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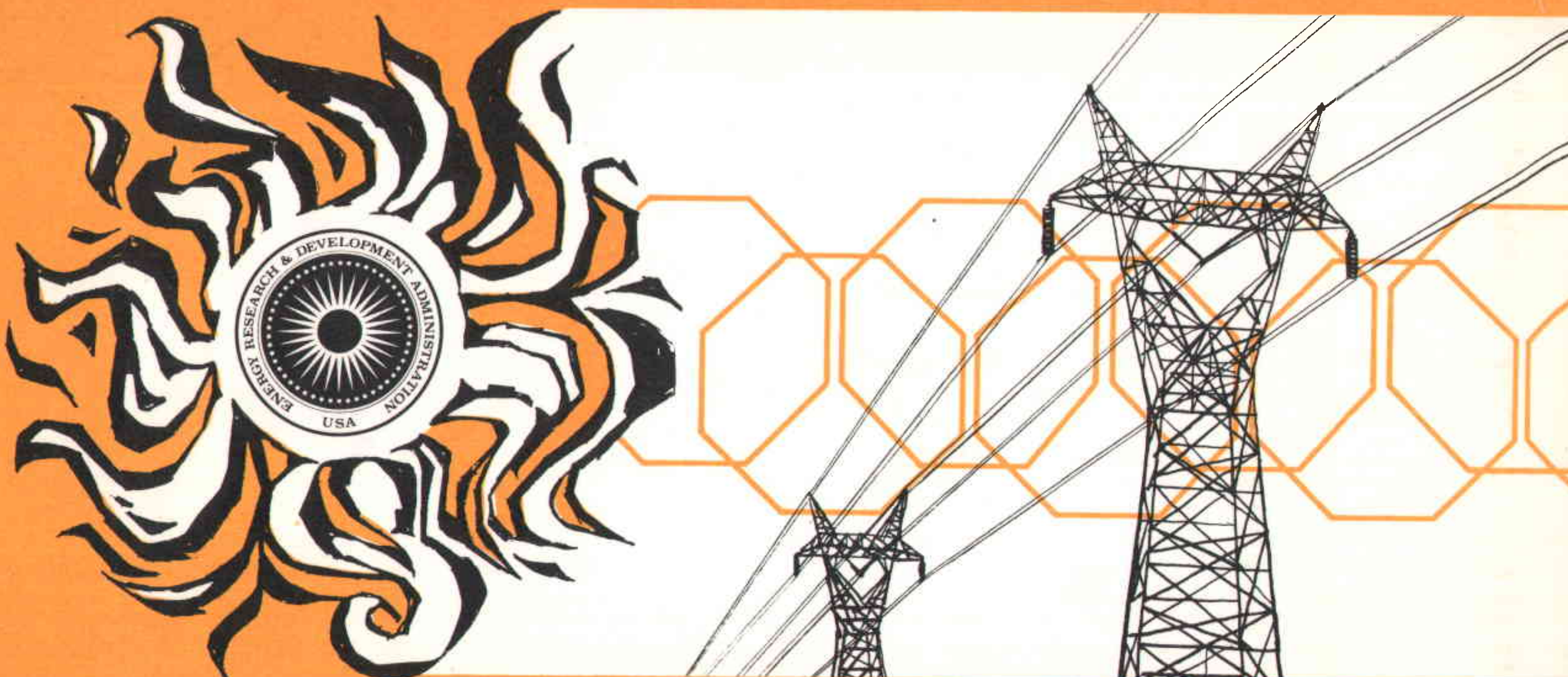

CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM, PHASE 1

CDRL ITEM 2
Pilot Plant
Preliminary Design Report
VOLUME IV
Receiver Subsystem

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY

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MDAC □ Rocketdyne □ Sheldahl □ Stearns-Roger □ University of Houston

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PREFACE

This report is submitted by the McDonnell Douglas Astronautics Company to the Department of Energy under Contract EY-76-C-03-1108 as the final documentation of CDRL Item 2. This Preliminary Design Report summarizes the analyses, design, test, production, planning, and cost efforts performed between 1 July 1975 and 1 May 1977. The report is submitted in seven volumes, as follows:

Volume I, Executive Overview

Volume II, System Description and System Analysis

Volume III, Book 1, Collector Subsystem

Book 2, Collector Subsystem

Volume IV, Receiver Subsystem

Volume V, Thermal Storage Subsystem

Volume VI, Electrical Power Generation/Master Control Subsystems and Balance of Plant

Volume VII, Book 1, Pilot Plant Cost and Commercial Plant Cost and Performance

Book 2, Pilot Plant Cost and Commercial Plant Cost and Performance

Specific efforts performed by the members of the MDAC team were as follows:

- McDonnell Douglas Astronautics Company
  Commercial System Summary
  System Integration
  Collector Subsystem Analysis and Design
  Thermal Storage Subsystem Integration

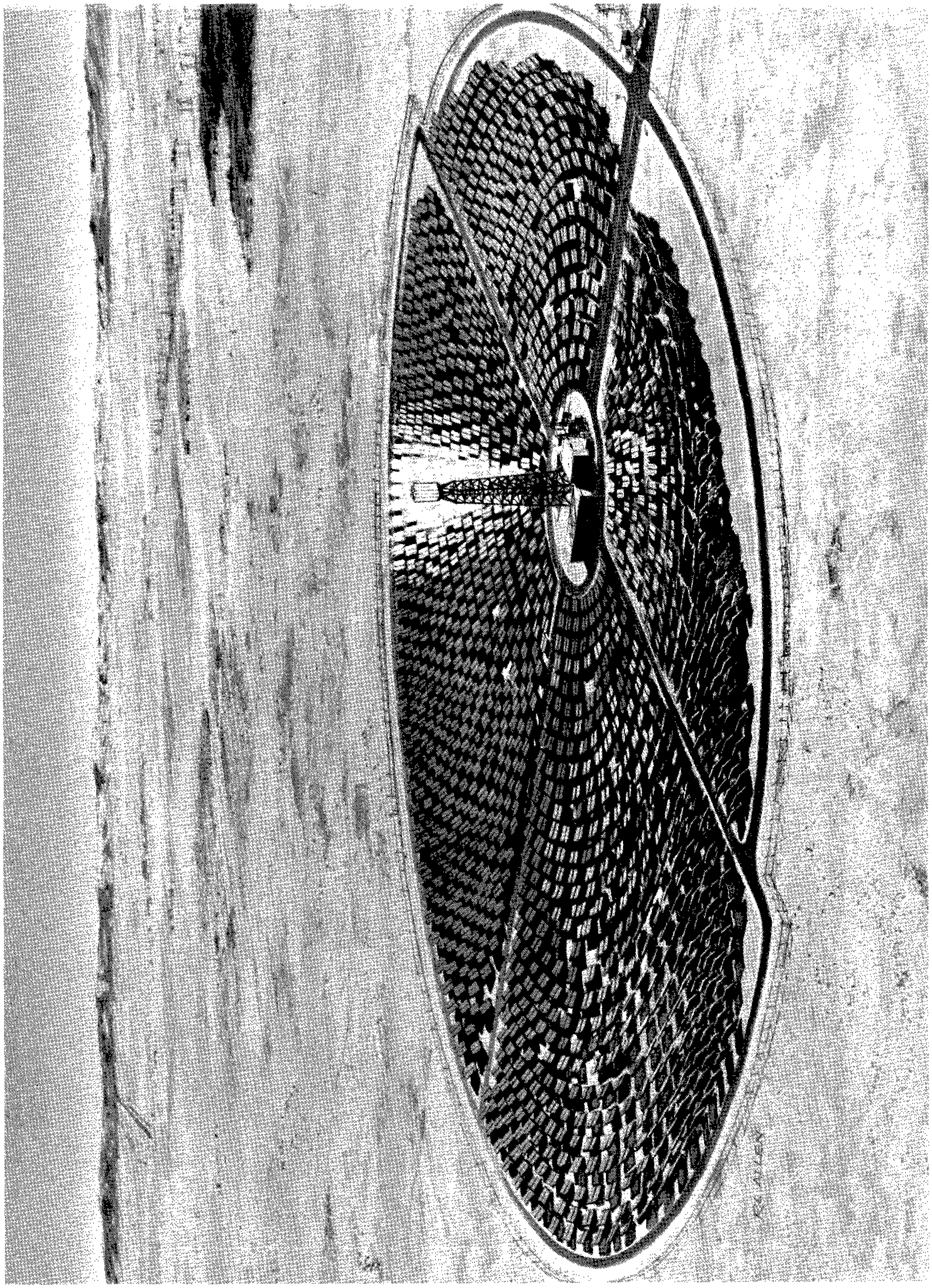
- Rocketdyne Division of Rockwell International
  Receiver Assembly Analysis and Design
  Thermal Storage Unit Analysis and Design

- Stearns-Roger, Inc.
  Tower and Riser/Downcomer Analysis and Design
  Electrical Power Generation Subsystem Analysis and Design

- University of Houston
  Collector Field Optimization

- Sheldahl, Inc.
  Heliostat Reflective Surface Development

- West Associates
  Utility Consultation on Pilot Plant and Commercial System Concepts



CONTENTS

1 INTRODUCTION AND SUMMARY

Section 1
INTRODUCTION AND SUMMARY

1.1 RECEIVER SUBSYSTEM

The function of the receiver subsystem in a central receiver solar powerplant is to absorb the solar radiation reflected from the collector subsystem and convert that energy into superheated steam for delivery to either the turbine of the electrical power generation subsystem or to the thermal storage subsystem (TSS). The receiver subsystem consists of the receiver unit, the tower on which the receiver unit is mounted above the collector field, and the supporting control and instrumentation equipment.

This Volume, IV, describes the conception, design, and testing of the receiver subsystem proposed by the McDonnell Douglas/Rocketdyne Receiver team for the Department of Energy's Pilot and Commercial central receiver solar power plants.

The McDonnell Douglas/Rocketdyne design team has selected the receiver concept which will best satisfy the Department of Energy solar central receiver program objectives of achieving the lowest Commercial Plant initial and operational costs. In summary, the proposed external multipanel concept provides:

- Lowest Commercial Plant cost.
- Identical modular panel assemblies to permit:
  - Low-cost assembly line fabrication.
  - Ease of transport, handling, and installation.
  - Developmental flexibility and adaptability to optimum system requirements.
  - Rapid maintenance.
- Rapid thermal response.
- Minimal seismic sensitivity:
  - Low weight.
  - Shorter tower.

- Low technical risk:
  - Pilot Plant scale demonstrated in subsystem research experiments (SRE).
  - High-capability materials.
- High tolerance to emergency conditions.
- A single receiver and tower with growth capability beyond 100 MWe.
- Minimum impact on other subsystems:
  - Reduced heliostat aiming accuracy requirement.
  - Optimum collector field shape.

1.2 RECEIVER CONCEPT RATIONALE

Conceiving the design of equipment which will pioneer a new field of energy technology is a unique and historically significant undertaking. Even though there is little or no prior experience to guide the conceptual process, the success or failure of the initial solar power plant receiver will not only influence the succeeding generations of design, but could significantly affect the pace of development of solar energy. In view of this responsibility, it is critically important that all of the significant concept selection criteria for the solar receiver be rigorously defined and carefully evaluated.

Clearly, the primary criterion by which the solar power plant designs must be judged is the cost of the electrical power produced. The receiver concept selected must be consistent with the Department of Energy's solar central receiver program objective to develop the solar Commercial Plant with the lowest investment and operational costs. The primacy of cost as a criterion is dictated not only in order for solar power to be competitive with alternate energy sources but also to make maximum use of available research and development funds.

The selection of cost as the foremost receiver design selection criterion automatically establishes many of the remaining criteria and their relative importance. For example, even though it is always extremely tempting for the engineer to provide the maximum possible performance in his design, when cost is the overriding consideration he is obligated to produce a design which provides cost-effective, but not necessarily maximum, performance. Similarly, the engineer is obligated to evaluate his design from the broader prospective of total system effects and not from individual subsystem performance alone. Not only will the capability of a design which exceeds requirements be wasted but to achieve its high performance it may impose unwarranted and costly requirements on other plant subsystems.

Similarly, a cost-effective design must necessarily be as simple as possible to manufacture, assemble, operate, and maintain. Ease of manufacture, handling, transport, assembly, and maintenance tends toward a modular design concept; however, simplicity of operation and the economies of material and parts count inherent in larger scale assemblies dictate that modular design be permitted only where there are clear cost advantages.

To minimize development time and therefore costs, the selected solar receiver design should provide a high probability of technical success. In a new technology development program such as solar power, the probability of success is directly related to the flexibility of the selected design to adapt to the unexpected. Not only should the design be easily modifiable to be compatible with the optimum system which will be defined during the development program, but it should also be reasonably insensitive to off-nominal conditions which may occur during development.

Finally, the receiver design selected must be compatible with the unique central receiver solar environment. The receiver must have high thermal response in keeping with the transient nature of insolation both due to the diurnal cycle and clouds. It must be capable of extracting in useful form the maximum amount of annual thermal energy under these transient conditions without damage to itself or associated subsystems. Since the central receiver concept locates the receiver on a tower several hundred feet above the collector field, the receiver must be designed to minimize the tower and receiver unit structural weights and associated costs required to resist seismic loads.

The McDonnell Douglas/Rocketdyne team has conceived, designed, fabricated, and test-proven the solar receiver design which best satisfies the specified solar Pilot and Commercial Plant criteria. An artist's view of the selected receiver concept is shown in Figure 1-1. The receiver subsystem includes

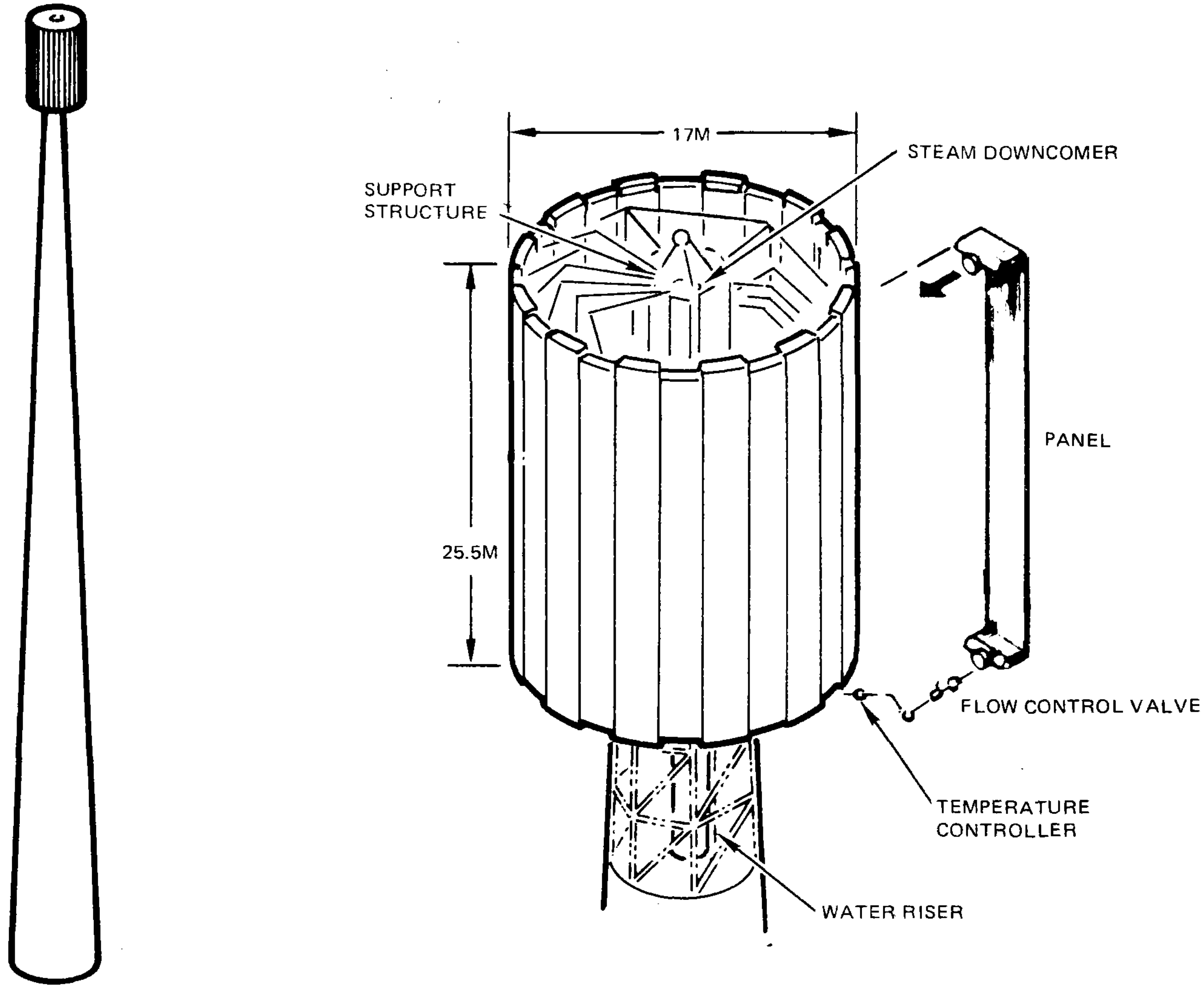


Figure 1-1. Commercial Plant Receiver

the receiver unit, the tower on which it is mounted above the heliostat mirror field, and the supporting control and instrumentation equipment.

The receiver unit comprises a number of structurally similar single pass to superheat panels. Each panel is constructed ot multiple tubes of Incoloy 800. The material properties of Incoloy 800 include high-strength, high-ductility, and corrosion-resistance. The tubes are laid side by side and joined by full-length longitudinal seam welds. This construction provides thermal and structural unity and makes the receiver "light tight."

In keeping with the "low technical risk" concept selection criterion previously specified, the welded multitube boiler panel concept had been tested during a Department of Energy R&D program accomplished prior to the present Pilot Plant preliminary design effort and demonstrated to be a valid design at flux levels approximately three times greater than the maximum anticipated for the Pilot Plant receiver. Moreover, although testing to date has indicated that tubing material less expensive than Incoloy 800 could be used to fabricate the receiver, the added safety margin and development flexibility provided by its superior material characteristics, and successful history in conventional boilers and superheaters, more than justifies its use for the first solar power plant. As an example of the forgiveness provided by the welded multitube configuration using Incoloy 800, if a tube were to become totally blocked at maximum incident flux conditions, conduction to adjacent tubes will be adequate to prevent panel damage during continued operation. Calculations show that even if water flow to the Pilot Plant receiver unit were to be totally lost during maximum power operation, the receiver could tolerate maximum solar insolation without damage for a period many times that required to slew the heliostats away from the receiver.

Technical risk was further reduced with the modular panel concept by permitting the receiver subsystem research experiments of the present contract to be carried out with Pilot Plant scale test articles. These experiments permitted early validation of the design, construction, and testing of actual Pilot Plant hardware and eliminated the dangers inherent in scaling from SRE test hardware and results. Although scaling will eventually be required to move from Pilot Plant to Commercial Plant power levels, the scaling risk will be minimal since the multitube boiler panel concept has been demonstrated by test to be compatible with flux levels greater than expected in the Commercial Plant. The additional output power required for the Commercial Plant receiver will be achieved by maintaining the Pilot Plant tube diameter essentially constant and increasing the length, number of panel tubes, and the fluid mass velocity.

The simple, welded, straight-tube panel design concept permits the use of easier and more economical assembly line techniques to fabricate the identical panel modules. The lightweight modular panels may also be easily transported and easily handled during the hoisting and installation of the receiver onto the tower. The modular panel concept also provides a receiver with a unique maintenance capability in that a panel could be removed from the tower and replaced within 12 hr if necessary to minimize system downtime.

The tubular panels are mounted firmly to the receiver unit support structure at the top end. Sliding clips and mating channels maintain panel shape under high thermal power loads while permitting unrestrained lateral and downward thermal expansion to prevent thermal stress buildup.

Water is introduced into the receiver unit through a series/parallel arrangement of several panels which function as preheaters. Subcooled water leaves the preheater panels, enters the water manifold at the lower end of the boiler panels, and flows vertically upward through the tubes absorbing heat from the incident solar radiation and leaving the upper end of the boiler panels as superheated steam (Figure 1-2).

Performance of the receiver is enhanced by the use of Pyromark, a highly absorptive paint which is applied to the external surface of the tubing.

The desired superheat condition of the discharging steam is controlled by a valve at the inlet to each of the boiler panels which adjusts water flow as required to maintain the desired outlet temperature. With this arrangement, active control of water flow through the preheater panels is not required.

