2-2-5

GA-A15743

SOLAR MOLTEN SALT HEAT TRANSFER LOOP
FINAL REPORT

by

G. H. EGGERS and J. R. SCHUSTER

CAUTION

This report may contain potentially patentable information and should not be further disseminated without the express written consent of the Office of Patent Counsel, DOE San Francisco Operations Office, or written notification of patent clearance from the Document Management Branch, DOE Technical Information Center, Oak Ridge, Tennessee.

Preapred under
Contract DE-AC03-76CS30167
for the San Francisco Operations Office
Department of Energy

DATE PUBLISHED: NOVEMBER 1981

GENERAL ATOMIC COMPANY

GA-A15743

SOLAR MOLTEN SALT HEAT TRANSFER LOOP FINAL REPORT

by

G. H. EGGERS and J. R. SCHUSTER

Prepared under
Contract DE-AC03-76CS30167
for the San Francisco Operations Office
Department of Energy

GENERAL ATOMIC PROJECT 3284
DATE PUBLISHED: NOVEMBER 1981

GENERAL ATOMIC COMPANY

ABSTRACT

The objectives of the work being reported were to design, fabricate, and operate a molten salt heat transfer loop in conjunction with a distributed solar concentrator. The work was supported by the Department of Energy and General Atomic Company and monitored by the Jet Propulsion Laboratory.

The collector consists of a fixed mirror solar concentrator with an aperture width of 2.13 m (7 ft) and a length of 22.86 m (75 ft). The heat transfer loop consists of a heated tank, heat-traced piping, and a special pump for fluid circulation. The heat transfer medium is a molten salt marketed under the trade name Hitec.

Startup problems were identified and resolved, and the system generally performed as expected. The system was successfully demonstrated up to a salt temperature of 844 K (1059°F), which is high enough to produce modern steam conditions. The heat collection efficiency of the fixed mirror solar collector was determined to be 30.3% for a test that reached a salt temperature of 812 K (1002°F). This was for a concentration ratio of 34 and a heat receiver without a glass cover and without a solar-selective absorber coating.

The molten salt facility should be useful for conducting future materials corrosion testing and component testing.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION AND SUMMARY

The purpose of the solar molten salt heat transfer program was to demonstrate the use of a molten salt as a heat transfer fluid for a concentrating solar collector of the distributed-receiver type. The reasons for conducting the program included the following:

1. Modern steam turbines for power generation run at temperatures up to 811 K (1000°F) in order to achieve high power conversion efficiency.

2. Water or steam at this temperature is at very high pressure and requires expensive high-pressure piping.

3. High-pressure steam storage is inefficient and expensive and is therefore not a good method for storing energy in order to increase the capacity factor of solar power plants.

4. Low vapor pressure heat transfer oils decompose rapidly at this temperature and therefore are unsuitable.

5. Molten salt has a low vapor pressure and good thermal stability at this temperature.

6. Molten salt has good heat transfer characteristics and is not excessively corrosive to high alloy steels at this temperature.

There are, however, some disadvantages with molten salt:

1. Molten salt has a high freezing temperature and, therefore, the piping has to be heat traced.

2. System components, such as flexible hoses or flexible joints, cannot be moved when they contain frozen salt.

Although the advantages are well known, the disadvantages require special design. Thus, this experiment was directed primarily toward demonstration of the functional performance of a molten salt heat transfer loop; it was not intended to demonstrate high thermal efficiency with the solar collector equipment.

A molten salt handling system was built and connected to a row of General Atomic Company (GA) fixed mirror solar concentrators (FMSCs). The FMSC row assembly and system operation were funded by the Department of Energy. General Atomic supplied the molten salt handling system, which included the storage tank, pump, flow control valves, and tank heating system, assembled as a unit. The Jet Propulsion Laboratory served as the technical monitor for the Department of Energy.

The system was started up on May 10, 1979 and operated for several hours. For the next few weeks the system was operated on almost a daily basis. On May 23, 1979 a molten salt peak temperature of 844 K (1059°F) was reached and maintained for 1 hour. A subsequent electrical short occurred in a trace heater, complicating startup procedures. A temporary fix was made that allowed operations to continue on an intermittent basis. On June 11, 1979 a run was conducted during which data were taken to determine the heat collection efficiency of the FMSC. Over a period of 95 min the efficiency, relative to the direct normal insolation, averaged 30.3% at a salt temperature ranging from 768 to 812 K (922° to 1002°F) at the heat receiver outlet. This high an efficiency was not anticipated since the receiver had no cover glass, the receiver tube did not have a solar-selective absorber coating, and the geometric concentration ratio was only 34.

In general, the system has operated well with very few problems and has demonstrated the feasibility of using molten salt as the heat transport medium for a high-temperature FMSC distributed collector system. The FMSC has demonstrated its ability to operate at the temperatures required for modern steam power conversion systems. Future use of the facility could take advantage of its temperature-controlled electric heaters and could include long-term materials corrosion testing in flowing molten salt, component freeze/thaw experiments, thermal storage evaluations, and high-temperature heat receiver tests.

2. SYSTEM DESCRIPTION

Figure 1 shows a schematic of the system, which consists of the molten salt handling system, the FMSC array, and associated instrumentation and controls. In order to provide corrosion resistance, high alloy steel construction is used throughout the system for those components that come in contact with the molten salt. Table 1 provides a list of these materials. The instrumentation readouts and some of the controls are located in an office trailer on the test site.

The molten salt used is manufactured by the Dupont Company and is sold under the trade name Hitec. It is a eutectic mixture consisting of 53 wt % KNO_3, 7 wt % $NaNO_3$, and 40 wt % $NaNO_2$. It has a melting point, when pure, of 416 K (288°F) and a density of approximately 1920 kg/m^3 (120 lb/ft^3). With the proper cover gas and containment materials, it is stable up to 867 K (1100°F), which is the system design temperature. Table 2 presents data on the thermophysical properties of Hitec.

2.1. MOLTEN SALT HANDLING SYSTEM

A photograph of the molten salt handling system is shown in Fig. 2. The system consists of an insulated tank, two flow control valves, a high-temperature submerged salt pump driven by a 10-hp variable-drive motor, two platinum RTD thermometers for tank temperature control, and an orifice-type flow rate sensor. The rectangular tank is made from 316 stainless steel (SS) and contains 590 kg (1300 lb) of salt. The tank is vented to the atmosphere and has facilities for maintaining a nitrogen gas cover over the salt. An access port in the tank contains a float level indicator. At the tank's low point there is a drain

