Physics Today

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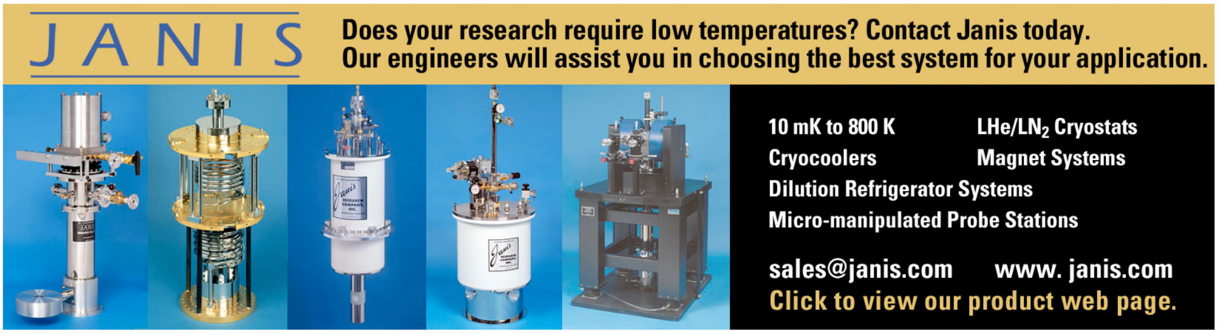
Citation: Physics Today **25**(2), 44 (1972); doi: 10.1063/1.3070725
View online: http://dx.doi.org/10.1063/1.3070725
View Table of Contents: http://scitation.aip.org/content/aip/magazine/physicstoday/25/2?ver=pdfcov
Published by the AIP Publishing



Physics looks at solar energy

Large-scale solar-powered "farms," covering thousands of square miles, could produce electricity cleanly and economically using technology we already have.

Aden Baker Meinel and Marjorie Pettit Meinel

The idea of using the sun as a source of energy has had a long history, but so far it has been a history of bright hope and dismal failure. In the middle 1950's newspaper headlines were full of glowing predictions of what solar energy could do for mankind; the first International Conference on Applied Solar Energy had been held, and solar energy seemed ready to take its place, along with peaceful uses of atomic energy and with interplanetary exploration, on Vannevar Bush's "endless frontier of science." And now in the 1970's nuclear power reactors and spaceflight are realities, yet solar energy, as recently as a year ago, was dismissed by a National Academy of Science–National Research Council committee as of no importance in our future—despite the admitted "energy crisis" looming ahead. Whatever happened to the grand predictions? Our search into the history of solar energy started with this question, because we were curious to know if 1970 technology might yield a different result.

We are all aware of the problems that face the successful transition from the present generation of nuclear power plants to the breeder reactor and the growing problem of disposal of the high-level radioactive wastes. We also read that, in spite of the advance made possible by laser ignition and by the Tokomak configuration, fusion power is still in the uncertain future. Our purpose here is to present our recent studies that may offer a new option—an option based on thermal conversion of solar energy—based upon current technology.

In reading about the history of solar energy it appeared to us that much of the work of the last two decades, with the exception of space applications, had approached solar energy from the wrong basic philosophical perspective. It has always been thought of as something for under-developed countries, those too poor to avail themselves of the world's other energy resources. It was conceived as something cheap and simple—simple enough to be operated by unskilled persons.

Another emphasis has been on solar-energy gadgets built on a scale suitable for the individual user—the dream of each household having a "rooftop" solar collector has been a recurring theme in the literature of the last 20 years or more. Even if such devices were economical, their big drawback would be the maintenance problem. With central-station power generation, nearly all maintenance is localized to the central station itself. Individual generators, on the other hand, would need individual servicing, and one would be faced with the need of finding a competent repair man.

The use of solar power by under-developed countries and the "rooftop" units have both been thwarted by the hard facts of economics, even though enterprising inventors can show us ingeneous ways to heat water and houses and operate cookers. We feel that solar energy must be viewed in a new perspective—as something for a technologically advanced nation, utilizing all of the arts of mass manufacturing, and operation on a large scale. Hundreds or thousands of megawatts per power plant begins to make sense when we want to obtain power at today's low electrical energy rates.

Figure 1 shows what such a power plant might look like, according to our proposals discussed in detail below.

Conversion methods

Solar energy can be converted to electricity in several ways. First is direct conversion, wherein a voltage or current is generated by the absorption of photons in a doped semiconductor such as silicon or cadmium sulfide. The second is by thermal conversion,

