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Summary of Energy Storage Activities Within ERDA's Division of Solar Energy Central Receiver Program

(Summary of presentation at Interagency Coordination Meeting on Energy Storage, September 14-15, 1977, in Washington, D.C.)

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SUMMARY OF ENERGY STORAGE ACTIVITIES WITHIN ERDA'S DIVISION OF SOLAR ENERGY CENTRAL RECEIVER PROGRAM

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ABSTRACT

Energy storage activities within the ERDA Solar Central Receiver Program are reviewed. Analyses and moderate-scale experiments were performed by three contractor teams as part of the preliminary design of the Barstow, California 10 MW_e Pilot Plant. Other storage investigations related to advanced central receiver systems are also described.

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ILLUSTRATIONS

SUMMARY OF ENERGY STORAGE ACTIVITIES WITHIN ERDA'S DIVISION OF SOLAR ENERGY CENTRAL RECEIVER PROGRAM

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Introduction

This paper provides an overview of the energy storage work being sponsored by the Solar Thermal Branch of the ERDA Division of Solar Energy for Central Receiver Electrical Power Plants. To date, this work has been mainly directed toward sensible and latent heat storage. The types of activities have included design, operational and economic studies, materials compatibility tests, small-scale engineering experiments, and a few comparatively large-scale subsystem experiments.

Most of this work has been done by three contractor teams as part of a competitive two-year preliminary design effort for the 10 MW_e pilot plant to be constructed at Barstow, California, by 1980 (overall schedule is shown in Figure 1). The teams were headed by McDonnell Douglas, Martin Marietta, and Honeywell. (A fourth contractor, Boeing, worked only on heliostats.) In these first systems, superheated steam is produced in the receiver and used for direct operation of the turbine and to charge storage. Lower pressure/temperature steam is subsequently generated from storage for turbine operation.

Work is also under way on second generation systems in which a heat transfer fluid other than water/steam (e.g. sodium or molten salt) is used to transfer energy from the receiver to a steam generator or to storage. These systems have the potential of generating higher pressure/temperature steam from storage, thereby achieving considerably better conversion efficiency. In addition to steam-Rankine systems, high temperature Brayton systems incorporating thermal storage are being investigated.

Various analytical and experimental investigations in support of the above contractor efforts and for other advanced central receiver concepts employing storage are ongoing within Sandia Laboratories. These are in addition to (1) the thermochemical storage activities being directed by Sandia, Livermore, for the DOE Energy Storage Division, and (2) the storage activities related to solar total energy systems at Sandia, Albuquerque.

10 MW_e Pilot Plant Storage Systems

As part of the 10 MW_e pilot plant preliminary design effort, one latent heat system and two sensible heat systems were investigated. The McDonnell Douglas (MDAC) team and the Martin Marietta (MM) team worked on sensible heat; both conducted relatively large scale subsystem research experiments (SRE). Honeywell worked on a latent heat system throughout most of the period; however, because of some programmatic cost problems, Honeywell was directed to defer further analysis and testing on the latent system and to instead incorporate sensible heat storage similar to MDAC or MM in their system design. Principal characteristics of the storage subsystems proposed by the three contractors are shown in Table 1. The subsystems and the respective experimental configurations are further described below.

All of the systems use a dual-admission turbine to accept either direct receiver-generated steam or the lower temperature/pressure steam generated from storage. Turbine steam conditions from the receiver are very similar in all three systems (950°F and about 1400 psi). Steam conditions from storage are necessarily lower (due to second-law degradations) and differ considerably among the three different storage subsystems (see Table 1).

McDonnell Douglas

The general central receiver power plant configuration proposed by MDAC is shown in Figure 2, and functional relationships of the principal subsystems are illustrated in Figure 3. The thermal storage subsystem investigated by MDAC and their principal storage subcontractor, Rocketdyne, was a dual-media sensible heat concept using a heat transfer oil (Caloria HT-43) and rock (see Figure 4). During the charge cycle, oil is heated by steam from the receiver and circulated down through a packed bed of rock and sand. Flow conditions and rock/sand sizes are such that heat transfer occurs in a narrow region, and a rather sharp, moving thermocline is maintained between the upper and lower portions of the bed. The storage is fully charged when the thermocline is driven completely to the bottom of the tank. During discharge, hot oil is pumped from the top of the tank, through a steam generator heat exchanger and back to the bottom of the tank. Temperature-enthalpy relationships between the oil and input/output steam are shown in Figure 5.

The concept was evaluated in a subsystem research experiment (SRE) at the Rocketdyne test facility shown in Figure 6. The storage experiment is in the foreground (other equipment is unrelated to this experiment). The storage tank, shown in the final stages of construction in

Figure 7, is 3.2 meters interior diameter and 13.3 meters high. Special manifolds, such as the one shown in Figure 8, were incorporated in the top and bottom of the tank to assure uniform oil flow. The rock bed in the nearly filled tank can be seen in Figure 9. The experiment demonstrated that a comparatively sharp thermocline could be maintained in the dual-media configuration. During a typical daily cycle, about 87 percent of the theoretical heat capacity of the dual-media was recovered at temperatures within 15°F of the charge temperature. Additional details on the experiment are available in Reference 1.

Martin Marietta

The overall plant configuration proposed by Martin Marietta is illustrated in Figure 10, and a functional schematic is shown in Figure 11. The storage subsystem is a two stage sensible heat type employing molten Hitec for the desuperheat/superheat stage and Caloria HT-43 for the condensor/boiler stage. The molten Hitec is cycled between 519 and 900°F, and the oil is cycled between 460 and 563°F. Separate tanks are used for storage of the hot and cold fluids.

The principal advantage of two stages in systems using water/steam receivers is that storage-generated steam can be superheated to a significantly higher temperature than is possible with a single stage. This results in higher turbine conversion efficiency and a corresponding reduction in the amount of thermal energy required per unit of electrical output. The cost reduction in heliostats and in the thermal power system (i.e. receiver, tower, piping, heat exchange, storage capacity) may or may not offset the increased cost of the two stage storage system; in the particular designs proposed for the 10 MW_e pilot plant, it did not.

A prototype storage subsystem was built and tested by Martin Marietta and the Georgia Institute of Technology at the Newnan, Georgia plant of the Georgia Power Company during late 1976 and early 1977. The maximum discharge energy was about 2.8 MWh_t. Figure 12 shows the experimental configuration, with storage-generated steam being discharged from a silencer unit. Figure 13 shows the vertical condensor/boiler that was used in a reversible mode during charge or discharge operations. Separate units would be used in a pilot or commercial plant to allow simultaneous charge and discharge. The two series-connected molten salt heat exchangers used for steam desuperheat/superheat are shown in Figure 14. These were also used in a reversible mode for the purposes of the experiment. The two oil storage tanks (one hot and one cold) are shown in Figure 15. The salt tanks are shown in Figure 16 prior to installation of insulation. The system was successfully operated and experimental objectives were met. Additional detail can be found in Reference 2.

Honeywell

The overall solar power plant configuration proposed by the Honeywell team is illustrated in Figure 17, and a functional schematic is shown in Figure 18. The two-stage thermal storage subsystem combines features of the MDAC and the MM systems. Molten Hitec in separate hot and cold tanks, similar to MM, is used for the desuperheater/superheater stage. A dual-media system of Caloria HT-43 and rock similar to MDAC's is used in a thermocline mode for the condensor/boiler stage. Discharge steam temperature is somewhat lower than Martin Marietta's but pressure is slightly higher (see Table 1). Further details are given in Reference 3.

As was mentioned earlier, Honeywell's original storage investigations were directed toward a two-stage system using latent heat for the condensor/boiler stage (Figure 19). Sodium nitrate with about 1 percent(wt) sodium hydroxide is used as the phase change material. During charge, the liquid/solid slurry is heated and melted by receiver steam in a condensor located in the bottom of a storage tank module. During discharge, the phase change material is solidified on the outside of boiler tubes located near the top of the module. Motor-driven rotary scrapers are used to prevent excessive buildup of solids and to maintain adequate heat-transfer rates at the boiler tubes. The small percentage of sodium hydroxide allows a large percentage of the material to freeze over a narrow temperature range but prevents formation of a strong rigid material that is difficult to scrape. A small-scale experimental unit used by Honeywell to test various scraper configurations is shown in Figure 20.

The solid particles, being denser than the liquid, settle toward the bottom of the tank to be replaced by fresh liquid at the surface of the boiler tubes. As the discharge cycle proceeds, the percentage of solids increases and the slurry becomes more viscous. Practical energy extraction rates are eventually limited by the kinetics of this natural circulation. Based on experiments with the heat exchanger test model (Figure 20) and supporting analyses, it appears that about 60 percent of the theoretical latent heat of fusion of the entire mass of phase change material can be utilized in a normal storage cycle. This effects sizing and economics, since about 1.7 times more phase charge material and tank volume is required than would otherwise be necessary if the material could be completely solidified. It does not, however, directly affect first or second law input/output storage efficiencies.

Components for a 1.3 MWh_t subsystem research experiment have been designed and fabricated. The storage tank is shown in Figure 21. Primarily because of some unforeseen cost overruns, final assembly and testing of the experiment was deferred. The experiment may be carried to completion and other improvements may be investigated if funds are available.

Pilot Plant Storage Selection

The three different storage subsystem designs were compared as part of the overall 10 MW_e pilot plant preliminary design evaluations during the spring and summer of 1977. Based largely on projected cost/performance at a commercial scale, the MDAC concept was selected as being best suited for the objectives of the 10 MW_e pilot plant. The lower cost of the single stage, oil/rock thermocline subsystem more than compensated for a thermodynamic conversion efficiency some 4 percentage points lower (when operating from storage) than that achievable with the two-stage Martin or Honeywell systems. Taking into account the additional heliostats and other incremental thermal power system costs resulting from the different conversion efficiences, cost/performance was somewhat better with the MDAC storage design. It should be emphasized that these evaluations were made for specific systems, operating conditions and constraints. Because storage must usually be tailored to and integrated with each application, conclusions should not be generalized or extended to other types of systems.

Advanced Systems

In response to an RFP issued by DOE in the spring of 1977,[4] a two-year effort is now under way by four contractor teams on a second generation of central receiver systems.* These systems are aimed at achieving higher efficiency and lower cost than the first generation technology reflected in the Barstow pilot plant. All use a heat transfer fluid in the receiver other than the water/steam specified for first generation systems. Substantial improvements in performance are expected, particularly when operating from storage.

Two teams headed by Atomics International and General Electric are investigating steam Rankine systems using liquid sodium as the receiver and storage fluid. High temperature, high pressure steam (1000°F, 2000-2400 psi) is generated which is compatible with a conventional single admission turbine with regeneration and one reheat. Conversion efficiency is around 40% when operating either directly from the receiver or from storage. The storage sodium, possibly operating with iron or other material in a dual-media thermocline mode, is cycled from about 500 to 1100°F.