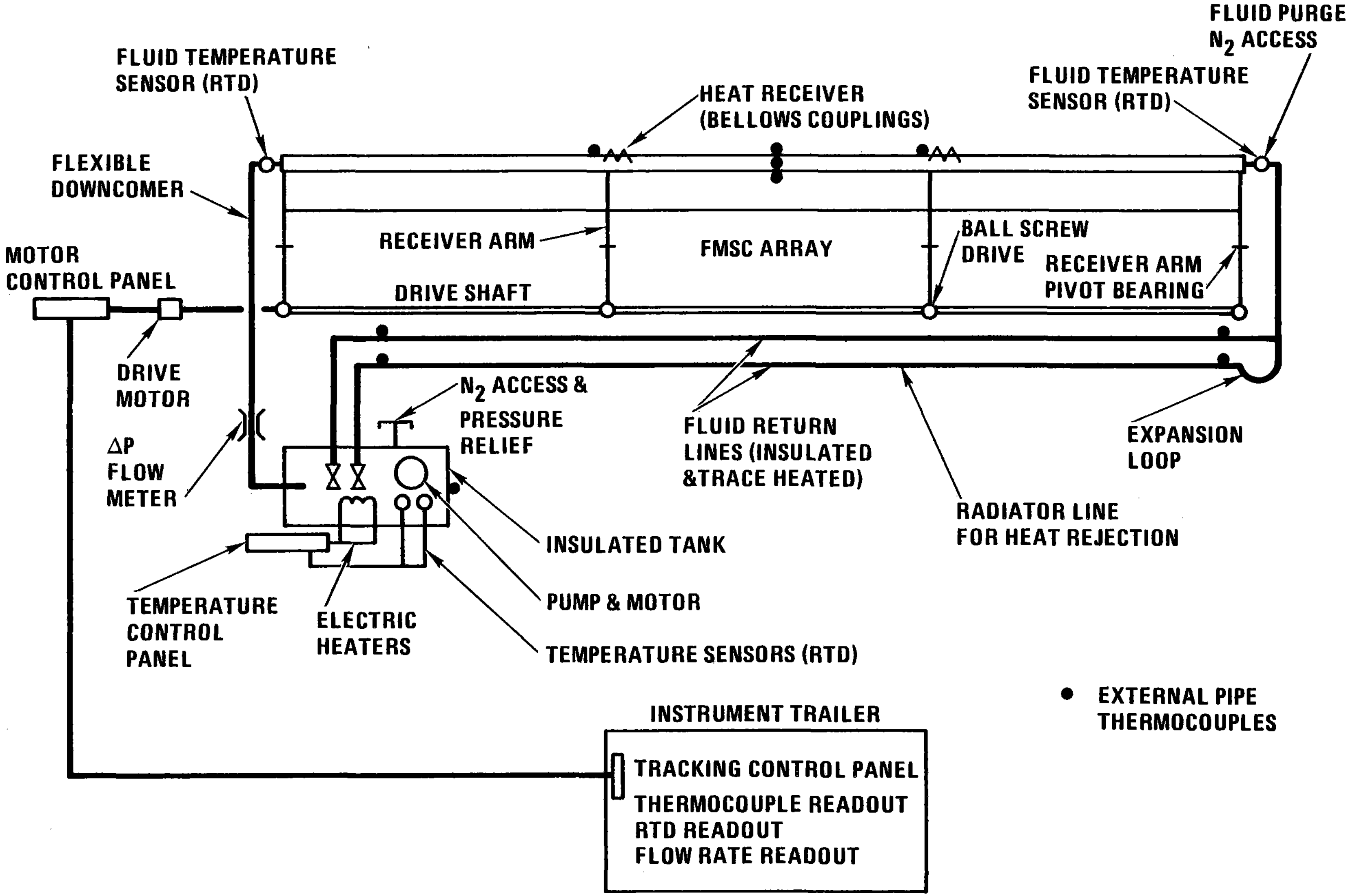


Fig. 1. Molten salt solar test loop schematic

TABLE 1
MOLTEN SALT HANDLING SYSTEM CONSTRUCTION MATERIALS

Item	Material	Source of Information (GA Drawing Number)
External piping	316 SS	024413
Tank	ASTM-A-312WP316	024329
Flexible hose	316 SS	024412
Heat receiver		
Pipe	316 SS	024374
Transitions	304 SS	024374
Valves		
Body	316 SS	Masoneilan, Inc. Quotation LAS 3818 (7/13/78)
Plug	316 SS	Masoneilan, Inc. Quotation LAS 3818 (7/13/78)
Pump		
Casing	304 SS	Lawrence Company Drawing No. B2656
Impeller	304 SS	Lawrence Company Drawing No. B2656
Bellows		
Bellows	Inconel 625	024347
Connections	347 SS	29486 (Babcock & Wilcox)
Heaters		
Immersion	Incoloy	Montgomery Brothers, letter dated June 28, 1978
Trace	SS	Montgomery Brothers, letter dated April 28, 1978
Flow meter	316 SS	Catalog and purchase order
Thermowells	304 SS	024395

TABLE 2
THERMOPHYSICAL PROPERTIES OF HITEC

Temperature [K (°F)]	Density [kg/m^3 (lb/ft^3)]	Specific Heat [kJ/kg-K (Btu/lb-°F)]	Viscosity [10^{-3} Pa-s (Centipoise)]	Conductivity [10^{-4} kJ/s-m-K (Btu/hr-ft-°F)]
		Liquid		
422 (300)	1970 (123.0)	1.56 (0.373)	17.5 (17.5)	0.529 (0.33)
478 (400)	1932 (120.6)	1.56 (0.373)	7.4 (7.4)	0.529 (0.33)
533 (500)	1889 (117.9)	1.56 (0.373)	4.3 (4.3)	0.529 (0.33)
589 (600)	1849 (115.4)	1.56 (0.373)	2.9 (2.9)	0.529 (0.33)
644 (700)	1809 (112.9)	1.56 (0.373)	2.2 (2.2)	0.529 (0.33)
700 (800)	1767 (110.3)	1.56 (0.373)	1.75 (1.75)	0.529 (0.33)
756 (900)	1727 (107.8)	1.56 (0.373)	1.4 (1.4)	0.529 (0.33)
811 (1000)	1685 (105.2)	1.56 (0.373)	1.2 (1.2)	0.529 (0.33)

Melting Point = 416 K (288°F)
Heat of Fusion = 81.4 kJ/kg (35 Btu/lb)

		Solid		
311 (100)	1975 (123.3)	1.34 (0.32)		
367 (200	2975 (123.3)	1.34 (0.32)		

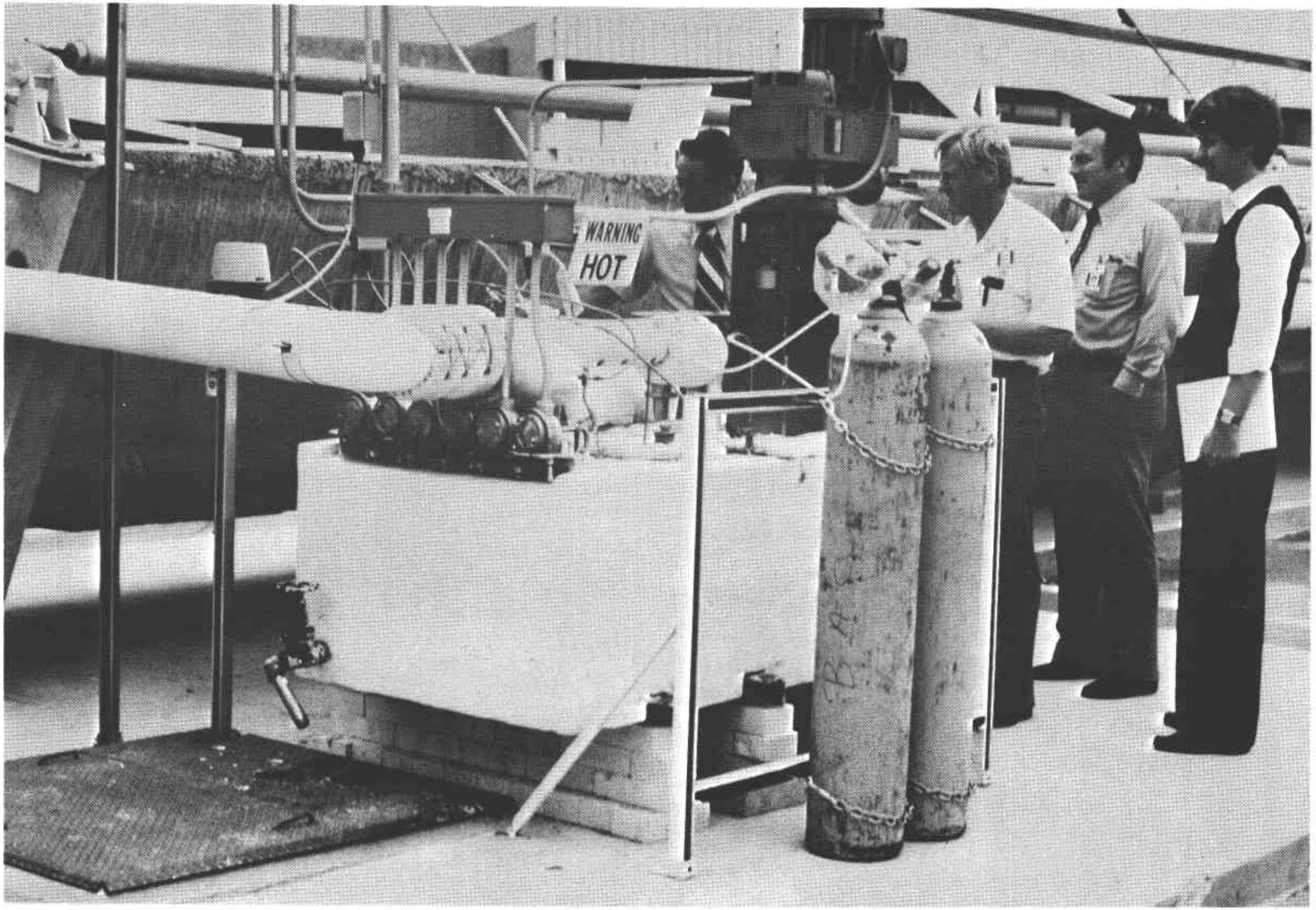


Fig. 2. Molten salt handling system

valve to permit drainage of the salt into a sump or containers placed in the sump. The sump is covered by a removable safety plate.

The tank heating system consists of six heaters of 8 kW each. The heaters are controlled in two banks by two relays. Each relay is controlled by a temperature controller, which receives its signal from a platinum RTD sensor. The salt temperature in the tank is regulated by turning the power to the heaters on or off. The temperature level can be set by a potentiometer.

The flow control valves are used to regulate the flow rate and to distribute flow between the return line and a heat dissipating or radiator line. The valves are mounted as an assembly on the tank.

The pump is specifically designed to pump molten salt. It is driven by a 10-hp constant-speed motor with a variable-speed clutch. The design flow rate is 0.001 m^3/s (16 gpm). The flow can be regulated over its whole range by controlling the pump speed. The pump and motor assembly is mounted on the tank by means of a flange.

The molten salt flow rate is sensed by measuring the pressure drop across the calibrated orifice. The pressure drop is transmitted to a transducer by means of NaK-filled lines; the transducer produces a current flow proportional to the pressure drop.

The piping is welded wherever possible. Flange connections are used where the pipe may have to be disassembled. Stainless steel spiral asbestos gaskets are used between the flanges. It is necessary, however, to use some threaded fittings in order to be able to maintain the system.

2.2. COLLECTOR

The collector used for this project is GA's FMSC. The concrete modules, borrowed from Sandia Laboratories, are test modules and spares made under the Sandia Solar Total Energy Program. The collector consists of six concentrator modules and three receiver modules. The aperture is 22.86 m (75 ft) long and 2.13 m (7 ft) wide with an area of 48.8 m^2 (525 ft^2). This particular FMSC was designed to heat an oil (Therminol 66) to a temperature of 589 K (600°F) and was not expected to be an efficient heat collector for heating molten salt to 867 K (1100°F). It was utilized unchanged except for minor changes to the heat receiver.

The concrete concentrator modules are mounted on concrete footings and surrounded by a concrete pad for containment of molten salt should a severe leak occur. The collector is built on a slope to facilitate drainage, with the west end 457 mm (18 in.) higher than the east end. The collector is installed with the longitudinal axis in the east-west direction and the heat receiver tracked north-south. The concentrator modules are tilted 35 degrees toward the south. Figure 3 is a photograph of the FMSC installed at the molten salt facility.

The mirror strips on the concentrator modules are symmetric about the tangent facet. There are 43 50.8-mm (2 in.) wide mirrors made from 0.157 mm (0.062 in.) thick Corning 0317 glass. The mirrors were silvered by a local vendor, who also applied protective coatings consisting of the following on the back:

Polyurethane enamel (699 mirrors)
Dow Corning 808 silicone (36 mirrors)
Dow Corning Q1-2577 silicone (36 mirrors)

Three mirrors of Schott glass had Schott-applied silvering and coatings.

