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Thermal Energy Storage Development for Solar Thermal Applications

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THERMAL ENERGY STORAGE DEVELOPMENT FOR SOLAR THERMAL APPLICATIONS

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ABSTRACT

Development of thermal energy storage technologies for solar thermal systems has been conducted since the mid-1970s. This report describes both the status of technology development activities and research needs for the future.

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Introduction

Major considerations impacting the development of solar thermal power systems for commercial applications are the need to provide continuous operation during periods of variable insolation, to extend operation into nonsolar hours, to buffer potentially harmful transients of abrupt changes in insolation, and to ensure power availability in emergency periods. Two options exist for meeting these requirements: conventional fuel backup systems and energy storage. Backup systems indeed provide a viable near-term solution. However, as conventional fuel supplies become more expensive or of limited availability, thermal energy storage will assume an increasingly important role.

Recognizing the important potential of thermal storage, the Department of Energy (DOE) has defined a comprehensive program and sponsored several research and development activities not only to establish technology readiness for various storage technologies but also to operate these technologies in a solar system (References 1 to 3). The development goals of the program are to provide:

- Second-generation storage subsystems offering cost/performance improvements over the first-generation storage subsystems being developed for solar thermal power applications.
- First-generation storage subsystems for those solar thermal applications that presently have no storage subsystems under development.
- A technology base to support thermal storage subsystem development for future solar thermal power applications.

Seven elements have been defined in the storage development program:

1. Storage for water/steam-cooled receivers
2. Storage for molten salt-cooled sensible heat receivers
3. Storage for liquid metal-cooled sensible heat receivers
4. Storage for gas-cooled sensible heat receivers

5. Storage for organic or silicone fluid-cooled sensible heat receivers

6. Dish-mounted latent heat buffer storage

7. Advanced storage technologies.

Six of the elements are keyed to storage development for specific solar thermal receivers; research on advanced storage technologies is performed within the seventh element. Solar thermal receivers of interest to this program include concentrating troughs, bowls, dishes, and central receivers having working fluids that operate at various temperatures and pressures. Project applications have been identified for the receiver-related elements to provide a focus for storage technology development.

Thermal energy storage technologies will be developed for the first six elements according to the technical approach presented in Figure 1. In the first phase, the technical feasibility of storage concepts is established. Small-scale laboratory experiments are included in this phase. In the second phase, storage subsystems are defined for the most promising concept(s), and larger-scale subsystem research experiments (SREs) are conducted. In the final phase, the thermal storage subsystem is integrated into an online or new solar thermal power plant or test facility. At the completion of this step, the storage subsystem is a proven alternative ready for retrofit into existing solar thermal systems or for incorporation into future solar thermal systems. The first two phases, which advance a storage subsystem to technology readiness, are the responsibility of the DOE Division of Energy Storage Technology (EST). The last phase is the responsibility of the DOE Division of Solar Thermal Technology (STT).

The advanced storage technology element, element 7, seeks to provide a technology base for future focused thermal storage development. Support is given to new approaches that have the potential for reducing the cost or improving the performance of thermal energy storage, or both, for the six focused development activities. Study is also directed toward new thermal energy storage technologies that have potential solar thermal applications beyond those now contained in the focused development program. Finally, analyses are undertaken to develop cost goals for thermal storage in each application element and to identify the most cost-effective storage technologies for development.

Factors Affecting Storage Technology Selection

The selection of a storage technology for any application depends on both cost and performance considerations. The total cost of a thermal energy storage subsystem (C_t) can be determined from energy-related costs (C_s) and power-related costs (C_p). The variable C_s includes the costs of the storage medium, container, insulation, and any other items associated with the actual storage of thermal energy; C_p comprises the price of heat exchangers, pumps, plumbing, heat transfer fluids, and any other items required to transfer heat to and from storage. For a storage capacity of h hours,

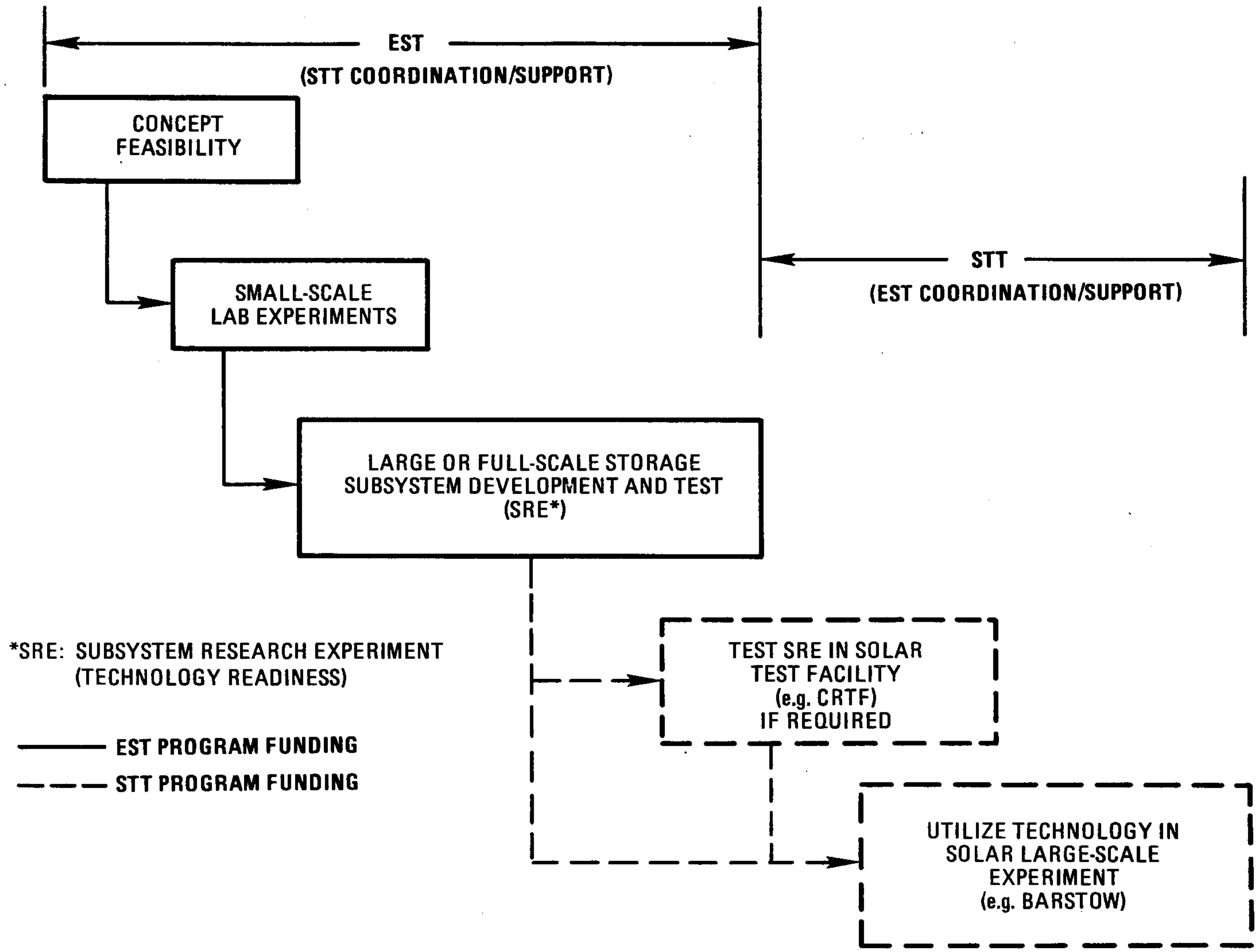

Figure 1. Technical Approach

$C_t = C_p + C_s h$. Thus accurate knowledge of C_p and C_s is needed to quantitatively assess the applicability of a storage concept.

Since C_t is usually a small fraction (approximately 10 to 20%) of the total cost of a solar thermal plant (Reference 4), C_t must be significantly reduced before it has a substantial impact on the cost of energy delivered from the system. Potential storage cost reductions of 25% or more are generally required to justify committing substantial resources to developing an advanced thermal energy storage concept.

However, the cost of delivered energy may be affected more by storage performance than by storage cost. If the quantity of thermal energy delivered from storage is less than that charged to storage, an extra price must be placed on the delivered energy to pay for the energy "lost" in passing through storage. This charge is beyond that needed to pay for the thermal storage system itself. Obviously, the greater the losses of energy from storage, the greater the delivered energy cost penalty. Systems with low storage efficiencies (< 50%) will probably not be acceptable for most applications. High efficiency storage systems (>90%) will be desirable.

Another important performance consideration when selecting an appropriate storage technology is the temperature of the thermal energy delivered from storage. Solar thermal systems are designed to produce output temperatures matched to application requirements. These requirements have led to two generic storage system configurations: direct and indirect. In the direct system, the same material is used for both the receiver working fluid and the storage media. Thus no heat exchanger is required to charge storage, and the temperature of the thermal energy delivered either from storage or directly from the receiver is nearly the same. In an indirect system, an intermediate heat exchanger is used to charge storage. Temperature drops must be provided between the receiver and storage and between storage and the load in order to transfer heat. Therefore, the receiver must be operated at a higher temperature to charge storage than is needed to operate directly to the load; or, a lower temperature must be produced at the load from storage than is produced directly from the receiver. To complicate matters further, some thermal storage systems may experience a continual drop in storage temperature with time, e.g., sensible heat storage, or the discharge cycle may occur at significantly lower temperatures than the charge cycle, e.g., thermochemical storage. Finally, the temperature of the energy delivered from storage is affected by those limits imposed by material properties (such as fluid degradation or media solidification temperatures).

All of these temperature limitations adversely affect the economics of the solar thermal system. If the temperature of the fluid from storage is lower than the temperature of the fluid available directly from the receiver, heat engines will run less efficiently; and less work will be produced per unit of energy delivered from storage than directly from the receiver. Alternatively, the temperature of the fluid from storage may not be adequate for process heat applications. If the receiver temperature is raised to make higher outlet temperatures for storage possible, the receiver efficiency will drop; and less energy will be available from storage per unit of energy incident onto the receiver.

These selection considerations imply that the appropriate thermal storage system is efficient, low in cost, and able to provide high-quality thermal energy. Of course, due to practical constraints, tradeoffs must be made among these factors to achieve the lowest possible cost of delivered energy from the integrated solar thermal-thermal storage system. Quantitative tradeoffs among thermal storage characteristics are beyond the scope of this discussion, but a methodology has been developed to identify thermal storage systems that have the potential to deliver lower energy costs (References 5 and 6).

Applications Program Activities

Development activities directed to specific application areas have been conducted since the mid-1970s. In 1975, DOE funded several studies to develop solar thermal power systems which use water/steam-cooled central receiver technology (References 7 to 9). As part of these studies, storage systems were developed for both a 10 MW_e pilot plant and a larger-scale 100 MW_e commercial plant. Laboratory experiments investigated concept feasibility and the thermal stability, compatibility, and fouling of various storage media. Finally, two subsystem research experiments were performed.

The first experiment, which was designed by Martin Marietta and the Georgia Institute of Technology, is shown in Figure 2. A 1.6 MWh_t two-stage sensible heat storage system used oil in the main stage and an inorganic nitrate salt (HITEC) in the superheat stage. In operation, the media were heated by removing colder fluid from one tank, heating it in a heat exchanger with steam from the receiver, and returning it to a second tank. For heat extraction, the process was reversed. Operation of the oil and salt stages was similar. For this experiment, the receiver steam for charging storage and the feedwater for discharging storage were simulated by tapping into existing supply lines at the site of the experiment, the Georgia Power Company's Plant Yates in Newnan, Georgia.

A second experiment designed by McDonnell Douglas and Rockwell is shown in Figure 3. The system, which had a 4 MWh_t storage capacity, employed dual liquid (oil) and solid (rock/sand) storage media, with the thermocline principle applied to store both hot and cold storage media in the same tank. Using solid media in the tank increases the volumetric energy density, reduces the quantity of costly liquid, and impedes the mixing of the hot and cold fluids. Heating of the storage media was achieved by removing colder oil from the bottom of the tank, heating it in a heat exchanger with steam from the receiver, and returning the oil to the top of the tank. During heat extraction, the process was reversed. The receiver steam for charging storage was simulated by heating the oil directly with a fossil-fired heater. For discharging storage, a steam generator heat exchanger at the site of the experiment, Rockwell's Santa Susana Test Facility, was used.

