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Solar Central Receiver Power Plants

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A. C. Skinrood

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ABSTRACT

The first solar central receiver pilot plant will be built in Barstow, California, starting in 1978. Experimental versions of competing subsystem designs have been constructed and tested. Sandia Laboratories is evaluating the technology that resulted from these experiments in order to develop a recommendation for the conceptual design for this pilot plant.

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SOLAR CENTRAL RECEIVER POWER PLANTS

10-MW Pilot Plant

A two-year research and development program to develop the necessary technology for a 10-megawatt electric (MW_e) solar central receiver pilot plant (Figure 1) has been completed. This represents a major milestone in the Energy Research and Development Administration's program to collect and use solar energy to produce electricity on a commercial scale. This pilot plant, the first of its kind, will be built in Barstow, California, starting in 1978. It will provide data on direct operating costs and will aid in identifying solar plant operational unknowns and indirect costs, all of which must be defined in order to assess the economic viability of a commercial central receiver power plant. The central receiver concept, illustrated in Figure 2, consists of a field of individually controlled mirrors, or heliostats, that redirect the sun's energy to a receiver mounted on top of the tower. In the receiver, the highly concentrated solar flux heats a circulating fluid that is then used directly to power a conventional steam turbine generator or is stored for later use.

Under the sponsorship of the Energy Research and Development Administration and the technical management of Sandia Laboratories, Livermore, California, three contract teams--headed by Honeywell, Martin Marietta, and McDonnell Douglas--have completed parallel and competing programs to develop conceptual designs for the pilot plant. Concurrent with these efforts, a fourth contractor, Boeing Engineering and Construction, designed a heliostat that could be incorporated into the three pilot plant designs. During this design period, the contractors built and tested experimental collectors, receivers, and storage subsystems to assess the technical feasibility of several designs. Sandia Laboratories is evaluating the technology that resulted from these contracts; based upon the results of these evaluations, Sandia will recommend a conceptual design for the pilot plant to ERDA. Upon completion of the design selection process, contracts for the pilot plant construction will be awarded early in 1978. A utility team headed by Southern California Edison Company is providing partial funding for the plant and will participate in its design and construction. The plant will be operated by Southern California Edison and will be connected to its grid network. In addition to ensuring technology transfer to private industry, the participation