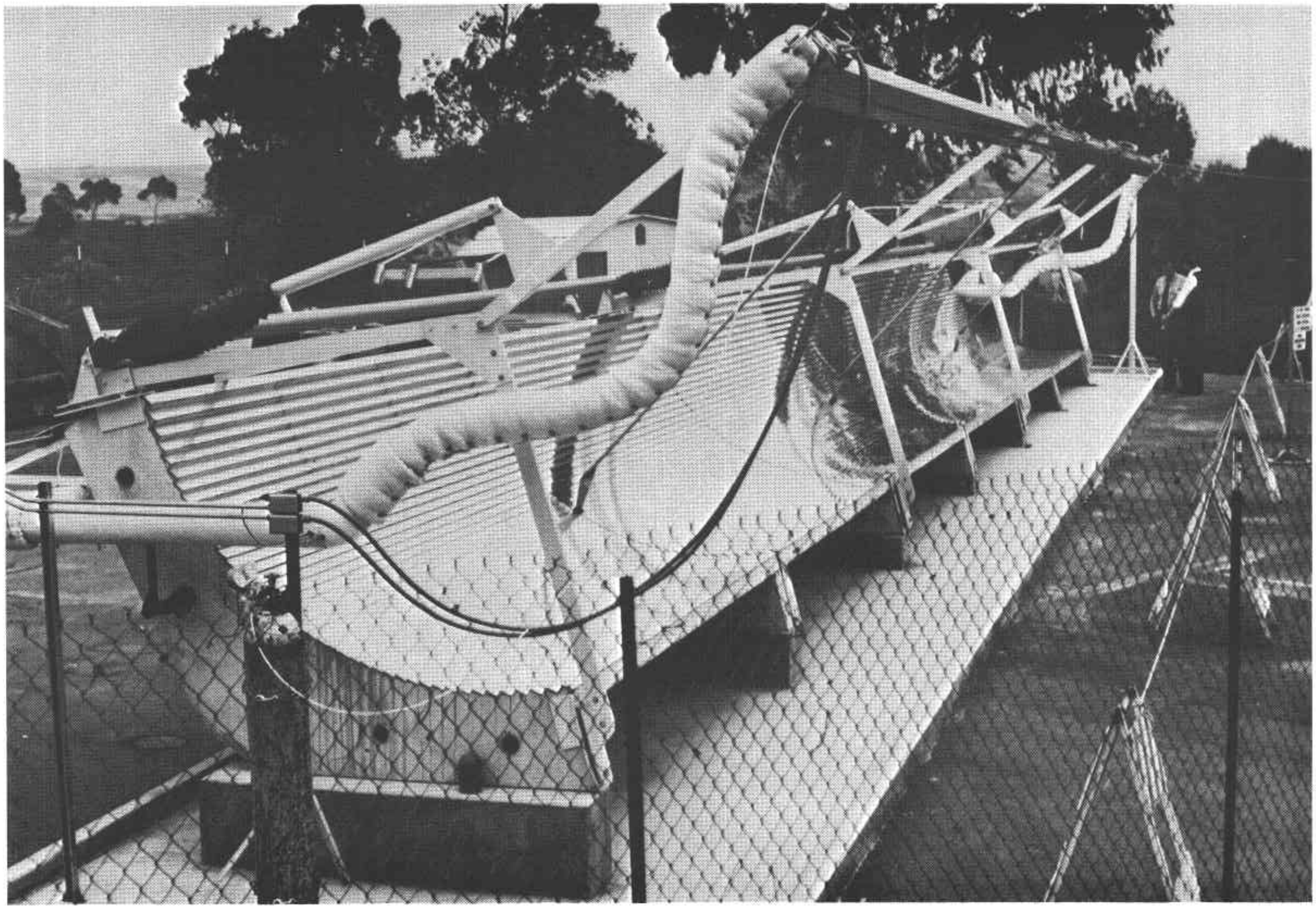


Fig. 3. Fixed mirror solar concentrator installed at molten salt heat transfer loop

Two different bonding agents were used:

3M 427 Neoprene-filled double adhesive (129 mirrors)
3M 468 0.127 mm (0.005 in.) transferable adhesive (645 mirrors)

Figure 4 is a photograph of the heat receiver under test at the molten salt facility. Figure 5 is a drawing of the receiver cross section. The heat receiver consists of four functional components including (1) the heat receiver pipe, (2) insulation, (3) the secondary concentrator, and (4) the support beam.

The 316 SS heat receiver pipe was made by pressing a round tube to a flat oval. The receiver pipe was fabricated from three pieces of flattened tube. Transition pieces of 304 SS were welded onto the ends of each receiver pipe to obtain a round section. To absorb thermal expansion of the pipe, diaphragm-type bellows (illustrated in Fig. 6) were welded to one end of the two end receiver pipes and to both ends of the center receiver pipe. Since diaphragm bellows tend to squirm easily, tubular retainers were placed around them. Marman clamp flanges were welded to the bellows and to the other end of each of the end receiver pipes. A special thermal well with a mating Marman clamp was fabricated to connect the flexible downcomers to the receiver pipe. The fluid temperature RTDs and thermocouples were inserted into these thermal wells. On the illuminated side of the pipe provisions are made for mounting a glass window on metal clips. The clips are used to reduce shadowing of the glass edge and thus reduce thermal stress in the glass. Corning 0317 glass is used for the window.

Operation at high temperature caused black nonselective oxide to form on the tube outer surface. The back and sides of the pipe are insulated with hydrophobic Microtherm, a silica foam insulation supplied by Micropore International.

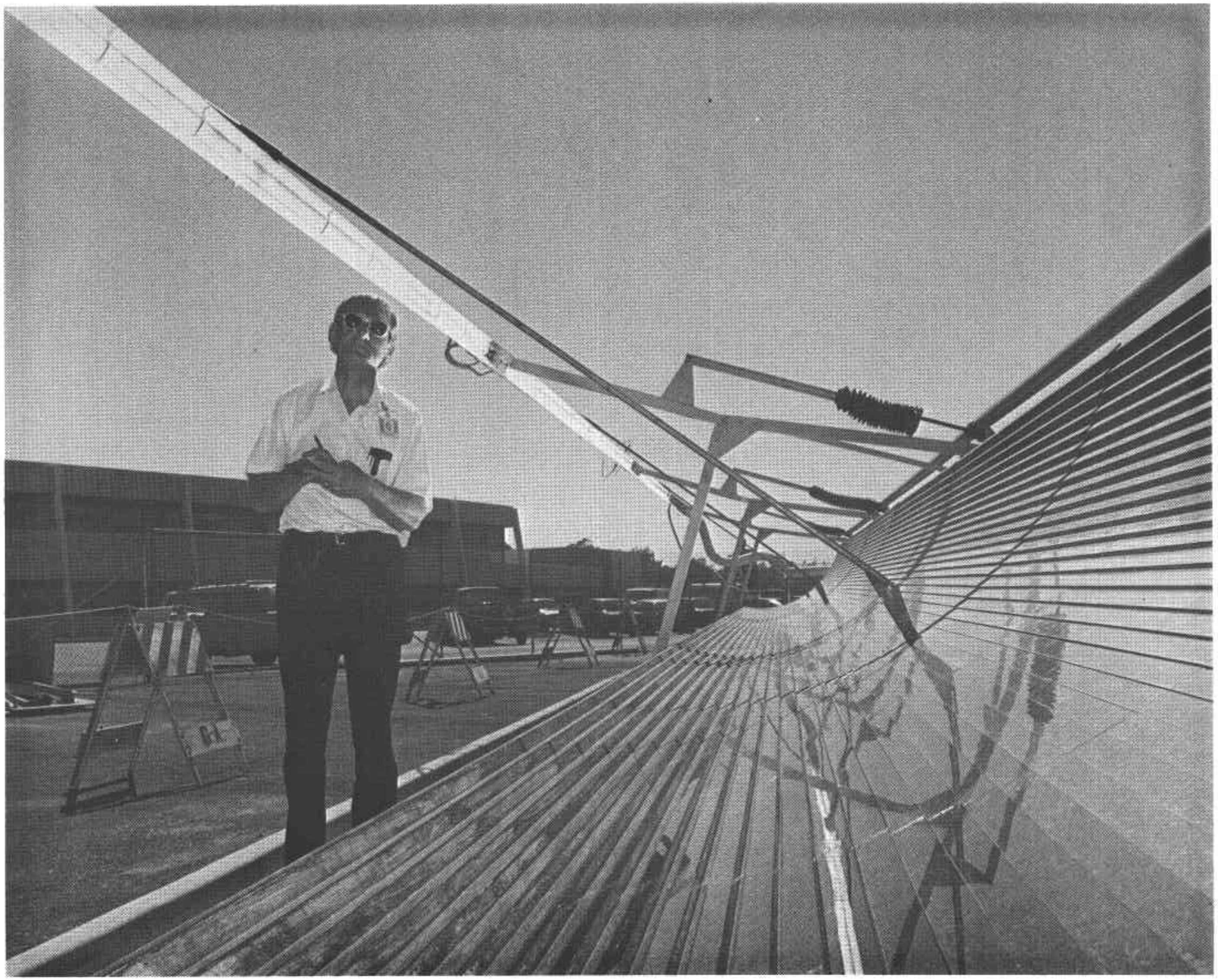
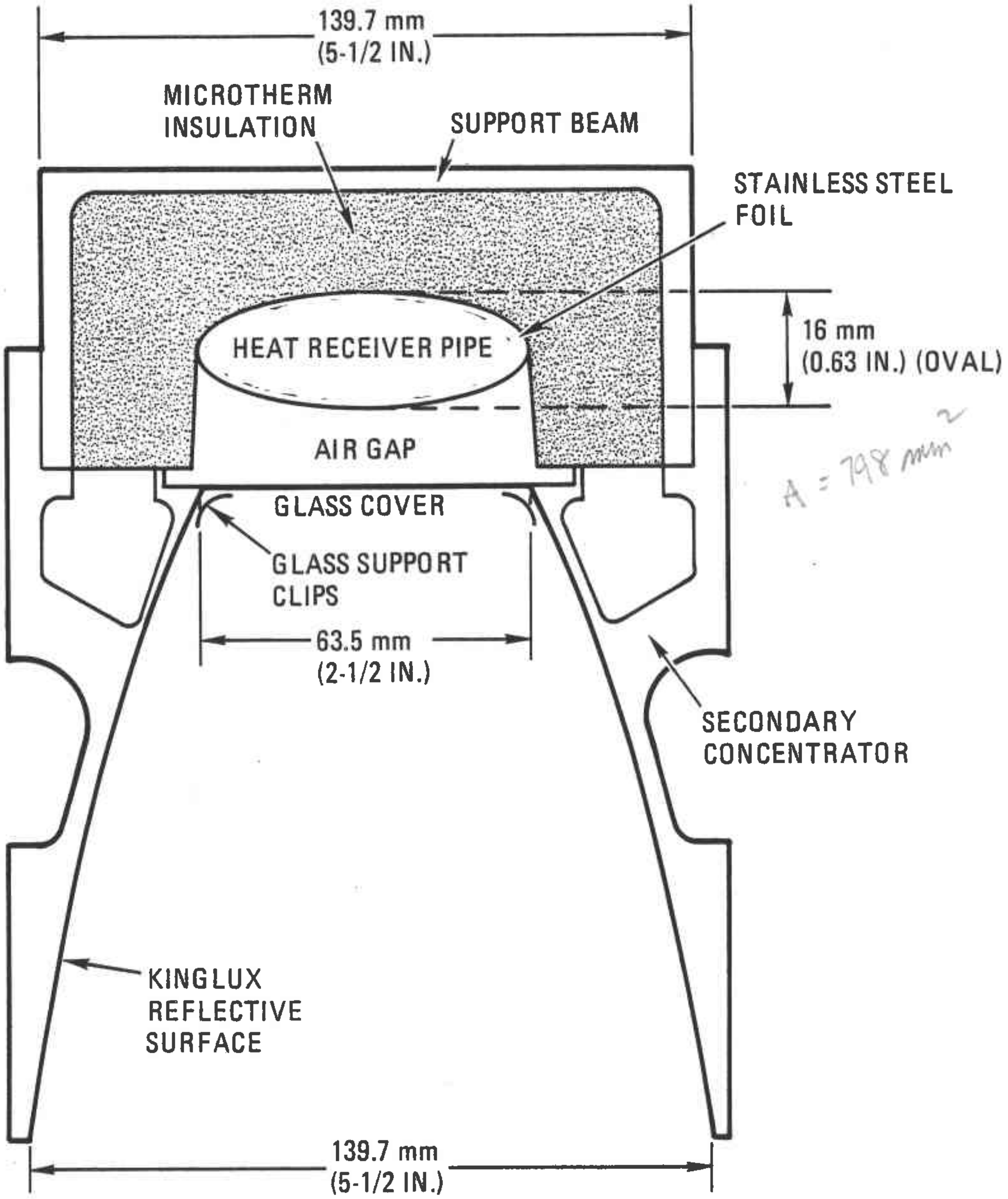