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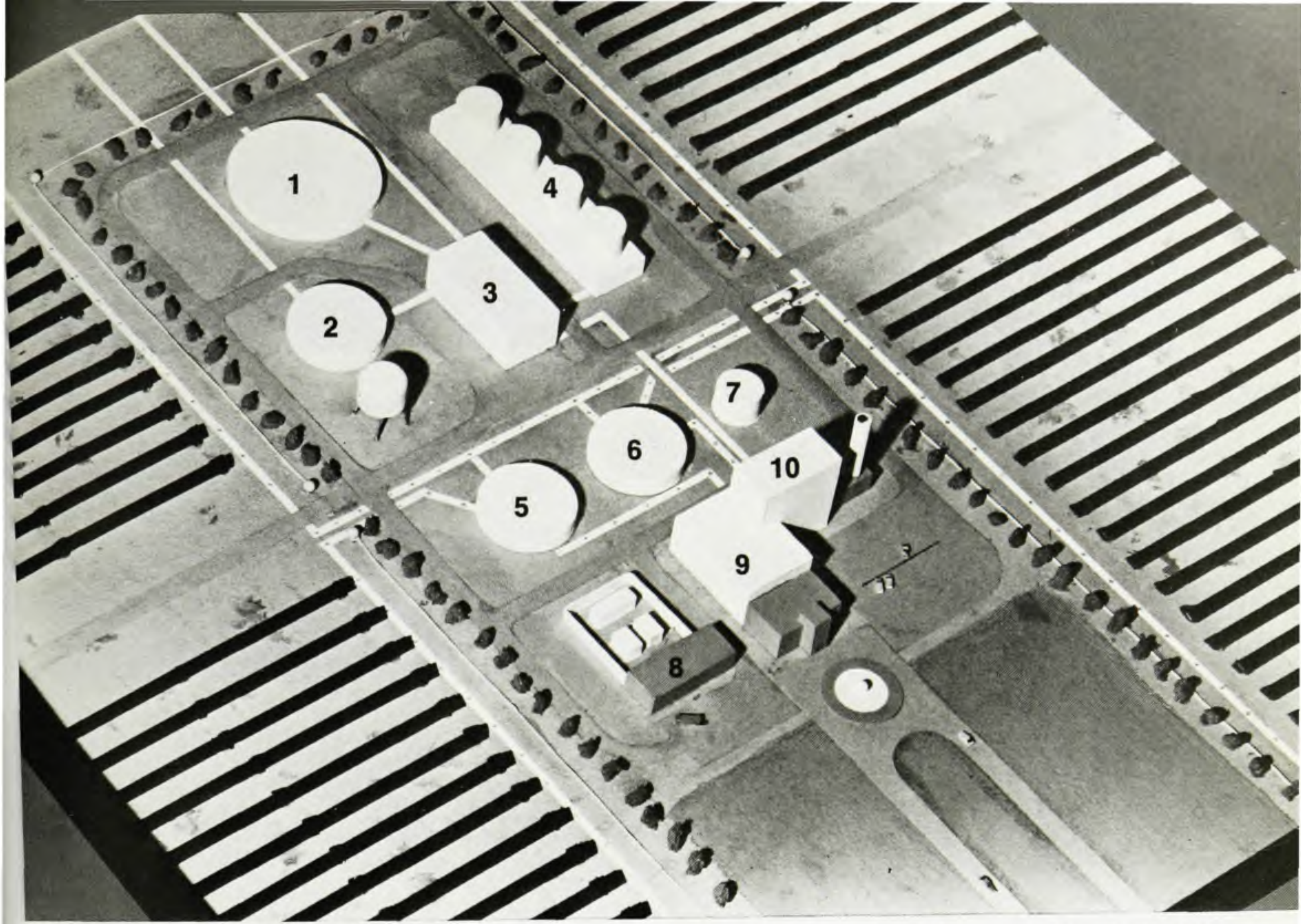
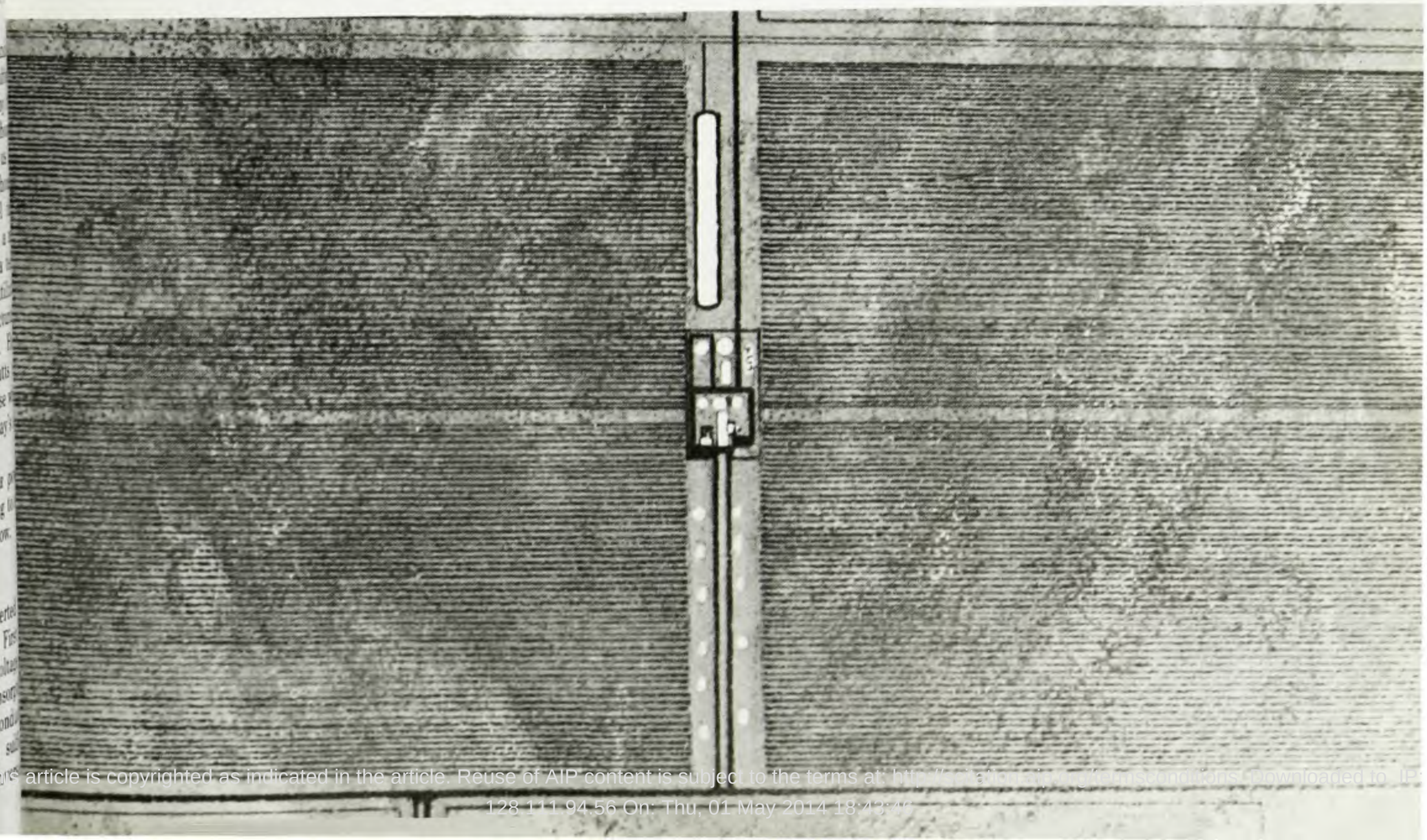
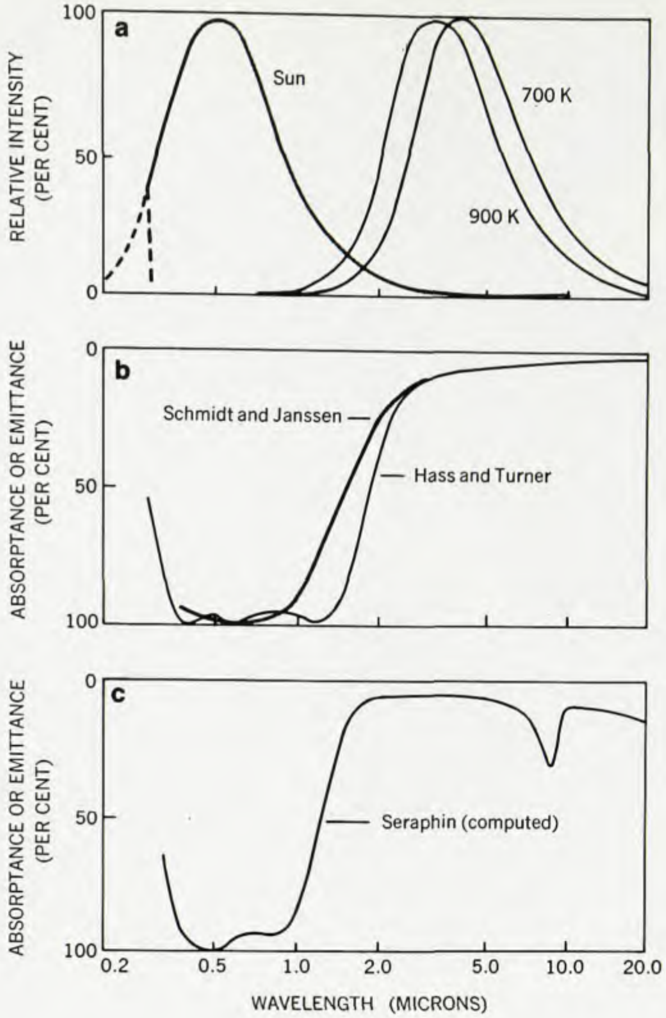