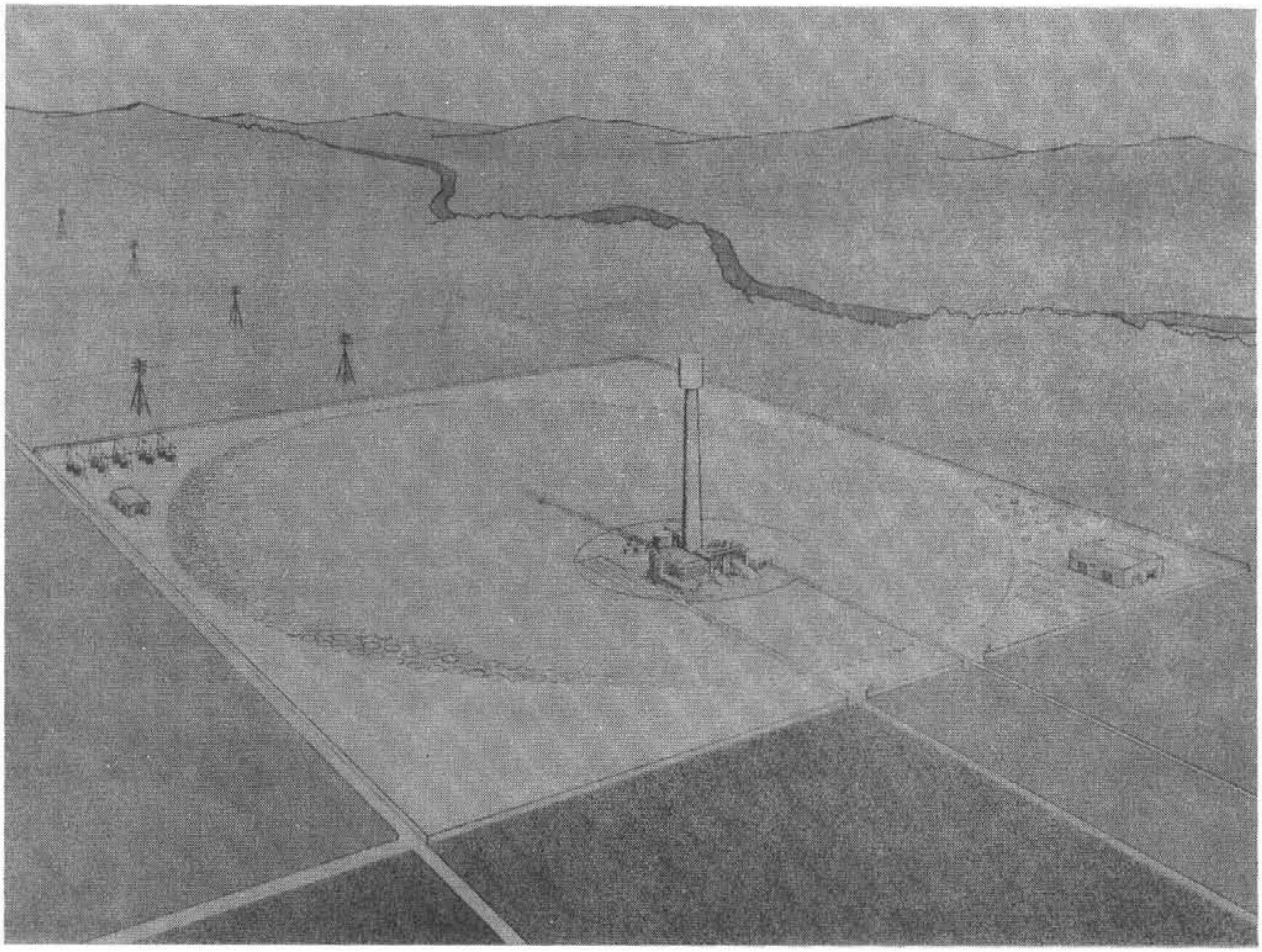

Figure 1. 10-Megawatt Solar-Electric Pilot Plant

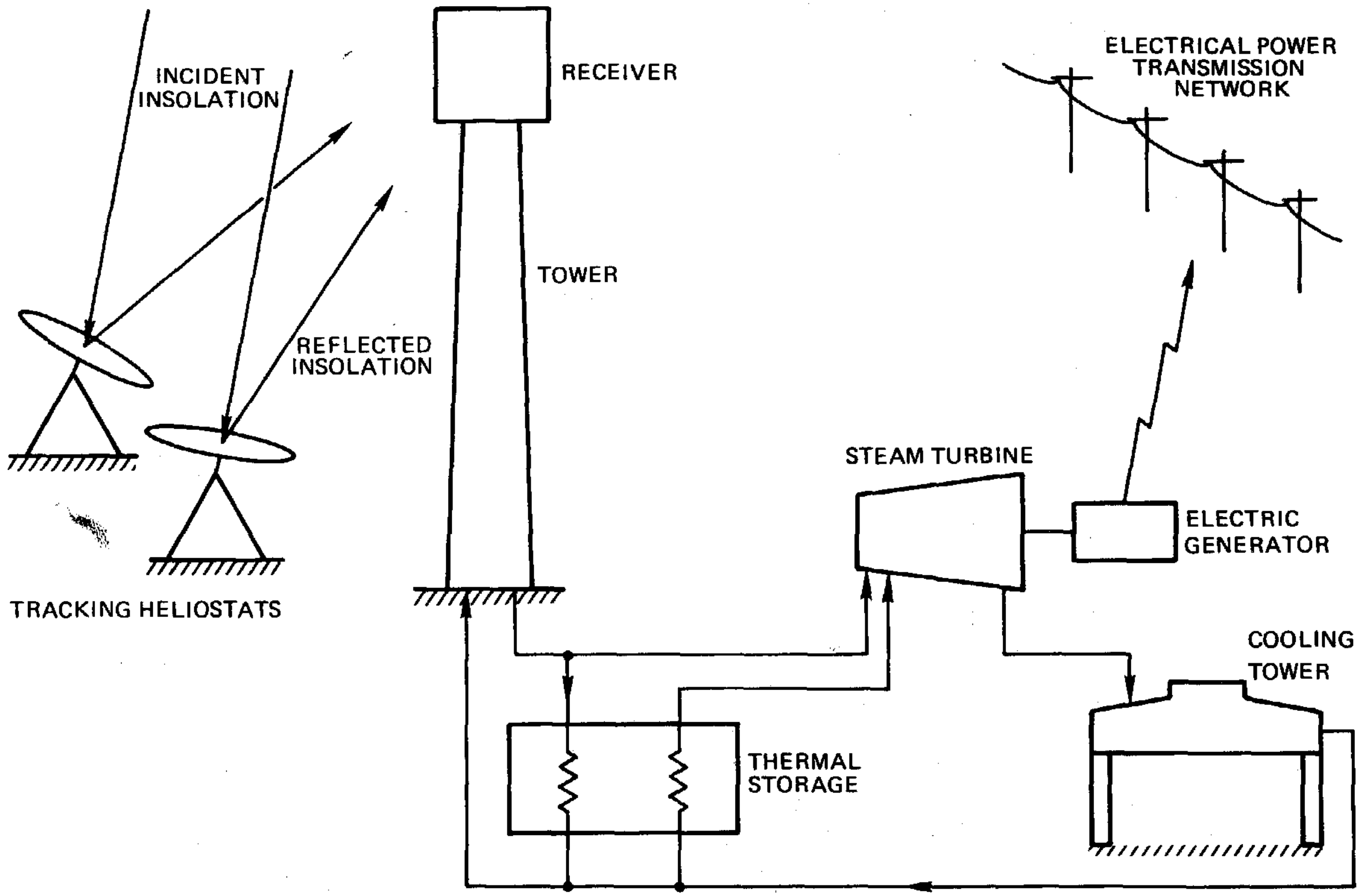

Figure 2. Central Receiver Solar Thermal Power System

of Southern California Edison brings to the program necessary expertise in power plant design and operation.

Why the Central Receiver Concept?

The rationale for the commitment to the central receiver concept is based on a number of factors. First, studies have shown that this concept is one of the more economically viable of the proposed solar power concepts. Second, large-scale demonstration of the concept within 10 years looks feasible without technological breakthroughs. Commercial technology in the power generation field, such as turbine and steam generator systems, can be integrated into this relatively straightforward solar power concept.

Third, tracking heliostats can produce relatively high concentrations of solar flux (1000 suns or more). This concentration minimizes radiation and convection losses, which leads to high receiver efficiency at high temperatures [500°C (900°F)], and reduces the required heliostat area. A field of modular reflectors was chosen since a single steerable reflector large enough for commercial power applications would be feasible only in space, not on the Earth's surface. (Approximately 0.7 km^2 (0.3 sq. mi.) of reflector area is required for each 100 MW(e) of capacity.)

Fourth, the transmission of the power optically may be more cost-effective than other concepts such as the distributed focused collector systems. In distributed systems, the energy is absorbed in a fluid at each collector and is then transported via a matrix of conduits to a central point.