Based on the results of these tests and cost/performance estimates for the commercial-size plant, the single-stage oil/rock thermocline concept was selected for the 10 MW_e Solar Central Receiver Pilot Plant, located near Barstow, CA (Reference 4). The thermal storage tank at the pilot plant contains Exxon's Caloria HT 43 heat transfer oil, one-inch gravel, and

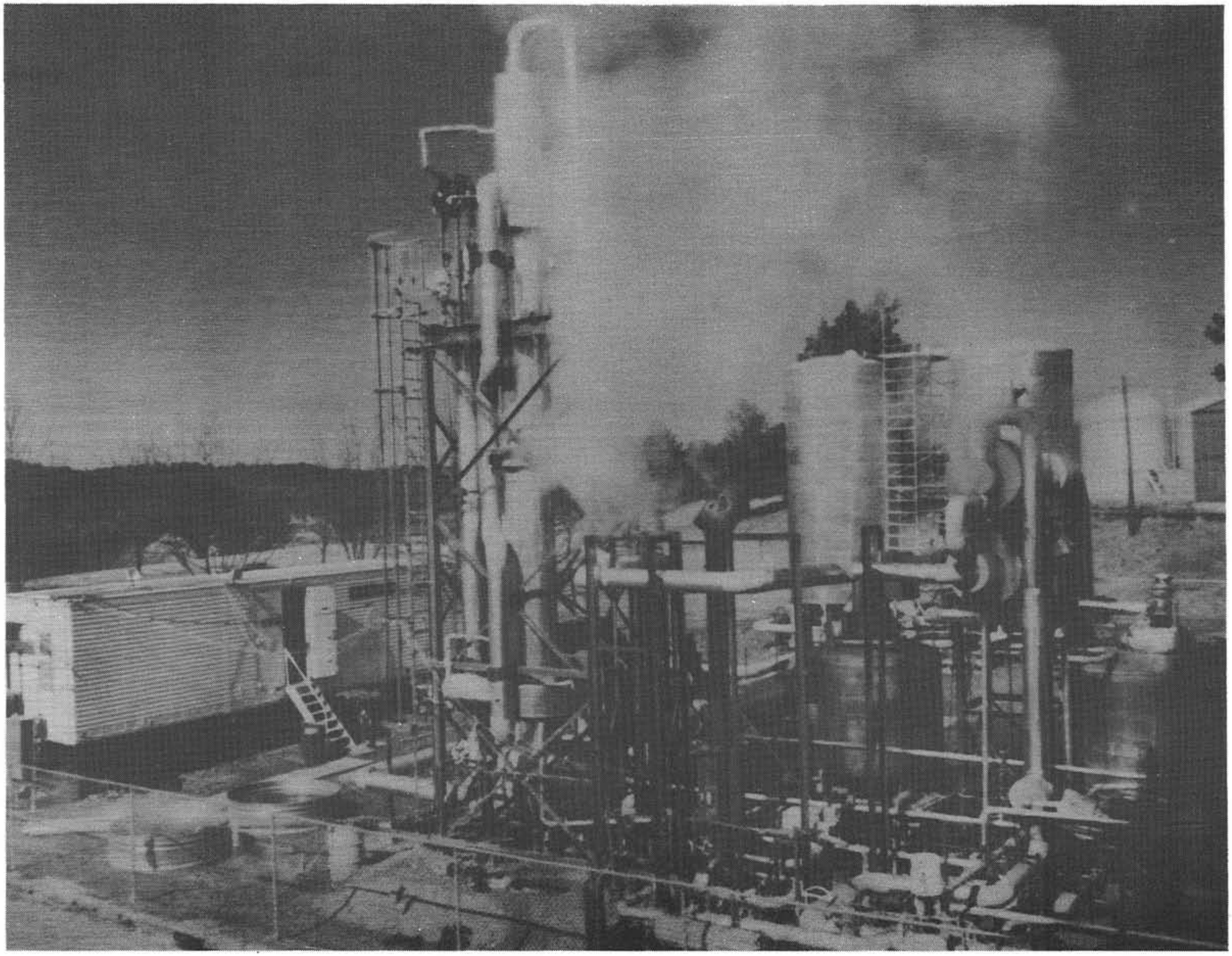

Figure 2. Martin Marietta Thermal Storage SRE

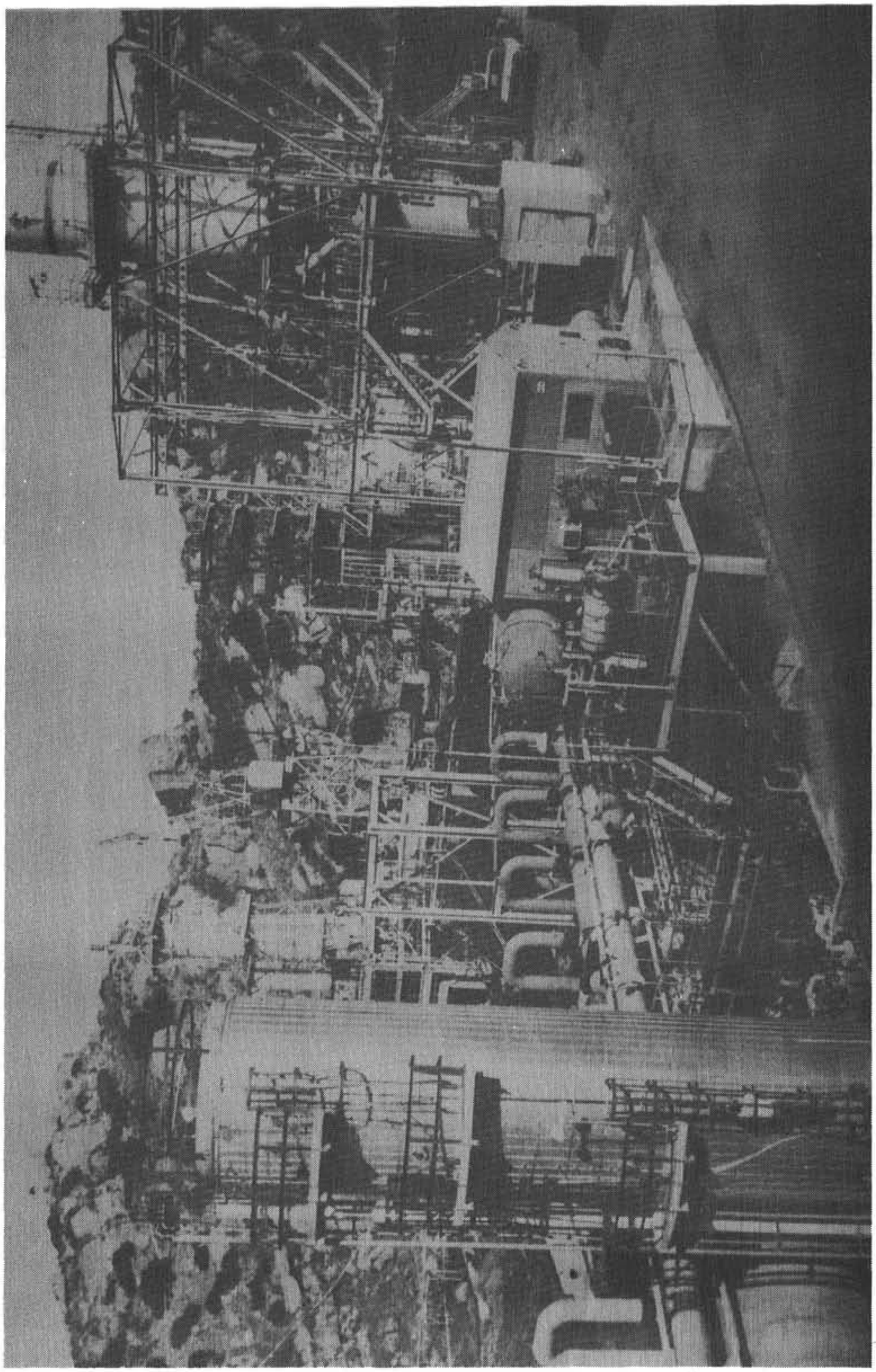

Figure 3. McDonnell Douglas Thermal Storage SRE

sand. The oil is distributed over the rock/sand bed by the diffuser manifolds to ensure a sharp and uniform thermocline. The system operates over a temperature range of 218 to 304°C (425 to 580°F) and is sized to deliver 7 MW_e over a four-hour period. Operating from storage occurs at reduced power because the temperature and pressure of steam generated from storage is less than that available directly from the receiver.

Figure 4 shows a schematic of the pilot plant storage unit; Figures 5 and 6 present aerial views of the plant and storage tank construction. Funded jointly by DOE and utility companies, the plant will be operated by the Southern California Edison Company in its grid network. Initial operation of the plant is scheduled for early 1982.

A second major application for thermal storage has been in the area of irrigation pumping. In recent years, two projects have been completed: the shallow well project at Willard, NM, and a deep well project at Coolidge, AZ (Reference 10). Both of these projects use a single media (Caloria HT 43 hydrocarbon oil) thermocline storage system. The system relies on the density difference between hot and cold oil to store both oils in the same tank. Cold oil is removed from the bottom of a tank, heated in a parabolic trough collector, and then returned to the top of the tank. In contrast to the Barstow indirect storage system, no charging heat exchanger is required for these direct systems since the collector and storage fluids are the same.

The Willard facility, shown in Figure 7, began operation in 1977. The facility was upgraded in 1978 by adding troughs, a second thermocline storage tank, and other modifications. The storage system operated over a temperature range of 116 to 216°C (240 to 420°F) and was sized to deliver 19 kWe (25 HP) over a period of 20 hours. The facility, which was used to obtain operational and performance data on all subsystems and components, was deactivated in 1981.

Figure 8 shows the Coolidge facility, which began operation in late 1979. Designed and constructed by Acurex Corp., the system is operated by the University of Arizona. The Coolidge storage system operates over a range of 200 to 288°C (392 to 550°F) and is sized to deliver 150 kW_e over a period of 6 hours.

The storage development that preceded or paralleled the Willard and Coolidge projects consisted primarily of laboratory testing and testing of hydrocarbon oil multitank and thermocline storage systems at the Midtemperature Solar Systems Test Facility (MSSTF) in Albuquerque, NM (Reference 10).

The multitank or "cascade" system had a capacity of 0.86 MWh_t. Three identical tanks could each be used either as a cold or hot tank. The test program, which was completed in 1980, investigated heat losses and the control strategies required to transfer the hot or cold storage fluid from one tank to another during operation.