Model of a solar-power farm on typical desert terrain. Note that the rows of collectors noticeably darken the desert. This 250-MW power station would use turbine waste heat to desalinate seawater. Figure 1

1. Sea water **2.** Fresh water **3.** Desalting plant
4. Cooling tower **5.** Thermal storage A
6. Thermal storage B **7.** Oil reserve **8.** Maintenance
9. 250 MW(E) Turbine **10.** Boiler





Frequency response of selective surfaces. Approximately 90% of the solar spectrum (a) is at wavelengths shorter than 1.3 microns, and the escaping infrared radiation, even at 900 K, overlaps it very little. The selective surface must be black for wavelengths shorter than 1.3 microns and mirrorlike for the longer wavelengths. Interference stacks have the characteristics shown in b, and the bulk-absorber stack of figure 4 is expected to have the spectral performance shown in c.
Figure 2

wherein heat is converted into electrical energy by way of thermionic, thermoelectric or magnetohydrodynamic devices, or by ordinary steam power turbines. The third is through biological processes by the growing of crops and subsequent power generation by the thermal system.

Direct conversion via silicon solar cells is a well developed technology with wide application in spacecraft systems. The cost of silicon cells is high—several hundred dollars per *watt*—and it is this high cost that led to solar energy being dismissed as a resource for the future. Some new efforts are being made to lower costs and solve degradation under terrestrial weather conditions, but the prospects are clouded for the cost reduction of a thousand-fold that would be required to get the cost close to the few hundred dollars per *kilowatt* typical of bulk electrical power systems.

