Energy research for physicists

Problems in fluid dynamics alone illustrate the challenge for physics in the development of such resources as solar and geothermal.

George T. Reynolds

The shortage of energy resources is both an urgent national problem and a challenging research field for physicists. The challenge lies not only in the technical problems to be solved but also in the need to interrelate the technical solutions with economic, political and environmental factors. The physicist may have to adapt in several ways to this new interdisciplinary atmosphere. However, many have already made the transition successfully, either in short-term advisory roles or as permanent members of energy-studies teams. The extensive shopping list of energy problems to which a physicist can contribute include conservation, coal technology, fission and fusion. Suffice it here to discuss interesting aspects of wind, solar and geothermal energy as only three examples and to illustrate ways in which just one branch of physics—fluid dynamics—can contribute.

Adapting to a new environment

A physicist who enters into energy research may well have to learn a little humility first. In an article in PHYSICS TODAY in 1970, concerning the contribution of physicists to environmental studies, Marvin L. Goldberger said: "It is part of the folklore of physics that physicists can not only do anything, but that they can do it better than anyone else." Whether this attitude is to be classified as healthy confidence or merely modest appraisal, it does cause certain limitations when physicists tackle energy problems, which interface with the real world. Technical goals must in general be placed alongside economic, political and environmental goals, and physicists must work side-by-side with their counterparts in other relevant fields. The attitude of healthy confidence could conceivably appear to less unbiased minds as one of arrogance and could hinder the start of a multidisciplinary effort.

A physicist may also have to adjust to a new way of evaluating numerical results. One example is the estimation of conversion efficiencies of energy systems. Physicists know, of course, that the first and second laws of thermodynamics impose a limit on process efficiency. In particular, the efficiency η is given by

$$\eta = 1 - \frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}$$

where T_{C} and T_{H} are the absolute temperatures of the cold and hot reservoirs, respectively. Thus the ratio $(T_{\mathrm{H}} - T_{\mathrm{C}})/T_{\mathrm{H}}$ is a figure of merit. Physicists should not be dissuaded from considering a process just because low numbers result from this arithmetic. A more complete assessment may well demonstrate compensating factors that make the system an advantageous one.

In the same spirit, a particular resource should not be rejected on the basis that it would contribute only a few percent of the national energy need. Possibly the solution to the energy problem will turn out to be the equation:

$$E = \sum_{i=1}^{i\ \mathrm{large}} \Delta E_i$$

where the ΔE_i's represent contributions from a number of systems favorable on the basis of social, political, regional or economic factors.

Next a physicist must recognize that energy problems are multidisciplinary in nature. Some physicists can still work strictly within their own laboratory expertise in such matters as fission or plasma physics. But more are involved in interaction with experts from other fields. Aside from the evident concerns of economics, politics and sociology, the technological dimensions of energy problems require input from chemical engineers, geologists or biologists. Thus the physicist will have to recognize that the multidisciplinary nature of the problem requires an interdisciplinary approach. The distinction between "multi-disciplinary" and "interdisciplinary" is important: It is not enough to bring a group of experts together. The interaction must be deep enough and persist over sufficient time for the participants to develop a common language and to gain some appreciation of the roles to be played by the individual disciplines.

Involvement by physicists

With various degrees of success, a number of physicists have made significant commitments to energy problems. Some have restricted their activity to occasional participation on ad hoc advisory panels. Several APS studies represent valuable contributions to the energy problem. Among these are the Topical Conference on Energy held in conjunction with the Chicago meetings of February 1974,[1] the Study Group on Technical Aspects of Efficient Energy Utilization[2] and the Light Water Reactor Safety Study.[3] Undoubtedly these panels result in useful output, but often the study group walks away after the temporary intensive effort and the ultimate contribution and effect is questionable. It is better to find some mechanism that permits what I have termed the "institutionalization of individual commitment." Properly realized, this mechanism provides the framework and resources for continuing multidisciplinary inputs es-

