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Molten Salt Receiver Subsystem Research Experiment — Executive Summary

Babcock & Wilcox

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MOLTEN SALT RECEIVER

SUBSYSTEM RESEARCH EXPERIMENT

- EXECUTIVE SUMMARY

FINAL REPORT - Phase I

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Abstract

This is the Executive Summary for a report which presents the preliminary design of a molten salt receiver subsystem for application to solar thermal central receiver power plants. The design is applicable to a repowered utility electric plant or to a stand-alone plant. The receiver subsystem consists of an elevated quad-cavity receiver, a concrete tower to support the receiver, riser and downcomer piping within the tower to transport the salt to and from the thermal storage sub-system, heat absorption panels within the receiver cavities to absorb the incident radiant energy, and the pumps, tanks, piping systems, valves, controls and instrumentation necessary to provide safe and efficient operation of the receiver subsystem. Incident radiant energy is concentrated on the receiver cavity openings by a surround heliostat field. The design is based on a 320 MWt receiver sited at Barstow, California.

The report provides the design requirements necessary to detail the design of the receiver subsystem, a detailed description of the subsystem components, and the design methods employed to produce the design. A development plan highlights the areas of technical uncertainty along with the required development effort to resolve these uncertainties. Manufacturing processes were developed to establish the fabricability of the heat absorption panels. The cost and schedule from design through start up for the receiver subsystem are also provided. The complete Phase I final report has been published as SAND82-8178.

EXECUTIVE SUMMARY

The Babcock & Wilcox Company, under contract to Sandia National Laboratories, has completed the preliminary design of a molten salt receiver subsystem for application to solar central receiver power plants. The design is applicable to a repowered utility electric plant or to a stand-alone plant. The receiver subsystem consists of an elevated quad-cavity receiver, a concrete tower to support the receiver, riser and downcomer piping within the tower to transport the salt to and from the thermal storage sub-system located at ground level, heat absorption panels within the receiver cavities to absorb the incident radiant energy, and the pumps, tanks, piping systems, valves, controls and instrumentation necessary to provide safe and efficient operation of the receiver subsystem. Incident radiant energy is concentrated on the receiver cavity openings by a surround heliostat field. Subcontractor support was provided by Martin Marietta Corporation, Black & Veatch Consulting Engineers, and Arizona Public Service Company.

The principal objectives of the program were:

- To evaluate receiver configuration improvements and select the configuration which maximized the performance/cost ratio of combined receiver and collector subsystems.
- To develop systems level requirements and specifications for the receiver subsystem.
- To prepare a cost effective preliminary design of a commercial receiver subsystem utilizing conventional design, shop fabrication, and field erection practices.
- To identify the requirements for a receiver subsystem research experiment and for a development plan to reduce any risks associated with the design and fabrication of a large scale receiver subsystem.
- To identify and resolve all uncertainties associated with the fabrication of the receiver heat absorption panels.

This summary presents the results of the program. First, the summary discusses the conceptual design evaluations that were made during the proposal phase to establish the quad cavity receiver as the base design. Next, the design requirements are presented establishing the functional requirements for the receiver subsystem, the design conditions, and the environmental requirements. A detailed description of the subsystem components is then given. Following the description of the components, the development requirements are outlined with a discussion of the need for a subsystem research experiment and appropriate laboratory tests. A 10 foot long tube panel was manufactured to prove acceptability of the fabrication procedures. The results of this effort are included. Finally, the cost and schedule are presented.

CONCEPT SELECTION

Prior to the contract work, the basic issues of the receiver type and the heliostat field configuration were evaluated. To understand the reasons for selecting the quad cavity receiver type with a surround heliostat field, it is necessary to make the comparison between the basic receiver concepts as follows:

- o external vs. cavity receiver
- o quad cavity with surround field vs. single cavity with North field

External vs. Cavity - The external receiver utilizes the heat absorption panels to form the external surface of the receiver. Because it eliminates the cavity and structural steel associated with the cavity shell, the external receiver has a simpler structure and, consequently, a lower capital cost. However, the exposure of the heat absorption panels leads to higher heat losses, relative to the cavity receiver, which in turn requires a larger heliostat field to compensate for the higher thermal losses. Evaluation of the design of an applicable external receiver indicated that the savings in the cost of the receiver structure did not make up for the increased cost of the heliostat field (Ref. 1).

Another major disadvantage of the external receiver is that it requires more care in the operation of the unit to ensure that the salt does not freeze within the receiver. The cavity receiver offers more protection against freezing. Each cavity in the quad design is insulated and doors are provided to seal off the cavity during shut down periods. Due to the insulated enclosure, the salt can be maintained in the liquid state during overnight, or for longer periods of time, without fear of freezing in the heat absorption panels. Doors may be supplied with the external receiver to minimize overnight heat losses. However, the curved surfaces require a more costly door arrangement, and would most likely have lower integrity door seals due to the overall complexity, thereby incurring higher heat losses than achievable with the cavity door seals.

The cavity receiver is designed mainly to minimize heat losses from the heat absorption panels by enclosing the panels within the cavity structure. Openings in the cavity face the heliostat field and are sized large enough to allow the concentrated radiant energy to impinge upon the heat absorption panels while sized small enough to minimize convective and radiative losses. In comparison with the external receiver, the cavity receiver heat losses are less, resulting in fewer heliostats for the same power levels. Based on previous studies (Refs. 1, 2, 3), it was concluded that the extra capital costs for the cavity receiver were more than offset by the reduction in heliostat field costs.

Quad Cavity vs. Single Cavity - Prior to the contract, studies (Refs. 1, 3) were performed to compare the quad cavity receiver using a 360° surround field with the single cavity facing a North only field. In these studies, it was concluded that the surround field arrangement was slightly more efficient, for a given power rating, than a North field arrangement, and consequently the surround field offered a slight reduction in total collector system cost. Also, in optimizing the tower and collector field layout, it was concluded that the surround field arrangement resulted in a considerably smaller tower and, therefore, lower tower costs. Sizing of the quad cavity concept indicated that it was a more compact arrangement, with shorter support spans for the structural steel resulting in less structural weight. Based on the preliminary sizing analysis, it was concluded that the quad cavity would incur less cost for structural steel, fabrication and erection than the single cavity*. Based on the evaluation performed in the early studies (Refs. 1, 3) on the costs of the collector field, tower and receiver, it was concluded at the beginning of the contract that the quad cavity receiver with a surround field was the preferred concept.

DESIGN REQUIREMENTS

The receiver subsystem is designed to meet the standards established by ASME, AISC Codes, etc., and the standards set by commercial practice as applied to products such as fossil fuel fired boilers. In general, these standards ensure that safety requirements are met, and that a high degree of reliability is ensured consistent with good economic practices. A "Requirement and Specification" document was produced which defines the necessary system requirements, applicable codes, requirements for design, fabrication, erection, quality assurance, and other special requirements. The general requirements are summarized below:

- The collector subsystem shall reflect solar radiation onto the receiver subsystem in a manner which satisfies incident heat flux requirements. Heat flux limits on the panels shall be established by consideration of thermal stress, temperature, fatigue damage, and corrosion limits.

- The receiver subsystem shall be designed to provide access for maintenance and inspection of the receiver, tower, panels, pumps, tanks, piping, controls, and other parts requiring maintenance.

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*More recent results show that, while the quad cavity does in fact have less structural steel, the complexity of the arrangement and the much larger number of panels, supports etc. required, results in total costs that are very similar to those of the single cavity.

- The receiver subsystem shall be capable of functioning in the following normal modes of operation:

  ---cold startup
  ---diurnal startup
  ---sustained operation within the specified load range
  ---transient operation during cloud passage
  ---hot standby during prolonged cloud passage
  ---diurnal shutdown and overnight hold
  ---prolonged shutdown

- The receiver shall be capable of safe controlled shutdown resulting from upset and emergency conditions due to:

  ---molten salt pump trip
  ---heliostat field scram
  ---loss of power to the heliostat field
  ---loss of salt flow or pressure
  ---flow control valve malfunction
  ---adverse weather conditions

- The receiver subsystem shall be designed for a 30 year operating life.

- Considerations shall be given in the design to achieving high reliability by providing design and operating margins and utilizing sound engineering design practices.

The normal design conditions upon which the design is based are shown on Table 1 with the environmental requirements shown on Table 2. The receiver is designed to accommodate infrequent insolation peaks of 1100w/m^2 at salt flow rates 115% of normal. Nominal design salt temperatures are maintained at salt flow rates down to 25% of the nominal design condition.

TABLE 1 - NOMINAL DESIGN CONDITIONS

Reference Site	Barstow, California
Insolation (direct normal)	950 w/m^2
Design Point	Day 172 at Noon
Receiver Working Fluid	Molten Nitrate Salt 60% $NaNO_3$/40% KNO_3 Mixture by Weight
Design Absorbed Thermal Power	320 MW_t (1.09 X 10^9 Btu/Hr)
Minimum Absorbed Thermal Power	30 MW_t (0.1 X 10^9 Btu/Hr)
Salt Inlet Temperature	290C (550F)
Salt Outlet Temperature	565C (1050F)
Salt Flow Rate	367 Kg/sec (5.85 X 10^6 lbm/hr)

RECEIVER SUBSYSTEM DESIGN

The receiver subsystem is defined as shown in Figure 1 and includes the following components:

- Receiver
- Tower and Foundation
- Receiver Structural Support
- Salt Pumps
- Riser/Downcomer in the tower
- Miscellaneous Receiver Internal Piping
- Controls
- Valves
- Insulation and trace heating
- Auxiliary Equipment