Martin Marietta is investigating a molten salt system to operate a similar steam-Rankine cycle. The storage salt is a molten mixture of sodium nitrate and potassium nitrate cycled between 500 and 1050°F. The current baseline design uses separate tanks for storage of hot and cold salt. However, alternate dual media methods employing rock or other materials will also be considered.

Boeing is continuing investigations which began under EPRI sponsorship into a recuperated, closed-air Brayton cycle. Maximum air tempera-

*Only the first year's effort is presently funded.

ture is limited by metal receiver tubes to around 1500°F, and turbine inlet pressure is about 500 psi. Conversion efficiency is expected to be about 40-42 percent. The thermal storage subsystem uses a packed bed of magnesium oxide bricks cycled in a thermocline mode between 875 and 1500°F.

Additionally, Sanders Associates is investigating a receiver concept for a recuperated open-air Brayton cycle. Air is heated from about 1200°F to 2000°F as it is passed through solar-heated silicon-carbide honeycomb material. The air is then circulated through a ceramic brick packed bed storage unit operated in a thermocline mode between nominally the same temperatures.

Sandia Supporting Research

Various analytical and experimental investigations are ongoing at Sandia Laboratories to support and augment contractor efforts on first generation and advanced central receiver systems. Relative to storage, analytical investigations include (1) the performance of single and dual media thermocline systems, (2) the effects of different amounts of storage and alternative dispatching strategies on plant operation and economics, and (3) feasibility studies of advanced storage concepts for commercial applications. Current experimental investigations include (1) the long-term decomposition of various heat transfer oils, such as Caloria HT-43, under thermal storage conditions in the range of 550-650°F, (2) the thermal stability of molten nitrate and other salts at temperatures up to about 1100°F, and (3) the compatibility of oil, molten salts, and other fluids with rock or other inexpensive dual-media materials. A cooperative effort on molten salt investigations with Oak Ridge National Laboratory is also in a formative stage. All of this work is being coordinated and integrated with other efforts by Sandia and with contractors working on storage and related aspects of central receiver power plants.

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1. Thermal Storage Subsystem, Volume V of Pilot Plant Preliminary Design Report, Central Receiver Solar Thermal Power System, McDonnell Douglas, SAN-1108-76-8, October 1977.

2. Thermal Storage Subsystem, Volume V of Pilot Plant Preliminary Design Report, Central Receiver Solar Thermal Power System, Phase 1, Martin Marietta, SAN-1110-77-2, April 1977.

3. Thermal Storage Subsystem, Volume V of Pilot Plant Preliminary Design Report, Solar Pilot Plant, Phase 1, Honeywell, ERDA Contract No. E(04-3)-1109, 1 May 1977.

4. Conceptual Design of Advanced Central Receiver Power Systems, ERDA RFP No. EG-77-R-03-148, Closing date August 1, 1977.

TABLE 1

PILOT PLANT THERMAL STORAGE CHARACTERISTICS

Characteristic	Honeywell	Martin Marietta	McDonnell Douglas
Storage concept	Two-stage sensible heat using an oil/rock thermocline and Hitec salt	Two-stage sensible heat using oil and Hitec salt	Single-stage sensible heat using an oil/rock thermocline
Net electrical output duration	7 MW(e) 3 hours	7 MW(e) 3 hours	7 MW(e) 3 hours
Discharging steam conditions from storage	3620 kPa (532 psia) 390°C (735°F)	3000 kPa (435 psia) 428°C (802°F)	2760 kPa (400 psia) 277°C (530°F)
Maximum charging rate	31.6 MW(t)	34.8 MW(t)	30 MW(t)
Storage media	Main stage-caloria HT-43 oil with crushed granite superheater stage - Hitec	Main stage-caloria HT-43 oil, superheater stage - Hitec	Caloria HT-43 oil with crushed granite and coarse sand
Number of storage tanks	Main stage-1, superheater stage-2	Main stage-2 superheater-2	1

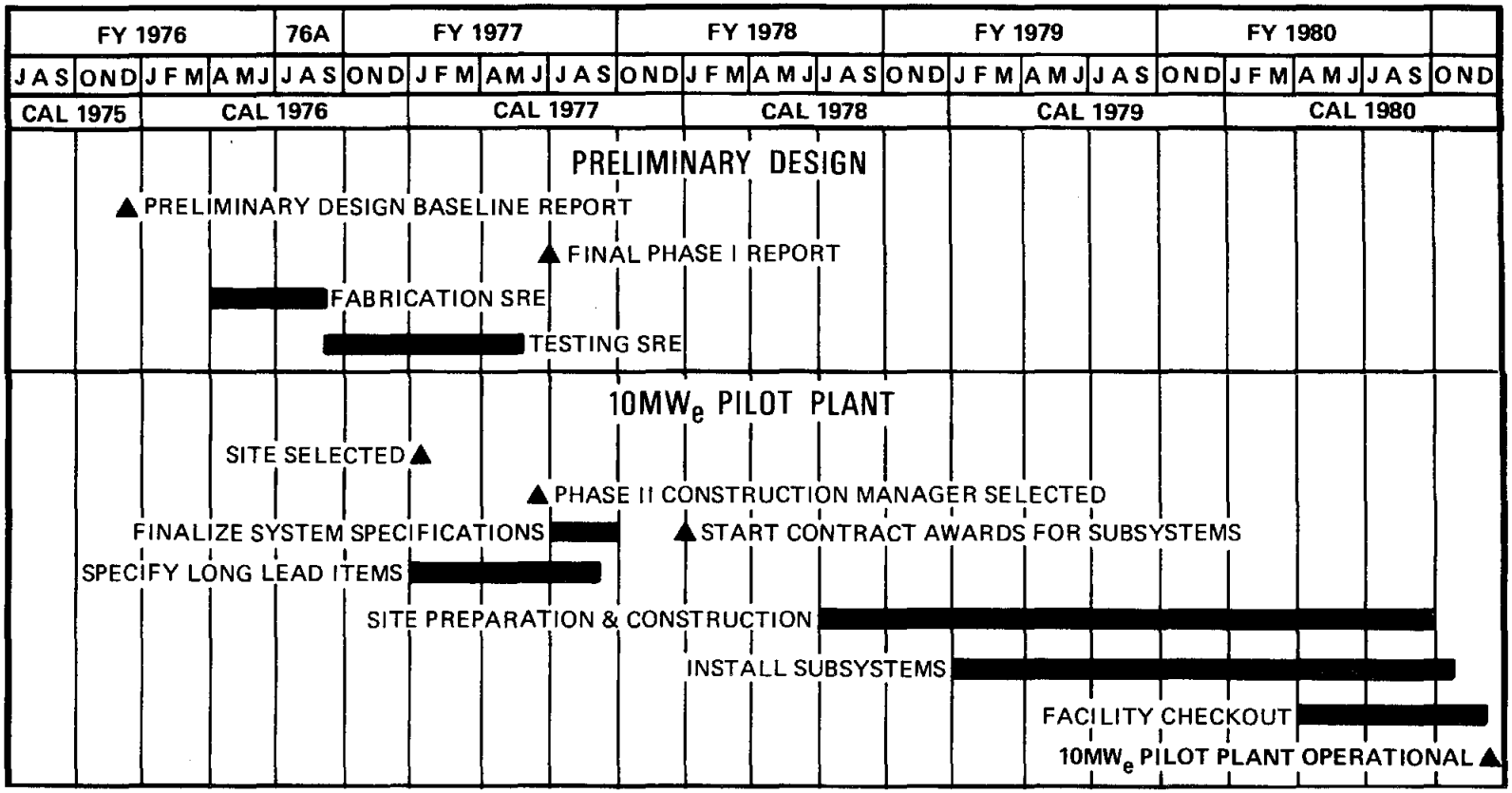

Figure 1 . **10 MW_e Pilot Plant Project 5 Year Milestone Schedule**

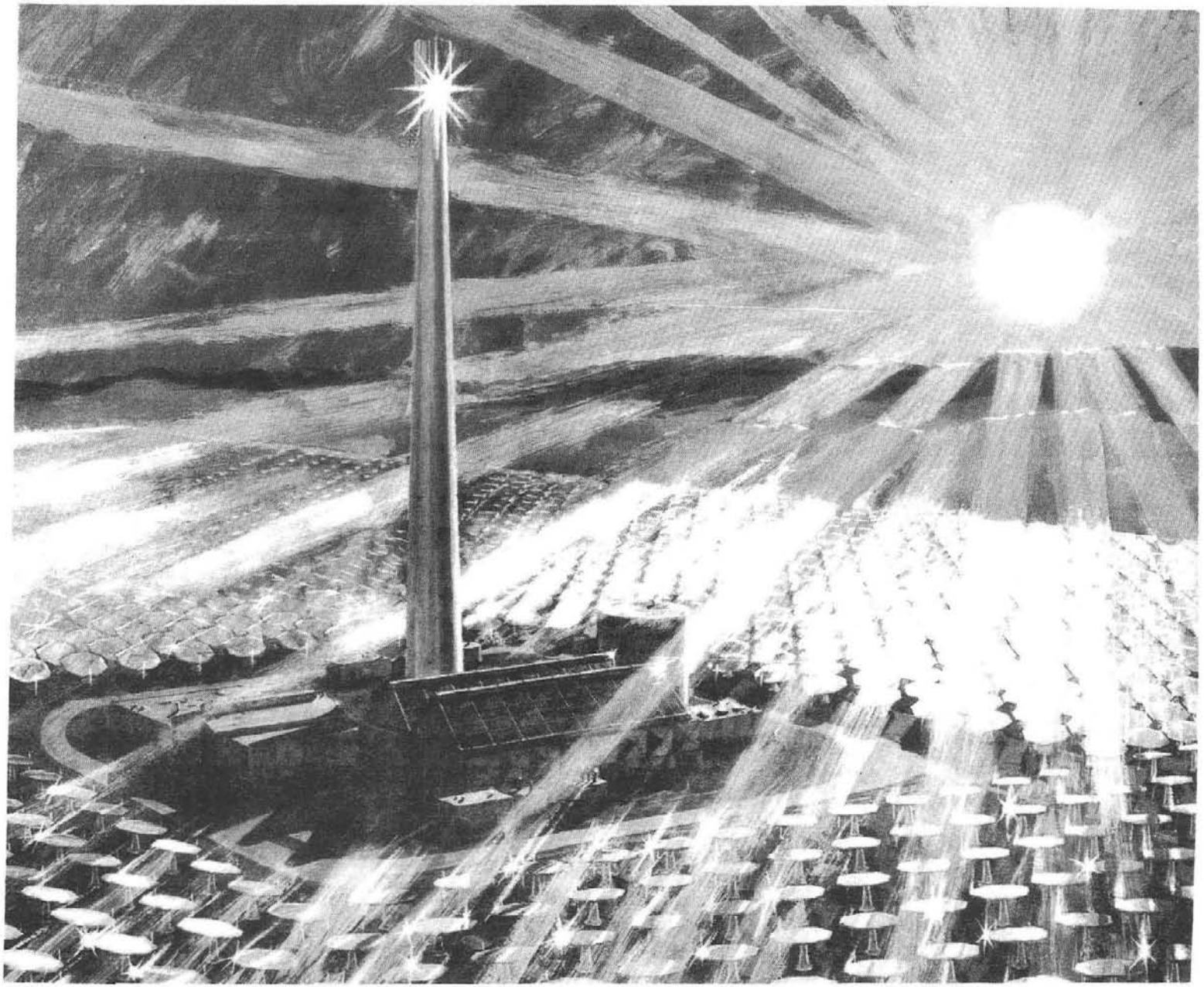

Figure 2. McDonnell Douglas Solar Central Receiver Plant Concept

(Courtesy of McDonnell-Douglas)