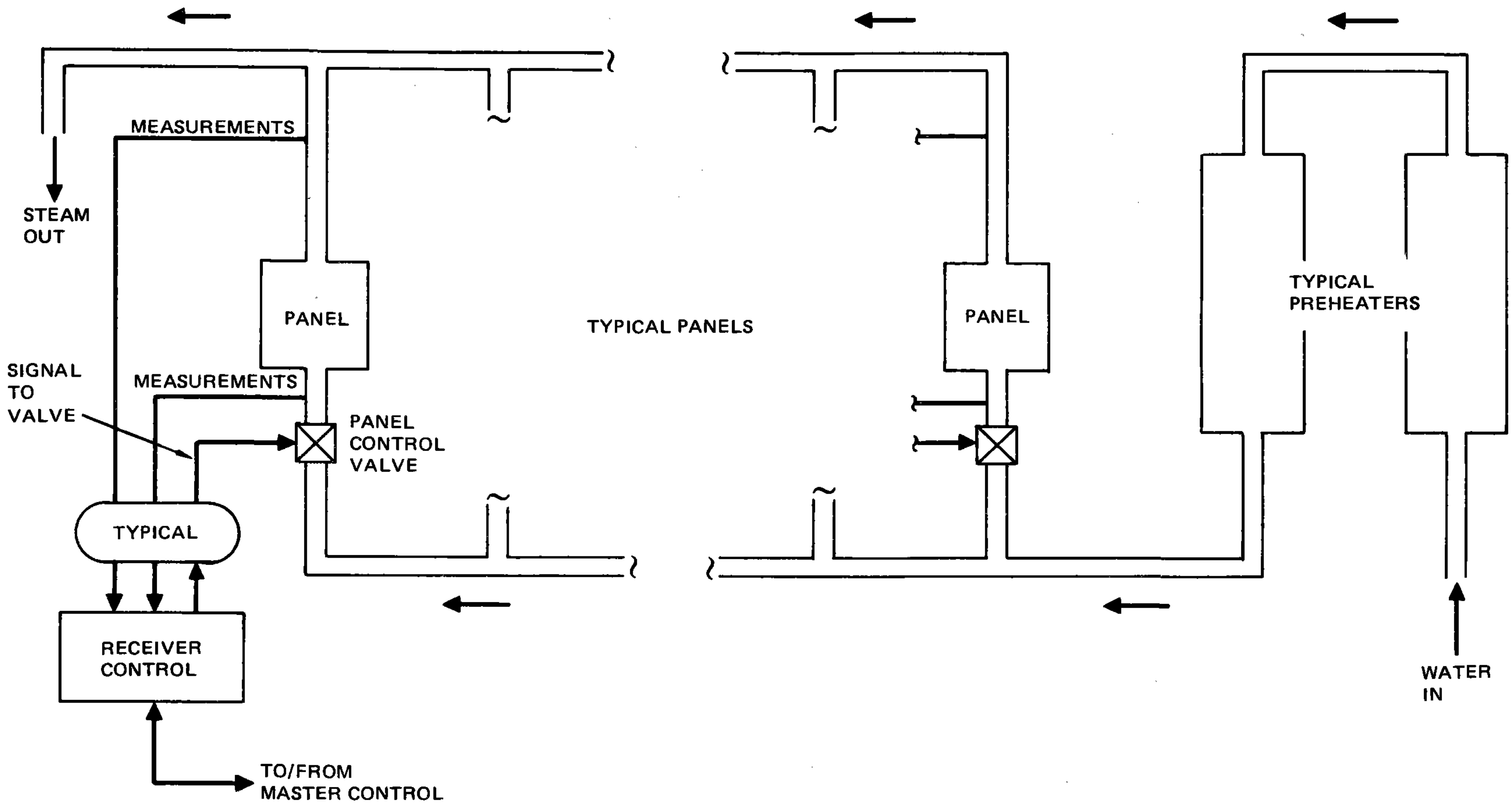


Figure 1-2. Receiver Control Schematic

The single pass to superheat tubular panel concept provides a receiver with the lightest possible weight and thus the highest thermal response of any available boiler type. This is consistent with the highly transient nature of insolation and the seismic sensitivity of a tower-mounted central receiver. The question of water carryover, or wet steam, which is sometimes considered to be the price that a single-pass boiler pays for its fast response, has been carefully considered as a potential problem and specifically addressed in the design concept. Although the multitube and discharge accumulator manifold construction of the individual boiler panels inherently tends to break up "slug" flow within the panels, steam flow from each panel is also passed through a cyclone (centrifugal) type water separator before entry into the receiver downcomer steam header. The modular panel concept further reduces the possibility of wet steam by the division of the total water flow into a large number of individually regulated flows. This concept also provides more precise control of steam outlet conditions by forced mixing of the multiple-panel discharges in the downcomer steam manifold. A root-sum-square averaging effect is produced that permits a wide variation in individual panel performance without exceeding overall receiver steam outlet requirements. A series of water quality sensors have been included in the receiver design to monitor steam quality. If necessary, receiver outlet flow will be diverted into a startup flash tank system to prevent wet steam flow to the turbine. SRE testing has indicated no tendency of the multitube boiler panel design to produce wet steam after startup even under highly transient conditions of flow, insolation, or pressure. Therefore, it is anticipated that the Pilot Plant test program will demonstrate that a redundant approach to wet steam protection will not be necessary in the Commercial system design.

Conceiving the solar receiver as a combination of modular panel assemblies provides freedom to size and subsequently arranges the panels into any geometric shape required by system analyses for optimum central receiver performance. Receiver geometry does not dictate the collector field shape, heliostat shape or pointing accuracy requirements, but is determined by the optimum combination of subsystem elements that produce the lowest system cost.

Systems analyses indicate that collector field performance per unit area of mirror tends to be generally greater for heliostats located on the north side of a receiver. Limiting the collector field to the north side of the tower, however, causes several detrimental cost effects. When consideration is given to mirror area required for the 100-MWe Commercial Plant, it is apparent that atmospheric attenuation, and the cost and seismic sensitivity of a receiver tower high enough for a reasonable look angle from the most distant heliostat, will prohibit the placing of all heliostats on the north side of a single receiver.

One solution to the problem is to reduce north field dimensions to the point where atmospheric attenuation and tower height become reasonable and use a multiple of the resulting field modules to achieve the required Commercial Plant output. The use of multiple modular field units, each with its own receiver and tower, not only sacrifices the cost benefits inherent in the fewest possible number of larger-scale units, but also incurs the additional cost, thermal losses, pressure drop, and operational complexity of the extensive piping network required to connect the widely separated receivers to the power station. Preliminary calculations indicate that a Commercial Plant made up of 10 modular field and receiver units would cost approximately 20% more than a single larger field and receiver with a thermal efficiency comparable to one of the modular units. Stated another way, the thermal efficiency of each of the 10 modular units would have to be approximately 20% greater than that of the single larger unit in order to compensate for the additional hidden costs inherent in the distributed collector field concept.

The simplest and most direct approach to the Commercial Plant is to design a single receiver which reduces the distance to the outermost heliostats, and the associated atmospheric attenuation and tower height, by distributing the heliostats in an optimum pattern 360° around the receiver. Energy collection and transmission to the power station is accomplished predominantly by optical means, thereby avoiding the cost and complexity of an extensive steam and water piping network.

Following the dictates of the foregoing analyses, the selected receiver design concept for both the Pilot and Commercial Plants mounts individual tubular panel assemblies on a central core support structure to form a single, large, multisided cylinder atop the tower. The heliostats surrounding the receiver direct their collected insolation onto the external surface of the cyclindrical receiver. By designing the receiver to accept insolation over the total external surface of the cylindrical receiver, the aiming accuracy and focusing requirements imposed on the heliostat and its drive mechanisms are minimized and heliostat costs are reduced. Moreover, the external receiver is relatively insensitive to damage from heliostat aiming inaccuracies since uncooled structure adjacent to the insolation target area is minimized. No structure is crossed by the heliostat beams when being slewed onto or away from the receiver.

Because of the exposed nature of the heat-absorptive surfaces of an external receiver unit, it must necessarily experience somewhat greater thermal losses than a more enclosed concept. This difference in thermal losses, however, will be more pronounced in Pilot Plant scale receivers where the flux levels are purposely held down to minimize the technical risk of the first solar plant. Since the thermal efficiency of an external receiver increases as the incident energy flux level increases, the thermal efficiencies become competitive at the higher Commercial Plant flux levels; therefore, the choice between the two concepts must consider other overall system related issues. For example, as noted earlier in the discussion of optimum collector field shape, although a north field receiver superficially appeared to be the most efficient design at the Pilot Plant scale, when the concept was applied to the Commercial scale, the complex piping network required to join the modular fields resulted in a cost penalty equivalent to a 20% loss in receiver unit efficiency.

Thermal responsiveness must also be considered as a measure of receiver thermal efficiency. Clearly, a lower thermal efficiency receiver concept which starts up faster each day, recovers more quickly from insolation transients, scavenges the maximum heat from low quality insolation, and thereby produces the maximum energy output per year per dollar, is superior to a less responsive receiver with a higher thermal efficiency.

Finally, it should be noted that the geometric flexibility and lightweight inherent in the multipanel external receiver concept provide design freedom during Pilot Plant development to investigate the cost-effectiveness of various means of improving thermal efficiency such as the shrouded receiver concept indicated in Figure 1-3.

1.3 VOLUME OVERVIEW

1.3.1 Section 2, Receiver Data List

Section 2 summarizes and compares the principal design and operating characteristics of the Commercial and Pilot Plant receiver subsystems and the subsystem research experiments test articles. Physical data such as weights, dimensions, and materials compositions are provided. Receiver working stresses are also listed. Operational flow rates and velocities and operating pressures and temperatures are presented along with pressure drop and heat-transfer correlations. Heat flux values are provided along with tabulations of total incident and absorbed power of the receiver under various operational modes. Receiver thermal efficiencies are tabulated as well as the net annual power production of the receivers.

Summary design discussions are also given in Section 2, along with directions to other paragraphs in Volume IV where further details concerning the particular subject are available if desired. The analysis of thermal losses for the SRE, Pilot, and Commercial Plants is described. Sensitivity of the receiver designs to cloud disturbances and other flux mal-distributions is discussed. Hydraulic stability analyses are discussed in terms of SRE results.

The resistance of the Pilot and Commercial receiver designs to seismic disturbances is discussed along with the substantiating analyses.

Startup procedures and other normal operating modes and time lines are presented with definition of the limiting factors in each mode.

Section 4 provides a more detailed summary of the Pilot Plant receiver subsystem design and should be referred to if further amplification is desired.

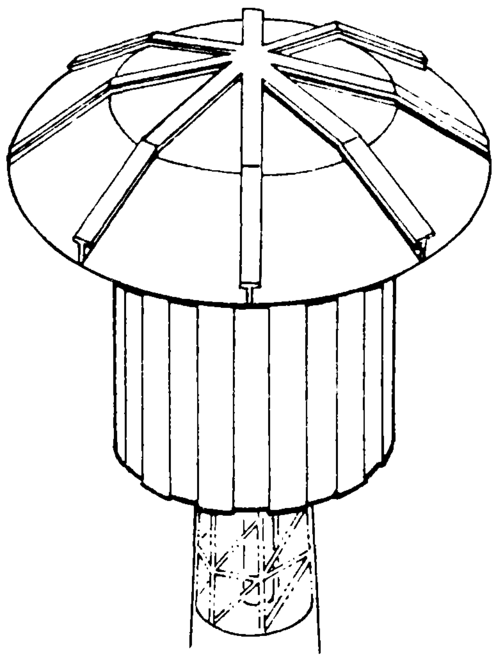


Figure 1-3. Shrouded Receiver Concept

1.3.2 Section 3, Commercial Receiver Subsystem Definition

Section 3 describes the analyses and design of the Commercial receiver subsystem for the 100-MWe Commercial Plant and the plans for its fabrication, installation, and operation.

The Commercial receiver design concept was selected to satisfy the Department of Energy solar central receiver program objective to achieve the lowest plant investment and operational costs. The design philosophy and/or rationale which directed the design selection process has been presented in detail in Section 1.2.

The mission of the Commercial receiver subsystem is to efficiently transfer the energy from the concentrated solar radiation reflected from the mirrors of the collector subsystem into the water supplied by the electrical power-generation subsystem to produce steam for delivery at precisely controlled superheat conditions to the plant turbine generator and/or the thermal storage subsystem.

Nominally, the Commercial receiver will be required to accept water from the flow distribution system at 15.5 MPa (2250 psia) and 234^{o}C (454^{o}F) and deliver superheated steam at rated conditions of 11.1 MPa (1,615 psia) and 516^{o}C (960^{o}F) to the electrical generation subsystem. Any rated steam generated in excess of turbine power requirements will be diverted to the TSS.

The receiver subystem must also be capable of accepting feedwater at 15.5 MPa (2,250 psia) and 249^{o}C (480^{o}F) and delivering steam at 11.1 MPa (1,615 psia) and 368^{o}C (694^{o}F) when it is required to charge the total receiver energy output into thermal storage.

The receiver must safely and efficiently absorb incident solar radiation at a maximum flux of 0.85 MW/m^2. In addition, the receiver must be able to accept, without damage, thermal gradients imposed by radiation transients from essentially zero to maximum flux in as little as 10 sec due to precipitation or the intermittent passage of clouds over the collector field.

The overriding need for efficient capture and use of insolation requires a high solar-absorptance value on the external surface of the receiver which is not less than 0.9. This value must exist regardless of degradation due to weathering, abrasion, etc., as may be expected in a desert environment. Additionally, the surface must be easily refurbished.

As a forced flow steam generator, the receiver will be designed and certified to the requirements of Section 1 of the ASME Boiler and Pressure Vessel Code. Fatigue life verification will be made using the more sophisticated analysis techniques of Section VIII, Division 2.

The major hardware assemblies comprising the Commercial receiver subsystem are the receiver unit, the tower on which the receiver unit is mounted above the collector field, and the supporting control and instrumentation equipment.

The receiver unit is in turn made up of four modular preheater panels and 20 boiler panels, flow control and instrumentation equipment, and the supporting structure.

All boiler panel assemblies are constructed of 170 tubes of high-strength, corrosion-resistant Incoloy 800 laid side by side and joined together thermally and structurally and made opaque to incident light by full-length longitudinal welds. All boiler tubes are 12.7 mm (0.5 in.) OD x 6.9 mm (0.27 in.) ID.

Preheater panels are of identical construction with the exception that they are made up of only 113 tubes which are 19.0 mm (0.75 in.) OD x 13.2 mm (0.52 in.) ID. As will be discussed later, the solar flux environment is much less severe on the preheater panels and larger tube size may be permitted to reduce the pressure drop through the preheater circuit.

An Incoloy 800 water header is located at the lower end of each panel assembly and functions to equally distribute water to all panel tubes. An Incoloy 800 steam header is also located at the upper end of each panel assembly to act as a steam collector manifold for all tubes. To ensure leak integrity, all panel tubes are welded to both manifolds.

All tubes are 27m (89 ft) long. The exposed length is 25.5 m (83.6 ft). Additional length provides for folding over at the top and bottom of the panels to protect the inlet and outlet manifolds and support structure from radiation.

The surfaces of the tubes exposed to solar radiation are coated with Pyromark paint which has demonstrated an absorptivity of 95% over a wide range of wavelengths. The coating is resistant to weathering and was tested for long-term compatibility with high-intensity solar radiation during the subsystem research experiments.

Each panel tube bundle is mounted to a panel backup structure to maintain the panel shape and hold it to the receiver tower structure in proper location while allowing for thermal growth and providing support for wind and seismic loads. A series of sliding clips and channels permit unrestrained lateral and vertical thermal expansion of the panels to prevent the buildup of thermal stresses. Each panel is insulated on the backside to reduce thermal loss and protect the support structure and control components.

The individual tubular panel subassemblies of the receiver unit are mounted on a central core steel support structure to form a single large and essentially circular (24-sided) cylinder 17 m (55.8 ft) in diameter by 25.5 m (83.6 ft) long. The heliostats surrounding the receiver tower direct their collected insolation onto the full 360° external surface of the receiver unit.

The receiver tower is of jump-formed concrete construction and extends 242m (794 ft) above grade to the interface with the receiver unit steel support structure which continues up through the receiver unit to an elevation of 281m (921 ft) where it is crowned with a 20-ton capacity service crane. Midpoint of the receiver unit is 268m (879 ft).

The top of the concrete tower has an outside diameter of 15.3m (50.25 ft) with a nominal 0.305m (12 in.) wall thickness. The base of the tower has a 45.7m (150 ft) OD and a 0.46m (18 in.) wall thickness. The foundation, which is 4.9m (16 ft) below finished grade, is a 61m (200 ft) OD annular circular mat with a 30.5m (100 ft) ID. The foundation thickness is 3.8m (12.5 ft).

Control of the receiver can best be understood by following a typical day's operation.

To initiate startup, water from the water treatment equipment of the electrical power generation subsystem is forced up the receiver tower riser by the receiver feed pumps and into the receiver inlet filter assembly. After leaving the filter assembly, the water enters a manifold which distributes the flow into the inlets of the two parallel sets of two panels in series located on the south side of the receiver and designed to function as preheaters. The water absorbs heat as it flows up through the first panel of each of the sets and then down the preheater through the second panel where it joins the flow from the other preheaters in a ring manifold supplying the remaining 20 panel assemblies designated as boiler panels. Passing through a modulating flow control valve located at the inlet to each boiler panel, the water again flows vertically upward, absorbing heat from the incident solar radiation and leaving the upper end of the boiler panels as superheated steam. The individual boiler panel inlet valves provide the flow control necessary to maintain constant outlet temperature despite diurnal and seasonal variations in heat load at each panel. The control valves also control cloud-induced transients and regulate the startup and shutdown sequences. With this arrangement, active control of the water flow through the preheater panels is not required.

As the steam exits from each of the panel discharge manifolds, it passes through a pair of cyclone type water separators as a precautionary measure to ensure absolutely dry steam. The steam then enters the steam downcomer collection manifold where it is mixed with the discharge flow from the other boiler panels and is finally carried away by the downcomer to the turbine of the electrical power generation subsystem or the thermal storage subsystem or both as directed by master control.

During startup or other conditions when insolation is too low to produce the proper superheat conditions, a combination of valves are used to divert receiver discharge flow away from the downcomer and into a receiver flash tank assembly until proper superheat conditions are achieved.

1.3.3 Section 4, Pilot Plant Receiver Subsystem Definition

Section 4 describes the analyses and design of the Pilot Plant receiver subsystem proposed for the 10MWe solar power Pilot Plant and the plans for its fabrication, installation, and operation. The receiver is shown in Figure 1-4.

The Commercial receiver design concept was selected to satisfy the Department of Energy's solar central receiver program objective to achieve the lowest commercial plant investment and operational costs. The design philosophy and/or rationale which directed the Commercial Plant design selection process has been presented in detail in Section 1.2 and will not be repeated here. Since the basic mission of the Pilot Plant is to demonstrate the validity of the Commercial Plant design concept, the Pilot Plant receiver design is dictated by a flow-down from the Commercial receiver concept. The Pilot Plant receiver design is therefore necessarily a scaled-down version of the Commercial receiver.

The mission of the receiver subsystem is to efficiently transfer the energy from the concentrated solar radiation reflected from the mirrors of the collector subsystem into the water supplied by the electrical power generation subsystem and deliver steam at precisely controlled superheat conditions to the plant turbine generator and/or the TSS.

Nominally, the receiver will be required to accept water from the flow distribution system at 13.8 MPa (2,000 psia) and 205°C (401°F) and deliver superheated steam at rated conditions of 10.4 MPa (1,515 psia) and 516°C (960°F) to the electrical generation subsystem. Any rated steam generated in excess of turbine power requirements will be diverted to the TSS.

The receiver subsystem must also be capable of delivering steam at 10.4 MPa (1,515 psia) and 349°C (660°F) when it is required to charge the total receiver energy output into thermal storage.

The receiver must safely and efficiently absorb incident solar radiation at a maximum flux of 0.30 MW/m^2. In addition, the receiver must be able to accept, without damage, thermal gradients imposed by radiation transients

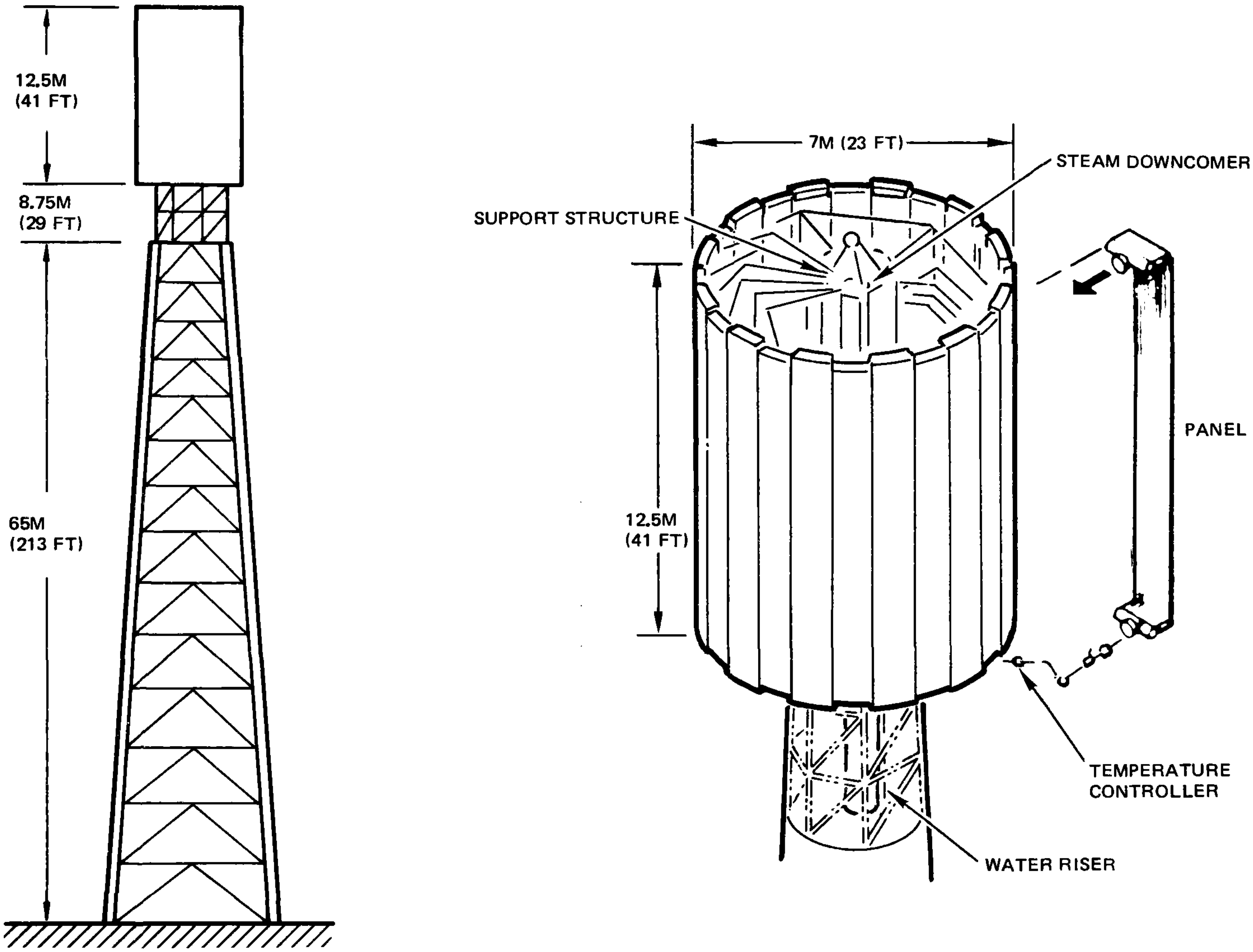


Figure 1-4. Pilot Plant Receiver

from essentially zero to maximum flux in as little as 10 sec due to precipitation or the intermittent passage of clouds over the collector field.

The need for efficient capture and use of solar radiation requires a high solar-absorptance value on the external surface of the receiver of not less than 0.9 regardless of degradation. The receiver surface must be easily refurbished.

The receiver will be designed and certified to the requirements of Section I of the ASME Boiler and Pressure Vessel Code. Fatigue life verification will be made using the analysis techniques of Section VIII, Division 2.

Major hardware assemblies comprising the receiver subsystem are the receiver unit, the tower on which it is mounted, and the supporting controls and instrumentation.

The receiver unit consists of six modular preheater panels and 18 boiler panels, flow control and instrumentation equipment, and supporting structure.

All panel subassemblies are constructed of 70 tubes of high-strength corrosion-resistant Incoloy 800 laid side by side and joined together thermally and structurally and made opaque to incident light by full-length longitudinal seam welds.

