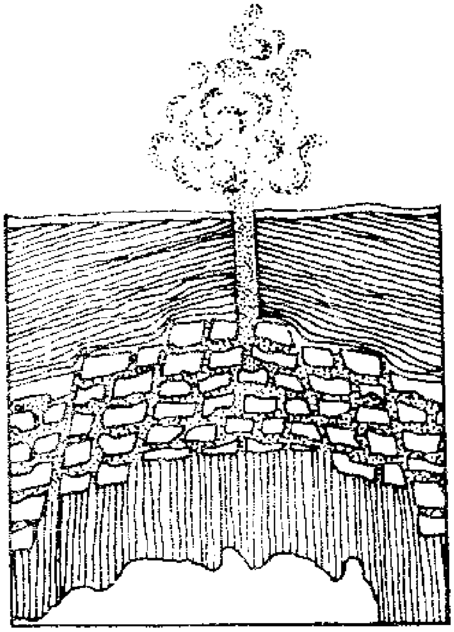
GEOTHERMAL RESOURCES FOR AQUACULTURE

Proceedings of a workshop, Boise, Idaho December 13-15, 1977

Sponsored by:
Pacific Sea Grant Advisory Program
Oregon State University
University of Idaho



OREGON STATE UNIVERSITY
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acknowledgment

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GEOTHERMAL RESOURCES: WHAT AND WHERE THEY ARE

GEOTHERMAL RESOURCES: AND AQUACULTURE

Introduction

Geothermal sites in the United States' Pacific Northwest may represent useful locations for commercial freshwater aquaculture. Awareness of this opportunity stems from the research observation that warmed water increases growth rates of certain species of fish and shellfish, and from the fact that some of these geothermal sites have already been tapped for electric power generation and other uses.

Geothermal aquaculture projects are underway at several levels, through private enterprise and through universities. Considerable interest beyond these existing attempts prompted the convening of the workshop whose proceedings are published herein. Participants included fish farmers, biologists, engineers, economists, planners, lawyers, food scientists, and educators, representing government agencies, industries, and the universities.

Workshop participants sought consensus on the initial potential of geothermal aquaculture for commercial success. Questions addressed included: what species can or should be produced; what biological constraints exist through nutrition, disease, or husbandry; and what engineering, economic, marketing, or institutional and legal problems must be solved. Research, training, and advisory needs were identified and priorities described.

We hope that these workshop proceedings will lead to further discussion on the potential of geothermal resources for aquaculture, and anticipate that such discussion will perhaps stimulate additional commercial opportunities in this field.

William Q. Wick, Director
Sea Grant College Program
Oregon State University

Geothermal resources: what and where they are

Geothermal energy: overview

by Gordon M. Reistad
Associate Professor
Department of Mechanical Engineering
Oregon State University

INTRODUCTION

Geothermal energy is the heat energy that exists within the earth's crust. This crustal heat does not represent the thermal energy remaining from the earth's origin. Calculations have shown that the earth, once completely molten, would have cooled and become solid many thousands of years ago were there not an energy input in addition to that from the sun. Many now believe that the ultimate source of geothermal energy is radioactivity, which is still active throughout the earth's crust. Through phenomena such as plate motion and volcanism, some of this energy has become concentrated at relatively high temperatures near the earth's surface. Also, some of this energy travels to the surface at relatively uniform levels by conduction through the crust.

CATEGORIES AND LOCATIONS OF THE RESOURCE

The United States Geological Survey distinguishes between "geothermal resource base" and "geothermal resources." These are defined as:

1. Geothermal resource base: all of the stored thermal energy above 15°C to 10 km depth in all 50 states.

2. Geothermal resources: all of the stored thermal energy, both identified and undiscovered, that is recoverable using current or proposed technology, regardless of cost. The geothermal resources are further divided into three categories, based on the cost of recovery:

a. Submarginal geothermal resources, recoverable only at a cost that is more than two times the current price of competitive energy systems;

b. Paramarginal geothermal resources, recoverable at a cost between one and two times the current price of competitive energy; and

c. Geothermal reserves, consisting of those identified resources that are recoverable at a cost competitive now with other commercial energy sources.

Table 1 shows the various categories of the geothermal resource base, which is described in the following sections.

	Temperature Characteristics	Natural Fluid Supply
1. Hydrothermal convection systems (relatively high temperatures at shallow depths; heat content estimated only to 3 km depth)		
a. Vapor-dominated systems	<240°C	Available; not always adequate.
b. Hot water systems		
(1) High-temperature systems	>150°C	Available; not always adequate.
(2) Intermediate-temperature systems	150°C to 90°C	Available; not always adequate.
(3) Low-temperature systems	<90°C	Available; not always adequate.
2. Hot igneous systems (excluding hydrothermal convection systems in (1) above; heat content estimated from 0 to 10 km depth.		
a. Assumed part still molten	>650°C	Inadequate.
b. Assumed not molten, but very hot ("hot dry rocks")	<650°C	Generally inadequate.
3. Conduction-dominated areas (by heat-flow provinces, utilizing available data on heat flows, radiogenic heat production, and thermal conductivity of rocks; heat contents estimated for 0 and 3 and 3 to 10 km depth; see Diment and others, this volume. This category includes the Gulf Coast geo-pressured environment with its fluid fraction.	15° to ~300°C	Adequate in parts of sedimentary basins, generally inadequate elsewhere.

Table 1. Categories of geothermal resource base (heat in the ground at temperatures above 15°C to specified depths and without regard for recoverability). (White and Williams 1975)

Hydrothermal Convection Systems

In hydrothermal convection systems, most of the energy is transferred by the convective circulation of water or steam in an aquifer rather than merely by conduction through solid rock. Convection occurs in permeable rocks because of the buoyancy effect of heating and the consequent thermal expansion of fluids in a gravity field. These systems are classified as either vapor-dominated or hot-water types depending on the temperature and pressure characteristics of the aquifer.

Vapor-Dominated Systems: The vapor-dominated systems have a temperature at depth that is higher than the saturation temperature of the aquifer's pressure. Because of this, a large portion of the aquifer is filled with steam. The basic elements of a vapor-dominated system, shown in Fig. 1, are (1) a high temperature body of rock at depth, (2) a relatively permeable layer of crust material that contains the aquifer, and (3) a cap rock.

The vapor-dominated systems are the most desirable because the energy can be readily extracted and used. Only three such systems have been identified in the United States, at the Geysers in California, Yellowstone National Park and Mt. Lassen National Park. The Geysers is currently in commercial development for generation of electricity, but the resources at Yellowstone and Mt. Lassen will most likely not be developed for energy in the near future.

Hot-Water Systems: These systems, although not quite as desirable as the vapor-dominated type, are more numerous and are expected in the short run to provide the most energy. Circulating liquid, which transfers most of the thermal energy, dominates hot-water systems. However, some vapor may occur, generally as bubbles dispersed in the water of the shallow, low-pressure strata of these systems. Hot-water systems can be found in geological formations similar to those of vapor-dominated systems (Fig. 1), or, particularly for lower temperature systems, may occur in like formations that do not have a capping structure, as shown in Fig. 2.

The Geological Survey has identified hot-water systems in the United States. Fig. 3 shows the locations of those systems that have temperatures greater than 150°C while Fig. 4 shows the locations for those with temperatures less than 150°C. These identifications are quite preliminary, and much exploration is needed to make good estimates of the temperatures, sizes, and recoverability of the resources.

Hot-Igneous Systems

This category of resource represents thermal energy in the hot materials, either molten or solid, that are associated with relatively recent or active volcanism. The Geological Survey has separated the overall category into (1) still molten and (2) not molten, but very hot. There are efforts underway to develop the technology for tapping these sources, but both present difficult problems, and commercial development of either appears to be quite a long way off.

Tapping the nonmolten, very hot material is more feasible of the two technologies, and current research is concentrating on this. Los Alamos Scientific Laboratory has undertaken most of this research work. Fig. 5 shows conceptually the laboratory's "dry hot rock" project. Two boreholes will be drilled to substantial depth into very hot rock. By injecting water first at very high pressures, hydraulic fracturing of the rock may occur so that the thermal energy can be recovered from it. Subsequently introducing cool water for heating into contact with the hot rock at the lower part of the fractured area could cause thermal stresses and increase the fractured area, providing additional heat transfer. Fig. 6 shows the areas in the United States that are promising for such systems.

Conduction-Dominated Systems

Throughout the earth's surface, wherever hydrothermal-convective or hot-igneous systems do not occur the energy flow from deep within the earth is dominated by conduction, and the temperature increases approximately linearly with depth. The average temperature gradient is about 10°C per kilometer of depth, with ranges of from 5° to 50°C/km in different regions. Fig. 7 compares conduction-dominated systems having various temperature gradients with some convective systems. For the average temperature gradient, drilling would have to penetrate very great depths for temperatures comparable to those of convective systems. This puts conduction-dominated systems at a great disadvantage since drilling costs rise rapidly with increasing depth. On the other hand, conduction-dominated systems that have a temperature gradient of 30° to 50°C/km, or 3 to 5 times the average, can provide temperatures comparable to those of

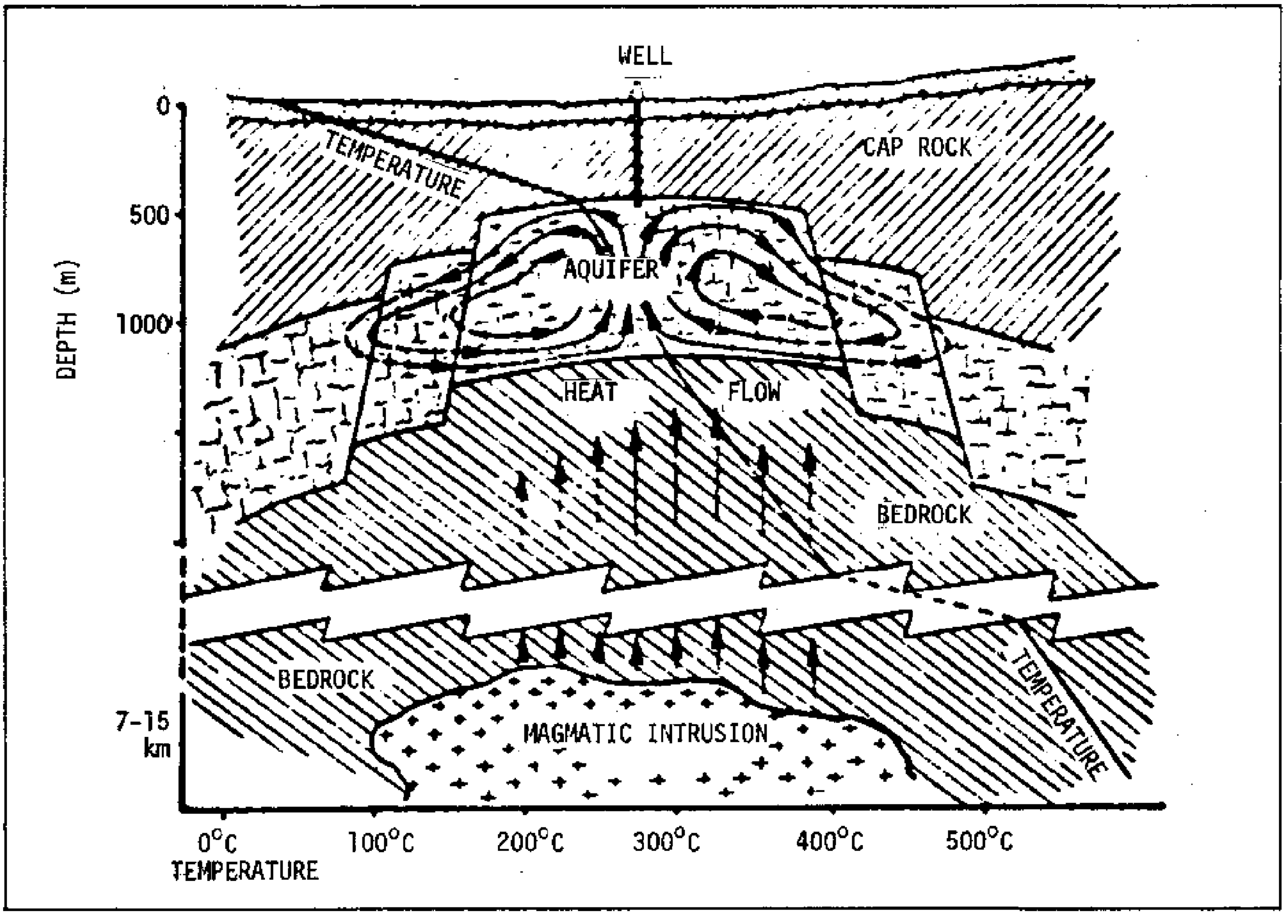

Fig. 1. Basic model of a steam field. (Facca, 1973)

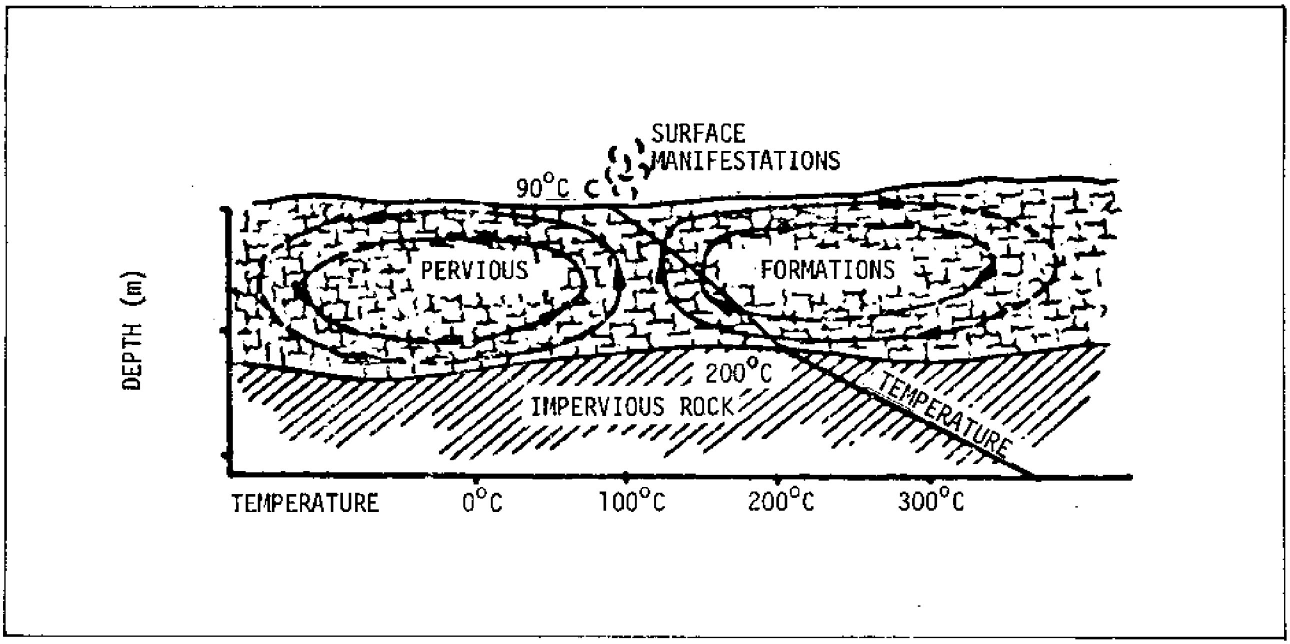

Fig. 2. Basic model of a low temperature hot water field. (Facca, 1973)

