ERDA'S CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM STUDIES

by

Lester J. Lippy

and

Thomas R. Heaton

Martin Marietta Corporation
Denver Division
Denver, Colorado

INTRODUCTION

The Energy Research and Development Administration is sponsoring research and development programs to study the utilization of solar energy for the production of electrical power. These programs are broad and cover the following four basic techniques for electrical energy generation:

1. Solar thermal systems

2. Photovoltaic systems

3. Ocean thermal systems

4. Wind systems.

The solar thermal efforts are divided between the distributed systems which are used to generate low pressure-low temperature steam and the central receiver systems which generate medium pressure-high temperature steam. It is these systems which seem closest to being advanced to the pilot plant stage. These programs are under the direction of Mr. George M. Kaplan of ERDA Headquarters.

This paper will only summarize the efforts underway on the central receiver solar thermal power system. At present, four contractors have completed studies on these types of system. Three of these contractors, Martin Marietta, Honeywell, and McDonnell-Douglas, have reported on their studies of the preliminary design of a 10 MW_e Solar Thermal Pilot Plant and the conceptual design of a commercial size solar thermal power plant. The fourth, Boeing Engineering and Construction Company, studied only the collector system, one of the major solar peculiar elements of solar thermal power systems. In addition, ERDA has selected a site near Barstow, California, for the construction of a 10 MW_e solar thermal power plant. The successful team in the competition for the pilot plant site was headed by Southern California Edison Company. This fall, it is expected that proposal requests will be issued for the solar peculiar elements of this pilot power plant. The objectives of this pilot plant will be to prove technical feasibility; to prove economic feasibility; and to gain development, production, and operational experience with this type of power plant.

The central receiver solar thermal power plant efforts are moving forward rapidly. These systems are taking advantage of knowledge and techniques developed in both the Skylab and Viking programs, particularly in the fields of optics, heat transfer, and system controls. Thus, this effort, sponsored by ERDA, is one of many making use of developments of the space age to help solve one of today's socio-economic problems; that is, harnessing the Sun's energy, an inexhaustable fuel source, for the generation of electric power.

SOLAR CENTRAL RECEIVER 5 YEAR MILESTONE SCHEDULE

ERDA's schedule for the efforts currently being pursued on the Solar Central Receiver Project is shown in Figure 1. The middle and upper segment of the schedule show the efforts connected with the 10 MW_e Pilot Plant. The lower segment show the effort connected with construction of the National Solar Thermal Test Facility (STTF) by Sandia Corporation at Albuquerque, New Mexico.

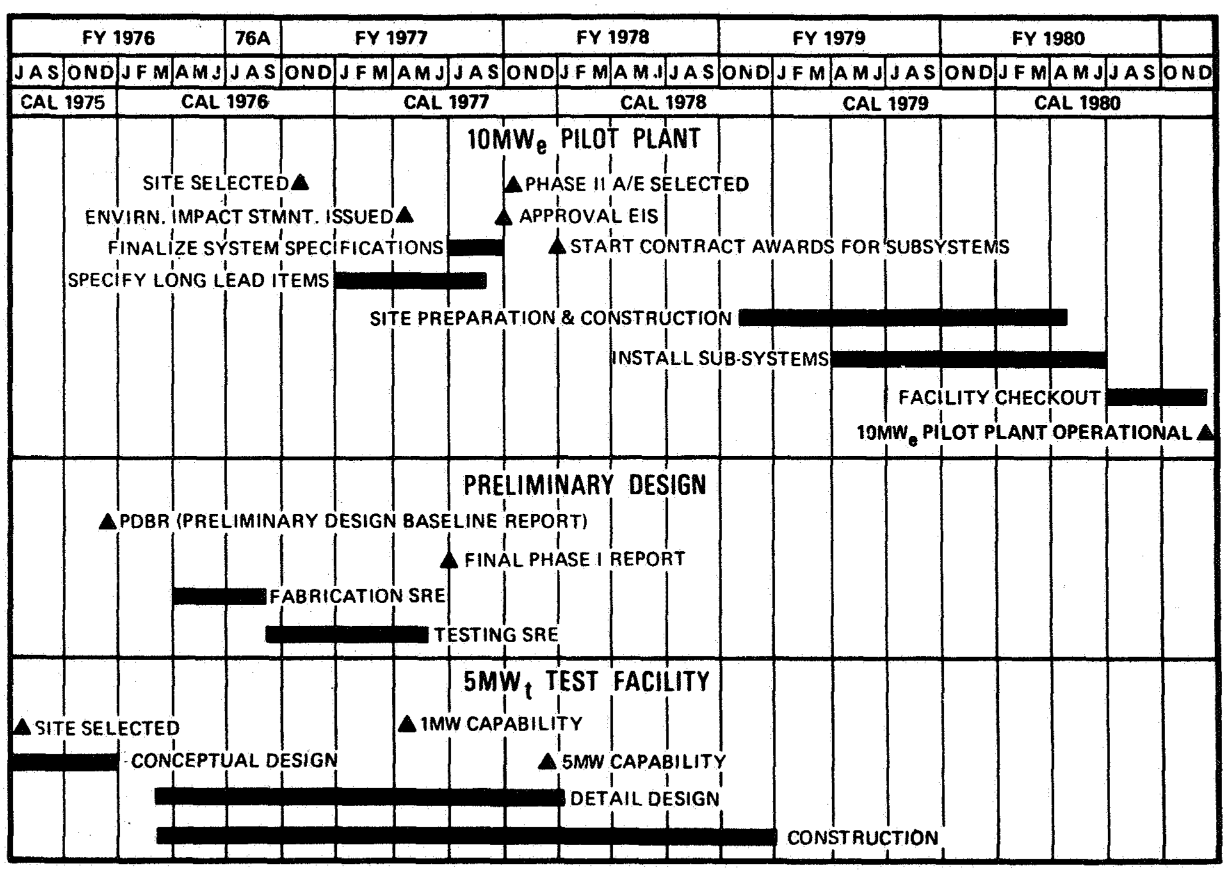


Figure 1. Solar central receiver project 5 year milestone schedule.

The preliminary designs for the 10 MW_e Pilot Plant by Martin Marietta, Honeywell, and McDonnell-Douglas have been completed and system evaluation and selection by ERDA is in process. The efforts completed by these three contractors consisted not only of design but also of system research experiments (SRE) on the solar subsystem to obtain the necessary design data. In the fall of this year, proposal requests are to be issued for the procurement of the solar peculiar subsystems.

The site of the 10 MW_e Pilot Plant has been selected at Barstow, California. The site was selected based upon the successful proposal of a team headed by Southern California Edison Company. ERDA and Southern California Edison are currently evaluating the solar peculiar subsystems resulting from the study efforts. These efforts will result in specifications for the solar subsystem for which proposals are to be submitted this fall. It is expected that the 10 MW_e Pilot Plant will reach an operational status in January, 1981. The long lead procurement items are currently being determined and ordered. This is mainly the turbine-generator subsystem.

The third effort is that of construction of the STTF. This effort is managed by Sandia Corporation and is being constructed on their site at Albuquerque, New Mexico. Currently, 78 heliostats have been installed and the tower is almost complete. The heliostats are designed, fabricated, and installed by Martin Marietta Corporation. The 78 heliostats result in a power of over 1 $MW_{thermal}$. Another 144 heliostats will be installed by October, 1977, and 50 heliostats are to be ordered to bring the power to 5 $MW_{thermal}$ at the test area on the tower.

MARTIN MARIETTA TEAM CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM

Figure 2 shows a schematic of the Martin Marietta proposed central receiver solar thermal power systems. The collector subsystem consisting of heliostats reflects solar energy into the receiver cavity. This energy is absorbed by the tubes of the receivers boiler and superheaters to generate steam at 1550 psig and 960° F. This steam then passes through the receiver downcomer and can either be admitted to the turbine generator subsystem or to the thermal storage subsystem. The steam enters the turbine at a pressure of 1350 psig and a temperature of 950° F, and is discharged at a pressure of 2.5 in. Hg. The steam is then condensed to water and is then pumped to the proper pressure and preheated by turbine steam and then reenters the receiver boiler elements.

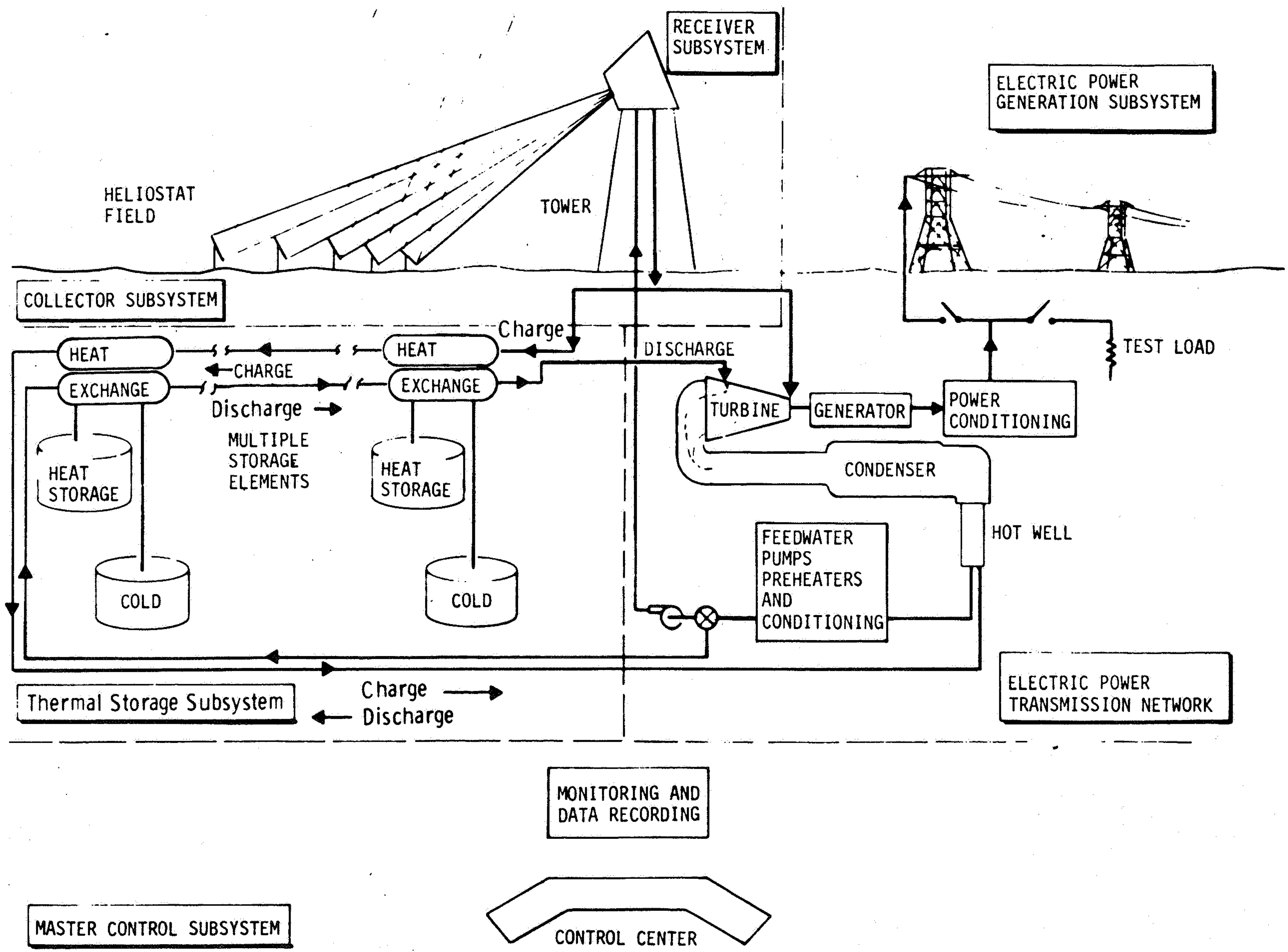


Figure 2. Overview schematic, Martin Marietta team central receiver solar thermal power system.