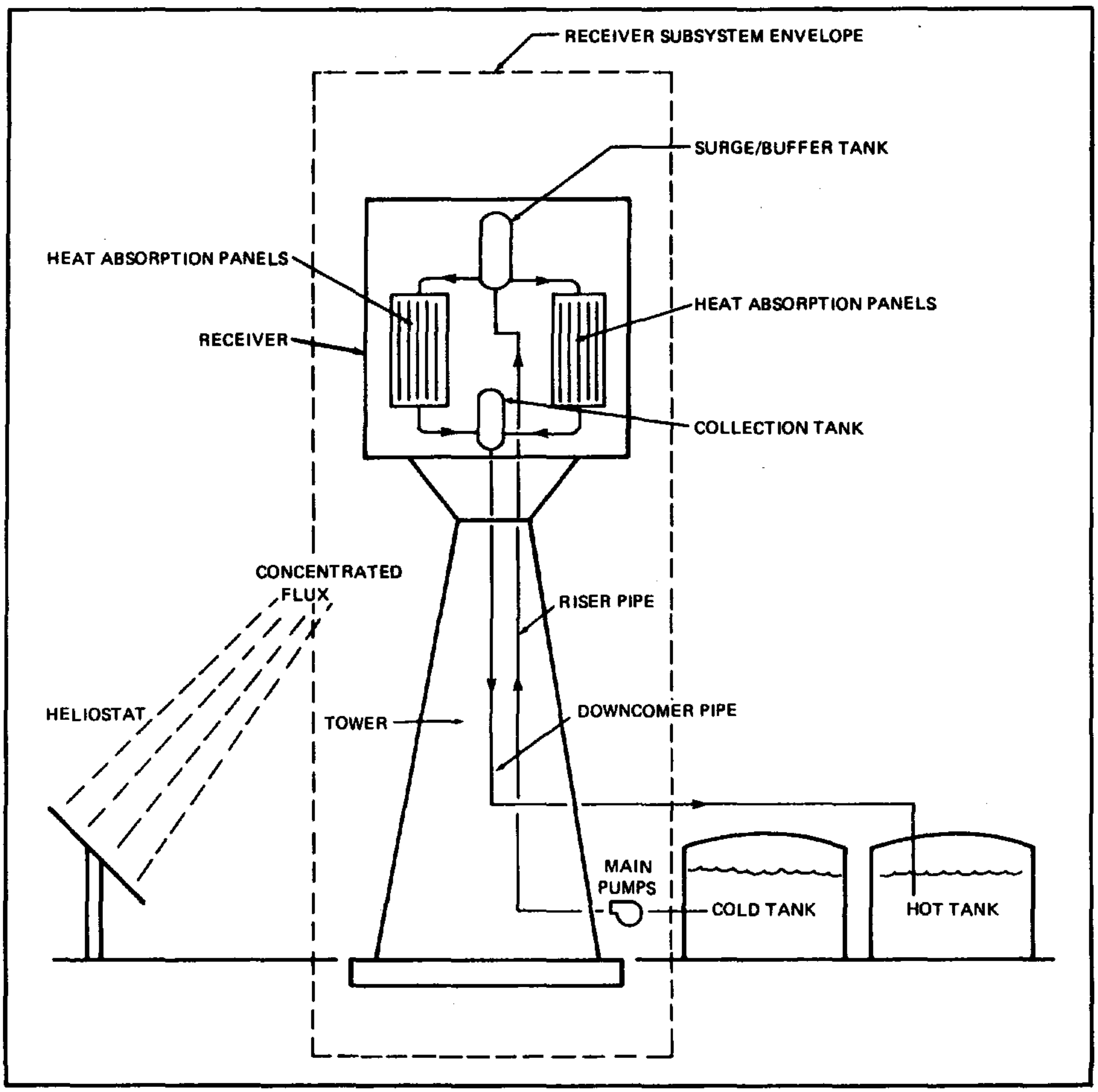

FIGURE 1 DEFINITION OF RECEIVER SUBSYSTEM

TABLE 2 - ENVIRONMENTAL REQUIREMENTS

Design	
Max. Change in Incident Flux	Caused by sharp edged, opaque cloud moving at 13 m/s (40 ft/s)
Maximum Wind Speed (for determination of receiver performance)	3.5 m/s (8 mph) at reference height of 10 m (33 ft.)
Temperature	Wet bulb 22C (74F) Dry Bulb 28C (82.6F)
Operating Temperature Range	-30C to 50C (-20F to 120F)
Earthquake	0.1g (ground response)
Survival	
Max. Wind Speed	40 m/s (90 mph)
Snow Load	240 Pa (5 psf)
Ice Layer	50 mm (2 inch) thick
Earthquake	0.25g (ground response)
Hail Diameter	25 mm (1 inch) Specific Gravity 0.9 Terminal Velocity 23 m/s (75 fps)

The receiver subsystem interfaces with other subsystems in the solar plant. The most important interface is with the heliostat field. While the heat flux in the receiver is defined by the receiver designer, some trial and error with the layout of the heliostat field is required to meet the receiver requirements. For the purposes of receiver design (after establishing actual heat fluxes) the interface is defined at the receiver aperture plane. The receiver subsystem interfaces with the thermal storage system at a point in the riser and downcomer pipes immediately outside the tower. The receiver controls interface with the plant master control subsystem. The receiver also requires electrical supply to the pumps, trace heating, lighting, etc.

A detailed description of the receiver subsystem is given in the following paragraphs covering the heliostat field, tower, cavity arrangement, flow circuits, heat absorption panels, materials, piping and tanks, steel structure, design verification, operation and control.

Heliostat Field - The receiver is situated near the south end of an almost circular field of heliostats (Figure 2) with the four cavities facing N, S, E, W as shown. A total of 10,500 Martin Marietta second generation heliostats was determined to provide the design power rating.

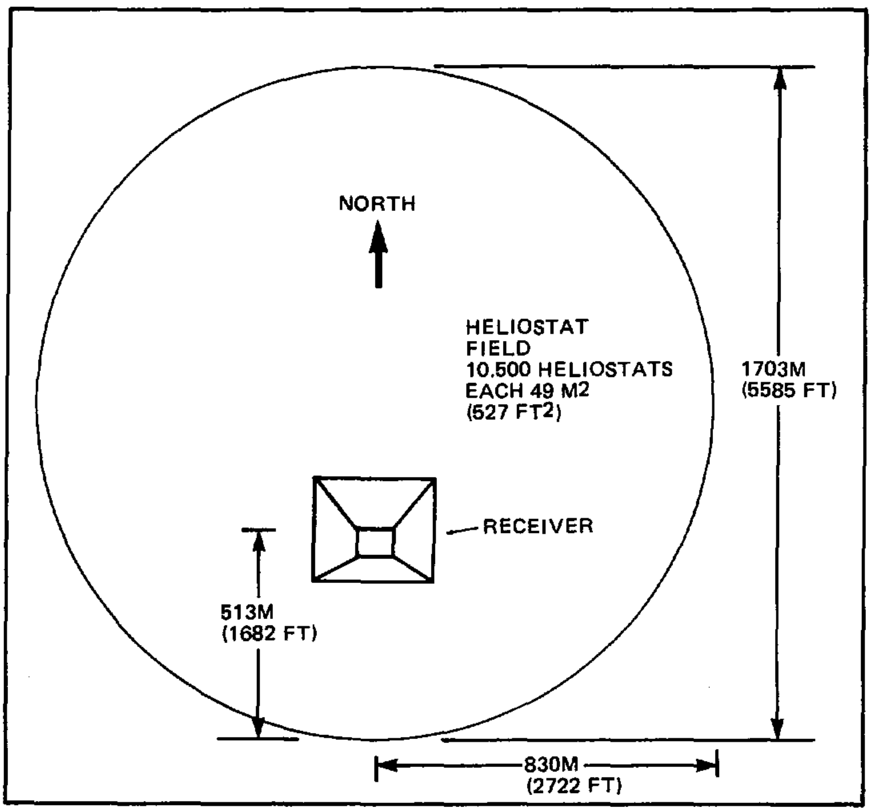

FIGURE 2 POSITION OF RECEIVER RELATIVE TO FIELD

Tower - To allow aiming of the heliostats onto the heat absorption panels within the cavity, the receiver is elevated by a tapered cylindrical, reinforced concrete tower. The tower is 508 ft. (155 m) high, with a top diameter of 60 ft. (18.3 m) and a base diameter of 80 ft. (24.4 m). The receiver is 106 ft. (32.3 m) x 105 ft. (32 m), 150 ft. (45.4 m) high, with a total weight resting on the tower of 2600 tons (2.36×10^6 Kg) (Figure 3).