An Incoloy 800 water header (manifold) is located at the lower end of each panel assembly and functions to equally distribute water to all panel tubes. An Incoloy 800 header at the upper end of each panel subassembly acts as a collector manifold and the effluent from all tubes. To ensure leak integrity, all panel tubes are welded to both manifolds.

The exposed tube is 12.7 mm (0.50 in.) OD x 6.8 mm (0.269 in.) ID by 12.5m (41 ft) long. The length is enhanced by a length folded over at the bottom to protect the inlet water manifold and lower support structure from radiation and length folded over on top to protect the outlet manifold from insolation.

Tube surfaces exposed to solar radiation are coated with Pyromark paint, which has demonstrated an absorptivity of 95% over a wide range of wavelengths. The coating is resistant to weathering and has been tested for long-term compatibility with high-intensity solar radiation.

Each panel tube bundle is mounted to a backup structure to maintain the panel shape and hold it to the receiver tower in proper location while allowing for thermal growth and providing support for wind and seismic loads. A series of sliding clips and channels permit unrestrained lateral and vertical thermal expansion of the panels to prevent the buildup of thermal stresses. Each panel is insulated on the back side to reduce thermal loss and protect the support structure and control components.

The individual tubular panel assemblies of the receiver unit are mounted on a central core steel support structure to form a single large and essentially circular (24-sided) cylinder 7m (23 ft) in diameter by 12.5m (41 ft) long. The heliostats surrounding the receiver tower direct their insolation onto the full 360^{o} external surface of the receiver unit.

The receiver tower is of steel and extends 65m (213 ft) above grade to interface with the receiver unit steel support structure. The latter continues up through the receiver unit to an elevation of 86m (283 ft), where it is crowned with a service crane of 5-ton capacity. Midpoint of the receiver unit is 80m (262 ft).

The base of the tower is 12.2m (40 ft) square, tapering to 4.6m (12 ft) at the 65m elevation. The square concrete foundation is composed of a 0.61m (2 ft) thick mat 15.2m (50 ft) on a side and located 3.96m (13 ft) below finished grade. Concrete wall and pedestals extend 5.48m (18 ft) upward to meet the steel structure at an elevation of 1.52m (5 ft) above the grade.

To initiate startup, water from the water-treatment equipment of the electrical power-generation subsystem is forced up the receiver tower riser by the receiver feed pumps and into the receiver inlet filter assembly. After leaving the filter assembly, the water enters a manifold which distributes the flow into the inlets of the three parallel sets of two panels in series located on the south side of the receiver and designed to function as preheaters. The water absorbs heat as it flows through the preheater panels and then joins the flow from the other preheaters in a ring manifold supplying the remaining 18 panel assemblies designated as boiler panels. The water passes through a modulating flow control valve located at the inlet to each boiler panel, then flows vertically upward again, absorbing heat from the incident solar radiation and leaving the upper end of the boiler panels as superheated steam. The individual boiler panel inlet valves provide the flow control necessary to maintain constant outlet temperature despite diurnal and seasonal variations in heat load at each panel. The control valves also control cloud-induced transients and regulate startup and shutdown sequences. With this arrangement, active control of the water flow through the preheater panels is not required.

As the steam exits from each of the panel discharge manifolds, it passes through a cyclone-type water separator as a precautionary measure to ensure absolutely dry steam. The steam then enters the steam downcomer collection manifold where it is mixed with the discharge flow from the other boiler panels and is finally carried away by the downcomer to the turbine of the electrical power generation subsystem, or the TSS, or both as directed by master control.

During startup or when solar insolation is too low to produce proper superheat conditions, a combination of valves is used to divert receiver discharge flow away from the downcomer and into a receiver flash tank assembly until proper superheat conditions are achieved.

1.3.4 Section 5, Pilot Plant Plans

Section 5 presents the plans for the design, procurement, fabrication, transportation, installation, and checkout of the Pilot Plant receiver subsystem.

The master schedule showing the major activity breakouts is shown in Figure 1-5. As noted therein, design will be complete by the end of 1978 with material procurement starting early that year to permit adequate

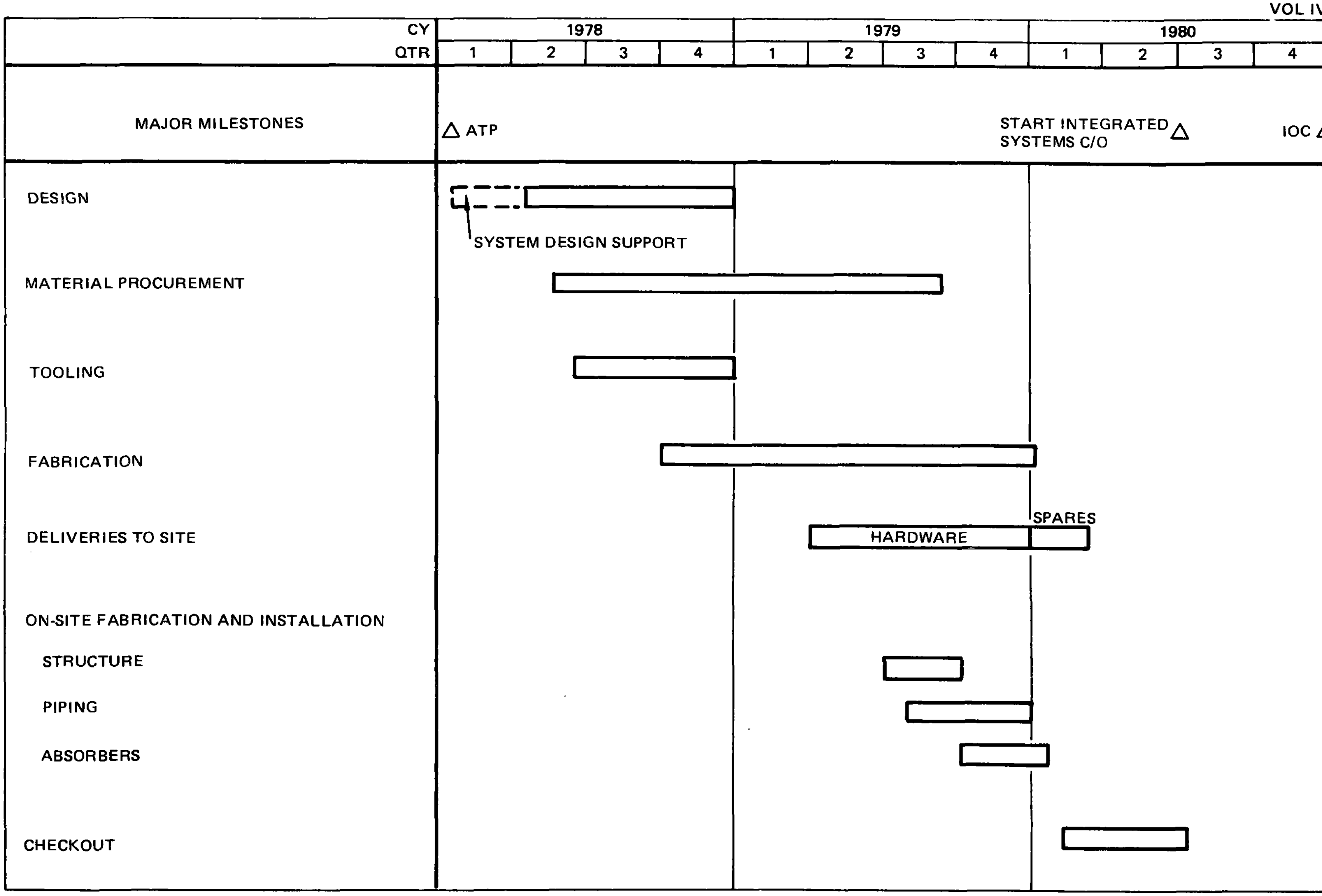


Figure 1-5. Receiver Schedule — Pilot Plant

leadtime for the tubing required for the absorber. Fabrication starts late in 1978 with all absorber panels being delivered to the site by the end of 1979. Field installation and checkout would be complete by the first quarter of 1980.

1.3.5 Section 6, Subsystem Research Experiments

The receiver subsystem research experiments (SRE) were designed to eliminate any risks inherent in the performance, control, stability, and mechanical integrity of the Pilot Plant receiver design. The conceptual and detail designs of the receiver subsystem research experiments and hardware were completed on schedule and accepted by ERDA as the basis for the SRE testing which successfully verified the following specific capabilities of the Pilot Plant receiver design:

A. Performance. Deliver specified steam conditions over the required range of input and output power.

B. Cooling Capability. Withstand peak heat flux and heat loads, as well as gradients within a panel.

C. Stability. Provide stable flow over the Pilot Plant power/flow spectrum.

D. Life. Capable of operating over 30 yr (10,000 cycles).

E. Structural. Withstand combined wind, seismic, pressure, and thermal loads.

F. Fouling. Maintain cooling surfaces free of corrosion and erosion when supplied with nominal power plant water.

G. Clouds. Capable of accommodating passing cloud cover over the collector field.

The receiver SRE included test of subassemblies and tests of a complete full-scale Pilot Plant receiver panel. The lower level tests included tests of single- and multiple-tube configurations to provide thermal, hydrodynamic, structural, and life data. A summary of SRE test requirements is in Table 1-1.

1.3.5.1 Single-Tube Tests

A single tube identical to Pilot Plant tubing in dimensions, material, and configuration was tested in vertical orientation at anticipated Pilot Plant operating conditions using a radiant heat input.

Table 1-1

RECEIVER TEST REQUIREMENTS

Design Considerations	SRE Test Requirements
Performance	Test single tube to establish initial flow stability and cooling capability.
Cooling Capability Stability Fatigue life	Test narrow panel to verify multitube stability, cooling, fouling resistance, and fatigue characteristics over normal and emergency range of pilot plant operating conditions.
Structural Fouling	Test full-scale Pilot Plant panel assembly over complete range of operating conditions to demonstrate performance, cooling, stability, and structural capability.
Clouds	Test panel surface coating under concentrated sunlight conditions.

Objectives of the tests were (1) facility checkout, (2) preliminary demonstration of thermal performance, (3) preliminary demonstration of safe tube operation under nominal conditions, and (4) demonstration of flow stability in a single tube.

The tests were conducted at the Rockwell B-1 facility in El Segundo. The tube was installed vertically in a reflectorized enclosure and heated by 13 graphite heaters oriented along the axis of the tube. Strain gage transducers were used to measure pressure, and thermocouples measured both surface and fluid temperatures. Data were recorded on strip charts and magnetic tape.

A total of 11 tests were conducted. Superheated steam was successfully produced without the need of orifices in the tube to stabilize the water flow.

The successful demonstration of unorificed flow stability and better than expected thermal performance of the single tube test article cleared the way for the initiation of the 5-tube panel testing.

1.3.5.2 Narrow-Panel Tests

The single-tube tests were followed by a series of tests of a 5-tube, full-length receiver panel beginning in early September 1976.

The objectives of the narrow-panel tests were to (1) demonstrate thermal performance of the absorber, (2) verify safe operation and wall temperatures consistent with 30-yr life under Pilot Plant operating conditions, (3) demonstrate flow stability in a multiple-tube panel, (4) provide a preliminary demonstration of fabrication and handling techniques (5) verify the adequacy of the backup structure with respect to restraint and thermal expansion capability, and (6) evaluate the effect of emergency operating conditions.

Fabrication of the 5-tube test panel was successfully completed in July 1976, as evidenced by its ASME certification in accordance with Section I of the boiler code. The panel consists of 5 Pilot Plant size receiver tubes with inlet and outlet manifolds and backup structure similar to the 70-tube Pilot Plant panel.

Following installation of the 5-tube panel into the test facility, 16 tests were conducted covering the full range of flux levels, pressures, and temperatures anticipated for the Pilot Plant receiver. Temperature and pressure data were recorded on strip charts for immediate visibility and on magnetic tape for subsequent printout and CRT display. The strip chart recorders included continuous plotting recorders and multipoint indicating recorders. Panel deflection was indicated visually by a calibrated pointer attached to the bottom of the panel. Absorbed heat loads were determined by multiplying the difference in the specific enthalpy of the water at the exit and inlet of the panel by the water flowrate. Steam temperature as high as 593°C (1,100°F) were produced without damage to the panel. All tests were conducted at approximately 10.4 MN/m^2 (1,500 psig) pressure.

Maximum predicted and experimental wall temperatures were compared for a high-heat flux test and for a low-heat flux test. The results of the comparison are shown in Table 1-2 and indicate the predicted values to be conservative over the entire range of heat fluxes.

Table 1-2

TUBE WALL MAXIMUM TEMPERATURE COMPARISONS

Test	Absorbed Heat Flux, MW/m^2	(Btu/in^2 - sec)	Quality at Maximum Temperature Point (%)	Wall Temperature °C (°F) Predicted	Wall Temperature °C (°F) Measured
5-6	0.026	(0.016)	98	354 (670)	332 (630)
5-15	0.28	(0.17)	85	657 (1215)	554 (1030)

One of the major items investigated was the ability of the panel to operate stably without inlet orifices or, if orifices were required, to determine the minimum orificing which would permit stable operation. All tests except one calibration run were run without orifices and confirmed the ability of the boiler to come on line stably without orifices in the system. Temperatures at the discharge of the tubes and at the entrance of the downcomer during the start transients indicated only minor oscillations which quickly damp out as steady-state is reached.

The time to achieve steady-state conditions depended upon the incident heat flux level and effluent temperature conditions desired. The times ranged from a maximum of approximately 12 min for low-heat fluxes with low discharge temperatures to 7 min with high-heat fluxes and high discharge temperatures.

All tests indicated reasonably uniform temperatures from tube to tube which implies equal flow in each tube. The flow uniformity is enhanced by the high ratio of hydrostatic head to frictional pressure drop in the tubes. Even at the high flow and high temperature conditions of Test 5-15, the predicted frictional pressure drop is in the order of 10 psi, while the hydrostatic head is the same order of magnitude. For low-flow and low-temperature conditions, the frictional pressure drop decreases to less than 1 psi and the hydrostatic head increases slightly. Thus, if one tube tends to produce a higher temperature steam, the hydrostatic head will decrease and flow will increase, thus reducing the temperature back toward the nominal value.

The effects of passing clouds were investigated on Test 5-8 when the electrical power was reduced to approximately 10% of the maximum test value and brought back over a total transient time of approximately 1 min. The transient was accomplished twice with no evidence of instability or temperature overshoot occurring.

In order to determine the ability of the panel to survive loss of water, the water flow was terminated by shutting off the inlet water valve for 2 sec, 10 sec, and 60 sec during Test 5-9. The 2-sec and 10-sec flow terminations had negligible effects on the discharge temperature. During the last termination, the discharge temperature decayed approximately 50^{O}F as the flow ceased in the vicinity of the thermocouple in the downcomer. The same time that the valve was being reopened during the last transient, heaters 4 and 7 failed. This accounts for the lower outlet temperature after the transient than before.

The maximum wall temperature during the transients was 880^{O}F (nominal 850^{O}F). Thus, stoppages of water flow for significant time periods can be tolerated by the panel without excessive wall temperatures or radical changes in effluent discharge temperature.

In summary, the 5-tube panel tests confirmed the functional capability of the thermal expansion mechanisms, flow stability during start and other transient and steady-state conditions, and tube-to-tube flow uniformity without individual tube orifices. The test results also demonstrated the ability of the panel to respond safely to rapid heat-flux transients and to temporary loss of water. In addition, the heat-transfer characteristics of the panel exceeded expectations, resulting in better performance and higher tolerance to abnormal operating conditions than predicted.

1.3.5.3 Full-Scale Pilot Plant Panel Testing

Objectives of the full-scale receiver tests were to (1) demonstrate Pilot Plant panel fabricability and transportability, (2) verify Pilot Plant receiver performance including compatibility with thermal storage and electrical power-generating subsystem interfaces and operation at safe wall temperature with design pressure drop, (3) verify control and stability of a Pilot Plant panel under steady-state and dynamic conditions, and determine component dynamic characteristics and (4) verify thermal stress and expansion provisions.

Fabrication of the full-scale Pilot Plant receiver panel was completed and the panel was transported to the B-1 test facility in El Segundo without difficulty in October 1976. More than 100 thermocouples were installed on the panel to measure heated, backwall, and steam temperatures. Grit-blasting of the heated surface and painting with Pyromark absorptive paint were successfully completed immediately thereafter.

Upon completion and erection of the test tower, the full-scale panel was vertically installed into the test tower and testing was begun.

Solar flux on the panel was simulated using a stack of 165 resistance heaters in front of and across the panel absorptive surface. Flow stability and uniformity testing of the 70-tube tube panel was initiated using Inconel heater elements to obtain long heater life during the low-flux phase of the test program. Test results fully confirmed the expectations created by the single- and 5-tube panel testing. No indications of flow instability were detected, even at very low flowrates. Flow uniformity was also excellent across the panel as indicated by uniform steam discharge temperatures. Flow stability and uniformity were maintained during simulated Pilot Plant starts in which temperature and pressure were manually stepped from 275°C (530°F) to 325°C (620°F) at 2.76 MN/m^2 (400 psi) and then to 450°C (840°F) and 10.4 MN/m^2 (1,500 psi).

The Pilot Plant panel tests provided the first opportunity to check out the panel temperature control loop using the Pilot Plant control valve, temperature sensors, and control electronics. Some difficulty was initially experienced in holding the steam discharge temperature within the target control band of ±28°C (50°F) at low panel powers due to the low flowrates. Adjustment of the control loop gains and modification of the control valve poppet size corrected the problem in later tests. Temperature control within ±17°C (30°F) of the set point was maintained automatically, even with instantaneous set point shifts from 315° to 515°C (600° to 960°F) and back again or with commanded variations of ±20% in input power level or back pressure.

The fundamental issue to be addressed required resolution of the ability of the panel to accept the required heat flux level successfully. If the panel could be shown to successfully accept heat-transfer conditions equal to or worse than the worst case Pilot Plant conditions even over a limited area, it would be qualified. It should be clearly noted here that the question was not one of basic survival of the panel since the properties of the Incoloy 800 material could accept full solar flux even if the tubes were totally dry for approximately one-half hour without rupture. What had to be shown was that the differential temperatures across the tubes under the highest flux conditions would permit a panel fatigue life of over 30 yr as required by the subsystem specifications.

The fatigue life capability of the basic panel design had been demonstrated during the 5-tube panel test program under high flux levels up to 90% of the maximum flux anticipated for the Pilot Plant. Maximum hot wall tube temperatures during those tests were 103°C (185°F) below the predicted values indicating a wide margin on panel fatigue life.

The Pilot Plant panel fatigue life verification testing was accomplished using Inconel element heaters to radiate the majority of the panel with high flux graphite heaters supplying heat to the most critical zone. Heat flux to flow ratios were extremely severe compared to maximum Pilot Plant conditions. Maximum flux levels up to 0.28 MW/m^2 were achieved with flux to water flow ratios exceeding 93 MW/m^2 per kg of flow per second, as compared to maximum Pilot Plant flux of 0.3 MW/m^2 and a flux-to-flow ratio of 5 MW/m^2 per kg of water flow per second.

Test results confirmed the margin in heat-transfer characteristics and fatigue life previously shown by the 5-tube panel tests. Tube wall differential temperatures were well below the predicted values, indicating a comfortable margin in the fatigue life of the Pilot Plant panel.

1.3.5.4 Absorber Surface Coating Test

The objective of the absorptivity surface coating test was to determine the effects, if any, of high-intensity solar radiation on candidate panel surface absorptivity coatings. The surface coating test article consisted of an Incoloy 800 bar grit-blasted and painted on the heated surface with both S-31 and Pyromark paints. Four thermocouples were installed to measure the temperature of the heated surface.

The absorptive surface durability test article was installed in the White Sands solar furnace test facility in October 1976. Cyclic solar exposure of the candidate absorptive coatings to concentrated sunlight at a level of 0.3 MW/m^2 was begun shortly thereafter.

An interim measurement of the absorptivity of the test article coatings was made in March 1977 after approximately 4 mo of testing. No appreciable change was noted in the absorptivity of either coating. Pyromark absorptivity was measured at 0.949, compared to 0.950 at the beginning of the test. S-31 absorptivity was 0.931, compared to the initial value of 0.934.

1.3.5.5 Receiver SRE Conclusions

The results of the SRE testing conducted on the Pilot Plant receiver test articles lead to the following conclusions:

1. The fabrication methods and materials selected for the Pilot Plant receiver are compatible with the production of a boiler acceptable to Section 1 of the ASME boiler code.
2. Transportation and handling of the panel in both urban and business areas are practical and can be accomplished without special equipment.
3. The devices which provide for thermal expansion of the panel function satisfactorily.
4. The receiver surface coating maintains its high absorptivity and structural integrity under extended exposure to cyclic and highly concentrated solar insolation.
5. The panel can operate at maximum Pilot Plant heat fluxes with tube temperatures well below the predicted values. Differential tube temperatures were such as to ensure a 30-yr panel life.

6. During steady-state operation, flow is uniform from tube to tube and is stable, even under extreme variations in pressure, flow, or solar insolation.
7. The panel can survive flow cessations for significant periods without excessive temperatures or damage.
8. The panel control loop will automatically maintain steam outlet conditions within specified limits under anticipated transient conditions of pressure flow or insolation.
9. The panel can reach steady-state temperature conditions in 7 to 12 min (depending on the heat flux) after a constant heat load is applied.

In general, the SRE tests have resulted in a high confidence in the satisfactory operation of the Pilot Plant receiver segment and thus in the Commercial receiver design concept.

2 RECEIVER DATA LIST

Section 2
RECEIVER DATA LIST

2.1 DATA LIST

Receiver design characteristics are contained in Table 2-1 for the SRE, Pilot, and Commercial receivers. Operating conditions are summarized in Table 2-2. Specific design issues requested by Sandia Livermore to be included in this section are as follows:

1. Maintenance and Repair. Maintainability and repairability aspects of both the Commercial and Pilot Plant receivers are identical. The systems have been designed such that control components can be easily removed and replaced with minimal impact to the solar plant mission. The modularity inherent in the design allows for the removal of panels if rework is necessary, and for overnight replacement. The details of maintenance and repair are in Section 5.4.
2. Thermal Losses. Thermal losses from the Pilot and Commercial Plants were calculated in detail. Reflected insolation was calculated from solar absorptance measurements obtained during SRE. Infrared radiation losses were calculated based on emissivity measurements obtained during SRE. Convective losses were calculated by a fairly complex procedure, the details of which are discussed in Section 4.3.2.1. Total losses are approximately 9.6 and 14% for the Commercial and Pilot Plants, respectively. Losses during shutdown periods are also discussed in Section 4.3.2.1.
3. Sensitivity to Clouds and Other Flux Disturbances. Each modular receiver panel, with a water flow/temperature control valve capable of approximately 10:1 flow turndown ratio, compensates for the power fluctuations caused by clouds moving across its part of the heliostat field without affecting the other panels. The approach to operations in the presence of passing clouds is as follows. It is anticipated that dense, fast-moving cloud formations will be forecast.