If the steam enters the thermal storage subsystem, it is used to heat other fluids to a higher temperature, but below their boiling points, in order to store energy in the form of sensible heat for use when solar energy is not available. The system in the schematic first cools the steam to saturated conditions against a thermal storage salt and then condenses the steam against thermal storage hydrocarbon oil. To generate steam with the thermal storage subsystem, the cycle is reversed with the water being boiled against the oil and the steam being superheated against the salt. Steam from the thermal storage subsystem enters the turbine at a pressure of 400 psig and a temperature of 800°F at an admission point downstream of the main admission inlet.

A master control subsystem is required to control the power plant, to monitor operational parameters, and to record operational data. This subsystem uses a computer to transfer commands to the collector subsystem and for the calculation of performance data. The plant operational control is performed by the operators, and the computer is used for command transmission only to the collector subsystem.

The new elements of the central receiver solar thermal power system are the collector subsystem, the receiver subsystem, and the thermal storage subsystem. The turbine-generator subsystem is the same as that of a conventional power system, and the plant is controlled in the same manner as conventional plant except for the use of the computer in controlling the collector subsystem.

PRELIMINARY DESIGN 10 MW_e CRSTPS PILOT PLANT

Figure 3 shows a rendering of the 10 MW_e Pilot Plant preliminary design as submitted by Martin Marietta. The north facing tower containing the cavity receiver is shown with the collector field located entirely north of the tower. The turbine-generator subsystem, administration building, and thermal storage subsystem are located around the base of the tower.

The collector field contains 1554 heliostats each with a collector area of 441 ft^2. The reflector is a second surface, float glass low iron mirror which is 1/8 in. thick. At the design point, 2:00 p.m. on June 21, the collector field transmits 67 percent of the available solar energy to the receiver inlet. The receiver cavity inlet is 24.5 ft^2 and the center is 295 ft off the ground. The receiver has an energy conversion efficiency of 94 percent. At the design condition of 10.8 MW_e gross power, the turbine-generator has an efficiency of 33.5 percent. This results in an overall efficiency of 19.4 percent for the pilot plant.

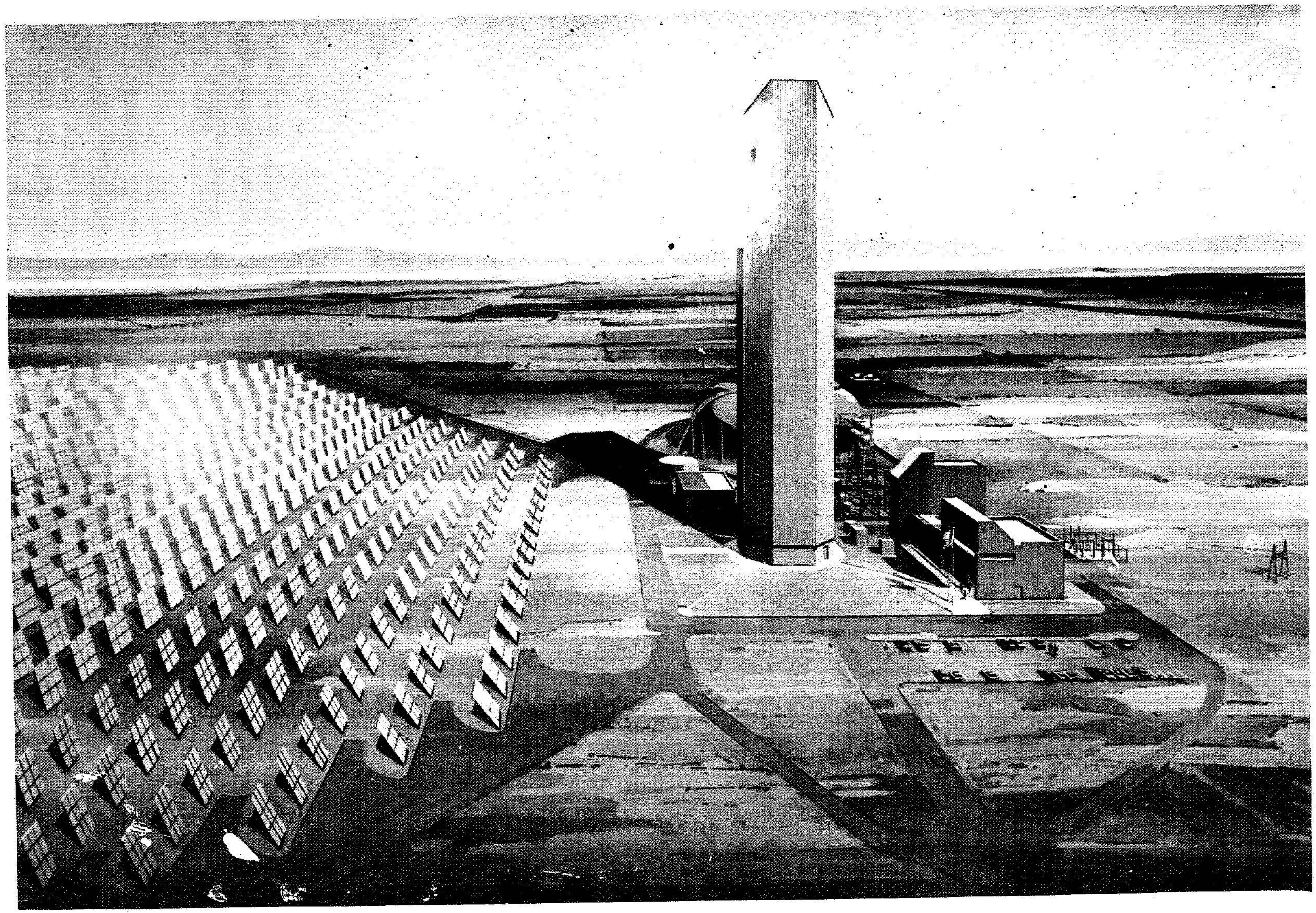


Figure 3. Rendering of preliminary design 10 MW_e CRSTPS pilot plant.

The thermal storage has a design capacity to supply steam to generate 7.6 MW_e gross power for a 3 h period after a 20 h hold. The energy efficiency of the thermal control subsystem is 91 percent. When operating on steam from the thermal storage subsystem, the turbine efficiency is 27.9 percent.

This pilot plant occupies an area of 128 acres.

COMMERCIAL PLANT CONFIGURATION

The 150 MW_e Commercial Plant as submitted by Martin Marietta is shown in Figure 4. This plant collector subsystem consists of 15 modules, each identical to the collector subsystem of the Pilot Plant. This results in a total of 23 300 heliostats and 15 tower-receiver elements. This modular concept results in a lower development cost for the Commercial Plant and also improves overall plant reliability.

The single turbine-generator and thermal storage subsystem are in the triangles between the collector modules and are single units. The turbine-generator is a 160 MW_e commercially available unit. The thermal storage subsystem consists of nine hydrocarbon oil tanks and two salt tanks.

The overall gross efficiency of this plant is 25.1 percent when operating on receiver steam. The plant occupies an area of 1498 acres. The cooling tower is located such as to provide the least shading of collector subsystem from the Sun. The prevailing wind will normally set the site of the cooling tower.

PILOT PLANT HELIOSTAT CONCEPTS

Renderings of the heliostat design concepts being proposed by the four contractors are shown in Figure 5. The concepts proposed by Martin Marietta, Honeywell, and McDonnell-Douglas are designed to be compatible with a particular type of receiver configuration. The receiver concepts are shown in a later figure.

The concept proposed by Martin Marietta consists of nine prefocussed mirror facets mounted on a yoke assembly. Each facet is individually oriented to give overlapping images at the receiver inlet. Each facet is a second surface mirror using low iron float glass. The entire assembly is rotated about the azimuth and elevation to track the Sun.