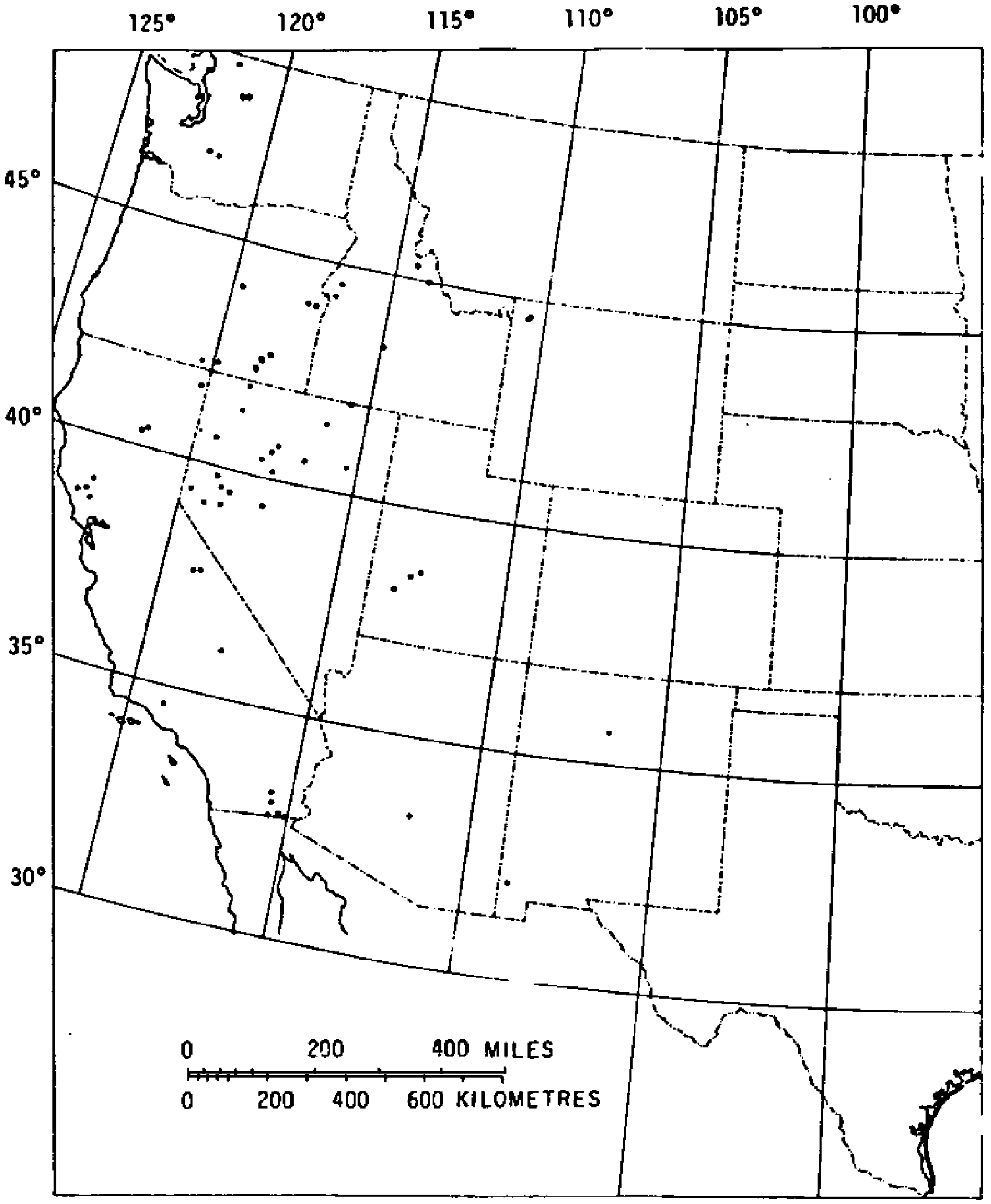

Fig. 3. Location of hydrothermal convection systems in the conterminous United States with indicated subsurface temperatures above 150°C. (White and Williams, 1975)

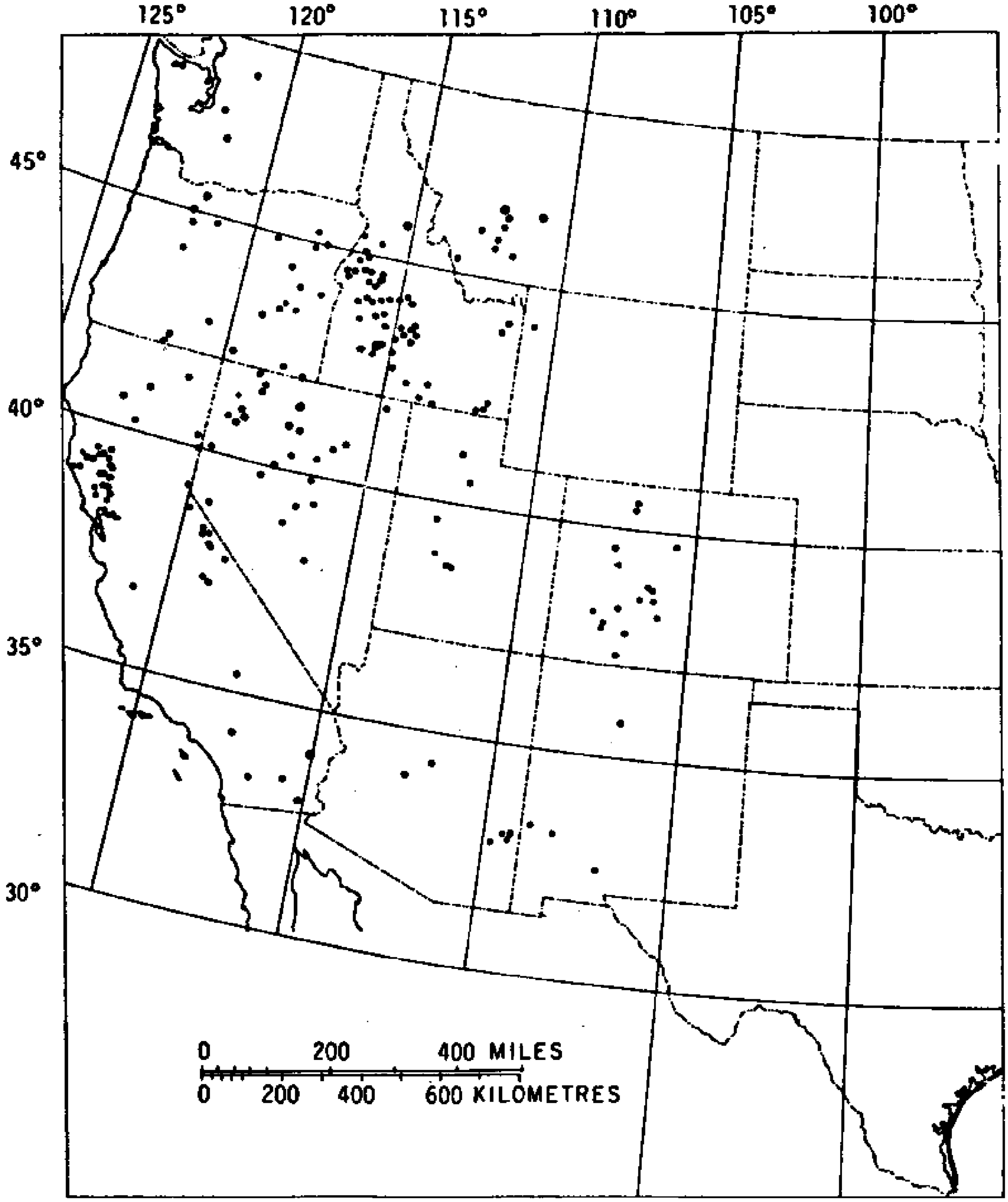

Fig. 4. Location of hydrothermal convection systems in the conterminous United States with indicated subsurface temperatures between 90° and 150°C. (White and Williams, 1975)

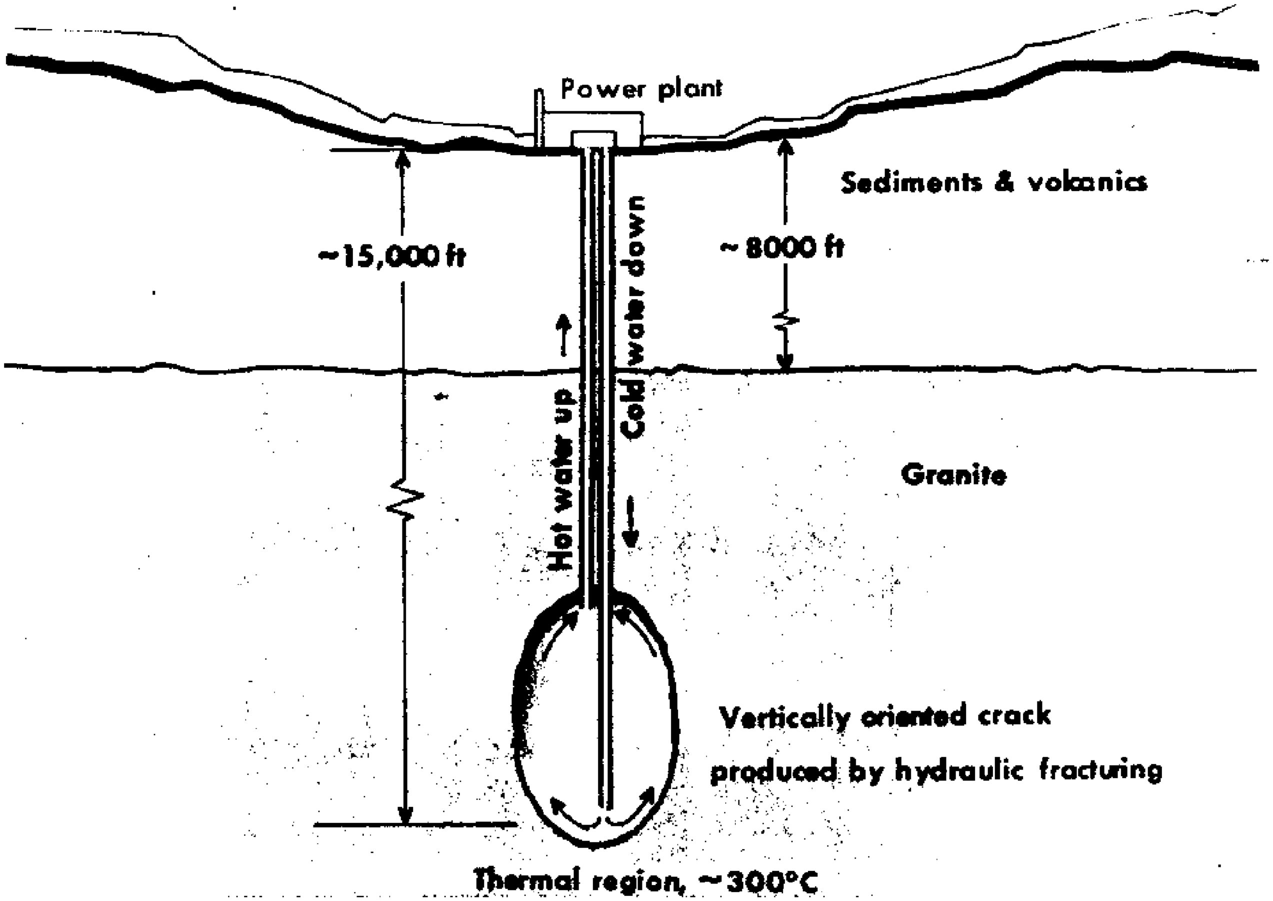

Fig. 5. Typical pressurized-water circulation loop for energy extraction in the western United States. (Smith, 1974)