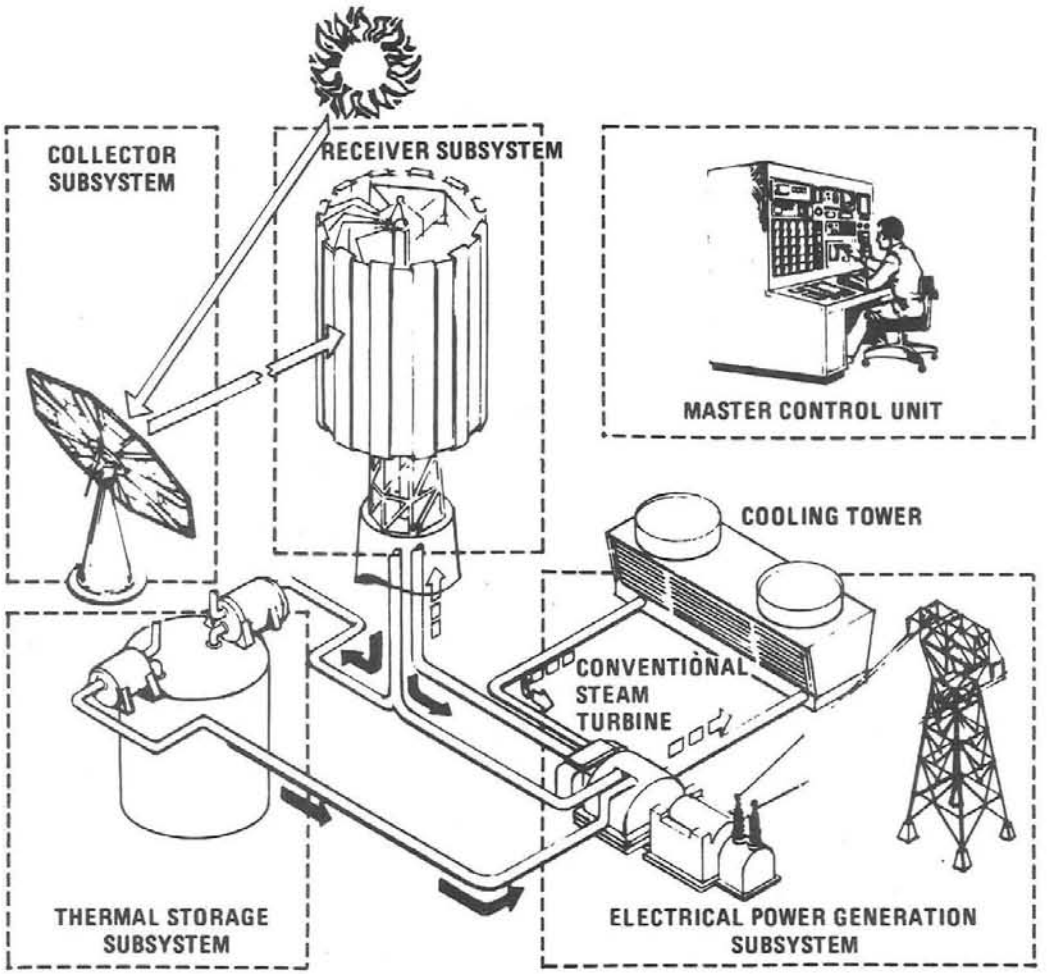

Figure 3 . McDonnell-Douglas Preliminary Central Receiver Solar Thermal Power System

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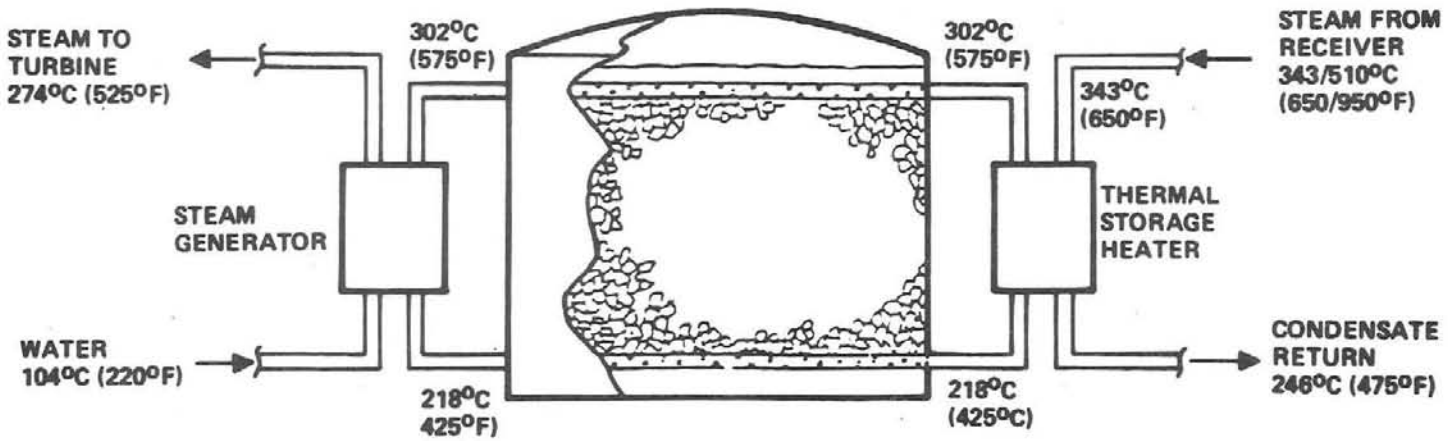
PILOT PLANT DUAL-MEDIUM THERMAL STORAGE SUBSYSTEM



TANK IS 19.4 m (63.7 FT) DIA X 17.3 m (56.8 FT) HIGH

9,590,000 kg (10,600 TONS) ROCK AND SAND

1,180,000 LITER (312,000 GAL) CALORIA HT43

Figure 4. McDonnell Douglas Pilot Plant Dual Medium Thermal Storage Subsystem

THERMAL STORAGE CHARGING AND DISCHARGING CHARACTERISTICS

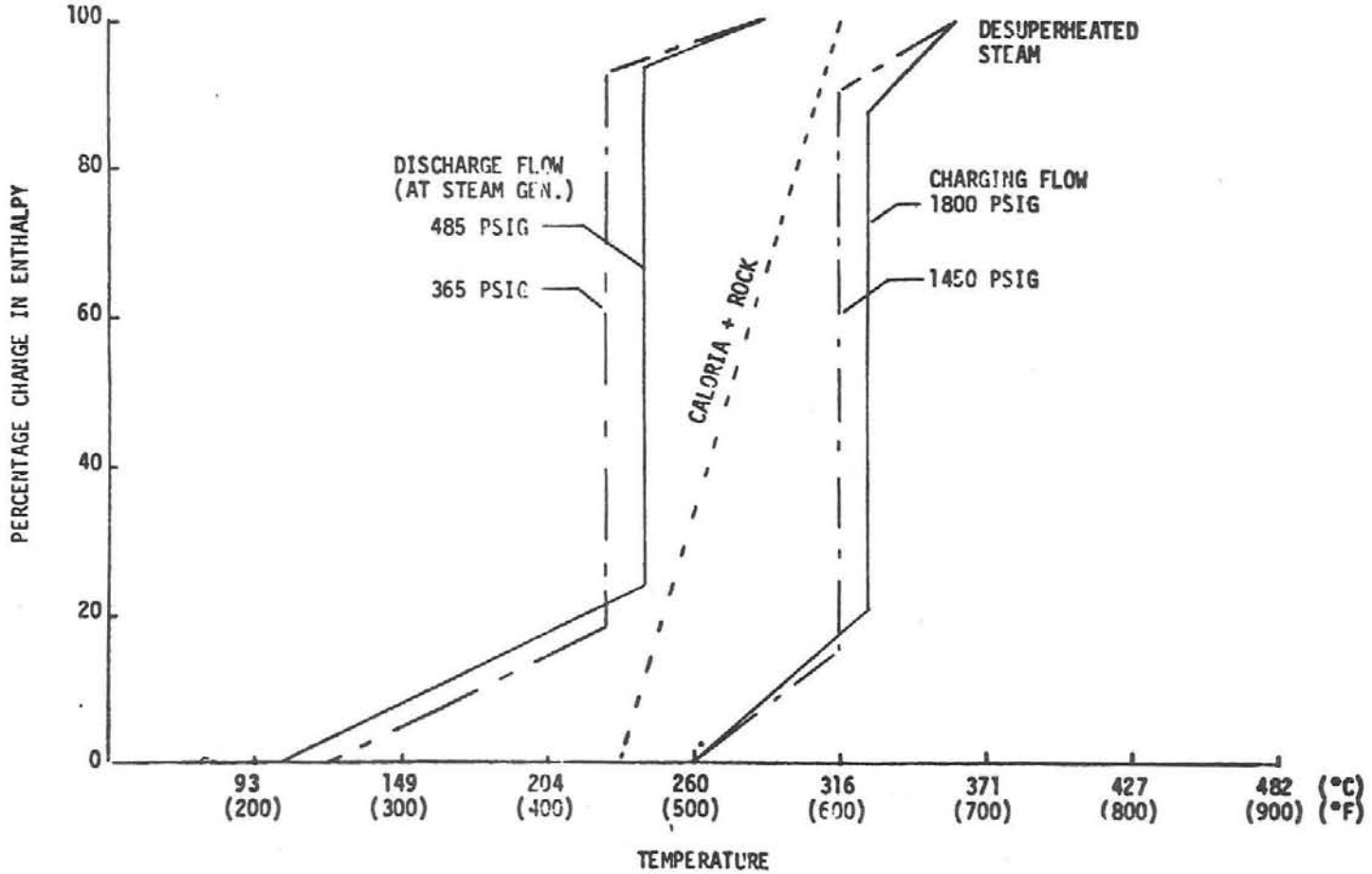


Figure 5. McDonnell Douglas Thermal Storage Charging and Discharging Characteristics