Fig. 4. Heat receiver under test



A = 798 mm^2

Fig. 5. Heat receiver assembly cross section

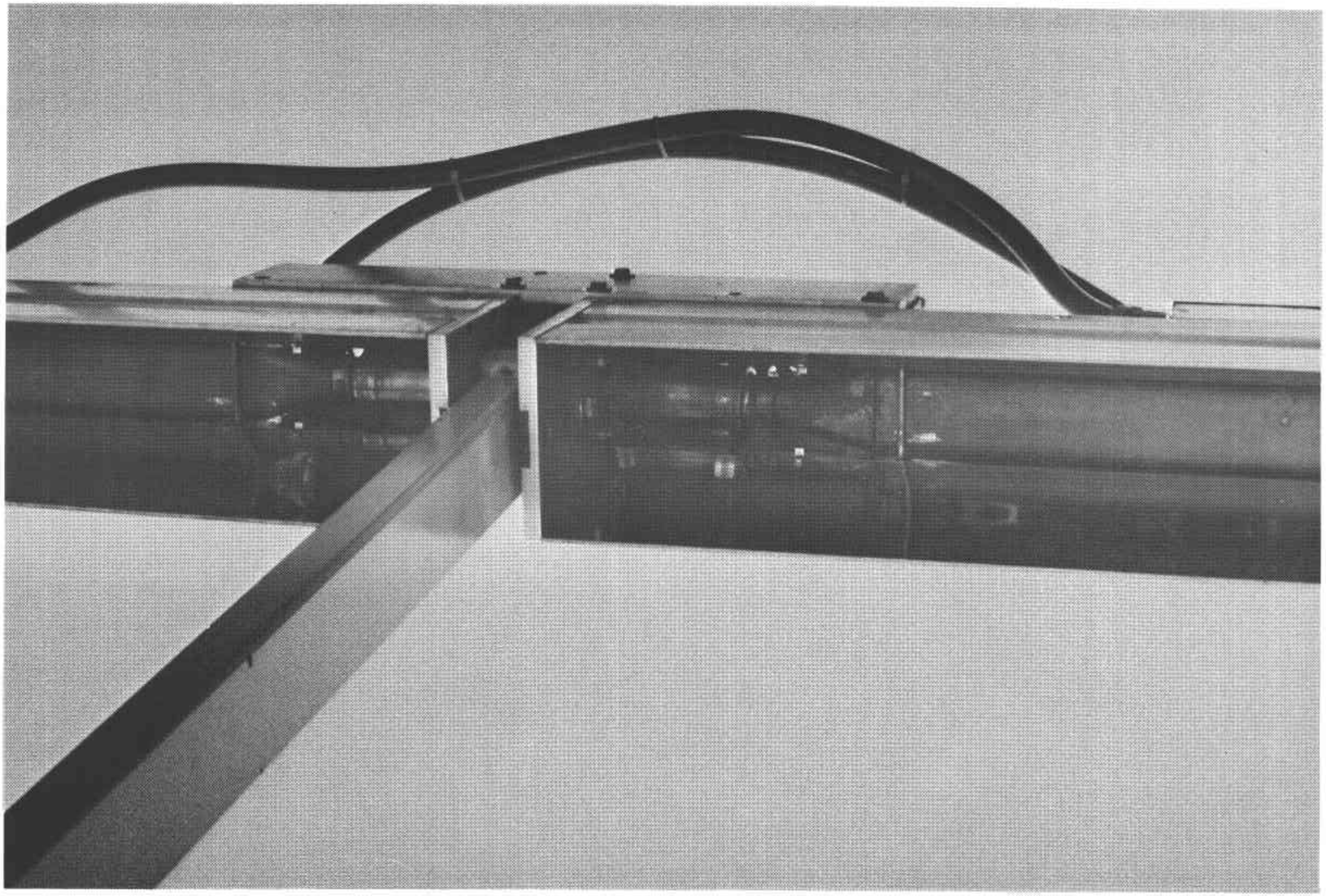


Fig. 6. Heat receiver pipe transitions

The secondary concentrator, formed of extruded aluminum, is of the compound parabolic (Winston) type. The inner surfaces of the secondary concentrator are covered with a thin sheet of polished anodized aluminum called Kinglux (Kingston Industries Corporation), which is bonded with 3M 468 adhesive to the aluminum base structure.

The support beam consists of an aluminum channel on which all other components of the receiver are mounted. The support beam is attached to the heat receiver support structure.

2.3. HEAT TRACE SYSTEM

All the molten salt piping, including the heat receiver, downcomers, and supply and return lines, is heat traced to provide for temperature conditioning of the piping prior to filling it with hot salt. The heat tracing can also be used to melt frozen salt plugging the piping. The heaters are Alumel wire sheathed in 347 SS, with an MgO insulator.

The heat receiver and downcomers are trace heated from the inside. The trace heaters for the receiver pipe and downcomers are inserted through fittings. The bellows trace heaters are vacuum-brazed in a fitting with Nioro braze.

The molten salt supply and return piping are trace heated from the outside with the trace heaters underneath the insulation and attached to the pipe by stainless steel hose clamps.

There are two electrical supplies for the trace heaters. The 110-V system has separate controllers for each heater and supplies the heat receiver thermal expansion bellows, the thermal wells, and the flow orifice ΔP diaphragm sensors. The receiver pipe, downcomers, return lines, flow straightener, and thermal expansion loop have 208-V heaters without individual controls. The total power capacity of the trace heaters is 17 kW.

2.4. PURGE SYSTEM

The collector is installed on a slope to allow the molten salt to drain back into the tank. To facilitate this drainage, a nitrogen supply fitting is built into each thermal well. When the pump is turned off, the receiver can be pressurized from the thermal wells to blow the fluid back into the tank. The gas will first blow into the tank through the return line and valve. When this occurs the valve can be closed and the gas will then blow into the tank through the pump, thus emptying all the lines.

2.5. CONTROLS AND INSTRUMENTATION

Controls are used to track the heat receiver and to control fluid conditions throughout the system.

The tank heater control consists of a manual setting for temperature level. When the sensing RTD indicates that temperature, the heater power relay opens and shuts off the heater.

The pump speed control is a variable-speed clutch, which is mounted on the pump. The pump speed is set manually to any desired flow rate. Although the pump speed controls the flow rate, the fluid temperature and receiver position cause the flow to vary. These variations can be compensated for by changing the pump speed.