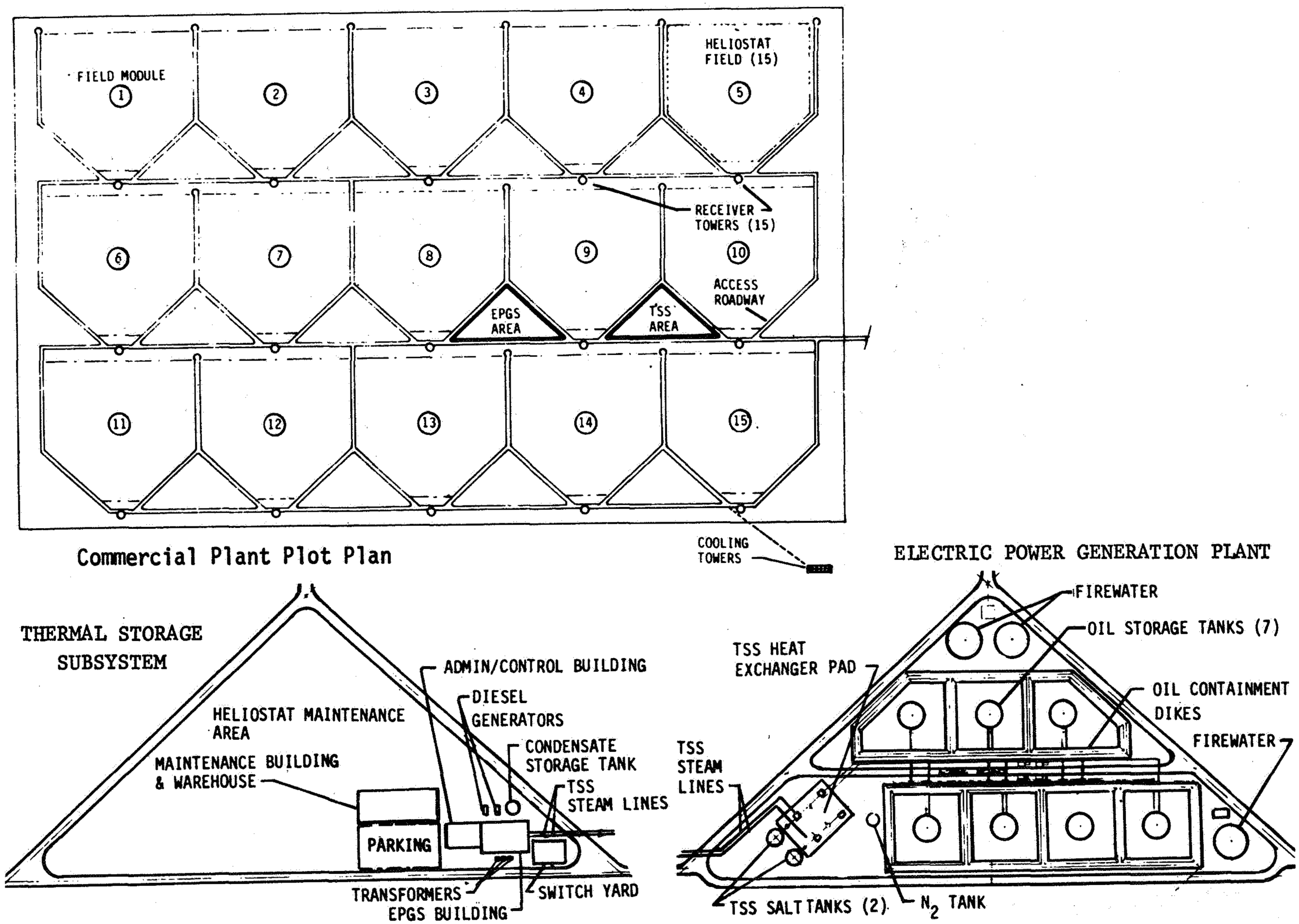


Figure 4. Commercial plant configuration.

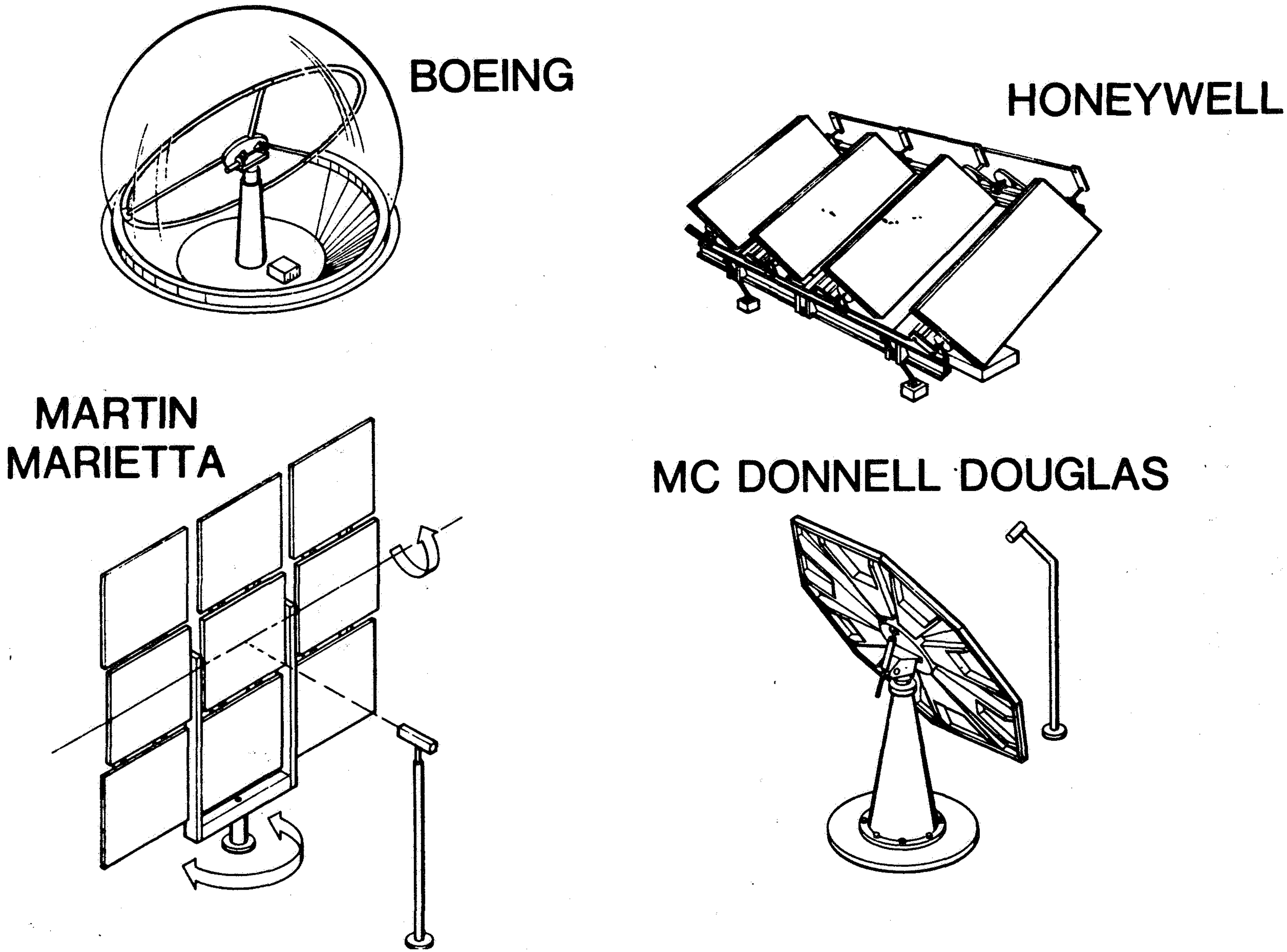


Figure 5. Pilot plant heliostat concepts.

The concept proposed by Honeywell consists of four focussed mirror facets located in a frame which is tilted about two axes to track the Sun. Each mirror facet uses a second surface mirror using low iron float glass.

The concept proposed by McDonnell-Douglas consists of mirror segments located in an octagonal frame. This frame is located on a single pedestal mount and is rotated about the azimuth and elevation axes to track the Sun. Each mirror segment uses a front surface mirror plated on to float glass. The mirror segments are not focused.

The concept proposed by Boeing consists of a aluminized mylar surfaced stretched over a ring. The assembly is located on a single pedestal mount and is rotated about the azimuth and elevation axes to track the Sun. The entire assembly is located within a pressurized Tedlar enclosure for environmental protection.

HELIOSTAT SUBSYSTEM RESEARCH EXPERIMENT

The heliostat concept proposed by Martin Marietta is shown in more detail in Figure 6. The nine mirror assemblies are each 7 ft^2 with a total area of 441 ft^2. The control is by an open-loop pointing system which uses a computer to calculate the solar coordinates and a microprocessor at the heliostat to determine the azimuth and elevation gimbal angles. A 13 bit encoder measures both these gimbal angles for comparison with the calculated angles.

The heliostat is anchored in the ground using a cassion which is 15.5 ft deep. At night and during inclement weather the heliostat is stowed face down for protection and cleanliness. Also the heliostat is stowed face down during high winds (50 mph) to reduce the angle-of-attach and, thus, reduce the loads on the structural assembly.

UNIQUE SAFETY HAZARDS OF CRSTPS

The Martin Marietta collector test area located at their facility in Waterton, Colorado, is shown in Figure 7. This facility consists of four heliostat test sites which represent selected locations in the 10 MW_e Pilot Plant collector field. The solar flux was measured by both a calorimator and radiometer rake. These were located 289 ft above the calorimator locations and thus