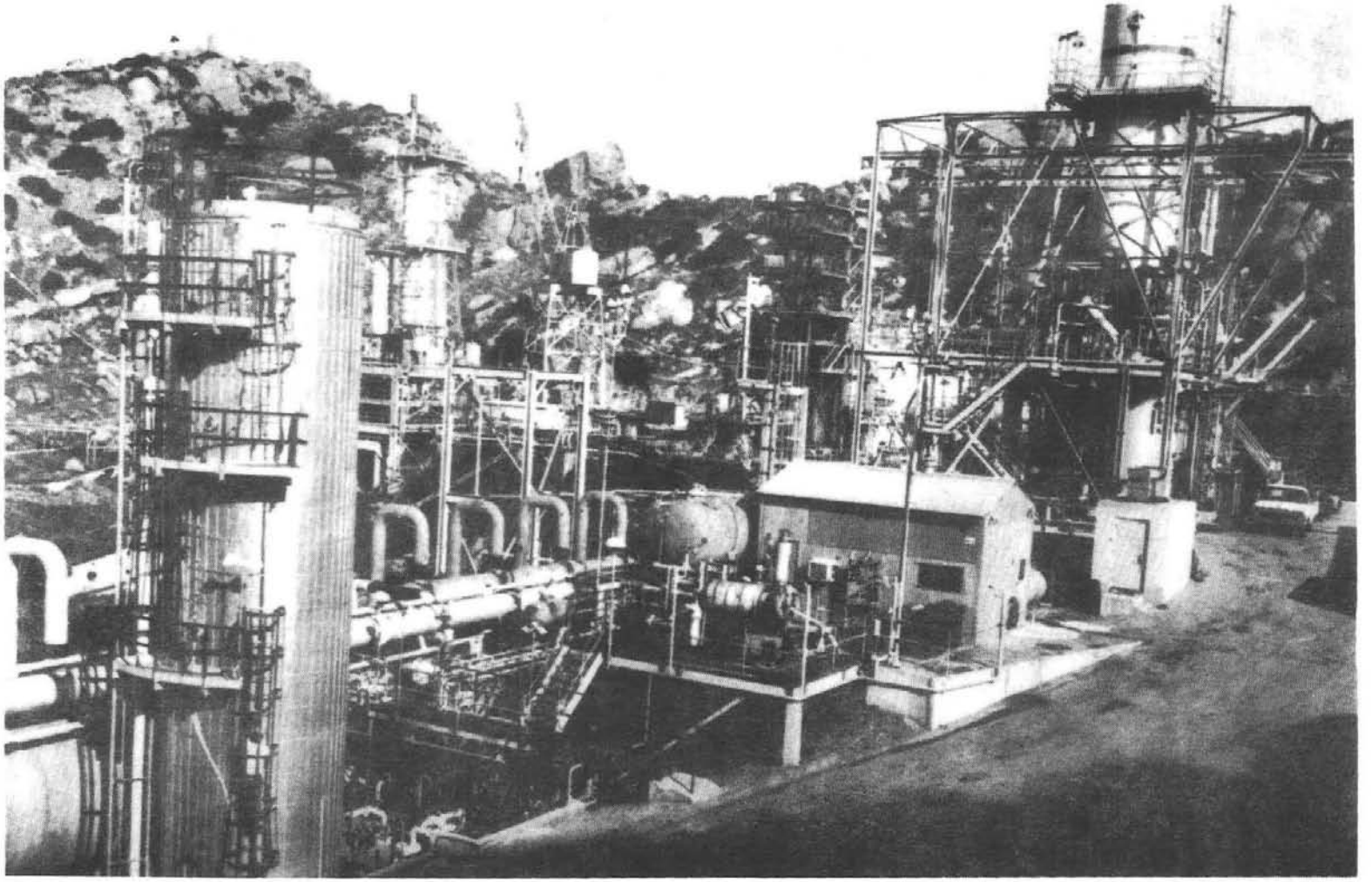


Figure 6. McDonnell Douglas Thermal Storage SRE Test Site

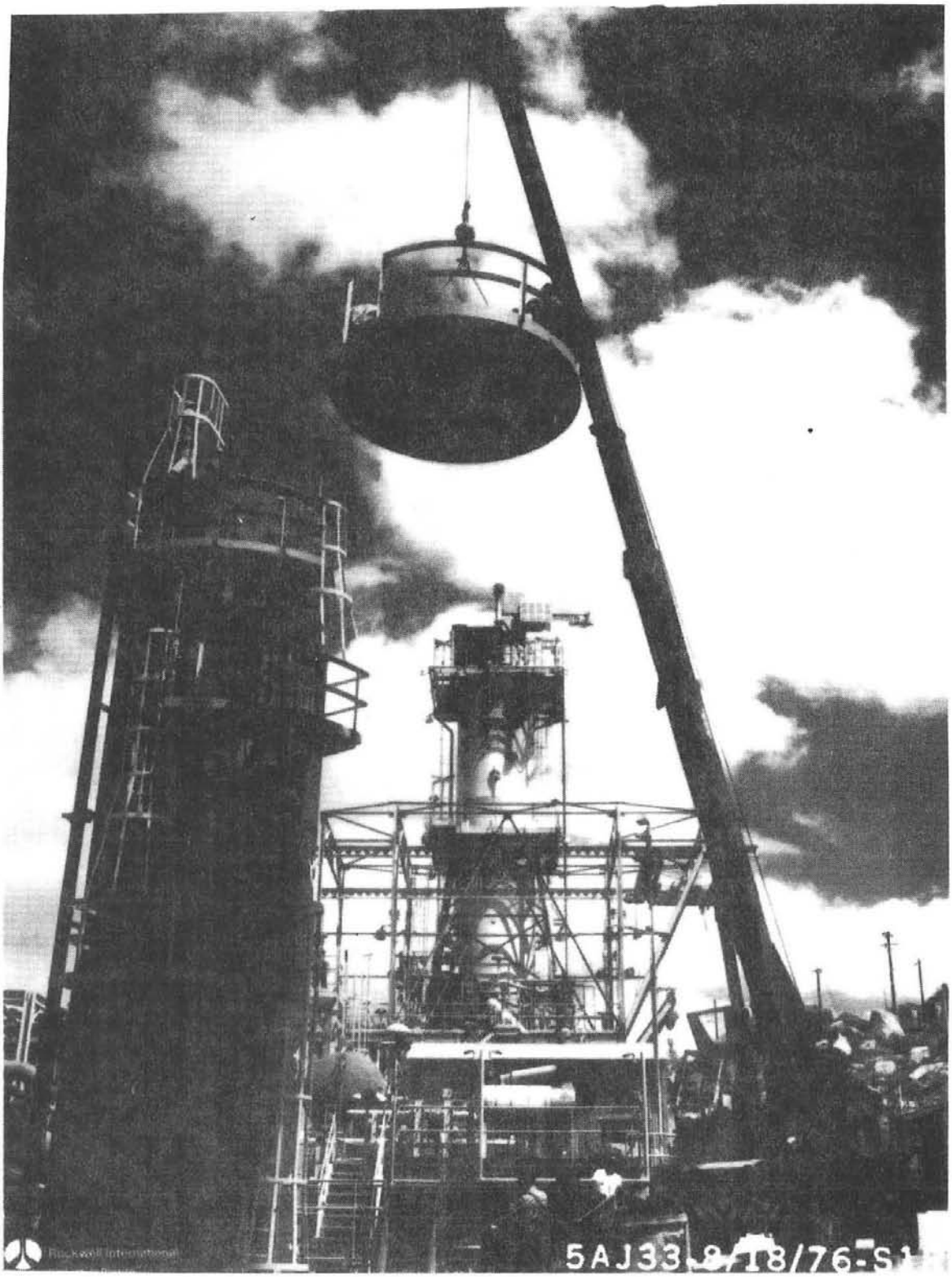


Figure 7. Cover Installation, McDonnell Douglas SRE Storage Tank

Figure 8. Manifold, McDonnell Douglas SRE Storage Tank