Proposed Design

The preliminary designs porposed by the three contractors all require approximately 100 acres of land for the 10-MW_e plant. About 1500 heliostats, each with approximately 40 m^2 of reflective surface, will be required for the 10-MW_e plant. As shown in Figure 3, both the Honeywell and McDonnell Douglas teams have proposed that the tower be surrounded by a heliostat field; the Martin Marietta approach is to locate the tower on the southern edge of a sloped field. Boeing used the McDonnell Douglas receiver for designing its field configuration.

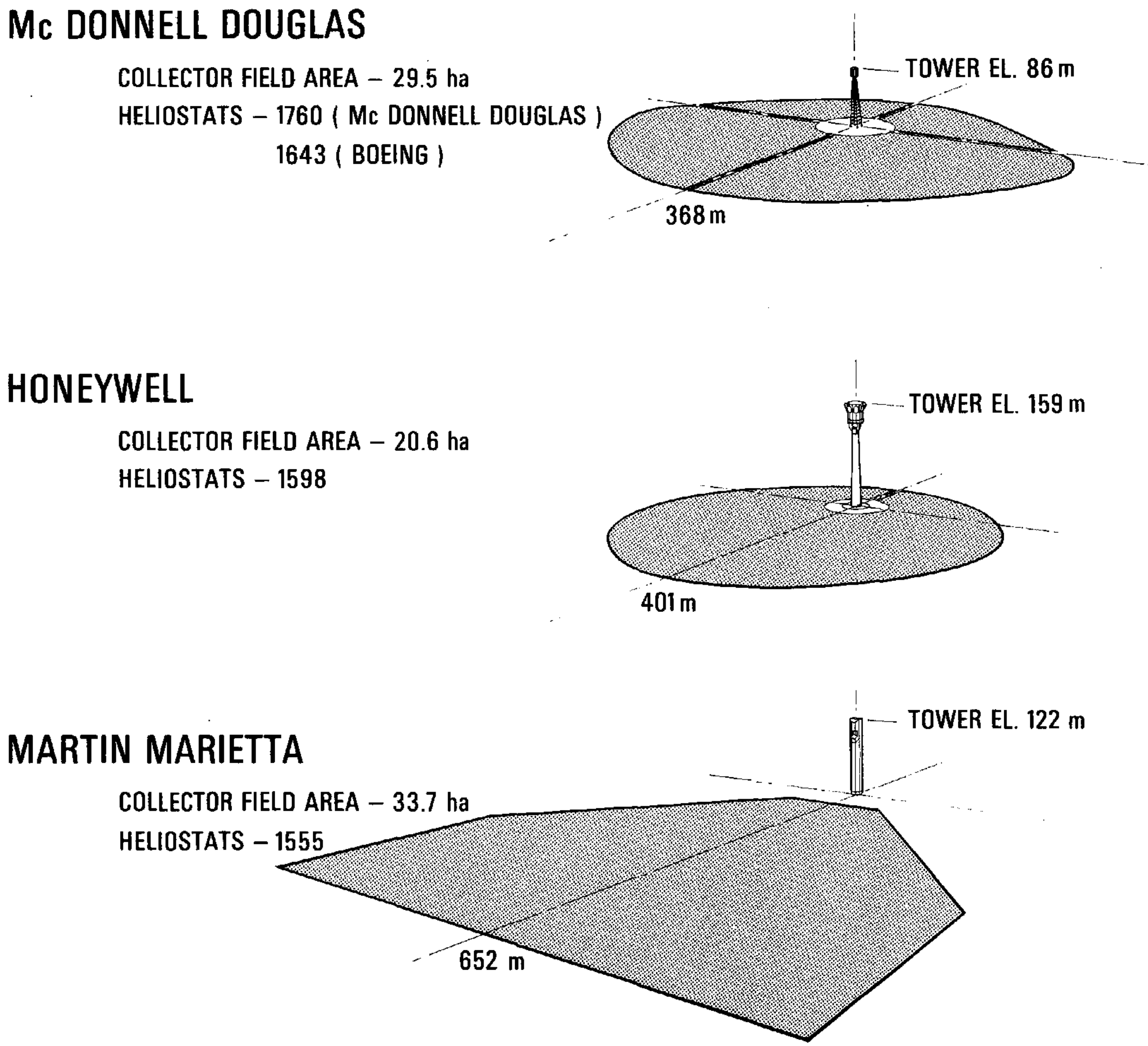

Figure 3. Heliostat Field Designs

The three pilot plant receiver/tower designs are illustrated in Figure 4. All of the receivers are drawn to the same scale to give an indication of the difference in the size. The Honeywell and Martin Marietta pilot plant receivers offer efficiencies of approximately 84 and 94 percent respectively. (Receiver efficiency is the ratio of energy transferred to the working fluid in the receiver to that incident on it.) They both consist of cavities in which energy is absorbed on the surface of coolant tubes that line the inner walls. The major difference between these two concepts is that the Martin Marietta cavity has a side-facing opening to accept heliostat-reflected solar radiation, while the Honeywell cavity aperture faces downward. The cavity designs use separate boiler and superheater sections integrated with an intervening steam drum. In contrast, the McDonnell Douglas receiver is an external boiler made of numerous vertical tubes in which the boiling and superheating processes occur in a single pass. The cavity designs are somewhat heavier. Honeywell weighs 600 metric tons and Martin Marietta weighs 420 metric tones, compared to 160 metric tons for the McDonnell Douglas receiver. This receiver, as designed for the pilot plant, has an efficiency of approximately 84 percent. McDonnell Douglas proposes to use a higher incident flux in commercial sizes of this receiver, which would result in an efficiency of 90 percent.