The 110-V trace heaters have temperature demand controllers. These controllers are installed on the junction box panel.

The tracking control system consists of two basic parts: the coarse tracking unit (CTU) and the focal line tracking unit. The CTU tracks the sun directly and brings the receiver into range of the focal line. A pair of photo cells in the receiver aperture then provides a signal to precisely position the receiver. Once the receiver is on the focal line, the CTU is not needed; however, should a cloud cover the sun for an extended time, the CTU is needed to bring the receiver into range of focal line tracking. The tracking control was supplied by Western Control Systems and is an improved version of the one used on the FMSC test module at Sandia, Albuquerque.

The flow rate sensor is a calibrated orifice. The molten salt pressure is sensed on both sides of the orifice by diaphragms. These diaphragms and the lines to them must be heated above the freezing point of the salt [416 K (288°F)]. NaK sealed in tubes transmits the pressure to the transducer, which produces an electric current proportional to the pressure drop across the orifice. The flow rate is proportional to the square root of the pressure drop and, therefore, to the square root of the transducer current. Consequently, the flow rate is read directly on a meter with a square root scale.

The receiver inlet and outlet fluid temperatures are measured by two sets of sensors in the thermal wells located at the inlet and outlet to the receiver. Each set consists of a sheathed Chromel-Alumel thermocouple and two platinum RTDs in one sheath. One of these RTDs is used to measure the fluid temperature directly and the other is coupled to an RTD in the other set to indicate the difference between the receiver inlet and outlet temperatures.

Ten skin thermocouples are located on the receiver, the pipe, and tank at the locations shown in Fig. 1. These thermocouples are also sheathed Chromel-Alumel. They are welded to the pipe for good thermal contact. The readout unit is a selective readout located in the instrument rack in the trailer (Fig. 7).

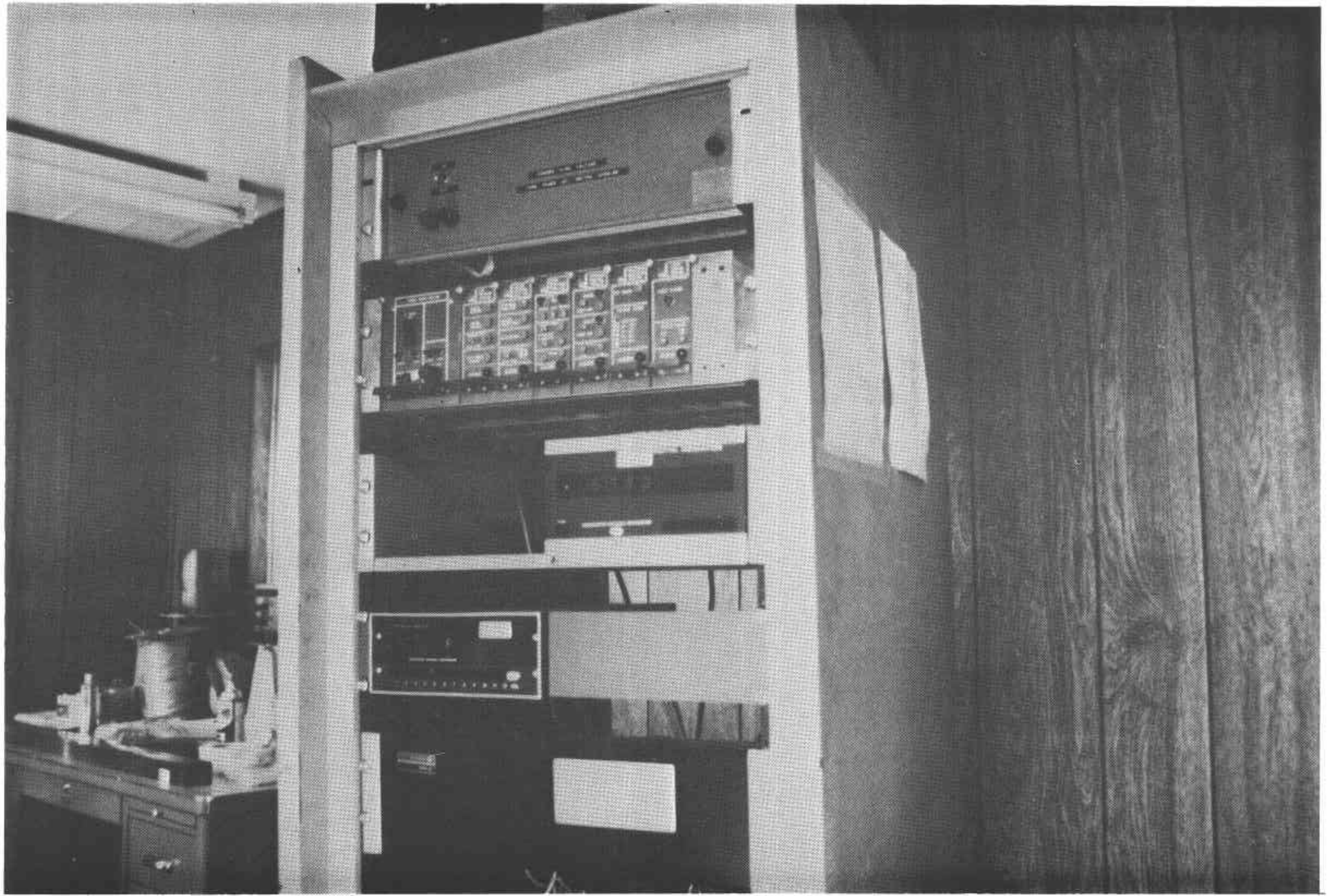


Fig. 7. Instrumentation readout and control panel

3. SYSTEM INSTALLATION

The various system elements are discussed in approximately the order in which they were installed.

3.1. COLLECTOR

The collector foundation was surveyed so that the collector would be exactly east and west. The receiver would then track north and south. Concrete piers were poured into excavations in the ground. Each pier supported the end of two modules except at the ends of the row. The piers were graded so that the collector would slope from west to east, with the west end 457 mm (18 in.) higher, to enhance gravity drainage of the molten salt into the storage tank. A concrete pad with a retaining lip was poured around the piers to contain any spillage or leakage of hot salt and thus prevent it from contacting the asphalt.

The mirror modules were installed on the piers with a forklift. Each module was positioned so that the center pivot of rotation would be in perfect alignment. The receiver support structure was installed and the alignment was checked. After the alignment was satisfactory, the tracking jacks and drive line were installed.

Initially, only one module had mirrors installed. As mirrors became available they were subsequently installed on the other modules. Several test groups of mirrors were obtained, as listed in Section 2.2. The surface of the concrete modules had weathered since they were poured, and the surface was coated with leached grout. The mirror adhesive would not stick to this surface and it could not be cleaned off by water washing. After a muriatic acid wash was used and a concrete sealer was applied, the adhesive adhered very well.

The receivers were installed by lifting them up into place with a forklift. When the receivers were anchored in place, the receiver pipe joints were made up by installing the Marman clamp. The thermal wells were installed on the downcomers and the downcomers were then attached to the receiver pipe with Marman clamps.

3.2. HEAT-TRACE SYSTEM

The trace heaters were installed in the receiver pipe when the receiver was assembled. The main pipe heater was installed inside the pipe through a ferrule-type fitting welded to the pipe transition section, and the bellows heaters were brazed in a fitting also welded to the pipe transition. The brazing was done in a vacuum induction furnace using Nioro braze.

The trace heater for the downcomers was also installed inside the flexible tube through a ferrule-type fitting welded to an elbow below the downcomer flange coupling. The downcomer heater extended up into the thermal well.

With the exception of the heaters on the return lines, the remaining trace heaters were spiraled around the outside of the pipe and held against the pipe with hose clamps. The heaters on the return lines were not long enough to spiral and thus were clamped along the side. This method causes a thermal contact problem in that the heater tends to expand away from the pipe between the anchor points as the pipe gets hot.

3.3. MOLTEN SALT HANDLING SYSTEM

The salt tank was set on piers of firebrick to elevate it to the correct height and to prevent deterioration of the concrete from the high temperature. The pump, motor, valves, and tank heaters had been installed at the tank fabricator's shop. After the tank was positioned, the various flange couplings were connected. The flow meter pressure tap lines and differential pressure transducer were then installed. When all the hardware was installed and connected, the heaters and motors were electrically wired and checked.

After the system was installed and initially checked out, the salt was put into the tank. After preliminary testing with salt, the tank and piping were insulated. Special removable bands of insulation were put around all flange and flow meter connections; this insulation can be easily removed for maintenance.

3.4. CONTROL SYSTEM

The tracking control system was installed after the drive system had been installed but before the receivers were delivered. The control system was the same one that had been used with the Sandia test module. Damage to the control system that occurred during its operation at Sandia required extensive repairs. The control system was therefore completely rebuilt, and many improvements were made. The CTU was undamaged and was used as received.

The control panel was installed in the office/instrument trailer. The CTU was set on a post elevated above the system to prevent interference from shadows. The fine tracking sensors were installed at the midpoint of the center receiver segment. The junction boxes interfacing the CTU, the CTU potentiometers, and the tracking control panel were mounted on a panel installed at the east end of the primary mirror (Fig. 8).

The main power switchgear, breakers, and fuse boxes were installed along the east boundary fence (Fig. 9). All power wiring was put into conduit. The power wiring and instrument wiring on the back of the receiver were put in separate conduits.