Figure 9. Rock/Sand Installation, McDonnell Douglas SRE Storage Tank

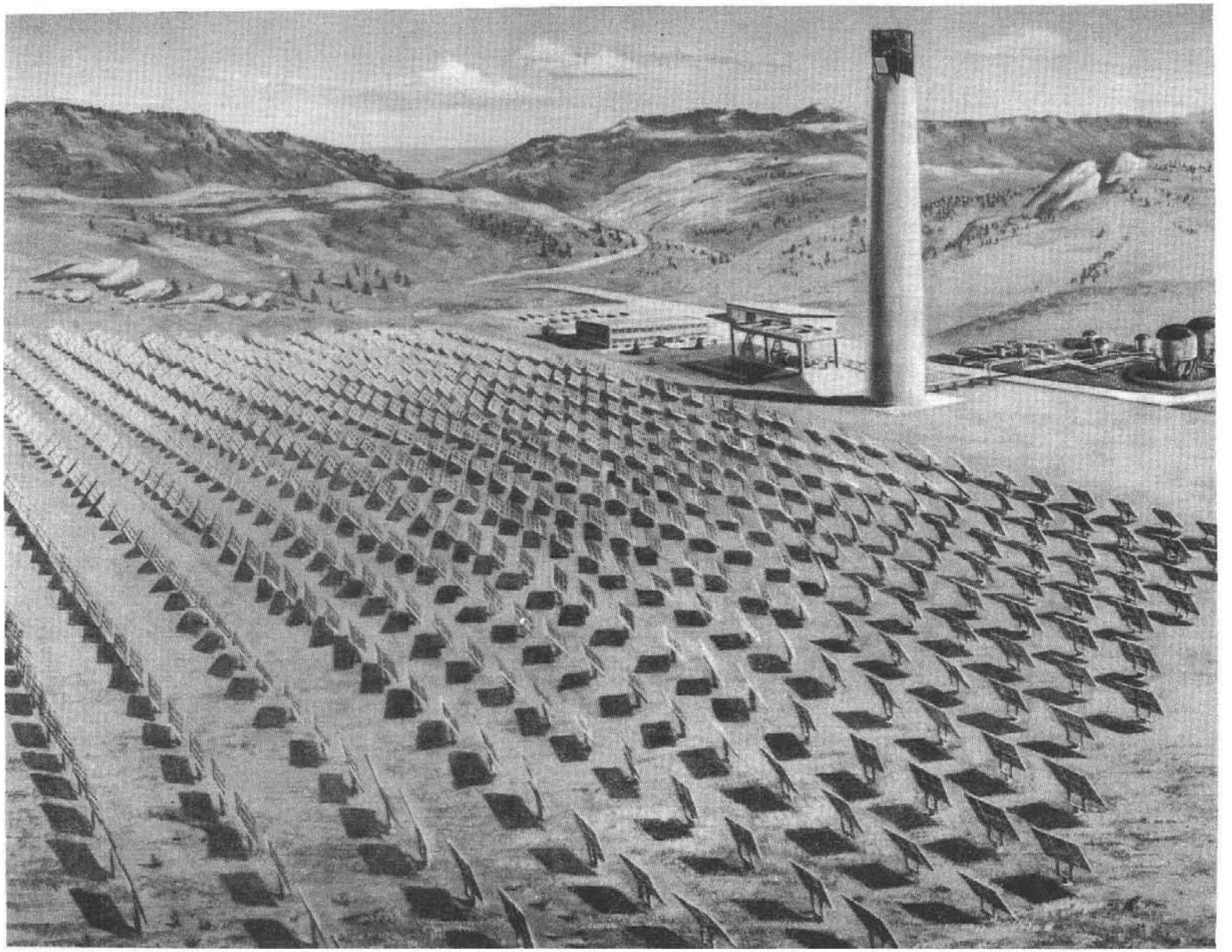
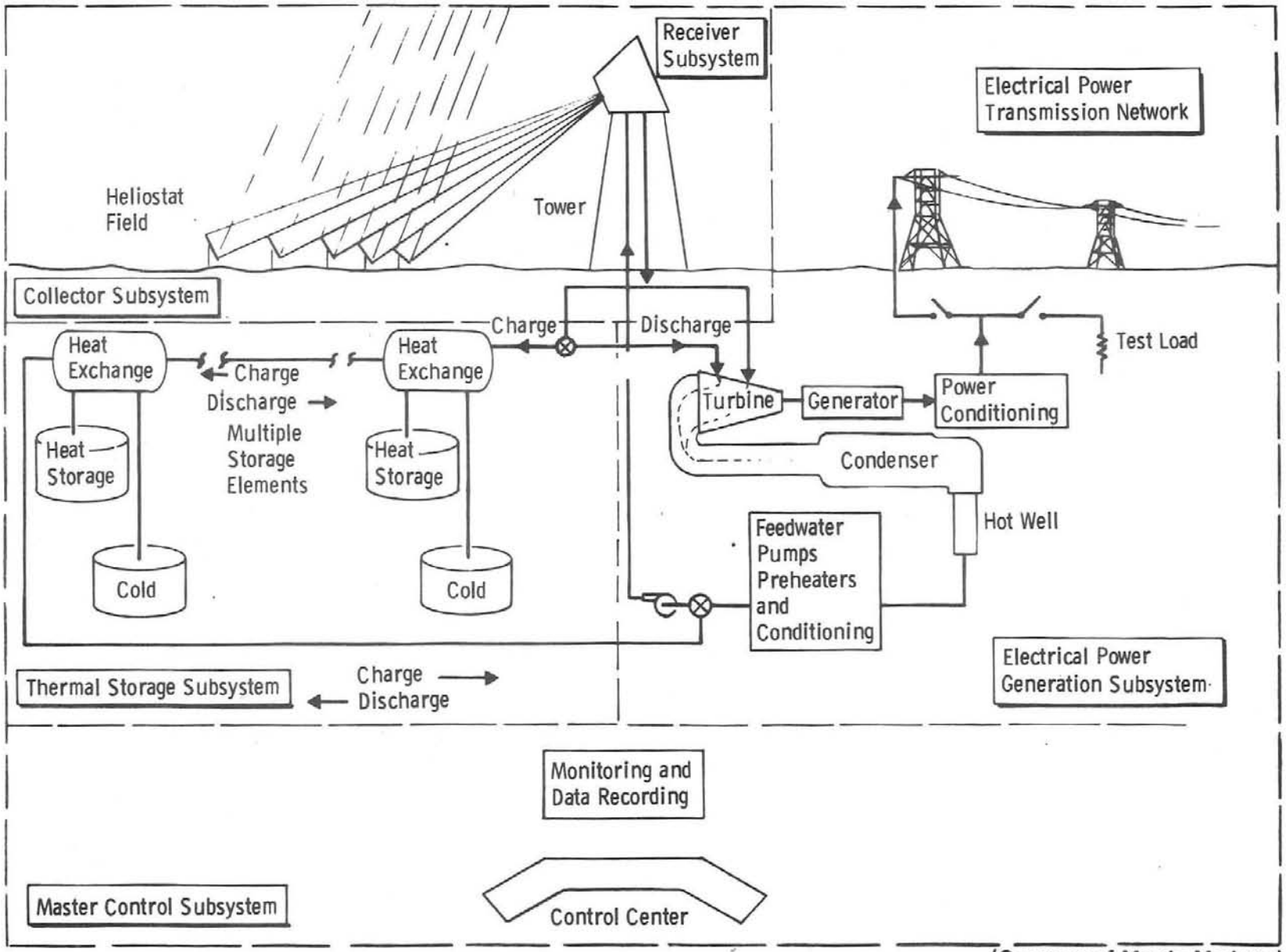


Figure 10. Martin Marietta Solar Central Receiver Plant Concept



(Courtesy of Martin Marietta)

Figure 11. Martin Marietta Preliminary Central Receiver Solar Thermal Power System