A thermocline storage system was also installed at the MSSTF. Initially, a low-carbon-steel pressure vessel with 2.5 cm (1 inch) thick walls was evaluated for storing hot and cold fluid in the same tank. Conduction along the thick walls enhanced heat losses and thermocline degradation; thus additional development was necessary. A new thermocline tank, made of 0.48 cm (3/16 inch)

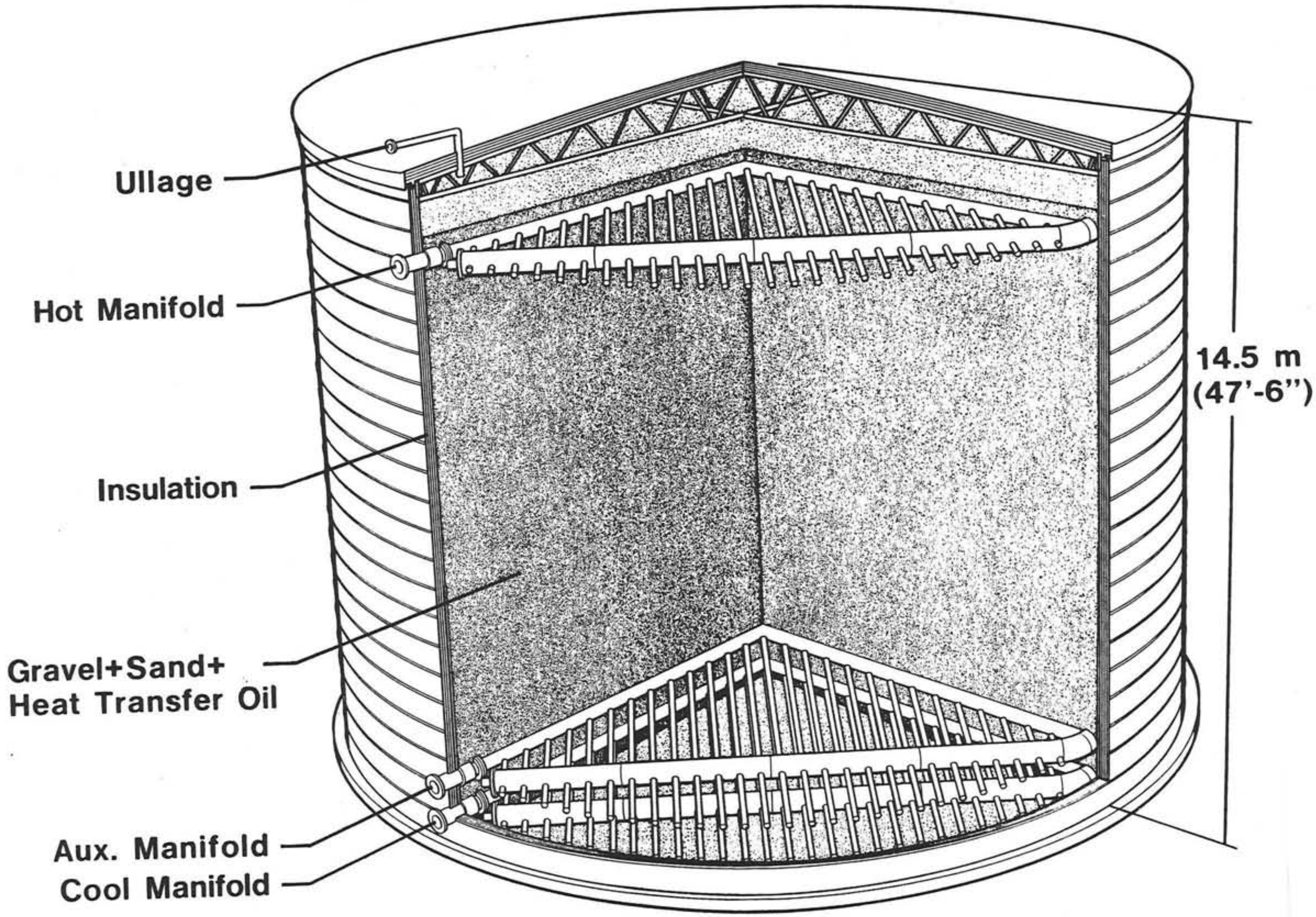

Figure 4. Thermal Storage Unit--Barstow Pilot Plant

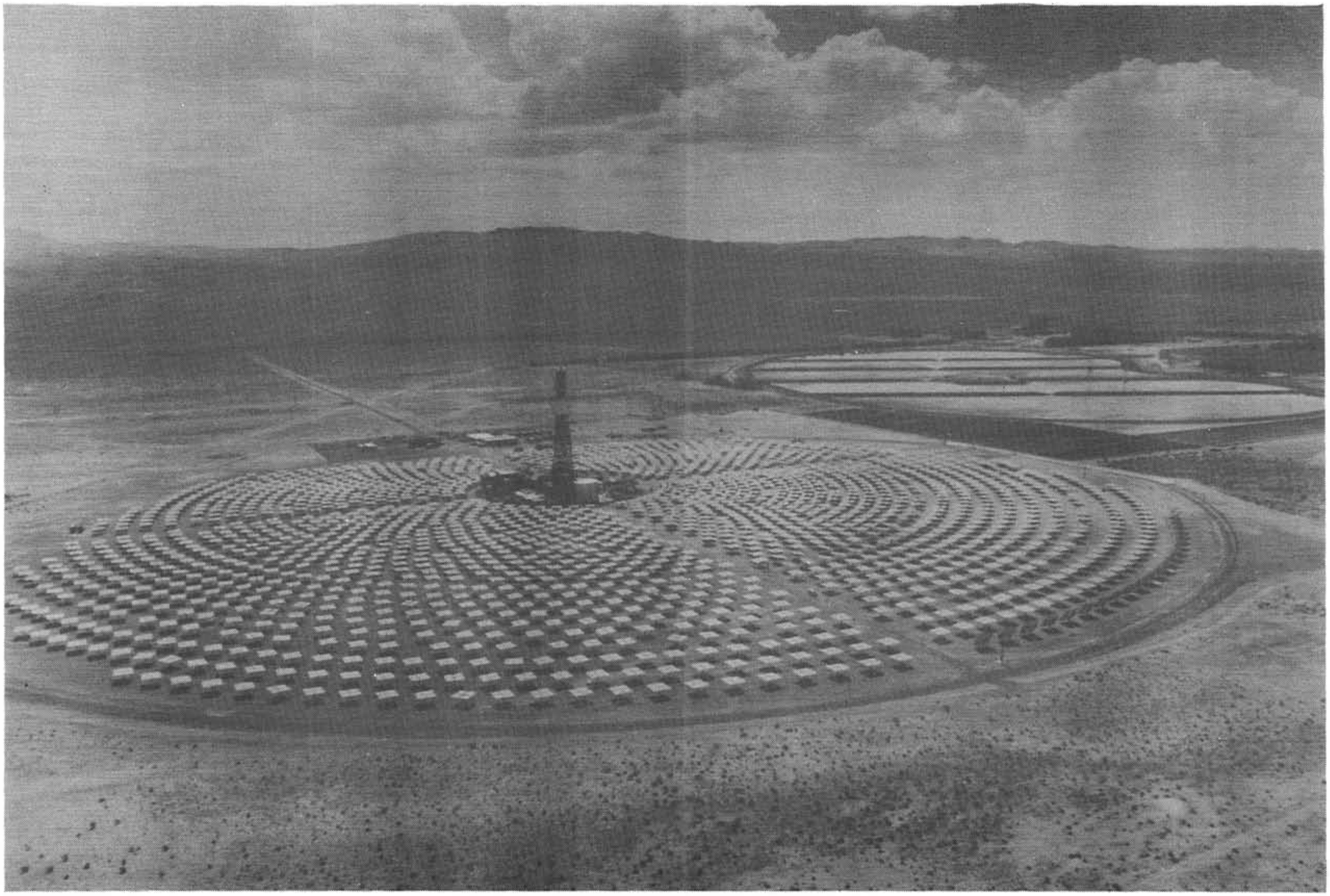

Figure 5. Aerial View of the Barstow Pilot Plant Project

Figure 6. Storage Tank Construction at the Barstow Pilot Plant

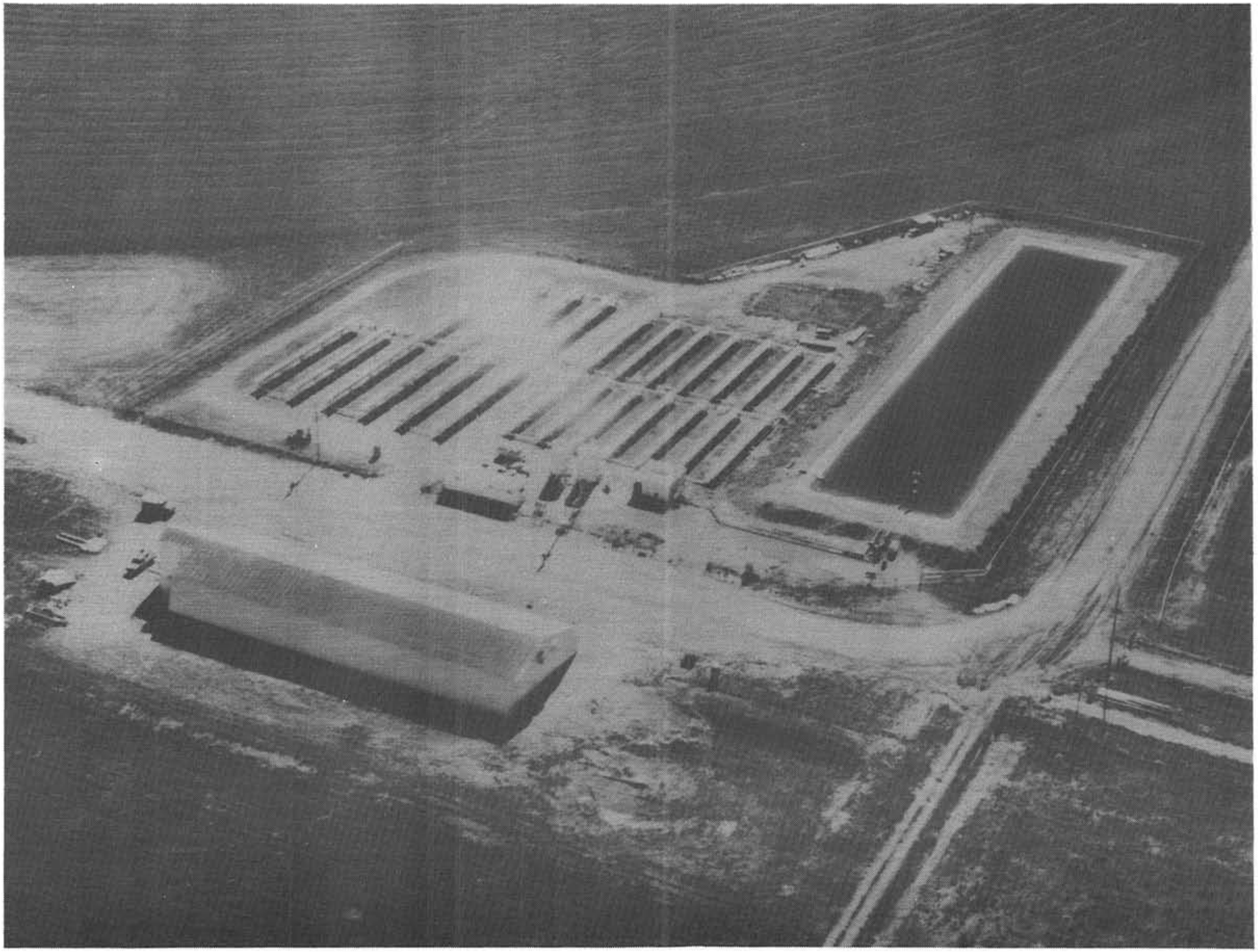

Figure 7. Aerial View of the Willard Solar-Powered Irrigation Pumping Project

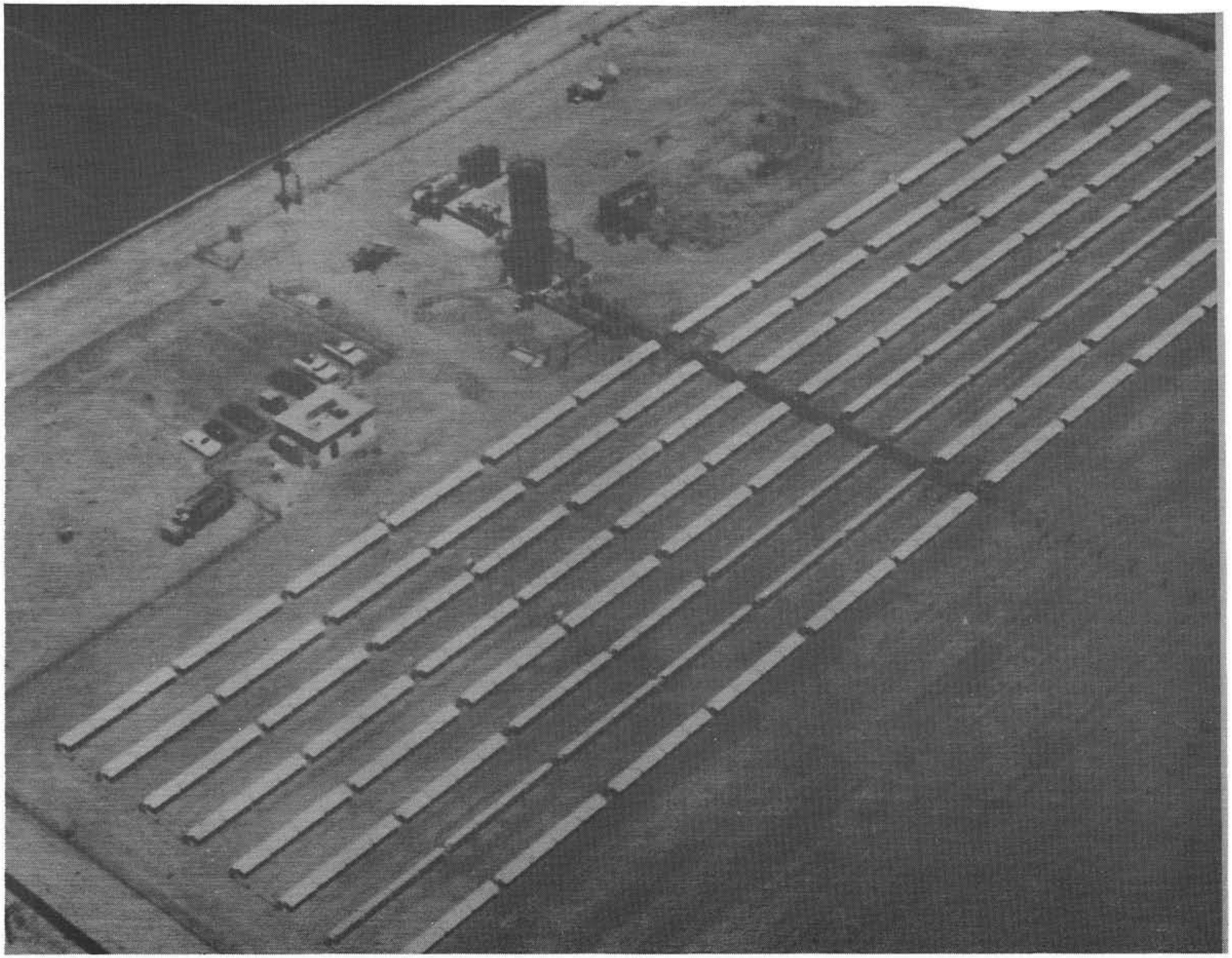

Figure 8. Aerial View of the Coolidge Solar-Powered Irrigation Pumping Project

low-carbon steel, replaced the old one during 1980 (Figure 9). Having a capacity of 0.21 MWh_t, the new tank was heavily instrumented to measure heat loss and thermocline performance. Subscale models of diffusers for distributing the fluid flow within the tank were also tested in the laboratory and then fabricated and tested full-scale in the tank. Testing of this system was completed in 1981, and the results are being incorporated into a process design handbook.

Single media thermocline systems are being constructed for such other applications as a solar total energy (cogeneration) project located in Shenandoah, GA, and an electrical power project located in Almeria, Spain. The Shenandoah project will supply 3 MW_t from a field of parabolic dish collectors to provide electricity, process steam, and space conditioning for a knitwear apparel factory. The dish working fluid and storage medium are the same: a silicone oil (Syltherm 800) heat transfer fluid operating over a temperature range of 260 to 399°C, or 500 to 750°F (Reference 11).