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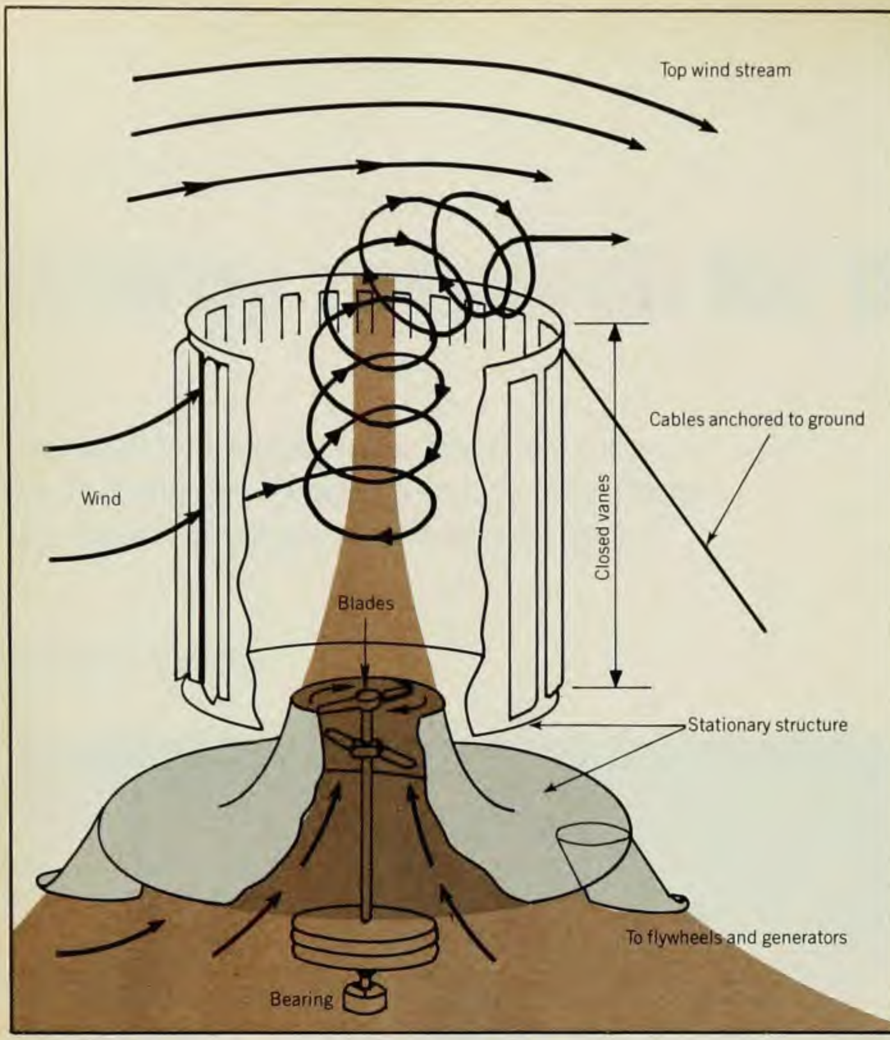
sential for the interdisciplinary attacks on the selected problem. One useful result of ad hoc study panels is that frequently a few of the participants will follow this activity with a full-time continuing commitment to an organized institutionally supported research effort. Several members of the Light Water Reactor Safety Study have done just that.

A consideration of the details of the evolution and activity of several interdisciplinary groups dedicated to energy studies on a continuing basis is instructive. In each case, the leadership has come from a small group of physicists, but has involved equally intensive commitment from members of other disciplines. In general, these efforts have developed within the structure of universities. The difficulties have been real, numerous, and time consuming, but have been overcome with sufficient patience, determination and excellence on the part of the participating individuals. One important aspect of the experience gained in launching a successful study center has been the discovery that the focus should be on restricted, specific problems at the start, in order to secure definition and support for the effort. Initial grandiose plans to study "the energy problem" led neither to support nor to results.

One example of an energy study center is the Center for Environmental Studies at Princeton University. In spite of the term "Environmental," the individuals who initiated the effort in late 1969 intended that the main thrust of the studies undertaken would be in the area of energy and energy policies. Initial funding was

To tap geothermal resources requires new drilling techniques. One example is an electrically heated molybdenum drill—subterrene—which melts rock and leaves its own casing.



Novel concept collects wind energy from over a large area. Wind entering side vanes spirals into a vortex. Ambient air drawn into this low pressure core turns the turbine blades. Figure 1

pitifully meager. In difficult economic times, the University could provide very little. A small foundation grant and NSF contract got things moving. Now, after five full years the total annual budget is over $600 000; several significant multidisciplinary studies have been completed and projects are funded currently for six diverse studies.

Members of the center come from physics, engineering (chemical, civil, aerospace), architecture, psychology, statistics, political science, economics. Several have had professional experience in environmental protection agency administration. Thus despite the slow and difficult start, the Center has succeeded and currently represents the research home of a number of physicists, some of whom started tentatively and part time.

One of the facts quickly learned in this business is that substantive activity interfaces directly with public policy, and conclusions based on technical expertise must be placed alongside social factors for evaluation. Nowhere is this more evident than in the sensitive question of fission power sources. This problem has become an emotional as well as a technical one. Sadly enough, physicists advertised as "physics experts" can be found speaking emotionally on either side of the question. It is not surprising that the nonphysics public has developed a healthy lack of respect for physicists in such situations. As Frank von Hippel has pointed out[4] the increasing polarization is having the unfortunate consequence of confusing the public rather than educating it. Despite the strong case to be made for nuclear power, further effort is needed to bring our nuclear energy capability closer to the technological limits of safety and environmental compatibility than it presently is. Instead of energy and effort being spent on the rhetoric that leads to further polarization, attention should be directed to thoughtful proposals for improvements, with due awareness that public acceptance has replaced economics as a primary obstacle to the deployment of nuclear energy. In such efforts, physicists would be performing their larger duties in a more constructive fashion.

A sampler of research problems

Because it is likely that the equation $E = \sum \Delta E_i$ may be a valid solution to both the near- and long-term energy problems, research efforts have been directed to the many so-called "alternative sources." The list includes hydroelectric, geothermal, solar, magnetohydrodynamic, wind, tidal and biological sources. Clearly each of these areas involves technical aspects that would benefit from the attention of professional physicists. For those physicists who feel particularly socially concerned, an objective study of the hazards to human life of hydroelectric power and dam failures—both historical events and future projections—might serve as a very useful comparison with similar studies and assertions made with respect to fission power.