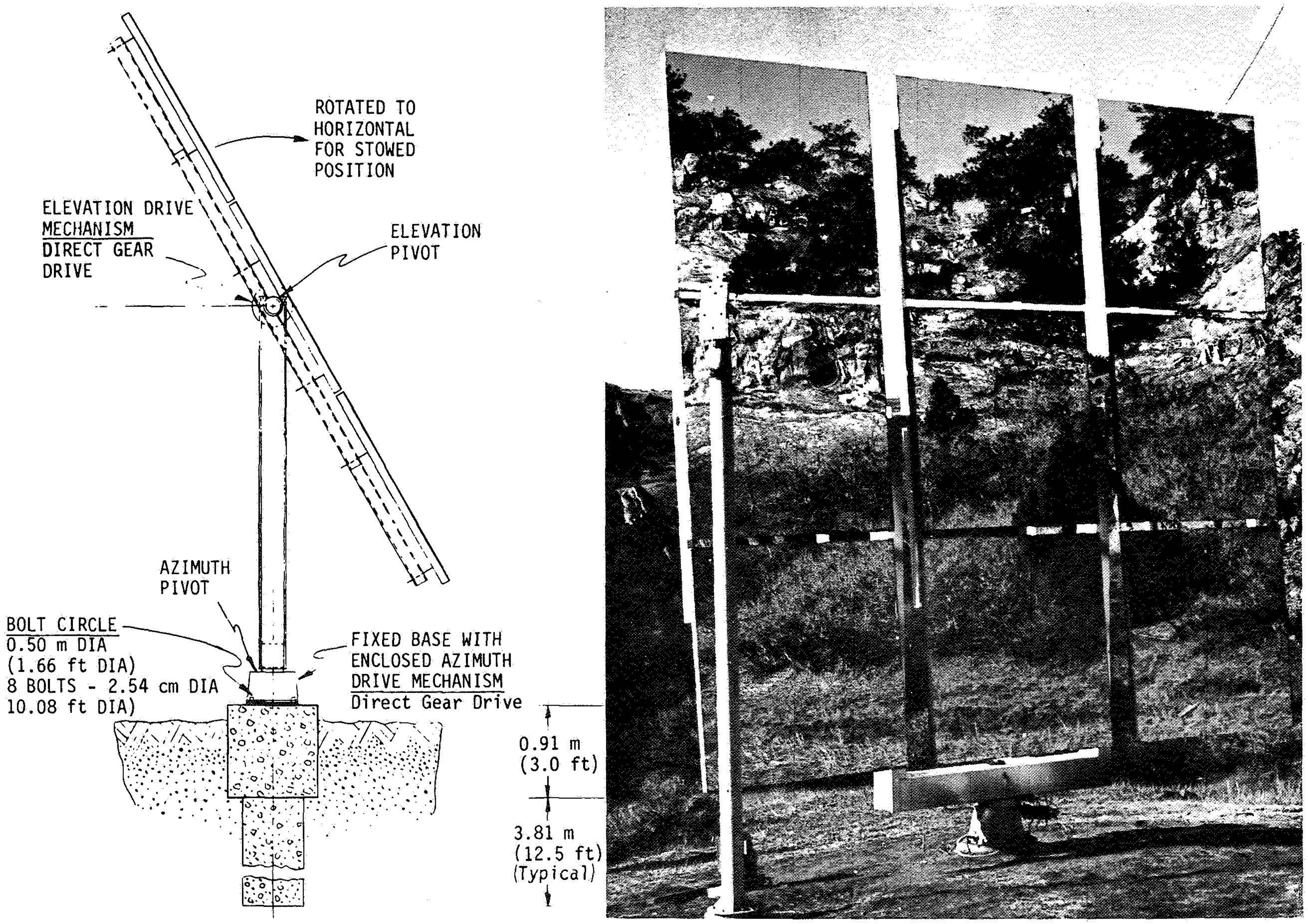
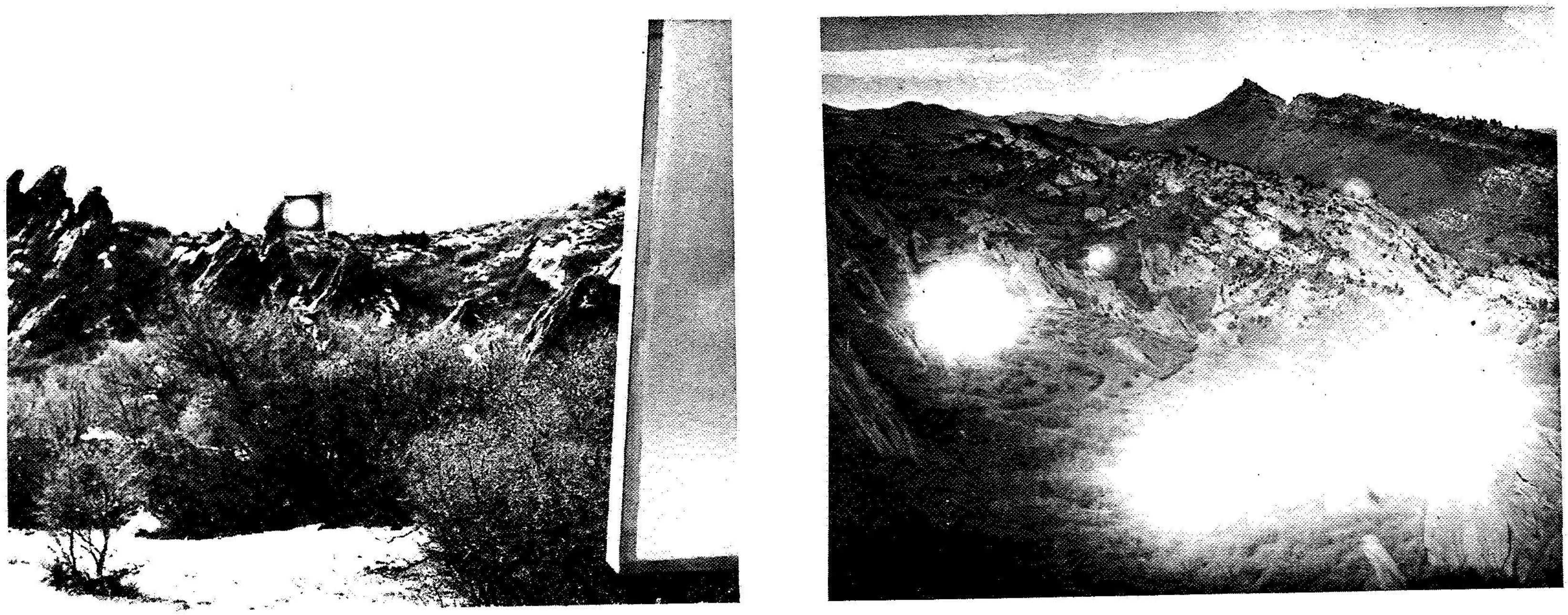


Figure 6. Heliostat SRE.



(a) Sun flashes from SRE heliostats.

(b) Combined images of four SRE heliostats.

Figure 7. Martin Marietta collector test area located at their facility in Waterton, Colorado (concentrated sunlight photographs highlight unique safety hazard of CRSTPS).

simulated the Pilot Plant receiver tower. The calorimator had an opening which was 24.5 ft^2 and, thus, it simulated the Pilot Plant receiver cavity. The calorimator was used to measure the heat input from single and multiple heliostat beams and the radiometer was used to measure the heat input from a single heliostat and also to measure the solar flux profile.

The photograph on the left of Figure 7 illustrates the safety hazards associated with solar power systems when one is near the focal plane, i.e., concentrated light and heat. In the Pilot Plant, each heliostat focuses 33.7 kW thermal of energy into the focal zone. The heat energy and light energy in the visible regime from several multiple beams is sufficient to quickly cause eye damage to the retina and burns to exposed skin. In addition, multiple beams contain sufficient energy to melt a steel plate as was recently demonstrated at the STTF using 63 of their heliostats.

STTF HELIOSTAT FIELD

Various views of the heliostat field and tower for the STTF being built by the Sandia Corporation for ERDA at Albuquerque, New Mexico are shown in Figure 8. The heliostats are supplied by Martin Marietta. Each of the heliostats consisted of 25 mirror facets which are focusable and use laminated float glass in which the second surface is silvered for reflection. The total area of each heliostat is 400 ft^2.

Currently 78 such heliostats have been installed, and installation has started on a second group of 144 heliostats. This installation will be complete in October, 1977. An additional 50 heliostats will be required to complete the facility and bring the energy level to 5 MW_e thermal. With the current 78 heliostats, the energy level is in excess of 1 MW_e thermal.

PILOT PLANT RECEIVER CONCEPTS

Figure 9 shows the receiver concepts for the 10 MW_e Pilot Plant proposed by Martin Marietta, Honeywell, and McDonnell-Douglas. Each of these receivers is located on a tower. For the Martin Marietta concept, the tower faces north towards the heliostat field while the collector fields for the other two concepts surround the towers.

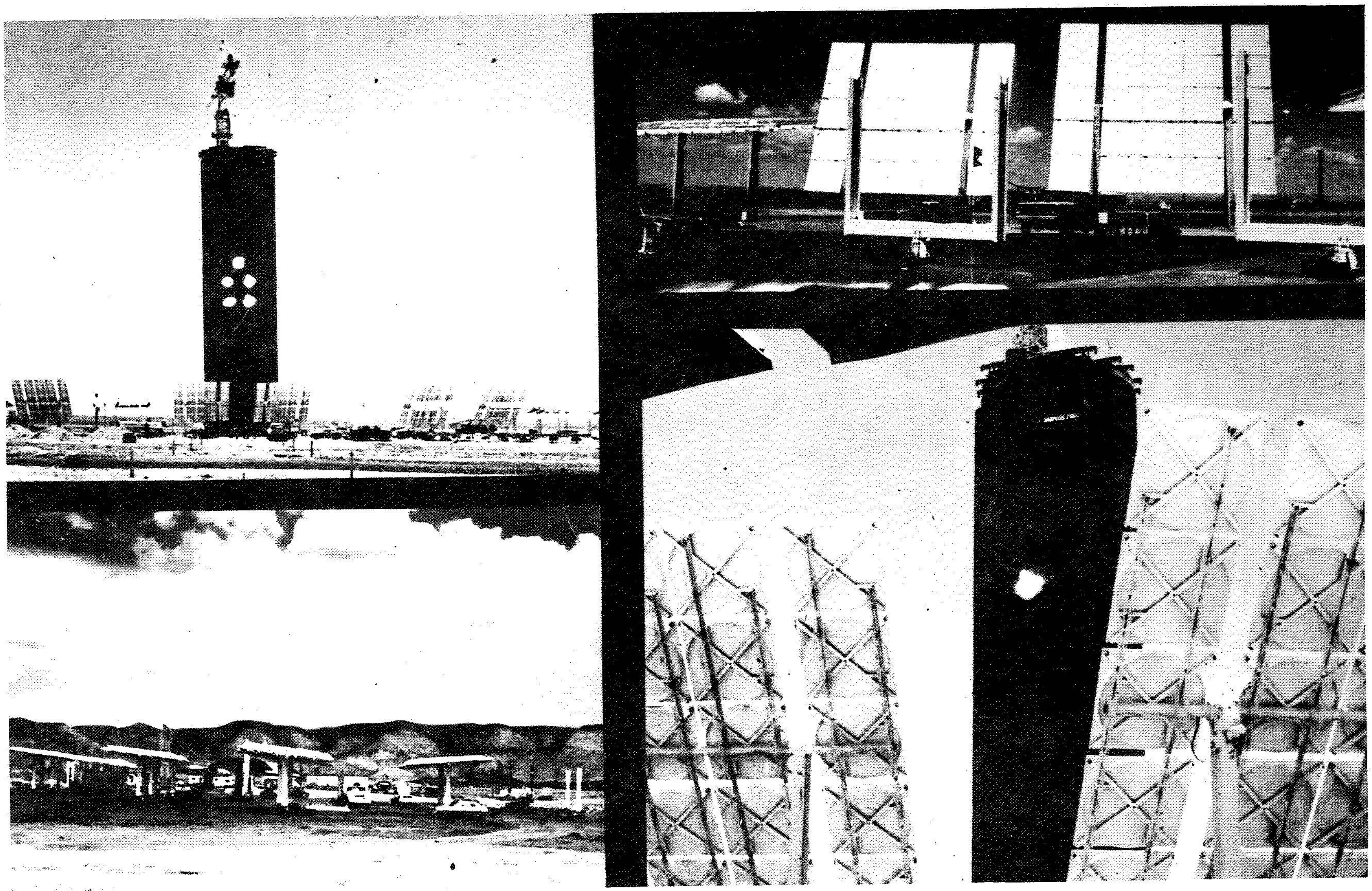


Figure 8. STTF heliostat field.