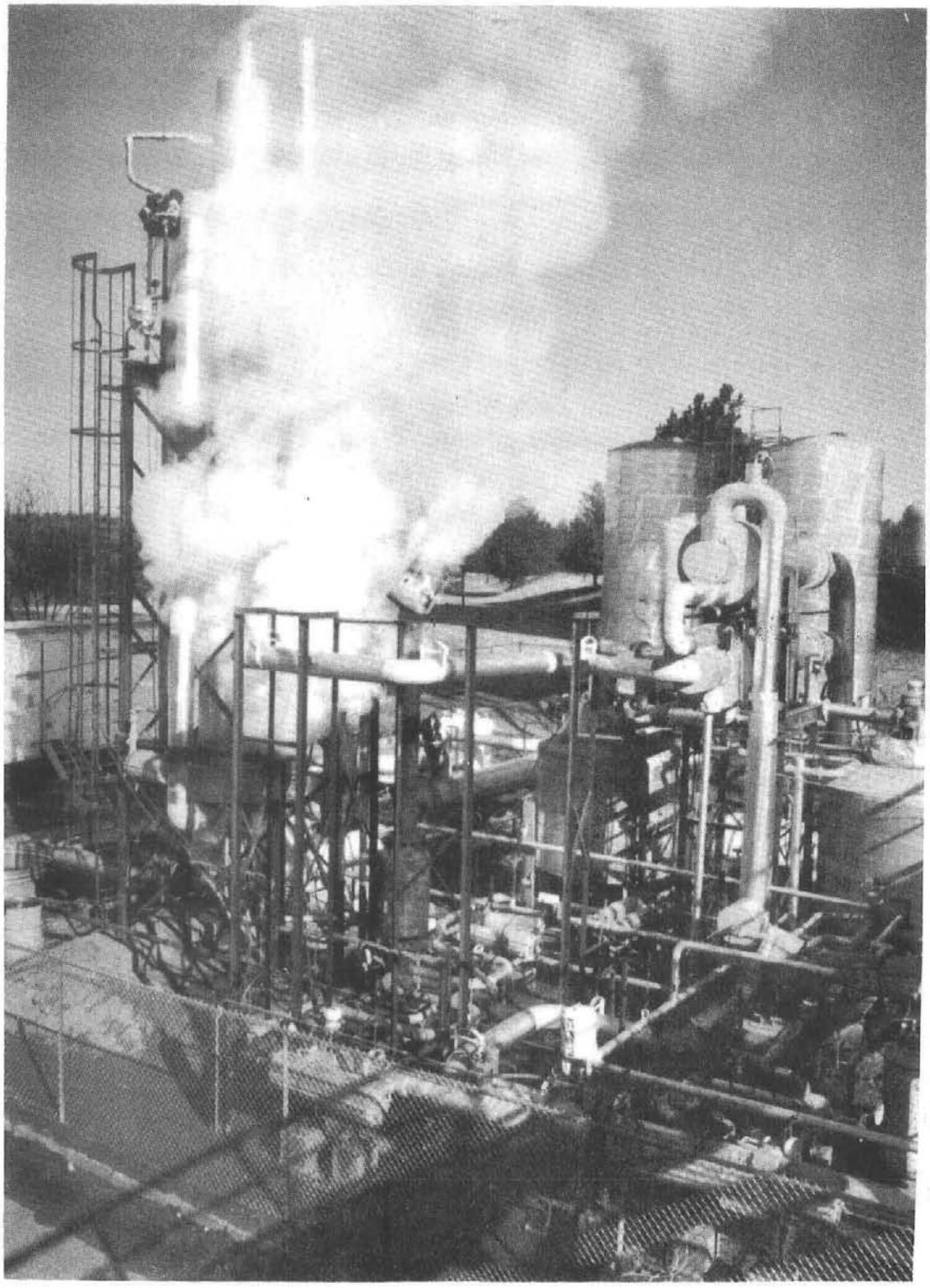


Figure 12. Martin Marietta Thermal Storage Subsystém Research Experiment

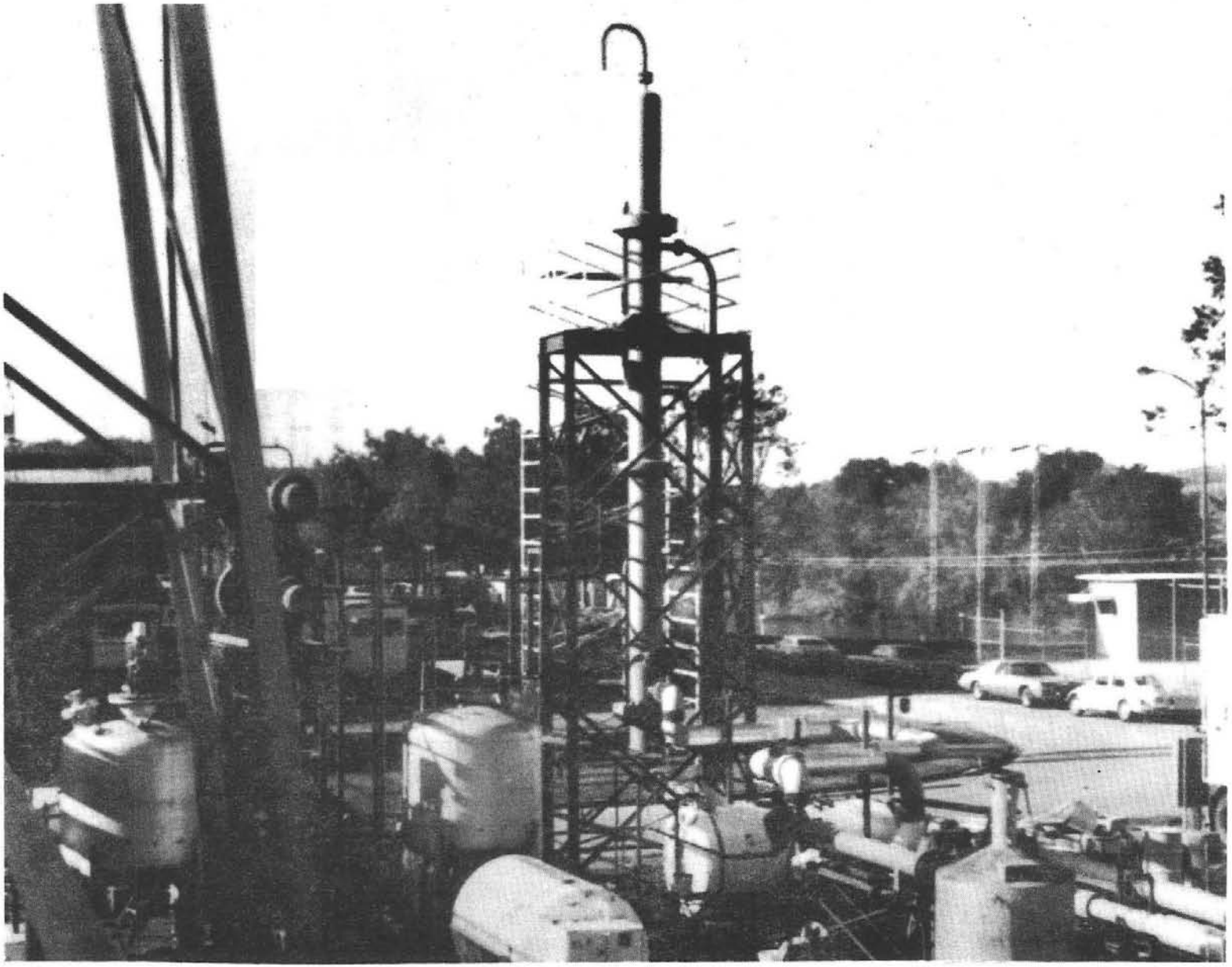


Figure 13. Condenser/Boiler Unit, Martin Marietta Thermal Storage SRE

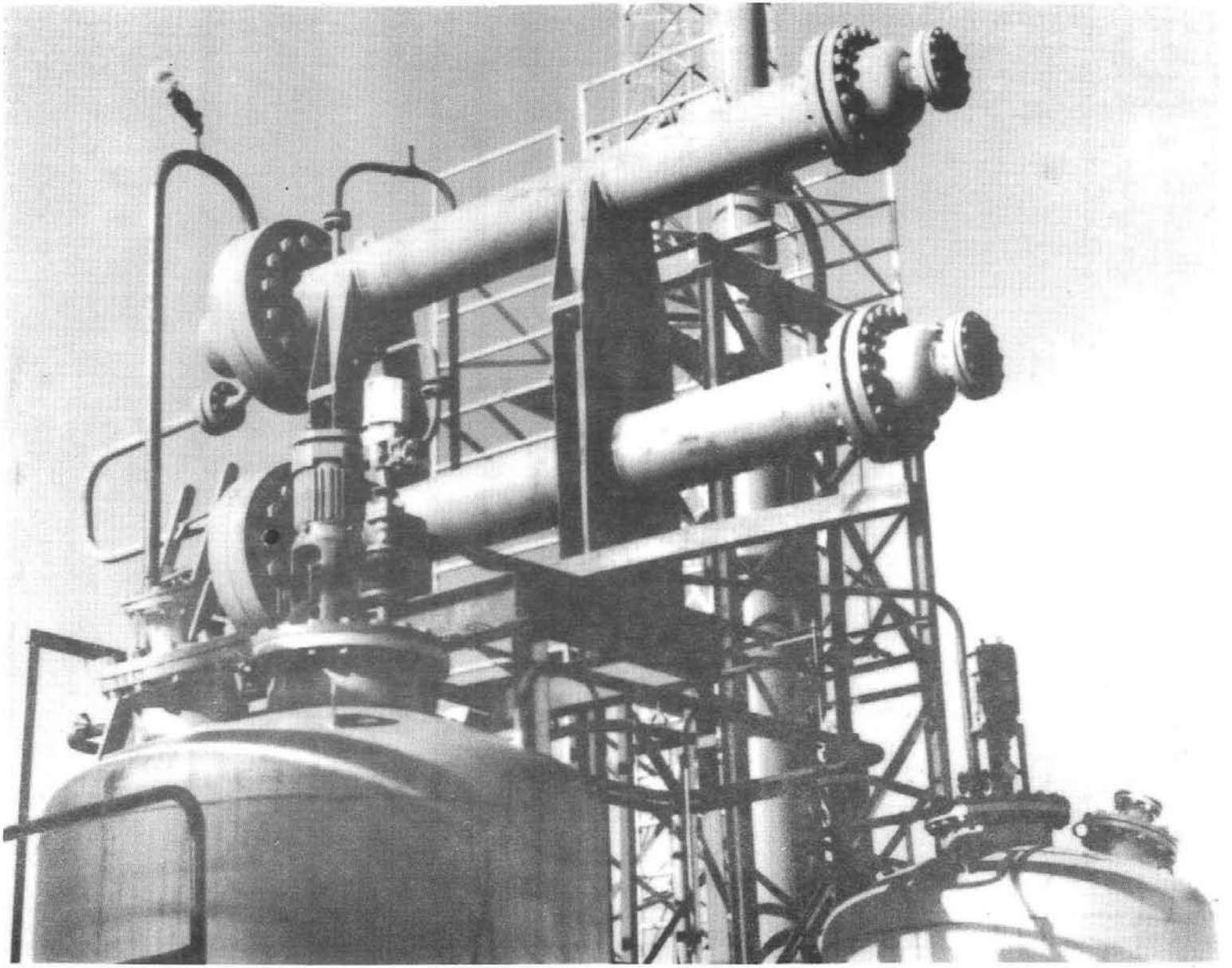


Figure 14. Molten Salt Heat Exchangers, Steam Desuperheat/ Superheat Stage, Martin Marietta Thermal Storage SRE