In the field of wind energy one novel concept illustrates the potential contribution that fluid dynamicists can make. This scheme, pictured in figure 1, could generate artificial local tornado systems and thus produce far more power than conventional wind turbines of similar size.[5] Wind blowing over the open top of the tower acts to collect and concentrate wind energy from a far greater volume than the air immediately around the turbine blades. The wind that passes through the tower enters through movable vanes arranged to be open on the windward side and closed elsewhere. This air spirals inward forming a vortex. As it moves upward it gains velocity by conservation of angular momentum and leaves the top as a rapidly swirling mass, where it is blown away by the wind passing over the top. A turbine is placed in the tower beneath the low-pressure core of the vortex. The pressure difference between the ambient air and the low-pressure core causes a secondary flow of air to drive the turbine blades. Calculations and preliminary wind-tunnel experiments indicate that the details of the fluid flow in this system provide significant advantages over conventional wind-driven turbines.

The one alternative source on which perhaps the highest hopes are resting is solar energy. In order to develop large commercial solar electric generating stations, much research has centered on the general problem of collecting energy from the Sun and directing this energy to suitable receivers. Over the past two years, a group at Argonne National Laboratory led by a high-energy physicist, Roland Winston, has been investigating new types of reflector geometries to serve as concentrators.[6] The new geometries are called "ideal concentrators" by Winston, and when compared to the flat mirrors, focussing parabolas, V-troughs, Fresnel mirrors, and lenses that are conventionally considered, they achieve significantly higher concentration values. These ideal concentrators act as radiation funnels and do not have a single focus. As a result, on the basis of such parameters as concentration, acceptance angle and sensitivity to mirror errors, they offer advantages over conventional reflector geometries.

Concentration of solar radiation becomes necessary when high temperatures are desired, or when (as in the case of photovoltaic cells) the cost of the absorber is much higher than the cost of mirrors. Further, the heat losses are approximately proportional to the absorber area. Thus the concentration C, defined as

$$C = \frac{\text{aperture area}}{\text{absorber area}}$$

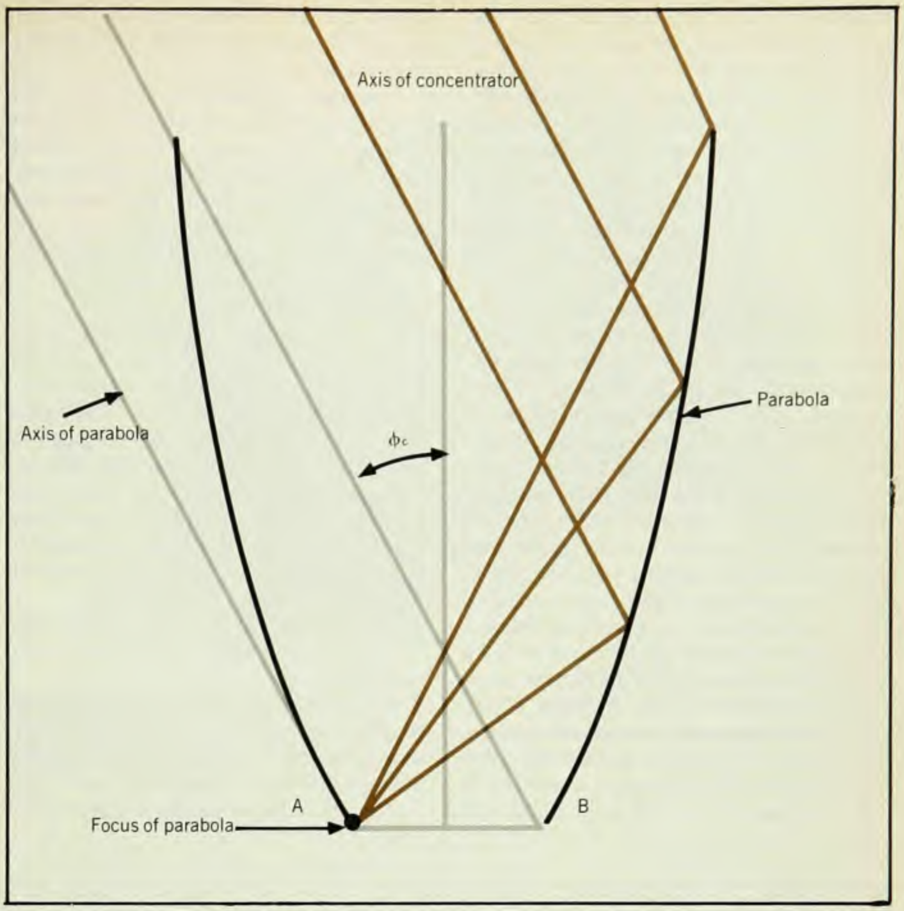
is an important parameter.