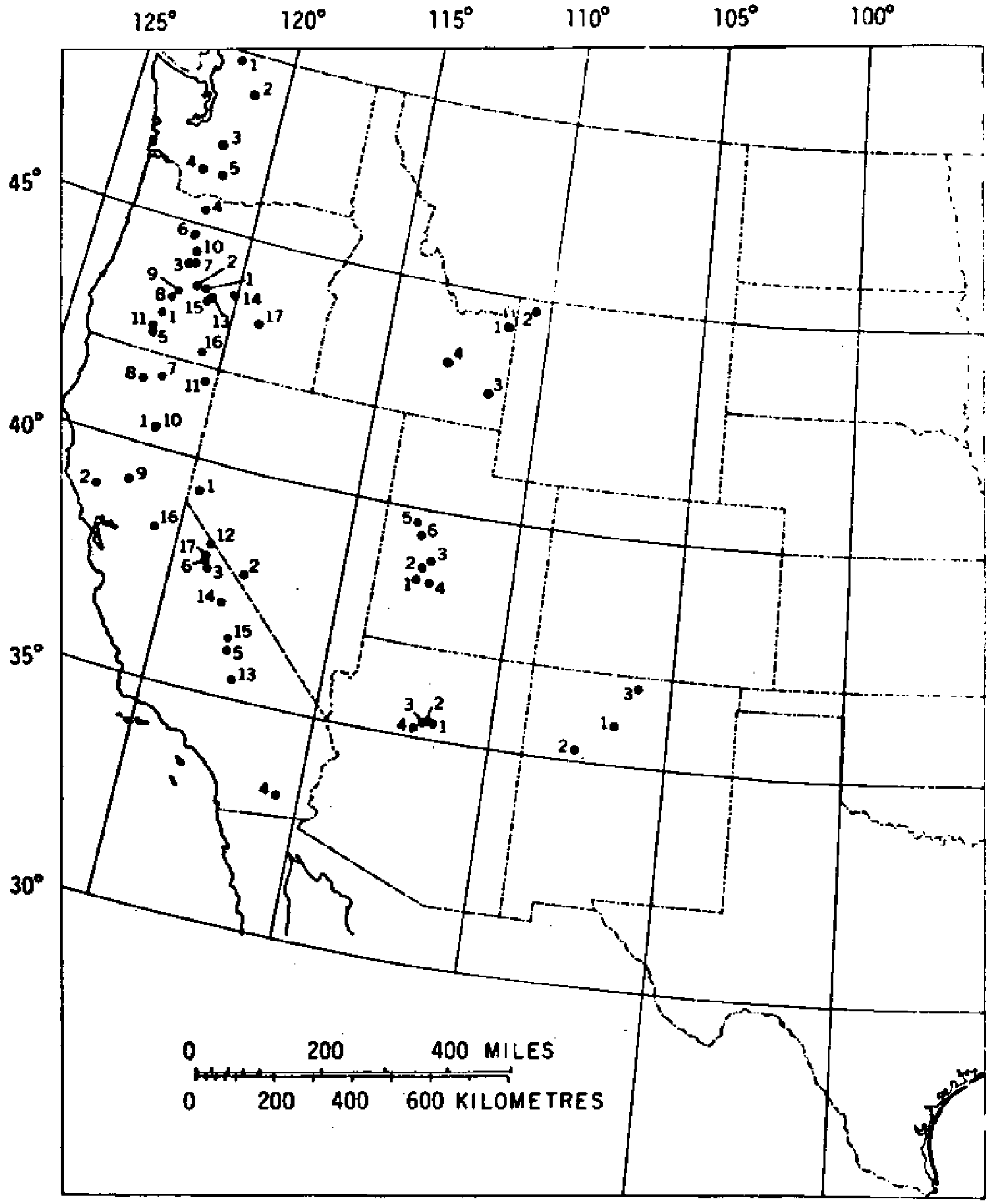

Fig. 6. Identified volcanic systems in the conterminous United States. Numbers are the same as in Table 7. (White and Williams, 1975)

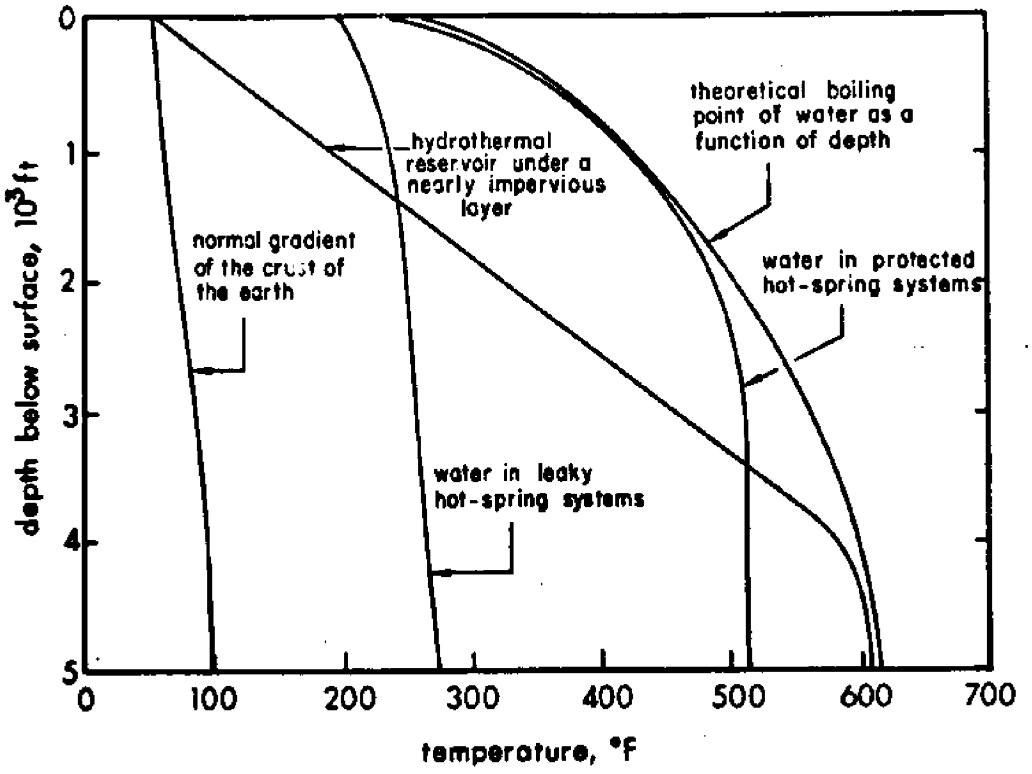

Fig. 7. Representative temperature-depth profiles for hydrothermal-energy reservoirs. (Penner, 1974)

convective systems at reasonable depths. Conduction-dominated systems would have to be tapped in a similar manner to dry hot rock systems, and little effort is at present directed to these lower temperature resources. Fig. 8 shows large crustal regions in the United States that are cooler, hotter, or about average in temperature.

This category includes both the overall conduction-dominated systems that occur throughout the earth's surface, as well as what is termed the "geopressured resource," a special type of conduction-dominated system that exists along the Gulf Coast (Fig. 9). An aquifer at depth within a conduction-dominated zone contains water at very high pressure and quite high temperature. Energy can be extracted from the fluid because of both its thermal energy and its high pressure. The fluid also contains dissolved natural gas, which when recovered greatly improves the projected economic picture for this resource.

UTILIZATION

The only geothermal resource currently used on a commercial scale is the hydrothermal convection system. Both the vapor-dominated and the hot-water systems are at present providing energy.

The inherent characteristics of geothermal energy prevent its efficient transportation over long distances. As a result geothermal energy has been put to two types of uses:

1. Electricity generation--the electricity can be generated at the geothermal site and either used locally or transmitted to other areas;

2. Non-electrical uses--the geothermal energy is used for some sort of heating in a relatively small region around the geothermal site.

Generation of Electricity

The worldwide electrical production from geothermal resources is shown in Table 2. Compared to the total U.S. generation, geothermal production represents the output of one to two large nuclear power plant installations. Generation of electricity from vapor-dominated geothermal systems resembles conventional power generation, since the geothermal fluid is steam. Differences particular to the geothermal resource are (1) minor scaling and corrosion; (2) minor erosion; (3) noncondensible gases that must be purged; and (4) environmental problems, most of which can be easily handled.

Electrical generation from hot-water systems is not quite so straightforward, and substantial research is currently underway to determine the best methods under varying conditions of temperature and fluid quality. In general, electrical power production seems not economically feasible at temperature below about 150°C.

Nonelectrical Uses

Many needs for thermal energy can be met within the temperature range available from geothermal resources. Table 3 lists many such potential uses. Fig. 10 shows the temperature range required for typical processes, and Fig. 11 shows that portion of the U.S. energy consumption required for a certain process at a particular temperature level. These figures show a great market potential for nonelectrical use of geothermal energy, but do not consider the need's location relative to that of the resource. Little work to date has explored how large a market for thermal energy might exist near geothermal resources, and thus how much of the total thermal energy required could feasibly be supplied by geothermal energy. Current nonelectrical uses of energy from geothermal resources worldwide are:

Agricultural	5400 Megawatts (MW)
Residential and Commercial	350 MW (avg) & 700 MW (peak)
Industrial	200 MW (avg)

This total represents about 3 to 4 times the current electrical production from geothermal resources.

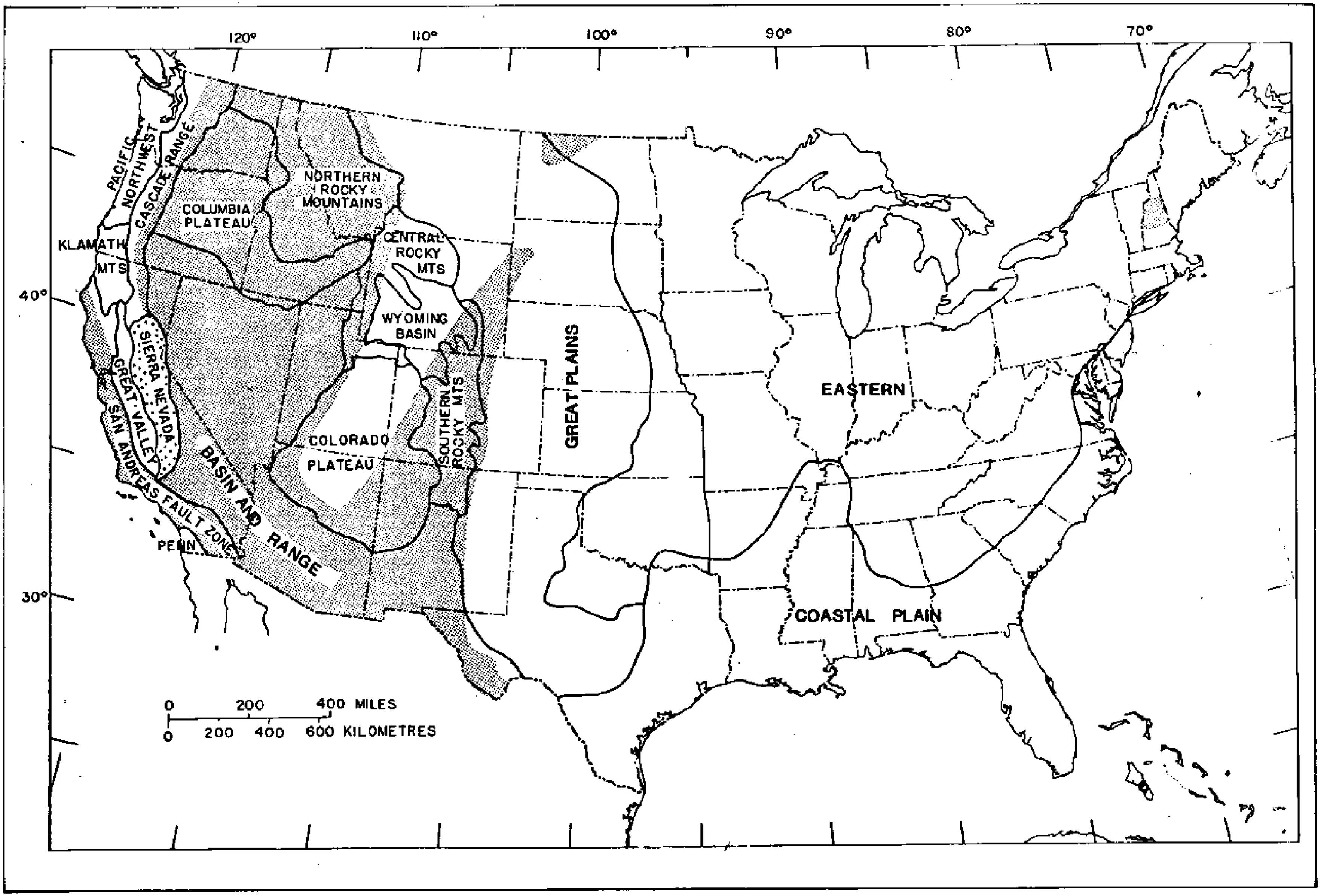

Fig. 8. Map showing probable extent of hot (stippled), normal (white), and cold (dotted) crustal regions of the United States based on data in Figs. 9 and 10. Physiographic provinces (largely generalized from Fenneman (1946)) do not necessarily represent heat-flow provinces. (White and Williams, 1975)

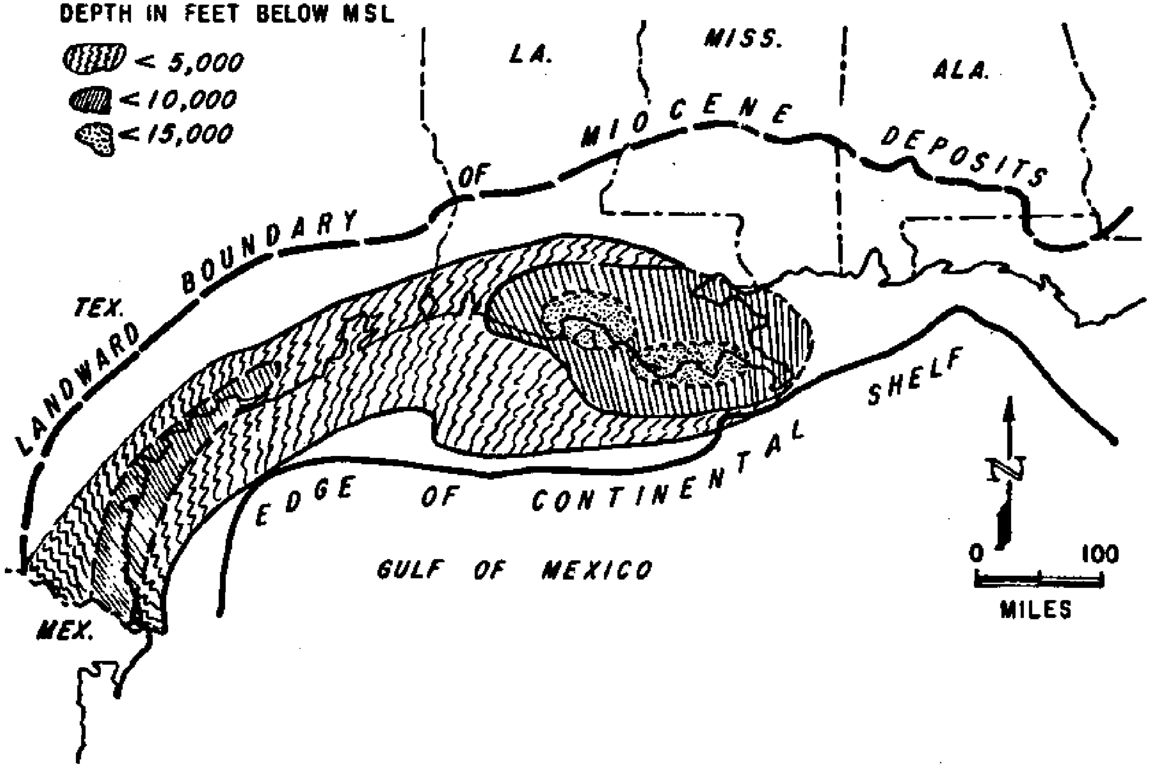

Fig. 9. Geopressured zone in neogene deposits northern Gulf of Mexico basin. (Dorfman, et al. 1975)