Table 2-1 (Page 1 of 2)

RECEIVER DESIGN CHARACTERISTICS

		SRE	Pilot Plant	Commercial
1	Wt on Top of Tower, kg x 10^3 (kips)		163 (359)	1, 229 (2704)
3	Wt of Pressure Parts, kg x 10^3 (kips)		59 (129)	461 (1015)
4 (a)	Height, m (ft)		12. 5 (41)	25. 5 (84)
4 (b)	Diameter, m (ft)		7 (23)	17 (56)
5	Absorber Working Surface, m^2 (ft^2 x 10^3)	11 (0. 120)	267 (2. 87)	1, 310 (14. 1)
6 (a)	Boiler Material	Incoloy 800 ASME-SB-163		
6 (b)	Tube OD, cm (in.)	1. 27 (0. 5)	1. 27 (0. 5)	1. 27 (0. 5) Boiler 1. 90 (0. 75) Preheater
6 (c)	Tube Wall, cm (in.)	0. 29 (0. 115)	0. 29 (0. 115)	0. 29 (0. 115)
6 (d)	Tube Length, m (ft)			
	Radiated Length	17 (56)	12. 5 (41. 0)	25. 5 (84)
	Total Length	18 (60)	13. 9 (45. 5)	27 (89)
6 (e)	Number of Tubes	70 (x 1 panel)	70 (x 18 boiler panels) 70 (x 6 pre-heater panels)	170 (x 20 boiler panels) 113 (x 4 pre-heater panels)
6 (f)	Weight of Tubes, kg x 10^3 (kips)	(0. 70)(1. 5)	17 (37)	37 (190)
7	ASME Code for Design	Sections I and VIII (Boiler and Pressure Vessel Code)		
8 (a)	Receiver Coating	Pyromark	Pyromark	Pyromark
8 (b)	Absorptivity	0. 95	0. 95	0. 95
8 (c)	Emissivity	0. 89	0. 89	0. 89
9	Pressure Drop Correlations			
9 (a)	Single Phase		Moody	

Table 2-1 (Page 2 of 2)
RECEIVER DESIGN CHARACTERISTICS

		SRE	Pilot Plant	Commercial
9 (b)	Two Phase		Martinelli-Nelson	
9 (c)	Absorber Rated ΔP, MPa (psi)	0.069 (10)	0.076 (11)	1.68 (245)
10	Heat-Transfer Correlations			
10 (a)	Water Heating		McAdams (Dittus Boelter)	
10 (b)	Subcooled Nucleate Boiling		Jens and Lottes	
10 (c)	Nucleate Boiling		Jens and Lottes	
10 (d)	Superheated Steam		McAdams (Dittus-Boilter)	
10 (e)	Nuc./Film Boiling Transition		Rocketdyne Experiments	

At that point the receiver will be directed to produce rated steam and all fluid would be sent to thermal storage. If the heat loads get sufficiently low such that power level for any panel is below the acceptable minimum, then the receiver output would be routed to the receiver flash tank and the receiver shut down. With this operating strategy, cloud transients will not cause any adverse impact on receiver life. No other means of cloud protection is necessary. The procedures will be the same for both the Pilot and Commercial plants. (See Section 4.4.)

4. Hydraulic Stability. Prior to the SRE, a detailed analysis of flow stability was performed. Briefly, it was found that there was a potential for instability at low power/low flow conditions. However, during SRE, extensive tests were performed with power levels

Table 2-2 (Page 1 of 4)

RECEIVER OPERATING CHARACTERISTICS

		SRE (1 Panel)	Pilot Plant	Commercial
1	Average Flow - kg/sec (lb/hr x 10^3)			
1 (a)	Maximum Flow	1.5 (12)	16.5 (130.5)***	213 (1,687)**
1 (b)	Design Flow	*	12.9 (102.4)#	213 (1,687)**
1 (c)	Minimum Flow	0.17 (1.5)	3.65 (28.9)	34 (269)
2 (a)	Maximum Inlet (Riser) Velocity, m/s (fps)***	3.0 (10)	3.27 (10.7)	5 (16.3)
2 (b)	Design Inlet (Riser) Velocity, m/s (fps)***	*	2.6 (8.4)	5 (16.3)
2 (c)	Minimum Inlet (Riser) Velocity, m/s (fps)***	0.64 (2.1)	0.72 (2.37)	0.8 (2.60)
3 (a)	Maximum Outlet (Downcomer) Velocity, m/s (fps)	30 (100)	25.7 (84.2)	69 (226)
3 (b)	Design Outlet (Downcomer) Velocity, m/s (fps)	*	20.2 (66)	69 (226)
3 (c)	Minimum Outlet (Downcomer) Velocity, m/s (fps)	7.6 (25)	5.7 (18.6)	11 (36)
2	Fluid States			
2 (a)	Maximum Inlet Pressure, MPa (psia)	14.1 (2,050)	13.8 (2,000)	15.5 (2,250)
2 (b)	Design Inlet Pressure, MPa (psia)	13.8 (2,000)	13.8 (2,000)	15.5 (2,250)
2 (c)	Minimum Inlet Pressure, MPa (psia)	13.4 (1.950)	13.4 (1.950)	15.2 (2,200)
2 (d)	Maximum Outlet Pressure, MPa (psia)	10.7 (1,550)	10.4 (1,515)	11.1 (1,615)
2 (e)	Design Outlet Pressure, MPa (psia)	10.4 (1,515)	10.4 (1,515)	11.1 (1,615)

Table 2-2 (Page 2 of 4)
RECEIVER OPERATING CHARACTERISTICS

		SRE (1 Panel)	Pilot Plant	Commercial
2 (f)	Minimum Outlet Pressure, MPa (psia)	10.2 (1,480)	10.24 (1,485)	10.24 (1,485)
2 (g)	Maximum Inlet Temp, °C (F)		212 (414)***	249 (480)***
2 (h)	Design Inlet Temp, °C (F)	205 (401)	205 (401)#	234 (454)**
2 (i)	Minimum Inlet Temp, °C (F)	157 (315)	157 (315)	157 (315)
2 (j)	Maximum Outlet Temp, °C (F)	543 (1,010)	516 (960)	516 (960)
2 (k)	Design Outlet Temp, °C (F)	516 (960)	516 (960)	516 (960)
2 (l)	Minimum Outlet Temp, °C (F)	488 (910)	349 (660)***	368 (694)***
3 (a)	Maximum Absorbed Heat Flux, MWt/m^2 (Btu/in^2-sec)	0.31 (0.19)	0.30 (0.18)	0.85 (0.52)
3 (b)	Design Absorbed Heat Flux, MWt/m^2 (Btu/in^2-sec)	0.28 (0.17)	0.30 (0.18)	0.85 (0.52)
4 (a)	Heat Flux Distribution on Panel		Figure 2-1 and Table 2-4	
4 (b)	Heat Load Distribution on Receiver			
5 (a)	Maximum Incident Power Power, MWt (Btu/sec x 10^3)	3.9 (3.7)	43.4 (41.1)	560 (531)

\# Winter 2PM, Rated Steam
* Representative of all pilot plant panels.
** Equinox noon, rated steam operation
*** Max TSS change, donated operation.

Table 2-2 (Page 3 of 4)

RECEIVER OPERATING CHARACTERISTICS

		SRE (1 Panel)	Pilot Plant	Commercial
5 (b)	Design Incident Power, MWt (Btu/sec x 10^3)	*	38.7 (36.6)	560 (531)
5 (c)	Minimum Rated Steam Incident Power, MWt (Btu/sec x 10^3)	0.4 (0.4)	14.9 (14.1)	118 (112)
6	Absorbed Power/Flow, MWt/kg/s (Btu/lb/s)			
6 (a)	@ Maximum Isolation	2.50 (1,080)	2.63 (1,133)	2.38 (1,025)
6 (b)	@ Design Insolation	2.52 (1,090)	3.00 (1,292)	2.38 (1,025)
6 (c)	@ Minimum Rated Steam	3.16 (1,360)	4.08 (1,757)	3.47 (1,494)
7	Absorber Efficiency, Percent			
7 (a)	@ Maximum Insolation	-	85.4	90.4
7 (b)	@ Design Insolation	-	84.3	90.4
7 (c)	@ Minimum Rated Steam	-	67.1	78.4
7 (d)	Annual Average	-	84.1	89.8
8	Annual Incident Energy, MW Hr x 10^3 (Btu x 10^9) **	-	106 (361)	1,558 (5,316)
9	Annual Absorbed Energy, MW Hr x 10^{-3} (Btu x 10^9) **	-	89.1 (303.5)	1,399 (4,774)
10	Peak Metal Temp on Panel, °C (F)			
10 (a)	@ Maximum Insolation	580 (1,077)	580 (1,077)	602 (1,115)
10 (b)	@ Design Insolation	569 (1,056)	569 (1,056)	602 (1,115)

* Representative of all pilot plant panels.
** Based on 1963 Inyokern Aerospace data tape.

Table 2-2 (Page 4 of 4)
RECEIVER OPERATING CHARACTERISTICS

		SRE (1 Panel)	Pilot Plant	Commercial
10 (c)	@ Minimum Rated Steam	501 (934)	501 (934)	509 (948)
11	Typical Design Heat Transfer Coefficients, MW/m^2-^oC (Btu/in.^{2}-sec-^oF)			
11 (a)	Minimum Two Phase	0.003 (0.001)	0.003 (0.001)	0.010 (0.003)
11 (b)	Superheat Region	0.003 (0.001)	0.003 (0.001)	0.012 (0.004)
12	Peak Working Stresses in Absorber, Mpa (psi)			
12 (a)	From Pressure	19 (2.7)	19 (2.7)	19 (2.7)
12 (b)	Combined Stress	350 (51)	350 (51)	400 (58)
12 (c)	Fatigue Allowable Stress	410 (59)	410 (59)	410 (59)
12 (d)	Allowable Membrane Stress	93 (14)	93 (14)	74 (10.7)

below 10% of nominal that showed that no instability within the tubes existed. This was apparently due to the high hydrostatic head on the tube inlet. It is therefore obvious that the flow in both Pilot and Commercial Plants will be totally stable throughout the range of receiver operation. See Section 4.3.2.2 and SRE Section 6.0.

5. Receiver Lifetime. The verification of receiver life is based on an analysis which uses a temperature distribution to calculate strain. The life is then calculated from low-cycle fatigue data used in connection with ASME boiler code procedures. The temperature distributions used in the strain analysis are based on empirical data taken during SRE and other related test programs. (See Item 10 below and Section 4.3.2.1.)

6. Seismic Analysis. A preliminary analysis of seismic loads and their impact on the receiver has been performed. Details of these calculations are included in Sections 3.2.2.2 for the Commercial Plant and 4.3.2.3 for the Pilot Plant. In general, all weights indicated for the receiver are sufficient to withstand 0.25 g of lateral acceleration at the base of the tower. Only minor, if any, damage is expected with these levels of seismic loading. It is anticipated that visual inspection of structural parts would have to be performed subsequent to a seismic occurrence and that functional checks of mechanical and electronic parts would also be necessary. No obvious weak points have been found.
7. Startup Procedures. Startup procedures for the SRE Pilot and Commercial Plants are basically the same. There are no receiver time constraints in that the rate at which heat flux builds up with sunrise is slow compared to the thermal time constant of the tubing in the receiver panels. Operational characteristics for the Pilot Plant and Commercial Plant are contained in Sections 4.4 and 3.4, respectively. In general, water flow may be established prior to sunrise, and at such time when the power is sufficient to allow normal operation, receiver steam production will begin.
8. Critical Startup Times. There are no critical startup times for most of the receiver components. In general, it has been found that the slowness of the sunrise process and the means of starting the receiver ensure that no thermal stress problems will occur during startup. See SRE Section 6.0.
9. Water Quality. The water quality used in the receiver is expected to be typical of that recommended for existing once-through boilers (Table 2-3).

A detailed discussion of feedwater treatment can be found in Section 3.3.11 of Volume VI (EPGS) of the PDR.

A detailed discussion of feedwater treatment can be found in Section 3.3.11 of Volume VI (EPGS) of the PDR.

Table 2-3

RECOMMENDED LIMITS FOR SOLIDS AND pH IN FEEDWATER FOR ONCE-THROUGH BOILERS†

Factor	Recommended Maximum Limit	Typical Concentrations
Total solids	0.050 ppm	0.020 ppm
Silica as SiO_2	0.020 ppm	0.002 ppm
Iron as Fe	0.010 ppm	0.003 ppm
Copper as Cu	0.002 ppm	0.001 ppm
Oxygen as O_2	0.007 ppm	0.002 ppm
Hardness	0.0 ppm	0.0 ppm
Carbon dioxide	0.0 ppm	not measured
Organic	0.0 ppm	0.002 ppm
Lead	0.0 ppm	---
pH	9.3 - 9.5	9.45

†Steam, Its Generation and Use. Babcock and Wilcox, 38th edition (1972).

10. Thermal Cycles. The number of thermal cycles that the receiver can withstand has been estimated as 100,000 for the Pilot Plant and in excess of 10,000 for the Commercial Plant. These are based on cold starts and are for the worst location on the receiver (north panel). (See Item 5 above and Section 4.3.2.1.)

11. Receiver Reflectivity. Reflectivity for the receiver surface is as follows. (See Section 6.5.2):

Wavelength (Microns)	Reflectivity (Percent)
0.25	5
0.4	4.5
0.8	4
1.0	4
1.5	6
2.0	7
2.5	10

12. <u>Receiver Optimization</u>. System optimization relative to receiver costs, weight, and performance can be addressed primarily to the ASME Boiler Code. The code considers the tube material Incoloy 800 a nonferrous alloy and therefore requires the addition of 1.7 mm (0.067 in.) to any wall thickness in the boiler section. This has an impact on life and on cooling requirements since the extra wall thickness results in additional temperature drop through the wall. Also, the additional wall thickness results in more metal, which is an additional cost and weight. Secondly, the analysis performed to ascertain fatigue life made use of a procedure that originated in the nuclear code. This inherently reduces allowable strains to extremely low level with undue conservatism. The net effect of all these items is to increase receiver surface area which increases losses and increases weight, and naturally, cost. Thorough rethinking of the ASME design procedure for solar equipment, and specifically with regard to the treatment of Incoloy 800 as a non-ferrous alloy would result in a lighter and less expensive receiver with a greater fatigue life.

13. <u>Receiver Sensitivity to Off-Design Operation</u>. A relative indication of the insensitivity of the Pilot Plant receiver to emergency operating conditions is presented in Section 4.3.2.2. In summary, the receiver material (Incoloy 800) and protective systems provide a tolerant subsystem even under the most extreme operating conditions such as the total loss of feed water flow at maximum power levels.

2.2 PILOT PLANT RECEIVER REFERENCE DATA

This section contains Tables 2-4 through 2-8 and Figures 2-1 through 2-9.

Table 2-4

RECEIVER ABSORBED POWER DISTRIBUTION - PERCENTAGE OF TOTAL RECEIVER POWER

		Panel Location			
		East	North	West	South
Day	Hr.				
Jun 21	12 Noon	4.63	5.92	4.63	2.00
	2 PM	5.36	5.97	3.85	1.98
	4 PM	6.00	5.48	2.54	2.12
	6 PM	6.47	5.55	2.51	1.98
Mar 21	12 Noon	4.62	6.40	4.62	1.65
Sep 21	2 PM	5.38	6.48	3.11	1.64
	4 PM	6.28	6.52	2.42	1.74
Dec 21	12 Noon	4.67	6.78	4.67	1.34
	2 PM	5.16	7.05	3.04	1.30
	4 PM	6.22	5.98	2.48	1.16

Table 2-5 (Page 1 of 2)

VALVE LIST, 10-MWe RECEIVER

Valve	Symbol	Qty	Nom. Size (In.)	Control	Function
Receiver Water Inlet	RWISK-1	1	4	Manual	Isolate receiver
Receiver Water Drain	RPWDV-1	1	1	Manual	Drain first pass preheater panels
Receiver Water Relief	RPWRV-1 through -3	3	2 1/2	Spring	Prevent preheater overpressure
Receiver Water Vent	RPWVV-1 through -3	3	1	Manual	Vent preheaters during fill
Receiver Nitrogen Charging Check	RNCK-1 through -3	3	1/2	Spring	Backfill preheaters during drain
Receiver Water Drain	RPWDV-2	1	1	Manual	Drain second pass preheater panels
Receiver Water Inlet	RBWIV-1	1	4	Manual	Limit of boiler panels
Receiver Nitrogen Charging	RCNK-4	1	1/2	Spring	Backfill boiler feed lines during drain
Receiver Water Vent	RBWVV-4	1	1	Manual	Vent manifold during fill
Receiver Water Flow Control	RBTCV-1 through 18	18	1	Pneumatic	Control boiler panel flowrate
Receiver Water Inlet	RBWIV-2 through 19	18	1	Manual	Limit of boiler panels
Receiver Water Drain	RBNDV-3 through 21	18	1	Manual	Drain boiler panels
Receiver Nitrogen Charging Check	RNCK-5	1	1/2	Spring	Backfill boiler panels and downcomer during drain
Receiver Water Vent	RSVV-5	1	1	Manual	Vent boiler panels during fill

Table 2-5 (Page 2 of 2)

VALVE LIST, 10-MWe RECEIVER

Valve	Symbol	Qty	Nom. Size (In.)	Control	Function
Receiver Steam Relief	RSRV-1 & 2	2	2 1/2	Spring	Prevent boiler overpressure (1700 psig max at 1,000°F)
Moisture Trap Water Drain	RTDV	2	1	Power	Drain moisture trap
Receiver Steam Outlet	RDSIV-1	1	6	Power	Isolate receiver downcomer
Receiver Nitrogen Charging	RNPV-1	1	1	Manual	Charge for backfilling during drain

Table 2-6

RECEIVER HEAT LOSSES

	Pilot Plant		Commercial	
	Max Rated Steam (MWt)	Max Derated Steam (MWt)	Max Rated Steam (MWt)	Max Derated Steam (MWt)
IR Radiation	3.2	2.5	20.6	14.3
Convection	1.00	0.87	5.4	4.5
Reflected Insolation	2.16	1.90	28.0	14.4
Total	6.36	5.27	54.0	33.2
Absorbed Energy	37.1	32.8	506.4	254.2*
Percent Loss	14.6	13.8	9.6	11.5

*Absorbed Power Limited by Thermal Storage Sizing Requirement per Sandia Guideline.

Table 2-7

10-MW SOLAR RECEIVER WEIGHT SUMMARY

Item	Weight kg x 10^3 (kips)	Distance Above 65m Interface, Meters (ft)
Carbon Steel	93 (205)	15.09 (49.5)
24 Panel Assemblies	38 (84)	15.09 (49.5)
Piping	21 (45)	11.89 (39)
Crane	11 (25)	26.21 (86)
TOTAL WEIGHT	163 (359)	

Table 2-8

VALVE LIST, 100-MW RECEIVER

Valve	Symbol	Qty	Nom. Size (In.)	Control	Function
Receiver Water Inlet	RW1SK-1	1	10	Manual	Isolate receiver
Receiver Water Drain	RPWDV-1	1	1 1/2	Manual	Drain first pass preheaters
Receiver Water Relief	RPWRV-1 through -4	4	3	Spring	Prevent preheater over-pressure
Receiver Water Vent	RPWVV-1 & 2	2	1	Manual	Vent preheaters during fill
Receiver Nitrogen Charging Check	RNCK-1 & 2	2	1	Spring	Backfill preheaters during drain
Receiver Water Drain	RPWDV-2	1	1	Manual	Drain second pass preheaters and boiler panels
Receiver Water Flow Control	RBTCV-1 through -20	20	3	Pneumatic	Control boiler panel flowrate
Receiver Water Inlet	RBWIV-1 through -20	20	3	Manual	Limit boiler panels
Receiver Nitrogen Charging Check	RNCK-3	1	1	Spring	Backfill boiler panels and downcomer
Receiver Water Vent	RSVV-3	1	1	Manual	Vent boiler panels during fill
Receiver Steam Relief	RSRV-1 through -6	6	3	Spring	Prevent boiler overpressure
Receiver Steam Outlet	RDSOV	1	16	Manual	Isolate receiver downcomer
Receiver Water Drain	RTDV-1 & 2	2	1 1/2	Power	Drain off water from accumulator
Receiver Nitrogen Charging	RNPV-1	1	2	Manual	Charge nitrogen system for backfill during drain