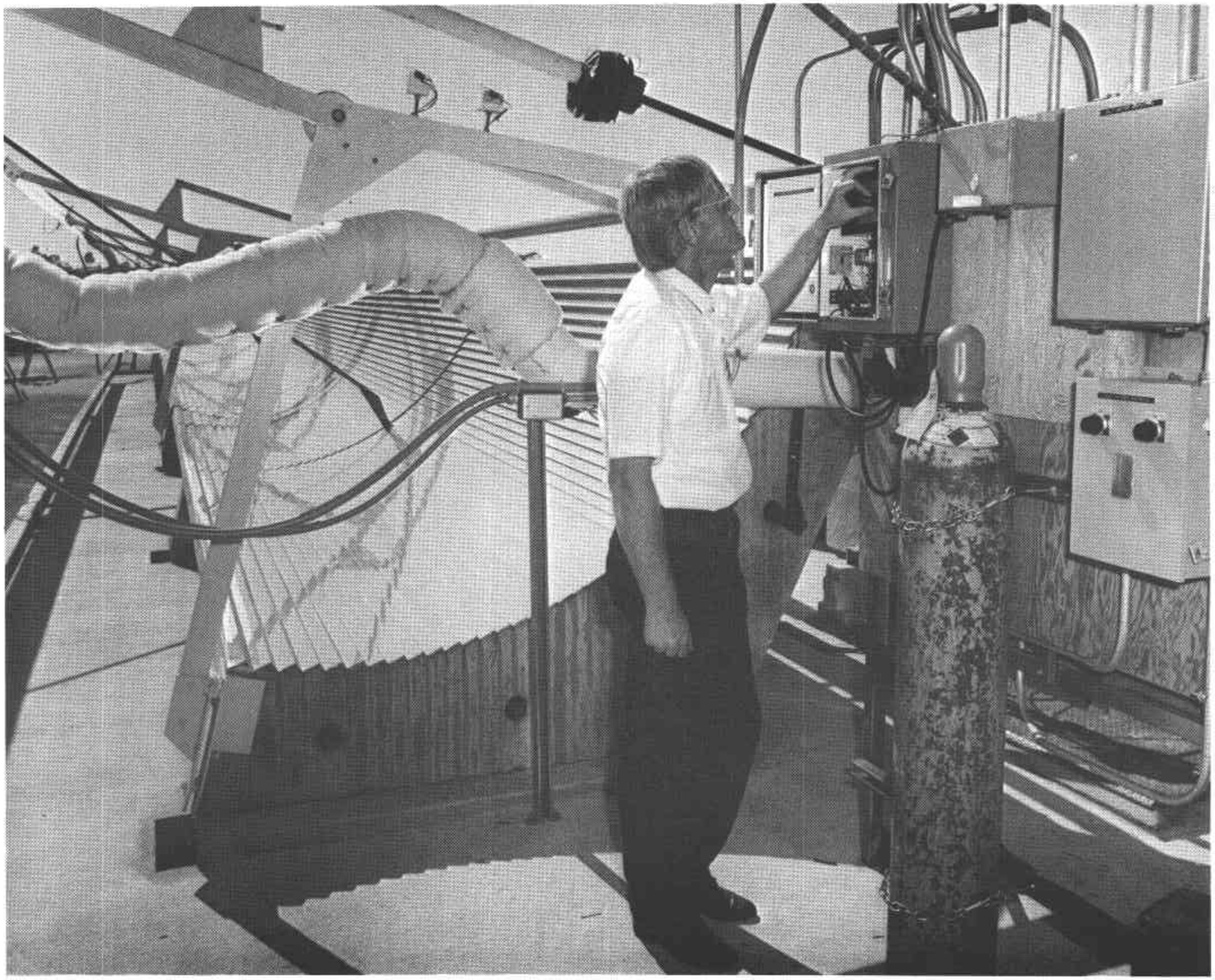


Fig. 8. Junction box and heater control panel

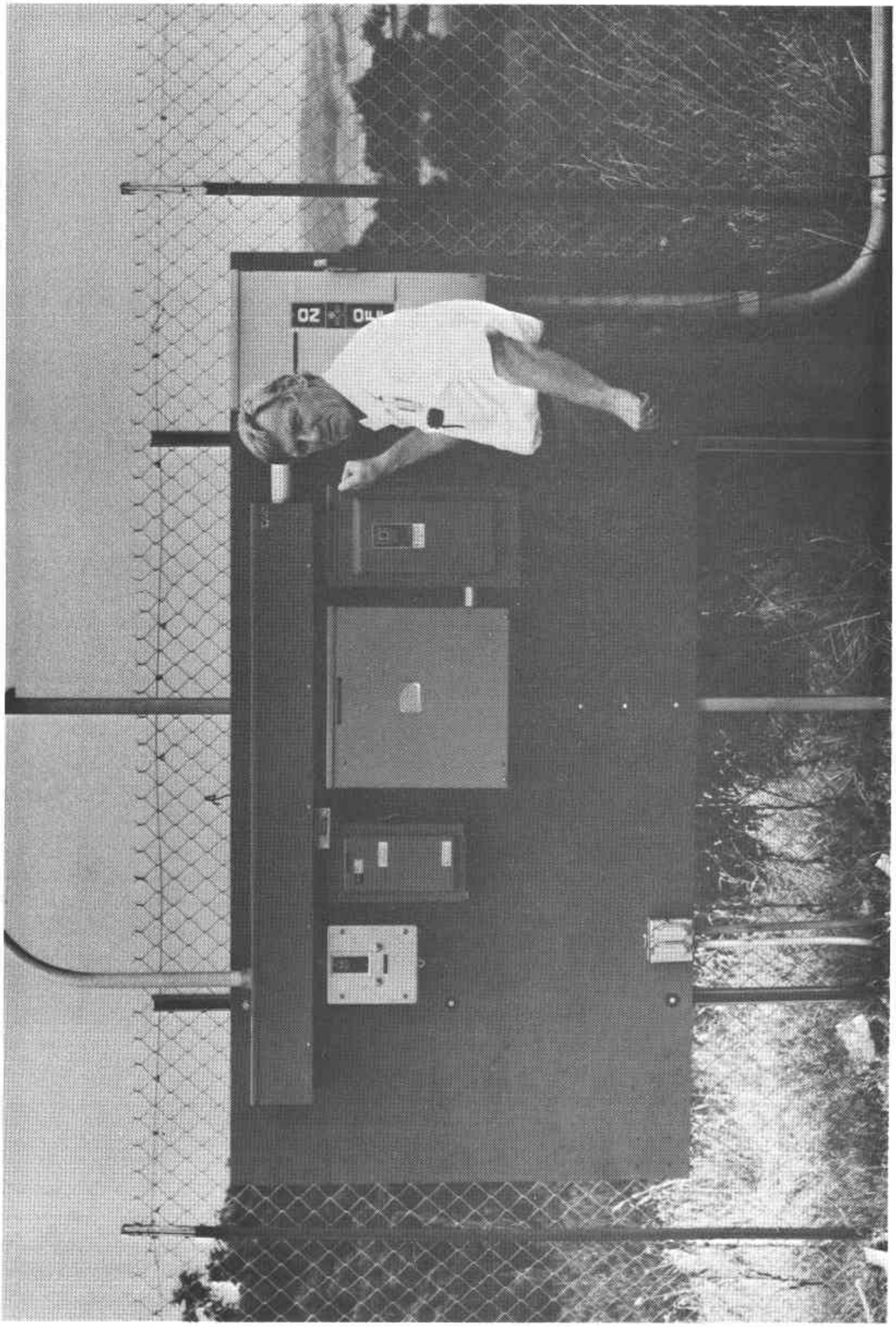


Fig. 9. Main power switchgear, breakers, and fuse boxes

The control panel for the tank heaters was installed on the junction box panel. This is primarily a manual control. The controllers for the 110-V heaters and the switches for the 208-V heaters were also mounted on the junction box panel.

The RTD monitor unit and the thermocouple readout unit were installed in the instrument rack in the trailer. The flow meter power supply and readout were also installed in this rack, but the transducer was installed near the tank.

3.5. COMPONENT TESTING

Every operational unit was tested for proper functioning after installation. A number of these tests and the results are given below.

1. The receivers were coupled together and hydrostatically pressure and leak tested prior to delivery. No leaks were observed, but one of the bellows squirmed out of place and deformed. (The retainers had not yet been installed.) This bellows was replaced.

2. The entire piping system was hydrostatically pressure and leak tested at 186 kPa (27 psig), which is somewhat above the maximum pressure obtainable during operation. It was found that the thermal expansion bellows began to squirm at 138 kPa (20 psig). Retainers were then installed around the bellows and the test was continued. No leaks or other problems were found.

3. The pump was started up and checked for rotation and general operation.

4. The receiver was heated in the sunlight to about 721 K (838°F) to expand the pipe. The expansion bellows functioned properly. No problems were observed.

5. Each thermocouple was connected to the monitor and observed for ambient temperature response.

6. The platinum RTD thermometers were checked at ambient temperature.

7. The differential temperature indicator did not indicate the correct difference. This error was due to improperly matched leads. A correction was made that reduced the error to a small value.

8. The tracking system was checked in place. The system tracked the focal line very well.

4. SYSTEM TESTING

After all component testing was completed and the system was completely assembled, system checkout was started. The system tests were made primarily while circulating and heating fluid.

4.1. PRELIMINARY TESTING WITH WATER

Tap water had been introduced into the system for the hydrostatic pressure tests. Since tap water contains chlorine, the system was flushed with distilled water and recharged. The pump was turned on and the flow meter checked. The flow meter indicated a flow rate proportional to the pump speed.

Each set of heaters was turned on individually and the temperature rise observed to determine if the heater was functioning. When it was confirmed that all of the heaters were functioning, the water was brought to boiling and all the sensor signals recorded. Each sensor indicated the boiling water temperature.

When these tests were completed, the receiver was put in the focal line and the temperature rise observed in the receiver.

During these tests, constant surveillance was maintained for leaks or any equipment malfunction. These preliminary system tests confirmed expected system operation.