A second quantity, the acceptance angle (the angular range over which radiation is accepted without moving all or part of the collectors) is related to the concentration: In general high concentrations require small acceptance angles. Winston's group has shown that the second law of thermodynamics implies that the maximum possible concentration for an acceptance angle θ_c is

$$C_{\max} = \frac{1}{\sin\theta_c} \text{ for two-dimensional concentrators}$$

$$C_{\max} = \frac{1}{\sin^2\theta_c} \text{ for three-dimensional concentrators.}$$

These maximum concentrations are then what the Argonne group defines as the "ideal" concentrations. Any given concentrator can be compared to this standard. Most conventional concentrators fall short by a factor of two to four. A representative ideal concentrator, called by Winston the "compound parabolic" concentrator, is shown in figure 2. A ray of sunlight entering parallel to the axis of the right-hand parabola will reflect through the focal point A. Any ray steeper than this will be reflected into the absorber between A and B. Thus all of the rays incident on the aperture inside the acceptance angle and none of the rays outside the acceptance angle pass to the absorber. This two-dimensional parabolic reflector has a concentration equal to the ideal.



Ideal solar concentrator. Light rays (color) parallel to parabola axis reflect through the focus A. Any rays within the angle ϕ_c will reflect into absorber between A and B. Figure 2

The ideal concentrator involves a comparatively large mirror area, which must be considered in evaluating its application to the large-area collecting fields proposed in current plans to provide solar thermal power systems. A large ratio of reflector area to aperture area can mean a large expense.

Other interesting current developments in the field of solar thermal power may be found among proposals being received by ERDA. In the past, a conventional system usually involved a central receiving tower as a nearly point receiver of the reflected solar energy. Various practical considerations of structural problems, height, stability, wind effects and error tolerances result in significant difficulties for such a receiver. Recent proposals envisage collecting fields that direct the reflected energy to line-type central receivers, based on modular construction.

The receiver consists of a horizontal cavity, open on one side, which is well insulated and contains boiler tubes. Such a system must have optimum energy exchange, flow and transfer characteristics. Here is an area to which physicists, particularly those familiar with fluid dynamics and the practical concerns of high temperature power-generation systems, can make significant contributions. Some of the more advanced proposals are funded for further study while others are nearing the 10 MW electric proof-of-concept pilot-plant stage.

Solar sea power

Another means of utilizing solar thermal power for conversion into electricity or stored energy has been suggested by Clarence Zener of Carnegie Mellon University.[7] Zener's particular plan is called the Solar Sea Power Project and is one aspect of the NSF program for Ocean Thermal Energy Conversion. Carnegie Mellon has studied the project intensively and issued a report of its findings about a year ago.[8] Briefly, the idea is to convert the solar energy stored as heat in tropical oceans into electricity by means of closed Rankine-cycle power plants. Warm surface water is pumped into a heat exchanger to evaporate a working substance under high pressure. The vapor expands and drives a turbogenerator. Cold water is pumped from below the thermocline into another heat exchanger to condense the low-pressure vapor leaving the turbine. The rejected heat is carried away by the condenser water. This scheme is illustrated in figure 3.

From the start, at least three serious limitations were realized with the Solar Sea Power Project. The first arises from that old criterion, the Carnot efficiency. In the tropics, the surface water reaches temperatures as high as 27°C to a depth of approximately 30 meters, and this warm water drifts to the poles. The denser cold water drifts deep below the surface from the poles to the tropics, and at a depth of the order of 500 meters in many locations there is a temperature difference of the order of 20°C. This gradient sets an efficiency limit of approximately 7% for any heat engine operating between these reservoirs.

Consistent with the above suggestion that low efficiencies alone should not rule out further investigation of a given device or system, the Carnegie-Mellon group initiated their study to consider the further difficulties associated with the heat transfer in the evaporator and condenser. Because of the low overall temperature differences, the heat transfer must be accomplished with the smallest temperature difference possible at the interface of the working fluid and the evaporator or condenser. Realization of this requirement depends on the available materials. Recent technological developments, such as coating the heat-transfer surface with a porous material to enhance nucleate boiling in the evaporator, may offer promising possibilities. The condensation process is simpler than the evaporation process but the heat-transfer coefficient deteriorates unless the liquid is continuously wiped or drained off the surface. One suitable device found to enhance drainage is a surface that is corrugated with distinct channels to guide the condensate downward. The resulting flow is shown in figure 4. Although the channels are covered with liquid and hence do not contribute significantly to the heat exchange, their role ensures an extremely thin film on the flutes because the liquid is drained off the raised sections toward the channels by surface tension. These corrugated tubes produce a very significant increase in condensation rate. Even with this enhanced heat transfer, the temperature difference available to the working fluid is still only about half that of the sea thermal gradient, or about 10°C. Thus the maximum possible efficiency is about 3.5%.

A second difficulty of the Solar Sea Power Project that is mentioned in the Carnegie-Mellon report is the working fluid. One of the fluids suggested is ammonia. This fluid admittedly presents a hazard for a manned installation, and calls for further studies of the practicality of unmanned systems, underwater installations and other alternatives.

