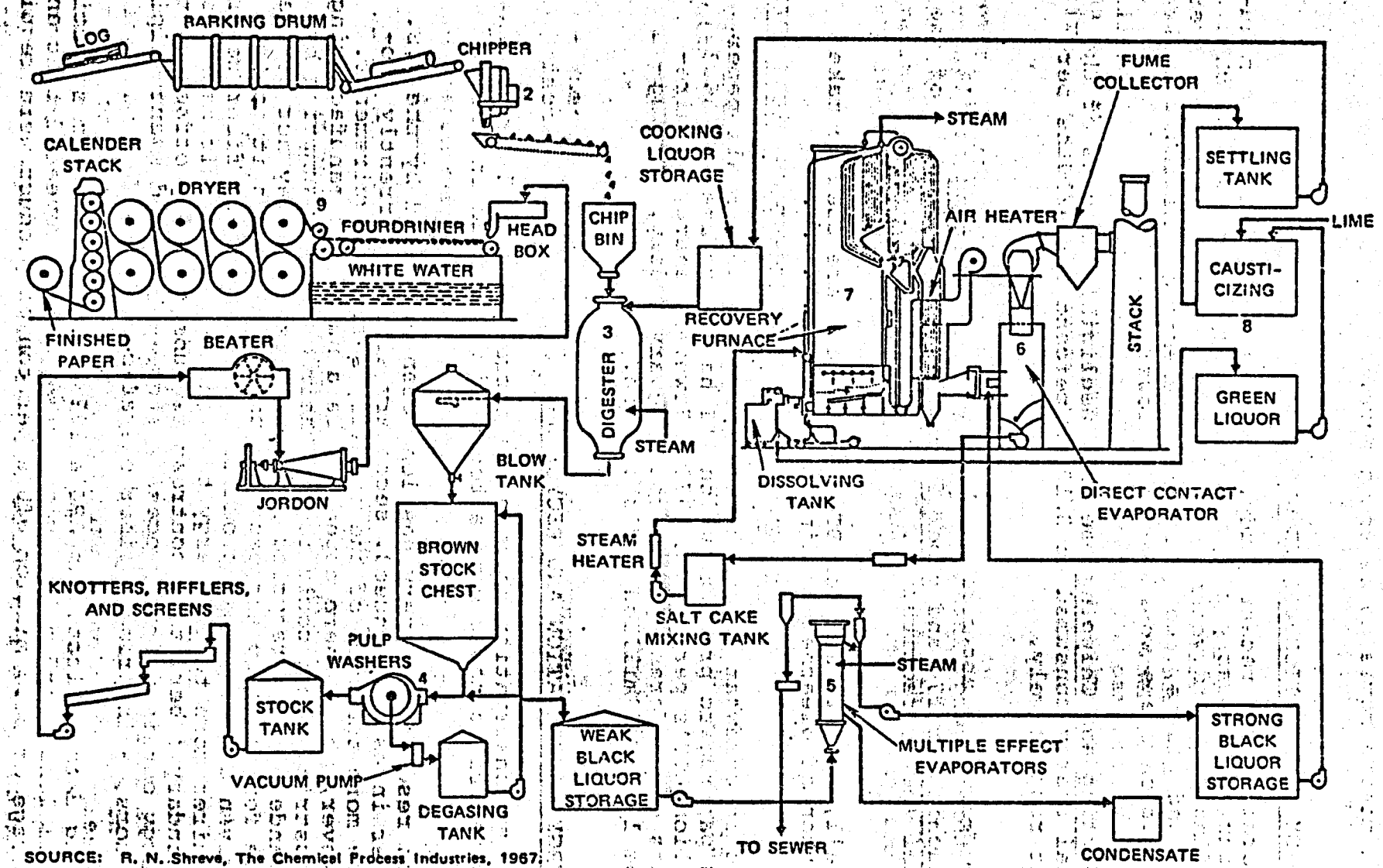


* Other includes Hogged Wood, Purchased Steam, Propane, etc.

SOURCE: American Paper Institute 1973 Survey.