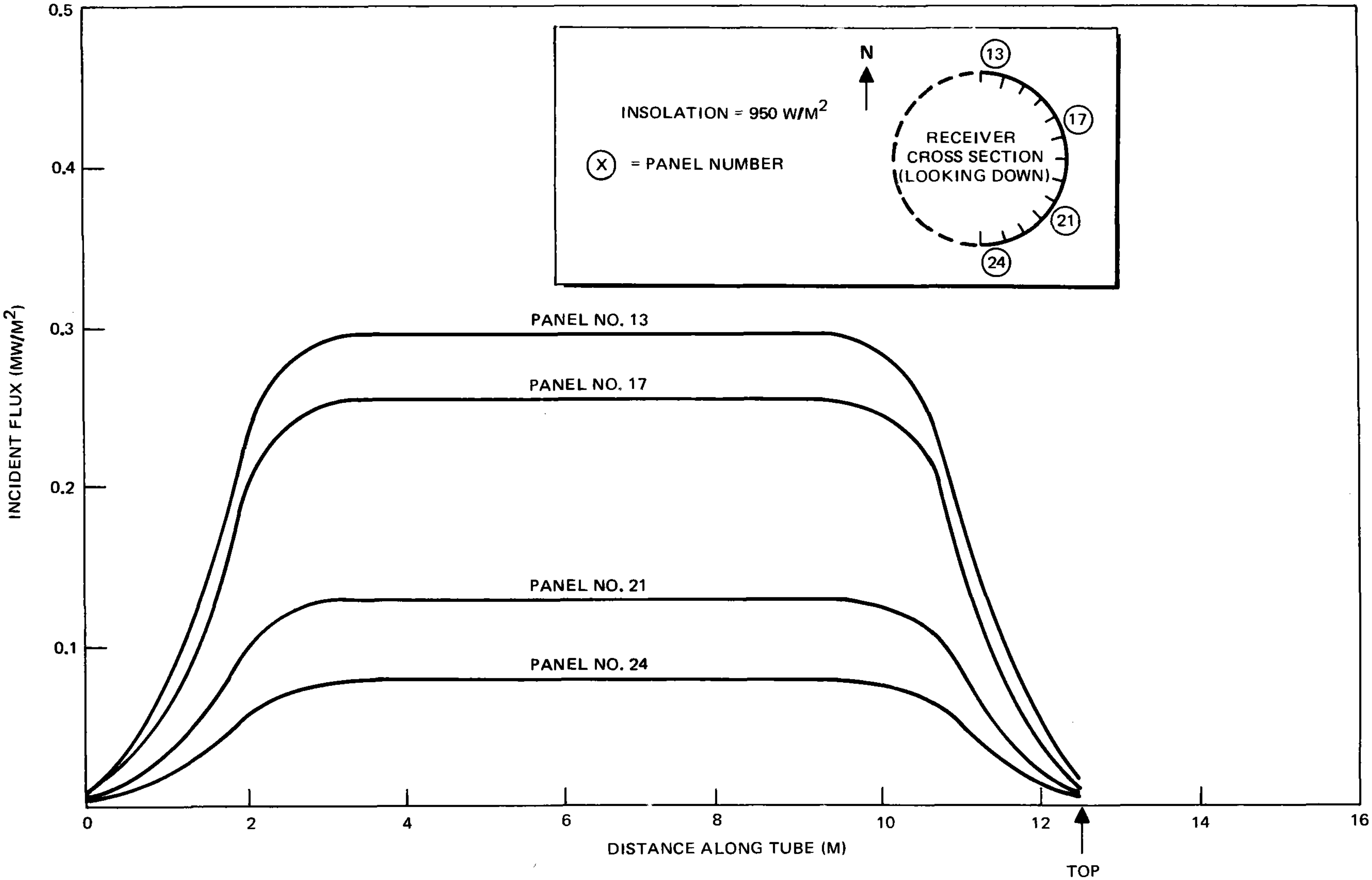


Figure 2-1. Pilot Plant Receiver Incident Heat-Flux Profiles (Equinox Noon)

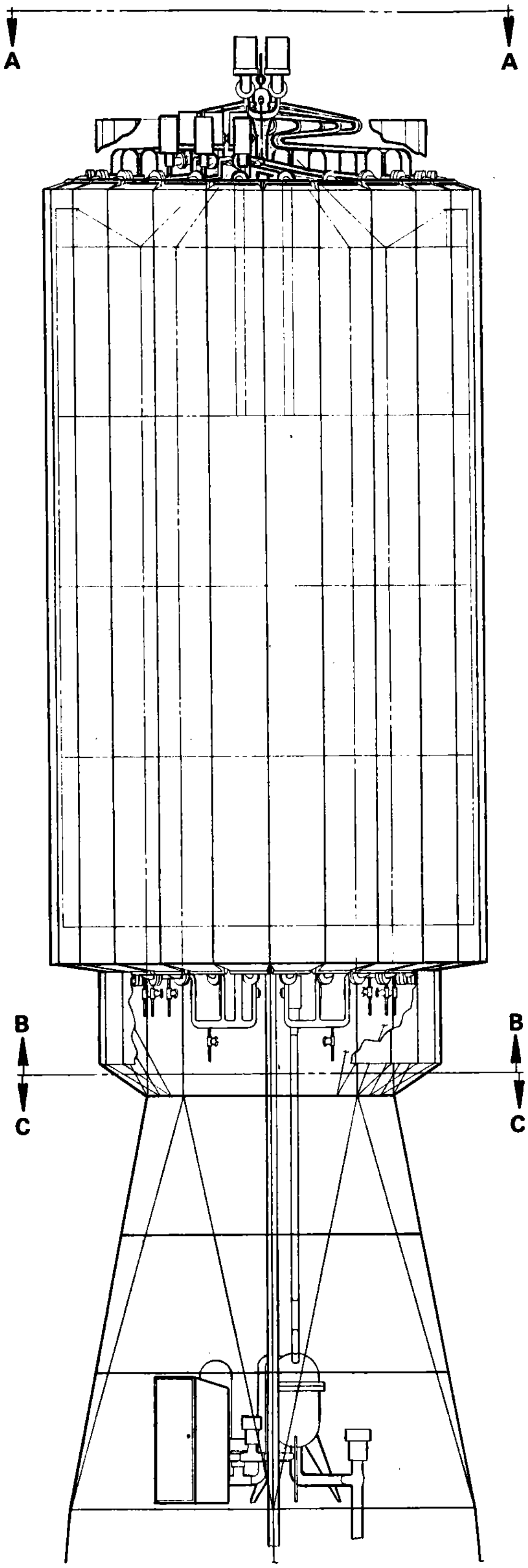
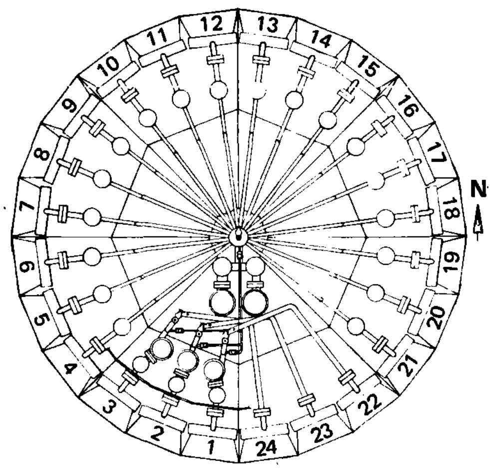
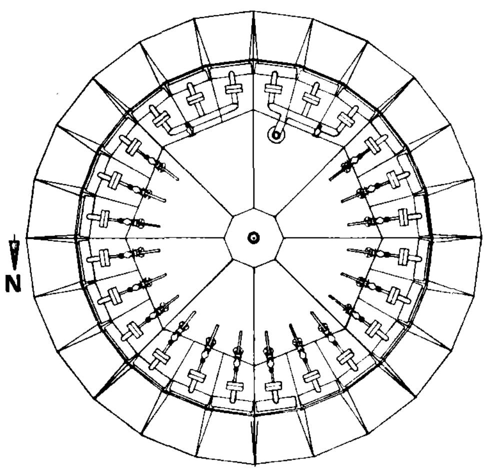


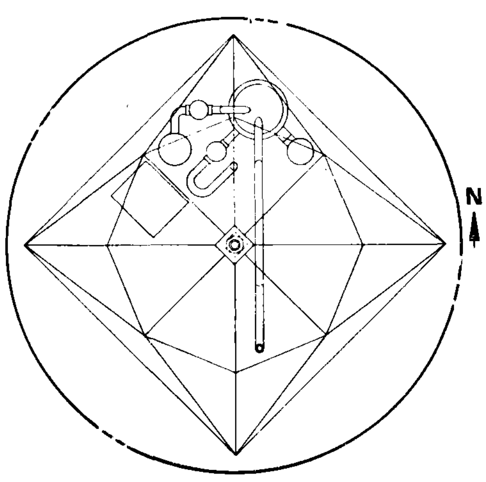
Figure 2-2. Pilot Plant Receiver Unit External View (Looking North)



VIEW A–A



SECTION B–B



SECTION C–C

Figure 2-3. Pilot Plant Receiver Unit Cross Sections

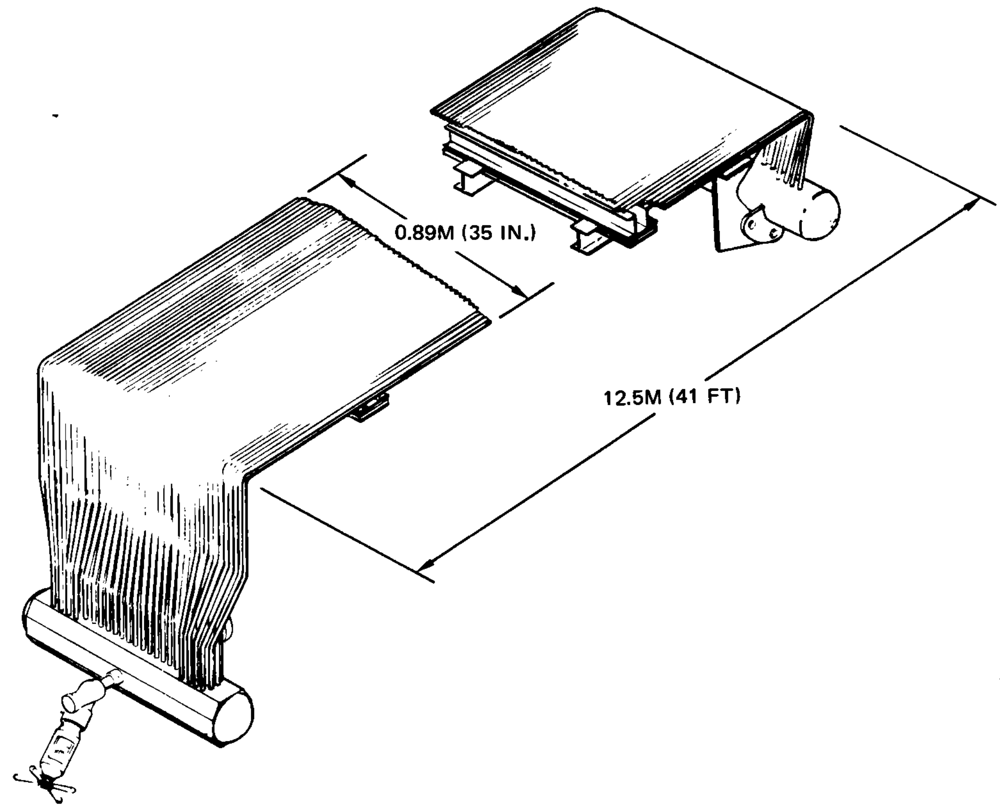


Figure 2-4. Pilot Plant Receiver Panel

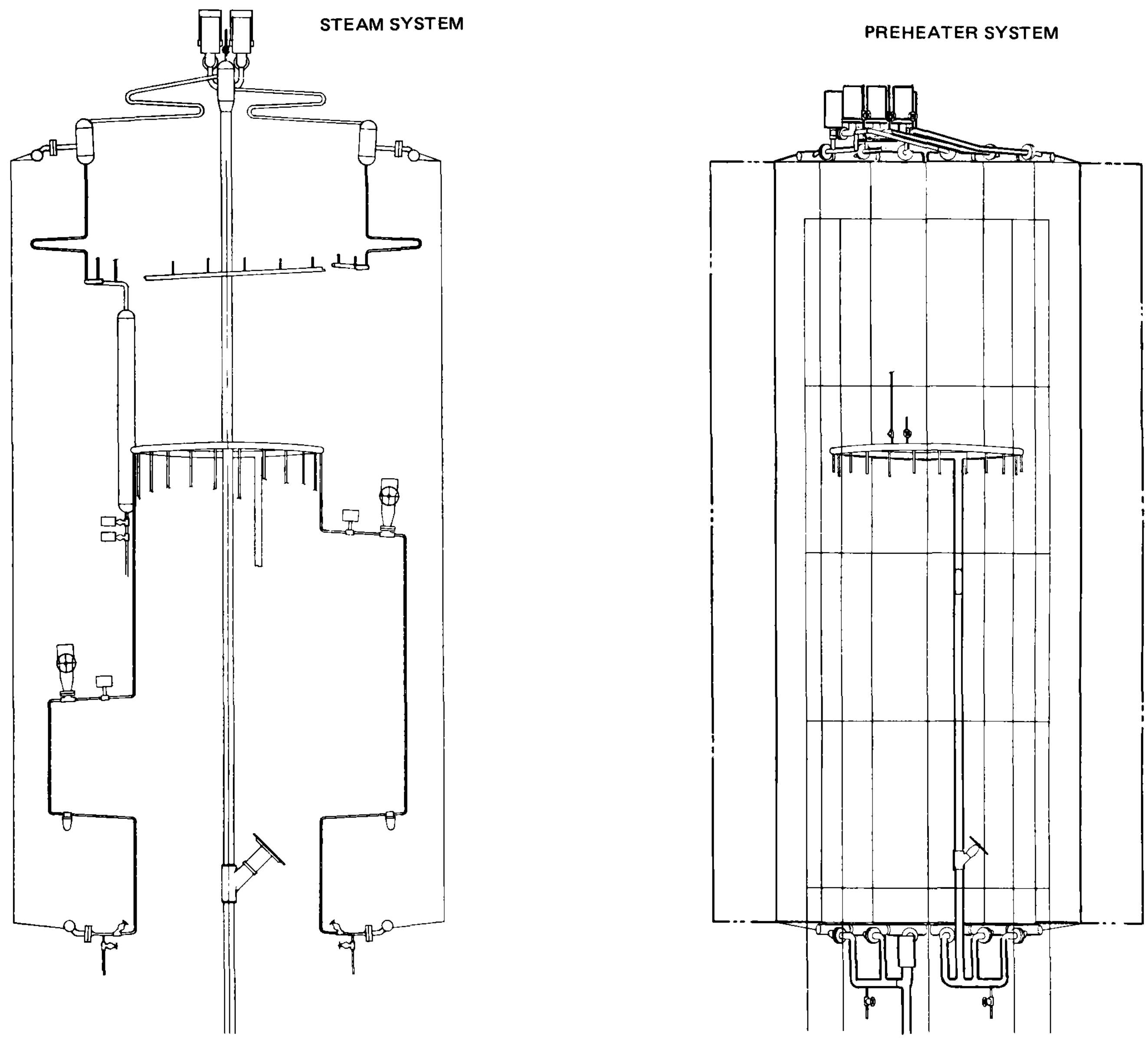


Figure 2-5. Absorber Feed System

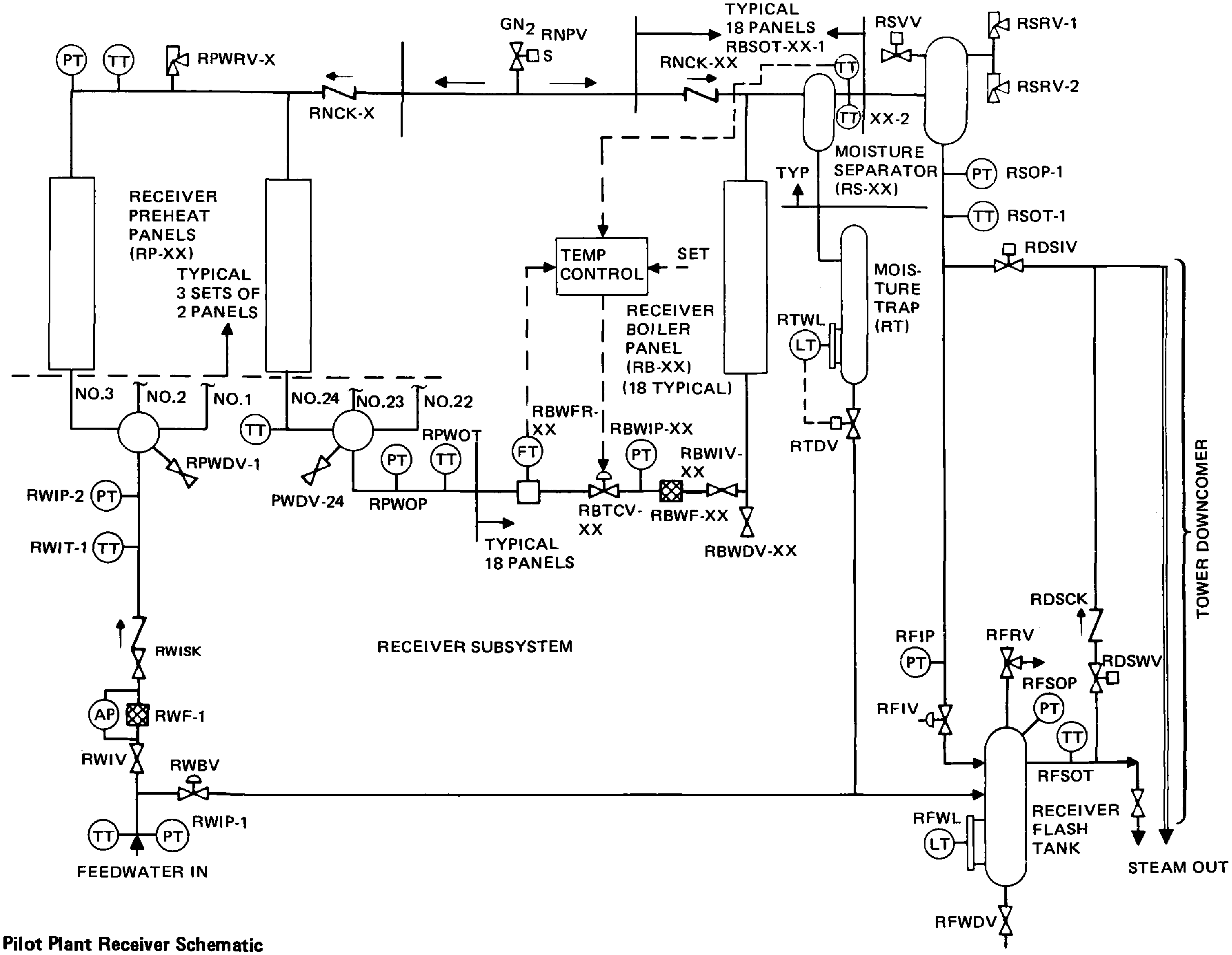


Figure 2-6. Pilot Plant Receiver Schematic

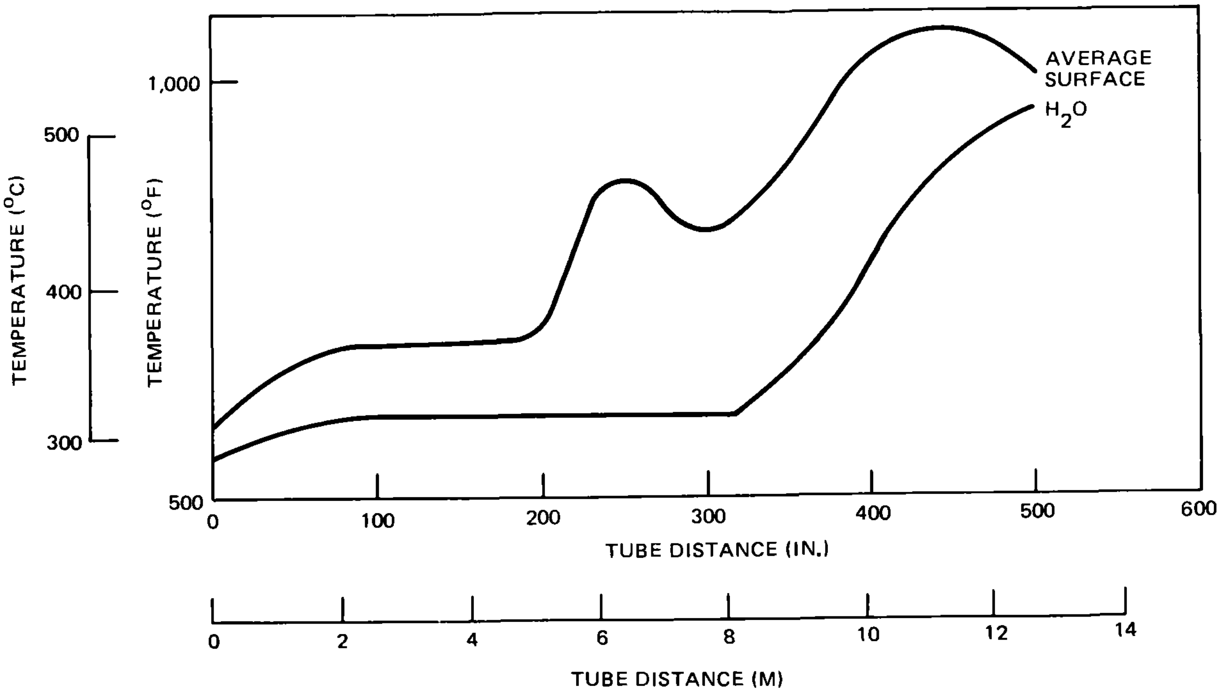
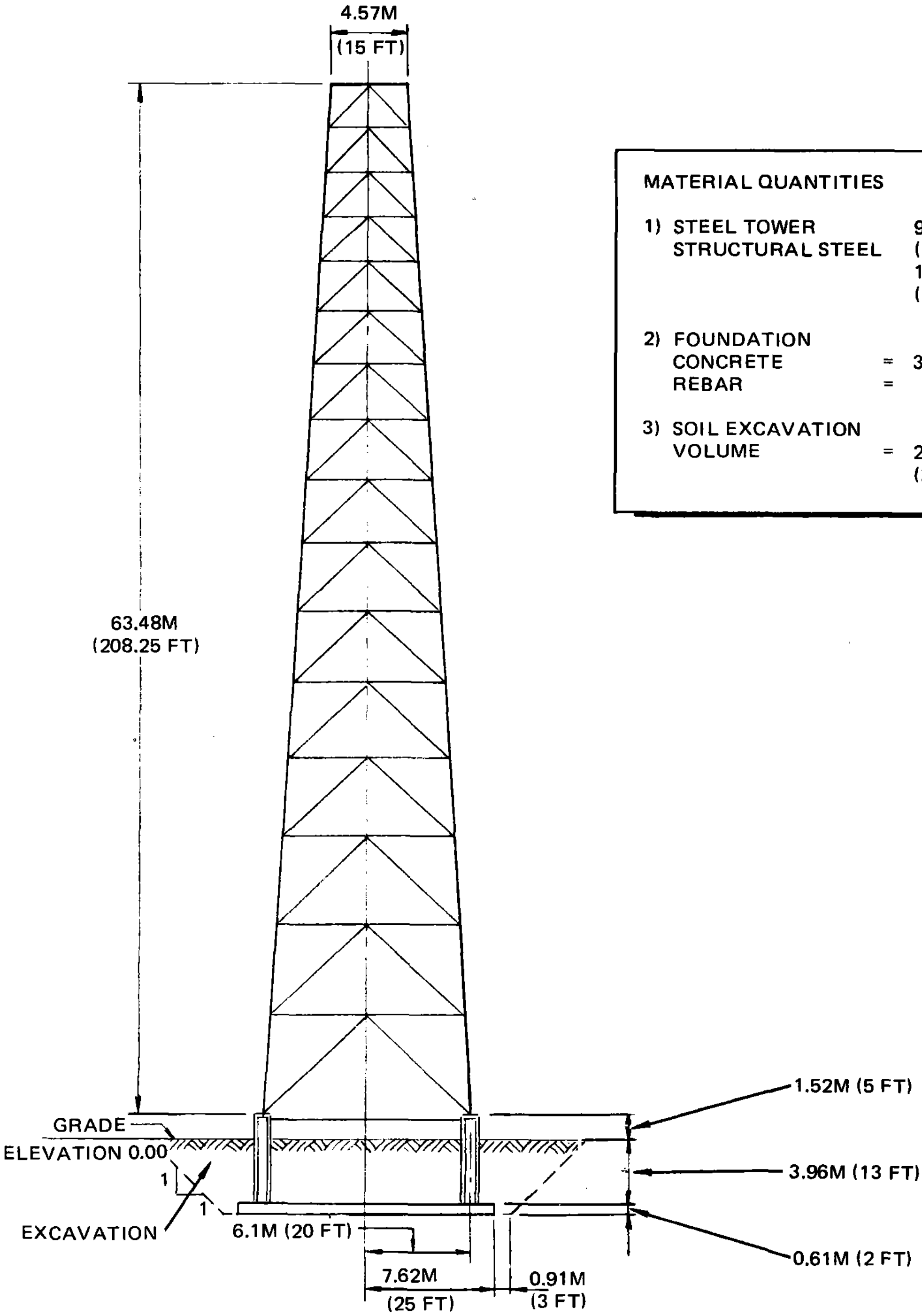