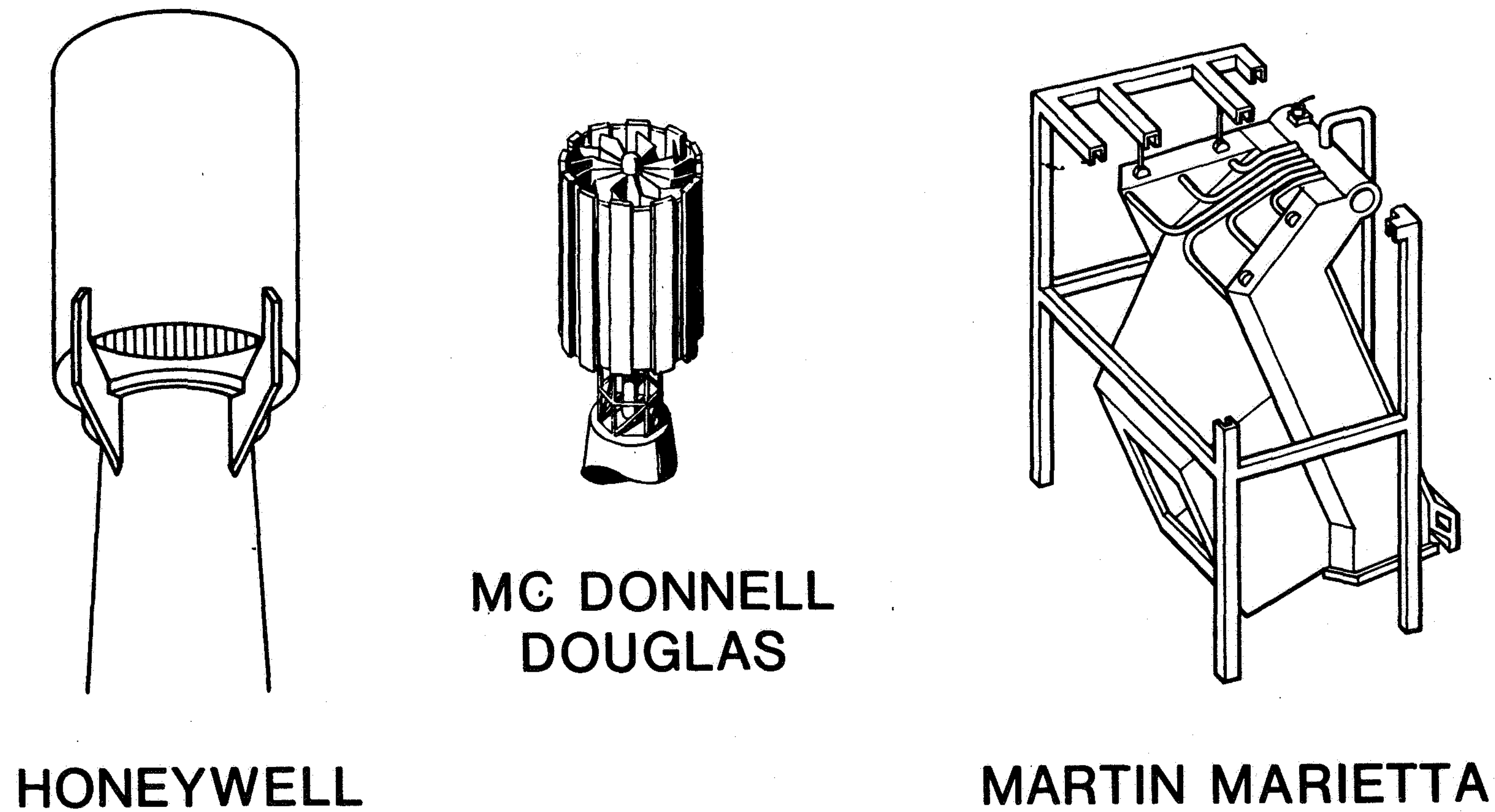


Figure 9. Pilot plant receiver concepts.

The Martin Marietta concept is a cavity receiver with front facing opening. This receiver employes a conventional design as used in fossil fueled power plants and uses separate boiler and superheater sections. This receiver uses natural circulation.

The Honeywell concept is a cavity receiver with a bottom facing opening. This receiver also uses conventional design techniques and has a separate boiler and superheater.

The McDonnell-Douglas concept is an external configuration in which the impinging solar energy is conducted through the cover plates into the tubes which are single pass boiler and superheater. This concept is similar to the cooling system of a rocket engine.

CENTRAL RECEIVER STEAM GENERATOR DEVELOPMENT PERSPECTIVE

Martin Marietta has completed the design, fabrication, and testing of a 1 $MW_{thermal}$ cavity receiver under a separate ERDA contract. In addition, a 5 $MW_{thermal}$ scale model of the cavity receiver for the 10 MW_e Pilot Plant was also designed, fabricated, and tested.

Figure 10 shows photos of the 1 $MW_{thermal}$ receiver and drawings of the 1 $MW_{thermal}$ receiver for the Pilot Plant which is rated at a maximum of 52.3 $MW_{thermal}$. The 1 $MW_{thermal}$ receiver has been tested using both IR heater lamps at the Sandia facility in Albuquerque, New Mexico, and solar energy at the CNRS solar furnace in Odeillo, France. The weight of these three units is 17 500 lb; 180 000 lb; and 400 000 lb, respectively.

PERSPECTIVE VIEW, CNRS PARABOLA AND FOCAL BUILDING WITH 1 $MW_{thermal}$ CAVITY RECEIVER IN OPERATION – SUMMER 1976

Figure 11 shows the 1 $MW_{thermal}$ receiver in the focal building of the CNRS solar furnace at Odeillo, France. This receiver required a flux redirector to spread out the concentrated solar flux of the solar furnace within the receiver. Also shown is the parabolic concentration of this facility.

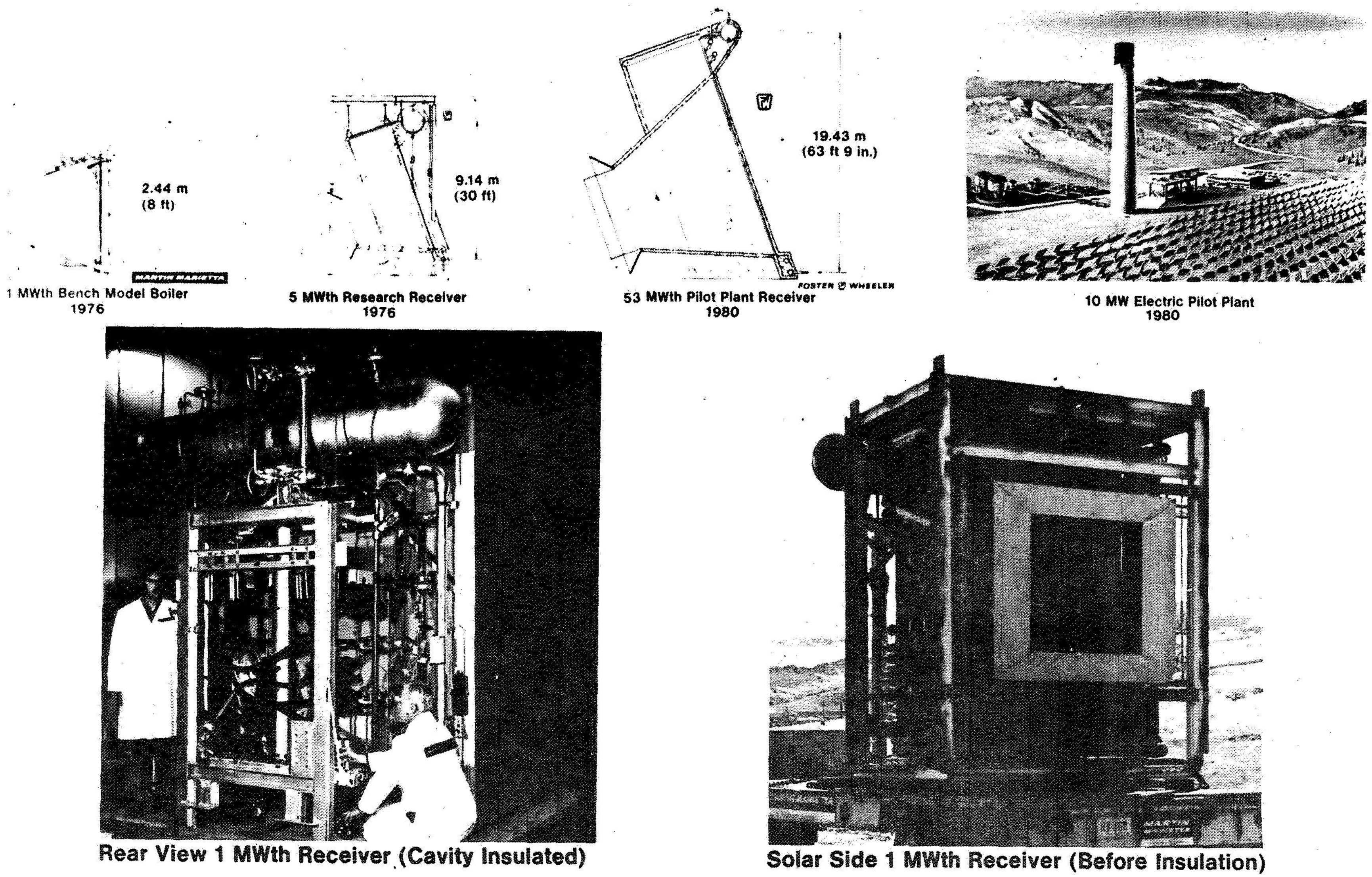


Figure 10. Central receiver steam generator development perspective.