FIGURE 17

KRAFT PAPER MANUFACTURING PROCESSES



SOURCE: R. N. Shreve, The Chemical Process Industries, 1967

FIGURE 18

presented to show an example of the relative energy requirements of the operation. The total energy requirement per ton of bleached folding boxboard is about 28 million Btu, which is somewhat below the industry average of 36.2 million Btu per ton for all paper and paperboard products in 1972. The three main energy consuming processes are pulping, bleaching and paper forming and drying. These processes consume about 40 percent, 18 percent and 40 percent respectively of the total energy requirement. The debarking and chipping processes use only negligible amounts of the total energy, their total amounting to less than one percent of the overall requirements.

The steam requirements in the pulp and paper industry, regarding conditions of supply for application in present processing equipment are approximately as follows:

Process	Required Steam Conditions
Digesting	∿ 150 psig (saturation temperature ∿ 185°C)
Evaporation	30 psig (minimum) (saturation temperature ∿ 121°C)
Bleach Plant	∿ 50 psig (saturation temperature ∿ 139°C)
Drying	∿ 50 psig for light fine papers and newsprint up to 150 psig in general

In addition, steam is required for turbine devices at pressures around 250 psig (sturation temperature 205°C) and for miscellaneous uses at nominally 150 psig.

From the above tabulated values and the previously presented values representing the approximate split of the energy consumption among the main energy intensive processes, several estimates can be made:

1. If the geothermal resource can provide steam at 150 psig (185°C saturation temperature), greater than 90% of the heating energy requirements for the processing can be met from this resource.

2. If the geothermal resource can provide steam at 50 psig (139°C saturation temperature), between 40 and 80 percent of the heating energy requirements can be met from this resource. The 80 percent value applies to newsprint and light fine papers while the 40 percent is for more general processes.
3. The geothermal resource must be able to supply at least 30 psig (120°C saturation temperature) steam to be applicable in the pulp and paper industry for present processing equipment.

This industry, with such large heating requirements at relatively low temperatures, deserves considerable research to consider not only how geothermal can be applied to the existing processes, but also how the existing processes can be modified in temperature requirements to allow optimization of the potential geothermal use.

Lumber And Wood Products Industry

The lumber and wood products industry includes operations ranging from logging camps and millwork to the production of wood products. The most important operations are sawmills and planing mills, and plywood and related products.

Energy is used for drying, curing, and mechanical drive operations. At present, there exists no hard data to evaluate the split of total energy among the various operations. However, a number of companies are presently implementing studies to evaluate the split of energy in their particular operation. The drying and curing operations are typically met with steam heat at pressures near 150 psig (saturation temperature ∿ 185°C) or by direct firing at somewhat higher temperatures. Since a large portion of this industry's energy requirement is for heating, it appears that geothermal energy has some potential, but

research is necessary to evaluate (1) if specific resources and innovative conversion systems can provide these higher temperatures and (2) if the temperatures can be reduced providing a cheap geothermal resource is available.

Chemicals and Allied Products

This sector contains a myriad of applications. Nationally, the largest energy consumers are shown in Table 8. These industries consume over half of the total for the sector, but only about one-third of the total that is consumed for purposes other than feedstock. Consider each of the major applications:*

(A) Chlorine - caustic soda: About three-fourths of the U.S. chlorine and caustic soda production is by electrolytic methods using diaphragm cells. Figure 19 shows a flow diagram of the diaphragm cell process for caustic soda and chlorine producing 76% caustic. In the typical process, major energy requirements (80 to 90%) are electricity for electrolysis and steam for evaporation. Additional energy (10 to 20%) is required for pumps, compressors, and refrigeration for liquified chlorine. The temperatures and specific amounts of steam depend on the type of caustic produced: The normal 50% caustic is produced in double or triple effect evaporators which require steam at 50 to 60 psig (but which commercially use up to 150 or 175 psig) for the first stage. Stronger, 70 or 75% caustic can be concentrated from cooled and settled 50% caustic in a single effect final of high evaporator requiring at least 75 to 100 psig steam. Also, caustic containing less than 1% water can be produced by finishing 50 of 75% caustic in Dowtherm heated evaporators or direct fired units at temperatures of 450 to 600°C. Since a majority of the

*The material on the major applications in the Chemicals and Allied Products Sector is taken from Reistad (1975).

