Solar Thermal Electricity: Power Tower Dominates Research

The centerpiece of the government's solar energy program is proceeding from small to large tests in a fashion that is remarkably parallel to the well-established pattern of nuclear reactor development. Big facilities, big expenditures, and a multidecade development program all characterize the program for centralized solar thermal generating stations.

The eventual cost will probably not be as large as the development bill for a reactor system, but the yearly payment is already great enough that it dominates the relatively small solar program. At the present time, the project to develop the "power tower" is consuming 60 to 70 percent of the research money devoted to the conversion of sunlight into thermal energy and thence electricity. It is still far too early to judge how successful the power tower will be, but the project is a paramount example of the tendency of the Energy Research and Development Administration (ERDA) to favor centralized solar concepts and to route the development of such concepts through its own laboratories.

This is the second in a series of Research News articles examining recent development in solar energy research.

The power tower concept is a way to collect solar energy from a large field of mirrors and to convert it into heat at a high enough temperature for efficient electrical generation. Optical studies show that the best way to get the high temperatures is with a point-focusing mirror that tracks the sun (heliostat), and systems studies made by the Aerospace Corporation in 1974 found that the cheapest way to combine the heat from many such mirrors was to focus them all on a single boiler set atop a large tower. Steam from the boiler can produce electricity in a conventional turbogenerator. There are some engineers who favor a central system using mirrors that are not point-focusing and others who question whether the cost savings are not offset by practical problems—the tower for a 100-megawatt plant would be about 1000 feet tall. But both ERDA and the Electric Power Research Institute (EPRI), the utility's research arm, are betting heavily that the power tower, with the benefits of "photon energy transport," is the best design for a centralized solar thermal generating plant.

Although there is some criticism that the solar program gives too little support to alternative centralized generating concepts, the research area that appears to be hardest hit by the power tower's generous funding is the development of intermediate-temperature solar thermal systems that would most likely be used on a smaller scale. Systems that employ mirrors that are less optically sophisticated than those of the power tower can convert sunlight to heat in a very useful temperature range, above the 100°C limit of flat rooftop collectors and below the 500°C level achieved by point-focusing heliostats. The intermediate-performance mirrors are generally variations of parabolic troughs—line-focusing elements that track the sun in only one direction during the day. They concentrate sunlight by a factor of 10 to 40 and focus it onto an evacuated tube suspended above the trough.

Small Systems May Compete

Intermediate-temperature systems are less efficient than heliostats if used for electricity generation alone, but they are simpler, cheaper, and more readily adapted to applications where, in addition to electricity, they produce heat for warming or cooling. A recent report* prepared by the Office of Technology Assessment (OTA) estimated that the useful annual output of a parabolic trough collector (that is, energy delivered after thermal and optical losses are taken into account) may be only 10 percent less than the output of a heliostat. Because of the lower temperature, a parabolic trough system would convert less energy into electricity. But by utilizing the waste heat, such systems could achieve an overall efficiency that exceeds the typical efficiency (16 percent) expected for a power tower central station. Intermediate-temperature collectors and systems that use them to produce both heat and electricity (called "total energy" systems by ERDA) will be discussed further in a future article.

The economics of small systems and intermediate-temperature systems are not well known—in large part because so little money has been available to study them. But one of the most striking conclusions of the OTA report is that there is "no clear indication that large solar electric plants are more efficient or produce less costly energy than small, onsite facilities."

Recent changes have upgraded research on solar-electric systems for nonutility applications, but the bulk of solar electric research is devoted to technologies designed exclusively for large electric utilities. In the solar thermal subprogram, ERDA spent $60 million on central systems in fiscal 1977 (almost all of it for the power tower), while allocating $9 million to total energy systems. This was the case despite the fact that small systems have the potential for making energy contributions in the near future. Very large solar thermal electric stations, because they are being developed according to the nuclear analogy, are unlikely to make a contribution to commercial energy supplies in less than 20 years.