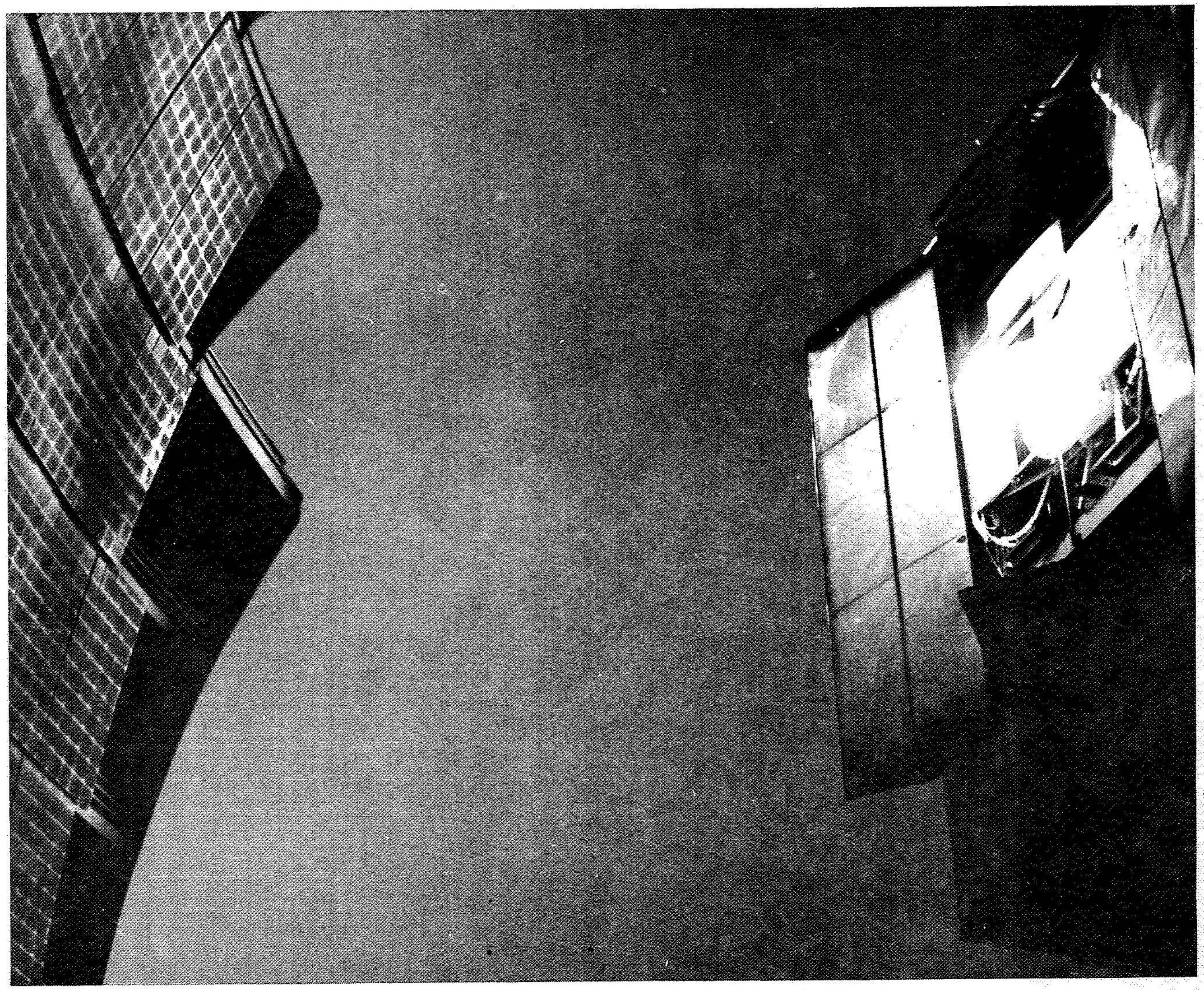


Figure 11. Perspective view of CNRS parabola and focal building with 1 $MW_{thermal}$ cavity receiver in operation — Summer 1976.

CNRS FACILITY HELIOSTATS

Figure 12 shows the 63 heliostats at the CNRS solar furnace. These heliostats are flat and have an area of approximately 400 ft^2. The heliostats are gimballed in both azimuth and elevation, and use a closed-loop pointing system. These heliostats redirect the solar energy to this parabolic reflector.

CNRS SOLAR LABORATORY AND FOCAL BUILDING DURING 1 MW_{th} RECEIVER TEST OPERATION – SUMMER 1976

Figure 13 shows the parabolic reflector of the CNRS facility. This facility was originally built to test high temperature ceramics and can create temperatures of 6000°C in the focal zone. The reflection of the test cell, with the 1 $MW_{thermal}$ receiver installed, can be seen in the parabolic reflector.

RECEIVER SRE AND TOWER

Figure 14 shows the 5 $MW_{thermal}$ receiver during the radiant heat testing at the Sandia facility in Albuquerque, New Mexico. This receiver was designed and fabricated by Foster Wheeler Development Corporation under subcontract to Martin Marietta. The radiant heat lamps are inserted into the cavity through the front opening. Doors cover the opening to minimize any heat leakage.

THERMAL STORAGE SUBSYSTEM

A scale model of the thermal storage subsystem was also constructed and tested. This effort was conducted by Georgia Institute of Technology under subcontract to Martin Marietta. The tests were conducted at Newman, Georgia and used steam from the Georgia Power Company station located at this site.

Figure 14 shows the testing in process on the scale model of the thermal storage subsystem. The scale model had a capacity of 2 $MW_{thermal}$ - h.

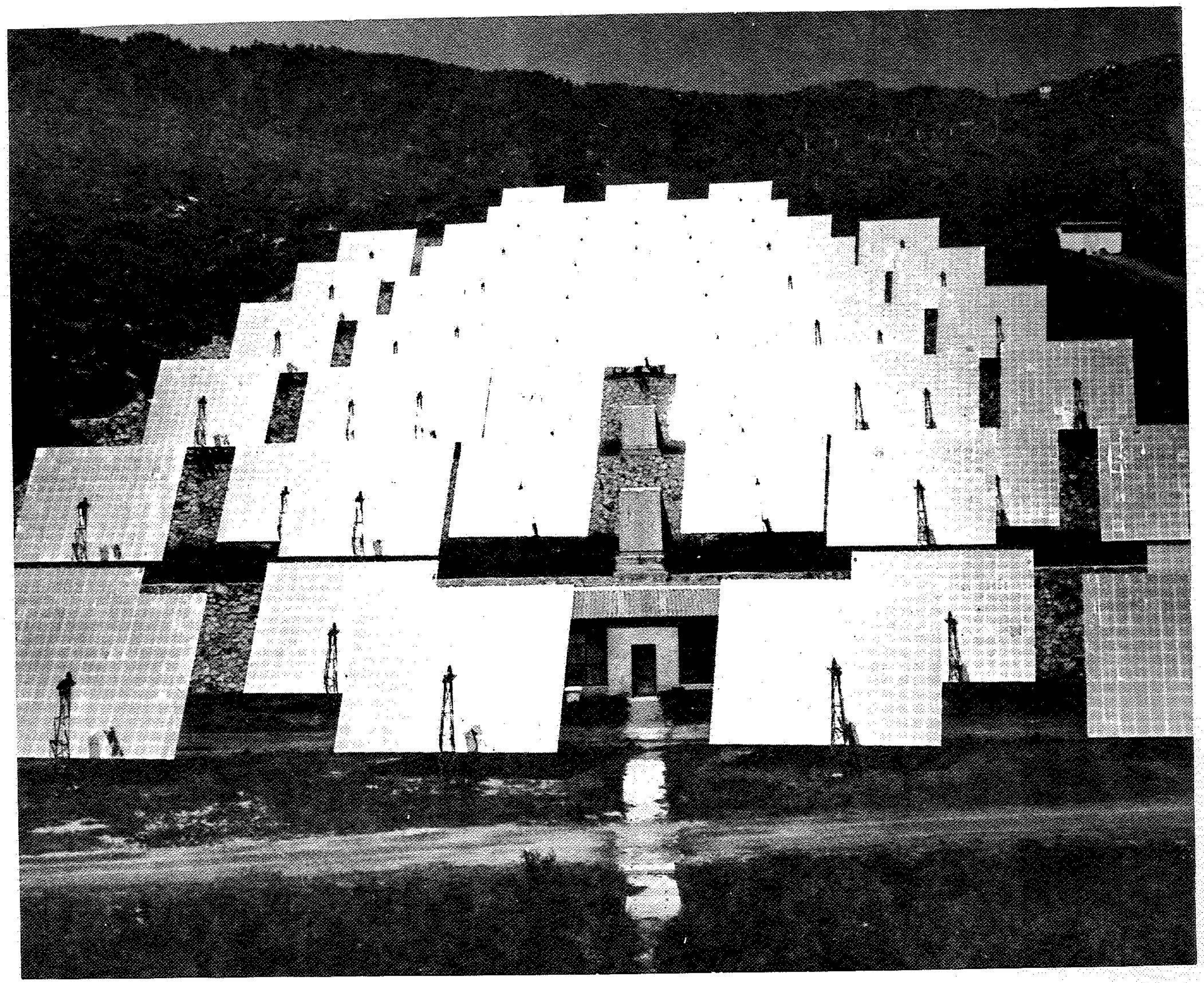


Figure 12. Sixty-three heliostat operation typical of maximum power runs of 1 $MW_{thermal}$ receiver solar test program.

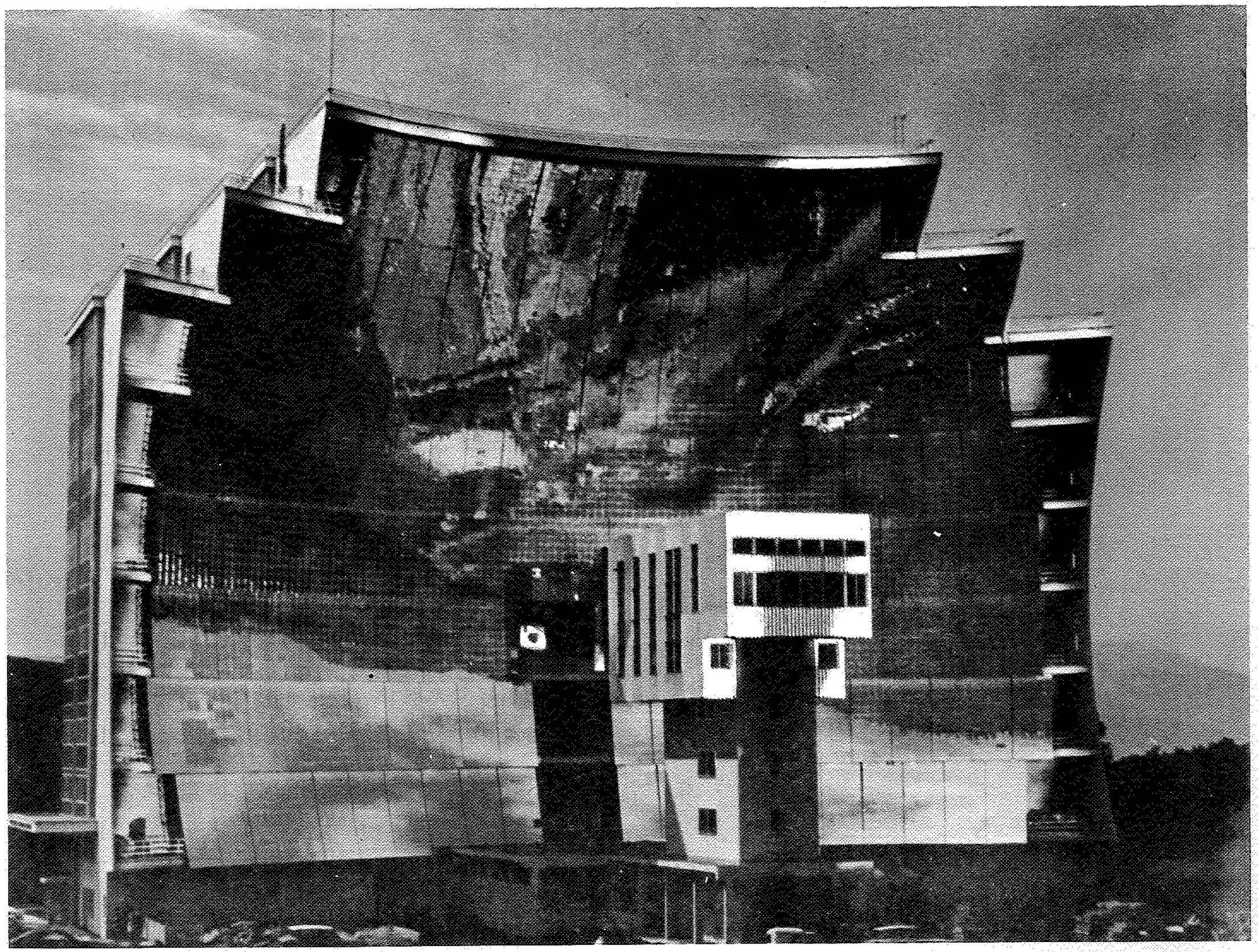


Figure 13. CNRS Laboratory, parabolic concentrator and focal building.