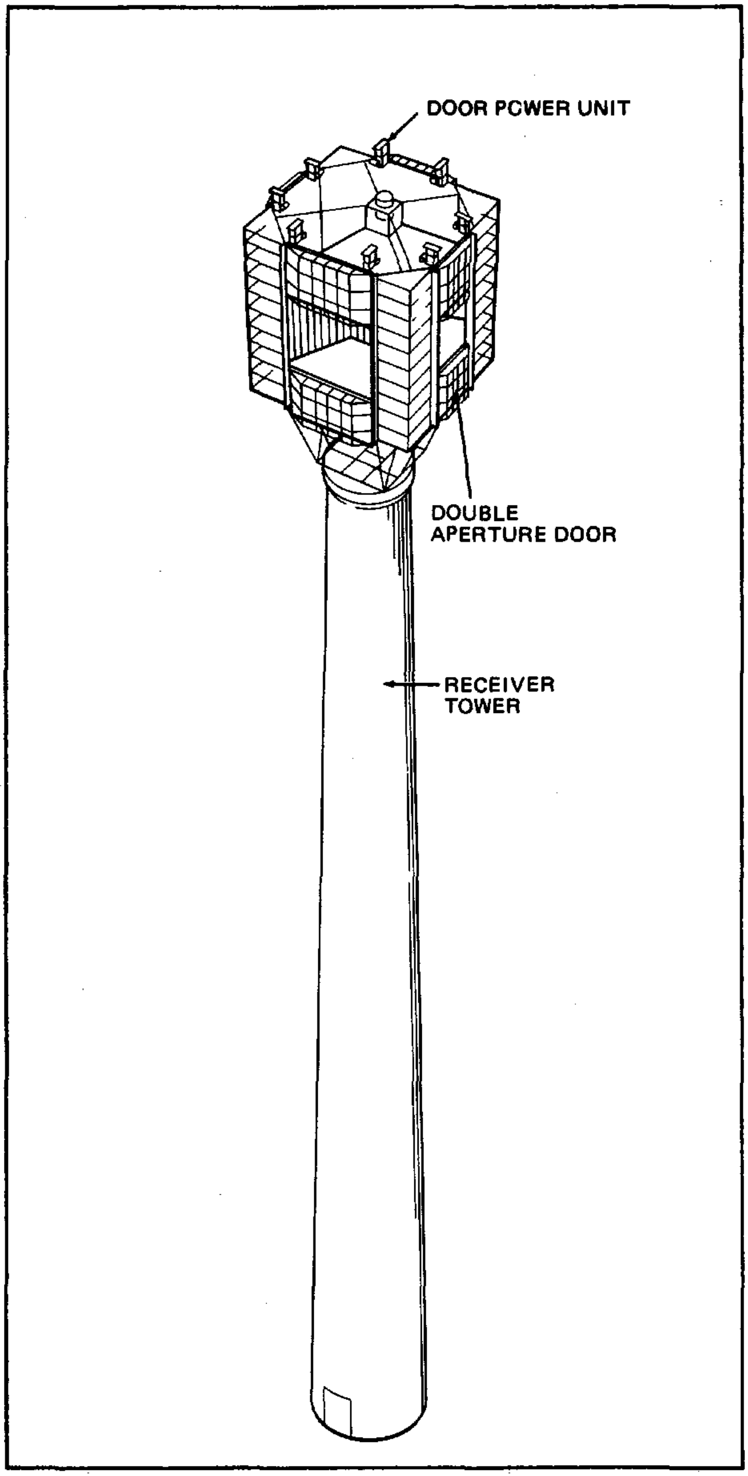

FIGURE 3 RECEIVER AND TOWER

Cavity Zones - The cavity zone arrangement is as shown in Figure 4. In the plan view shown, each of the four cavities is bounded by heat absorption panels, the aperture, and the casing which connects the panels to the aperture perimeter to form a sealed cavity. The heliostats beam the concentrated insolation through the square apertures to the heat absorption panels. Heat flux distribution on the panels is established by a distribution of aim points in the aperture plane. These aim points are located by groups of heliostats and thereby spread out the heat flux to optimize the use of the heat absorption panels.

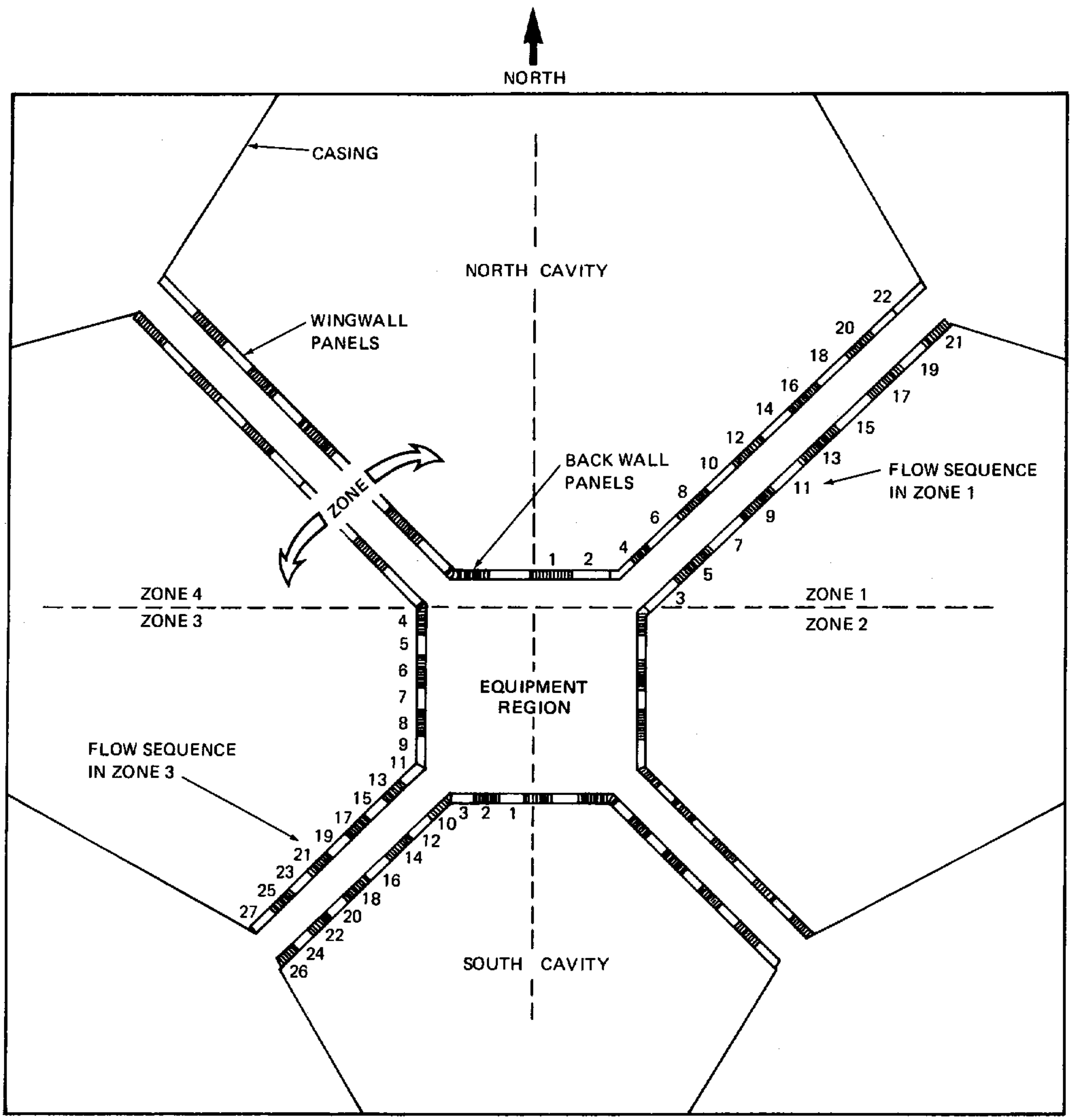

FIGURE 4 CAVITY ZONE ARRANGEMENT

The heat absorption panels are laid out in a 'X' shape to make maximum use of the heat transfer surface. A square area is left open near the center to accommodate structural supports, tanks, piping, and other equipment. The depth, height and width of the cavity were derived from earlier studies (Refs. 1, 2) and are based on considerations of optimal use of structural steel and thermal efficiency considerations.

There are four control zones in the receiver as defined by the dotted lines in Figure 4. Each zone operates as an independent flow circuit with cold salt entering each circuit at 550F (290C) and exiting at 1050F (565C). In each zone the flow passes from the back of the cavity to the outer corner. Typical flow paths are indicated where the individual heat absorption panels are numbered 1 through 22 in Zone 1 and 1 through 27 in Zone 3.

Basically, the cold salt is designed to enter at the center region where heat fluxes are high and flows to the outside where heat fluxes are lower. This flow arrangement prevents overheating in the regions where heat fluxes are high. The numbering of the panels also shows the path of the salt in crossing from one wing wall to the adjacent wing wall. This criss-crossing ensures the presence of cold salt in the high heat flux areas of both cavities and also helps to even out the effect of cloud transients which may effect one cavity more than the adjacent one.

Flow Circuit - The salt flow circuit is shown in Figure 5. Cold salt is pumped to the surge/buffer tank via the riser pipe by the main booster pumps located in the tower base. The surge buffer tank has a controlled salt level with an air cover gas to provide

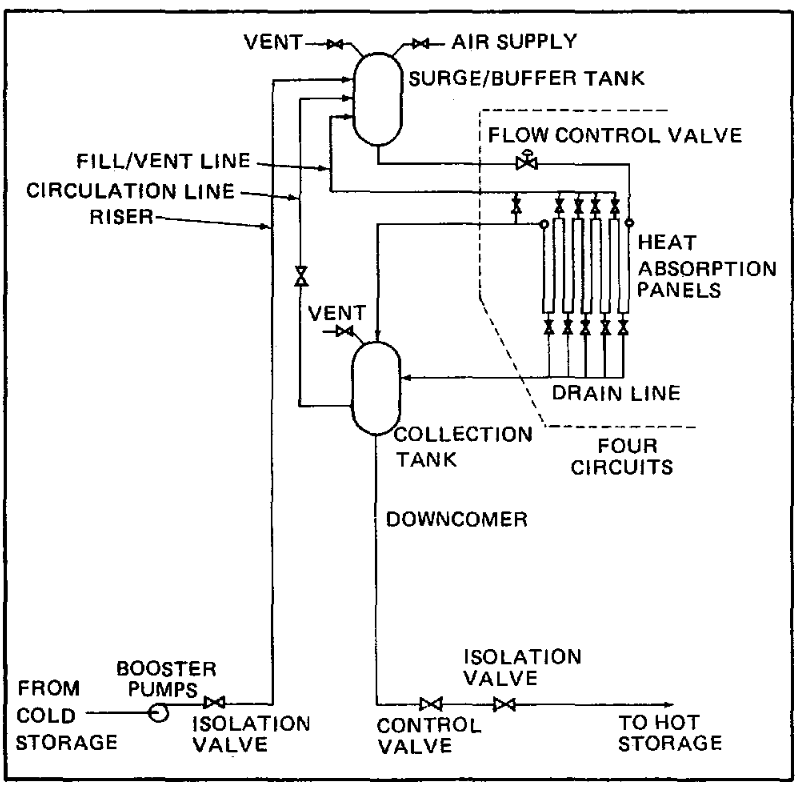

FIGURE 5 SALT PRESSURE BOUNDARY SCHEMATIC

isolation from pressure surges. From the surge/buffer tank the salt flows through the heat absorption panels to the collection tank. Within the heat absorption panels of each zone, the salt is heated from 550F (290C) to 1050F (565C). As indicated, the salt flows down in some panels and up in the adjacent panels. Each circuit or zone is controlled independently to maintain required flow rates and salt temperatures, and each flows into the collector tank where the salt streams are mixed. From the collection tank the salt flows down twin downcomer pipes to the hot storage tank located at ground level. The salt level in the collection tank is regulated by the control valves in the downcomer lines to ensure the required flow rate.