All three receivers presently under consideration are designed to use water/steam as the circulating coolant. This approach was chosen because of low technical risk. Although it is possible that other coolants could lead to higher system efficiencies, water/steam is an existing commercial technology with little development required.

Honeywell built an experimental receiver and successfully tested it to a power level of 3.8 MW_t at the Northern States Power Company in Minneapolis, Minnesota. A radiant heat lamp array installed in the interior of the cavity simulated the solar energy which would be redirected from a heliostat field. Martin Marietta built a 5-MW_t experimental receiver which was successfully tested in the Sandia Laboratories Radiant Heat Facility in Albuquerque, New Mexico. Quartz heat lamps were used to heat the boiler tubes. McDonnell Douglas built a single panel which was a full-scale representation of one of the 24 panels proposed for use in the pilot plant receiver. The panel was successfully tested at a maximum power level of 0.5 MW_t in the McDonnell Douglas B-1 facility at Los Angeles, California.

The four heliostat designs developed are illustrated in Figure 5, and experimental versions of these heliostats are shown in Figures 6 through 9. With each of these designs, the goal is to accurately orient the mirror surfaces (often allowing only a few milliradians of rotation) in winds up to 13 m/s (30 mph) and survive in 45 m/s (100 mph) winds. Other important requirements are maintaining high surface reflectivity, long lifetime, and minimum maintenance. The distinctive features of the Boeing design are the lightweight aluminized polyester film mirror and the transparent air-supported Tedlar