The Almeria project is jointly funded by several countries under the auspices of the International Energy Agency. The project involves the construction and operation of two 0.5 MW_e plants, one using oil-cooled parabolic trough collectors and the other a sodium-cooled central receiver. The trough system includes single media oil thermocline storage that operates over a temperature range of 225 to 295°C (437 to 563°F). The central receiver system uses liquid sodium sensible heat storage that operates over a temperature range of 275 to 530°C (527 to 986°F), with the hot and cold fluids stored in separate tanks. Both systems are sized to provide about two hours of storage at the plant rated output. As shown in Figure 10, construction of these systems is complete. Plant start-up was initiated in mid-1981 (Reference 12).

The liquid sodium central receiver system is one of several advanced concepts under study by DOE for electrical power and process heat applications (References 13 and 14). These concepts also include molten salt- and gas-cooled central receivers (References 15 and 16) and dish receivers where the storage system is ground-based or mounted directly on the dish (References 17 to 19).

Compared to first-generation water/steam technology, the advanced central receiver concepts offer greater thermodynamic availability when operating from storage. This advantage results from using receiver heat transport fluids that also serve as the storage medium, such as sodium or molten salt, or from using high operating temperature fluids and media, such as air and refractory brick.

Molten nitrate salt sensible heat storage is currently being singled out for development. A $NaNO_3$-KNO_3 salt mixture appears particularly attractive because of its low cost, high energy density, and potentially high operating temperature. Salt material studies are being performed to establish the physical properties and long-term stability and corrosion behavior of molten nitrate salts at elevated temperatures (Reference 20). During 1980, DOE funded Martin Marietta to begin storage subsystem development for nitrate salt sensible heat storage. This effort includes a full-size subsystem design, laboratory experiments, and the design, construction, testing, and evaluation of a subsystem research experiment of sufficient size to insure successful operation of the full-size subsystem. A major objective is to advance the state of the art in high-temperature containment.

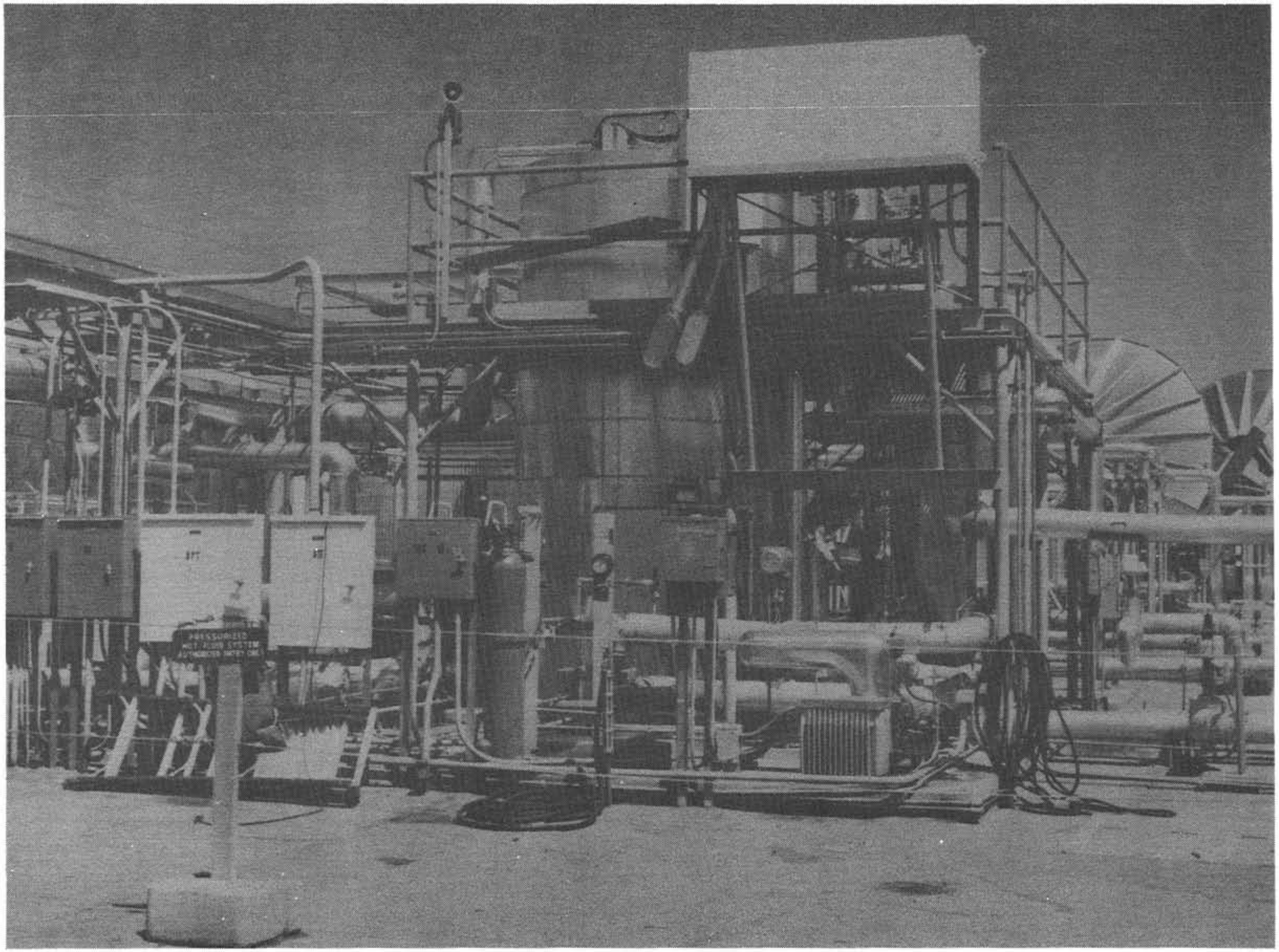

Figure 9. Thermocline Storage Tank at the Midtemperature Solar System Test Facility