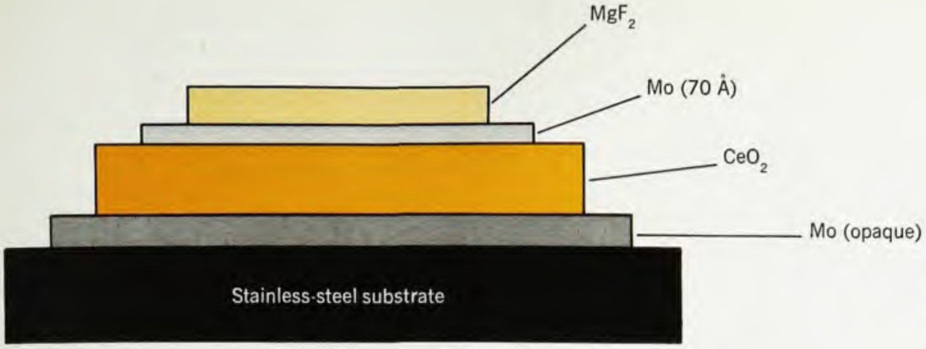
When we examine biological conversion, we find that each step in the process from the growing of the crop, such as algae or good Iowa corn, its harvest and conversion to methane, and its burning to provide steam power, is technologically feasible. A problem is apparent in a low net quantum efficiency, 1 or 2 percent, which requires that extensive land areas be devoted to the crop. The basic problem however, is economics: It appears impossible to approach a cost of the order of a dollar per million BTU's. Conventional fuels cost about 15 cents for coal and 35 cents for natural gas. A dollar per million BTU's of a crop means a cost of about ½ cent per pound of the harvested crop or 10 dollars a ton, far below the best cost figures for algae obtained to date.

The history of thermal conversion shows attempts to use steam engines or turbines driven by various working fluids but with very low efficiencies, of the order of 1 to 2 percent of the incident energy. The reason for this low efficiency is clearly assignable to the low operating temperatures of the devices. The obvious answer is to increase the operating temperature. In fact, why not operate them at the temperature and pressure of modern steam power turbines? They convert fossil fuels into electrical power at efficiencies of approximately 40%. Here we will adopt a provisional goal of a system operating at 500 deg C.

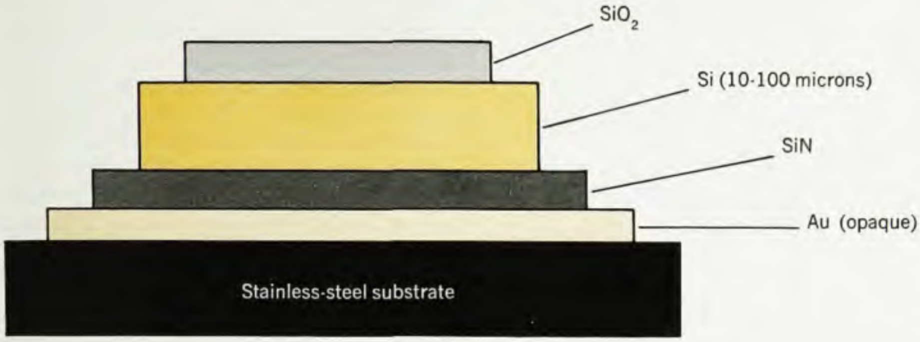
A search for the necessary technology for achieving high temperatures by an incident radiation field must start with the basic physics. Figure 2a shows the situation both for the incident solar flux and for the escaping infrared radiation, which is the dominant cooling mechanism when the absorbing surface is located in a vacuum enclosure. Approximately 90% of the solar spectrum is at wavelengths shorter than 1.3 microns. We want a surface that is black over this wavelength interval. Now consider the escaping radiation. Even at 900 K there is little overlap of the heat spectrum with the solar spectrum. Therefore it is possible to imagine a surface that is black for wavelengths shorter than 1.3 microns and low emitting—mirrorlike—at wavelengths longer than 1.3 microns. Such a surface will get hot because it inhibits the escape of the heat photons. The figure-of-merit for this selective behavior is the ratio of the absorptivity in the visible, a, to the emissivity in the infrared, e.

Selective surfaces

The peculiar spectral characteristic of the collector surface can be generated in a variety of ways. We have explored two avenues, both based on technologies that were still in their infancy a decade ago. The first is based on the principle of the interference filter, in particular, interference effects in metal–dielectric multilayer stacks. If sufficient complexity is permitted, such stacks can generate almost any spectral profile. Solar application, however, calls for longtime stability under high-temperature operation. Degradation of the delicate phase balance between the various component layers through evaporation or interfacial diffusion must be kept to a minimum. Figure 3 shows a promising interference stack made by Roger Schmidt and John E.



Interference stack made by Roger Schmidt and John E. Janssen, which has the optical characteristics shown in figure 2b.
Figure 3



Bulk-absorber stack proposed by Bernhard Seraphin, which is expected to have the characteristics shown in figure 2c.
Figure 4

Janssen at the Honeywell Laboratories. Its optical characteristic is shown in figure 2b. The classic stacks by George Hass and A. Francis Turner, although superior in their room-temperature profile, do not meet the requirements of high-temperature operation.