TABLE 8 ENERGY CONSUMPTION BY END USE IN THE CHEMICAL INDUSTRY 1967 (Trillions of Btu)

	Space Heating			Process Heat			Mechanical Drive			Electrical Uses**				
	Fuel	Steam	Electric	Fuel	Steam	Electric	Fuel	Steam	Electric	Lighting	Electrolysis	Other	Total	Feedstock
Chlorine - caustic soda	--	--	--	--	69	--	--	--	1	*	80	--	150	--
Soda ash (synthetic)	--	--	--	124	57	--	--	--	Negl	Negl	--	--	181	--
Acetylene (hydrocarbon source)	--	--	--	--	9	--	--	--	1	Negl	--	--	10	45
Oxygen	--	--	--	--	--	--	--	36	13	Negl	--	--	49	--
Carbon black	--	--	--	4	--	--	--	--	--	Negl	--	--	4	212
Ammonia	--	--	--	85	113	--	--	--	2	Negl	--	--	200	299
Aluminum oxide (excluding natural)	--	--	--	24	52	--	--	--	1	Negl	--	--	77	--
Phosphorus	--	--	--	1	--	--	--	--	*	*	26	--	27	20
Methanol	--	--	--	13	13	--	--	--	1	*	--	--	27	39
Sulfur (frasch)	--	--	--	72	--	--	--	--	--	*	--	--	72	--
Ethylene, propylene, butadiene, aromatics, C_2, C_3, and C_4	--	--	--	5	25	--	--	--	5	*	--	--	35	1,200
Subtotal				328	338			36	24		106		832	1,815
Space heating		20											20	--
													852	1,815
Balance of industry		60		170	500	--		220†	367	21‡	12		1,350	--
Industry total		80§		498	838			256	391	21	118		2,202	1,815

* Included in electrolytic load.
† Energy used for electrical generation highly integrated with process steam production.
‡ Taken to be 5% of total electric load after deduction for electrolytic consumption.
§ Taken to be 5% of total direct and steam input.
†† 1 kWh = 3,413 Btu.

Source is Stanford Research Institute, 1972.

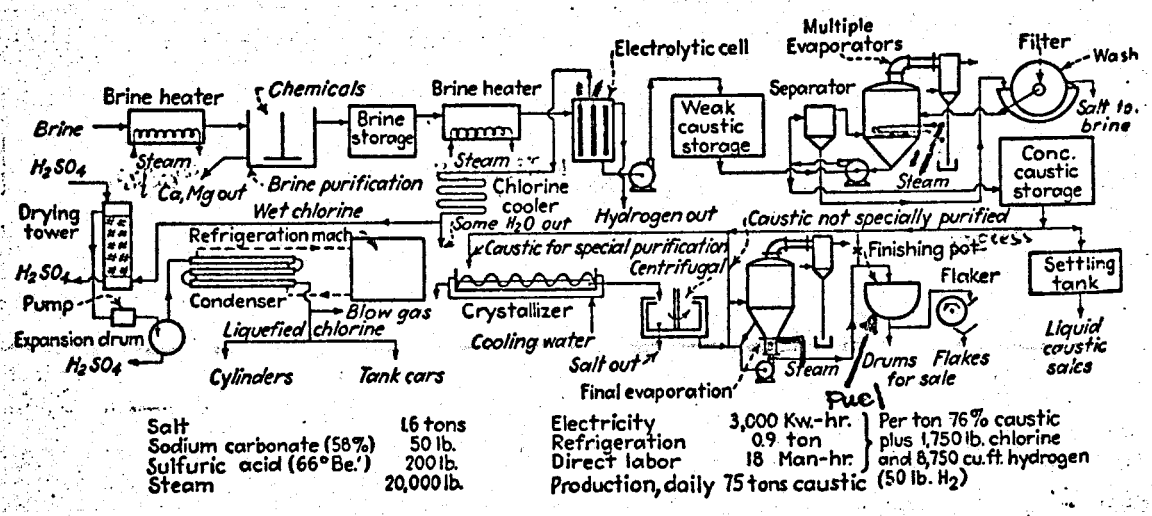
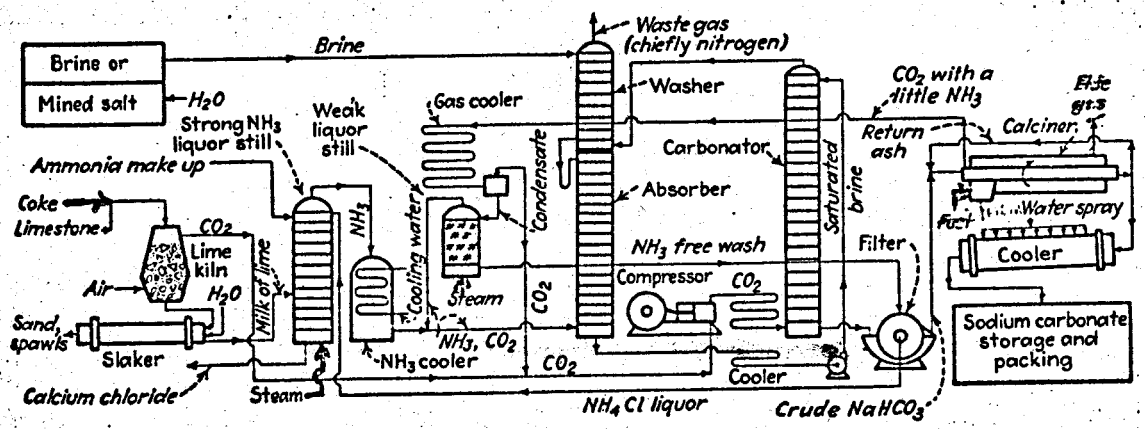