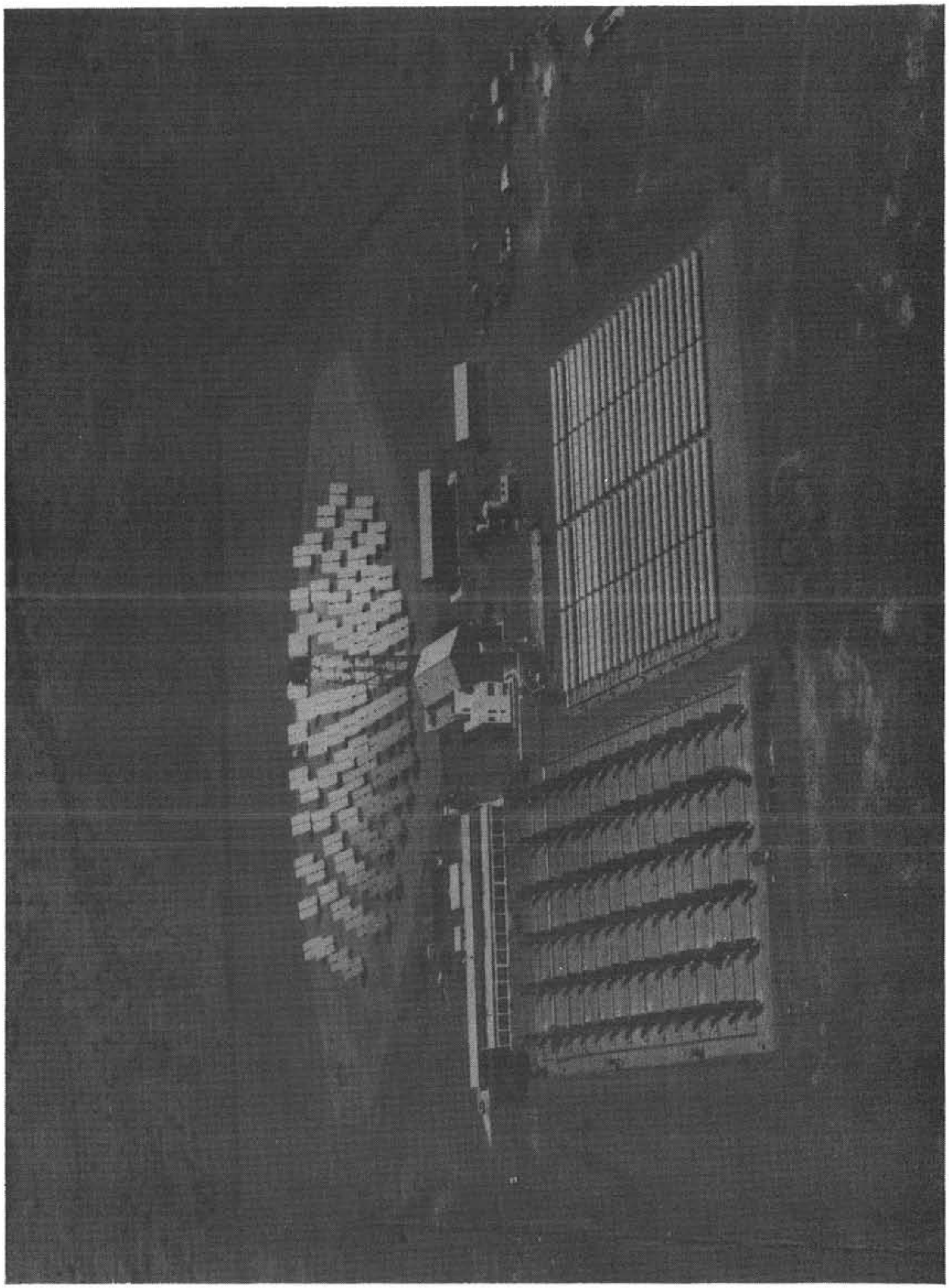

Figure 10. Aerial View of the IEA Central and Distributed Receiver Projects

Martin Marietta's design approach is to contain the high-temperature (566°C or 1050°F) salt in a lined and internally insulated hot tank (Figure 11) and to contain the cold temperature (288°C or 550°F) salt in a separate tank made of carbon steel. Because the hot tank is internally insulated, less expensive carbon steel can be used for the shell material. The liner is a liquid-tight waffled membrane design of the type used in liquefied natural gas storage applications. Laboratory experiments to establish the fatigue life of the liner are complete; testing of the SRE will begin in early 1982. The SRE, which will use a propane-fired heater to heat the salt and an air-cooled heat exchanger to cool the salt, will be conducted at the Central Receiver Test Facility (CRTF) in Albuquerque, NM (Figure 12). The SRE site is close enough to the CRTF tower to permit integrated solar central receiver/storage testing. The subsystem development is scheduled for completion in 1982.

Conceptual designs of storage systems for gas-cooled central receivers and parabolic dishes have been completed by Boeing and Sanders Associates, Inc., respectively (References 16 and 19). Both concepts use a porous ceramic matrix as the storage medium with air flowing through the matrix to add or remove heat. The ceramic material, typically aluminum oxide or magnesium oxide, is heated to a temperature of 816°C (1500°F) and is contained in a pressurized storage tank. No hardware development has been conducted for the larger central receiver storage system, but Sanders has successfully tested a smaller Dish/Brayton storage system (Reference 19).

Storage development for parabolic dishes also includes dish-mounted latent heat storage systems for use with Rankine, Brayton, and Stirling engines. Since the engines are also mounted on the dish, the overall concept is generally a highly integrated receiver/storage system with storage sized to provide energy only for short durations or buffering. Conceptual designs and some hardware development have been completed for Dish/Rankine and Dish/Stirling systems (Figures 13 and 14), and a Dish/Brayton conceptual design was also recently completed. Work is also being performed at the Jet Propulsion Laboratory to determine the heat transfer and corrosion behavior of the salts (Reference 1).

A receiver/storage design, which uses phase change material (PCM) packaged integrally within the receiver walls (Figure 15), has been proposed for the Small Community System Experiment (Reference 18). This project, for which site selection is now underway, will use a field of parabolic dishes with dish-mounted organic Rankine engines to generate 0.25 MW_e of electrical power (Reference 21). The use of the design is uncertain because recent funding constraints have limited the required hardware development.

Research Needs of the Program

Development activities not only have led to some promising options for near-term storage applications but also have pointed to areas for further work. Sensible heat storage has immediate promise. However, for applications such as Barstow, Coolidge, and Shenandoah, even lower-cost media are needed. Low-cost liquid and solid media are being sought to reduce the amount of the more costly liquid media. Even advanced storage systems, such as molten nitrate salt storage, could benefit from a low-cost solid media like rock.