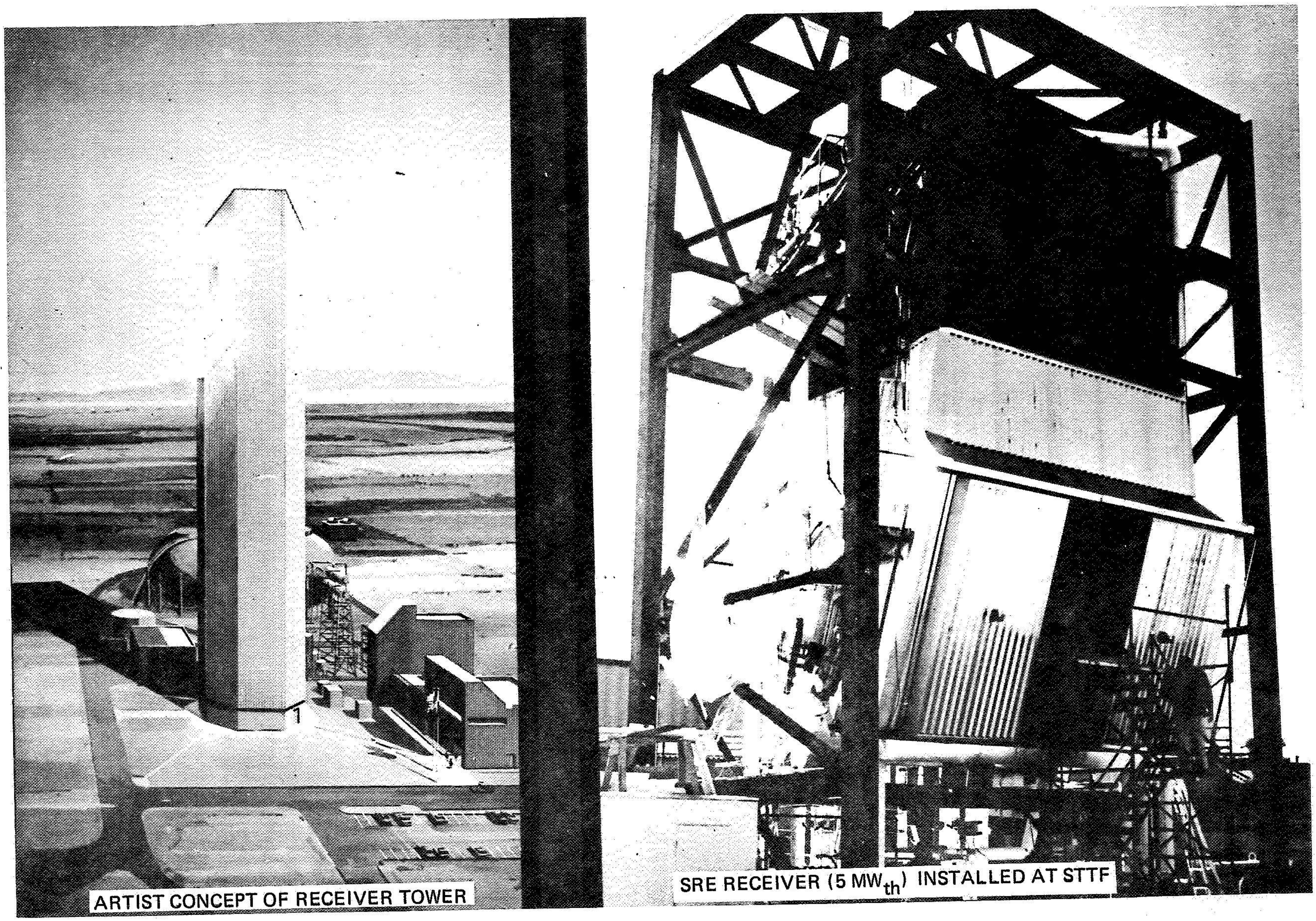


Figure 14. Receiver SRE and tower.

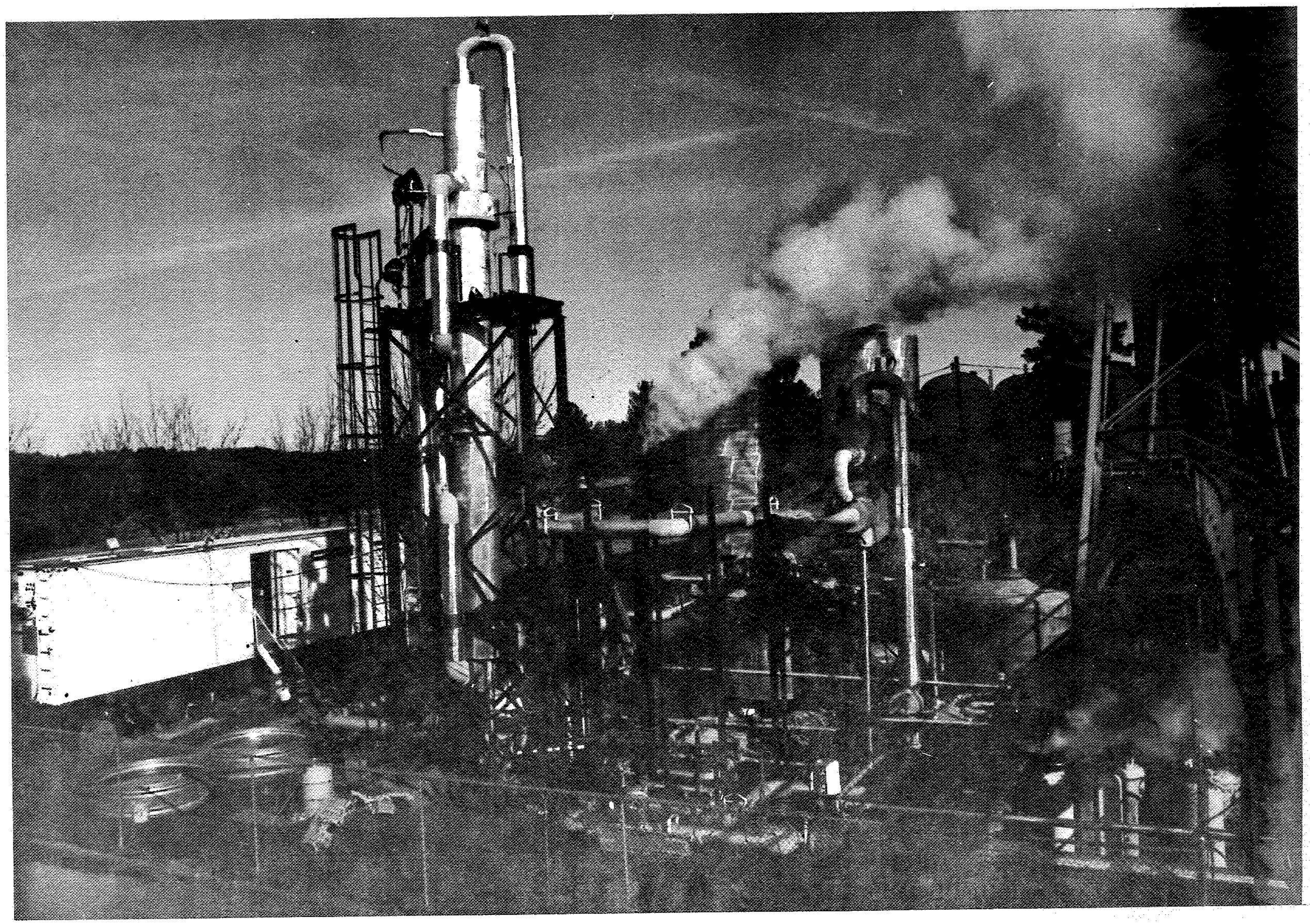


Figure 15. Thermal storage subsystem.

PERSPECTIVE VIEW OF THERMAL STORAGE SYSTEM RESEARCH EXPERIMENT

Figure 16 shows a rendering of the thermal storage SRE. The two hydrocarbon oil tanks with their heat exchangers, and the two salt tanks with their heat exchangers are also shown. The hot and cold temperatures of both the oil and salt are shown. This SRE duplicated operation of the thermal storage subsystem with the exception that it used a single heat exchange system for both charge and discharge. The 10 MW_e Pilot Plant proposed concept for the thermal storage system uses independent heat exchange systems for charge and discharge. This independent charge and discharge system increases the operational flexibility of the plant.

TOTAL ANNUAL HOURS OF SUNSHINE

Solar thermal power generation is most feasible if the power plants are located where there is a large amount of sunshine. There are also certain advantages associated with operation at lower latitudes.

Figure 17 shows the areas in the United States in which the annual number of sunshine hours is high. These areas are in the "sunshine belt" and contain portions of the states of California, Nevada, Utah, Arizona, New Mexico, and Colorado. A solar thermal power plant located in this area would be of maximum utilization and the electrical power could be distributed throughout the United States by the national grid. This does not say that solar thermal power plants can not be located in other portions of the United States, but the viability would be more dependent upon economics.

The question of economic viability of solar thermal power generation has recently been studied by the Aerospace Corporation and by the Electrical Power Research Institute, Inc., (EPRI). Both of those organizations have concluded that solar thermal power generation is most suited for the grid intermediate power load range in that it can be economically competitive and its output matches the power load requirement. The intermediate power load is approximately 25 percent of a system total power load. Their conclusion is that by 1991, when commercial size solar thermal power plants have been developed, solar power will be competitive with fossil-fuel or nuclear-fuel power plants based upon a capitalization period of 30 years. This is predicted upon the reduction of the collector subsystem cost to about $10 per square foot of collector area.