General Arrangement - The arrangement of components within the receiver is shown on the artists' sketch (Figure 6). The major features requiring amplification are the cavity layout, panel arrangement, wing wall features, central box region, tank locations, support structure, and doors. Table 3 gives general design data on the receiver subsystem.

TABLE 3 - GENERAL DESIGN DATA

Receiver Outer Dimensions	
Height	45.7 m (150 ft.)
Width E/W	32.3 m (106 ft.)
Depth N/S	32.0 m (105 ft.)
Total Receiver Wet Weight	2.36 X 10^6 Kg (2600 tons)
Tower Data	
Type	Reinforced Concrete
Height	155 m (508 ft.)
Base Dia.	24.4 m (80 ft.)
Top Dia.	18.3 m (60 ft.)
Number of Heat Absorption Panels	98
Active Panel Heat Absorption Area	2080 m^2 (22,400 $ft.^2$)
Receiver Thermal Efficiency	91%
Max. Incident Heat Flux on Panels	0.5 MW/m^2 (157,000 $Btu/Hr\text{-}Ft^2$)
Pressure Drop Through Receiver	2.8 MPa (400 psi)

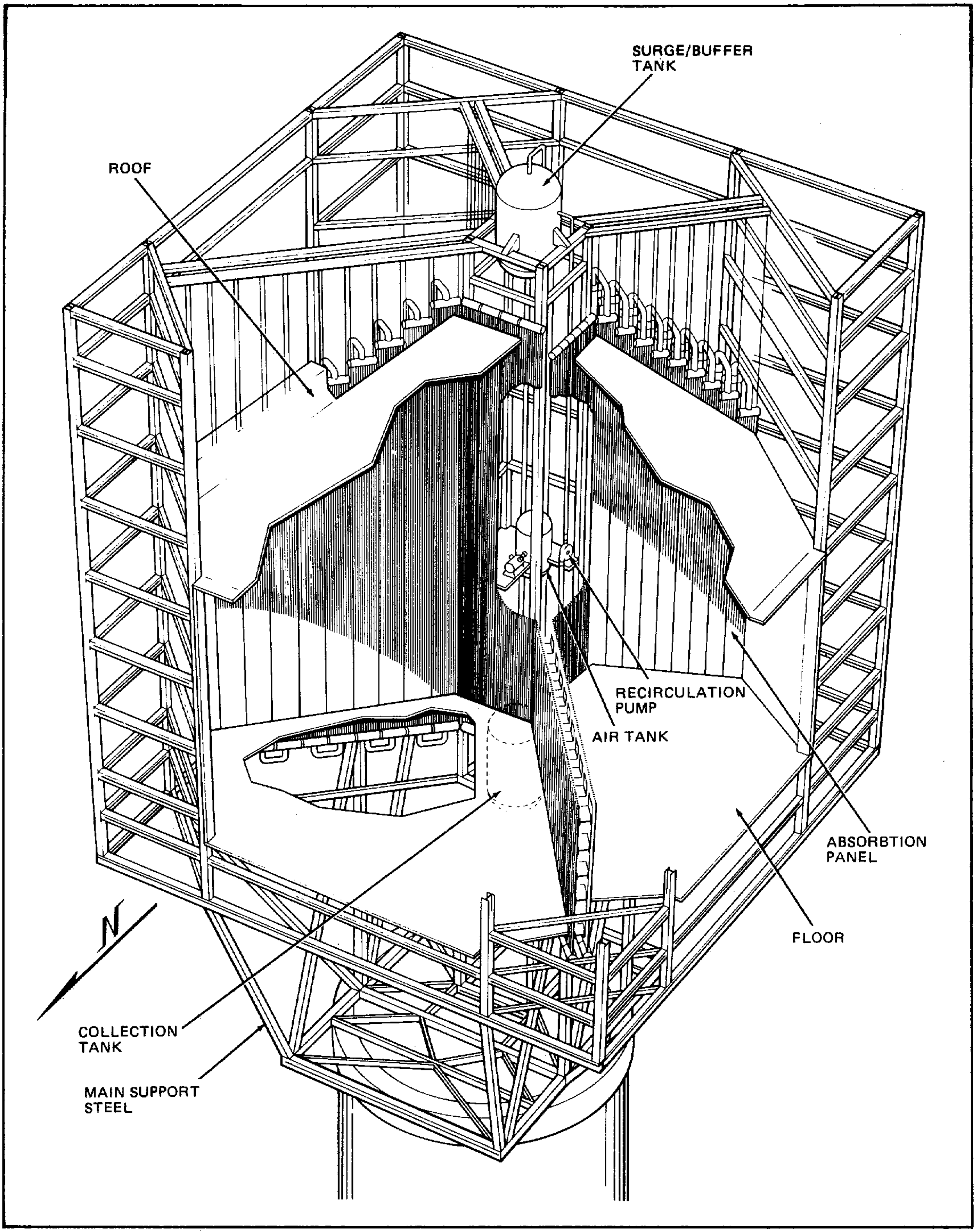

FIGURE 6 GENERAL ARRANGEMENT

As shown previously in Figure 4, each cavity is independently defined by several parts. Each cavity is bounded by panels, roof, floor, and casing which connects them to the aperture perimeter. Insulation is placed behind the panels, on top of the roof, under the floor, and behind the casing to insulate each cavity independently.

An insulated split door is located at each aperture and, when closed, is sealed at the junctures with the roof, floor, and casing to retain cavity heat. The split door enables one-half of the door to be used as a counter weight for the other half minimizing the power needed to operate the doors.

The panels are top supported by hangers from structural steel which runs directly above the line of each wing wall. The panels are supported by structural members and are allowed to expand in the horizontal and vertical downward directions. Those panels near the central box are the largest with decreasing panel lengths towards the outer corners of the receiver. Figure 7 shows the panels forming the double wing walls and highlights the panel insulation, steel supports, and interconnecting piping between walls.

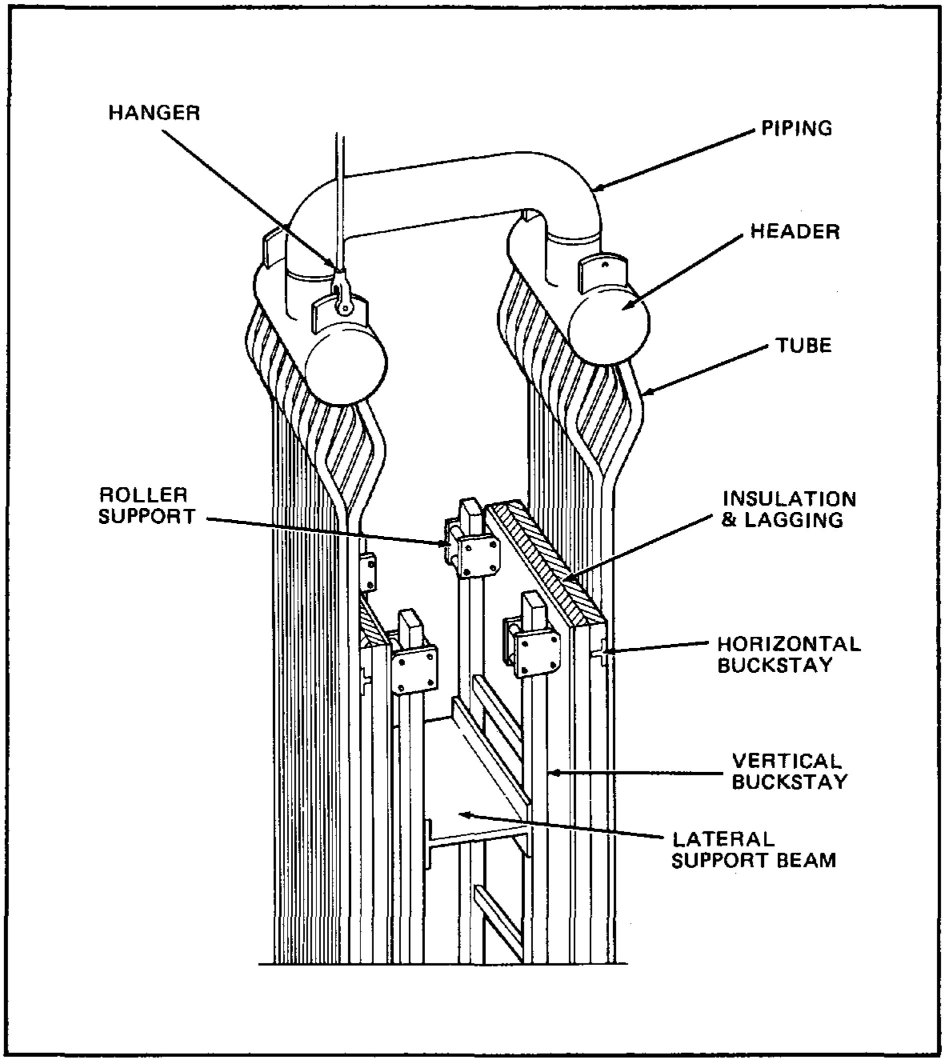

FIGURE 7 DOUBLE WING WALL

The central box region houses the surge/buffer tank at the top, the collection tank at the bottom, and, in between, the air tank to supply compressed air to the **surge/buffer** tank for emergency operation.

The receiver structure consists of standard wide-flange steel members arranged as a space truss that effectively surrounds each cavity and provides adequate support to the heat absorption panels, tanks, piping and other components. Loads on the receiver such as dead weight, seismic winds and others are transferred to a reinforced ring section at the top of the tower.

Heat Absorption Panels - The panels are comprised of a number of tubes welded together to form a membrane wall with a header at each end of the panel (Figure 8). Molten salt enters the header via a nozzle located at the center of the header, flows through the tubes and exits via a similar header at the opposite end. The tubes are 2" O.D. (50.8 mm) X 0.065 inch (1.65 mm) wall, made of Alloy 800H material. In the region of the panel where heat is absorbed, the tubes form a continuous membrane. A membrane wall was chosen to provide panel integrity, a light tight barrier and weathering protection for the insulation. Outside of the membrane wall region, the tubes are bent out of plane (safe ends) to provide flexibility to reduce stresses on the safe end to header weld connection. Panel materials are listed in Table 4.