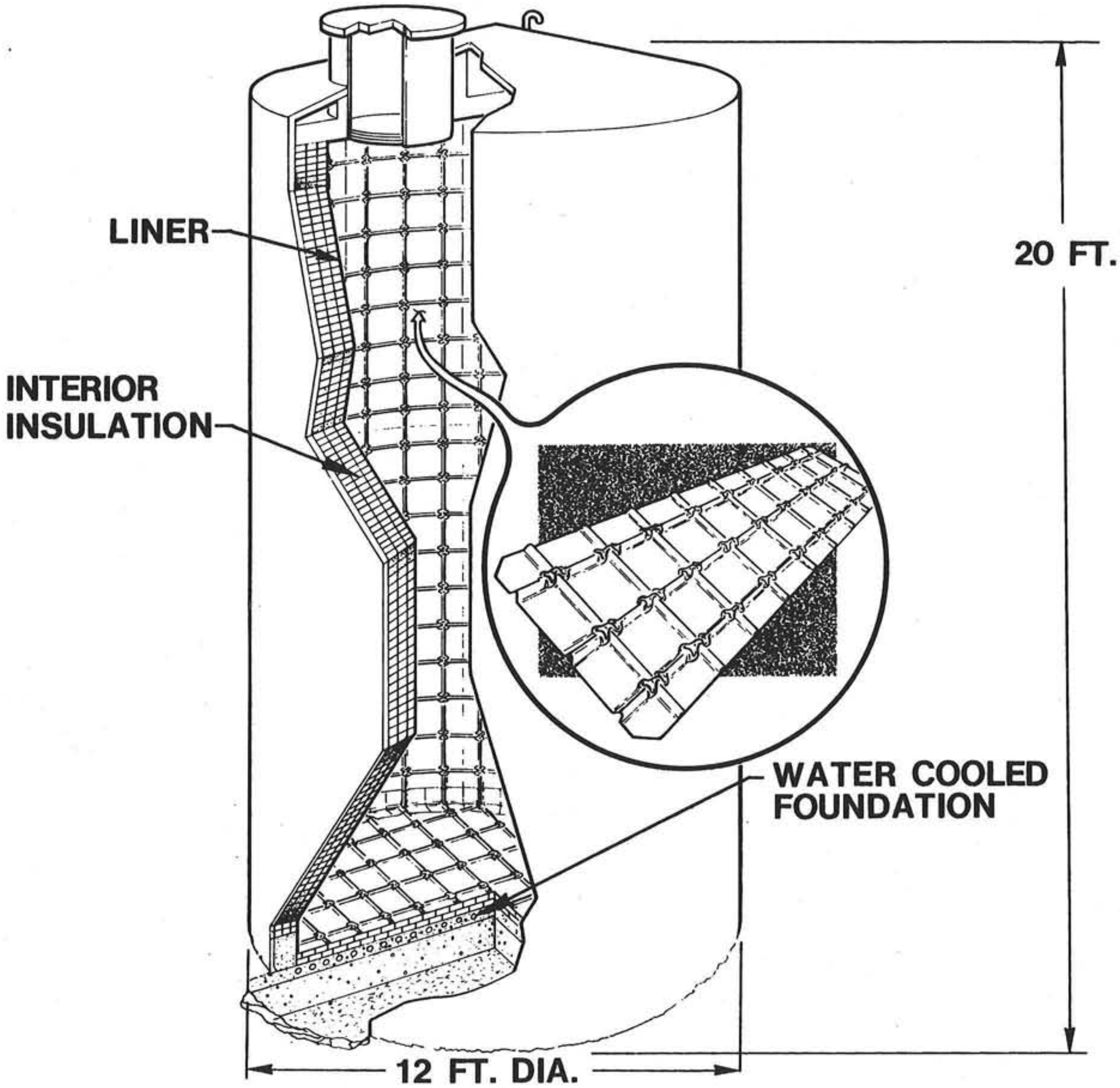

Figure 11. Molten Salt SRE Hot Tank

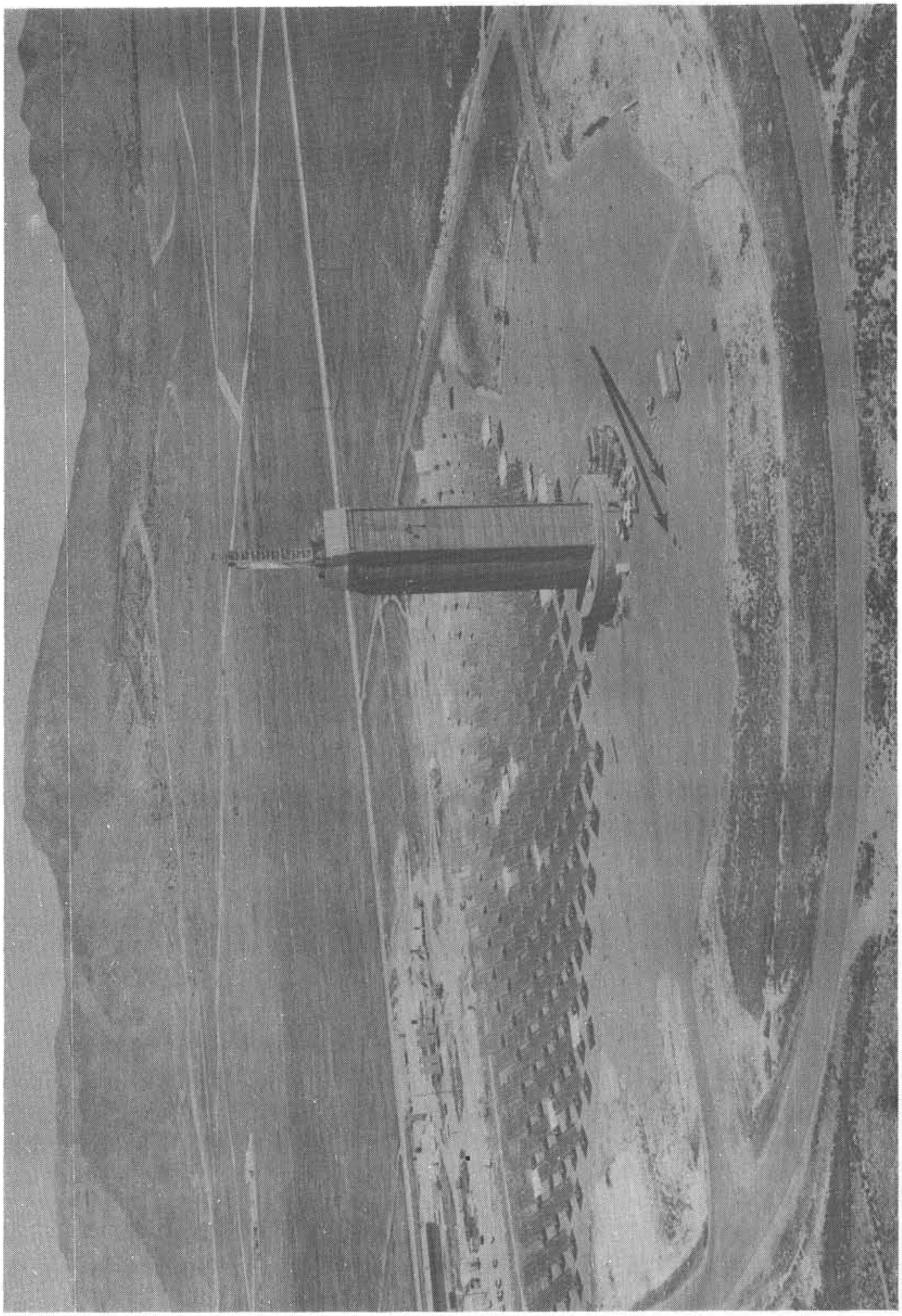

Figure 12. Aerial View of the Central Receiver Test Facility

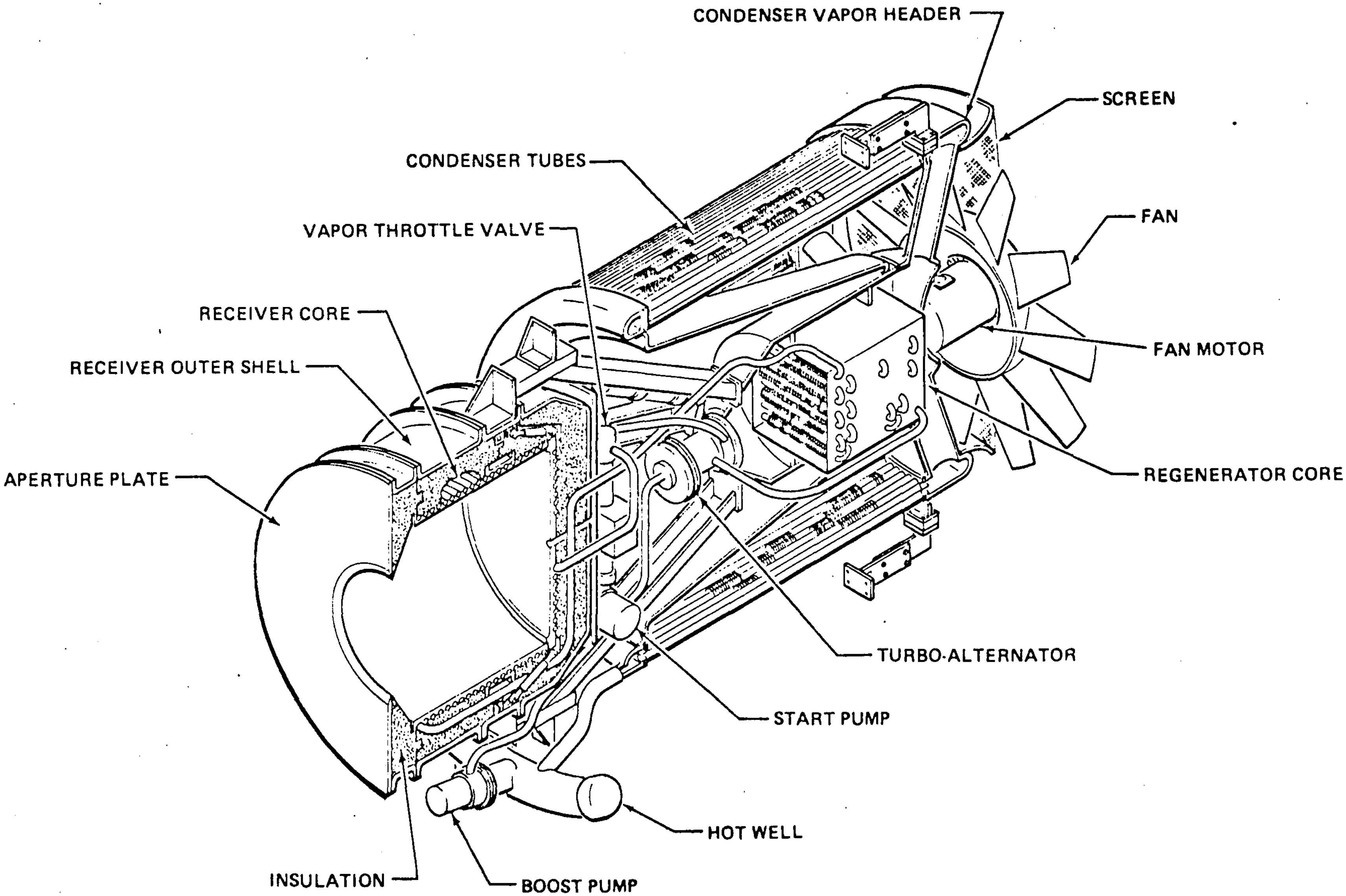

Figure 13. Dish/Organic Rankine Power System

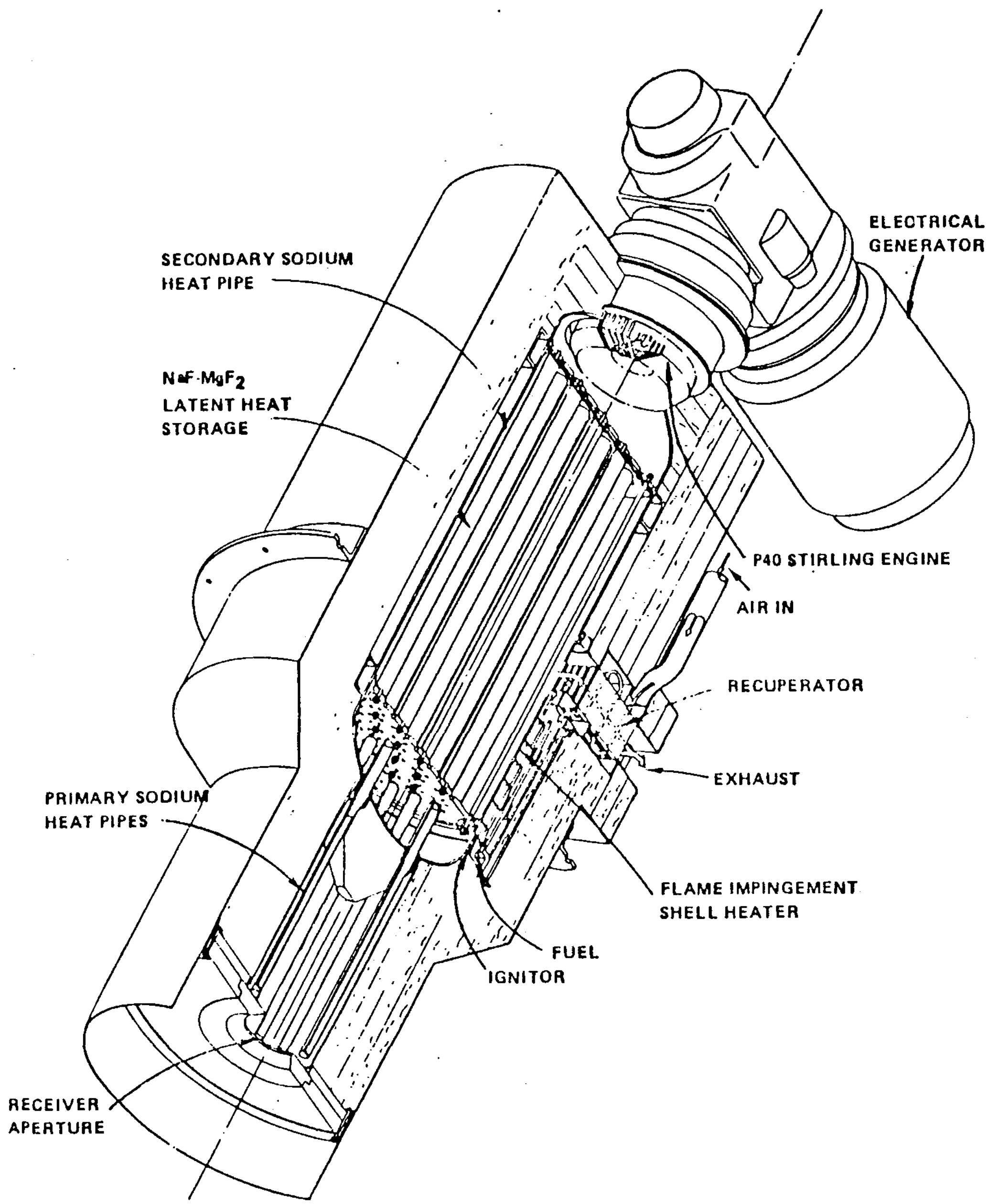

Figure 14. Dish/Stirling Buffer Latent Heat Storage System

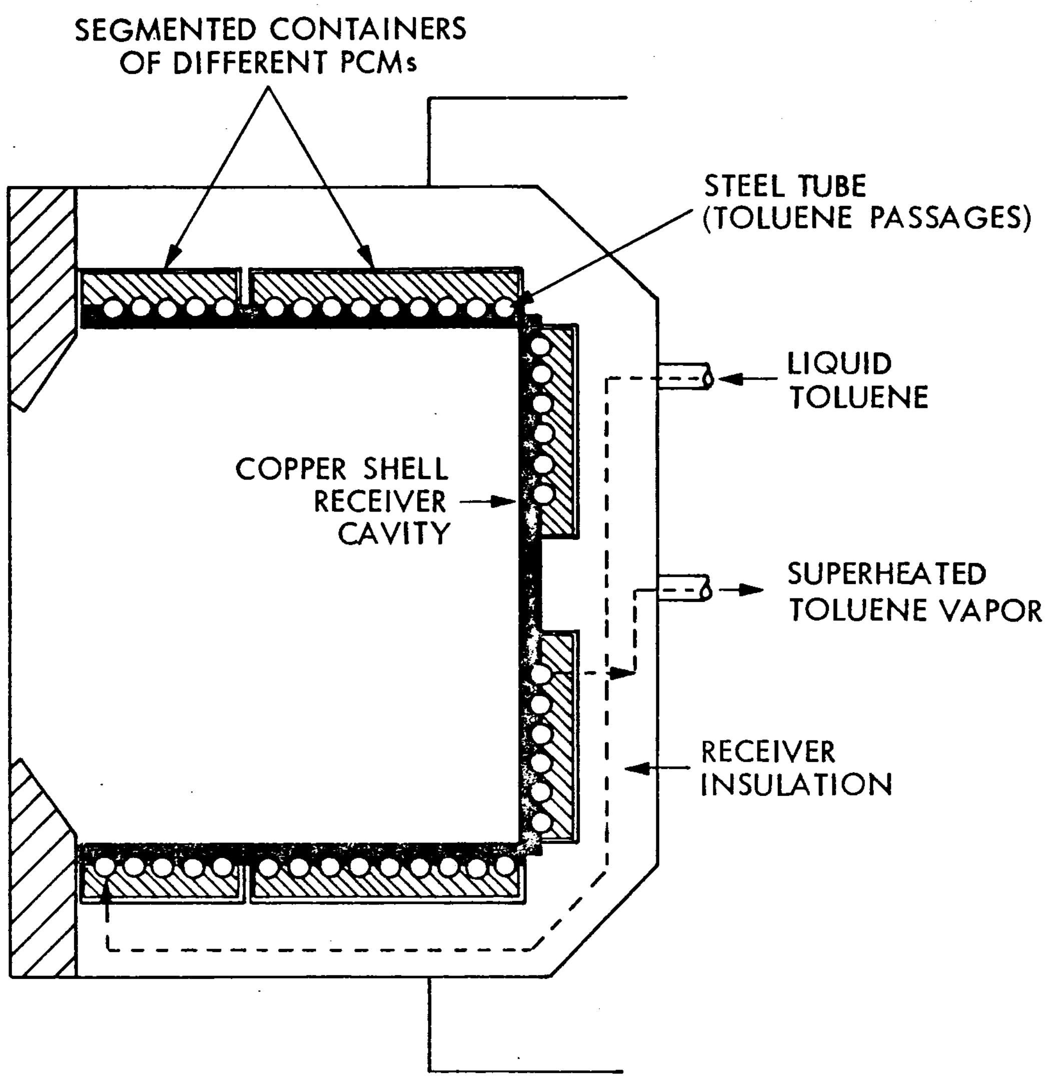

Figure 15. Integrated Receiver/Storage Design for Dish/Organic Rankine System

The fluid-rock combination should be capable of reaching the maximum receiver temperature without significant degradation.

For sensible heat storage, direct storage systems provide a high thermodynamic availability, which results in performance and potential economic advantages over indirect systems. In direct systems, the fluid employed in the receiver is stored in a large tank until heat is required. Heat exchangers are thereby eliminated. The problem then is finding suitable low-cost fluids for both storing and collecting solar thermal energy. Molten nitrate salt appears suitable for both roles, while liquid sodium is suitable for collection but is less attractive for storage due to its lower density and heat capacity and higher cost. Collection fluids other than those considered in the six focused development elements should be investigated for direct storage. In addition, inexpensive vessels for fluid containment are needed, as are low-cost options for providing high-temperature energy from storage to maximize the work production capability.