Thus, much like the breeder reactor, the power tower is scheduled to proceed from a small test to the first commercial plant in four stages. If bar graphs for the two projects were overlaid, they would show a striking similarity. The first solar stage is a 5-megawatt thermal (Mwt) test facility due to be completed next year near Albuquerque, New Mexico, for $21 million. The second will be a 10-megawatt electric (Mwe) pilot plant to be built near Barstow, California, at a cost of $120 to $130 million; construction is due to begin in 1978. These two stages, funded entirely by the government, are due to be followed by a 100-Mwe demonstration plant in the mid-1980's and finally a 100-Mwe prototype commercial plant in the 1990's. As with the breeder, the government hopes to share major parts of the costs of the latter two projects with the utilities that will use them. One difference in the solar case is that the utilities, through EPRI, are contributing small amounts of funding for studies in parallel with the first phase of the government program, and a California utility group is contributing $20 million to the Barstow project.

Whereas the government's nuclear program nurtured four large heavy-equipment companies that are now the sole suppliers of nuclear reactors in the United States, the power tower program

*"Application of Solar Technology to Today's Energy Needs," a two-volume report by the Office of Technology Assessment of the U.S. Congress published June 1977, Washington, D.C. 20510.

Fig. 1. The $21 million power tower test facility at Albuquerque, New Mexico. Seventy-eight sun tracking mirrors or heliostats are in place, and eventually 200 more will be added. The mirrors focus sunlight on the top of the 200 foot tower, on which experimental boilers will be tested. Note the pickup trucks in the background to indicate the scale of the facility.

is dispensing the bulk of its work to four large aerospace contractors. The companies that are building test hardware for the Albuquerque facility and competing for contracts on the much larger Barstow facility are Martin Marietta, Honeywell, McDonnell-Douglas, and Boeing. If the power tower proceeds apace, their names will become as synonomous with solar electricity as the names Westinghouse, General Electric, Combustion Engineering, and Babcock and Wilcox have become with nuclear power. The success of the power tower concept will probably hinge on the development of the novel high-technology components, such as collectors, receivers, and thermal storage units. But the rate of development will more likely be controlled by the logistics of designing and building the sequence of solar plants, which will be huge construction projects requiring large amounts of steel and concrete.

Commenting upon apparent similarities with nuclear development, the newly appointed head of ERDA's solar thermal branch, Gerald Braun, says that common features are less deliberate than automatic. "Because you are looking at something at the same scale," says Braun, "you go the same way. But there was certainly no intention to follow the nuclear model."

The name power tower has a friendly ring to it which conjures up something on a human scale. A view of the Albuquerque facility illustrates how large the system will actually be (Fig. 1). The tower is the height of a 20-story building, built with 5700 cubic yards of concrete. The collectors at the Albuquerque test site will cover 100 acres. Each heliostat is anchored with a 10-ton concrete footing. As the collector field size increases, higher towers are needed. The tower for the Barstow plant will be about 500 feet high, and double that height will be needed for the customarily projected commercial size plant producing 100 megawatts.

A commercial power tower generating plant would cover about 1 square mile of land, probably at a desert site, collecting sunlight from as many as 10,000 heliostats. In the designs produced by the four ERDA contractors, the heliostats are 37 square meters in area and they concentrate the sunlight by as much as a factor of 1000. To counter the effect of passing clouds, the ERDA pilot plant will have a thermal storage capability for 3 hours electrical generation. Although the storage could allow operation to continue briefly into the early evening, the plants are primarily intended to supply electricity to meet the midday diurnal load (often called an intermediate load) experienced by most utilities. The ERDA plans call for a steam (Rankine) cycle that would require a considerable amount of cooling water, but the concept favored by EPRI (a Brayton or gas turbine cycle) would require little or no cooling. The ERDA power tower concept would operate by evaporative cooling, and would use about as much water as a comparably-sized fossil plant.

According to most estimates, the major factor influencing the costs of the power tower plant will be the design and cost of the collector. The shape of each collector must approximate a parabola focused on the receiver, but the four aerospace contractors have accomplished that end in rather different ways. Three of the contractors have designed mirrors using steel and glass construction, while Boeing has designed a mirror made of aluminized polyester stretched across a circular frame (Fig. 2). The Honeywell design uses rectangular mirrors mounted on a geared tracking frame that tilts in two directions. The McDonnell-Douglas heliostat is a solid dish, made of 8 mirror segments, mounted on a radar pedestal. The Martin Marietta heliostat uses nine mirrors mounted on a common tracking frame. In some cases, the flat mirrors have to be stressed slightly to give a parabolic shape, and the facets have to be aligned to point at a common focus.