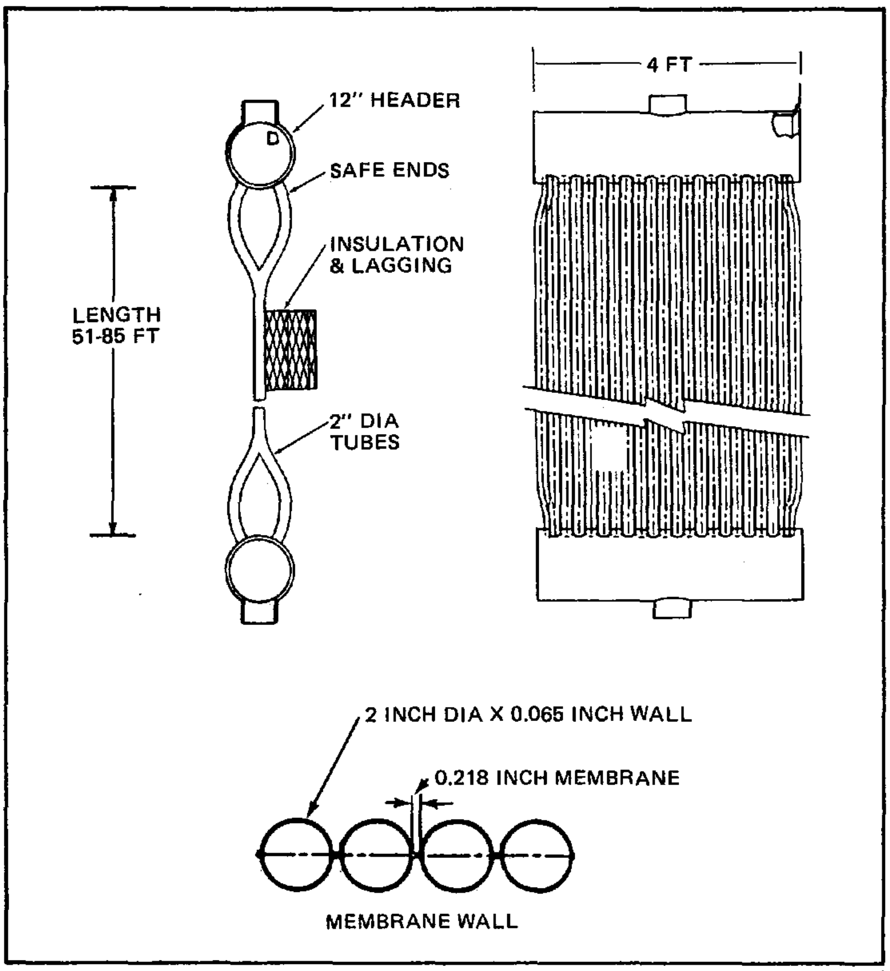

FIGURE 8 PANEL DESIGN

TABLE 4 - COMPONENT MATERIALS

Heat Absorption Panels	
Tubes	Alloy 800H
Safe Ends to Headers	304 SS
Headers	304 SS
Panel Buckstays (T)	304 SS
Vertical Buckstays	CS-SA 36
Piping	
Riser	CS-SA 106 GrC
Downcomer	304 SS
Panel Interconnecting Piping	304 SS
Tanks	
Surge/Buffer	CS-SA 515 Gr70
Collection	304 SS
Structural Steel	CS-SA 36
Panel Insulation	2" Med. Temp. Block 4" Int. Temp. Block 2" Kaowool K3000 (at gaps)

Panel sizes have been optimized for each zone. Because the south zones (2 and 3) have lower total energy input, the panel dimensions which best satisfy the energy requirements, heat flux inputs, and tube thermal stress requirements, are slightly different than those in the north zones (1 and 4). Table 5 shows the comparison of general dimensions of the panels.

TABLE 5 - ABSORPTION PANELS

	Zone 1 & 4	Zone 2 & 3
Number of Panels/Zone	22	27
Number of Tubes/Panel	22	15
Tube O.D. mm (in.)	50.8 (2.0)	50.8 (2.0)
Tube Wall Thickness mm (in.)	1.65 (0.065)	1.65 (0.065)
Length of Panel m (ft.) (Header to Header)	26.0 (85.4) max. 19.4 (63.5) min.	26.0 (85.4) max. 15.7 (51.6) min.
Width mm (in.)	1220 (48)	813 (32)
Panel Dry Wt. (Avg) - Kg (lb)	1450 (3200)	977 (2150)

The panels are designed to be shop fabricated and shipped as an assembly complete with headers, insulation, and structural supports (Figure 9). The tubes forming the panel are restrained by horizontal Tee buckstays which are welded to pads on the tubes. These Tee buckstays are welded to the roller supports which allow the panel to expand vertically downward when heated. The assembly is also designed to allow expansion in the plane of the panel face. Insulation is attached to the panel by impaling the blocks on studs welded to pads on the tubes. Lagging is located at the back of the insulation and held in place by studs attached to the panel. The panel with insulation and lagging is attached to a structural support truss at the factory, and the motion of the rollers checked out before shipping. In the field, the gaps between the panels are covered by insulation and lagging such that the cavity has a continuous insulation/lagging boundary thereby minimizing conduction and convection heat losses. Design codes applicable to the panel assembly are listed in Table 6.

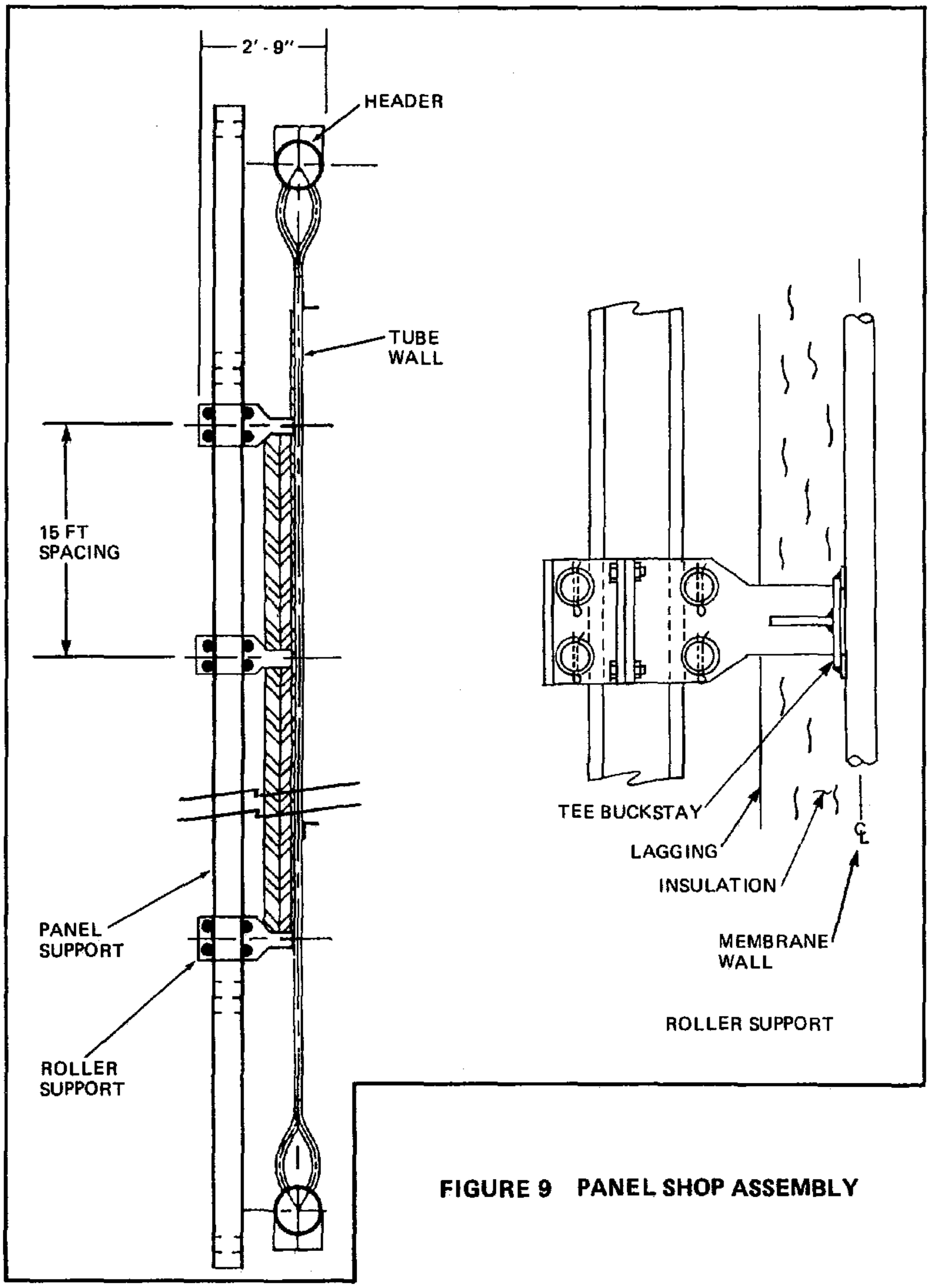

FIGURE 9 PANEL SHOP ASSEMBLY

TABLE 6 - CODES APPLICABLE TO PANELS

Tubes and Headers	Section I of the ASME Boiler and Pressure Vessel Code
	Power Piping Code, ANSI/ASME, B31.1
Remainder of Panel Assembly	Uniform Building Code
	American Institute of Steel Construction

Heat Fluxes - The panels have been designed to ensure successful operation for the life of the plant. Limits on heat fluxes were established based on thermal stress limits, creep-fatigue limits, and based on the maximum allowable metal temperature that will meet corrosion limits. Figure 10 shows the limits and the actual heat fluxes imposed on the panels in Zone 3. At the lower temperatures, the flux limit is established by maintaining thermal stresses in the elastic stress range. At the higher temperature the limit is established by maintaining the metal temperature at the inside of the tube under 1100F (593C). This temperature limit is based on the evaluation of corrosion data for alloy 800H in molten salt. The actual heat fluxes shown for the design point lie well below the limits in most regions thereby providing a healthy margin of safety. Detailed analysis of the panels has shown this margin to be necessary to accommodate uncertainties and the effects of skewed heating (fluxes not normal to the panel face). Based on detailed analysis and evaluation of the panel assembly, there is a high degree of confidence that the panels will perform successfully for the life of the plant.