An alternate approach suggested by Bernhard O. Seraphin at the Optical Sciences Center employs the chemical vapor-deposition methods of modern semiconductor device technology for the fabrication of the solar collector surfaces. The double function of the surface—high absorption over the solar emission band and low emissivity over the black-body emission range—is divided between two different components. The high infrared reflectance of a noble-metal base layer suppresses the emittance. A thin semiconductor film deposited on top of the reflector catches the solar radiation through its intrinsic absorption. The steep absorption edge typical for semiconductors renders the absorber transparent in the infrared, so that the reflector "looks through." A silicon layer between 10 and 100 microns thick is a suitable candidate for the absorber. The absorption edge near 1.4-micron wavelength separates the spectral bands of figure 2a fairly well, and its technology is sufficiently established. The cross section of such an absorber stack is shown in figure 4. Note that the performance of the system relies on the intrinsic properties of the component materials with no phase-match between interfaces required. The reduced sensitivity to degradation, together with convenience and economy of the manufacture, recommend this approach. A projection of the expected spectral performance, calculated on the basis of available data for the optical constants of the component materials, is shown in figure 2c.

The basic uncertainty regarding these selective surfaces is their lifetime at high temperatures; this must become known for economic reasons. Some interesting physics may lie along the path to this answer.

Complete systems

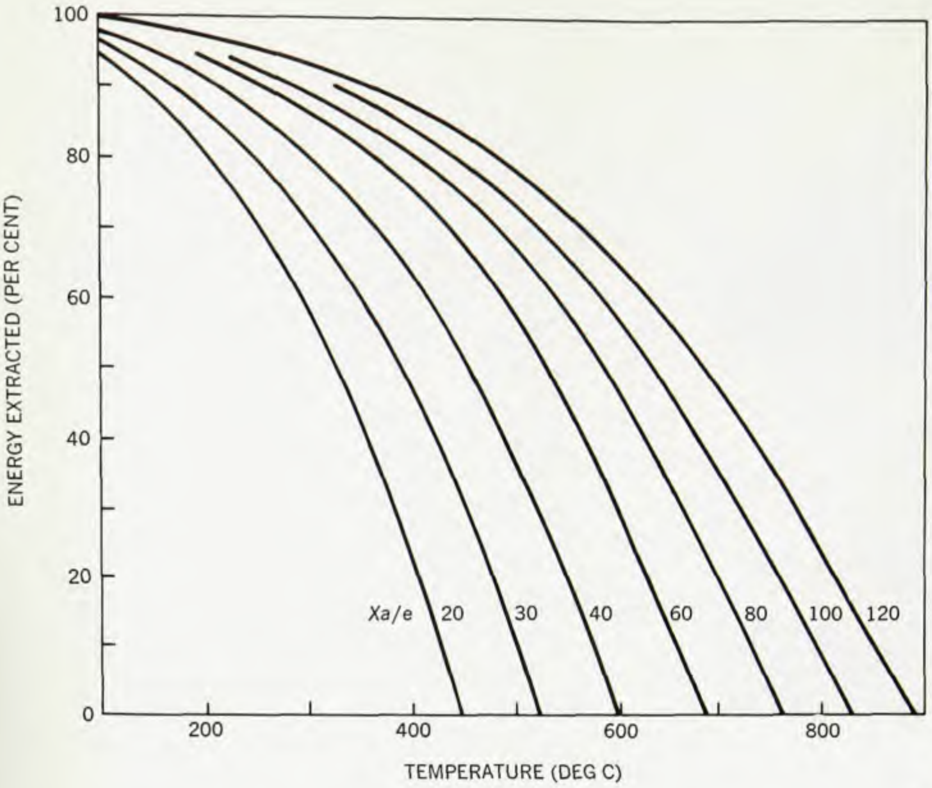
Today we can get selective films with an a/e of 10 at 500 deg C, and we have reasonable expectations of reaching higher values. The resulting temperatures are shown in figure 5, where X is the optical concentration of sunlight on the absorbing surface. On looking into the system engineering we find that selective coatings alone cannot reach the required temperature, since it must be higher than a stagnation temperature of 500 deg C if we are to extract energy from the surface. Setting a reasonable goal of being able to extract approximately 90% of the energy at 500 deg C we need a surface with $X\ a/e = 100$.

There are various ways to make a unit containing a selective surface, but we prefer the one shown in figure 6 as an engineering model. The flux concentration is provided by either a cylindrical Fresnel lens (or the equivalent parabolic reflector) injecting the energy through a window slot into an evacuated pipe that has a highly reflective inside surface. The selective surface is placed on the exterior of a steel pipe suspended in the vacuum enclosure, and the heat is extracted via a thermal fluid flowing inside the pipe. Engineering considerations point to liquid sodium as the fluid, but some organic fluids and salt eutectics could also be considered. A basic design that meets the requirements of $X\ a/e = 100$ is a surface that has $a/e = 10$ and $X = 10$, where X includes both the effect of flux concentration of the lens or mirror and the reduction in the effective emissivity due to the reflective cavity. These numbers represent modest values obtainable with current technology.

To understand how our proposed system extracts energy let us look at the operating parameters along a long collector element of the type shown in figure 6. The liquid sodium enters cool and increases in temperature until it exits at 500 deg C. The percentage of energy that is extracted as a function of temperature is shown in figure 5. The average energy extracted is therefore larger than that at the system operating temperature. A better way of estimating the effectiveness of the collector might be to multiply P by the Carnot potential at each temperature, since one is interested in the ability to extract power from the heat collected.

One must take a basic capability represented by the engineering model and make a meaningful system. Figure 7 shows a system consisting of three subsystems. The top portion is the energy-gathering subsystem, connected to the adjoining subsystem by means of a liquid-metal loop. This intermediate subsystem brings us face-to-face with the fundamental problem of solar energy; people like to have power 24 hours a day, and the sun only shines part of the day—and some days are cloudy.