If direct storage is not cost effective, low-cost heat exchange is required between the receiver heat transfer fluid and the storage media. Since conventional heat exchangers generally require expensive alloys to withstand high-temperature corrosive environments, alternative modes of heat exchange are needed. One system under investigation uses direct contact between the storage media and the heat transfer fluid (Reference 22). As illustrated in Figure 16, three tank modules are coupled by two separate fluid loops: one for the molten salt latent heat thermal storage media and the other for the liquid metal heat transfer fluid. The liquid metal is injected at the top of the heat transfer column, becomes heated as it flows down through the column, and is pumped from the bottom of the column to the heat sink. Molten salt bubbles into the bottom of the column and transfers both latent and sensible heat to the countercurrent flow of liquid metal as the salt rises through the system. When the solidified drops of salt reach the top of the column, they are directed over the edges and fall to the bottom of the surrounding tank. During the next charging cycle, the solid salt is melted and drained back to the molten salt tank, ready for the next discharge cycle. Although the system now being studied employs latent heat storage media, the concept also has potential for reducing the cost of sensible heat storage. Preliminary indications are that a direct contact latent heat storage system has strong economic potential for producing saturated steam, but considerable research and development must still be completed to prove this concept's technical feasibility.

Significant thermal storage improvements are particularly needed at very high temperatures (approximately 816°C or 1500°F, or above). Thermal storage in this temperature range can be used to supply heat to high efficiency Brayton and Stirling cycle engines. Storage vessels and heat exchangers required to withstand such high temperatures are costly. If direct contact heat exchange is used between the heat carrier fluid and the storage media (e.g., refractory brick), the containment vessel must also be capable of operating at the generally high pressures associated with the hot gas heat transfer fluids. Innovative system configurations, low-cost containment approaches, or new storage concepts might be devised to lower the cost of very high temperature storage.

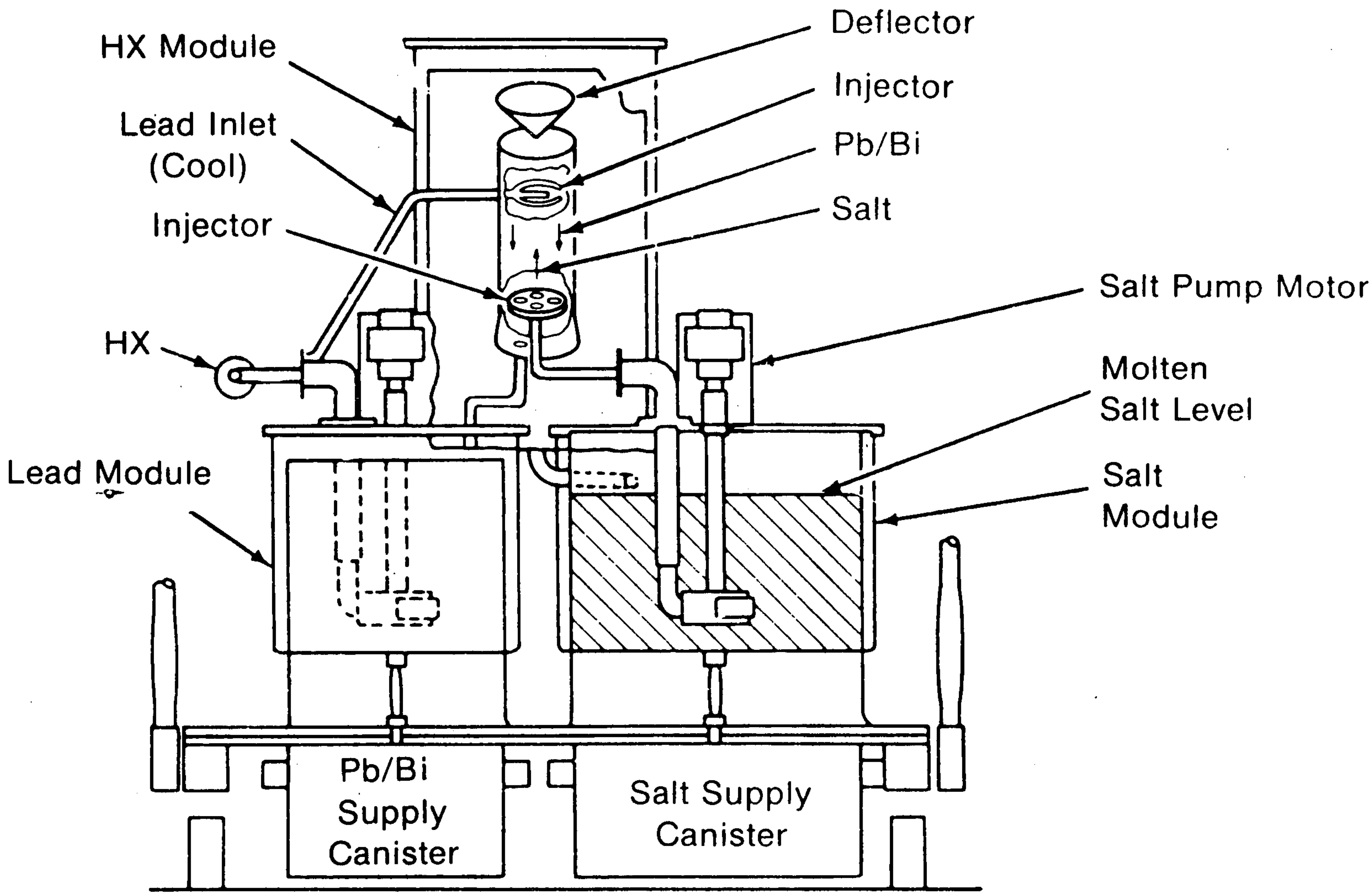

Figure 16. High-Temperature Direct Contact Heat Exchanger

One proposal is a high-temperature (727 to 1727°C, or 1340 to 3140°F) combination storage and heat transfer system. A uniform aggregate of refractory oxide beads, such as alumina or silica, is injected directly into a solar receiver where it melts (Reference 23). As shown in Figure 17, the liquid refractory oxide, which is stable at high temperatures, is then piped to a storage vessel. When heat is needed, the melt is pumped into the high-pressure heat exchanger shown in Figure 18. There the melt is sprayed as droplets through a countercurrent stream of high-pressure working gas, giving up heat by convection and solidifying in the process. The hot gas is then used to drive a heat engine while the solid beads are transported back to an appropriate storage vessel, ready for reinjection into the solar receiver. Although this concept has favorable economic potential, many of the basic ideas underlying the concept are unproven, and substantial research and development are required to determine its technical and economic viability.

Another potentially economical thermal storage concept for high-temperature applications uses thermal storage media with both sensible and latent heat components (Reference 24). This concept involves the retention and immobilization of phase change salts within a porous ceramic matrix. Discrete, submicron-sized particles may be distributed through the ceramic phase as shown in Figure 19, or the dispersed phase may be interconnected in a partially sintered, porous body. Capillary forces are primarily responsible for retaining the latent heat storage salt within the ceramic void space. Experiments have demonstrated the feasibility of retaining 65 volume percent molten alkali carbonates at 700°C (1292°F). If the concept is proven feasible, composite pellets, bricks, or other shapes can be fabricated for use in direct contact with compatible fluids, thereby eliminating heat exchanger tubes. However, research must be performed to prove the technical merits and limitations, and a system must be evaluated to determine the economic potential of the idea.

Latent heat energy storage suffers two major cost penalties. First, the costs of pure materials are high relative to competing sensible heat media, such as rocks. Second, heat exchange from the media requires extensive surface area (at high cost) to provide adequate heat transfer through the solidifying material by conventional shell-and-tube devices. The direct contact system described previously is a possible solution to this high cost of heat transfer, but other approaches to latent heat storage are also desirable to overcome these limitations.

One concept that has received recent attention is a latent heat storage unit which can be interfaced with a saturated steam receiver and a process heat application requiring saturated steam (Reference 25). The latent heat storage module, shown in Figure 20, is a rectangular, externally insulated carbon steel tank containing five tube assemblies. A tube assembly has 15 single tubes, each bent into a serpentine. (Drawing shows an earlier design of six tubes per serpentine). The serpentine tubes are supported by carbon steel channels and separated horizontally by aluminum channels (not shown) which also enhance the thermal conductivity. The storage medium is an 18.5 $NaNO_3$ - 81.5 NaOH (mole %) salt eutectic with a melting point of 256°C (493°F). The storage module is charged by condensing 288°C (550°F) saturated steam into saturated liquid. On discharge the storage module produces 232°C (450°F) saturated steam from saturated liquid. The storage capacity of a module is 19.0 MWh_t. Hardware development is needed to further assess the technical and economic merits of this concept.