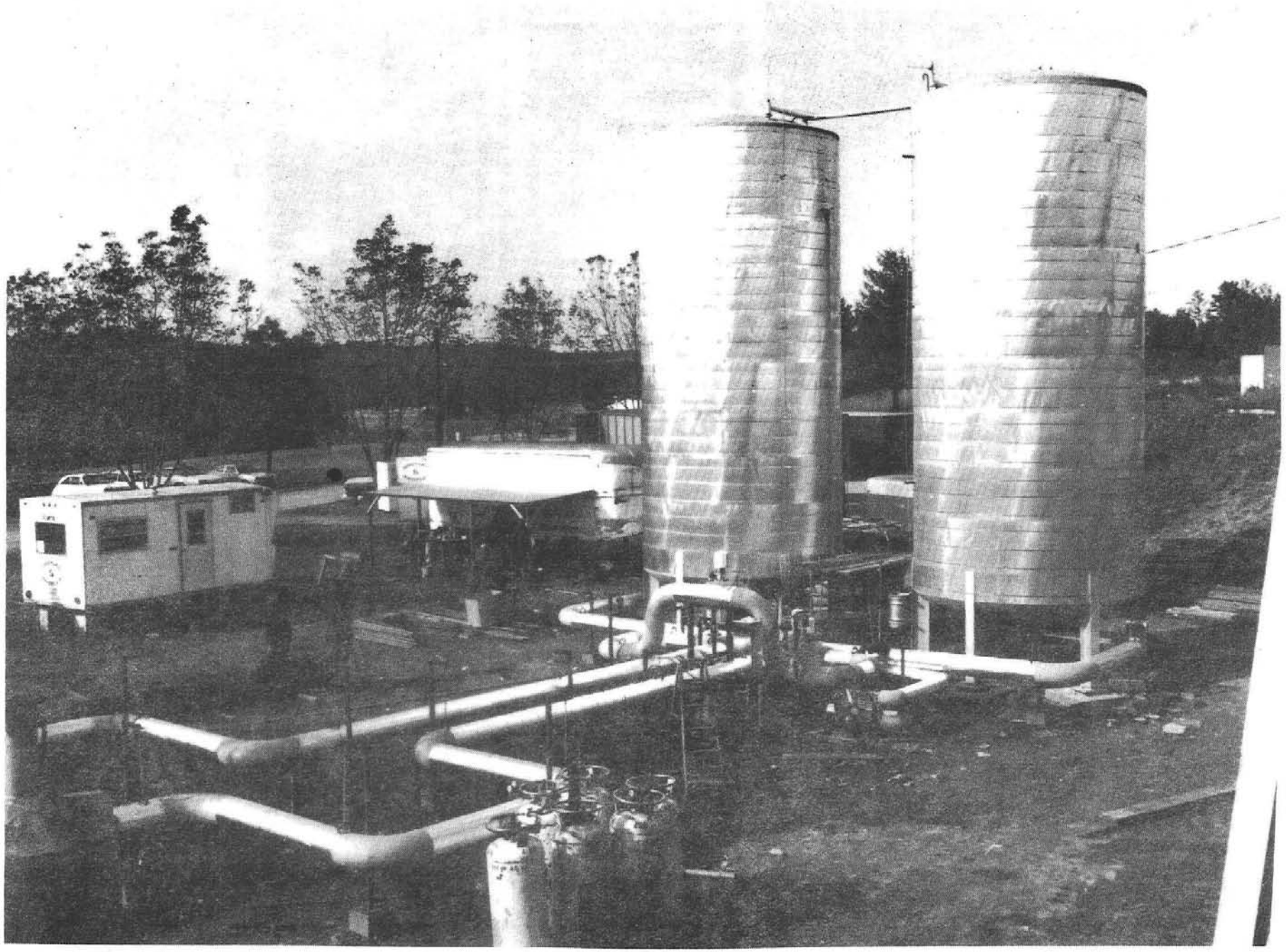


Figure 15. Oil Storage Tanks, Martin Marietta Thermal Storage SRE

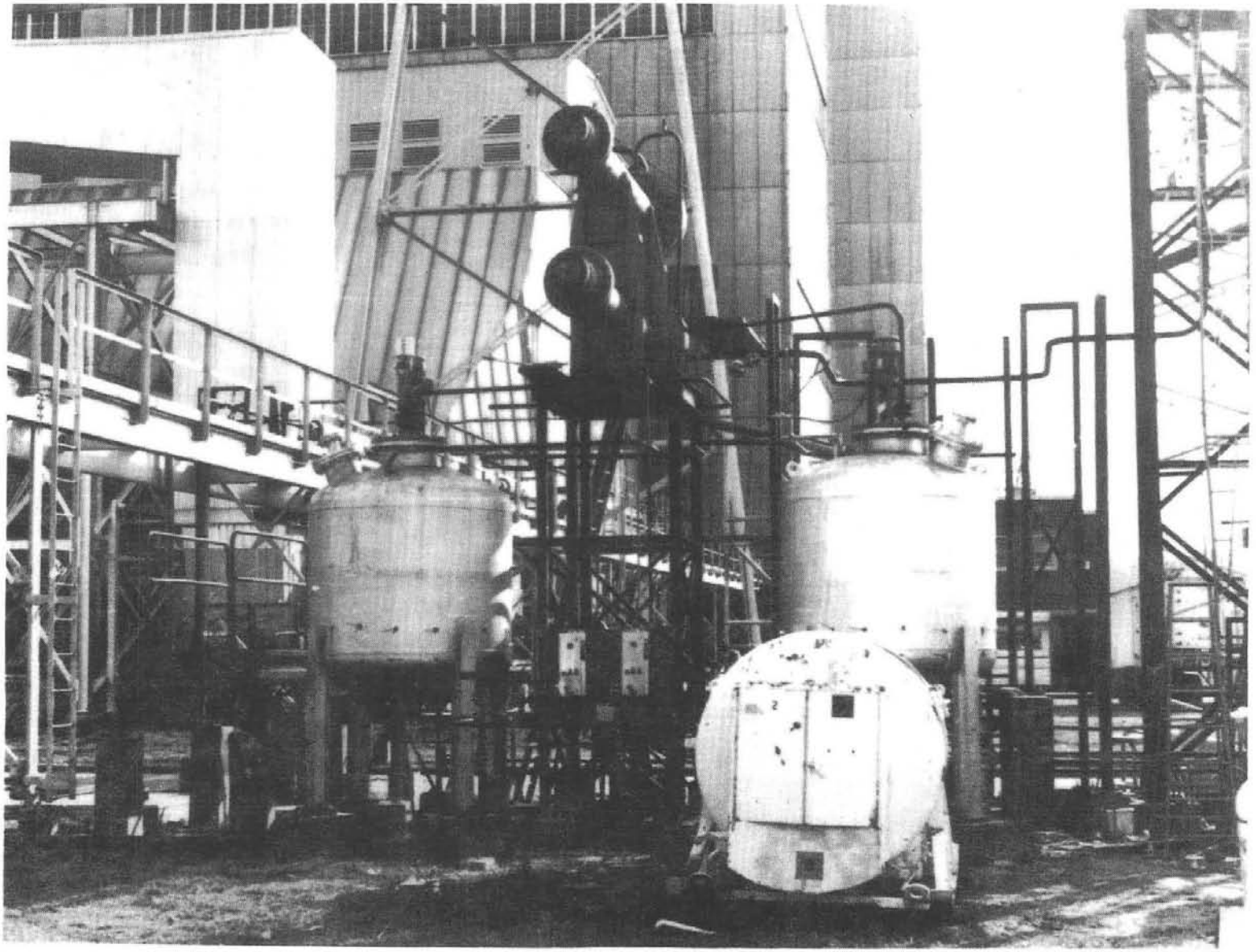


Figure 16. Molten Salt Storage Tanks, Martin Marietta Thermal Storage SRE

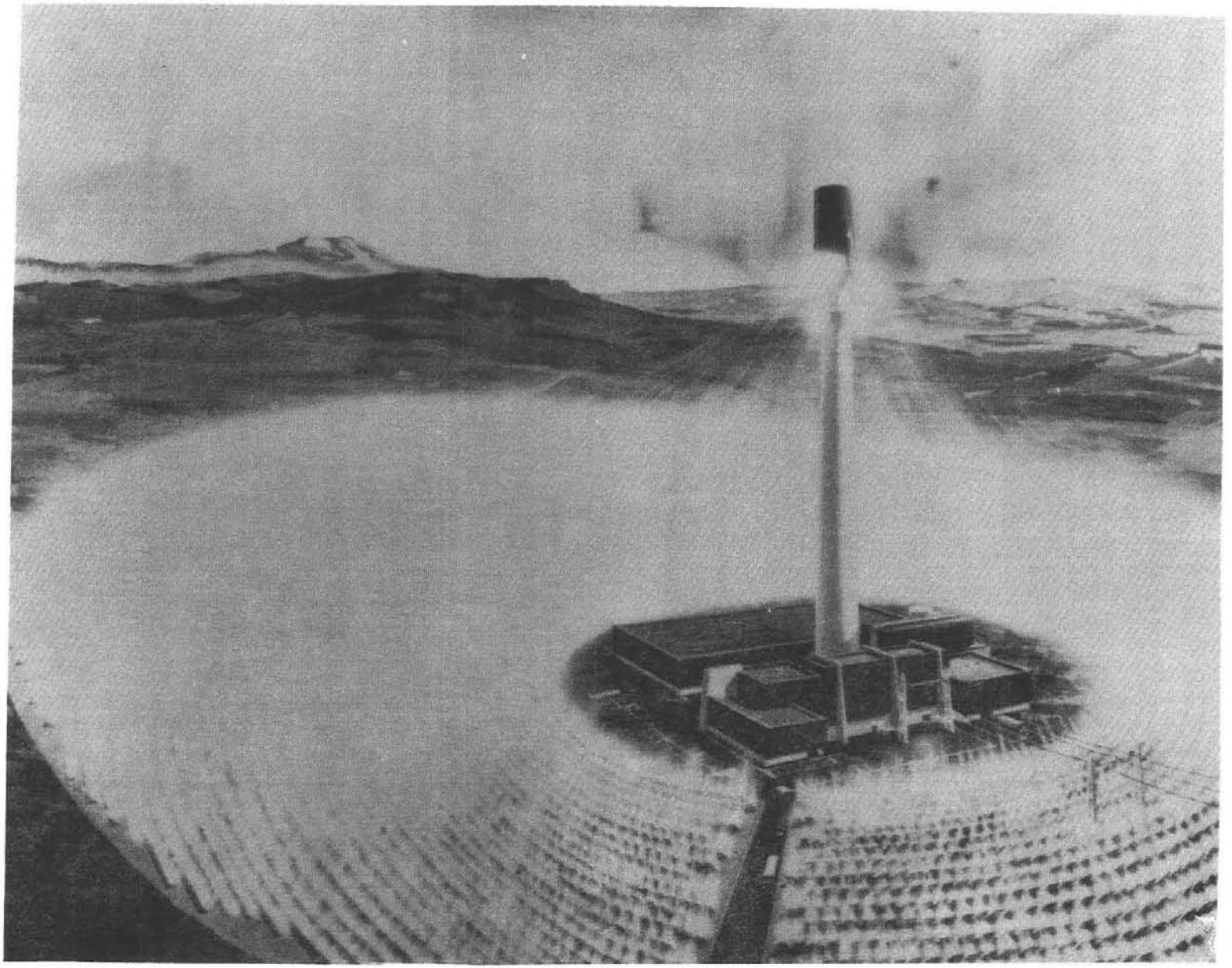


Figure 17. Honeywell Solar Central Receiver Plant Concept

(Courtesy of Honeywell)

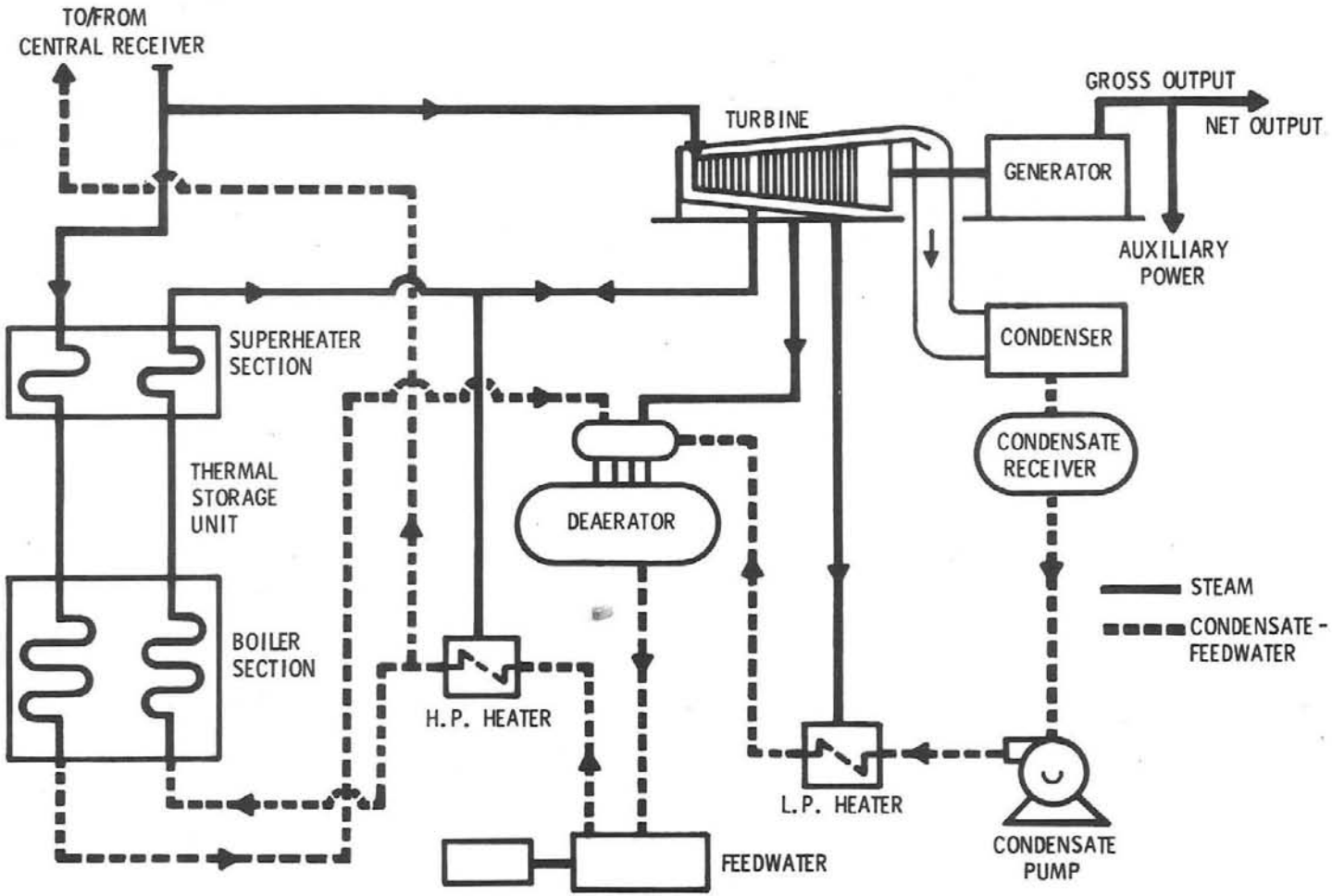


Figure 18 . **Honeywell Preliminary Central Receiver Solar Thermal Power System**