Country	Field	Operating (MW)	Planned (MW)
Iceland	Namafjall	2.5	55
Italy	Larderello	358.6	
	Mt. Amiata	25.5	
Japan	Matsukawa	20	
	Otake	13	
Mexico	Pathe	3.5	
	Cerro Prieto	75	75
New Zealand	Wairakei	160	
	Kawerau	10	
United States	Geysers	522	55
U.S.S.R.	Pauzetka	5.	
	Paratunka	0.7	
Total		1195.8	185

Table 2. World geothermal power production. (Howard 1975)

1. RESIDENTIAL AND COMMERCIAL
    - A. Space heating and cooling
    - B. Water (potable, hot/cold utility, etc.)
    - C. Waste treatment (disposal, bioconversion, etc.)
    - D. Refrigeration
    - E. Deicing
    - F. Total energy systems (e.g., cascade utilization)
2. AGRICULTURE AND RELATED AREAS
    - A. Crops (greenhouses, hydroponics, heated soil, etc.)
    - B. Animal husbandry (cattle, pigs, chickens, etc.)
    - C. Aquatic farming (fish breeding, hatching, growing, etc.)
    - D. Processing of agricultural products (waste disposal or conversion, drying, fermentation, canning, etc.)
3. INDUSTRIAL PROCESSES
    - A. Chemical production (acids, fertilizer, fuel, etc.)
    - B. Pulp treatment
    - C. Mining (heat, water)
    - D. Drying (cement, clay, fish, etc.)
    - E. Water desalination/distillation
    - F. Mineral recovery from hydrothermal fluid
    - G. Waste treatment and disposal

Table 3. Nonelectrical uses of geothermal resources. (Howard 1975)

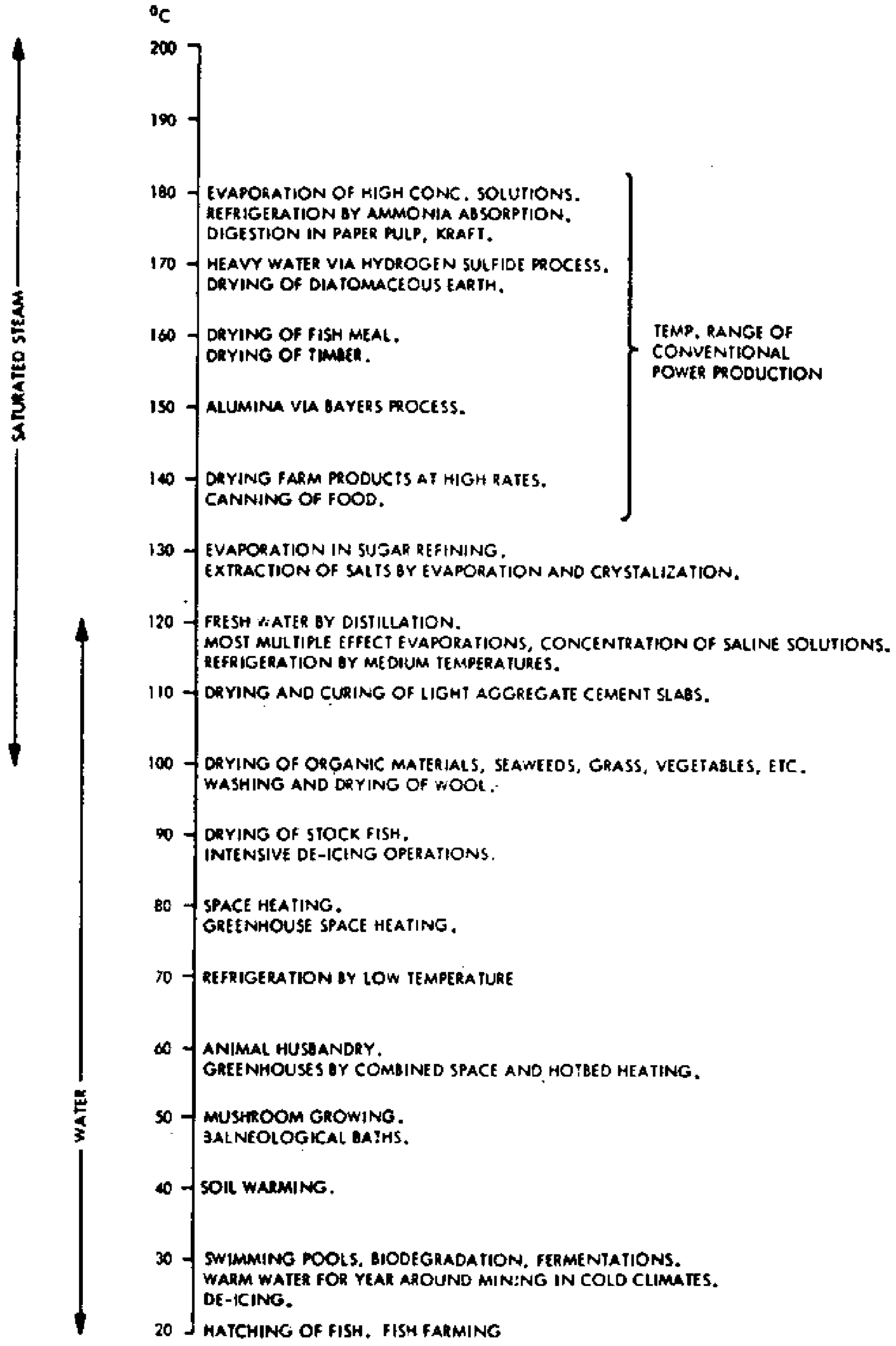

Fig. 10. Required temperature of geothermal fluids for various nonelectrical applications. (Lindal, 1973)

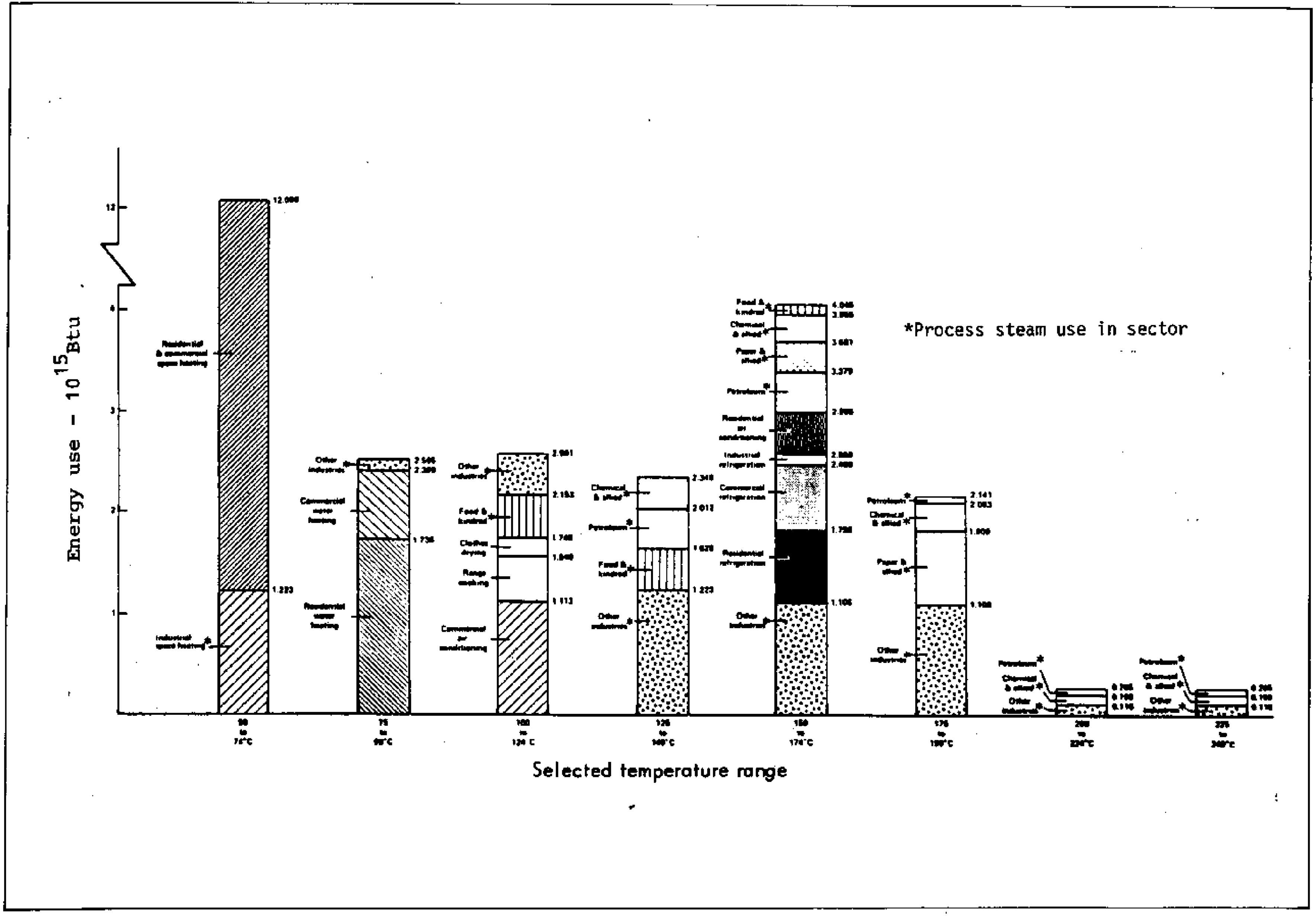

Fig. 11. Estimated heating energy use in selected 25°C temperature ranges in the United States. (Reistad, 1975)

MAGNITUDE AND EXPECTED USE

In the fall of 1975, the U.S. Geological Survey released tentative estimates of the magnitude of the geothermal resource base and the various classifications of geothermal resources. Table 4 shows the estimate for the resource base of thermal energy in the ground, without regard to its recoverability. The column labelled "Identified and Estimated for Undiscovered" must necessarily be regarded as questionable, since it represents a four-fold increase relative to identified resources.

Table 5 shows the Geological Survey's estimate of hydrothermal convection resources, for which "reserves" are economically recoverable now. Electrical generation from identified reserves for the high temperature systems is estimated at 11,700 Megawatts (MW) for 30 years. The paramarginal resources, which will cost between 1 and 2 times current levels, are estimated at the same magnitude. The submarginal resources and undiscovered resources add to these estimates by about 130,000 MW for 30 years. The total for discovered resources of lower temperature systems which would probably be used for nonelectrical requirements is equivalent to about 92,000 MW for 30 years, and undiscovered resources are estimated at 3 times as much. As indicated, the technology for hot-igneous and conduction-dominated systems has not yet been proven, so an estimate of the resources is not appropriate.

Table 6 shows the estimated deployment schedule as of August 1975 for electricity production from geothermal energy, according to a group of U.S. geothermal experts. The hydrothermal resource would contribute an electrical output of between 7,000 and 50,000 MW by the year 2000, while the geopressured resource and the dry hot rock could contribute as much as an additional 13,000 MW of electricity if the technology to exploit them comes of age. The range of 7,000 to 63,000 MW represents 1.5 to 13 percent of the 1975 electrical generating capacity in the United States. By the year 2000, this capacity is projected to increase about 2 times. Thus, the 7,000 to 63,000 range represents about 1 to 6 percent of the anticipated electrical generation capacity in the year 2000. No projection was made for nonelectrical uses, though a total of similar magnitude to that of electrical generation was considered a reasonable estimate. Table 7 presents a history of geothermal electrical power forecasts for 1985. These forecasts show that the estimates given in Table 6 are perhaps slightly optimistic, but are certainly in the correct range.

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	Identified Systems		Identified + estimate for undiscovered
	Number	Heat Content 10^{18}cal[1]	Heat Content 10^{18}cal[1]
1. Hydrothermal convection systems (to 3 km depth, ∿10,000 ft, near the maximum depth drilled in geothermal areas).			
Vapor-dominated (steam) systems	3	26	∿50
High-temperature hot-water systems (over 150°C)	63	370	∿1,600
Intermediate-temperature hot-water systems (90° to 150°C)	224	345	∿1,400
Total	290	∿741	∿3,050
2. Hot igneous systems (0 to 10 km)			
Molten parts of 48 best known, including Alaska and Hawaii		∿13,000	
Crystallized parts and hot margins of same 48		∿12,000	
Total		∿25,000	∿100,000
3. Regional conductive environments (0 to 10 km; all 50 states subdivided into 19 heat-flow provinces of 3 basic types, Eastern, Basin-and-Range, and Sierra Nevada).			
Total, all states		∿8,000,000	∿8,000,000
Overall total (as reported)		8,025,741	8,103,050

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[1] 10^{18} calories equivalent to heat of combustion of ∿690 million barrels of petroleum or ∿154 million short tons of coal.

Table 4. Estimated heat content of geothermal resource base of the United States (heat in the ground, without regard to recoverability). (White and Williams 1975)

	Heat in ground 10^{18}cal 1/	Heat at well-head 10^{18}cal 2/	Conversion efficiency	Beneficial heat 3/ 10^{18}cal	Electrical energy MW•cent 4/	MW for 30 years 5/
High-temperature systems (>150°C; for generation of electricity)						
Identified resources	257	64	0.08 to 0.2			
Reserves					3,500	11,700
Paramarginal resources					3,500	11,700
Submarginal resources					>1,000 6/	>3,300 6/
Undiscovered resources	1,200	300	0.08 to 0.2		38,000 7/	>126,700 7/
Intermediate temperature systems (90° to 150°C; mainly nonelectrical uses)						
Identified resources	345	86	0.24	20.7		
Undiscovered resources	1,035	260	0.24	62.1		
TOTAL	2,837	710		82.8	46,000	153,400

1/ 10^{18}cal (a billion-billion calories) is equivalent to heat of combustion of 690 million barrels of oil or 154 million short tons of coal.