4.2. MOLTEN SALT TESTING

After the tests with water were completed, the water was drained from the system. The heaters were turned on in order to dry the system as much as possible. The salt was then put into the tank. The raw salt was in granular form and was of lower bulk density than the solid salt. It was necessary to melt the salt in the tank several times, as salt was added, to get the required salt charge into the system. When all the salt was melted, it looked very much like fresh, clean Therminol 66 at room temperature.

When the pump was first turned on, the discharge line plugged, probably in the flow straightening section. All the heaters were on and the receiver was in focus, but the tank temperature was only 482 K (407°F). The pump was turned off and the system temperature allowed to increase. After about 30 minutes (at 11:20 AM) another attempt was made to start flow. A little fluid flowed, as indicated by the surge on the flow gauge, but the flow quickly dropped to zero. The pump was turned off and restarted again after about 15 minutes. Fluid started flowing at 11:45 AM, May 10, 1979 with the inlet thermowell temperature at about 707 K (813°F), the outlet thermowell temperature at about 673 K (752°F), the receiver skin temperature at about 711 K (820°F), and the tank temperature at 497 K (435°F). After fluid started to flow, the system temperature stabilized close to the tank temperature. With the receiver in focus at close to noon, the outlet from the receiver was higher than the inlet, as it should be if there is a net heat gain in the receiver. The system was allowed to heat up to about 532 K (497°F) at the receiver outlet and then the heaters were turned off. The heaters remained off for about 1 hour, at which point the outlet temperature was 534 K (502°F). The tank heaters were then turned on to increase the fluid temperature more rapidly. At 4:10 PM, when the outlet fluid was 647 K (705°F), all the trace heaters were turned on and the pump was turned off in preparation for shutdown. Prior to turning the pump off, the salt flow rate was 5.20×10^{-4} m^3/s (8.25 gpm).

About 15 minutes after the pump was turned off, nitrogen pressure was applied at the purge access. The gas bubbled through the return line first. The valve was closed and gas then bubbled through the pump. A nitrogen pressure of 138 kPa (20 psig) was used. The system was then secured.

All of the heaters were turned off for complete shutdown and the tank was allowed to cool over night. The tank temperature at 7:45 AM the next morning was still above the Hitec melting point. All the heaters were turned on to heat up the system. Every attempt throughout the day to start flow failed. The line was plugged but the location of the stoppage could not be determined. The system was secured with the tank temperature at about 589 K (600°F). The tank was allowed to cool over the weekend.

On Monday morning the salt was frozen over the top but not completely solid. All the heaters were turned on to heat both the fluid and the piping. Several attempts were made to start flow but they failed. The purge system was open through the valves but closed through the pump, indicating that the blockage was either in the flow straightening section or the inlet downcomer. Using a thermometer and punching holes through the insulation, it was found that the inlet pipe was only about 311 K (100°F), even though the thermocouples showed higher temperatures. Two more heaters were added to the inlet pipe and flow straightener section. With the additional heaters, the line opened in about an hour and fluid flow was reestablished.

After the initial startup, a number of tests were conducted on the system. The results of these tests and observations are discussed below. The contract objective was to heat and circulate molten salt at about 811 K (1000°F), although the informal goal was to reach 867 K (1100°F).

Heating the system enough to start fluid flow was a severe problem. The shortest time to get the system started was about 2 hours. This occurred with the tank still at 571 K (568°F) from the night before, and it required all the heaters and the sunlight to achieve startup. Generally, it was 11:00 AM to 12:00 noon before the system was operating.

The tank did not freeze solid over night. When the system was operated to about 811 K (1000°F) and then shut down, the tank temperature the next morning was 571 K (568°F). Even over the weekend the tank did not freeze up; however, it did freeze up after a 3-day shutdown.

The system was started once by applying the heaters with the salt solidly frozen and at ambient temperature. Other than a lot of popping and cracking noises, no unusual problems were observed. Initial heating was done slowly to free the heaters from the solid salt, but this probably was being overcautious. No problems were observed in melting the salt from a completely solid condition.

Several attempts were made to achieve the peak operating temperature goal, but the day would end just short of the goal. One deterrent to success was the high heat loss from the receiver because it did not have insulating glass. This was particularly apparent on windy days. Prior experience with the FMSC system supplied to Sandia Laboratories had showed that the receiver glass would crack and eventually fall out. The glass in the Sandia system was supported along its edge, which in turn shadowed the glass edge causing it to be cooler than at the center. Therefore, special support tabs were put on the molten salt receiver and the insulating glass was installed on these tabs. The system was operated with the heaters on and the receiver in focus with the inlet fluid temperature reaching 813 K (1003°F). The glass began cracking in from the edge when the inlet fluid temperature reached 783 K (950°F), as measured by the RTDs, and the receiver pipe skin temperature was 781 K (945°F), as measured by the thermocouples. The receiver was losing heat as the weather was intermittently cloudy. At the inlet fluid temperature of 813 K (1003°F), 10 of the 18 pieces had cracked.

The receiver glass was examined for residual stress at room temperature and found to be stress free. This was the case for both the cracked and uncracked pieces. As the glass had originally been cut into strips with a glass cutter, it is thought that the sharp edge, having slight irregularities, could have developed stress concentration points under heating conditions on the heat receiver, thus contributing to the cracking. Fire polishing the edges might eliminate the cracking problem.

The remaining glass was removed and another attempt was made on May 23, 1979 to achieve operation with the fluid temperature above 813 K (1003°F). All of the heaters (both trace and tank heaters) were left on. The receiver was tracking automatically in order to put as much heat as possible into the system. The peak fluid temperature reached and sustained for about 1 hour, between 2:50 PM and 3:50 PM, was 844 K (1059°). This was the maximum temperature achieved during this program. Since the trace heaters were on, no measurement could be obtained on the solar input to the heat receiver. During this test the project formal temperature goal was achieved and the system functioned as designed. All of the instrumentation functioned as intended. The control system also tracked accurately throughout the day.

The objective of the next test was to obtain some high-temperature solar performance data. On June 11, 1979 the system was heated up with all the heaters on until the fluid temperature was above 756 K (900°F). The trace heaters were then turned off, but the tank heaters were left on to help increase the system temperature. Solar input to the receiver was the only heat source outside the tank. The inlet and outlet fluid temperatures could be measured accurately by means of the RTDs in the thermowells. The flow was also monitored continuously and was maintained at full scale [0.001 m^3/s (16 gpm)] on the readout meter. The data recorded are given in Table 3.

During this period the pyrheliometer was malfunctioning, but based on visual observation and previous measurements, the direct normal insolation was estimated to be approximately 1000 W/m^2 (317 Btu/ft^2-hr). From the data, and using the specific heat and density of Hitec, the average heat collection efficiency of the FMSC can be calculated to be 30.3% relative to the direct normal insolation for this period. This efficiency is higher than expected. The following factors were expected to contribute to a lower efficiency:

1. The receiver was operating without a glass window.

2. The oxidized 316 SS receiver tube did not have a selective absorber coating.

3. The geometric concentration ratio for the FMSC with the 63.5 mm (2.5 in.) wide receiver tube is only 34.

The salt tank contains about 590 kg (1300 lb) of salt. If the tank is not frozen at startup [i.e., salt temperature close to 416 K (288°F)] and the operating temperature is 811 K (1000°F), then the amount of heat required to bring the salt only to the operating temperature is 101 kW-hr. With 48-kW heaters, the time required is 2.11 hours, assuming no system heat losses during startup. Of course, solar input can provide about 14.8 kW, as shown previously, but making up the system heat capacity and heat losses exceeds the solar input. The system heat capacity outside that of the salt and also the system heat losses are

TABLE 3
SOLAR PERFORMANCE DATA TAKEN JUNE 11, 1979

PD Time	Inlet Temperature [K (°F)]	Outlet Temperature [K (°F)]	Temperature Difference [K (°F)]	Flow Rate [10^{-4} m^3/s (gpm)]
12:50	763.0 (913.4)	768.2 (922.8)	5.2 (9.4)	10.1 (16)
1:05	772.8 (931.0)	778.4 (941.2)	5.6 (10.2)	10.1 (16)
1:15	779.4 (943.0)	784.7 (952.4)	5.3 (9.4)	10.1 (16)
1:30	786.6 (956.0)	793.0 (967.4)	6.3 (11.4)	10.1 (16)
2:05	799.9 (979.8)	804.6 (988.2)	4.7 (8.4)	10.1 (16)
2:25	806.2 (991.2)	812.3 (1002.2)	6.1 (11.0)	10.1 (16)
Avg.	784.7 (952.4)	790.2 (962.4)	5.5 (10.0)	10.1 (16)

↳ 4.1 ft/sec

poorly known but are indicated approximately by the following observations. Time to start up has been about 4 hours. The tank heaters put in 48 kW. The trace heaters put in about 17 kW and solar puts in about 14.8 kW for a total of about 320 kW-hr. Therefore, the system heat capacity (not including the salt) and heat loss over the time of startup is approximately 320 kW-hr - 101 kW-hr = 219 kW-hr. If the salt is frozen solid at the time of startup, the heat required for startup is greater because of the latent heat of fusion. This is equivalent to 13.3 kW-hr, which was not included in the above approximation.

4.3. OBSERVATIONS BASED ON OPERATING EXPERIENCE

As previously stated, the system operated much as expected. The experience gained can contribute to improvement in design. Experience pertaining to particular items is discussed below.

1. The molten salt does not present any problems. The salt melts readily and flows smoothly once flow is established. The system performed as expected once it was started up.

2. The system takes a long time to heat up. Even after two extra trace heaters were added and the salt was fluid, it took 2 to 3 hours to get fluid flow started through the system.

3. Trace heaters installed inside the pipe give the best performance and are the easiest to install. The heaters on the long return line proved to be very inefficient. They were too short to spiral around the pipe and so were mounted along one side. During use these heaters expanded away from the pipe between the clamps.