Once energy has been converted into electricity it becomes awkward to store. This is a basic problem of direct con-



Energy that can be extracted from a selective surface, expressed as a percentage varying with surface temperature and surface quality Xa/e. X is the optical concentration factor, a the absorptivity in the visible and e the emissivity in the infrared.
Figure 5

version devices such as the silicon solar cell. One possible answer is storage batteries. In fact, in reading about solar-power inventions at the turn of the century, we often find that the inventor dismissed the problem because "cheap long-lived batteries are just around the corner." We are still waiting to turn that corner. Storage batteries are feasible only on spacecraft and in other special situations where cost is secondary and the required lifetime short.

Electrical utilities store some electrical energy for "peak-shaving" by hydrostorage, where water is pumped into an elevated storage dam during hours of excess power. This energy is collected later by letting the water flow down through hydroelectric generators. The problem for solar energy is one of magnitude, however. To store overnight energy for the US would require Lake Mead (Hoover Dam) to be filled and emptied every day. Also, people do not appear to like hydrostorage dams any more than they like a nearby power plant, as evidenced by the opposition to the "Storm King" project in New York.

Physicists store energy from their synchrotron magnets between pulses in mechanical form, using rotating flywheels. Imagine an iron flywheel 30 meters in diameter and 310 meters long; if they could be kept together at 6000 rpm, one would need 100 such flywheels to store enough energy for overnight for the entire US!

Conversion of energy into a chemical fuel such as hydrogen is also possible, but storage remains a major problem except in liquid form. The recent paper by Lawrence W. Jones in *Science*[1] points to some attractive consequences of using liquid hydrogen as a fuel in the future. Reconversion of a chemical fuel by burning is not particularly attractive, because it entails a second Carnot loss and reduces the total system efficiency by 60%. If cheap and long-lived fuel cells were available, this problem would be greatly reduced, but such devices are also still "around the corner."

The solution in the system that we have proposed is to store the energy needed for overnight and cloudy days in the form of thermal energy, prior to conversion. Figure 7 shows a thermal-storage subsystem with a salt eutectic wherein heat is stored as heat of fusion of the eutectic as well as bulk heat capacity of the material. Other material could be used as the thermal-storage medium, even liquid sodium itself, thus avoiding one heat-transfer stage. One needs a large mass of eutectic, about 320 000 metric tons per day of reserve energy for a 1000 MW power plant, but costs are low enough per kilowatt-hour to be reasonable; in fact, they are lower than hydrostorage of energy, as with the Luddington project of Consumers Power and Detroit Edison.

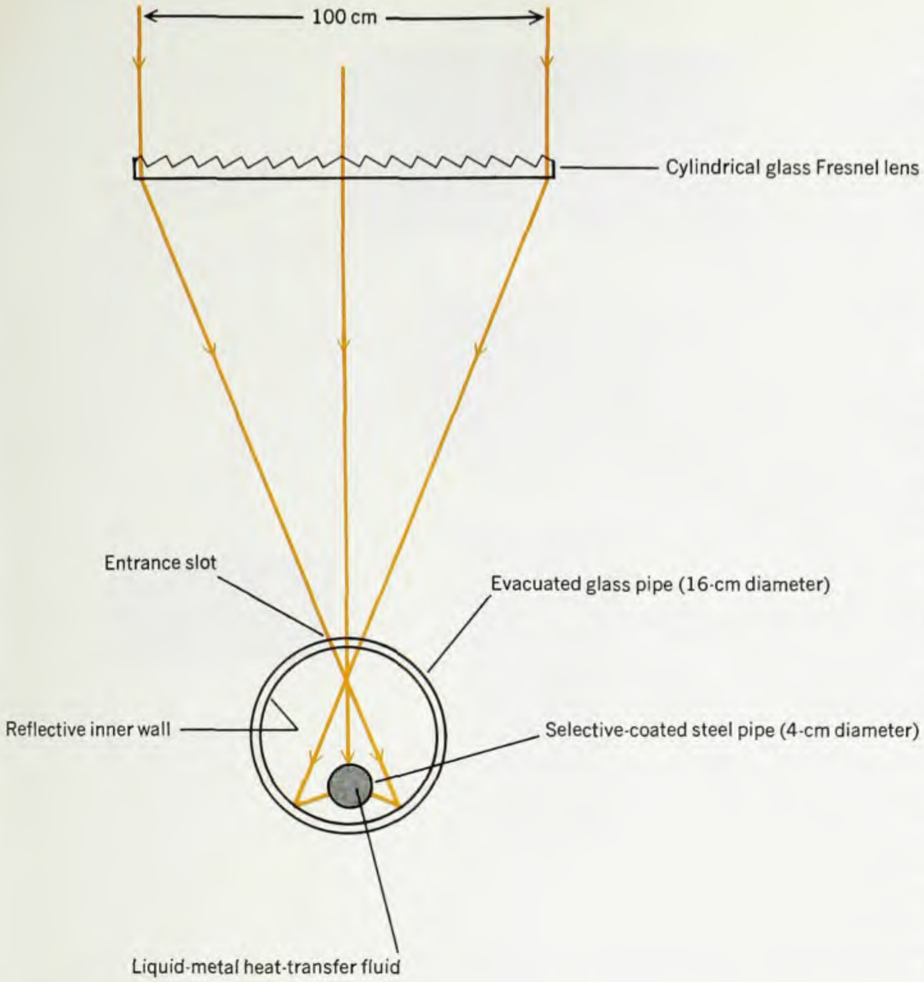
The lower part of figure 7 shows the "using" subsystem, in this case a standard high-pressure steam-turbine system. The turbine draws energy from thermal storage at the rate demanded by the utility, thus completely decoupling the rate of solar input from the use rate.