FIGURE 19 Flowchart for diaphragm caustic soda and chlorine cell. (Source is Shreve, 1967)

volume in the industry is 50% caustic with the next largest share being 70 to 75% caustic, most of the 69 x 10^{12} Btu of steam required for this industry could be supplied by a geothermal source at a maximum temperature of 170°C.

In this industry, the refrigeration would probably not be able to be done by absorption units because the low temperatures would require the ammonia-water system to be used. In addition to having to operate with ammonia at a vacuum, for the -50°F refrigeration, which poses many operating problems, the chance of having ammonia and chlorine come in contact upon which they form a very explosive mixture would probably be too much of a risk to consider this type of operation.

B. Soda ash (synthetic): The term "synthetic soda ash" refers to sodium carbonate produced by Solvay (ammonia-soda) process. Further growth of this production has been limited by an increasing shift to "natural soda ash" produced from trona (sodium sesquicarbonate). Although there has been a substantial shift for new plants to produce the "natural soda ash", the synthetic process still consumes tremendous amounts of energy and is important on a national and global basis. Figure 20 shows a flowchart for the Solvay process. The process requires energy for a variety of purposes: the kilning process requires coke for burning with the limestone; steam is required in the weak and strong liquor stills; energy is required in the calciner, the older units being direct fired, but the more modern ones utilize steam heating; substantial amounts of energy are required for various pumping, compressing and "mill drives". The calciner requires steam at about 235°C of an amount roughly 40 to



Salt	1.50-1.75 tons	Per ton of 58% soda ash
Limestone	1.10-1.35 tons	
Coke	0.095-0.11 tons	
Coal (boilers)	0.25-0.5 tons	
NH_3 loss	2-4 kg. as $(NH_4)_2SO_4$	
CO_2	1,000-1,200 cu. ft.	
Na_2S	0.001-0.002 ton	
Cooling water	15,000-18,000 gal.	
Direct labor	1 man-hr.	
Repair and maintenance	0.7-4.0 man-hr	

FIGURE 20 Flowchart for the manufacture of soda ash by the ammonia-soda process (Source is Shreve, 1967).

50% of the total energy requirement for soda ash production, excluding the coke requirement; mechanical drives account for about 15 to 20% and steam for the stills at about 120°C accounts for the other major use, roughly 35 to 45% of the energy requirement. (Kirk & Othmer, 1969)

The steam requirements in this industry are thus, largely at temperatures at which geothermal could satisfy them, 235°C for 40 to 50% of the requirements and 120°C for 35 to 35% of the requirements.

C. Ammonia: Ammonia production consumes very large amounts of steam, but has little potential for direct geothermal applications because the steam is required at very high temperatures and the overall reaction is highly exothermic thus providing energy from the process for steam generation. The temperatures required for steam use are 775°C for reforming CH_4 and 400°C for the shift conversion.

D. Alumina: Almost all of the alumina produced in the world is extracted from bauxite. The almost universally used process is known as the Bayer process.