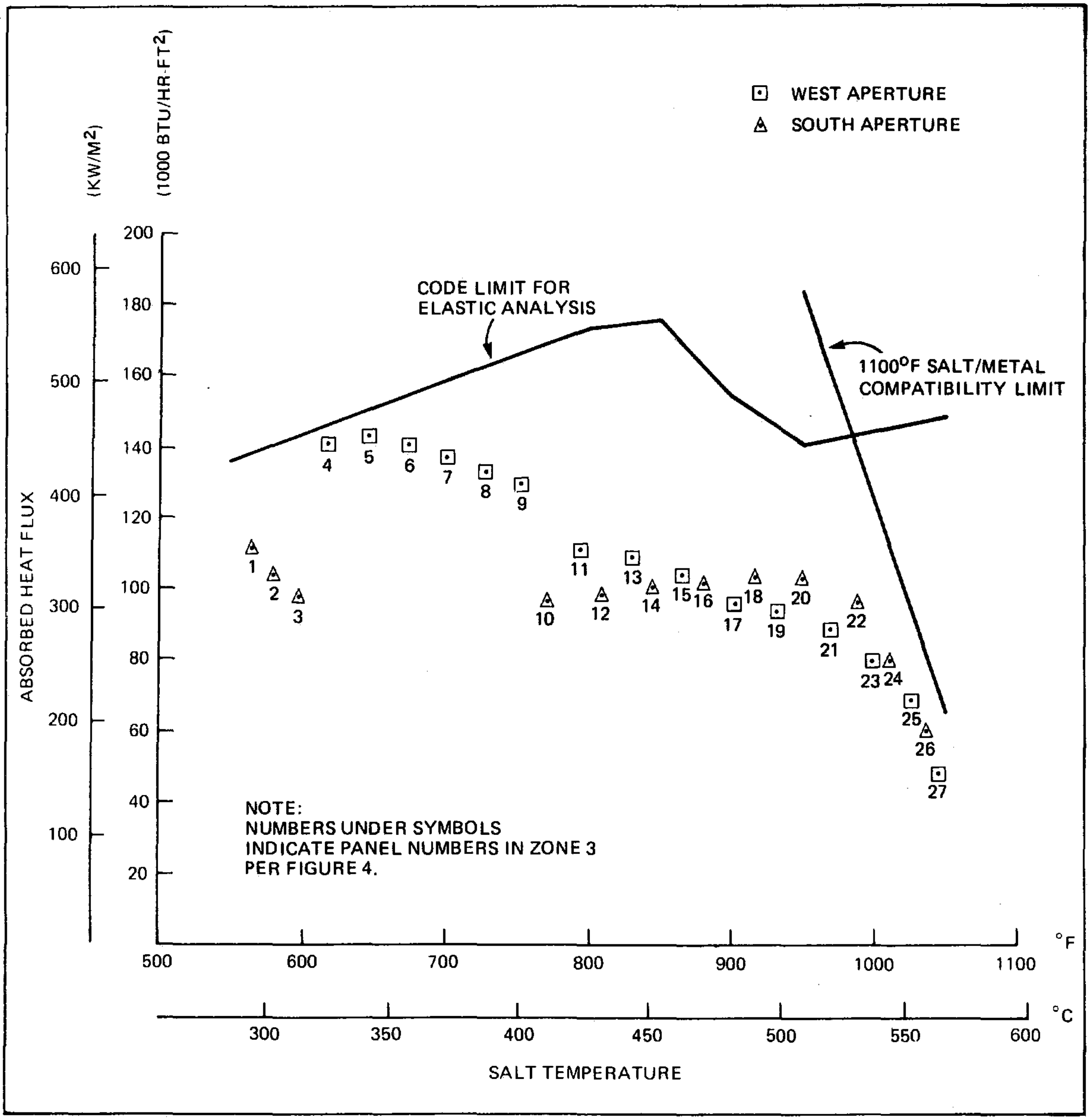

FIGURE 10 ZONE 3 PEAK FLUX AND LIMIT

Tanks - The major tanks in the system are the surge/buffer tank and the collection tank. The surge/buffer tank encloses an air space which dampens pump pressure surges. It also retains a salt inventory sufficient to buffer any difference that may exist under transient conditions between the salt needs for the panel and the flow supplied by the pumps.

The surge/buffer tank is sized to provide sufficient inventory to ensure continued flow in the panels during emergency conditions which may give rise to a loss of salt flow up the riser. A total flow, equivalent to two minutes of full flow, is available to cool the panels until the heliostat field can be de-focussed. To assure flow in the event of pump trips, the salt is forced through the panels by high pressure air from an air tank adjacent to the surge/buffer tank.

The collection tank is designed to collect flow from the four control zones. It also retains an inventory of hot salt to maintain temperature in the panels during overnight hold, in order to ensure quick start up in the morning. This is accomplished by pumping salt from the collection tank to the surge/buffer tank and back through the panels (Figure 5).

Piping - The major pipe sections are the riser and downcomer pipes and the panel interconnecting pipes. The 20 inch (508 mm) riser carries cold salt up the tower to the surge/buffer tank. Twin 14 inch (356 mm) downcomers carry the hot salt from the collection tank to the hot storage tank. Twin pipes are used for the downcomer to reduce the size of expansion bends within the concrete tower. The panels are connected by 10 inch (254 mm) diameter pipes. Materials for the cold pipes and tank are carbon steel; for the hot pipes and tank are 304 stainless steel. Table 4 gives a more detailed listing of the material selections.

Structural Steel - The structural steel provides support for the heat absorption panels, tanks, pipes, doors, maintenance platforms, elevator, and other miscellaneous items. It is designed to accommodate seismic loads, wind loads, platform loads, and dead loads, and transfer the loads to the concrete tower.

The main feature of the structure is a central support region which permits a large percentage of the receiver weight to be transferred directly to the concrete tower. Four triangular shaped corner regions support the remaining receiver weight and provide adequate stiffness to maintain lateral deflection within limits.

The five regions are interconnected by lateral supports which extend from the central box to the outer triangular regions. Loads on the wing wall panels are carried by these lateral supports, which run between the wing walls through to the five main support regions.

The structure was analyzed to ensure compliance with AISC, UBC, ANSI A58.1, and OSHA Codes. A finite element lumped mass dynamic analysis was performed on a model of the tower and receiver to assess the amplification of seismic effects at the receiver elevation. The results indicated that under the operational seismic load of 0.1g the load at the receiver would be 0.82g horizontal and 1.08g vertical.

A finite element analysis of the receiver structural steel was then performed with the seismic loads as inputs. In addition, the structure was analyzed for wind loads of 115 mph (55 psf) at the receiver elevation. Taking into account other dead loads and platform loads, the structural steel design was optimized for the loading conditions stated. Loading conditions and resultant steel weights are as indicated on Tables 7 and 8.

TABLE 7 - STRUCTURAL STEEL LOADS

Seismic	0.82 horizontal 1.08 vertical
Wind Load	1.44 KPa (30 psf) - ground 2.64 KPa (55 psf) - receiver
Platform Load	4.79 KPa (100 psf) with 407 M^2 (4370 ft^2) area.
Dead load	
Receiver Internals (wet)	
Panels & Buckstays	0.67×10^6 Kg (1.47×10^6 lbs)
Tanks	0.29×10^6 Kg (0.64×10^6 lbs)
Piping, Roof, Floor, Misc.	0.31×10^6 Kg (0.68×10^6 lbs)
Total Receiver Internals (wet)	1.26×10^6 Kg (2.79×10^6 lbs)
Doors/Frame/Mechanism	0.114×10^6 Kg (0.25×10^6 lbs)
Total Dead Load	1.38×10^6 Kg (3.04×10^6 lbs)

TABLE 8 - RECEIVER WEIGHT

Receiver Internals (wet)	1.26×10^6 Kg (2.79×10^6 lbs)
Doors	0.11×10^6 Kg (0.25×10^6 lbs)
Platforms	0.09×10^6 Kg (0.19×10^6 lbs)
Main Steel	0.91×10^6 Kg (1.99×10^6 lbs)
Total Dead Weight (wet)	2.37×10^6 Kg (5.22×10^6 lbs)

Doors - Each cavity has a two piece door over the aperture which can be closed during long hold periods to seal off the cavity and minimize heat losses to the environment. The door is divided horizontally with each half moving vertically up or down. Vertical motion of the door is preferred over horizontal motion because it exerts equal forces on the door tracks ensuring a more reliable operation. To save weight, the doors employ a space frame design fabricated from aluminum tubing. The inside surface of the doors is covered by 6 inches (15 mm) of insulation which in turn is covered by sheet steel to isolate the door structure from the cavity hot air.

Pumps - The main salt booster pumps, located at the base of the tower are two half capacity pumps each with a 2600 KW (3500 HP) variable speed motor.

Design Verification - Following the establishment of design requirements and design principles, the major features of the receiver were defined. To establish a design which meets requirements, thermal-hydraulic analysis was performed to optimize the heat transfer surfaces, cavity geometry etc., and Code type stress analysis was done. After the general features of the design were established, detailed analysis of the design was performed to verify performance, and to ensure that the entire receiver met the imposed thermal, deadweight, wind and seismic loads. A brief outline of the analysis performed is as follows:

- Thermal-hydraulic analysis was performed to verify performance, verify thermal efficiency, and provide boundary conditions for detailed stress analysis.
- ASME Code calculations for pressure boundary parts were completed.
- Thermal stresses in panels and panel/header junctions were analyzed to ensure the components met thermal stress limitations for steady state and transient conditions.
- Elevated temperature and fatigue analysis of critical areas in tubes was performed to ensure the panels met the lifetime operational requirements.
- Finite element analysis of steel structure and doors for wind and seismic effects was performed to minimize structural steel weight.
- Analysis of tower and receiver for seismic effects was performed to assess amplification at the receiver and achieve optimum design of tower and receiver.