2/ Assumed recovery factor 0.25 for all convective resources.

3/ Thermal energy applied directly to its intended thermal (nonelectrical) use; 10^{18}cal of beneficial heat, if supplied by electrical energy, would require at least 1,330 MW•cent (or 4,400 MW for 30 years); however a user of this geothermal energy must be located or must relocate close to the potential supply; insufficient data available to predict demand or to subdivide into reserves, paramarginal, and submarginal resources.

4/ Unit of electrical energy; 1 MW-cent is equivalent to 1000 KW produced continuously for 100 years.

5/ Assumes that each MW•cent of electricity can be produced at rate of 3.33 MW for 30 years.

6/ Small because of exclusion of systems with temperatures below 150°C.

7/ Perhaps as much as 60 percent will be reserves and paramarginal resources; costs of discovery and development are more speculative than for identified resources.

Table 5. Geothermal resources of hydrothermal convection systems assumed recoverable with present and near-current technology and without regard to cost. (White and Williams 1975)

	1985	2000
Hydrothermal	2,500 - 5,000 MW	7,000 - 50,000 MW
Geopressured	-	0 - 3,000 MW
Dry Hot Rock	0 - 100 MW	0 - 10,000 MW
Total	2,500 - 5,100 MW	7,000 - 63,000 MW

Table 6. Estimated geothermal electric power capacity. Not included is the contribution of direct thermal energy applications, which might equal or exceed the electric energy applications. (Kruger et al. 1975)

SOURCE	CAPACITY (MWe)
University of Alaska, Seattle Conference September 1972	182,000
U.S. Department of the Interior, U.S. Energy Through 2000, December 1972	Not Considered
National Power Commission, U.S. Energy Outlook, December 1972	3,500-19,000
Federal Energy Administration, Project Independence, November 1974	20,000-30,000
Energy Research and Development Administration National Plan, June 1975	10,000-15,000
Oregon State University, Portland Conference, July 1975	2,500-5,000
Energy Research and Development Administration, Definition Report, October 1975	6,000
U.S. Department of Energy, U.S. Energy Through 2000, (Rev.) December 1975	3,000
Nuclear Energy Research Commission, Electric Utility Generation, June 1976	2,078

Table 7. History of geothermal power forecasts: Electricity generating capacity for 1985. (Kruger et al. 1977)

Geothermal resources and the energy industry

by Paul H. Howe
Northwest Natural Gas Company

Between 1960 and 1970, the United States' population increased by 12 percent. During this period, the nation's energy requirements increased by more than 41 percent and natural gas consumption by more than 50 percent. Maintaining an adequate energy supply depends upon conservation, new energy sources, and efficient use of all forms of energy, including oil, natural gas, hydroelectricity, solar and nuclear power, coal, and geothermal energy.

The Northwest has an adequate natural gas supply for years to come; however, 70 percent of the gas comes from Canadian fields. More than half of our oil supply is imported, mostly from the OPEC countries.

Geothermal energy will not eliminate the need for additional supplies of natural gas or oil, but it could potentially take over the lower range of temperature applications, perhaps amounting to as much as one-fifth of our total heating load.

In September 1977, Northwest Natural Gas Company began preliminary explorations in the Old Maid Flat area west of Mt. Hood, Oregon, to determine the existence and availability of geothermal hot water that might be transported by insulated pipeline to the Portland metropolitan area as a new and more economical source of heat. The initial hole reached a depth of almost 1,900 feet before operations were suspended for the winter. The initial well will probably be deepened when drilling operations are resumed in the spring of 1978. John Hook, consulting geologist, reported that the initial bottom hole temperatures in the well were above 38°C and termed the indicated temperature gradients thus far as "very favorable."

In order to make such an energy project economically feasible, three conditions are necessary:

1. The existence of a large and relatively inexhaustible subterranean geothermal water table;

2. A sustained wellhead water temperature of at least 74°C; and

3. A relatively high degree of water purity and potability.

If we made a favorable discovery that meets these three conditions, we would undertake more detailed marketing and feasibility studies before drilling additional exploratory wells. A third phase envisions the physical construction of a large insulated pipeline (42 to 48 inches in diameter) to transport the water to industrial and residential heating needs in the Portland area.

We anticipate a fourth phase, perhaps two or three years following the completion of the first line, particularly in the event that fossil fuel energy supplies diminish and energy costs continue to escalate. Looping of the original line with one or more additional lines would enable us to enlarge the customer load substantially. Because of the reduced temperature extraction possible in domestic applications, and because of the heavier investment costs necessary in a dual pipe street distribution system, the present economics of 74°C geothermal water appear to be marginal for domestic use at this time. Delivered costs at today's prices would run in the neighborhood of 20¢/therm. However, should available water temperatures be found higher than 93°C, the project would become extremely attractive even for domestic applications.

The thermal capacity of a 48 inch line, even with the limitations of 13°C heat extraction, is substantial. On an annual basis, however, a major geothermal resource could provide enough heat to serve about one-fifth of our residential customers.

While the precise identification of our application needs further refinement, we would expect the wood products and food processing industries to account for a major portion of our initial target loads. However, any industry that uses hot water below 65°C could potentially be considered for geothermal water applications. Over and above these industrial loads, some demonstration residential space-heating projects would be initiated, involving both existing homes as well as new subdivisions. This technology has been proven in Iceland, Klamath Falls, Oregon, and elsewhere. If the resource exists as outlined here, the success of the project becomes extremely predictable.

Northwest Natural Gas Company operates over 10,000 miles of underground system and presently services over 218,000 gas customers. The Company has also been recently involved in gas exploration within the State of Oregon; hence, I consider the Company to be well-qualified to participate in this venture.

Geothermal resources and aquaculture

Overview

by **William J. McNeil**
Oregon Aqua-Foods, Inc.

INTRODUCTION

Several recent trends are influencing new initiatives in fisheries development programs:

1. The world fisheries harvest has stagnated in recent years at about 70 million metric tons annually, despite increased fishing effort.

2. As world demand for fisheries products continues to grow, many nations are declaring exclusive jurisdiction over management of marine food resources in extended territorial waters.

3. Costs of harvesting natural stocks of fish and shellfish are escalating, mostly owing to the cost of energy.

4. The market price of fish and shellfish has increased at a more rapid rate than the price of farm animal products.

Many fishery products, once staples, have become luxury food items. Pacific salmon is a good example; per capita consumption has declined steadily in the United States during the past several decades. Because the market economics of fishery products are changing, traditional attitudes toward harvesting fish and shellfish by hunting are shifting more and more toward fish farming or aquaculture.

Approximately 10 percent of the world supply of food fish and shellfish is currently supplied by aquaculture. Statistics reveal that world aquaculture production has doubled in the last five years. How long this rapid growth can be sustained is uncertain, but several countries, such as Japan, China, and the USSR are emphasizing aquaculture. The U.N. Food and Agriculture Organization (FAO) projects that production of fish and shellfish through aquaculture will increase approximately sevenfold by the year 2000, while "hunting" fisheries will increase only marginally, if at all.

Aquaculture in the United States is lagging well behind the world trend, and accounts for only 3 percent of U.S. fishery production. Lack of national policy and government support or leadership has impeded domestic development of aquaculture. However, Congress is at present considering legislation that would create a National Aquaculture Organic Act to establish public policy for aquaculture and to provide resources to stimulate other aquaculture. Other legislation has given the U.S. Department of Agriculture increased responsibility for aquaculture. The National Oceanic and Atmospheric Administration (NOAA) has also proposed a national plan for aquaculture, and the National Academy of Sciences has underway a nationwide study of aquaculture. Because of these and other initiatives, a national aquaculture policy will undoubtedly begin to unfold within the next several years.

ROLE OF HEAT IN AQUACULTURE

Because body temperature of fish and shellfish corresponds to the ambient water temperature, metabolic processes, including growth, are controlled by the water temperature. Optimum temperatures for growth can vary somewhat among stages of development among species, and among genetic stocks within a species. Even species that tolerate temperatures near freezing commonly exhibit little growth unless exposed to warmer temperatures.

Zones of temperature tolerance can be defined in terms of survival, growth, and reproduction. Salmon can typically survive in temperatures ranging from near freezing to perhaps 24°C, depending on species and acclimatization. Salmon and trout can grow within a temperature range of 40°C to 20°C with adequate food, but growth is slow below 10°C regardless of the amount and quality of food provided. Reproduction occurs in a much narrower temperature range, from 5°C to 13°C.

When raised in environments in which temperature, food rations, and other factors can be regulated, fish and shellfish can express rapid growth and high efficiency of feed conversion to usable protein. Sockeye salmon have been grown in laboratory tanks from small fry weighing only 1/1000 of a pound to robust, one-pound fish in six months--a doubling of weight every eighteenth day, on the average--when water temperature is maintained near 15°C. Other fish and shellfish species, including oysters and shrimp, exhibit similar growth responses to controlled temperature regimes.

Temperature affects aquacultural systems beyond just the physiological responses of fish and shellfish to their environment. As temperature increases, fish and shellfish activity increases, placing increased demands on dissolved oxygen supply. However, the availability or saturation level of oxygen in the water decreases as temperature increases. Thus the carrying capacity of an aquacultural facility, expressed as weight of organisms per unit volume or flow of water, declines with increasing temperature.

SOURCES OF HEAT FOR AQUACULTURE

Heat for aquaculture can come from a variety of sources. These include:

1. Production of heat on site for specific aquacultural operations.

2. Reuse of waste heat from industrial processes.

3. Reuse of waste heat from thermal power generating stations.

4. Capture of heat from geothermal and ground water sources.

Production of heat from fossil fuels or other energy sources specifically for aquacultural applications is probably limited for the most part to small-scale research or pilot projects. The escalating cost of oil has greatly reduced the economic feasibility of this convenient source of energy. Use of solar energy is largely experimental and limited to certain geographic locations that possess the proper climate.

Reuse of waste heat from industrial processes is finding application in aquaculture, and this practice seems destined to grow. The Weyerhaeuser Company has under construction in Oregon a large salmon hatchery that will use up to six million gallons per day of heated water from a forest products industrial complex to accelerate growth of juvenile salmon. The Weyerhaeuser program seeks to reduce by one year the time required to grow coho salmon to smolt size for release into the ocean.

Reuse in aquaculture of waste heat from

thermal power generating stations has been a popular topic for at least a decade. Some initiatives have been made in the United States, but most have been on a pilot scale. Other countries, including the United Kingdom and Japan, have undertaken commercial operations, primarily with marine fish and shellfish. Speculation on potential use of waste heat from nuclear power plants has been slackened considerably, because U.S. regulatory agencies consider such applications to be a hazard to human health.

USE OF GEOTHERMAL WATER IN AQUACULTURE

The term "geothermal water" describes the relatively warm water that flows naturally from deep reservoirs or is extracted from various subsurface sources such as steam and hot water reservoirs. These more conventional sources of geothermal water are not used as extensively in aquaculture as ground water, which also derives its temperature characteristics from the earth. To the extent that ground water temperature is modified by subterranean heat sources, ground water sources can be thought of as low-grade geothermal water, having temperature profiles characterized by relatively low and constant temperature.

The Idaho trout industry is one of the outstanding successes in U.S. aquaculture. Commercial growers in Idaho produce most of the domestically grown trout sold in the United States. The industry is sustained by an abundant supply of low-grade geothermal water flowing from large artesian springs. Natural water temperatures in the 10°C to 15°C range provide optimum environmental conditions for growing rainbow trout.

Additional low-grade thermal spring resources may be available for aquacultural applications in the United States. Some of these are known to exist in Alaska, at potential locations for salmon hatcheries (Forbes 1976). Relatively cold (15°C and lower) geothermal water of suitable quality can be used directly for raising cold-water fish such as trout and salmon. Warmer water might be usable for warm-water fish such as catfish, or might be tempered through dilution with cooler surface water for raising cold-water fish. If the geothermal waters are hot or contain toxic dissolved substances, heat exchange systems can be used to warm surface waters.

Geothermal sources currently contribute about 0.1 percent of the nation's electrical energy, but the potential exists for at least a modest increase in geothermal energy's contribution. Hot geothermal fluids for power generation are usually highly mineralized, and contain chemicals that are often toxic to aquatic organisms. Most applications of waste hot water in aquaculture would probably involve a secondary heat exchange system to avoid contamination of aquacultural water with mineralized geothermal fluids. Disposal of geothermal fluids after heat extraction can present difficulties, and these fluids are sometimes reinjected into the earth.

OTHER CONSIDERATIONS

In a social and economic context, aquaculture is an emerging industry. For only a limited number of species is the technology advanced enough to permit commercial operations. Even for established aquacultural technologies, investment and operation costs are high and profit margins are modest.

Use of heated water in aquaculture is economically feasible only if the cost of obtaining heat is low and the volume of heated water fairly large. Thus costly methods of obtaining heat from geothermal sources for direct application in aquaculture are not likely to be usable, at least in the near future. Waste heat from geothermal power generation systems might be used in aquaculture, provided heated water of adequate quality and adequate quantity can be made available as a low-cost by-product. Otherwise, geothermal heat for aquaculture will probably remain limited for some time to large artesian springs or wells drilled into shallow aquifers providing water of suitable temperature, large volume, and low cost.

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Biology and husbandry of organisms in geothermal aquaculture: *panel discussion*

Use of geothermal resources in aquaculture can have significant benefits for the biology and husbandry of organisms reared in aquacultural facilities, though a number of research needs exist. Geothermal resources may also have innovative applications in aquaculture.

BENEFITS OF GEOTHERMAL RESOURCES

Geothermally heated water allows the aquaculturist the capability of maintaining a constant, optimal environment for rearing aquatic organisms. Temperate species particularly, under naturally varying conditions, undergo fluctuating growth rates owing to seasonally varying water temperatures. Slowed growth rates in the colder seasons could be "tempered" with geothermal water, thus retaining maximum growth.

Geothermal aquaculture could minimize stress among the organisms and problems related to stress, such as fish and shellfish diseases. This potential means that at present goethermal resources could be most productively utilized in intensive rather than extensive aquaculture, making the most effective use of the resource to produce biomass. Also, depending on temperature and other characteristics of the geothermal source, the water supply may be free of disease-causing organisms.