Figure 21 illustrates a flow diagram of the Bayer process. The dashed lines show the major energy inputs: steam for solution of the alumina; steam for evaporation of the water introduced for washings; and fuel for calcination; The calcination process occurs at very high temperatures; about 1200°C, and could not utilize geothermal energy. The two steam uses in the Bayer process could utilize geothermal energy. Steam for evaporation of the water introduced for washings can be at temperatures between 120°C and 150°C: In the solution of alumina, there are two types of

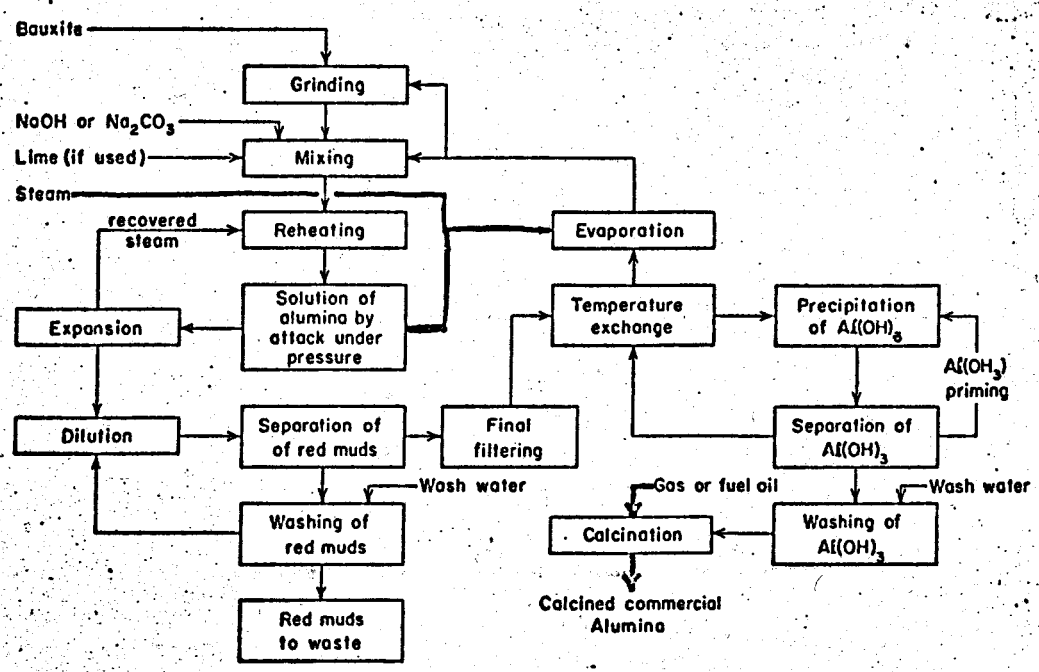


FIGURE 21 Production of alumina from bauxite by the Bayer process (Source is Kirk-Othmer, 1963a).

treatment which have different steam requirements, the European type and the American type. In the European type, it has been necessary to use heavy concentrations of caustic soda and temperatures of 200 to 250°C in order to deal with the European bauxites containing boehmite. In the American type lighter concentrations of caustic soda can be used at corresponding lower temperatures of between 120 and 140°C to deal with the trihydrated tropical bauxites. Recent use in the Americas of bauxites from Jamaica which contain some boehmite have necessitated the high temperature treatment typical in Europe.

The temperature requirements on the alumina manufacture are such that geothermal energy at 150°C could satisfy the steam requirements of the industry except for the bauxites containing boehmite, then temperatures around 250°C would be required. Most of the 52 x 10^{12} Btu consumption in the U.S. could be replaced by 150°C geothermal energy.

E. Methanol: The most important method of manufacturing methanol is by a medium pressure process from hydrogen and carbon monoxide with small amounts of carbon dioxide. The mixture of gases, referred to as "synthesis gas" are mainly produced in the U.S. from coke and natural gas. Although methanol manufacture uses steam, mainly in the "synthesis gas" production, the use is at a quite high temperature, such as 300 to 500°C in the "water-gas shift reaction" or at 875°C for the reforming conversion of natural gas and geothermal use does not appear feasible.

F. Sulfur (Frasch): Sulfur mining by the Frasch process is a major but decreasing percentage of all of the elemental sulfur. The Frasch

process appears to be a very good potential for geothermal use since water at 165°C and under pressure is pumped down into the sulfur deposits to melt the sulfur and allow it to be brought out by a combination of air lift and hydraulic pressures. Hot water is required in amounts of 4 to 50 tons per ton of mined sulfur. Energy is also required for driving pumps, compressors, miscellaneous electrical uses and steam-heating of the sulfur lines from the bore-hole, hence present practice has about one fourth of the volume flowrate of mining water being converted to high pressure steam which upon exhausting from the prime-movers is used to preheat mining water.