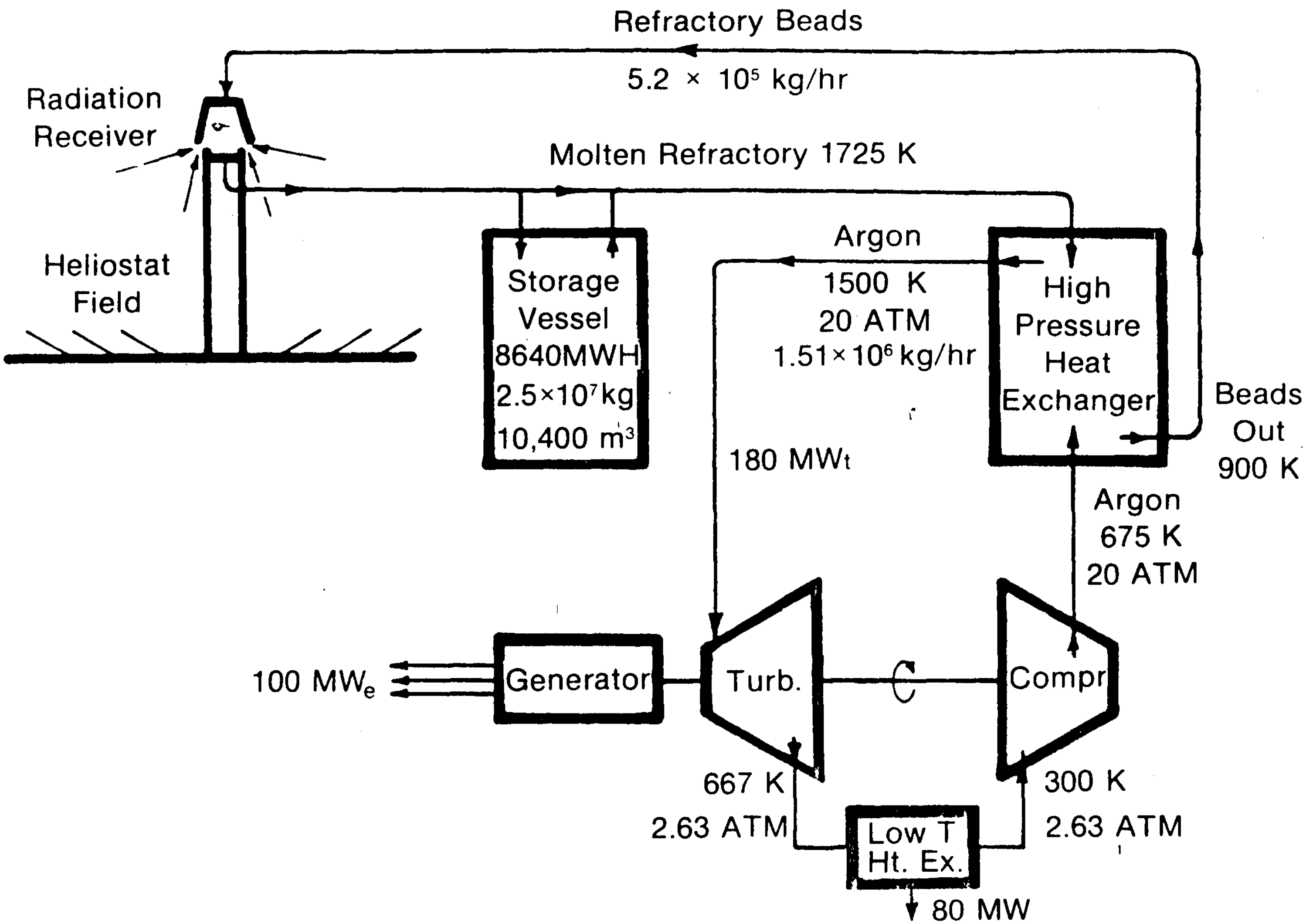

Figure 17. Schematic of Proposed High-Temperature Solar Thermal Power Plant

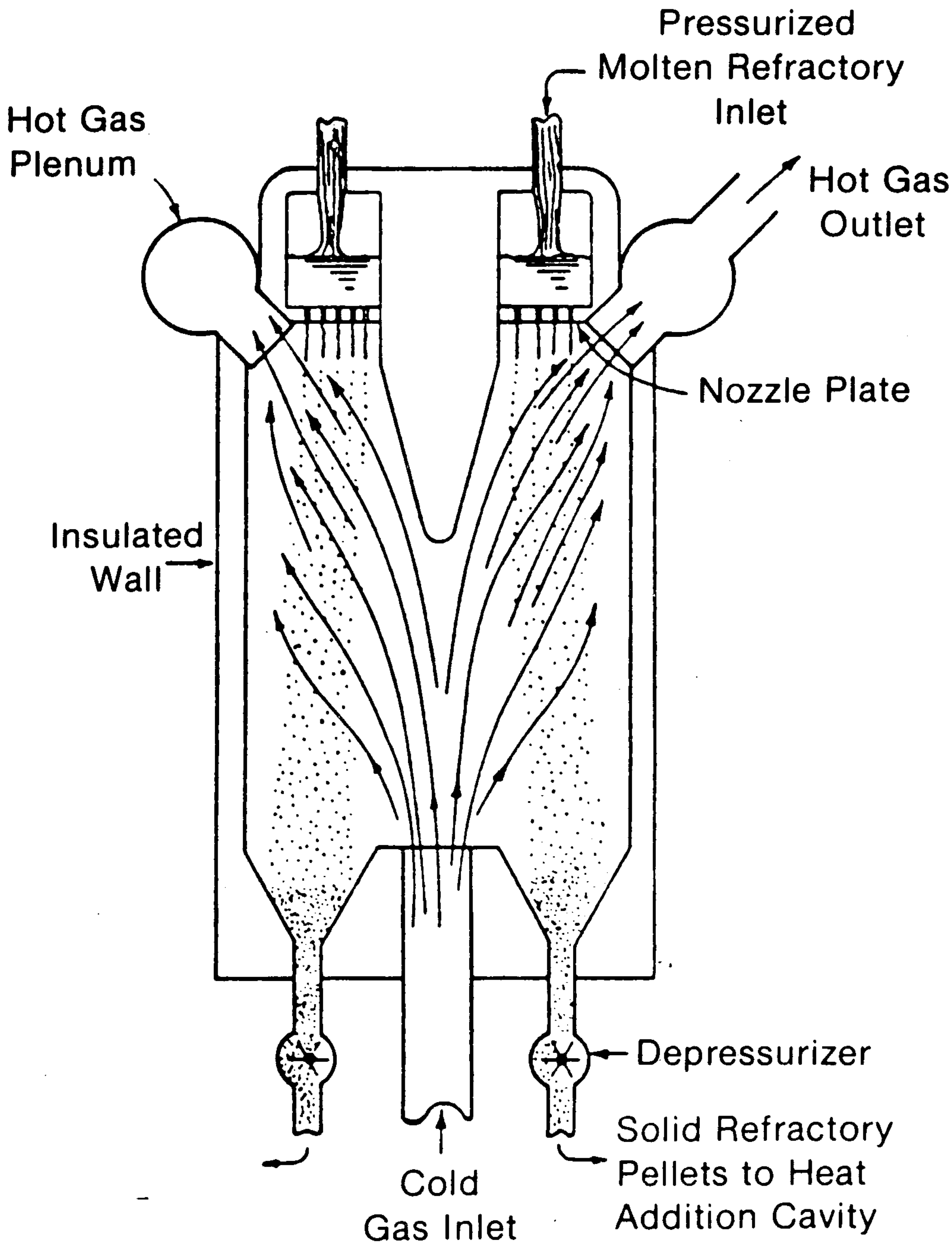

Figure 18. High-Temperature Direct Contact Droplet Heat Exchanger

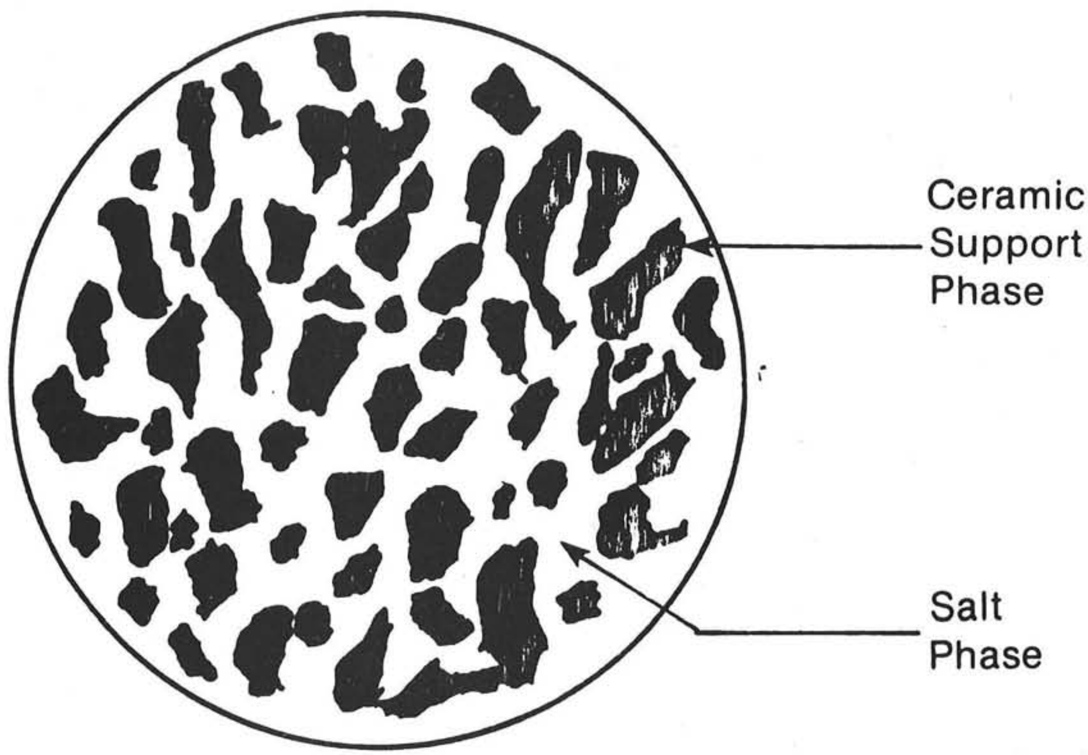

Figure 19. Schematic Microstructure of Composite TES Media: Molten Salt Supported by Ceramic Matrix

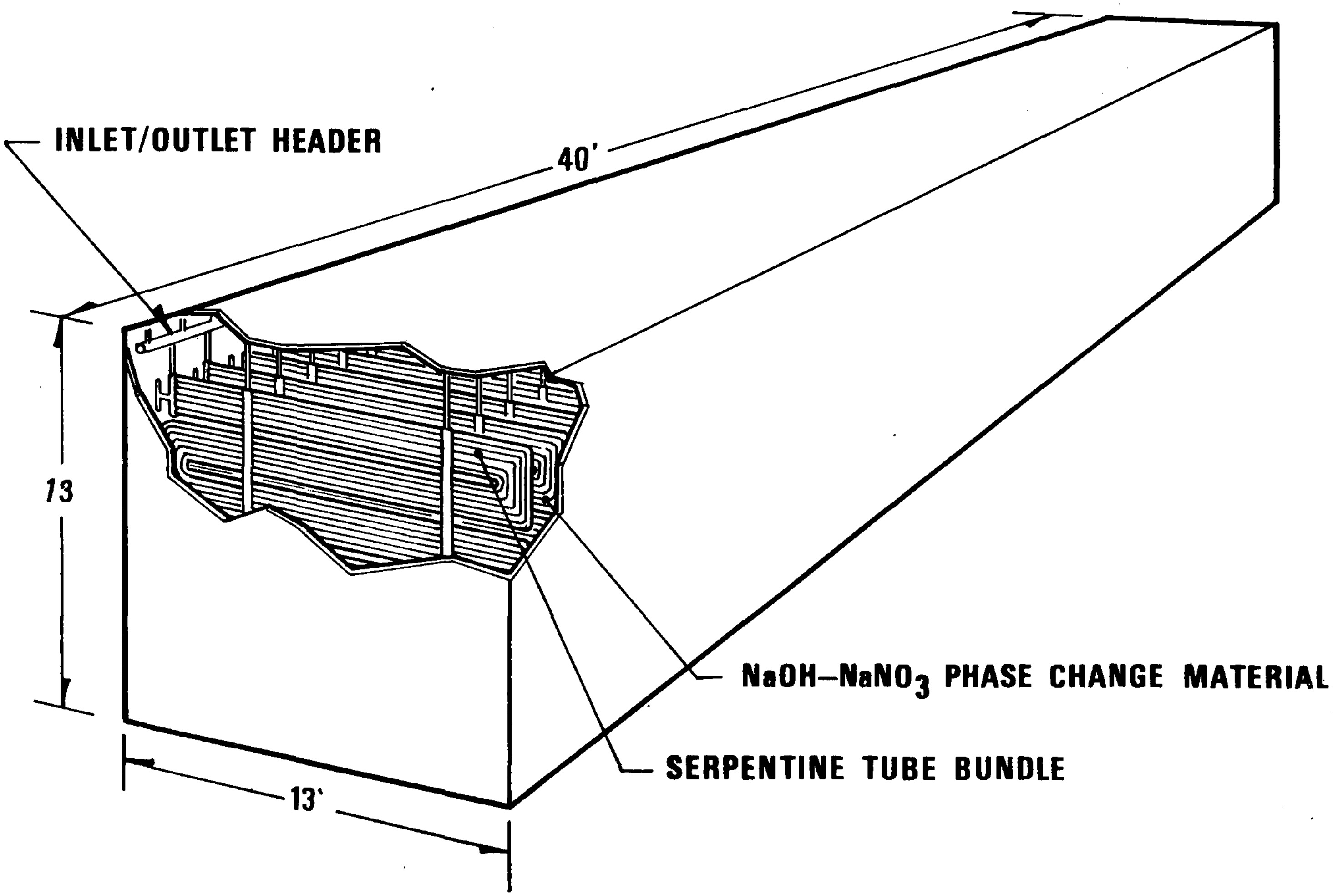

Figure 20. Latent Heat Thermal Storage Module

An area of interest in the far term is long-duration thermal energy storage subsystems. At this time, only two options are potentially low enough in cost to be reasonable candidates for baseload storage: air-rock storage and thermochemical storage. For the air-rock system, the heat transfer limitations of air raise serious doubts about the ability to obtain low power-related costs. Thermochemical storage is conceptually attractive because high-grade heat could be stored at ambient temperature; but only a few compounds have low enough material costs to be considered. However, gases are produced during the known high-temperature reactions. Even if the gases can be easily condensed for storage at ambient conditions, the heat of condensation, a substantial fraction of the stored energy, is released at too low a temperature for use in the solar thermal system. Therefore, when the liquids are used to regenerate heat by the exothermic reaction, the quantity of thermal energy produced is far less than that used to drive the endothermic reaction (Reference 26). If the gases do not condense, the cost of gas containment, with or without compression, is probably too high for thermochemical storage to be cost effective; and serious questions have been raised about the cost of thermochemical storage (Reference 27). New alternatives which meet the low cost requirements of long duration storage but overcome the difficulties of the known concepts are of interest.

Thermal transport of energy is of significant concern. As the temperature of receiver operation rises, movement of the thermal energy from the collector to storage or to the load, or to both, becomes increasingly difficult. Some research and analyses have been done in using reversible reactions with only gaseous reactants and products for ambient or near-ambient temperature transport. Although a few reasonably promising reactions have been identified, cost and efficiency problems have cast doubt on this approach. A need exists for new transport approaches for high-temperature users. Such ideas might include better fluids, cheaper pipelines, low-cost insulations, or entirely new concepts.

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