Using geothermally heated water makes possible rearing an expanded array of organisms in geographic locations having natural conditions that might prohibit these species' survival. For instance, one grower is commercially raising catfish, tilapia, and bass in 27°C water in Colorado. The heated water can help in treatment of disease: raising the water temperature to 29°C-32°C controlled "Ick" in catfish. Thus, in terms of biology and husbandry, geothermal resources provide aquaculturists the benefits of: (1) maintaining an optimal rearing environment; (2) maximizing biomass production in intensive culture and minimizing some stress factors; (3) enlarging the array of organisms that can be reared, particularly in temperate climates; and (4) aiding some basic rearing techniques such as disease treatment.

RESEARCH NEEDS

Although growth can be maximized through the use of geothermal resources in intensive culture, little is known about the total energy budgets of aquatic organisms over a wide range of temperatures, and the effects of an altered temperature regime on the natural performance of aquatic organisms have for the most part not yet been determined. For instance, growth rate in salmon is at a maximum within a relatively narrow range of temperatures. This probably reflects changes (from growth to maintenance) in the allocation of the total energy available, as is characteristic of a poikilothermic animal.

For efficient aquaculture, we need to determine the temperatures at which food is most efficiently converted to fish flesh. Data is needed to identify growth curves, ration sizes, production functions, and energy budgets for organisms in aquaculture over a broader spectrum of temperatures. At present, such information is available for only a few species over a relatively narrow range of temperatures.

Information is also lacking on the response of aquatic animals to disease organisms under elevated temperatures. Concurrently, little is known concerning the physiological response and infectivity of common fish pathogens under such conditions. Further research should identify the responses of aquatic organisms to pathogens, and delineate the characteristics of pathogenic organisms in heated water.

The final major research need identified concerns the quality of water available, of particular importance when the geothermal resource is utilized directly in rearing. Often sources of geothermally heated water are highly mineralized or contain other chemicals noxious to aquatic organisms. If the levels of either minerals or chemicals are too high, engineering solutions must be found for removing the substances or constructing a heat exchange system. However, in marginal situations little information is available to guide the aquaculturist on the feasibility of direct use of water. Additional research is needed to determine how the minerals and other compounds found in geothermal sources affect organisms reared in aquaculture.

Thus we can identify three primary research needs related to biology and husbandry of organisms in geothermal aquaculture. (1) determine the energy budgets of organisms under a broader range of temperatures to specify the most efficient rearing conditions; (2) characterize the response of aquatic organisms to pathogens under elevated temperatures and define the physiological and infective characteristics of pathogenic organisms under these conditions; and (3) describe the interaction of aquatic organisms with minerals and chemical compounds found in geothermal water to determine the best method for using this water in aquaculture.

RELATED USES OF GEOTHERMAL RESOURCES

Several uses of geothermal resources are indirectly related to biology and husbandry of organisms, but could significantly affect an aquacultural operation. First, heated water could be used more completely by diverting it to some of the functions related to production of finished items, such as processing or operating storage facilities. This allows more complete use of the resource and decreases overhead costs.

A second suggestion for auxiliary uses of the resource concerned production of food organisms or cheaper sources of protein. Microorganisms (single-cell protein) represent good possibility for an inexpensive source of fish food protein. Water temperature increased through geothermal resources could make possible mass production of such organisms in aquacultural facilities, even in temperate climates. This heated water could be used in conjunction with other industrial by-products such as potato waste from processing plants, to grow a source of high quality protein. Also, some invertebrates such as daphnia, commonly used in aquacultural operations as food for fish, could be more effectively grown in large volumes of warmed water.

Finally, the feasibility of polyculture increases with the availability of geothermal water sources. Since the organisms currently considered most amenable to polyculture are tropical species, geothermal resources broaden the potential for this kind of operation. In addition, constant water temperatures make possible a relatively continuous supply of the aquatic plants and plankton necessary for fish lower on the food chain.

Thus geothermal resources could have several uses related to direct culture of organisms: (1) in processing and/or storage of finished products; (2) in the culture of cheaper sources of protein and/or other organisms as food for the primary species; and (3) in polyculture.

CONCLUSIONS

While a number of gaps exist in our knowledge of biology and husbandry in geothermal aquaculture, the problems of marketing and economics are the major limiting factors in the success of aquaculture in general and geothermal aquaculture in particular.

SHRIMP

The Malaysian prawn, *Macrobrachium rosenbergii* sp., has been the subject of aquaculture efforts in the United States for the past 10 years. Only a couple of aquaculturists have experimented with raising this shellfish in geothermal waters.

During the last two years, William Johnson, of Oregon Institute of Technology (OIT) in Klamath Falls, has been culturing *Macrobrachium* in geothermal water that has first been used for heating. The project, sponsored by the Pacific Northwest Regional Commission, will determine the feasibility of raising prawns in geothermal water and of developing the technology for commercial production. The OIT researchers have reared postlarvae to adults and have hatched eggs in brackish water, completing a full life cycle for the prawns.

The largest raceway pond used for rearing is 30 meters (m) long, 3.6 m wide, and 1.2 m deep. The inflow pipe, which delivers 200 liters per minute, is located on the bottom of the pond and extends for the full length of the pond. Diffused holes in the pipe extract waste water. The pond's temperature is maintained at 27°C, although the optimum for growth may be about 29°C. During winter months, 54°C water is necessary to maintain a desirable temperature.

Work to date has shown that engineering problems can be solved if the water quality is suitable; no apparent disease problems exist, though cannibalism and territoriality can cause trouble; a reliable source of brine shrimp or other food is essential; a production yield of 500 kilograms (kg) to 1350 kg per surface hectare (ha) per year could be expected with feeding; and the product is marketable.

The project's success in raising prawns from postlarvae to adults and in hatching eggs holds great promise, as does the possibility of obtaining natural food from Upper Klamath Lake and Abert Lake. If stocking density can be increased without resulting in greater mortality from cannibalism, and if structures placed in the rearing area to provide shelter and territory do not interfere with harvesting, a significant increase in economic return should encourage the establishment of prawn aquaculture at locations in which geothermal waters and other factors are suitable.

Another experiment, undertaken by Jack H. Stevens of Radium Hot Springs, Inc., Haines, Oregon, involved growing out a few juvenile prawns imported from Hawaii by the National Marine Fisheries Service's Pacific Utilization Research Center, Seattle, Washington. The test proved that prawns would grow in this area's geothermal water, even though the water's pH was 9.2. This alkalinity could have been reduced, and water temperature controlled, by introducing cold water, which has a pH of 6.7. Prawns fed on frozen brine shrimp and flaked fish flesh supplied by the National Marine Fisheries Service grew well, and were later maintained on a pelleted food supplied by Syntex.

TROUT AND SALMON

Geothermal resources generally constitute relatively hot water. However, for trout and salmon culture we must include temperate groundwater from wells or springs that ranges in temperature between 12°C-15°C. Groundwater in this temperature range typically has a number of advantages, as compared to surface water, industrial waste water, or hot geothermal water. It is stable in flow, temperature, and chemistry, and can be used directly in culture with existing proven technology.

As long as groundwater of adequate quantity and quality for use in fish culture is available, we should perhaps not even consider use of hot geothermal water in salmonide culture. Hot water can temper cold water in hatcheries to stabilize temperatures and accelerate fish growth. However, use of hot goethermal water brings up problems of water quality, engineering, and waste water disposal. Thus geothermal waters could be more important as a source of process energy or heat than as a supply of water for salmonid culture.

Much geothermal water has a mineral content that makes it unacceptable for direct use in culture. The technology for heat exchangers exists, but the expense of construction and operation make these economically impractical. Improving growth or survival of high-return items, such as salmon smolts, may be a practical application of hot water, but its use in producing catchable marketable trout is not feasible. The effects of trace minerals on fish are generally unknown. Geothermal water's mineral content makes the use of such water questionable without thorough research, including test rearing of species proposed for culture.

Heated water can accelerate growth of salmonids, but a variety of problems attend such use. For fish reared in water of constant temperature diet becomes very important, and additional research is needed on the nutritional needs of salmonid cultured at various temperatures.

Disease control and genetics are also related to temperature. While the best growth and food utilization occurs at 13°C-15°C, chances of disease problems greatly increase above 12°C. Sanitation and prophylaxis are increasingly important as warmer waters are employed. Use of heated water may cause genetic modification: selection for a stock that will perform in a heated water hatchery may alter stock genetics or its performance outside of the hatchery.

Reproductive fitness of certain portions of the stock may be altered by accelerating growth. The age at maturity may be reduced so that fish maturing earlier may contribute more to subsequent year classes than late-maturing fish. In heated water, larger fish can be produced in a shorter period of time, which can result in better survival in the wild and earlier maturity for the accelerated fish. Additional problems associated with accelerating fish growth and maturity include:

1. A higher percentage of jacks may result in some anadromous populations, though the opposite has been observed in other anadromous fish.
2. Fry or fingerlings accelerated in warm water may be ready to plant or release at unsuitable times, such as during high water or before plankton blooms.
3. Accelerated growth at early life stages may result in smaller mature fish.

This is acceptable in the case of improved coho survival in a commercial operation, but not in the instance of Kamloops trout maturing at less than trophy size.

CATFISH

Catfish production in the United States occurs primarily in pond culture in the Southeast. All of the 27-32 million kg of catfish that are farmed are raised in ponds, and Mississippi is the leading state in raising catfish from the standpoint of water area: the more efficiently operated farms are now producing 720-1100 kg per hectare annually. An additional 450,000 kg of catfish are raised in geothermal raceways by Leo Ray in Idaho and Burley Jenkins in Colorado.

Sixteen million kg are harvested from wild catfish stocks, mainly from Louisiana and North Carolina rivers. These fish are intended primarily for markets in the Chicago area. Nine million processed kg are imported, most from Brazil with a lesser amount from Mexico. These processed imports represent 15 million kg round weight.

Pond culture generally yields 360-1,100 kg of catfish per surface ha of water. Ideal water temperatures are 27°C-30°C, since fish growth is slow below 21°C-24°C. This precludes catfish pond culture in the Pacific Northwest, as the cost of keeping several hundred hectares of water at these temperatures is prohibitive. To be successful, catfish culture in the Pacific Northwest must be at high density, with a flow-through or reaeration system. Geothermal water sources, providing constant temperature and volume, lend themselves to this type of culture. Since most geothermal water is extremely hot, the aquaculturist usually needs sources of both hot and cold water for blending to achieve the desired temperature, though cooling ponds could also be used. The water source should be artesian or spring wells to avoid the high cost of pumping water out of the ground.

Leo Ray has produced 18,000-22,500 kg of catfish per second foot of water, and hopes to achieve 45,000 kg of catfish per second foot of water during 1978. He has three artesian wells at 32°C and 35°C, as well as cold water springs.

Reaeration of the water occurs through gravity flow (Fig. 12). The oxygen saturation point at the operation's elevation of 900 m is 8 ppm at 30°C. The initial concentration is 8 ppm. Under ideal carrying capacity, this will drop to 6 ppm (a loss of 2 ppm) in the top raceway section. The

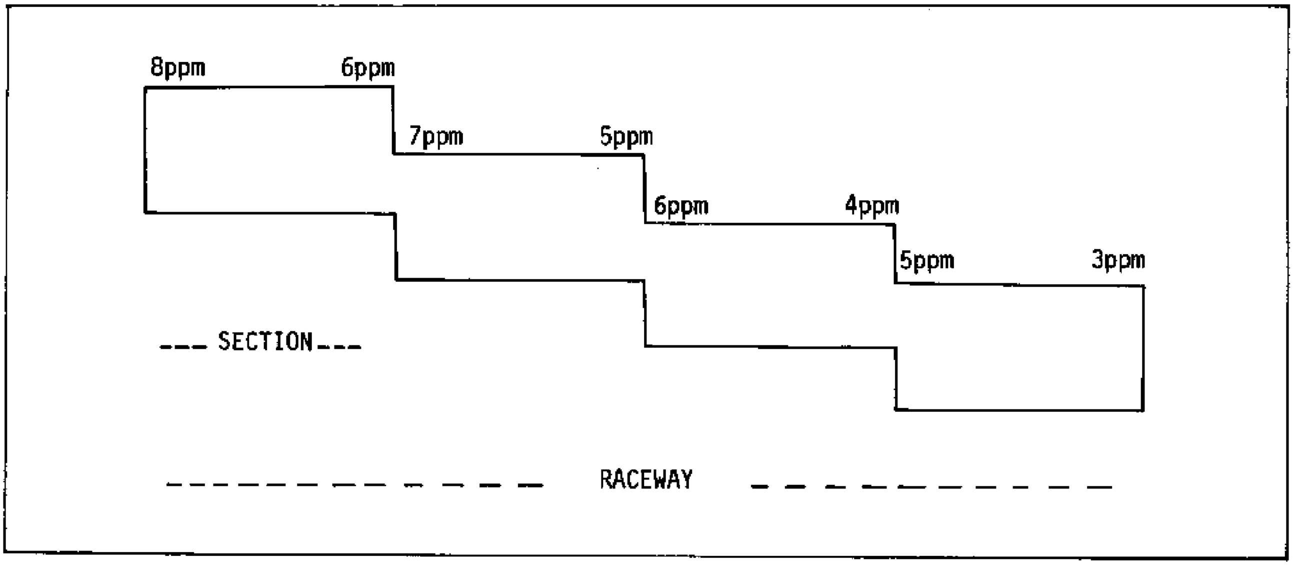

Fig. 12. There is a .6m drop between each section. Section dimensions are 1.2m X 3m X 7.2m. There are three raceways separated by a 3 to 3.6m drop over a 90m distance.

.6 m drop will pick up about 1 ppm, resulting in a net loss of approximately 1 ppm in each raceway section.

If the oxygen concentration drops below 4 ppm, feed is cut back, as feeding rate is geared to oxygen levels as much as to kilograms of fish. However, research is needed on the percent of body weight as food that a catfish should consume for maximum growth and feed conversion efficiency. Heat loss, minimal in this system, depends on the amount of time the water is retained in the settling ponds. Temperatures should not exceed 30°C as disease problems will increase geometrically at elevated temperatures.

Ray is also involved in farm-out operations. If an acceptable farmer has a source of hot water and will construct a raceway to Ray's design, Ray will supply the small fish, feed, and technical services, and will harvest and process the fish. The farmer is paid five cents per kilogram on the gain.