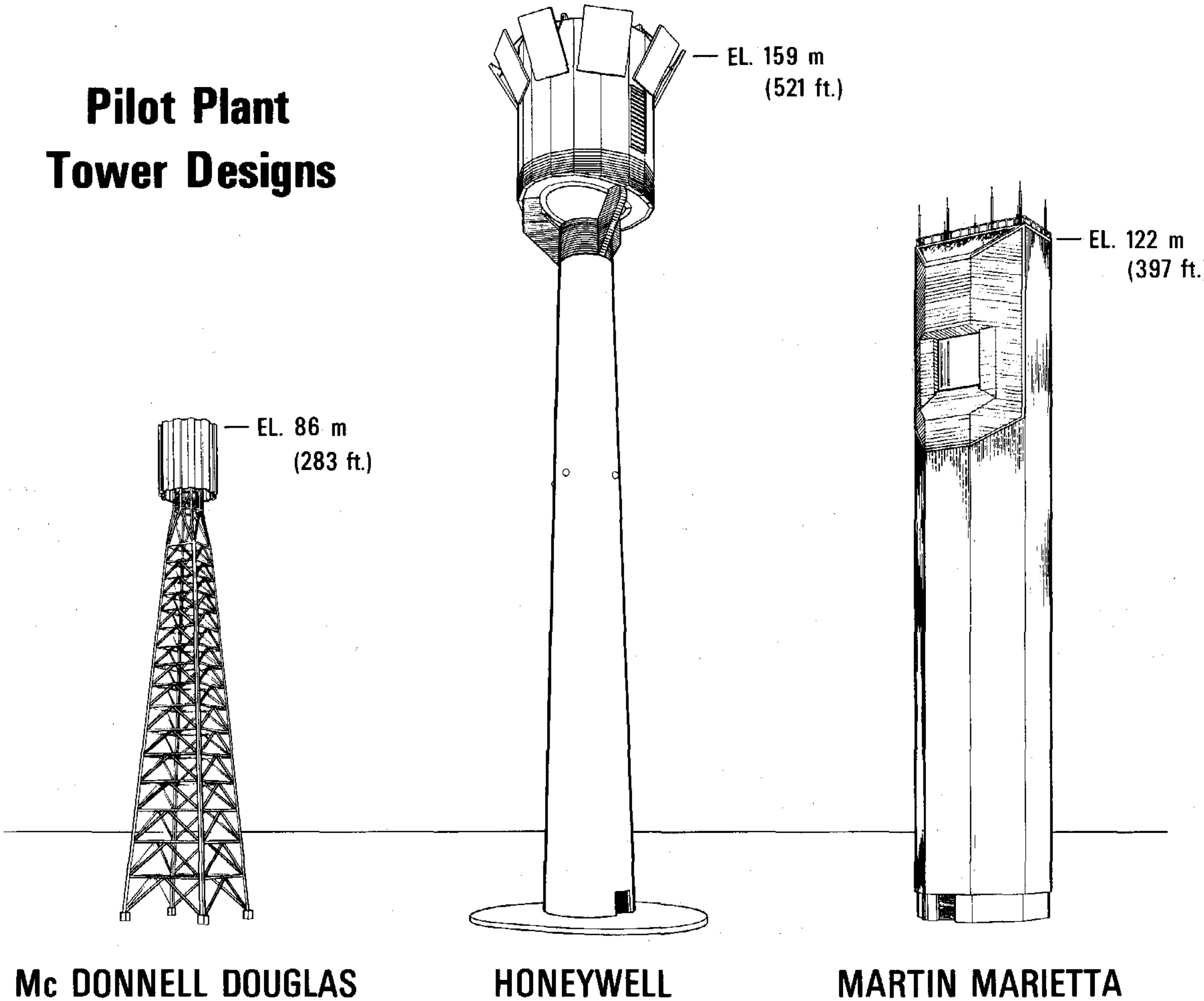

Figure 4. Pilot Plant Receiver/Tower Designs

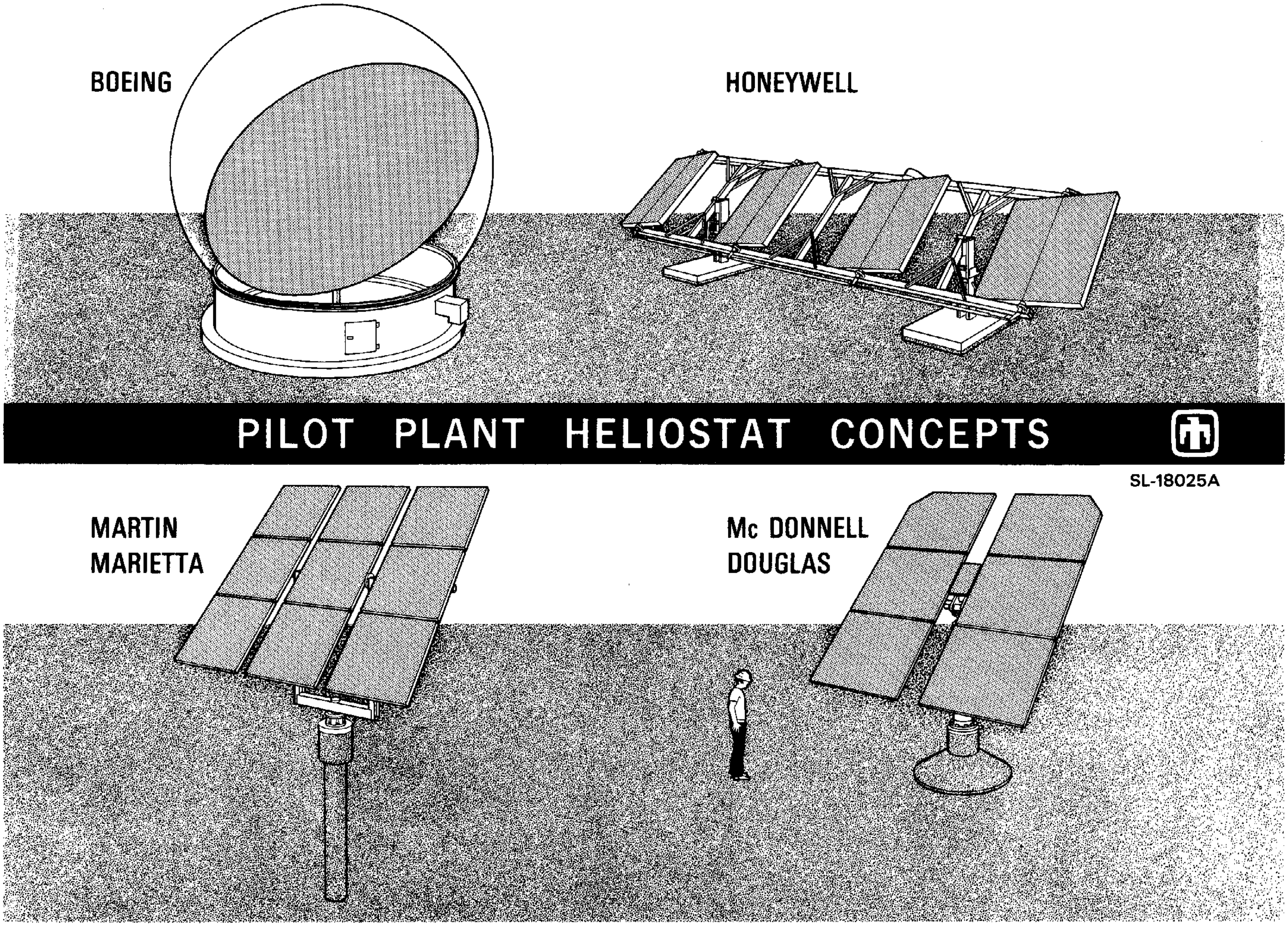

Figure 5. Pilot Plant Heliostat Concepts

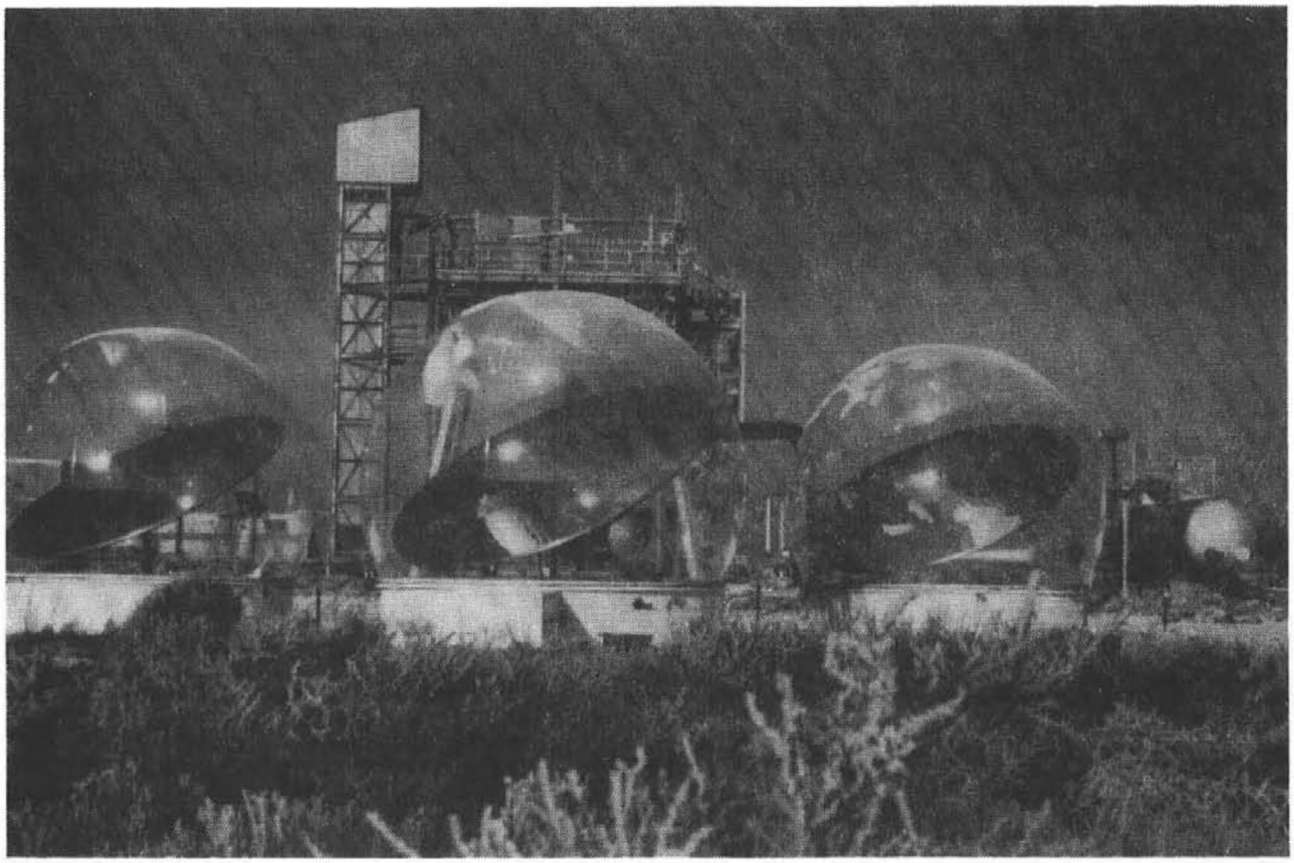

Figure 6. Boeing Heliostat Design

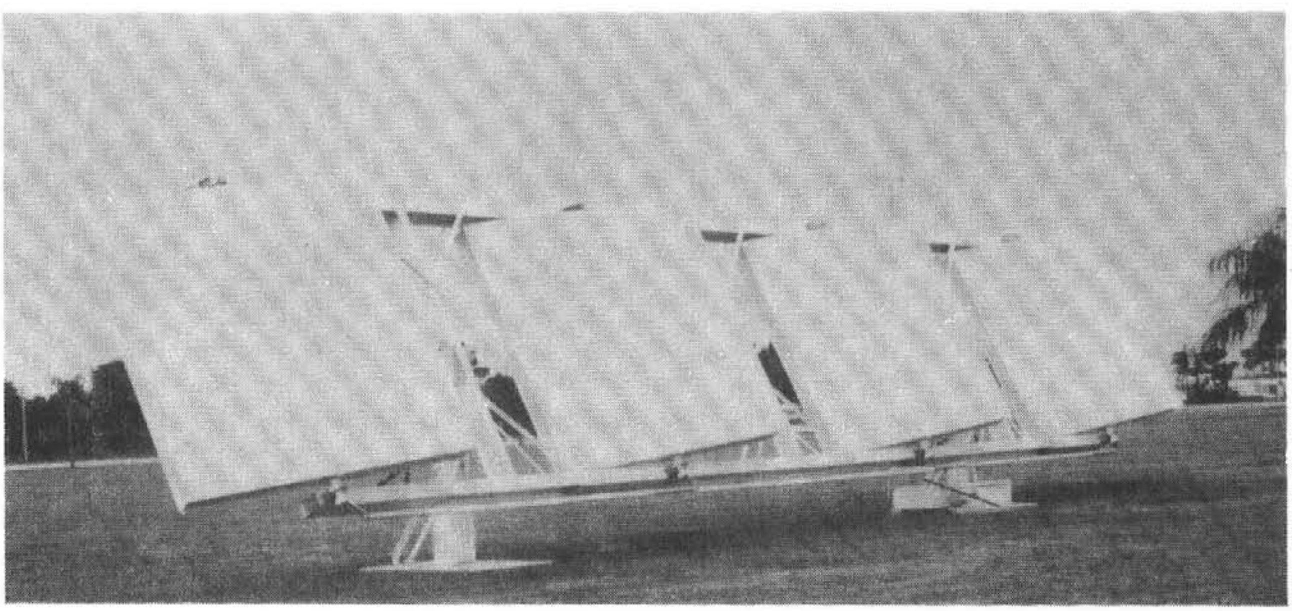

Figure 7. Honeywell Heliostat Design

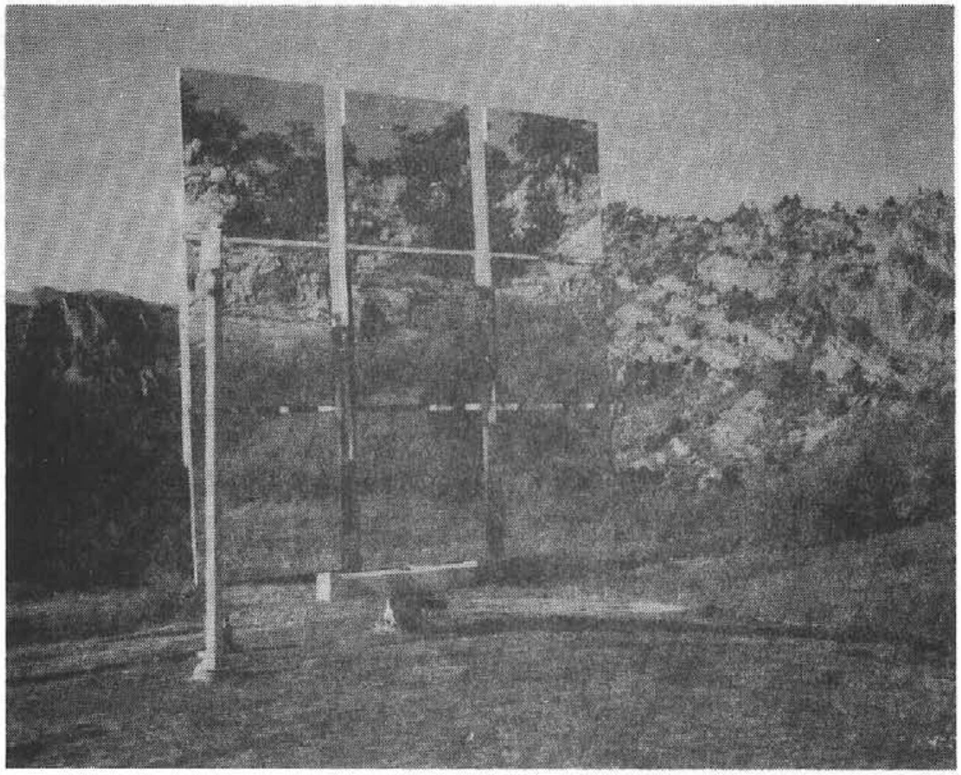

Figure 8. Martin Marietta Heliostat Design

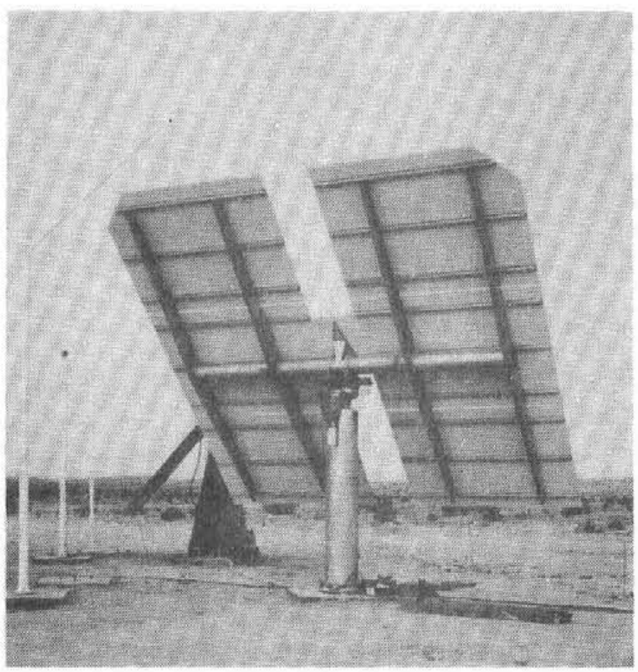

Figure 9. McDonnell Douglas Heliostat Design

dome that protects the heliostat structure from the environment. The reflector is aimed by means of two digital-controlled stepper motors, one on each of the two axes. The commercial version of this heliostat has a 48 m^2 mirror surface. The heliostat configurations proposed by Honeywell, Martin Marietta, and McDonnell Douglas are based upon more conventional designs that use steel frame construction and glass mirrors. The Honeywell design, Figure 7, uses four second-surface glass mirrors (40 m^2 total) that are backed by an aluminum honeycomb/steel sheet substrate and mounted on a steel frame. The frame is tilted by two ball screw linear actuators, and the facets are rotated by means of gear reducers. The Martin Marietta design, Figure 8, uses nine