The Boeing heliostat is potentially less expensive than the others because it uses very lightweight materials. The collector is protected from weather, wind and dust by a plastic bubble supported by air pressure. Boeing estimates that the optical loss that occurs when sunlight passes through the bubble (about 20 percent) is more than compensated by the cost reduction achieved by using light, thin materials. All four heliostats follow the sun by tracking along two axes. The Boeing and Honeywell versions are directed by computer control. The other two versions will be controlled by feedback signals from a sensor in the reflected beam of each heliostat.

The four contractors have each tested about half a dozen heliostats built as prototypes for the 10 Mwe Barstow plant. Data on their costs and performance may become available soon, since ERDA is due to decide on the preferred prototype next month. Heliostats of the same size have been ordered and built for the Albuquerque facility, and their costs have been quite high—in the range of $500 to $1000 per square meter. One critic has commented that, so far, the heliostats being produced by the aerospace firms are being delivered at "aerospace prices." This is also the price range of satellite tracking antennas, which are parabolic dishes and resemble heliostats in a number of ways. Clearly an important challenge to the power tower program is the problem of reducing these costs. The official goal of the ERDA program, which many observers consider unattainable, is a cost of $70 per square meter.

The reason that the heliostat cost reduction is so crucial is that the heliostats may represent 60 percent of the total cost of a power tower plant. There has been a wide range in early cost estimates prepared by McDonnell, Martin Marietta and Honeywell—from $40 per square meter to $96 per square meter. In a study of the detailed economics of many types of solar electric systems, Richard Caputo at the Jet Propulsion Laboratory concluded that with careful development work a heliostat cost of $145 per square meter (in 1975 dollars) should be attainable. But he indicated that the costs could go higher. At a cost of $145 per square meter, he calculated that the plant capital cost would be $2000 per Kwe.

The group of four aerospace contractors, minus Boeing, which is only studying the heliostat subsystem, is preparing designs for other components of the 10-Mwe plant. The design of the receiver that will sit atop the tower may determine to a large degree the ultimate size of a power tower plant. Cavity-type receivers appear to be considerably more limited in total power than externally mounted receivers. Two of the contractors, Martin and Honeywell, are planning cavity receivers, while McDonnell-Douglas proposes to use an external receiver.

The heliostats of a power tower will require manufacturing techniques that meet exacting tolerances (0.1° alignment), but many solar engineers think that the greatest problem will be the receiver or boiler. With very high concentration of sunlight, the power density inside the receiver will be quite high and variable. (Some designs offset the focus of different groups of heliostats slightly to spread out the power profile.) Nevertheless, the materials used in the boiler must be able to withstand instantaneous changes in energy densities from 0 to 5 megawatts per square meter. Although the receiver may be kept operating overnight at a reduced temperature to ease the problem of a start-up each morning, the system will be subject to frequent temperature cycles. According to Charles Backus at Arizona State University in Tempe, "The design of the absorber or boiler for this concept will be the major technical challenge."

The analysis contained in a power plant study conducted for EPRI tends to substantiate and—if anything—carry further Backus' critique of the problems to be encountered in developing a power tower receiver.

Under a contract to Black and Veatch Consulting Engineers of Kansas City, EPRI commissioned a conceptual study of the general features of a large system that would use a gas turbine (not steam) generator (Fig. 3). The EPRI study found that the best operating temperature, twice that of a steam turbine system, would be so high that it would rule out the use of metals in the high-temperature face of the receiver cavity. Instead, the study recommended the use of ceramic (silicon carbide) heat exchanger tubes and highlighted problems with installing the ceramic tubes and suitably insulating the hot air ducts in the plant.

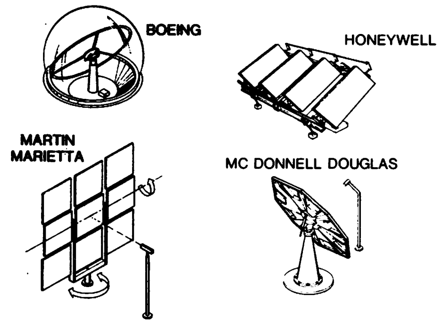

Fig. 2. The heliostat designs proposed for ERDA's 10-megawatt solar thermal pilot plant.