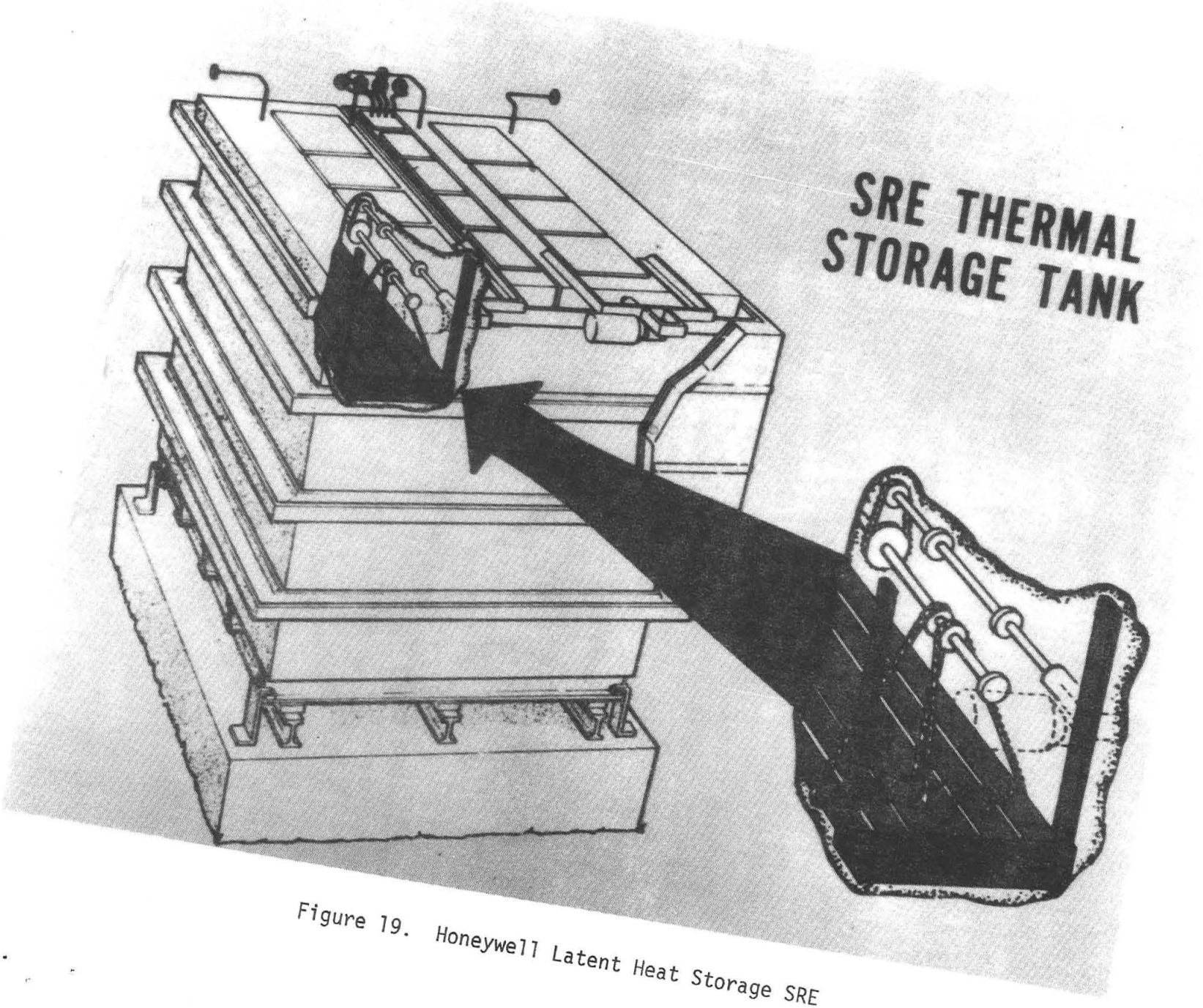


Figure 19. Honeywell Latent Heat Storage SRE

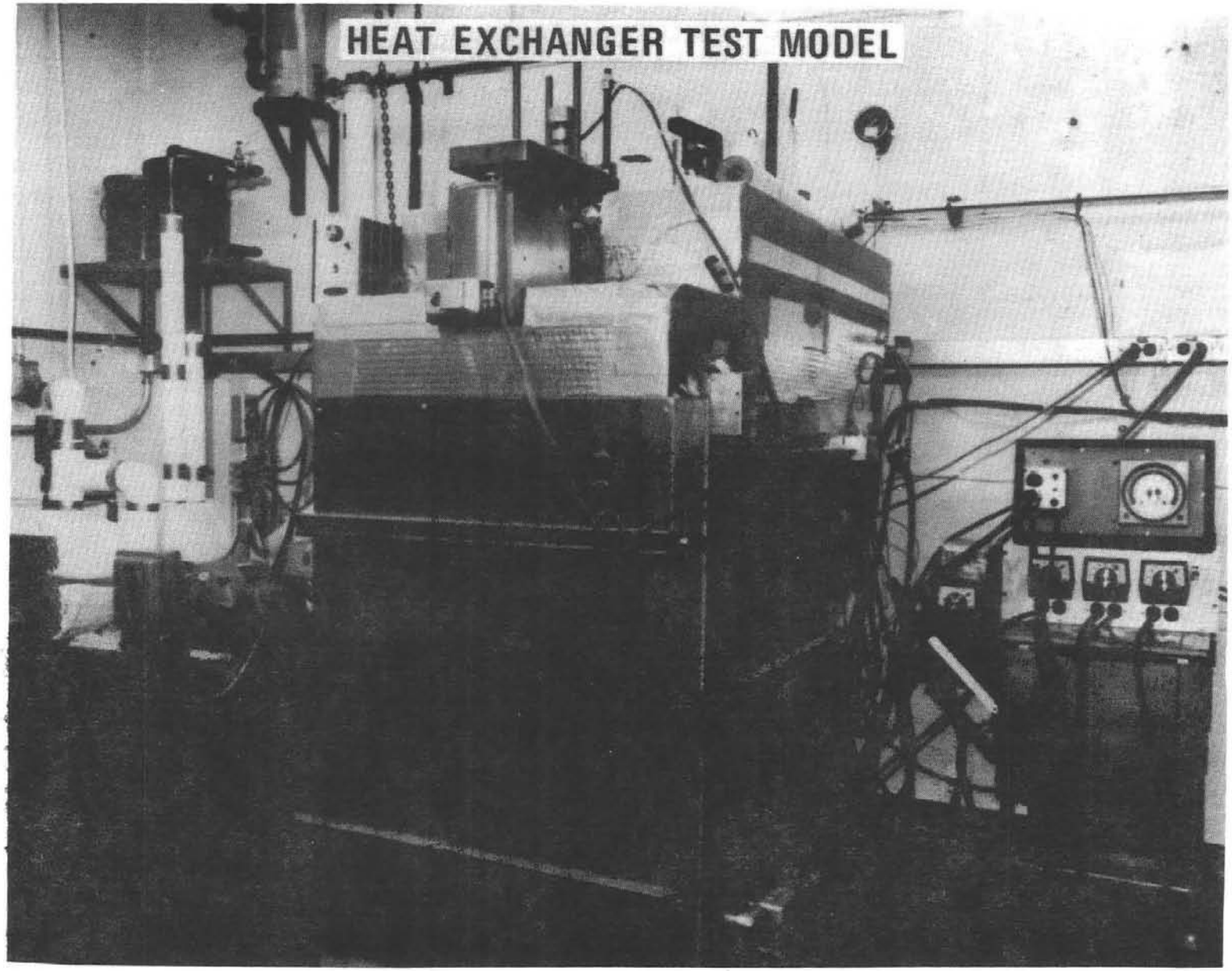


Figure 20. Honeywell Heat Exchanger Test Model, Latent Heat

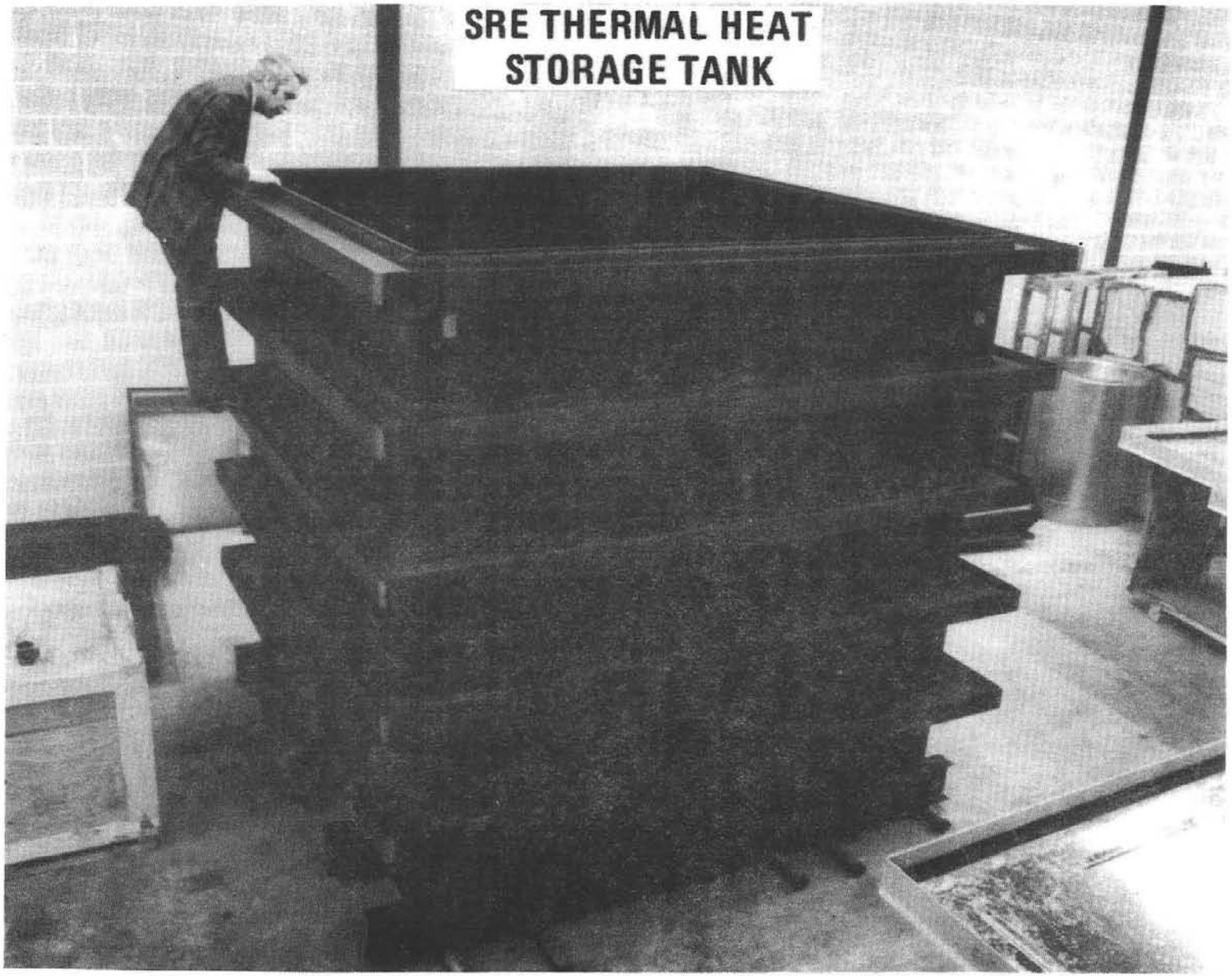


Figure 21. Honeywell Latent Heat SRE Storage Tank

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