second-surface glass mirrors (41 m^2 total) that are backed by an aluminum honeycomb/steel sheet substrate and mounted on a steel yoke structure. Azimuth and elevation motion is provided by electric motor/spur gear drives. The McDonnell Douglas heliostat, Figure 9, uses six rectangular second-surface mirrors backed by foamed core/steel sheet laminates which are attached to a support structure consisting of a main torque tube and four channel cross beams. Azimuth and elevation motion are provided by two-stage speed reducers coupled to electric motors. McDonnell Douglas and Martin Marietta used active reflected beam sensors to control the drive motors on the heliostat axes. The Honeywell and Boeing experimental heliostat systems tracked the sun with a preprogrammed, computer-controlled algorithm. In the case of the latter three designs, environmental protection for the reflective surfaces is accomplished with second-surface mirrors and by designing the heliostat so that it can be stowed in an inverted position.

Some thermal storage is needed to smooth out operating transients and extend the operational hours of the plant. Studies are being done to establish how much storage is cost effective. The storage concepts being developed by each of the contractors vary significantly. Both Martin Marietta and McDonnell Douglas employ sensible heat storage systems; Honeywell originally proposed a phase change storage system but has recently also designed a sensible heat system. Rock immersed in oil is employed by McDonnell Douglas in their system to reduce the amount of fluid required. Martin Marietta and Honeywell both have multistage (boiling and superheat) storage systems to raise the quality of the steam produced from storage. Heat transfer oil and molten salt are employed by Martin Marietta in the boiling and superheat regions respectively, while Honeywell uses a similar system except that the boiling section uses a rock/oil combination. Both Martin Marietta and McDonnell Douglas have built and tested experimental storage systems with a thermal capacity in the 1/2-MW hr range. An experiment on the Honeywell system has not been performed.

The technology associated with the sensible heat systems is rather straightforward. The major uncertainties with the proposed sensible heat systems are the severity of the degradation with time and the required replenishment rate, or maintenance techniques, for the oils. The molten salts employed are not being exercised in a temperature regime where degradation is expected.