This diagram is highly simplified, and when engineers translate it into a practical system it can get quite a bit more complicated. For example, one does not simply dump heat into a tank and then attempt to remove it. Also, in actual operation various modes must be anticipated. The system can be made to collect energy on a bright cloudy day if a portion of the collector field is made with $X \leq 2$, but a subsequent clear day is needed to upgrade the stored, partially heated, eutectic. One also wants to minimize energy losses at night and the consequent thermal inertia in the morning. This can be done by purging the collectors of their hot sodium and storing it overnight. The empty system heats rapidly in the morning sun and the sodium is pumped back into the collectors.

Land use

A solar-power farm, according to our concept, is shown in figure 1. This illustration shows rather dramatically that solar energy collection requires large areas of land, even at 30% conversion efficiency. To produce 1 000 000 MW (electrical) of power, a substantial fraction of our probable need in the year 2000 (if one ignores the "exponential idiocy" currently used to make long-range predictions and instead substitutes a more rational *per capita* consumption prediction) our concept will require the area equivalent to a square 75 miles on a side, a bit over 5000 square miles of land, of which only 3000 square miles is actually covered with collectors.

In discussing these matters some time ago before a student gathering we got an immediate response from some of these students who thought that 5000 square miles was an intolerably large use of land. We realize that environment has become a special area of concern to many students, and sometimes perspective gets lost in enthusiasm. Our reply has been two-fold. First, we point out that the US has a long-established "energy project" that uses not the 5000 square miles that we propose but 500 000 square miles—and it only produces 1% of our energy needs. We are referring, of course, to farms and farming. Actually solar farms need less than one per cent as much land as is used by agriculture to produce a major fraction of the remaining energy needs.



Linear energy-collecting element, shown in schematic cross section. A "solar module" would consist of six to eight of these elements mounted on a single supporting structure.
Figure 6

Farms appear to be generally acceptable as one price we must pay for civilization. With power plants it seems to be different. In our talks to various groups (many with environmental interests), we note that there is a definite negative response to the words "power plant." We find no one really upset with "farms," so we take the visual appearance shown in figure 1 and call our concept "solar-power farms." This term is in fact correct, because the solar-power farm is producing a crop—an energy crop—out of incoming sunshine.

The second point is that we must establish a relative scale for land usage. An important fact was pointed out to us by Arizona Public Service Co, the operators of the negatively famous "Four Corners" power plant, the archetype of the strip-mined coal power plant. They noted that their engineering staff had reported they already have under lease more land for strip mining around that plant than would be required for its operation by solar energy—and with solar energy the Navajo's "sheep may safely graze" the area used. As a matter of fact, almost 2 000 000 acres of land are currently leased by the Department of the Interior and the Bureau of Indian Affairs for strip mining of coal for power plants and coal gasification, about the amount that would be needed for solar generation of the 1 000 000 MW (electrical) needed by the US in the year 2000.

If this is so, why not utilize solar power? The problem is that power is needed now and the strip-mined coal plants are required to meet that need. Even an intensive program, such as the "Apollo" program, could scarcely make solar power a significant contributor a decade from today. Our need for power dwarfs even the space program; however, it is not visible because private industry takes care of most of the task of building new power-generating facilities. In the past year approximately $17 billion will have been committed for new power plants. In that context even an average of a billion dollars a year for the next decade would be reasonable development costs, and such an effort could make solar power a reality because no technological or science breakthroughs appear to be needed.