Figure 2-7. Pilot Plant Temperature Profiles, Equinox Noon, North Tube



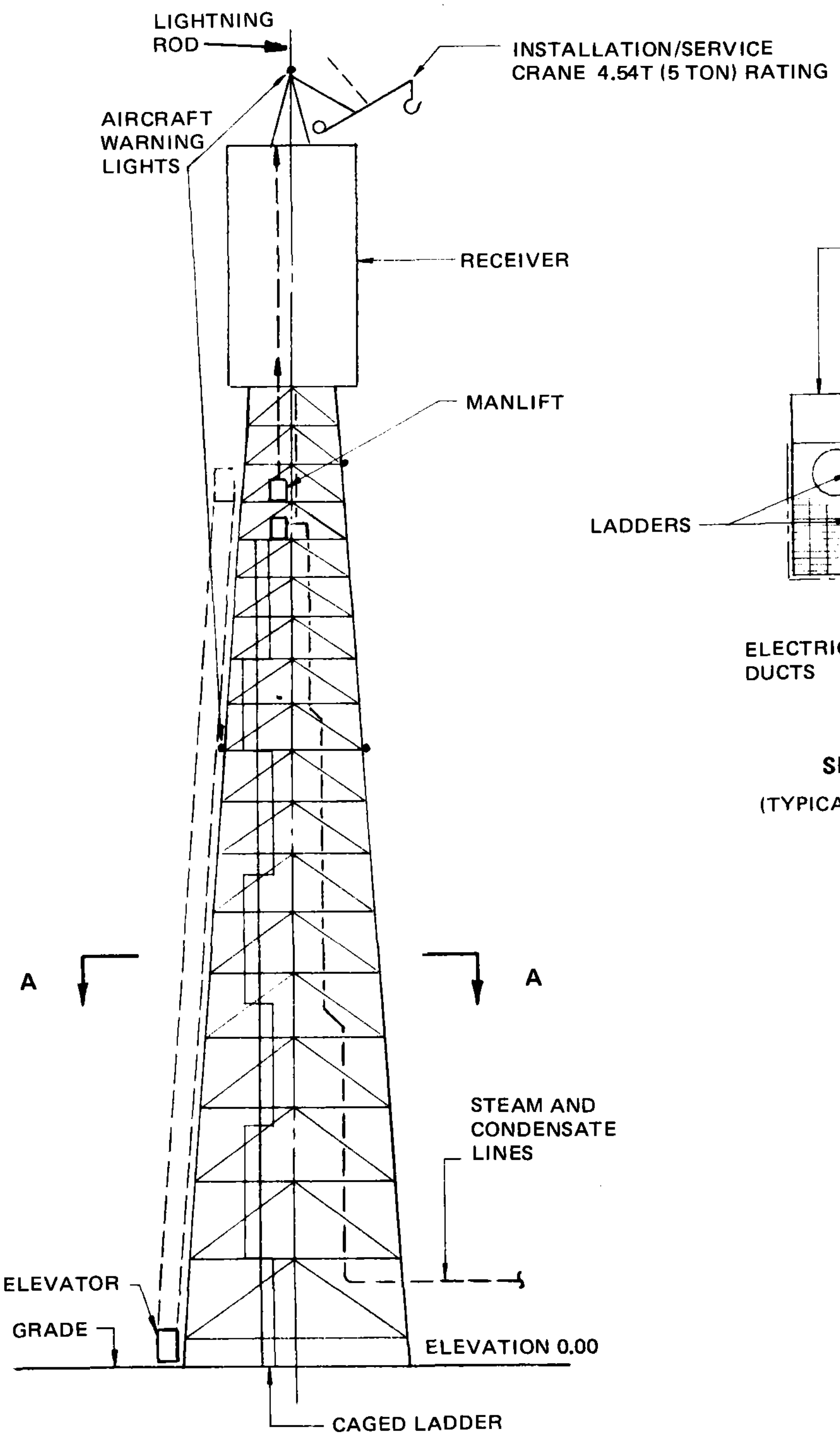
MATERIAL QUANTITIES

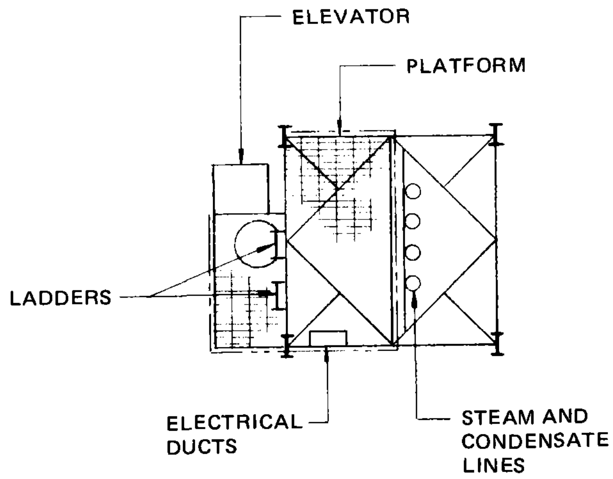
1) STEEL TOWER STRUCTURAL STEEL — 94.5T (104 TONS) (FOR 0.25G SEISMIC); 117.94T (130 TONS) (FOR 0.33G SEISMIC)

2) FOUNDATION
   CONCRETE = 305.83 CU M (400 CU YD)
   REBAR = 27.22T (30 TONS)

3) SOIL EXCAVATION
   VOLUME = 2,140.78 CU M (2,800 CU YD)

Figure 2-8. Pilot Plant Steel Receiver Tower





SECTION A–A

(TYPICAL ARRANGEMENT)

Figure 2-9. Pilot Plant Steel Receiver Tower with Auxiliary Equipment

2.3 COMMERCIAL RECEIVER REFERENCE DATA

This section contains Table 2-9 and 2-10 and Figures 2-10 through 2-17.

Table 2-9

COMMERCIAL RECEIVER LOSSES

	Values - MW	
Type of Loss	Rated Steam	Derated Steam
IR Radiation	20.6	14.3
Convection	5.4	4.5
Reflected Insolation	28.0	14.4
Total	54.0	33.2
Absorbed Energy	506.4	254.2
Percent	9.6	11.5

Table 2-10

COMMERCIAL RECEIVER WEIGHT SUMMARY
(AT .25g SEISMIC INPUT)

Item	Weight in kg x 10^{-3}	(kips)	Assumed cg Location* in Meters	(ft)
Carbon Steel (ASTM A-572 Grade 50)	653	(1437)	25.91	(85)
24 Panel Assemblies*	155	(340)	25.91	(85)
Piping	307	(675)	18.59	(61)
Crane	42	(92)	44.20	(145)
Other Components	73	(160)	20.88	(68.5)
Total Weight	1229	(2704)	*Above tower interface	

*Boiler Panel Wt = 13,200 lb (each of 20 panels)
Preheater Panel Wt = 19,000 lb (each of 4 panels)