The third major difficulty that is apparent in the scheme arises from the hostile ocean environment, which introduces two major factors: biological fouling and corrosion. All components are subject to fouling, but the heat exchangers will be particularly vulnerable. Various possible solutions have been suggested, each with its own technical or economic drawbacks. Typical possibilities and their disadvantages are:

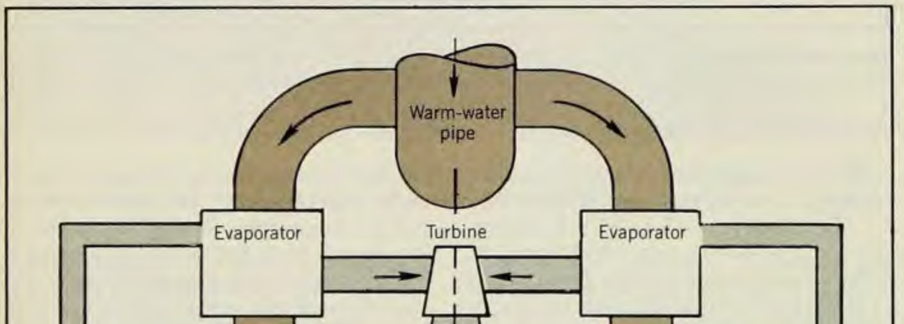
- use of 90% copper–10% nickel alloy (This alloy is expensive for the large areas involved.)
- use of aluminum with a continuous feed of chlorine into the water stream (Chlorine obtained by on-site electrolysis takes some of the power generated, and injection could cause a number of detrimental environmental effects.)
- use of a high water velocity flow to restrict biofouling to a thin tolerable layer (This method might cause an unacceptable corrosion rate.)
- use of aluminum with a loose copper helix within the tube, depending on a minute concentration of copper ions to inhibit fouling (This technique requires further demonstration.)

A solar sea power plant could be based on a modular concept, according to one proposal. For example, a 200 MWe plant would be made of six or more modules, each about 30 MWe. The Carnegie-Mellon study envisioned an unmanned stationary power plant with the cold water pipe in a vertical position, resting on the ocean floor. Start-up could be by means of a diesel generator capable of driving the pumps and auxiliary components for one module. Thereafter, one module could start the next, and so forth. By electrolyzing water and storing a sufficient supply of hydrogen and oxygen, each plant could be made self-sustaining once it is brought into operation.

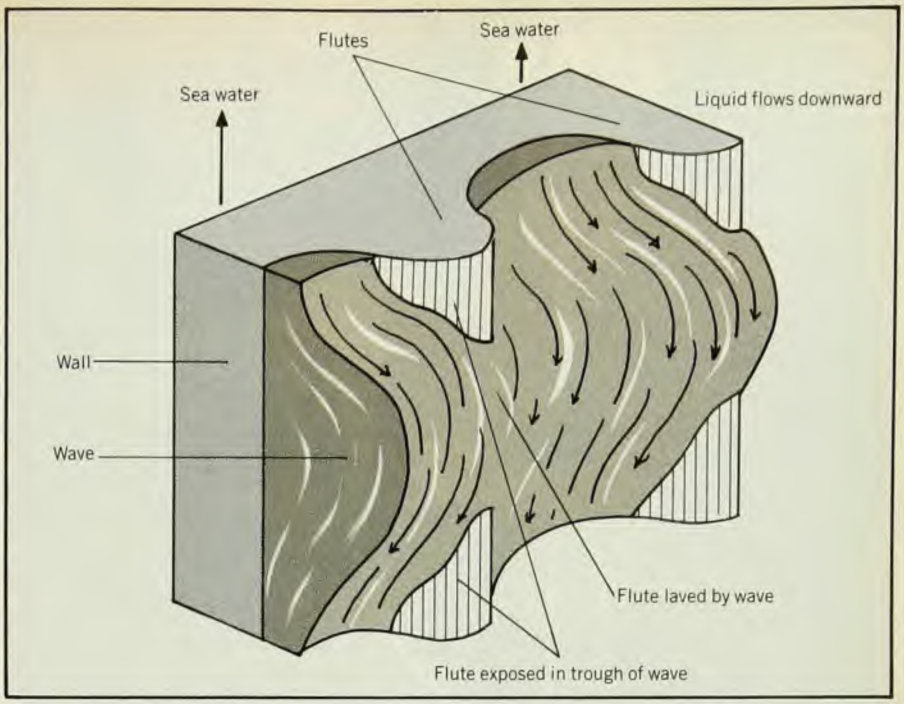
Intuitively one senses that capital costs for such a system would be high, but this high capital cost must be weighed against the low (in fact zero) cost of the fuel. Although cost estimates cannot be precise at this point, a reasonable estimate might be somewhere between \$500 to \$1 000 per installed kilowatt (based on 100 MW net output). By contrast coal- or oil-fired plants may exhibit lower capital costs; but the high cost of imported oil, or even coal, once stringent environmental requirements are met, has recently led to an estimate that nuclear plants costing \$850/kW would be competitive with oil-fired plants. Thus a solar sea power installation, free from the fuel and fuel processing costs associated with nuclear power, could be competitive at the high end of the estimated range (say at \$900/kW).