In systems using water/steam in the receiver, there is a loss of quality (a result of the second law of thermodynamics) which occurs when the steam is condensed and later generated from storage. Consequently, the thermodynamic cycle efficiency of each of the above systems is significantly reduced when operating from storage-generated steam. This also leads to the use of a dual-admission turbine and a somewhat more complex control system. The energy density achieved in the storage materials varies from 15 Wh/kg in the rocks to more than 90 Wh/kg in the molten salts. The ratio of enthalpies of steam generated in the energy subsystem to that of steam generated in the receiver varies between 0.85 and 0.90.

10-MW Pilot Plant by 1981

The system designs and subsystem research experiments have been completed, and it appears that the pilot plant can be operational in 1981. With the completion and testing of this pilot plant, many questions regarding the functional operation capability, the economic viability, construction, and maintenance will be clarified.

Although major reductions in costs will be necessary before the central receiver concept will be economically competitive, the high predicted costs for the pilot plant (approximately $10,000/kW of capacity) should not be construed as prohibitive during this initial stage of development. The pilot plant is a first of its kind, and therefore its costs do not reflect the evolutionary design improvements which normally occur as a technology progresses. Further, the plant is much smaller than the optimum size, which is expected to be in the 50- to 200-MW_e range.

What's Next

In each of the three major subsystems being developed, opportunities exist for significant performance or cost improvement.

The Heliostat

Heliostat efficiency is dependent on specular reflectance and the ability to maintain the desired mirror contour and orientation accurately. Although some improvements in this efficiency may be possible, development effort will be focused on reducing costs while maintaining efficiency.

Some improvement in the present specular reflectances, which vary between 0.83 and 0.90, is probably possible. Phenomena that must be more thoroughly understood in order to maintain or improve optimum specular reflectance at minimum cost include surface smoothness, reflective surface composition, thickness and composition of overlayed protective surfaces if used, angle of incidence, and degradation due to environmental aging. These are in addition to the commonly addressed effects of rain, hail, dust, and abrasion; ultraviolet radiation exposure; and temperature cycling impact degradation. Finally, the effects of experimental parameters such as experimental source, collector cone angles, spectral regime of measurements, and exposure history must be determined.

Optimum mirror substrates that offer both protection and support for the mirror surfaces must be developed. These substrates must form an effective composite structure with the mirror surface that resists contour changes during wind loading and must be thermally and environmentally stable, holding their original contour over the life of the solar plant. Organic and glass foams look particularly attractive for this application.

Mirror support and drive structures presently account for more than half of the total heliostat cost. Ways of implementing large-scale production techniques and minimizing structure weights will be thoroughly investigated in an effort to reduce these costs.

The Receiver

Compared to the present pilot plant receiver designs that are based upon well-developed water/steam technology, more advanced concepts such as liquid metals and molten salts may offer advantages. Significantly increased system efficiency (especially when storage is used) and reduced receiver and tower costs may be possible. Liquid metals or molten salt receivers will be investigated more thoroughly to confirm whether initial indications of significant receiver and system improvements are valid.

An interesting molten salt concept originated by T. Brumleve at Sandia employs a partially opaque, molten salt flowing down the inside wall of a cavity. Highly concentrated solar energy directly impinges and is absorbed by the molten salt, eliminating the need for piping and the thermal stress and fatigue problem, and reducing radiation losses.

Some apparent advantages of these advanced concepts are: lower pressures, which permit thinner and lighter tubes (no tubes with Brumleve's concept); higher overall heat transfer rates (highest with liquid metals); reduction in tube fouling; very light receivers--potentially a factor of 5 below that for water/steam--which are simple to control; lower pumping costs; greater potential for availability retention when the working fluid is also used as the storage medium; and more easily implemented turbine reheat. These and other advantages must be weighed against some of the disadvantages such as relatively high toxicity, possible rapid oxidation of some of the materials under accident conditions, and any additional development required for pumping and receiver fabrication.

Storage

The commercial acceptance of solar thermal electric power may be tied to the ability to store large quantities of thermal energy. Most of the storage concepts presently being pursued are expensive, amounting to about 20 to 30 percent of the total system cost for approximately 6 hours of storage. To keep storage costs and thus system costs to a minimum, it is necessary to build efficient storage systems. To avoid costly system overdesign, it is also important to be able to predict storage system performance with accuracy.

In the solar central receiver project, change-of-phase and sensible heat thermal energy storage concepts are being considered. At the same time, chemical storage appears to have potential advantages. Probable fruitful development areas in sensible heat and change-of-phase thermal energy storage are in the fields of material response and thermal and fluid kinetics. Most common heat transfer fluids degrade considerably at temperatures consistent with efficient steam generation; therefore methods for developing low-cost fluids or for rendering fluids thermally stable for high-temperature applications should be investigated. Methods of fluid maintenance should also be developed. In addition, the fluid and thermal kinetics in pebble bed systems, liquid thermocline systems, and tank-fluid-rock concepts are not completely understood at this time.

Significant improvements are needed in the methods used to remove or inhibit the solidifying media from the heat exchanger surfaces in a change-of-phase system. Various scraping and vibratory cleaning techniques should be investigated as well as the possibility of developing inexpensive adherence-resisting surface coatings or encapsulation methods.

Summary

Prototype heliostats, receivers, and storage subsystems have been built and tested as a part of the recently completed two year research and development program for solar central receiver system technology. This technology will serve as the basis for the detailed design and construction of a 10-MW pilot plant scheduled for operation in 1981. Successful operation could lead to the construction of a demonstration plant, similar to that illustrated in Figure 10, in the mid to late 1980s. Progress in understanding the technology necessary for large-scale utilization of solar energy to generate electricity is well under way.

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