Operation and Control - The operating procedures for the receiver subsystem are designed for safe, efficient collection of thermal energy. The plant control system supports these goals by providing automatic plant control, while also providing warnings and alarms for system failures. Operating procedures encompass two major divisions: normal operation and abnormal operation.

The control system sets the salt outlet temperatures within the system by modulating flow using control valves at the inlet to the heat absorption circuits. Control is accomplished with a quasi-feedforward algorithm using salt temperature measurements at the outlet of each panel to protect the system from cloud transient effects. Performance of the control system has been verified by computer simulation of the effect on the receiver subsystem of typical cloud transients.

Normal operations center around the diurnal cycle for the plant and are designed for maximum utilization of daylight hours for power collection. Important features of normal operation are:

- Automatic control to maintain salt outlet temperature within specified limits during varying load conditions and cloud transients.

- Automatic protection of the receiver panels from overheating which could occur following the passage of clouds across the collector field.

- Minimum of 25% full load flow rate at design salt outlet temperatures to ensure flow stability in all panels.

- Forced recirculation of salt within the tower with doors shut for hot standby and overnight hold.

- Gravity draining of salt for prolonged system shutdown.

Abnormal operations are the responses to a system failure of some type. Procedures for abnormal operation are designed to ensure safe operation with minimum impact on the system resulting from various failure modes. Important features of abnormal operation are:

- Emergency flow for a minimum of two minutes available from the surge/buffer tank supported by air pressure in the event of salt booster pump stoppage. This allows 2 minutes for the operation of emergency power systems to defocus the heliostats.

- Redundant instrumentation and voting circuits to assure reliable shutdown of the equipment during emergency events.

- Redundant flow control valves used in parallel, on panel circuits, to ensure flow in the panels in the event of valve blockage or inadvertent closure.

SRE DESIGN AND DEVELOPMENT PLAN

To support the development of a large scale commercial receiver subsystem, a Subsystem Research Experiment (SRE) was defined along with a complementary Development Plan identifying analytical studies and laboratory tests. Together the SRE and Development Plan will resolve uncertainties in the design and fabrication of the full size units, reduce design margins, simplify design features, and lead to lower cost units.

A two step SRE program is proposed. First, a 5 MW_t receiver is proposed for testing at the Central Receiver Test Facility in Albuquerque. Successful testing of the 5 MW_t unit will prove out some of the basic design features of the unit and develop acceptance of the design by the utilities. Second, a 30 MW_t receiver test is proposed at, as yet, an unidentified facility. The major advantage of the larger test unit is that it will test the full size panels. Since the panel and its support structure are generally considered to be the critical parts of the receiver component, testing under a wide variety of steady state and transient conditions would provide valuable data on performance, mechanical integrity, and the ability to accommodate thermal expansion. Test of a 30 MW_t size unit would greatly facilitate design extrapolation to larger sizes. The major benefits of a 30 MW_t test unit are listed as follows:

- Allows more accurate prediction of large commercial unit performance.
- Would prove out the control system applicable to the large units.
- Would demonstrate the integrity and reliability of door seals.
- Allows more accurate prediction of fabrication costs for the panels and the fabrication and erection costs of the structure.

The proposed Development Plan identifies analytical studies, and laboratory testing to support development of the commercial receivers. The development work is more in the nature of proof tests designed to lower the maintenance and capital costs of the components. No issues are identified which need resolution before building a large scale receiver. The major development areas are:

- Re-assessment of mechanical design limits on the heat absorption panels to determine if flux limitations can be increased with resulting reductions in receiver costs.
- Examination of innovative approaches to panel restraint to minimize complexity and reduce costs.
- Molten salt corrosion testing of alternate panel materials to ascertain the viability of lower cost materials.
- High flux insulating materials tests to examine the effects of accident conditions on the insulating materials.
- Salt properties verification tests.
- Reinforced concrete tower design studies to further examine the tower/receiver interface to minimize the number of parts and reduce costs.
- Dynamic response studies to optimize tower/receiver structure configuration.

PROCESS DEVELOPMENT

Conventional fabrication techniques were used wherever possible to fabricate the receiver subsystem. One area that required development was the tube to tube weld along the tube length to form the membrane wall. The concept of a membrane wall has been used for many years to fabricate boiler wall panels. For boilers, however, the membrane weld process is relatively straight forward. Since the panels are constructed with thick walled (0.140 inch - 3.6 mm), carbon steel tubes, a sub-arc weld process adequately produces the desired quality weld. Essentially this process is relatively straightforward since it does not demand close fit ups or a high degree of cleanliness to meet quality standards.

By contrast, the membrane weld process for the receiver panels is somewhat more difficult since it uses thin wall, Alloy 800H tubes (0.65 inch - 1.65 mm thick). The relatively thin walls require much more care than boiler tubes during the weld process to prevent burn through. Also, the weld process for Alloy 800 needs to be conducted with a higher degree of cleanliness than is necessary for carbon steel.

Two methods of producing the membrane wall panel were pursued. One, to use weld deposits along the entire tube length to form the membrane; the other to develop a drawn tube with an integral fin. The results of the two approaches are shown in Figures 11a and 11b.

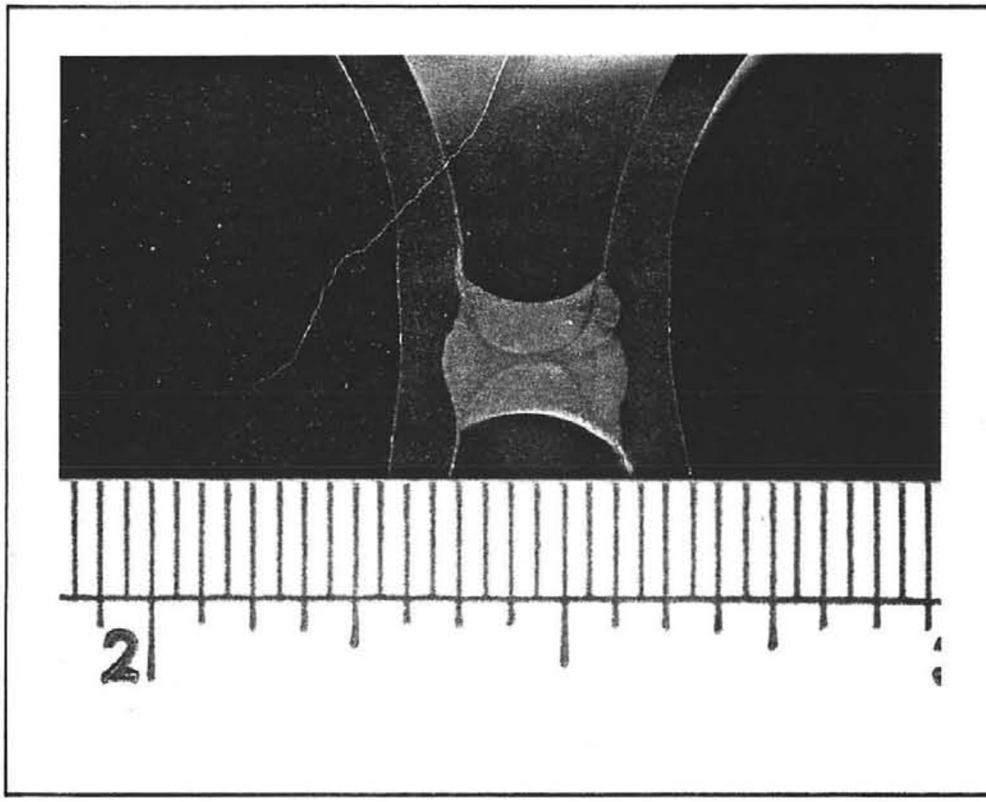

FIGURE 11a
TUBE TO TUBE MEMBRANE WELD

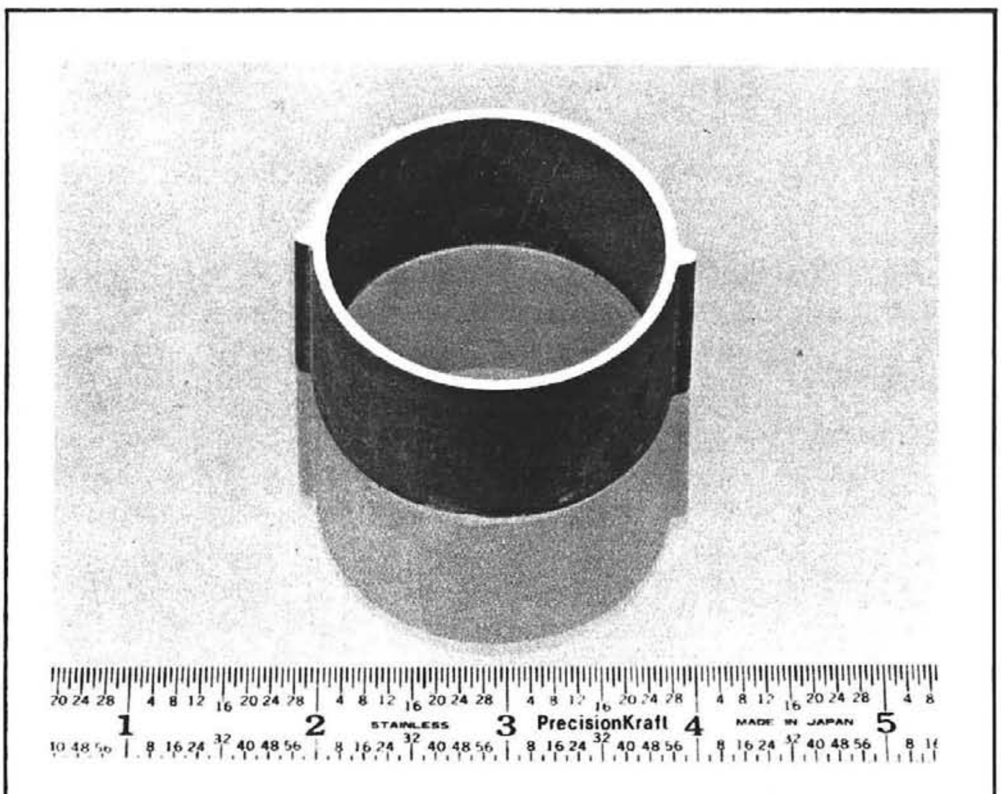

FIGURE 11b
DRAWN TUBE WITH INTEGRAL FIN

In the weld deposit method, two weld passes (one on top of the other) are laid on the tube outside at one location and another two weld passes are laid down on the outside diametrically opposite the first two. A MIG process was used with water cooling inside the tube to control the penetration depth of the weld and to control the weld contour. Tubes with these external fins can then be laid fin-to-fin and the fins welded together using a TIG process to form the membrane panel.