4. The diaphragm bellows function well for the in-line thermal expansion joints; however, as they tend to squirm under pressure,

a segmented tubular retainer was put around each bellows. This shielded the bellows from any solar input. An open rod-type retainer would function just as well and allow the bellows to be exposed to the sunlight.

5. The salt apparently climbs up the pump shaft to the lower bearing, and freezes after shutdown, since the tank has to be heated to 589 K (600°F) to free the pump.

6. The glass window below the receiver pipe was installed on special tabs to help maintain the temperature at the edges. The glass survived much higher operating temperature as a result. The cracking always started at an edge, progressed in to the center of the strip, and then progressed longitudinally until the strip broke. It appears that the cracks propagate from stress points resulting from the ragged edge left by cutting the glass. Fire polishing these edges would remove these stress points and might permit low cost glass, such as Corning 0317, to be used in place of an expensive, high-temperature borosilicate glass.

7. There was considerable concern about personnel safety around the operating system. During the startup and subsequent operation, no safety-related incidents occurred. With this experience, and observing such precautions as not standing under the heat receiver and not touching hot equipment, the system is seen as very safe.

8. Trace heaters cannot be bent too sharply around connecting joints, particularly flanges. This was done on the return lines, partly because the heaters were initially too short. The error resulted in a short circuit that severely damaged the heater.

9. The Taylor Instruments flow meter works very well. The orifice and flow straightener pipe has to be fully preheated to get fluid flow started, but it then functions very well.

In conclusion, the molten salt system has functioned well, with the exception of the burned-out trace heaters, and has demonstrated the feasibility of using molten salt as the heat transport medium for a high-temperature FMSC distributed collector system. The FMSC has demonstrated its ability to produce the temperatures required for modern steam power conversion systems. The molten salt system has been repeatedly started and shut down, and rather straightforward operating procedures have been developed. The system can be run with other fluids.

Future use of the facility could take advantage of its temperature-controlled electric heaters and could include long-term materials corrosion testing in flowing molten salt, component freeze/thaw experiments, thermal storage evaluations, and high-temperature heat receiver tests.

APPENDIX A
OPERATING PROCEDURES FOR THE SOLAR MOLTEN SALT HEAT TRANSFER LOOP

These operating procedures are for the experimental and routine operation of the molten salt heat transfer loop after the initial startup. These procedures have been divided into the following categories:

1. Safety.
2. Startup.
3. Shutdown.
4. Interrupted insolation.
5. Heat receiver salt outlet temperature control.

A.1. SAFETY

The system is designed to be safe. The safety aspects were reviewed with the GA Safety Department prior to finalizing the design and again prior to starting up the system. The collector was placed on a concrete pad to prevent the possibility of hot molten salt contacting asphalt pavement. A concrete-lined sump is provided to drain the system below ground to contain the molten salt. Retainers were put on the heat receiver diaphragm bellows as a precaution to prevent possible squirming.

Warning signs have been placed around the system to warn personnel of possible hazards. The major safety rules are as follows:

1. Only authorized personnel will be in the facility while it is operating. Visitors will be escorted by the operating staff while touring the facility when the loop is operating.

2. The loop is designed to operate at 867 k (1100°F). Therefore, it should be assumed that all piping and the tank are hot and they must not be touched.

3. Personnel will not stand under the receiver while it is tracking. Tracking jacks have been known to fail suddenly, dropping the receiver. If work is to be performed on the receiver, it must be stopped before starting work.

4. Density four (4) or darker goggles or sunglasses will be worn while working in the vicinity of the mirror because of the high intensity sunlight in the focal line, which can cause retinal burns.

A.2. STARTUP

The startup of the system from ambient temperature involves the hazard of frozen (solid) salt in the lines. The following procedure is followed:

1. Do not turn the pump on until all the salt in the tank is melted and the system piping is above 422 K (300°F). This is verified by the tank thermocouple.

2. Check the pump shaft for freedom of rotation before turning on the pump motor. Salt can creep into the lower bearing, freezing the shaft, even if all the salt in the tank is melted. If the pump shaft is frozen, raise the tank temperature until the pump shaft frees. It may be necessary to heat the tank to 589 K (600°F) to free the shaft.

3. Do not move the receiver until the downcomers have been heated to at least 422 K (300°F). Solid salt in the convolutions of the flexible steel tube may crack the tubing as it

moves. The fluid temperature sensors in the thermocouple wells give an indication of the downcomer temperature. They should read about 700 K (800°F) to guarantee that the salt is melted in the downcomers.

4. Turn on the tank heaters by raising the temperature demand level to the desired point. If the tank is frozen solid, i.e., tank thermocouple indicates below about 363 K (194°F), set the temperature demand just high enough to turn on the heaters. If popping and cracking noises occur, turn heaters off to allow the heat around the heaters to dissipate. Continue to turn heaters on and off until popping and cracking stop. The heaters must slowly melt themselves free of the solid salt.

5. Turn on flow meter heaters.

6. Turn on the thermal expansion bellows trace heaters before turning on the receiver pipe trace heaters. Allow them to heat to about 367 K (200°F) before turning on the main receiver trace heaters. This will free the bellows of solid salt before the receiver pipe expands against them. The bellows temperature is indicated by a thermocouple at each bellows.

7. Turn on the receiver pipe trace heaters and allow them to heat to about 473 K (392°F). Three thermocouples in the middle of the center receiver segment indicate the temperature.

8. Turn on the return pipe trace heaters at beginning of startup and allow the pipe to heat to about 473 K (392°F). A thermocouple at each end indicates the pipe temperature.

9. When all parts of the system are assured to be heated above 422 K (300°F), and checking items (1) and (2), turn on the pump.

10. If flow is not indicated on the flow meter, leave all heaters on, turn off the pump, wait for about 15 minutes, and then turn pump on again.

11. When flow has been established, set the tank heaters to the desired temperature level and adjust the flow rate to the desired level.

12. The receiver should now be put into automatic mode and allowed to track.

13. The trace heaters may now be turned off, but the tank heaters must stay on to ensure that the salt stays molten and does not freeze up with the pump running.

A.3. SHUTDOWN

The system is designed with a slope toward the salt storage tank so that the salt in the system will drain. As much of the fluid should drain back to the tank as possible before it freezes.

1. Prior to shutting down, raise the receivers to an elevated position. The receivers should be high enough so that there is not a fluid trap in the downcomers.

2. Raise the fluid temperature in the tank to 533 K (500°F) before turning off the pump.

3. Turn on all the trace heaters and allow them to heat up to the salt temperature.

4. Turn off the pump and the nitrogen blanket on the tank.
5. Allow about 15 minutes for drainage and apply nitrogen to the west thermocouple well nitrogen access. (Note: This line may be plugged by frozen salt. It may be reopened by thawing with externally applied heat.)
6. Nitrogen will bubble into the tank first through the valve(s). When this bubbling occurs, close the valves and the nitrogen should bubble into the tank through the pump. When this occurs, shut off the nitrogen.
7. Wait another 15 minutes and open the valves and repeat item (6). Finally, leave return line valve open.
8. Turn off bellows trace heaters.
9. Wait 10 minutes and turn off all other trace heaters.
10. Turn off tank heaters.
11. Record tank temperature.

A.4. INTERRUPTED INSOLATION

Interrupted insolation does not pose a problem unless the system is operating on solar only. The previous requirement of maintaining the tank heaters at 473 K (392°F) ensures sufficient heat to maintain the salt fluid. This level may be reduced once experience is gained on system behavior and the heat loss of the system has been established. Previous experience has shown that the receiver cools very rapidly if the insolation on the receiver is interrupted. Therefore, the following procedure will be followed if the insolation is interrupted by clouds or defocusing:

1. Turn on the tank heaters to maintain the desired temperature or set them to the 473 K (392°F) minimum.

2. If the insolation is interrupted for an extended time, turn on the trace heaters as needed and/or increase the heater setting.

3. If the experiment is terminated by insolation interruption, proceed to shut down manually.

A.5. HEAT RECEIVER SALT OUTLET TEMPERATURE CONTROL

No provision has been made to regulate the salt outlet temperature automatically. However, the salt outlet temperature can be stabilized by manually setting the flow rate, which is done by adjusting the pump speed. The flow also can be controlled by adjusting the exit valve.

The return line from the receiver has a dual line segment that exits through two valves into the tank. One of the lines is fully insulated; this line is used for normal flow. The other line is equipped with segmented insulation blocks, which can be removed as needed to dissipate the required heat to maintain the outlet temperature. The procedure is outlined as follows:

1. Establish the desired outlet fluid temperature.

2. With the receiver tracking, allow the outlet fluid temperature to rise to the desired level with the valve from the cooling line closed.

3. Regulate pump speed to obtain desired flow rate at this temperature.

4. When the desired temperature is reached, open the valve from the cooling line to allow some fluid to flow through it to cool. Also, close the valve from the insulated return line to properly divide the flow. Adjust the valves until the temperature stabilizes at the desired level. (_Note_: It may be necessary to increase pump speed to maintain the desired flow rate.)

5. If the temperature still increases, remove insolation sections from the cooling line until the temperature stabilizes.

6. If the solar input is insufficient to maintain the desired temperature, turn on the tank heaters to supply additional heat.

Note: It will be necessary to determine the amount of uninsulated pipe needed to maintain the temperature control over a wide range of temperatures. Also, experience will tell how to set the two valves to maintain control.

A.6. GENERAL

Record all data, particularly the flow rate and temperature. There are 10 pipe surface temperature thermocouples, two fluid temperature thermocouples, two fluid temperature platinum RTDs, and one flow meter.

GENERAL ATOMIC COMPANY
P. O. BOX 81608
SAN DIEGO, CALIFORNIA 92138