Still, economics should not be the overriding criterion for deciding whether the investigation of a particular system should be supported. Not long ago, some schemes were discouraged because they would be "equivalent to oil at \$5 per barrel" (at a time when oil was \$3 per barrel). Nor should it be necessary that a scheme be "*the* answer to the energy crisis." Furthermore, the time is past when simply demonstrating engineering feasibility will lead to the development of a technology. Broad social, political and national policy objectives must be included in the determination of whether large-scale implementation should be undertaken. With increasingly high capital risks it is clear that government support is required in the energy field.

The environmental effects of the solar-sea-power concept require careful study. If applied, the concept would extract energy from the ocean and perturb the thermocline. Although short-term



Solar sea power plant uses warm water from surface ocean layers to evaporate working fluid. Cold water from bottom condenses the fluid. The temperature difference is about 20°C. Figure 3 global effects might be small, local and long-term effects could be significant. Even though the volumes of water are a small fraction of the ocean, careful analysis of long-term global effects should be made—for example, with computer modeling techniques such as those developed at the Princeton University Geophysical Fluid Dynamics Laboratory.



Corrugating walls of condenser in solar sea power plant enhances drainage of water off surface. Increased heat transfer is important because of low net temperature differences. Figure 4

Geothermal energy

The search for new energy alternatives has intensified interest in using heat from below the Earth's surface. Working plants are in operation in several locations in this country and abroad. Even a brief study of the large volume of literature leads to some interesting observations. One is the large magnitude of the stored geothermal energy. A second observation is that the magnitude of the difficulty of extracting, converting and delivering this energy is equally large. Yet another feature of the literature is the wide variation in the estimate of costs, and in the optimism, for the delivery and conversion processes. Both lead to corresponding variations in the estimates of the available geothermal energy. The differing degrees of optimism can be illustrated by comparing two statements by "experts" in the recent literature. One asserted that geothermal energy probably will be insignificant as a factor in national power capacity (less than 1% of total) through the year 2000.[9] The other stated that "the power produced from geothermal sources should increase to the point at which it can satisfy a significant fraction of man's total energy needs."[10] The general tone of advisory statements however is best illustrated by the following assessment by Goldberger: "Most of this vast energy is too diffuse to be economically useful but the fraction of it that is concentrated and probably readily recoverable even with present-day technology is staggering. The utilization of this resource is well worth our attention."

The general geological phenomena involved in a geothermal source are shown in figure 5. Molten mass, or magma, still in the process of cooling, underlies solid rock, which conducts the heat upward. In some areas cold surface water penetrates to depths many kilometers beneath the surface and is heated and chemically altered by contact with hot porous rocks. Overlying rock prevents an upward convection cycle except for fissures—fracture zones created by faults or igneous intrusions. Hot water–steam vents appear as fumeroles, geysers or hot springs. The rock strata saturated with hot fluids or the fissures themselves may be tapped by wells.

Formations containing geothermal resources may be categorized in terms of the amount of water present—they may be wet or dry—or in terms of their temperature regimes. One of the four basic types are the **convective hydrothermal reservoirs.** These regions contain relatively high-temperature water at shallow depths. Into this category fall the vapor-dominated reservoirs, which produce dry or superheated steam. Such regions are the most sought-after because the steam is directly usable in low-efficiency steam turbines. The temperatures are 150° to 250°C. The only large geothermal power plant in the US—the Geysers in California—is a vapor-dominated region. Somewhat less desirable are liquid-dominated reservoirs, which produce hot water or a mixture of steam and water. Temperatures range from 90° to 350°C. Using such reservoirs to drive a turbine requires flash vaporization of the hot water and separation of the steam. This process results in low efficiency and serious waste-disposal problems. Unfortunately, this type of reservoir is believed to be many times more abundant than the vapor-dominated type.

A second basic type of geothermal resource is the **geopressured reservoir.** It consists of interstitial waters trapped in large deep sedimentary basins at temperatures from 150° to 180°C and pressures up to 6 000 psi. Well-production rates might amount to millions of gallons of fluid per day. Because significant concentrations of methane are dissolved in the fluid, this type of reservoir might be considered as a dual energy source.