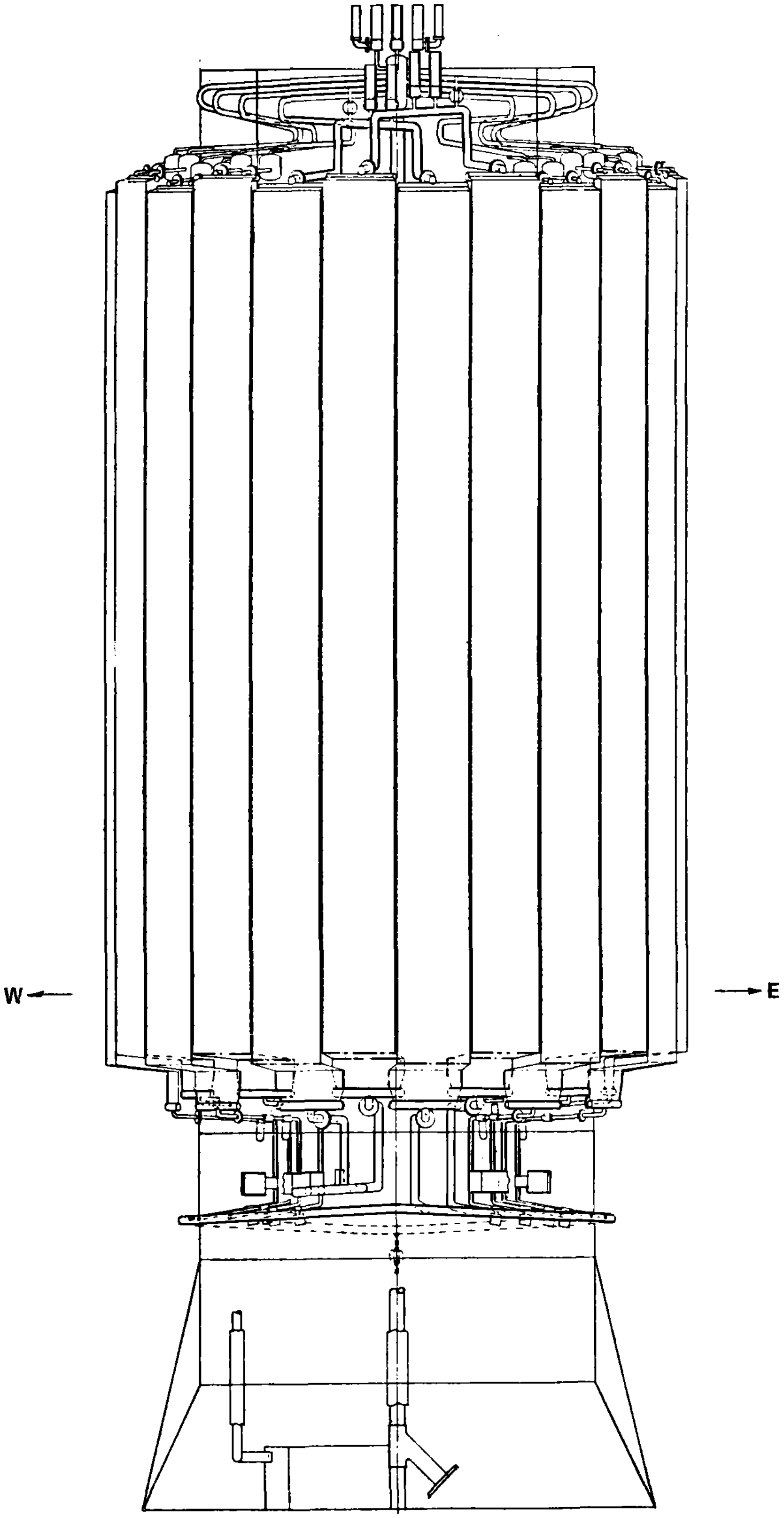


Figure 2-10. Commercial Receiver Unit

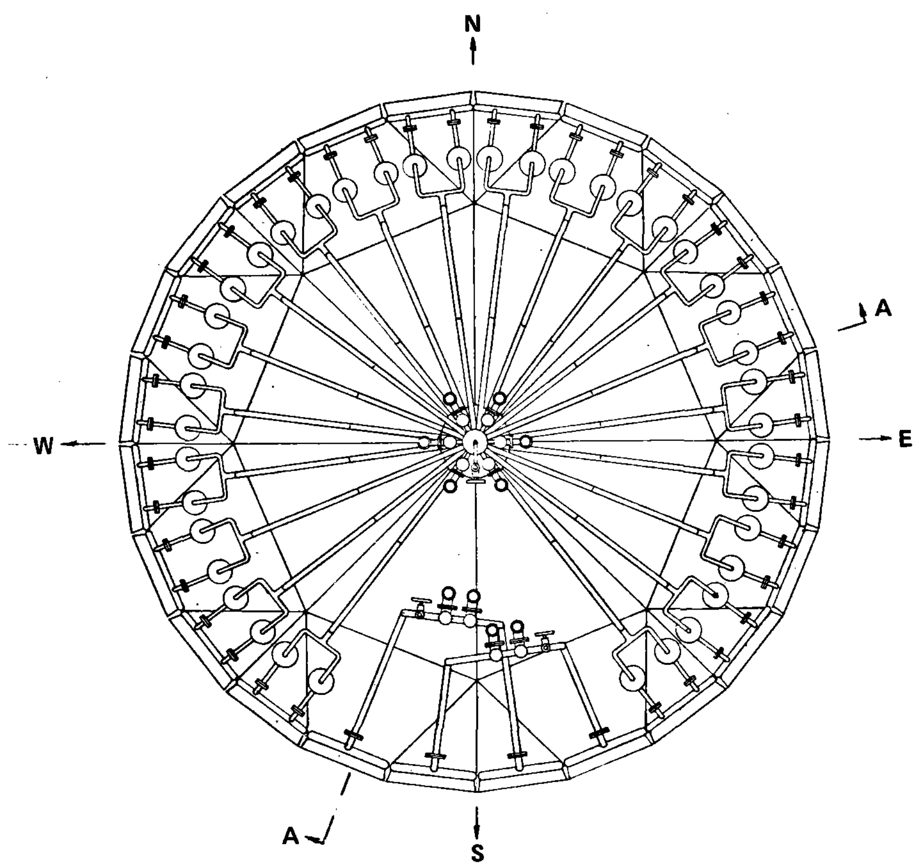


Figure 2-11. Commercial Receiver, Top View

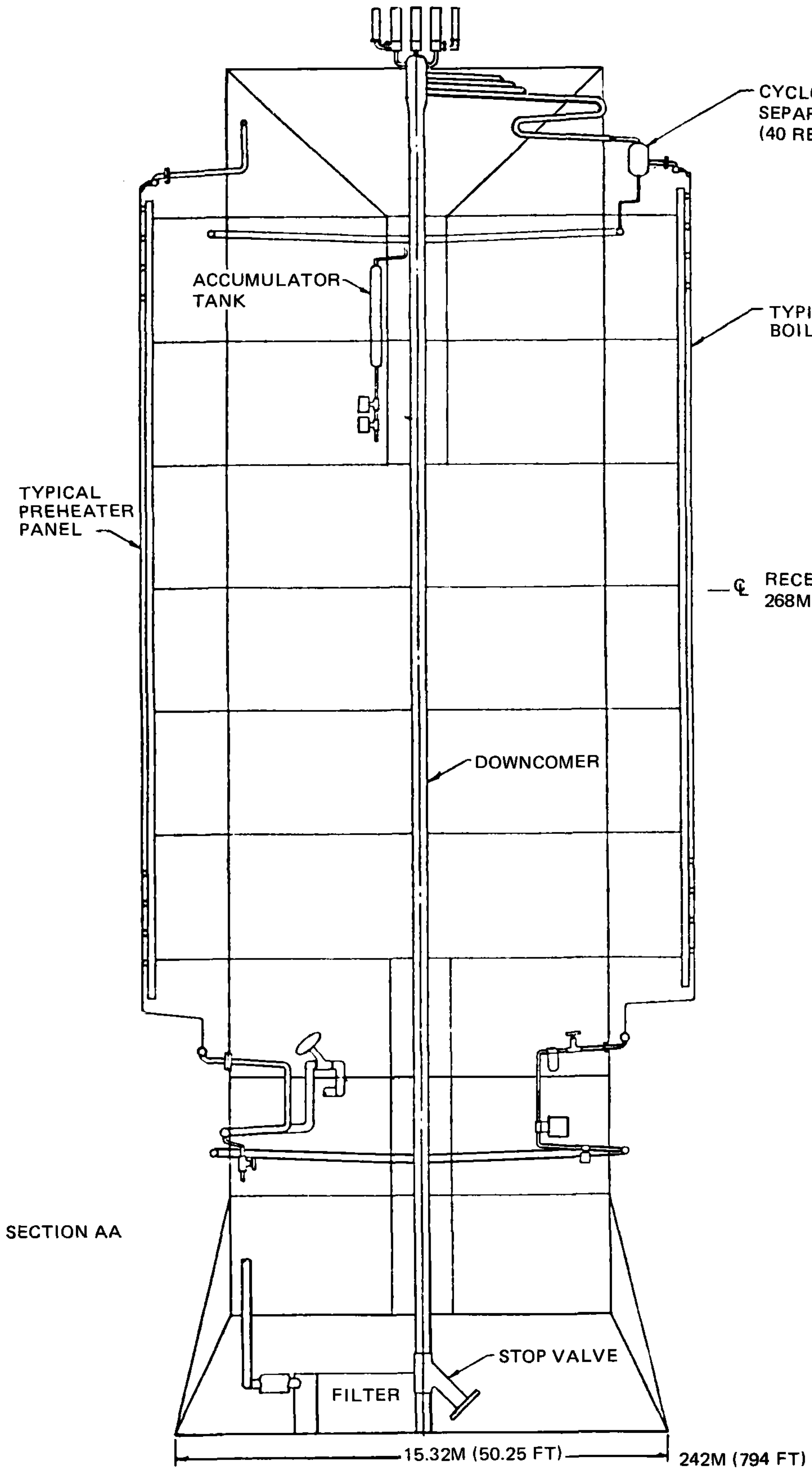


Figure 2-12. Commercial Receiver, Section View

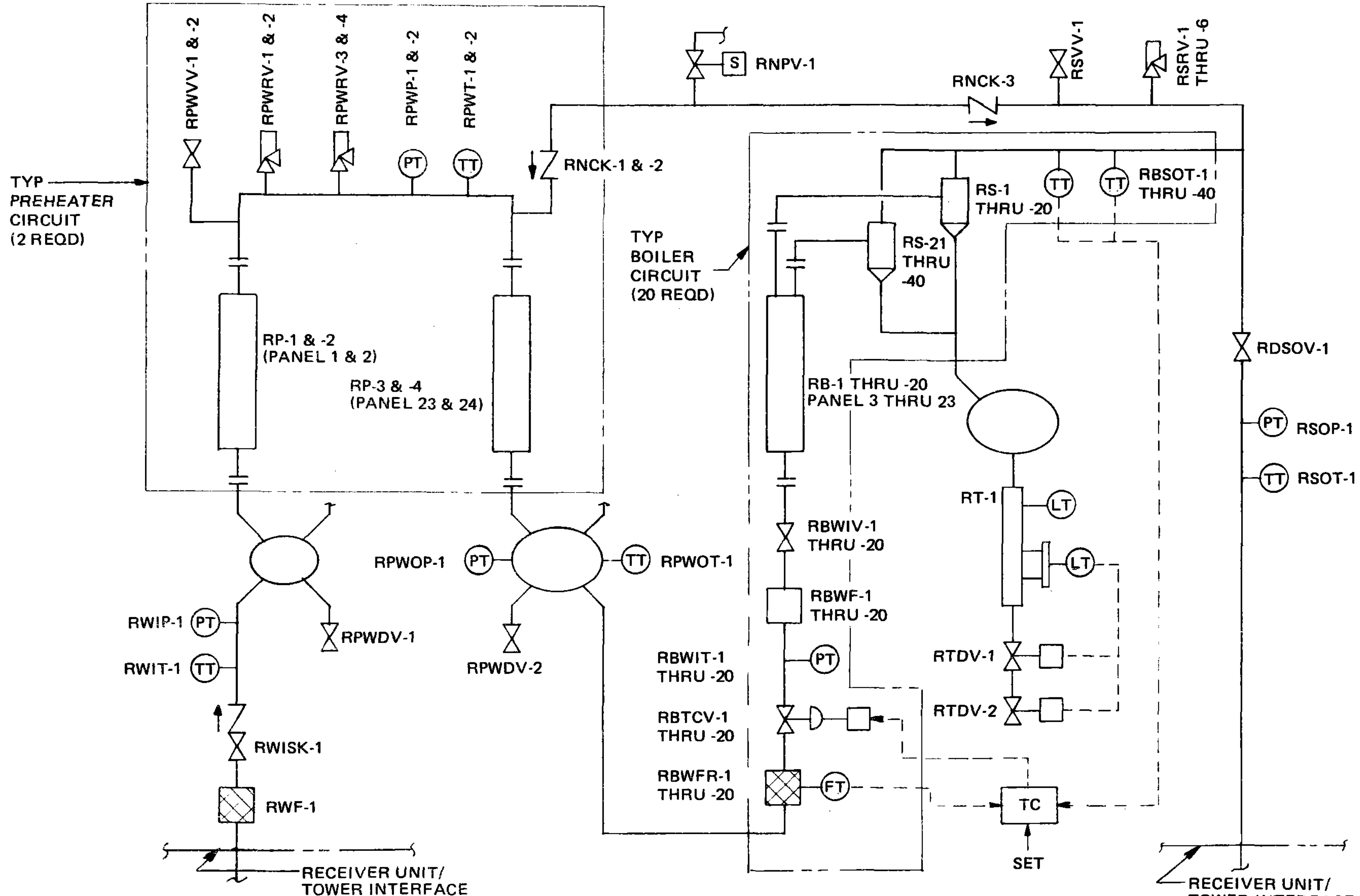


Figure 2-13. 100-MW Receiver Schematic

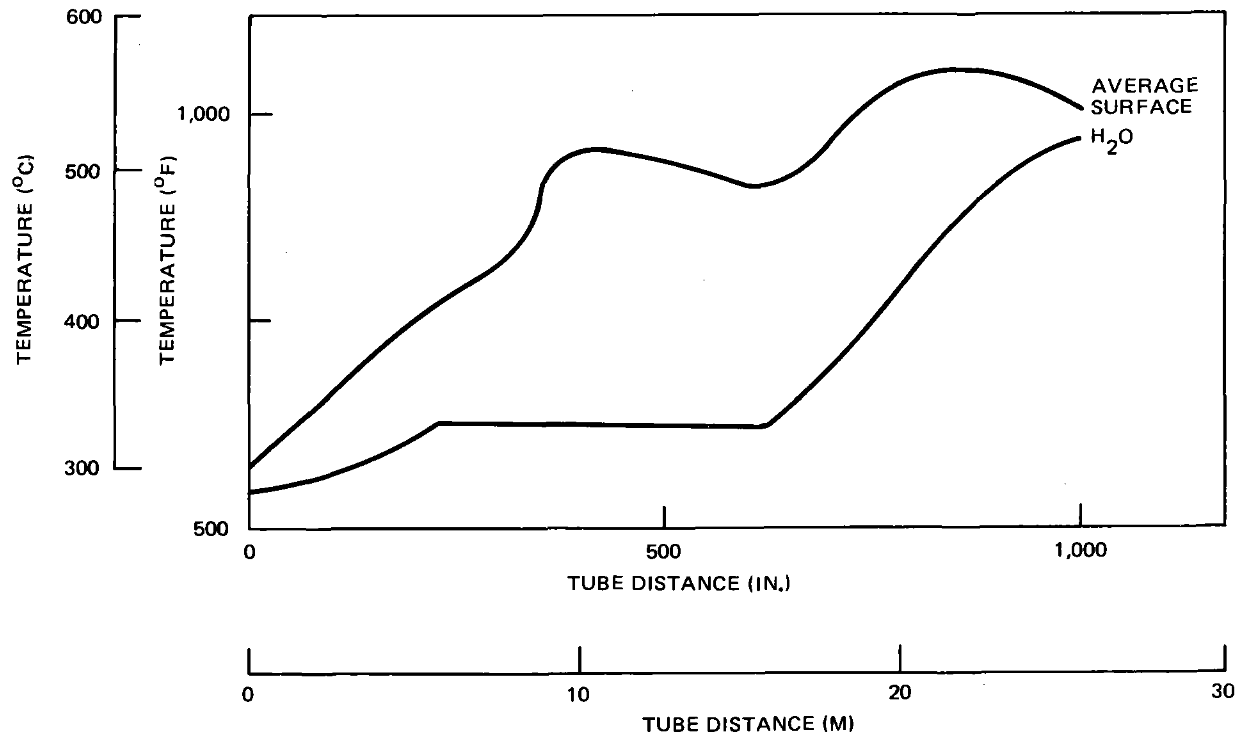


Figure 2-14. 100-MW Temperature Profiles, Equinox Noon, North Tube

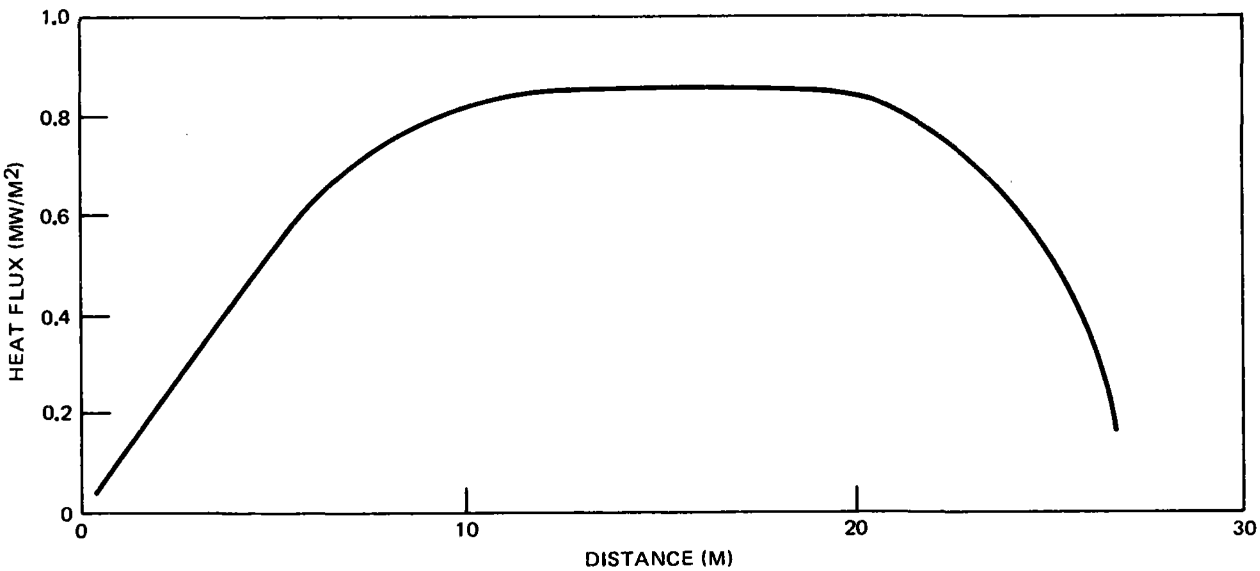
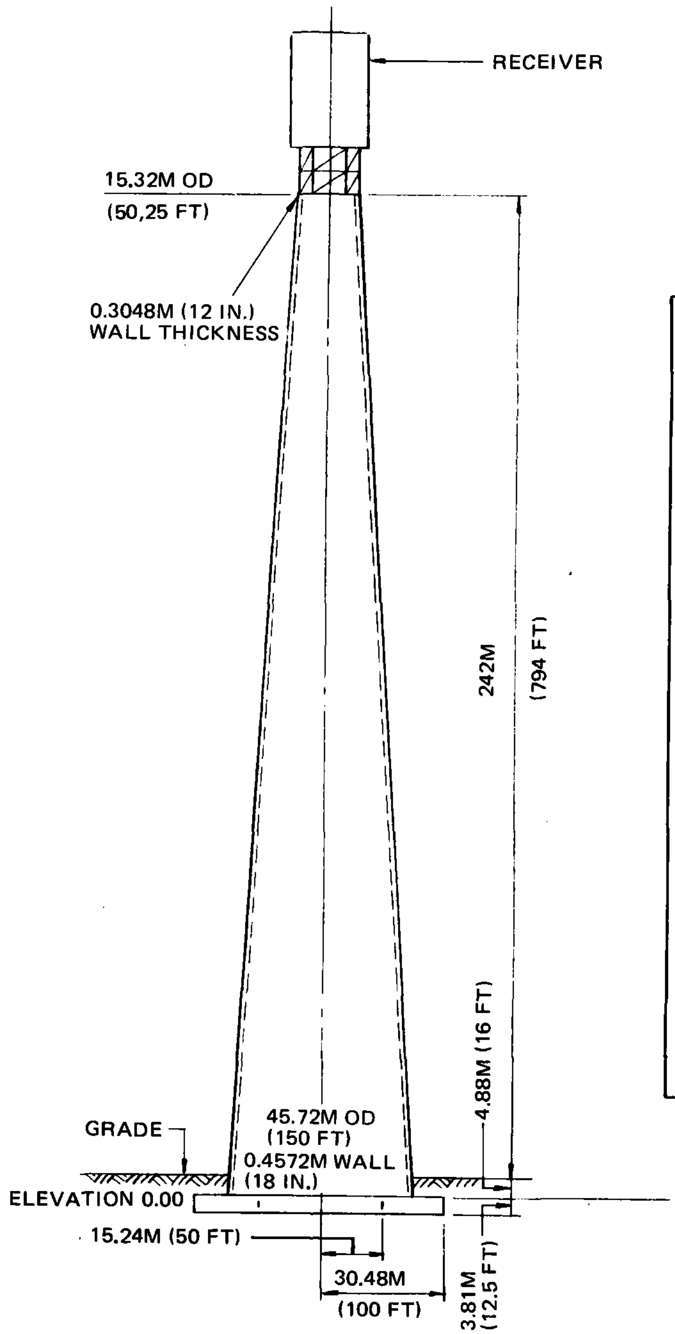


Figure 2-15. Commercial Receiver Heat Flux, Equinox Noon, North Panel



MATERIAL QUANTITIES

1) CONCRETE TOWER		
CONCRETE	=	9,203.83 CU M (12,038 CU YD)
REBAR	=	967T (1066 TONS)
2) FOUNDATION MAT		
CONCRETE	=	8,339.85 CU M (10,908 CU YD)
REBAR	=	363T (329 TONS)
3) SOIL EXCAVATION VOLUME	=	35,026.92 CU M (45,813 CU YD)

NOTES:

1) MIN CONCRETE STRENGTH SHALL BE 27.6 MPa (4,000 PSI) COMPRESSIVE STRENGTH AT 28 DAYS

2) REINFORCING BARS SHALL BE NEW INTERMEDIATE GRADE DEFORMED BARS WHICH SHALL CONFORM TO ASTM 615 GRADE 60

Figure 2-16. Commercial Plant Concrete Receiver Tower

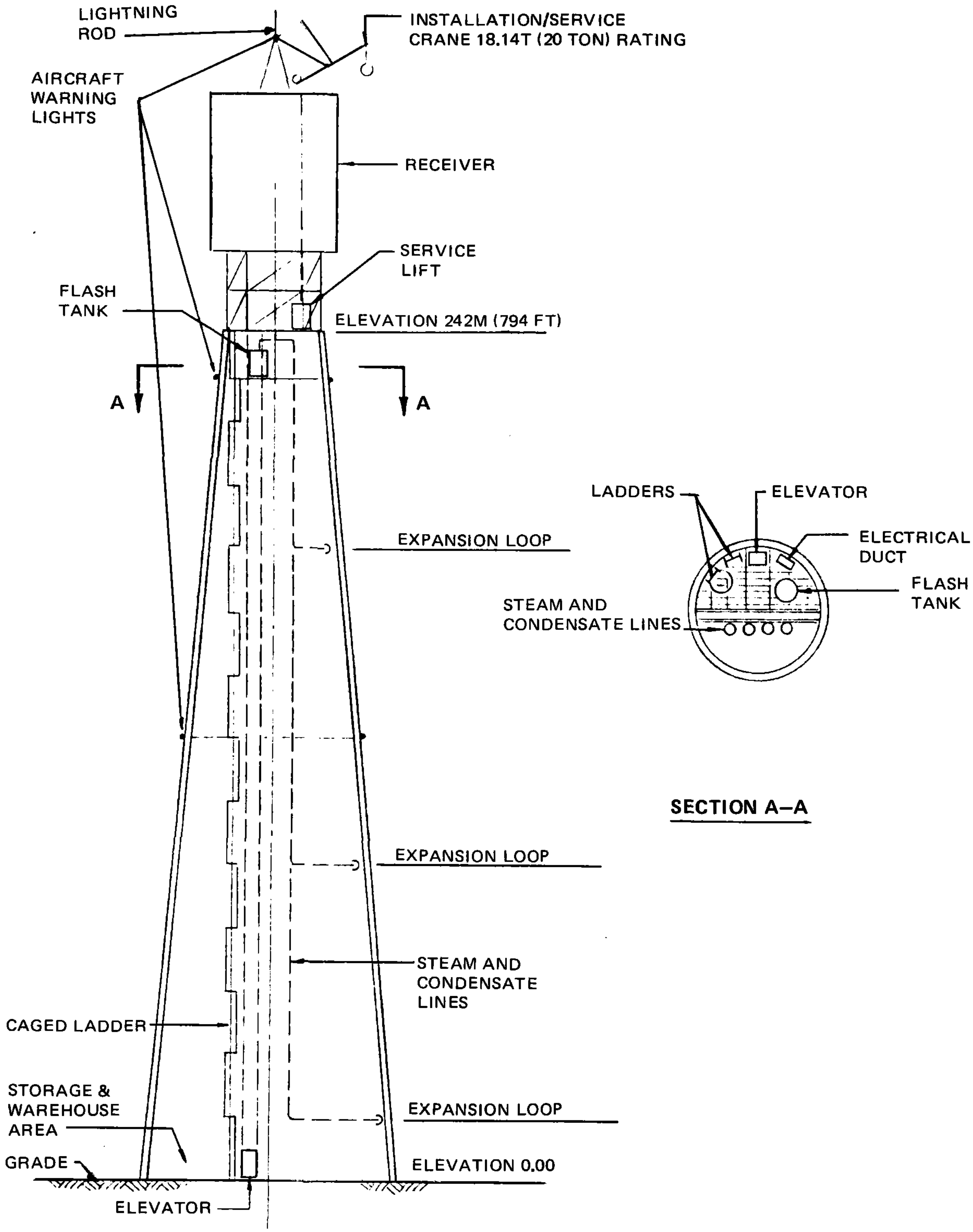


Figure 2-17. Commercial Plant Concrete Receiver Tower with Auxiliary Equipment

3 COMMERCIAL PLANT RECEIVER DEFINITION

Section 3
COMMERCIAL PLANT RECEIVER DEFINITION

This section describes the analyses and design of the Commercial Plant receiver subsystem for the 100-MWe solar powerplant and the plans for its fabrication, installation, and operation (Figure 3-1).

The Commercial Plant receiver design concept was selected to satisfy the Department of Energy's solar central receiver program objective to achieve the lowest plant investment and operational costs. The design philosophy and/or rationale which directed the design selection process has been given in detail in section 1. 2.

3. 1 REQUIREMENTS

The mission of the Commercial Plant receiver subsystem is to efficiently transfer the energy from the concentrated solar radiation reflected from the mirrors of the collector subsystem into the water supplied by the electrical power generation subsystem and deliver steam at precisely controlled superheated conditions to the plant turbine generator and/or the TSS.

The receiver subsystem design will also minimize complexity and cost, and maximize ease of fabrication and maintenance within the limitations permitted by performance requirements.

3. 1. 1 Fluid Conditions

Nominally, the receiver will be required to accept water from the flow distribution system at 15. 5 MPa (2250 psia) and 234°C (454°F) and deliver superheated steam at rated conditions of 11. 1 MPa (1,615 psia) and 516°C (960°F) to the electrical generation subsystem. Any rated steam generated in excess of turbine power requirements will be diverted to the thermal storage subsystem.

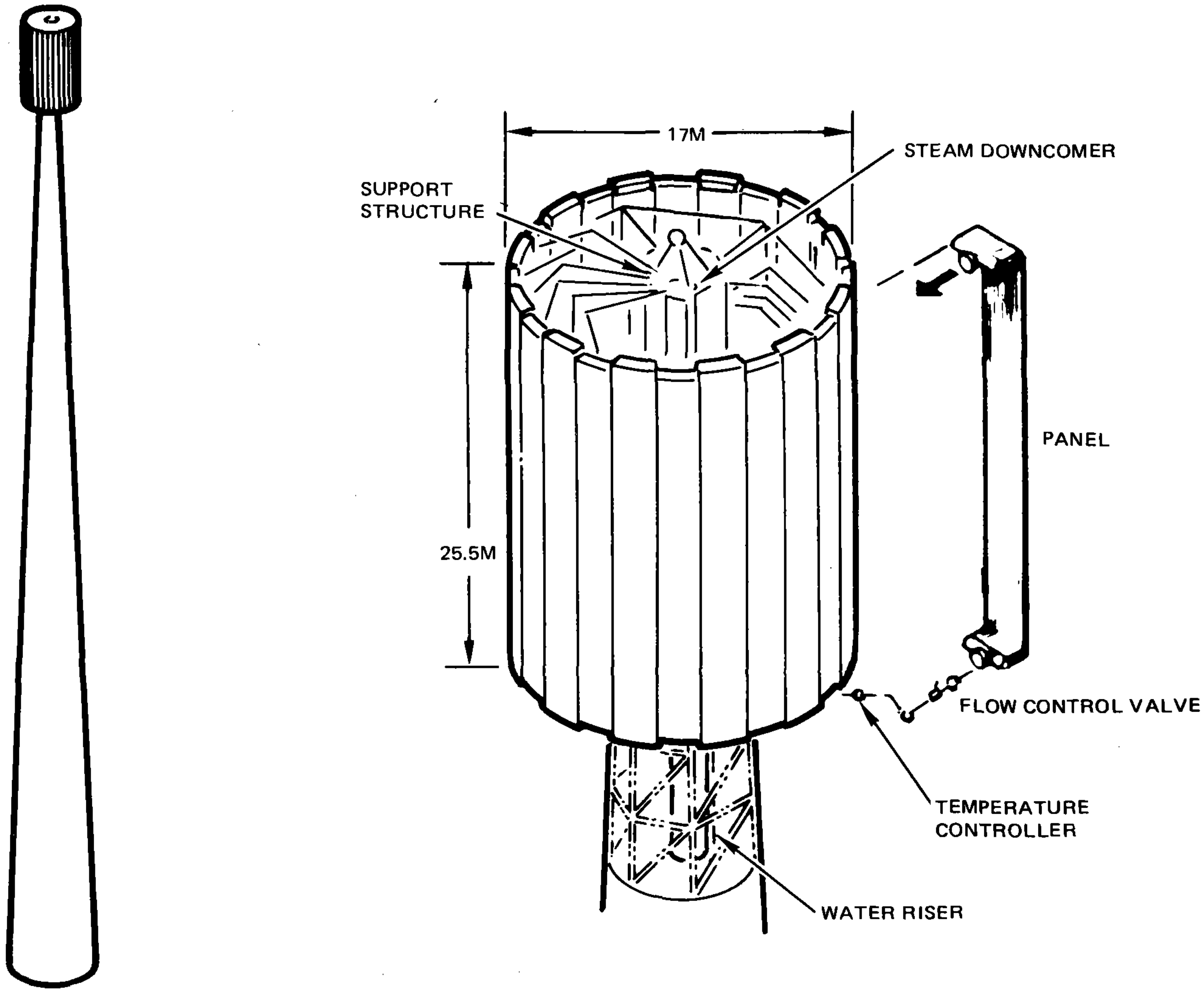


Figure 3-1. Commercial Plant Receiver

The top of the concrete has an outside diamter at 15. 3m (50. 25 ft) with a nominal 0. 305m (12 in.) wall thickness. The base of the tower has an outside diameter of 45. 7m (150 ft) with a 0. 46m (18 in.) wall thickness. The foundation, 4. 9m (16 ft) below finished grade, is a 61m (200 ft) OD annular circular mat with a 30. 5 (100 ft) ID. Foundation thickness is 3. 8m (12. 5 ft).

To initiate startup, water from the water-treatment equipment of the electrical power generation subsystem is forced up the receiver tower riser by the receiver feed pumps and into the receiver inlet filter assembly. Leaving the filter assembly, the water enters a manifold which distributes the flow into the inlets of the two parallel sets of two panels in series located on the south side of the receiver and designated to function as preheaters. The water absorbs heat as it flows up through the first panel of each of the sets and then down the preheater through the second panel where it joins the flow from the other preheaters in a ring manifold supplying the remaining 20 panel assemblies designed as boiler panels. The water passes through a modulating flow control valve at the inlet to each boiler panel, then flows vertically upward absorbing heat from the incident solar radiation and leaving the upper end of the boiler panels as superheated steam. The individual boiler panel inlet valves provide the flow control necessary to maintain constant outlet temperature despite diurnal and seasonal variations in heat load at each panel. The control valves also control cloud-induced transients and regulate startup and shutdown sequences. Active control of the water flow through the preheater panels is not required.

As the steam exits from each of the panel discharge manifolds, it passes through a pair of cyclone-type water separators as a precautionary measure to ensure absolutely dry steam. The steam enters the steam downcomer collection manifold where it is mixed with the discharge flow from the other boiler panels and is finally carried away by the downcomer to the turbine of the electrical power generation subsystem, the thermal storage subsystem, or both as directed by master control.

An Incoloy 800 water header at the lower end of each panel assembly equally distributes water to all panel tubes. An Incoloy 800 steam header is also located at the upper end of each panel assembly to act as a collector manifold for all tubes. To ensure leak integrity, all panel tubes are welded to both manifolds.

All tubes are 27m (89 ft) long. The exposed length is 25.5m (83.6 ft). Additional length provides for folding over at the top and bottom of the panels to protect the inlet and outlet manifolds and support structure from radiation.

Tube surfaces exposed to solar radiation are coated with Pyromark paint which has demonstrated an absorptivity of 95% over a wide range of wavelengths. The coating is resistant to weathering and was tested for long-term compatibility with high-intensity solar radiation during the subsystem research experiments.

Each panel tube bundle is mounted to a panel backup structure to maintain the panel shape and hold it to the receiver tower structure in proper location while allowing for thermal growth and providing support for wind and seismic loads. A series of sliding clips and channels permit unrestrained lateral and vertical thermal expansion of the panels to prevent the buildup of thermal stresses. Each panel is insulated on the backside to reduce thermal loss and protect the support structure and control components.

The individual tubular panel subassemblies of the receiver unit are mounted on a central core steel support structure to form a single large and essentially circular (24-sided) cylinder 17m (55.8 ft.) in diameter by 25.5m (83.6 ft) long. Heliostats surrounding the tower direct collected insolation onto the full 360° external surface of the receiver unit.

The tower is of jump-formed concrete and extends 242m (794 ft) above grade to the interface with the receiver steel support structure which continues up through the receiver unit to an elevation of 281m (921 ft) where it is crowned with a 20-ton capacity crane. Midpoint of the receiver unit is 268m (879 ft).

The receiver subsystem must also be capable of delivering steam at 11.1 MPa (1,615 psia) and 368°C (694°F) when it is required to charge the total receiver energy output into thermal storage.

3.1.2 Power

The peak incident power to which the receiver is designed is naturally dependent on the mirror field interface. For the collector subsystem as considered herein, incident power onto the receiver is 560 MW_t. Other power requirements are as follows:

	Rated	Derated
• Maximum Absorbed Power	506.4 MW_t	254 MW_t
• Minimum Absorbed Power	92.4 MW_t	63.7 MW_t

The peak heat flux associated with the thermal environment influenced by the collector is 0.85 MW_t/m^2. Diurnal variations in receiver power are shown in Figure 3-2. The need for efficient capture and use of solar insolation requires a high solar absorptance value on the external surface of the receiver of not less than 0.9, regardless of degradation. Also, the surface must be easily refurbished.

3.1.3 Geometry

Geometric requirements for receiver design are as follows:

• Tower Height		242m (794 ft)
• Receiver Centerline Elevation		268m (879 ft)
• Receiver Envelope	Diameter	17m (56 ft)
(Absorbing Surface)	Height	25.5m (84 ft)

3.1.4 Structure

The structural requirements to which the receiver are designed are made up of two parts. The first refers to those areas of concern relative to internal pressure and temperature distribution. The second refers to external influences, namely wind and seismic loading.