The gas turbine power tower study also took a novel approach to the problem of energy storage, and gave some concrete indications of the size of a commercial installation. Rather than use a huge and expensive tank for energy storage, as the ERDA concept would, the EPRI concept would use fossil fuel (oil or gas) firing of the solar turbine as a backup option, one that would add very little extra cost. The tower would have two large decks at the top to hold the 750-ton receiver and the 880-ton turbine. The EPRI study found that providing stability against wind and seismic activity for the heavy load at the top would be the principal structural problem in designing the tower. The overall efficiency of the system was calculated as 18 percent and the cost was estimated between $1250 and $1660 per kilowatt, depending on heliostat costs. The study concluded that hybrid (fossil-solar) operation was feasible and in fact desirable, since fossil fuel can serve the purposes of both short- and long-term energy storage.

Although most power tower research is focused on large towers and large heliostats, there is a smaller, cheaper, simpler power tower that has been operating successfully for more than a decade. First tested by G. Francia at the University of Genoa in 1965, the system uses mirrors one meter in size, controlled by a common mechanical drive, and collects the light in a receiver hung from a short, lightweight steel tower. The system is now available in a package from ANSALDO, SpA, the major heavy electrical equipment manufacturer of Italy. A 400-kwt system, built by ANSALDO and delivered to the Georgia Institute of Technology, is due to begin operation late this summer (Fig. 4). According to Steve Bomar at Georgia Tech, 75 percent of the mirrors are aligned and the system is scheduled to make steam for the first time in August.

With a range from 400-kwt working models to 60- to 150-Mwe conceptual studies, the optimum size of a power tower plant is a matter of much guessing and some reevaluation just now. Braun at ERDA says that when the preliminary designs are in hand later this summer the agency will be in a position to rethink the validity of the 100-Mwe goal chosen 3 years ago. Charles Grosskreutz, now at the newly inaugurated Solar Energy Research Institute, says that the 100-Mwe

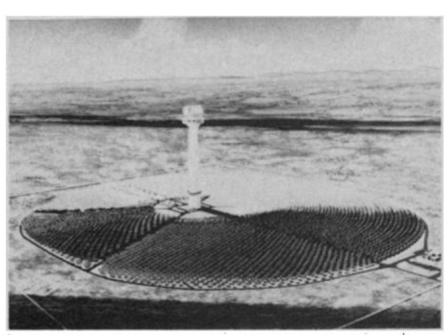

Fig. 3 (left). Artist's drawing of a 60-megawatt solar generating plant following the engineering design of an Electric Power Research Institute study. Fig. 4 (right). A small, lightweight power tower due to begin operation this summer at the Georgia Institute of Technology. The system, using 550 mirrors and sized to produce 400 kilowatts of thermal power, is based on the design of Giovanni Francia.

size was not "the result of a careful study in which someone found a curve with a dip in it," but a reaction to practical limiting factors. The administrator who is in charge of evaluating the competing design studies, Alan Skinrood at the Sandia Laboratories in Livermore, California, says that it is "fairly clear" that the optimum plant size for the United States is 50 to 200 Mwe.

The outcome of the design competition may shed more light on the thinking of those in the ERDA program, because one design (Martin Marietta) has a maximum modular size of 10 Mwe. The Martin scheme would be to build up a 100-Mwe plant from ten or more modules. Its technically limiting feature is the use of a narrow-angle cavity-type receiver in a north-facing tower.

Whatever the outcome of the aerospace competition, it is clear that the costs of power tower systems are far too high just now. The present price of collectors is about ten times the $70 price ERDA set as a goal, and the total pilot plant costs—which will be over $10,000 per kilowatt for the Barstow facility—are in excess of those in other energy technologies that have reached a similar stage of development. The ERDA plan is to reduce these costs—particularly for heliostats—by bulk manufacturing techniques and steadily improved designs.