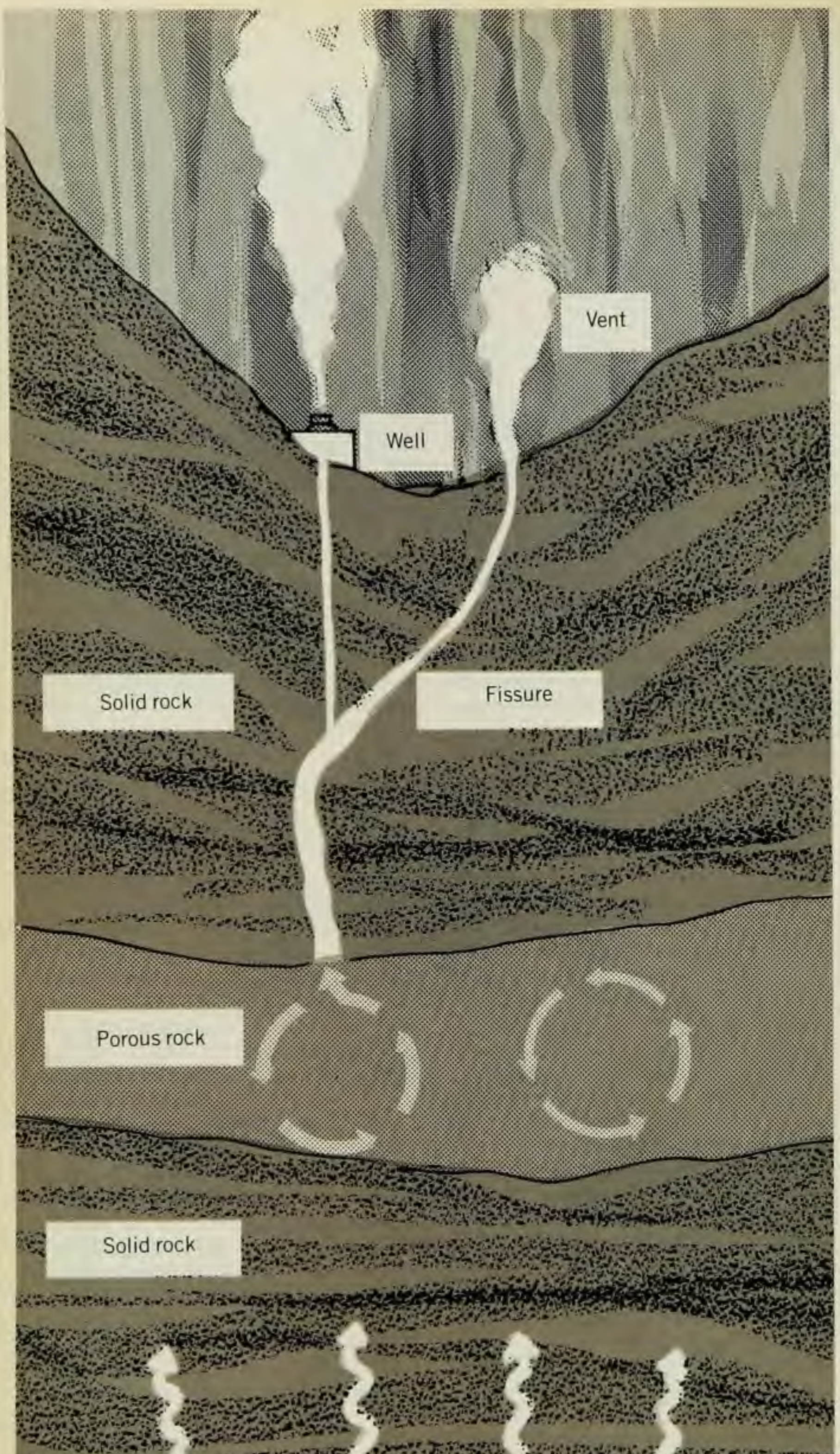
The **hot igneous systems** are a third type of reservoir. Such systems may consist of hot, dry rocks associated with active volcanism—not molten but very hot (around 650°C). Extraction of this energy would require artificial circulation systems. This category also encompasses magma, assumed still partly molten at temperatures above 650°C.

A final type of geothermal reservoir is the **conduction-dominated area.** Here, normal gradients are the result of heat flows, radiogenic heat production and thermal conductivity of rocks. Temperatures range from 150° to 300°C within the outer ten kilometers of the crust. Because natural fluid supply is generally inadequate except in parts of some sedimentary basins, artificial circulation systems are required to extract the heat.

The way in which the geothermal energy is tapped from these underground sources depends upon their temperatures. Those resources with temperatures exceeding 180°C are suitable for electric power production by direct steam or flashed steam. At moderate temperatures between 100° and 180°C the heat can be converted to electrical power by binary fluid conversion technology. Thermal waters with temperatures below 100°C are useful primarily for thermal energy applications.

How much geothermal energy?

The amount of heat energy contained in these various types of geothermal reservoirs might be usefully compared to the total annual energy consumption in the US. That figure is approximately 80 quads (80×10^{15} Btu) or 2×10^{19} calories. The estimated geothermal energy stored in the upper crust of the Earth—to a depth of ten kilometers—is 3×10^{26} cal. Beneath the US alone is stored 6×10^{24}



Heat from Earth's interior can produce steam to run a turbine-generator. In the convective hydrothermal reservoir above, hot magma heats solid rock above it. Ground water trapped in porous rock becomes superheated; as it escapes through either a natural fissure or a manmade vent it turns to pressurized steam. Dry steam reservoirs are most desirable but least abundant. Wet steam fields have hot water mixed with steam. Energy from hot dry rock might be extracted by developing artificial circulation systems. Figure 5

cal, the equivalent of the heat content of 8×10^{14} metric tons of coal, or about 300 000 times the annual US energy consumption.

Unfortunately this geothermal heat is too diffuse to be an exploitable commercial energy resource on a wide basis. Furthermore this heat is at a low temperature and results in low second-law efficiencies. Thus, unqualified accounting in terms of calories or tons of coal equivalent can be misleading. Geophysical techniques must be used to determine those local sites where heat is concentrated at attainable depths, in confined volumes, at temperatures sufficiently high for electric thermal power use.