An alternate approach was to develop a cold drawn tube with an integral fin. Again, the fins were fused together using a TIG process to form the membrane panel. Both approaches resulted in welds with contours which blend in well with the tube profile offering very low stress concentration factors. Metallographic examination and tensile tests of mock ups verified the integrity of the attachments. Both approaches to the fabrication process are acceptable, however, based on the limited data at present, the weld deposit method appears to be the more economic approach.

To demonstrate the fabrication process used to assemble the membrane panel, the safe ends and connection to the header, a 10 foot (3.05 M) long mock up was fabricated. The mock up used 8 Alloy 800H tubes, with 304 stainless steel safe ends, and a 304 stainless steel header at one end (Figure 12). The attachment on the tubes was also demonstrated. The welds were inspected by visual and dye penetrant methods. The entire assembly was successfully hydrotested.

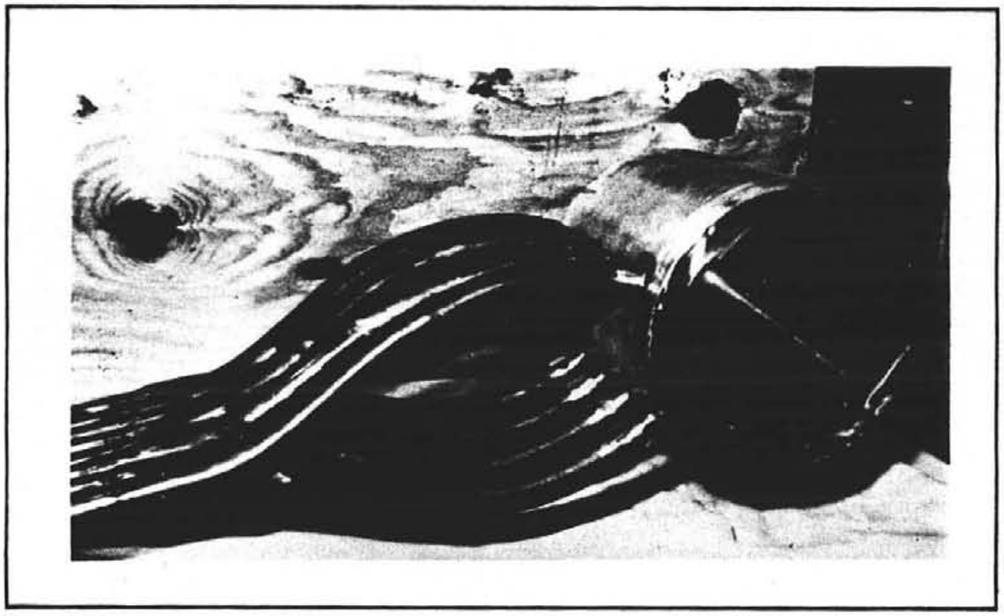

FIGURE 12

The completion of the 8 tube panel showed that the development of the basic fabrication processes, which are applicable to large size panels, have been successfully demonstrated. Remaining development efforts only need to concentrate on methods to utilize the same fabrication processes to produce large numbers of full size panels at low cost.

COST AND SCHEDULE ESTIMATE

Plans, schedules, and cost estimates were developed for shop fabrication and field erection of the full scale receiver subsystem. The proposed construction methods are based on conventional techniques and those developed as part of this contract. An integrated design, shop fabrication, and field erection schedule for the subsystem is shown in Figure 13. A cost estimate for this work is presented in Table 9. This estimate is based on standards data, actual cost data from previous contracts, vendor quotations, and catalog prices. Costs are expressed in current dollars (November 1982).

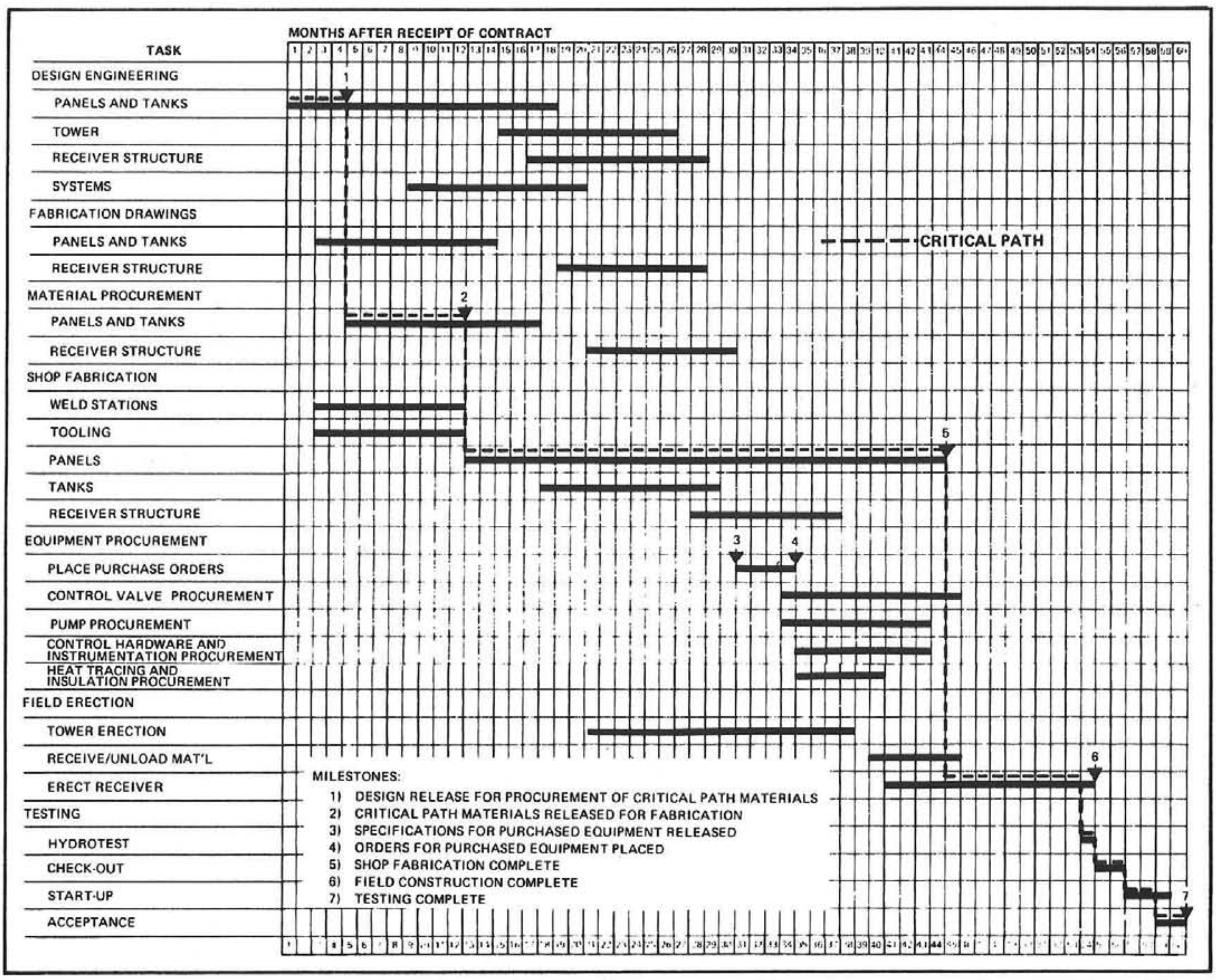

FIGURE 13 DESIGN, FABRICATION AND FIELD ERECTION SCHEDULE

TABLE 9 - COST ESTIMATE FOR RECEIVER SUBSYSTEM
(In Thousands of Dollars)

Receiver		
o Engineering	1,943	
o Fabrication		
Panels and Insulation	17,054	
Surge/buffer Tank	455	
Collection Tank	578	
Structural	5,415	
Procured Equipment[1]	4,824	
o Erection	23,752	
Subtotal		54,021
Tower		
o Foundation and Erection	3,932	
o Electrical Equipment[2]	2,247	
o Accessories[3]	985	
o Procured Equipment	3,898	
Subtotal		11,062
Systems		
o Engineering	625	
o Testing	709	
Subtotal		1,334
Indirect Costs[4] (15% on all Items Except Receiver and Systems Engineering)		9,577
TOTAL		72,994

NOTES:

1. Includes pumps, valves, piping, compressor, air tank, trace heating, door motor and mechanism, instrumentation, and controls.

2. Includes all electrical equipment except lighting, communications, and lighting protection.

3. Includes stairs, elevator, lighting, communications, lighting protection, ventilation equipment, and painting.

4. Indirect costs cover field costs, field engineering, procurement, and construction management.

REFERENCES

1. Conceptual Design of Advanced Central Receiver Power system, EG-77-C-03-1724, Martin Marietta Aerospace, Denver, CO, September, 1978.

2. "Saguaro Power Plant Solar Repowering Project," Final Report, Executive Summary and Vols. I, II, & III, DOE/SF10739-1, 2, 3, & 4, Arizona Public Service Company, Phoenix, AZ, July 1980.

3. "Advanced Conceptual Design for Solar Repowering of the Saguaro Power Plant," DOE/SF 11570 - 1, 2, & 3, Arizona Public Service Company, Phoenix, AZ, April, 1982.

CONCLUSION

The preliminary design effort has established that current technology will successfully support the design, fabrication, and operation of large scale solar thermal receivers. It is projected that a large receiver subsystem (320 MWt) can be operable 5 years after award of contract at a total cost of approximately $76M. It is recommended that research and development efforts be continued with emphasis on sub-scale component tests with the objective of a) proof testing critical components and demonstrating technical feasibility to potential users, and b) refining designs to lower capital and maintenance costs.

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