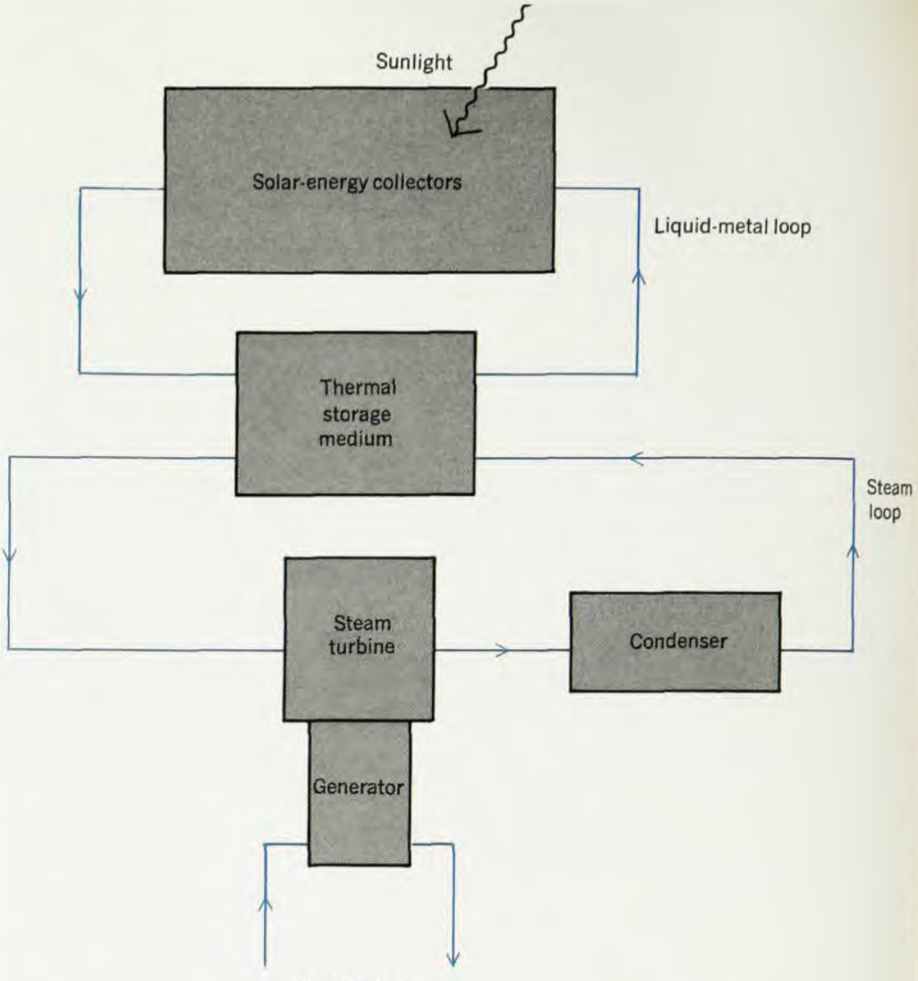
Note also a second aspect of figure 1. People ask us: "Won't solar collectors alter the climate of the desert?" The solar collectors do noticeably darken the average color of the desert. This is good: Otherwise the extraction of energy in the form of electrical power and the delivery of it elsewhere would cool the desert. One finds that the solar-power farm is so close to an exact local thermal balance that painting the ironwork of the collectors black or white makes a difference. Solar power is the only source of power conversion where careful design makes an exact local thermal balance possible. Even the use of geothermal power changes the local heat balance, not to mention the highly mineralized effluent that must be safely disposed of. Collection of solar energy does, however, increase the net thermal balance of the earth. The only way to balance this term is to "paint" other areas near the power-consuming areas white, to offset the blackness of the solar collectors. Then we could truly have "alabaster cities gleam . . ."!

The most suitable locations for solar-energy farms like these is in the great western deserts—particularly the area around the conjunction of California, Arizona and Nevada, and also the area along the Rio Grande valley in Texas and New Mexico. These regions are all very far from the major energy-consuming areas of the mid-west and the eastern seaboard; clearly, new technology will be required to develop efficient power-transmission lines for such great distances as these. Cryogenic alternating-current aluminum lines and superconducting direct-current lines are two possibilities already proposed. For the immediate future, transmission will not limit development of solar energy because the power needs of the southwestern and Pacific states would absorb any new energy they could produce.

Economics

Early in our studies it became clear that the central problem associated with solar energy would not be technical feasibility. We have identified the relevant technology as being available today. We are lacking only the verification of this technology and the construction of demonstration units. The central problem is economics. This hard fact will undoubtedly eliminate most of the contenders now being proposed as the new look at solar energy proceeds.

Let us assume that one can convert solar energy at 30% efficiency, a possible goal via thermal conversion following our concept. Assume also: The power must cost no more than 5.3 mills/KWh (energy cost), which is what the 1971 fuel cost is for generation using



Thermal conversion system. In this basic schematic model note the three subsystems —an energy-gathering subsystem at the top, a thermal-storage subsystem in the middle, and the "using" subsystem at the bottom. The turbine draws energy from thermal storage according to the demand, and the use rate is therefore decoupled from the solar-input rate. Figure 7

natural gas; the interest rate is 10%; the capital amortization is done in 15 years; the site has 330 clear days a year (for example Yuma, Arizona), and the lifetime of the plant is 40 years. One then has a budget of $60 per square meter for the entire collection and energy-storage system. This cost represents a tight constraint but we feel it can probably be met.

The waste heat from the turbines of our solar energy farms, which must be returned to the environment to preserve the thermal balance, can constitute a new energy source if it is properly handled. The critical need of the Southwest at present is not power—it is water. Why not use the waste heat from solar energy farms to desalinate seawater? If one were able to use the waste heat from 1 000 000 MW (electrical) of farms one could produce 50 billion gallons of fresh water per day, enough for 120 million people. There are, however, a few problems in finding that much saline water and in safely disposing of the resulting brine.

We feel that the quest for solar power can represent a great domestic research goal for the next decade. There are many questions to be explored, and some interesting physics must be done. For example, understanding and predicting the diffusion phenomena that will be the determining factors in the lifetimes of the thin films is essential in accelerated testing of these thin films. There will be much engineering to be done, such as determing the best way to inject and extract heat from the thermal storage media. We hope that public awareness of the importance and potential reality of solar energy will soon make it possible to begin this effort with the necessary resources. We are convinced that some day, perhaps within the next century, mankind will view the deserts of the earth as one of earth's greatest resources.

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This article is adapted from talks presented at the 1971 Fall meeting of the American Physical Society's Division of Nuclear Physics, in Tucson, Arizona, and at the January 1972 joint APS–AAPT meeting in San Francisco.

Reference

1. L. W. Jones, Science **174,** 367 (1971). ☐