The Geological Survey made just such a determination to estimate the *recoverable* energy from each type of geothermal reservoir.[11] They found that the combined vapor- and liquid-dominated convective hydrothermal regions have a potential of about 7×10^{20} calories recoverable above 90°C. (Hot-water-dominated are about 20 times more common than vapor-dominated areas.) Converted into electrical power at current efficiencies, this energy would produce about 45 000 MW-centuries. Current electrical use in the US is about 400 000 MW. Other estimates suggest that there are 8×10^{22} calories of recoverable energy in dry hot rocks, capable of delivering 8 500 000 MW-centuries of electricity. A comparable or larger amount of energy exists in known geopressured sources and in hot igneous systems, but techniques for recovery are unclear and costs might be prohibitive. The great bulk of the 6×10^{24} calories mentioned above is to be found in the conduction-dominated areas (normal gradient) and this would be the most difficult of all to concentrate for exploitation. As for an approximate cost figure, estimates based on limited experience to date indicate that for the most favorable category, hydrothermal reservoirs, installation costs would be in the neighborhood of \$500–\$800/kW, comparable to the solar-sea-power costs discussed in an earlier section.

The exploration, development and production of goethermal energy will require great improvements in drilling technology. Drilling is a billion-dollar a year industry in which apparently only incremental progress has been made for a generation. Severe problems can be anticipated in hot porous formations and especially in regions where a high-velocity flow of a geothermal fluid is encountered. More attention from physicists would benefit programs to develop improved methods for creating voids in rock by abraiding it with fluid jets or suspensions of hard particles; or by melting or vaporizing it; or by creating stresses by explosives, fluids, or thermal gradients. More imaginative, less conventional techniques may result from such attention and prove to be of key importance in the development of geothermal energy.

Geothermal energy has traditionally been attractive to environmentally concerned groups. It appears to be "clean," and the fact that the stored energy is already in the form of heat seems to suppress the environmental hazards of air pollution due to solid particulates and gases associated with fossil-fuel plants on the one hand and radiation associated with nuclear plants on the other. However, a look beneath the surface reveals that geothermal energy has its own array of potentially deleterious environmental impacts, predictable on assessment and borne out in practice to date. The major impacts include gaseous emissions, liquid-waste disposal and geophysical effects. Also, of course, there would be the inevitable thermal releases to the environment, shared with fossil and nuclear-fueled plants.

Atmospheric effects will result from the emission of noncondensible gases such as hydrogen sulfide and carbon dioxide. Traces of the following have also been found: hydrogen, methane, ethane, ammonia and boric acid. Radioactive effluents may also be present.

Except for noncondensible gases, substantially all of the chemical effluents are dissolved in the waste water. This water may flow into surface water and thus contaminate it. Predominant problem minerals are silica, and carbonate, sulfate, chloride and fluoride salts. For example, the water from the Salton Sea area contains more than six times the salt in sea water. The list of significant and trace elements found in natural and stimulated geothermal reservoirs is a long one, including sodium, chlorine, silicon, rubidium and mercury.

To prevent the immediate polluting effects of these elements, the waste water may have to be reinjected into deep wells. This procedure may in fact be necessary to minimize the subsurface geophysical effects associated with exploiting the resource: subsidence and seismicity. Because thermal resource areas are generally associated with regions of seismic activity, seismicity is an indicator used in prospecting for the resource. Also, continuous withdrawal of geofluids may well lead to land subsidence. Even reinjection of condensates may substantially alter existing stresses and normal patterns of earthquake activity.

Clearly the environmental impacts of geothermal energy development will require examination by experts in many disciplines. These experts will not come solely from technical areas: some of the impacts are social in nature.

Even this brief discussion of the geothermal energy resource makes it apparent that there are clearly identifiable roles for physicists. Representative challenges include the following:

- stimulating fluid production from presently unproductive hydrothermal reservoirs;
- creating fluid circulation in dry geothermal reservoirs;
- solving materials, environmental and mechanical problems associated with uttilization of mineralized geothermal fluids from relatively low-temperature heat sources;
- providing revolutionary (rather than evolutionary) advances in drilling technology in a difficult and dangerous environment;
- improving methods for flashing water to steam;
- designing improved efficiency, low-temperature power cycles.

Although this list is only a partial one, it serves to indicate the extent of the spectrum of problems that are suitable for the attention of physicists and associated with utilization of an important energy resource. Morton C. Smith of Los Alamos Scientific Laboratory once encouraged the participation of physicists in the field of geothermal energy but his words are appropriate to any energy problem in general:[10]

> "Physicists as a class have, historically, been greatly concerned with the problems of the microcosm and the megacosm, and in general have remained largely uninvolved in humanity's day-to-day problems of eating, drinking, breathing, moving about, and keeping warm. In a time of world-wide energy and pollution crises, it is heartening that a large group of physicists is now actively seeking ways in which their special types of knowledge can contribute to solution of the immediate problems that beset mankind and threaten his future."

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