To guarantee a year-round supply of marketable fish, spawning must take place throughout the year. Spawning will occur in catfish only if they have gone through a cold cycle, believed to be below 18°C for an undetermined length of time, during which egg development begins. Development is completed after temperatures increase above 23°C and up to 26°C, at which point the eggs will expand and take on water. The natural drop in temperature occurs over a 90-day period, but egg development can be initiated artificially during a 2-3 week period if the temperature is lowered to 18°C-21°C. After the temperature is raised again, spawining may occur if the eggs are ready, but this cannot be predicted. Other factors, such as pH and photoperiod, are involved in spawning and should be investigated. Hormone injections have been used to induce spawning in the research environment but have not been practical for commercial use.

Those interested in conducting research projects on catfish aquaculture should follow several steps:

1. Learn how to raise the fish successfully. They should be kept alive for six to nine months in the research facility to allow elimination of the technical and cultural problems arising during this time.

2. Design a culture system that will be economically feasible on a larger scale.

3. Develop systems that are not energy intensive.

The keys to aquaculture are, first, water quality oxygen levels, mineral composition, temperature, and other factors, then feed quality and the human element. Successful aquaculture ventures are frequently the result of persistent trial and error, since every system is unique. Establishment of a geothermal aquaculture research station that could be used by professors and students from several universities and institutes would help to avoid duplication of effort, promote sharing of ideas, and provide trained individuals for the local industry.

OTHER SPECIES

The National Academy of Sciences, in its 1977 World Food and Nutrition Study, recommended a number of high priority research tasks that were considered necessary parts of a proposed U.S. program to contribute to solutions to world hunger and malnutrition problems. Development of aquatic food sources was among these solutions, and, reasonably, was defined as including both capture fisheries and aquaculture.

Two lines of aquaculture research were proposed:

1. A long-term effort to improve the breed and supplies of seed stock, concentrating on tropical or semitropical locations.

2. Research to improve the use of managed water in the tropics through polyculture.

The aquaculture study team estimated that research could increase the annual yield of pondfish in southeast Asia by five times the present average of 600 kg/ha through studies on polyculture and nutrition. Geothermal aquaculture, or aquaculture in general, will only reach its full potential with large-scale production of species that are analogous to marine bottom species.

In the longer run, fish genetics will permit larger gains. The breeding potential of tropical and aquatic species has scarcely been tapped. Fish geneticists estimate that selective breeding alone could quickly increase production by 2 to 5 percent per year. Advances in breeding milkfish, mullet, and tilapia, for instance, could eventually result in the production of several million additional metric tons of these and similar fish.

The number of species of fish that are grown in intensive culture are few indeed, when one considers that there are some 25,000 species of vertebrate fish. Even fewer invertebrates have been cultured successfully. The reasons for this are both biological and economic. Species have been selected on the basis of their compatibility with culture systems, consumer preferences, and rearing costs which are often determined by the cost and availability of appropriate feed.

The biological properties of species that would lend themselves to intensive culture are--

1. Ease of reproduction in confinement;

2. eggs or larvae hardy and capable of hatching under controlled conditions;

3. food habits of larvae or young such as to be satisfied by prepared feeds or natural feeds that can easily be provided; and

4. quick growth on low-cost prepared diets or easily obtained natural food. (Bardach).

One could add resistance to disease and fishes' ability to grow in high density. There are relatively few species that meet both these biological requirements and the necessity for high consumer demand and therefore high value. Usually, and unfortunately, high market value accompanies high production costs.

But there are species that meet Bardach's biological requirements, and have characteristics giving them considerable potential as supplements to the high U.S. and world demand for marine bottom fish species. Some of these species are tropical and require water of a temperature found in few places in the United States. Others can be grown in colder waters with the usual penalty of a slow growth rate. In any case, the availability of ground water at temperatures below that needed for the production of power and above that available in area's ponds, lakes, and streams makes possible twelve-month growing seasons and provides the opportunity to culture species foreign to this country.

Idaho trout and catfish growers have shown the large production capacity of geothermal water in raceway systems. Water quality in such systems can be maintained at a high level by regulating fish density, aeration, length of raceway, and rate and volume of water flow. But many questions remain. Are valuable species available whose resistance to low-quality water is such that they can be grown in degraded water ready for discard? What are optimum geometries for raceways in relation to available water volume, quality, and species to be raised?

Species such as trout and catfish are in most cases totally dependent on prepared feeds. What problems of feed and feeding are novel because of raceway systems, particularly for the culture of herbivores? How is the feeding of herbivores handled? Is it economical to raise algal food in external ponds, perhaps using waste water as a source of nutrients, for introduction at the head of raceways? Can raceways replicate the environment in tropical countries, where vegetation grows naturally and abundantly? Is this necessary? How severe are the problems of heat loss in cold climates? Are shelters necessary to maintain proper growing temperatures? Are artificial sources of light necessary during winter months? What are these fish species' vegetation (food) requirements for raceway bottom substrates? What are water quality and substrate requirements of aquatic plants and plankton?

Harvesting should be greatly simplified, costs reduced, and efficiency increased in raceway systems. Will this be so in fact? What is optimum depth for each species? What species have temperature requirements so similar that polyculture is practical? What polyculture or serial culture can be practiced based on temperature requirements of different species and heat loss from head-end of raceway to tail-end?

Regardless of pond or raceway culture, will state laws present obstacles to the introduction of "exotic" species? In terms of ultimate use, how will market form determine species selection?

When considering suitable species for aquaculture, we need to establish criteria for their selection based on--

1. biological requirements;

2. economically related aspects, such as costs of production (feed, growth rate, and reproduction); and

3. consumers' preferences and versatility for use as protein sources.

The following are examples of species that have demonstrated a potential for aquaculture or that are worthy of consideration.

Candidate Species

1. Common carp

natural feed: protozoa, small crustacea, insects, decayed vegetables.

supplemental feed: silkworm pupae, potatoes, soy meal, duckweed

culture history: China, Japan, Thailand, Sri Lanka, India, Philippines, eastern European countries, Israel

production capability:

India	1,500 kg/ha
Indonesia	1,500 kg/ha to 500,000 in cages suspended in sewage water
Japan	5,000 kg/ha

2. Chinese carp

grass carp, *Ctenopharyngodon idellus* (phytoplankton feeder; also higher plants, rice flour, bean meal; not an obligate herbivore)

big head, *Aristichthys nobilis* (zooplankton and phytoplankton feeder)

black carp, *Mylopharyngodon piceus* (omnivore)

mud carp, *Cirrhinus molitonella* (omnivore)

3. Indian carps - *Catla catla,* rohu, mrigal

4. Tilapia species

natural feed: vegetation and insects, omnivorous

supplemental feed: rice bran, oil cake, flour, chopped leaves

production capability:
Jhingran reports production from tilapia grown together with carp to be 3,000 kg/ha without artificial feeding or manuring. However, carp production was reduced because tilapia feed on carp fry. Total population was greater than that from either species alone.

special considerations: problem of early sexual maturity with *T. mossambica* seems to be solved by *T. aureau* with another species.

5. Gourami

Jhingran refers to the desirable characteristics of gourami (*Osphronemus goramy)* a native of southeast Asia. This fish prefers insects, crustacea, and zooplankton, but feeds well on oilseed cake. Bardach refers to gourami as an excellent food fish, which has attracted the attention of European culturists. Young gouramis feed on zooplankton until 10 days old. They then are cultured on ants or peanut waste for about three months. They are grown to size on the floating plant *Azolla pinnata*, supplemented by minced plant leaves and are ready for harvest in about five months.

6. Paddlefish *(Polyodon spathula)*
A zooplankton feeder with excellent flesh; the roe make good quality caviar. These fish do not spawn in standing water.

7. Walking catfish (*Clarias* species)
Originally from Thailand, these fish have produced spectacular successes in Africa. Their feeding habits are not clear.

The foregoing is concerned with production, species selection, and use. In terms of geothermal aquaculture, aquaculture facilities would perhaps best be located in areas that attract other geothermal industries, so that a self-sustaining food production and waste-use center can be mutually supportive, resulting in lowered operating costs.

The Soviets have done a fair amount of work on the mass culture of invertebrates for use in feeding fish, and have prepared a monograph on the biology and methods of mass cultivation. They report that although the production of thousands of kilograms of live organisms (daphnia, insect larvae, earthworms) is a trying task, it is practicable and depends upon careful management of the population under culture, with particular attention to environmental conditions, selection of feed, and density control. Geothermal water has a very useful function here, too, because of the greater biomass produced at the optimum temperature (about 20°C) for such species.

Quite some work has been done on the small-scale production of algae for use as food for herbivorous fish and crustacea, and on the use of waste materials--even human waste as fertilizer for algal production and as a direct food for some species. This kind of work is very important for the economically successful production of herbivores, and its expansion should be encouraged.

Over the years some very significant work, such as Pirie's in England at Rothanstead, has been done on the extraction of protein from herbage, including grass. A number of technological problems have slowed the progress of this work, but it too holds such great promise that it should be encouraged. Incidentally, the beneficiaries of the development of leaf protein are not limited to fish culturists: the entire animal industry worldwide would benefit from the availability of low-cost leaf protein concentrates.

Production and distribution of organisms in geothermal aquaculture: *panel discussion*

ENGINEERING

Sources of geothermal water suitable for aquaculture appear to be abundant. These include conventional hot water geothermal sources of 54°C and above, as well as cooler sources more commonly referred to as groundwater, which have steady temperatures between 13°C and 14°C. At any geothermal location, a major limitation will most probably not be the quantity of heat energy but rather the availability of fresh water. Geothermal aquaculture shares with any warmed fresh water aquacultural operation the common problems of waste-water disposal, temperature control and heat balance, mixing, and others. These general problems might also crop up in aquacultural installations at geothermal sites over those that use waste heat:

1. Siting. This includes cost and availability of land, and the location of heat and water sources.

2. Reliability of the heat source. Problems with waste heat sources include periodic or intermittent shutdown owing to equipment failure or plant maintenance.

3. Variability of temperature and water conditions. Effects would depend on the magnitude and rates of variation, and on the species grown.

4. The proximity of food-growing areas to waste heat discharges. For aquacultural ventures this may be more a problem of appearance, except in the case of nuclear power plants, which have the potential for radioactive contamination. On the other hand, waste heat aquaculture could provide beneficial public relations for a power plant.

Frequently a geothermal aquaculture venture will represent the final use of geothermal heat, as at the Oregon Institute of Technology. The ultimate disposal of spent warm water can be accomplished in three ways: discharge into natural waterways; discharge as irrigation water on field crops; and reinjection into aquifers.

Reinjection generally appears to be one acceptable technique for the ultimate disposal of warm water, having the advantages of replenishing groundwater sources, often requiring no pumping, and being technically feasible--the oil companies commonly reinject brines into the ground. Problems associated with reinjection in include:

1. Volume of water. Geothermal water mixed with larger amounts of cold surface water to control temperatures may represent too large a volume to be reinjected.

2. Plugging. This can occur if the water is used directly in raising fish and is not pretreated before reinjection.

3. Government regulations. At present several government regulations restrict injecting water near potable water aquifers. One prohibits injection within one mile of any potable water source. This regulation uses two different definitions for "potable"--one for drinking water and one for geothermal water. In most cases, restrictions do not differentiate between water directly used for any process and that indirectly used by passing it through a heat exchanger. Some of the regulations, included in the Clean Water Drinking Act, are currently under review and may be changed. In any case, pretreatment of water from geothermal aquaculture operations may be required before reinjection.

For geothermal or waste-water aquaculture, a number of problems attend the discharge of warm water into natural waterways, such as elevated temperatures--in many areas, regulations say that stream temperatures cannot be raised more than 1/2°F--and the presence of amonia, nitrogen, suspended solids, and excessive biological oxygen demand. Depending on the location and quality of the geothermal water source, discharge of geothermal water can introduce traces of arsenic, boron, or fluoride. Secondary and tertiary treatment of waste water is expensive, and would probably make most geothermal aquaculture operations economically impossible.

Geothermal water may be directly used to grow animals or indirectly used by passing the water through heat exchangers to control the temperature of a secondary fluid. In either case, temperature control is critical, but well within the current state of the art. The capability of using water directly depends on the species raised and the location. The Pacific Northwest has fewer problems with geothermal water quality than many other areas of the country. If the geothermal water is directly used, a reliable source of cold water and a reliable mechanism to control dilution to produce the correct temperature would be required. Various species' tolerance to the minerals that might exist in geothermal water is not well known, and perhaps needs further investigation. Depending on the upstream use of the geothermal water, the water may require aeration owing to oxygen's low solubility in water of elevated temperatures. Oregon Institute of Technology, which uses water that has passed through several cascading heat exchange systems, does not have this problem.

The transfer of heat through heat exchangers is possible if the direct use of geothermal water is not. The technology for building and maintaining geothermal heat exchangers is currently available. One type of commonly used heat exchanger consists of stainless steel plates that can be dismantled for periodic acid wash to remove scale. A second type is the fluidized bed, which promotes selfcleaning of mineral or scale buildup. In the Pacific Northwest, scaling and fouling of heat exchangers does not appear to be a serious problem. Currently, the technology for producing and maintaining underground heat exchangers is not fully developed, though research is proceeding. Heat exchangers of any type to allow secondary heating of a fluid can represent a considerable capital and operating expense, which will affect the economics of a geothermal aquaculture project, especially if its heat source is a plant that discharges a caustic or potentially radioactive fluid.

Information is needed on the comparative design and economics of ponds--stationary water--and raceways--simulated streams. Some factors varying considerably between these two types of installations include:

1. Temperature control. Related to this is the rate of change different species tolerate, decisions on indoor or outdoor installation, water mixing, and crowding of species seeking an optimum temperature.

2. Disease control.

3. Waste disposal.

4. Feeding. This includes a need for data on the efficiency of feeds and techniques and on the growth on natural foods in the water system.

5. Harvesting techniques.

A major need exists for collection of existing empirical data and the generation of new data to allow the accurate calculation of heat balances for both ponds and raceways in geothermal aquaculture systems. Reliable data developed should include the effects of radiation heating and cooling, wind on the water surface and evaporative cooling as it relates to wind and atmospheric humidity. Apparently the data and techniques used in the determination of heat release rates for swimming pools cannot be used to extrapolate accurate data for designing an aquaculture process.