But the economies of scale presumed to be possible with large power towers could prove illusory, and the benefits of systems on smaller scales may be overlooked and forgotten by the time the final answer to the power tower is known. In particular, the rule of thumb that "energy transport by light is more economical than by heat" may only be true for large systems, The heat losses in piping depend on the average distance in the heat transport system, so the economics of distributed collectors connected to a generator by heat (rather than light) transport should cross over and become favorable at some point. For much the same reason, total energy systems should be preferable on small scales. But the energy agency appears to be supporting such projects principally as a backup in case the power tower project should fail.

The history of the nuclear development program offers some pointed lessons in the dangers of over-concentration of effort on too few technologies. In a huge development program, the ideas of talented workers may be wasted because of the necessity of working within rigid management structures on programs with externally imposed goals. For a number of technologies there is very little choice. But for solar energy, even for the specific purpose of converting solar energy to electricity via thermal systems, there are many choices and new inventions are appearing rapidly. It would appear to be far too soon for the solar program to be discarding innovative options and sinking its research money into steel and concrete.

—WILLIAM D. METZ

Electron Probe Microanalysis: New Uses in Physiology

Elemental analysis can be performed on samples that are orders of magnitude smaller than samples that can be analyzed by conventional techniques. Elements within substructures of cells can be identified and quantified. Ionic movements within cells and across cellular membranes can be studied with ease. These are but a few of the many problems that can be solved with electron probe microanalysis (EPM), a 25-year-old technique that has only recently surfaced in biology.

EPM, also known as x-ray microanalysis or analytical electron microscopy, was developed by Raymond Castaing of the University of Paris in 1951 and its use was quickly adopted in metallurgy and mineralogy. Theodore A. Hall of Cambridge University pioneered in the use of EPM for study of hard biological samples, such as bone, but preparation of other types of biological samples proved much more difficult. Within the last 5 years, though, preparation of liquid samples has become almost routine, and preparation of tissue samples is nearing that stage, so that EPM is beginning to have significant application in biology. The results obtained thus far have been so impressive that many scientists now feel that EPM may be more valuable to physiology than electron microscopy has been to anatomy.

The heart of an EPM spectrometer is an electron beam with which the sample is bombarded. When an individual atom is struck by the beam, one of its inner-shell electrons is boosted into an outer shell of higher energy. Relaxation of the atom—refilling the inner-shell vacancy—is accompanied by either emission of a low-energy Auger electron or emission of x-irradiation at a wavelength characteristic of the atomic number of the element. Heavier elements are more likely to emit x-irradiation, whereas lighter elements are more likely to emit Auger electrons. The x-irradiation is collected for analysis of the sample in EPM, but elements lighter than magnesium emit so little radiation that they can be studied only with difficulty. Elements lighter than boron have no outer electron shells, and thus cannot be studied at all.

For many applications, the emitted x-irradiation is collected with what is known as a wavelength-dispersive spectrometer. In this device, each wavelength of interest is diffracted onto the detector by an appropriate crystal; several such crystals can be mounted on the probe simultaneously. The intensity of the radiation that reaches the detector is directly proportional to the quantity of the element in the sample. The characteristic wavelengths of the elements, furthermore, are generally well separated, and there is little overlap. It is thus possible to identify and quantify each element unambiguously. In most cases, it is possible to analyze a sample for as many different elements as desired.

The electron beam itself can be focused into a very small circle; routinely, a diameter of 50 Å can be obtained but, with special equipment, the diameter can be as small as 3 Å. It is thus possible to analyze small samples or small areas of a sample. The EPM spectrometer is frequently attached to an electron microscope, so that the user is able to identify visually the precise portion of the sample that is in the beam. Visualization can also be achieved with a light microscope. A good example of the wavelength-dispersive EPM spectrometer can be found in the Biotechnology Resource in Electron Probe Microanalysis at Harvard University. The Harvard facility, headed by Claude P. Lechene, was built to demonstrate the utility of EPM for studying biological materials.

Biological samples can be divided into two major categories—liquid droplets and intact cells or tissues. The easier of these to study is liquid droplets. With EPM, elemental analysis can be performed routinely on liquid droplets as small as 10 picoliters (10^{-12} liter) provided that the concentration of the desired element is at least 100 parts per mil-