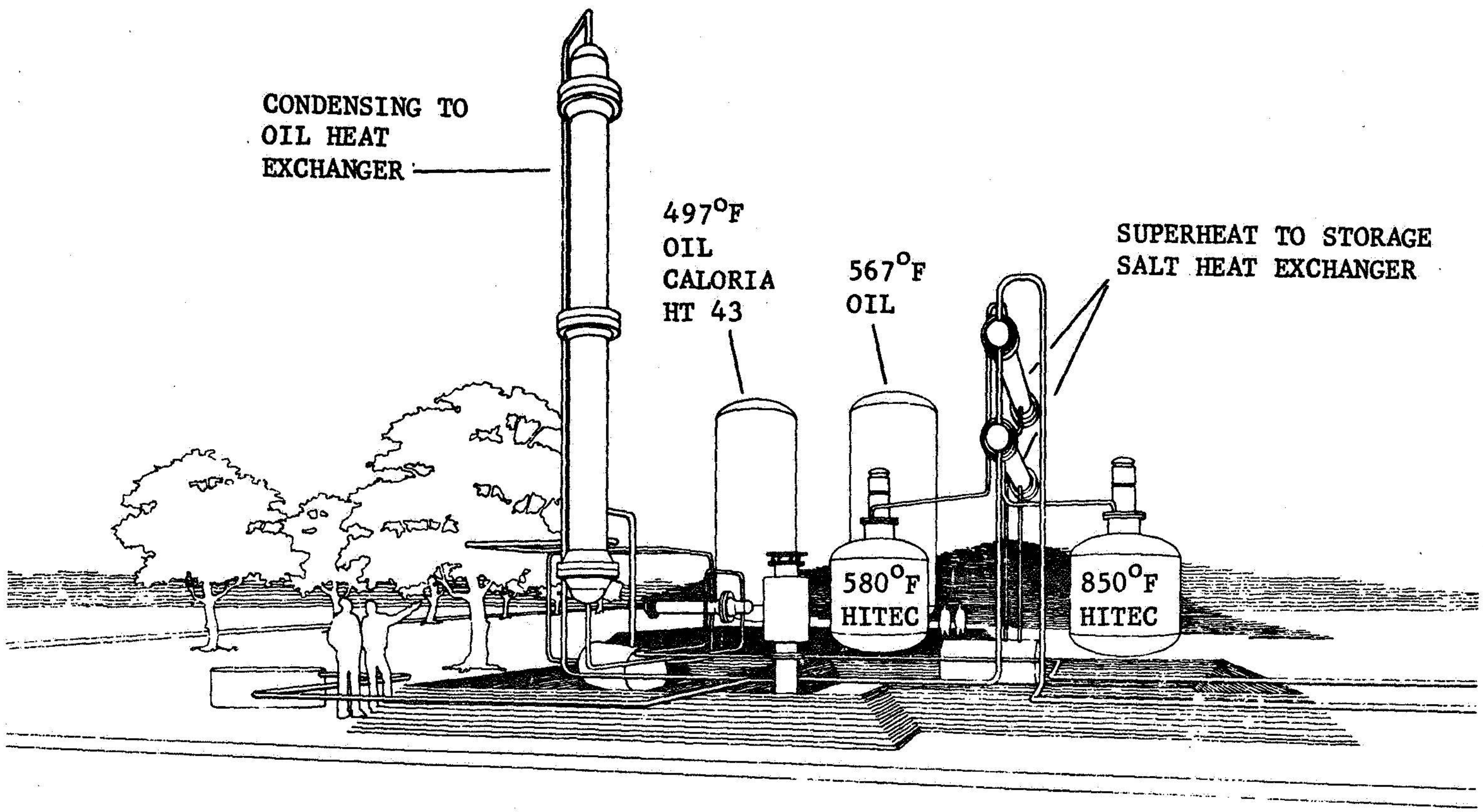


Figure 16. Perspective view of thermal storage subsystem research experiment (without supporting structures).

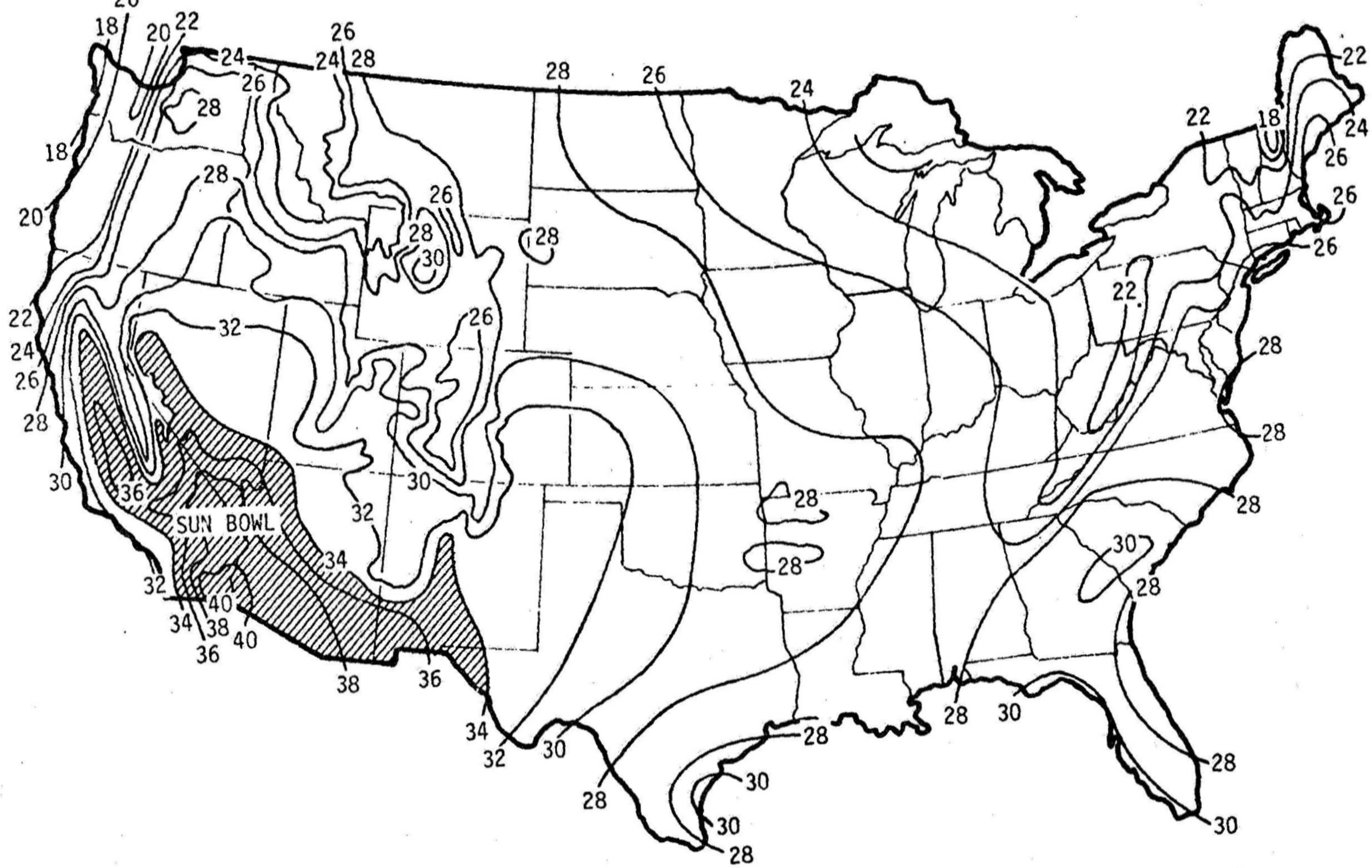


Figure 17. Annual mean total hours of sunshine (in hundreds).

FUTURE EFFORTS

The central receiver solar thermal power program is being vigorously pursued in the United States by ERDA. Technical feasibility has been demonstrated by the studies just completed by Martin Marietta, Honeywell, and McDonnell-Douglas and have shown that no new technology developments are required. However, studies are still required to obtain the lowest costs possible on the solar peculiar subsystems, particularly the collector subsystem.

Other efforts are also in progress to increase the performance of central receiver solar thermal power plants. ERDA is to soon request proposals to study some advanced systems which use liquid sodium or a high temperature salt as the heat transfer medium in the receiver. EPRI is currently funding a study using Brayton cycle in which the air is heated by solar thermal energy.

Europe is also starting to develop central receiver solar thermal power plants. France operates a central receiver solar thermal power plant at the CNRS solar furnace in Odeillo, France. The European Energy Organization is currently planning a joint venture to design, fabricate, and operate a 500 kW_e central receiver solar thermal pilot plant in Spain. In addition, Spain is also planning to design, fabricate, and operate a 1.5 MW_e central receiver solar thermal power plant.

Many important and interesting efforts are in progress which have the ultimate goal of the development of central receiver solar thermal power plants. However, continued efforts must be undertaken to demonstrate the economic viability of central receiver solar thermal power generation.

BIBLIOGRAPHY

Highlights Report, Solar Thermal Conversion Program — Central Power Projects. December 1976, Washington, D.C., SAND 77-8011, March 1977. Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161.

Central Receiver Solar Thermal Power System, Phase I. Contractors' Reports (quarterly and annual):

Contractor[1]	Report No.
McDonnell-Douglas	SAN-1108-76-1
McDonnell-Douglas	SAN-1108-76-2
Honeywell	SAN-1109-76-T1
Honeywell	SAN-1109-76/2
Martin Marietta	SAN-1110-76T1
Martin Marietta	SAN-1110-76-1
Martin Marietta	SAN-1110-76-2
Boeing	SAN-1111-75-1
Boeing	SAN-1111-76-2
Boeing	SAN-1111-76-3

Central Receiver Solar Thermal Power System, Phase I — 10-MW Electric Pilot Plant. Sandia Laboratories/Livermore, January 1977. Available on request from ERDA San Francisco Operations Office, Solar Energy Division, 1333 Broadway, Oakland, California 94612.

Doane, J. W., et al.: The Cost of Energy from Utility-Owned Solar Electric Systems. ERDA/JPL-1012-73/3, June 1976. Available from NTIS.

Skinrood, A.C., et al.: Status Report on a High Temperature Solar Energy System. Sandia Laboratories, SAND 74-8017, September 1974. Available from TIC, US-ERDA.

Solar Program Assessment: Environmental Factors — Solar Thermal Electric. ERDA Division of Solar Energy, ERDA 77-47/4, March 1977. Available from Technical Information Center, US-ERDA, P.O. Box 62, Oak Ridge, Tennessee 07830.

1. Available from NTIS.