Chlorine and caustic soda production is a major product in the Pacific Northwest because of the marketing to the paper and allied products industry. Thus, this industry would be a potential target for heating from geothermal resources in the Pacific Northwest. It must be noted, however, that although geothermal has the potential to be used directly in a number of industrial applications for supplying steam at somewhat reduced temperatures, it may not be desirable or wise from an energy conservation viewpoint to do so. Many industries that use low-pressure steam get that steam either from processes such as in ammonia systhesis or from high pressure steam that has been expanded to generate electricity or drive steam turbines for direct mechanical drive. In the first case, where the steam comes from a process, there appears to be little incentive to reallocate the amount to possible geothermal use. In the second case, the steam generation is a very good thermodynamic process and should not be replaced unless (1) the energy supply gets so short that fossil fuels cannot be burned for any heating, and electrical energy is then supplied by a nuclear or remote geothermal source, or (2) the geothermal resource

is such that it can provide the electrical generation at the site as well as the steam requirements, or (3) the use of geothermal energy could save significant quantities of fossil fuels. The chlorine-caustic soda and the Solvay soda ash processes are good examples of the second case because they have substantial electrical and/or mechanical drive requirements and can get the process steam almost as the waste product from the electrical generation or mechanical drive. Almost all chlorine-caustic soda and Solvay soda ash plants presently produce their low pressure steam in this manner.

Because ammonia and methanol production is not amenable to heating from geothermal resources and there is little if any alumina production or sulfur mining in the Pacific Northwest, the potential for geothermal applications in this sector is dependent on the chlorine-caustic soda and soda ash processes. As noted above, a detailed investigation of these processes must be accomplished before the desirability and potential for geothermal substitution can be assessed.

Food and Kindred Products

At the national level, the processes that are the major consumers of energy in this sector are shown in Table 9 with their respective energy consumption values. With the exception of the bakery products industry, most of the energy required in this category of uses is needed for mechanical drives, relatively low temperature heating which could be accomplished with steam at pressures less than 50 psig, and refrigeration that could be met with absorption refrigeration systems. The process steam usage has been estimated to be 10% at pressures between 50 and 100 psig and 90% at pressures less than 50 psig (Miller, 1971).

In Oregon, significant classifications, in order of importance are, canned, cured and frozen foods, bakery, meat, dairy, and grain products.

TABLE 9 CONSUMPTION OF ENERGY IN THE FOOD AND KINDRED PRODUCT INDUSTRIES
(Trillions of Btu)
(1967)

Category	Coal	Oil	Gas	Electric	Total
Meat	15.7	11.9	48.0	37.2	112.8
Dairy products	12.2	13.8	45.1	31.8	102.9
Canned and frozen foods	8.4	9.6	39.1	24.5	81.6
Grain mills	45.6	4.3	38.6	38.6	127.1
Bakery products	0.3	8.7	27.7	17.1	53.8
Sugar	26.5	11.5	58.4	11.4	107.8
Candy	1.5	3.3	4.8	9.0	18.6
Beverages	25.7	13.0	34.7	20.4	93.8
Miscellaneous	25.9	15.0	49.6	25.3	115.8
Total	161.8	91.1	346.0	215.3	814.2

Note: Factors used are: 26.2 million Btu per short ton of coal
6.0 million Btu per barrel (42 gallons) of oil
1,035 Btu per cubic foot of gas
9,250 Btu per kwh
Source is Stanford Research Institute, 1972.

Thus, there is a potential market for geothermal applications in the food and kindred products industries particularly in the canning and freezing processes.

Research Necessary For Using Geothermal Energy in Direct Applications

With the potential for direct applications as indicated above, the utilization research necessary to allow widespread use is:

A. Research to develop methods of using geothermal energy for applications at existing energy requirements.

B. Research to develop methods of efficiently (optimally) using geothermal energy for existing or projected requirements.

C. Research to develop new methods of processing to allow use of the lower temperatures available from geothermal resources.

D. Thermo-economic feasibility studies to show the profitability of direct use.

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