In many geothermal aquaculture operations, the geothermal heat might be alternatively or additionally put to use in related tasks:

1. Absorption refrigeration. This may not be feasible at common geothermal temperatures of less than 104°C.

2. Thawing of frozen fish food.

3. Heating or defrosting of work areas.

4. Preheating in the processing operation.

5. Acceleration of waste-water treatment by increased bacterial action at higher temperatures.

ECONOMICS AND MARKETING

Aquaculture in the western United States, and especially in the Northwest, has been established for and operates with species of fish native to cold marine or fresh water, such as salmon and trout, which have been successfully reared and marketed. U.S. geothermal energy sources are largely in the western states. Tapping sources of heated water would enable aquaculturists to temper cold surface waters to raise temperatures to levels that would allow the culture of species of fishes and shellfish ordinarily found in warmer waters.

At present, geothermal research is oriented to the use of this energy for power generation. Aquaculture use of this heat may become secondary, thus posing a potential problem for the aquaculturist who may have to depend upon an unreliable source of heat. Many of the known sources of geothermal energy are located in remote mountainous areas, distant from population centers. Construction and operating problems may be so compounded as to make the use of the geothermal heat impractical. In addition, disposal of hatchery discharge waters may further complicate the location of hatcheries and rearing ponds in these areas.

In some areas, geothermally heated waters surface as springs or can be tapped by drilling into shallow aquifers. Drilling will involve some risk and costs unless the aquifers are known to be shallow. Flowing springs are the best geothermal source, as the flow rate is a known factor. Pumping of geothermal waters should be avoided, because the energy costs required for pumping may offset any advantage gained in the use of the heated water.

Heated waste water from nuclear power and utility plants, as well as from industrial plants might well be the better way to acquire heated water closer to population centers and at more reasonable costs. The quality of the water and the potential for flow interruption should be carefully investigated.

Large corporations are looking at aquaculture with interest as a use for waste heat from existing manufacturing processes in order to derive a sales return through utilization of wasted energy, or, in the case of wood products manufacturing companies, as a use for land adjacent to streams. Current energy costs are high, and all indications are that those costs will increase. Geothermal utilization, or the use of heated waste water, will certainly enable the production of seafoods at costs attractive to the marketplace. Solar energy should also be considered as a supplemental heat source, or as a means of controlling temperatures, by enclosing ponds, troughs, or pools in greenhouses.

Several factors relate to the economics of geothermal energy use. A 10 percent tax credit is allowed for drilling a geothermal well. Depletion allowances may also be possible and should be investigated. State revenue departments should also be questioned about individual state tax allowances for goethermal aquaculture plant construction.

Seafoods fall into two general categories--gourmet and protein. The gourmet species include salmon, trout, lobster, crab, and shrimp because of their current high market prices. Because of these species' cost, the consumer and institutional feeding establishments are turning to other seafoods, causing a gradual increase in value of some whitefish species, those normally falling within the protein category. This category comprises primarily cods, rockfishes, soles, flounders, turbot, pollock, and whiting, all marine species of saltwater or brackish environments, and therefore not adaptable to geothermal aquaculture since geothermal resources are located inland.

Geothermal wells can be well utilized in nursery operations for anadromous species such as salmon. Juveniles are transplanted to their natural habitat for growing to marketable size, or released at the proper time to the ocean, bay, or river, to forage at sea and return to the hatchery at adulthood, as in ocean ranching. Trout can also be raised in hatchery-release programs.

Pen-rearing of salmon to marketable size requires feeding for growth. Feed costs have risen so high that optimum conditions must be provided to attain a satisfactory conversion rate. A plentiful flow of fresh, well-oxygenated water, tempered by geothermally heated water during the cold winter months, will result in a greater growth rate with the same amount of feed than achieved in colder water. The fish feed better at higher temperatures and less feed is wasted.

Aquaculture is not a "get-rich-quick" operation, but, for the dedicated and patient individual entrepeneur, it can be a rewarding endeavor. Trout farming is an example of aquaculture's profitability structure. Trout raisers are meeting tough competition from imports. Returns on investment are now at about 2 percent. Costs of feed, labor, and supplies have increased, yet prices for the finished product cannot increase because of prices of imported trout.

In geothermal aquaculture, the higher valued species will provide better opportunities for profit. Products that will serve a diversified market rather than an exclusive market, such as a single country or export market, will provide better returns. Economically attractive possibilities exist for culture of complimentary products, fish or shellfish and an agricultural product that benefits from the heated water source.

Freshwater shrimp--the Maylasian prawn (*Macrobrachium* species)--seems to offer possibilities for geothermal aquaculture. The technology for raising *Macrobrachium* has been well developed through existing operations in Hawaii. The current high price of shrimp--16 to 20 count per pound @ $4.10--could provide the return on investment necessary for a profitable operation. However, freshwater shrimp is not as durable a product as salt water shrimp, so that special care in handling, and consumer education in the product's use would be required.

Other than salmon, trout, and shrimp, species adaptable to geothermal aquaculture are crayfish, lake perch, pike, carp, tilapia and, of course, catfish. Goldfish and tropical fish for the home and institutional aquarium market might also be considered as suitable species. At present the two most profitable species for aquaculture are trout and catfish, with salmon and shrimp following closely, but the industry is still in its infancy and much technology remains to be developed.

The industry has been unable to maintain a year-round supply of catfish for marketing. Fall and winter demand can be met with domestic fish, but imports must be relied upon to meet spring demands. Between 120 and 125 million pounds of catfish are marketed annually; with minimal promotion and advertising this could be increased five to seven times, and an elaborate marketing and promotional program could increase demand 10 to 15 times total current production. Past markets have been retail and institutional, but current trend leans towards institutional markets.

Catfish has great marketing potential. Leo Ray's annual increase in production of 50-100 percent for the last four to five years has been matched by an equal or greater increase in demand from wholesalers. The recreational fish market in California could support a threefold increase in production. All the catfish farmed in California are trucked up and down the coast to catch-out ponds. Fish are now selling to pond owners at a minimum of $1.25/lb for large volume sales, and are resold by the pound, inch, or fish. Fillets that go to California's restaurant trade are resold at $12.00 a plate.

Rough fish--carp and tilapia--should be reared in a compound operation. These fish serve to keep down growth of vegetation such as algae and mosses, both natural foods, and also scavenge uneaten food used for the primary species. Even if a profitable market does not exist for these secondary species as food, such fish may well provide a return, from meal, oil, pituitary glands, or other products that can cover part of the basic operating costs. Tilapia may also be a marketable commodity for transplanting into irrigation canals and reservoirs to suppress unwanted vegetation, though state fishery officials should be contacted for clearance beforehand.

Selection of an aquaculture species will depend upon potential markets and eventual returns. The amount of investment and return will depend on the species' reproductive cycle and the length of time required to hold and feed the fish or shellfish to marketable size. In many cases it has been difficult to obtain financing for aquaculture endeavors because local advisory boards whose members often know very little about fish or aquaculture approve loans. This is frequently a problem of education rather than unwillingness to help. Once local banks have seen examples of successful aquaculture ventures, they are more apt to provide financial assistance.

Cyclical species that mature at a specific time of year--salmon--could tend to flood the market at harvest time, causing low prices. However, refrigeration or freezing will hold the product for sale later in the year or during a period of stable prices and the aquaculture operation that dresses its own product for holding in a public cold storage warehouse has an advantage in this regard. However, the producer who sells the finished product in the round to a processor may well add to a surplus at harvest.

The foregoing is an example of the critical management decisions, or judgements, that will have to be made in establishing a geothermal aquaculture operation. Individual entrepeneurs have an advantage over corporate operations, since they can make decisions or react to conditions more readily than corporate personnel. Fish farming requires the owner-operator's dedication, a type of dedication not normally found in corporations.

Very often, corporate operations do not have adequate expertise to manage the investment involved or to allow experts to operate without interference. Also, corporations, anticipating rapid returns, have been disenchanted with the percentage of returns in relation to investment and overhead costs.

Such experiences have led to closure or failures in some fish farming ventures. Other reasons for failures include water quality, poor stock selection, and site location. In the past 10 years, over 100 catfish raceway operations have been started, but today only two are operating. Trout aquaculture facilities of the same sort have also had a large share of failures or marginal operations. The initial investment in construction costs were too great for the returns realized. Natural pond rearing is less expensive.

Large corporations do have the ability and expertise for studying market potentials and for developing and promoting a product, areas in which the individual entrepeneur has a more difficult time. Individual producers can use the services of a large corporation to market aquaculture products. However, one plant may not be able to produce enough for a large marketing entity, and cooperative production of several plants may be necessary.

The failures or poor profit stories do not mean that the art of fish farming is unprofitable. Aquaculture is a new industry and much remains to be learned. After all technical considerations, the greatest and most important need is sound management of an operation.

INSTITUTIONAL AND CULTURAL FRAMEWORK

Geothermal aquaculture is affected by local, state, and federal regulatory systems, and by the general social context in which geothermal aquaculture as an innovation would take place. Institutional barriers do not appear to prevent development of aquaculture in connection with geothermal operations, though the possibilities for geothermal aquaculture in the United States appear limited in scope at present. Communication within and between governmental agencies, industry, and the public is essential, particularly if the real potential of aquaculture is to be realized.

No federal regulations or agencies exclude the possibility of geothermal aquaculture development on federal lands, but neither are there regulations or agencies promoting such developments. Federal leasing laws appear flexible enough to permit geothermal development. Projects on federal lands face permit and impact assessment costs that initially make the use of federal lands more costly and difficult than private land development.

The lead federal agencies in geothermal development are the Bureau of Land Management and the U.S. Geological Survey. The Fish and Wildlife Service has prepared a geothermal handbook and the Department of Energy is conducting some research. Several federal agencies are considering aquaculture for the use of geothermal waters, but to date energy development and other national interests have higher priority. Geothermal aquaculture must compete for agency attention, personnel time, and resources that are usually committed to other pressing social problems. Further, few people knowledgeable in this area are available to the agencies. However, several bills recently passed or under consideration would give aquaculture greater federal recognition, and both a lead federal agency in aquaculture and a national aquaculture policy are likely in the future. At present, interagency task forces are discussing the potential of aquaculture.

No federal incentives currently promote geothermal aquaculture. The federal government could take a stronger leadership role in research and public information, and in easing aquaculturists' passage through the regulatory maze. Information should be sought on the chemical characteristics of geothermal waters, aquacultural experimentation, thermal agriculture, and other related aspects. Public education on the meaning and usefulness of aquaculture and geothermal resources is necessary.

Government controls on various facets of geothermal aquaculture inhibit the development of private operations. These controls cover: discharge of hatchery effluent, particularly heated waters or waters containing substantial amounts of dissolved or suspended solids; disease certification; transport of fish and translocation of stocks; use of chemicals; land use planning and zoning. The growth of aquaculture has stimulated the evolution of regulations, but progress in aquaculture depends upon the development of realistic regulations.

Geothermal aquaculture should be linked with land use and renewable natural resource planning. A clearing house for permit applications would ease the bureaucratic maze faced by the innovator in geothermal aquaculture.

Because of problems in limited research, public information, and regulations, the federal government is viewed as a barrier to development of geothermal aquaculture on federal land. New geothermal aquaculture will thus come slowly and will probably be confined to secondary uses that are tied into power production facilities and perhaps large-scale process heating operations. While a number of reasons underlie these problems, any potential innovator should recognize the government's responsibility to protect many diverse public interests. in pollution control, wildlife protection, recreational and commercial fishing, disease control, interstate commerce, and land use, which may conflict with the interests of the geothermal aquaculture innovator.

The current lack of strong federal involvement in geothermal aquaculture results partly from low levels of public attention or mandate given to this new industry. Given such institutional and social constraints, two kinds of geothermal aquaculture development are most feasible on federal lands. One would be as part of another geothermal use. Geothermal aquaculture tied into a multiple-use scheme would be more likely accepted as a good use of resources. The second would be small-scale development that takes advantage of some unique quality, location, or water supply.

At the state level, interest in geothermal aquaculture varies widely. Idaho has more experience in aquaculture than other Northwest states (Ref. Klontz, Aquaculture in Idaho, Idaho Department of Water Resources). State water laws vary and these might provide a vehicle for obtaining geothermal water supplies.

While geothermal aquaculture may not occupy a predominant place in competition with other national priorities, individuals and local communities with geothermal resources may find it a major opportunity. In such situations the Small Business Administration and regional economic development programs might be the best agencies for aid in development of the geothermal resources.

Geothermal aquaculture must find a place in a general social context. Both geothermal resources and aquaculture are new fields. If heated water is beneficial for aquaculture, heated discharges from power plants, municipal sewage treatment facilities, or food processing plants all exceed in quantity the heated water available from developed geothermal sources, are closer to population centers, and might have greater potential for thermal agriculture or aquaculture.

Geothermal aquaculture is an innovation seeking both a place and public attention. It would be unfortunate if the regulatory structure, lack of information, or lack of research prevented a useful innovation from occurring. On the other hand, a number of public interests compete for the use of society's resources, and geothermal aquaculture has to find its place in this context. If geothermal aquaculture is to be successful, it will have to answer successfully the question: What are the benefits of this innovation to society? To win public support and cooperation from local, state, and federal governments, innovators in geothermal aquaculture will have to identify the public interests that can be served.

Summary

Geothermal resources in the United States, particularly in the Pacific Northwest, and elsewhere appear to offer opportunities for aquaculture, provided that technical, economic, and institutional constraints can be overcome. In the Pacific Northwest, major factors preventing development of aquaculture are lack of experience with successful ventures, lack of capitol or inability to obtain financing, an insufficient supply of warm water--which use of geothermal resources could help to solve--and a dearth of useful information.

Major research areas that must be explored for successful geothermal aquaculture include:

1. the technology needed for the direct and indirect use of geothermally heated water--the chemical and physical properties of the water, reaeration, heat exchangers, and problems of scaling or fouling of equipment and disposal of spent warm water;

2. the characteristics of the fish and shellfish species appropriate for geothermal aquaculture--temperature tolerances, feeds, stocking densities, disease control, and polyculture; and

3. the economic and institutional aspects of geothermal aquaculture operations--multiple use of geothermal resources, financing of development, and marketing of different species.

As aquaculture in general, and geothermal aquaculture in particular, expand, persons trained in advisory and Extension work in aquaculture will be needed to meet a growing demand for useful information that can be applied by aquaculture entrepreneurs. Public education efforts should also be undertaken to promote support for aquaculture as an innovative method of developing food supplies and for geothermal aquaculture as an innovative use of natural resources.

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