As a forced flow steam generator, the receiver will be designed and certified to the requirements of Section I of the ASME boiler and local and state

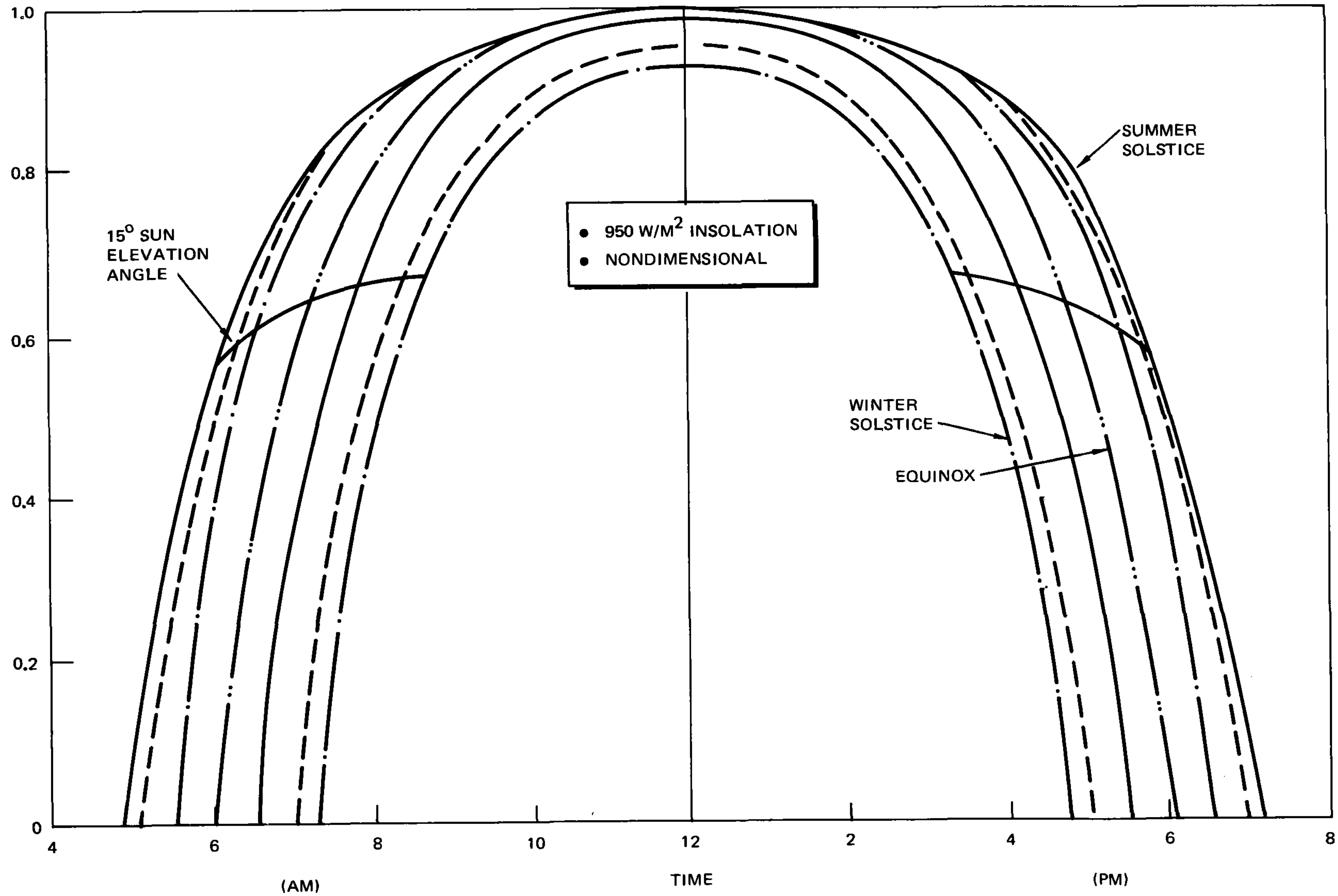


Figure 3-2. Monthly Diurnal Variations in Absorbed Thermal Power, Commercial System

piping codes. The receiver will also be designed for a 30-yr (10,000 cycle) fatigue life.

The second requirement, external influences, is covered by the following:

• Receiver Centerline Sway (16 m/s (36 mph) sustained wind at 10m)	0.67m (2.2 ft)
• Tower Survival (sustained wind at 10m)	40 m/s (90 mph)
• Seismic Load at Base of Tower	0.25g lateral input

3.1.5 Environment

This set of requirements refers to the conditions that govern heat losses:

• Ambient Temperature	28°C (82.6°F)
• Wind Speed at 10m Elevation	3.5 m/s (8 mph)
• Velocity Profile	$V_H = 3.5 \text{ m/s} \left(\frac{H}{10\text{m}}\right)^{0.15}$

The set also considers the nighttime conditions to which the evening thermal control is designed:

• Ambient Temperature	5°C (41°F)
• Wind Speed at 10m Elevation	3.5 m/s (8 mph)

3.1.6 Operation

The receiver must operate throughout the day within the envelope of power and fluid conditions described in earlier sections.

The receiver design must provide for smooth, stable, and safe transition from each of the following modes to another:

- Startup
- Derated operation to TSS
- Rated operation to turbine and TSS
- Rated operation to turbine only
- Intermittent cloud operation to TSS
- Emergency and normal shutdown
- Standby

Additionally, the receiver must be available for 96.7% of the sunlight exposure time (including 1.61% forced and 1.42% planned outages).

3.1.7 Functional and Physical Interfaces

The receiver interfaces optically with the collector, subsystem, mechanically and hydraulically with the riser and downcomer of the electrical power generation subsystem, and electronically with the master control subsystem. Interface requirements with the collector, thermal storage, and electrical power subsystems were covered in terms of fluid conditions and thermal power requirements in Sections 3.1.1 and 3.1.2.

The interface with master control requires that the receiver be capable of responding to commands from master control and also be capable of furnishing input data to master control for use in Pilot Plant status reporting/or control.

3.2 DESIGN CHARACTERISTICS

3.2.1 Subsystem Summary

The major hardware assemblies that comprise the commercial receiver subsystem are the receiver unit, the tower on which the receiver unit is mounted above the collector field, and the supporting control and instrumentation equipment.

The receiver unit consists of four modular preheater panels and 20 boiler panels, flow control and instrumentation equipment, and supporting structure.

Boiler panel assemblies are made of 170 tubes of high-strength, corrosion-resistant Incoloy 800 laid side by side and joined thermally and structurally and made opaque to incident light by full-length longitudinal welds. All boiler tubes are 12.7 mm (0.5 in.) OD x 6.9 mm (0.27 in.) ID.

Preheater panels are identical except that they are made up of only 113 tubes, 19.0 mm (0.75 in.) OD x 13.2 mm(0.52 in.) ID. The solar flux environment is less severe on the preheater panels, and larger tube size may be permitted to reduce the pressure drop through the preheater circuit.

During startup or other conditions, when insolation is too low to produce the proper superheat conditions, a combination of valves divert receiver discharge flow away from the downcomer and into a receiver flash tank assembly until proper superheat conditions are achieved.

A drawing of the overall receiver is shown in Figures 3-3 and 3-4. The apparatus at the center base of the receiver is the main filter element, which contains provisions for automatically backflushing at night. The requirement for filtration will depend on a final selection of material for the riser pipe line. A line is shown leading up from the filter to the inlet manifold for the two preheaters. Two boiler relief valves (code requirement) are shown on top of the receiver and two preheater relief valves are shown to the right of center near the top. Portions of the passive radiation shield are shown which protect the central top portion of the receiver from spillover radiation. Portions of a lower shield are shown at the bottom of the panels. The configuration of the preheater crossover lines are shown in the top sectional view (Figure 3-4).

The manifolding and feed system components are shown in Figure 3-5. The steam lines, with expansion sections which conduct steam from the separators of each panel to the downcomer are shown at the top of Figure 3-5. The water drain lines from each of the separators and the drain line manifold are also shown. The drain line feeds into the receiver moisture trap which is equipped with remotely operated blowoff valves and level sensors. The blowoff valves operate in conjunction with the level sensors to maintain a specified water level in the tank. If the level exceeds the control level, a sensor higher up in the tank sends an alarm to master control.

3.2.2 Receiver Unit

Preliminary drawings of the receiver unit are shown in Figures 3-3, 3-4, and 3-5. Reference can be made to them for component placement and arrangement.

3.2.2.1 Absorber Description

This section contains the analysis and tradeoffs conducted to ascertain the proper configuration.

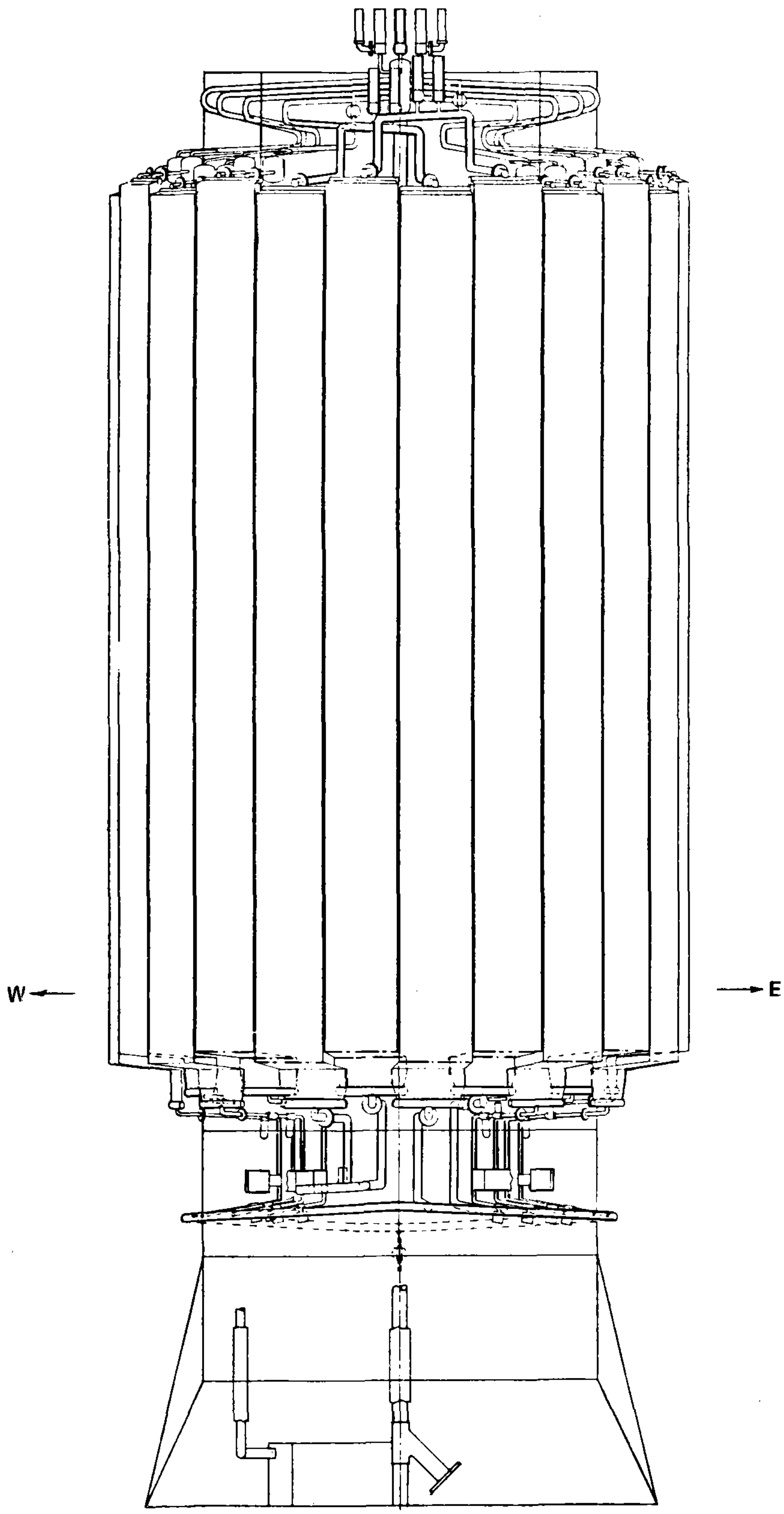


Figure 3-3. Commercial Receiver Unit

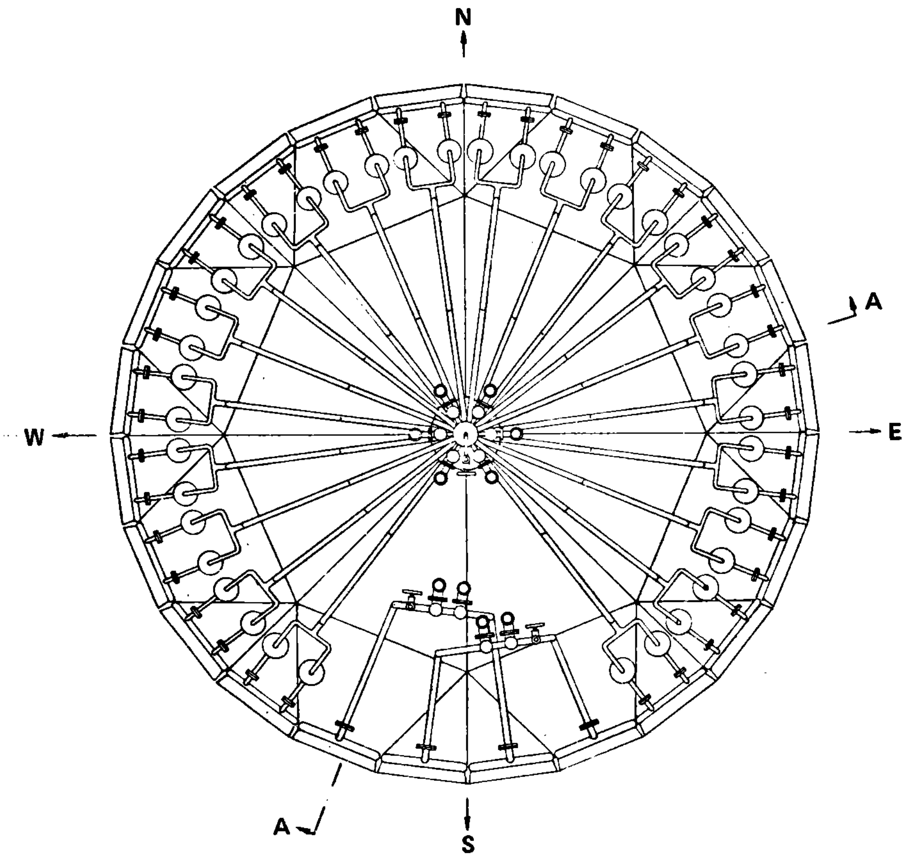


Figure 3-4. Commercial Receiver, Top View

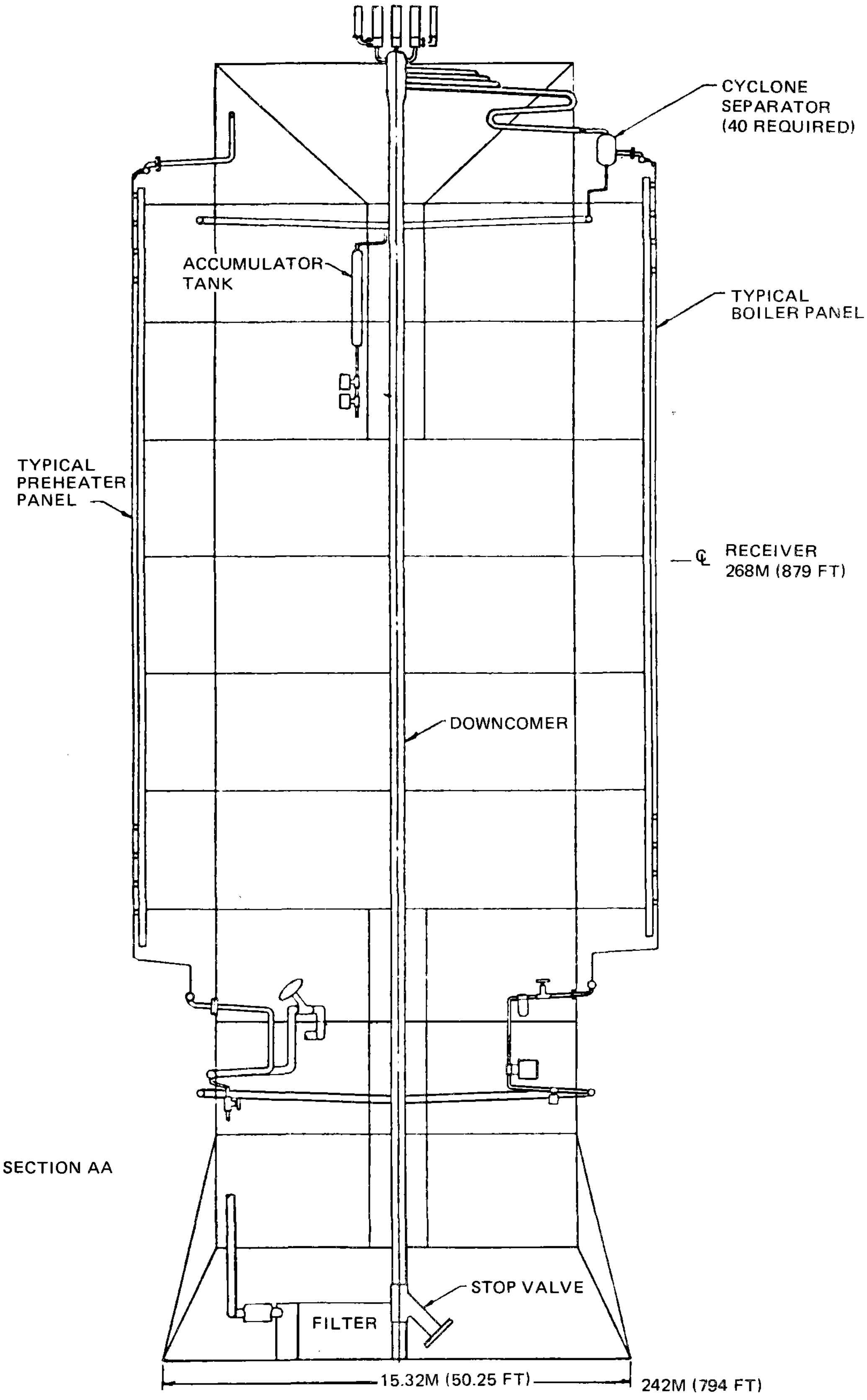


Figure 3-5. Commercial Receiver, Section View

Analyses and Trades

The commercial receiver design concept was selected to satisfy the Department of Energy solar central receiver program objective to achieve the lowest plant investment and operational costs. The primary design philosophy and rationale which directed the design selection process are in Section 1.2.

Similarly, details of the analysis techniques for both the Commercial and Pilot Plant designs are essentially identical and only a summary treatment is given of the commercial analyses. However, because the selection of basic receiver design configuration using both boiler and preheater panels was established by commercial considerations, the rationale of that decision is discussed in more detail below.

Receiver Panel Configuration

Implicit in the optimization of the commercial receiver and collector field were the cost of the individual receiver panels, the beam interception characteristics of the receiver, and receiver heat-loss considerations. The expanded optimization analysis considered a variety of receiver configurations which were aimed at exercising these receiver-related issues in the overall optimization and thereby ensuring that a minimum cost per unit energy system is defined. The three basic approaches to receiver design were:

A. All 24 receiver panels are identical single-pass-to-superheat boiler panels.

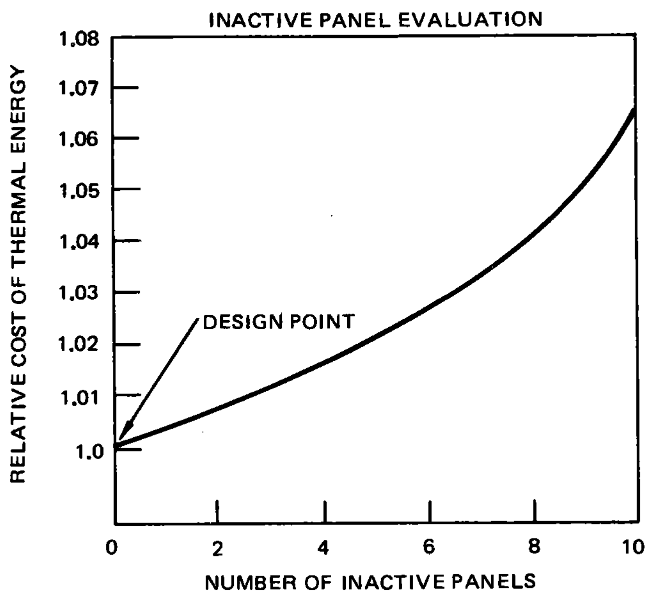
B. South-facing receiver panels are assumed to be preheat panels with the remaining panels being of the single-pass-to-superheat type. Considered were 2, 4, 6, and 8 such preheat panels.

C. South-facing receiver panels are assumed to be inactive, i.e., they are not actively cooled by the water/steam flow and are included only for aerodynamic symmetry; 2, 4, 6, 8, and 10 such panels were considered with the remaining panels being of the preheat and single-pass-to-superheat type.

The rationale used to arrive at these parametrically specified receiver configurations directly relates to the nature of the thermal power available on the south side of the receiver. In general, the thermal power arriving on the south side of the receiver is significantly less than that incident on other faces due to the minimal extent of the south side collector field indicated from previous optimization studies and the lower field cosine effects involved. As a result, flows through south-facing single-pass-to-superheat panels must be drastically throttled relative to other panels which can impact flow control design. In addition, elevated temperatures associated with the boiling and superheat processes result in an undesirably high percentage of heat loss from the south side of the receiver. The replacement of the panels with preheat panels allows that part of the receiver to operate at lower tube temperatures that correspond closely to feedwater temperatures. This significantly reduces heat losses from that part of the receiver. Also, the lack of flow control equipment and the possibility of significantly reducing preheater panel design requirements, i.e., which would be governed by peak north side conditions if identical preheater and boiler panel designs were used, permits appreciable cost savings to be anticipated.

The use of inactive panels essentially reduces those panel costs to zero. They do, however, totally compromise the contribution of the south side collector field. Optimization studies carried out with the use of these panels produced partial south fields or completely north-biased fields depending on the number of inactive panels used. This permitted a direct cost and performance comparison to be carried out between an optimized full 360° collector field and an optimized north-side only field as well as for a series of intermediate configurations.

The results of the optimization study as it influences receiver design are shown in Figure 3-6. The figure shows the relative cost of thermal energy on an annual basis with the use of successively larger numbers of inactive panels. In this analysis, it was assumed that the cost of an active panel is saved when an active panel is replaced with an inactive panel. The curve which represents the locus of optimized system costs indicates that the full 360° field is superior even when no costs are assumed for the inactive panels. Thus, as indicated, the "design point" which was selected includes a full 360° collector field with a 360° receiver containing all active heat-absorbing panels.



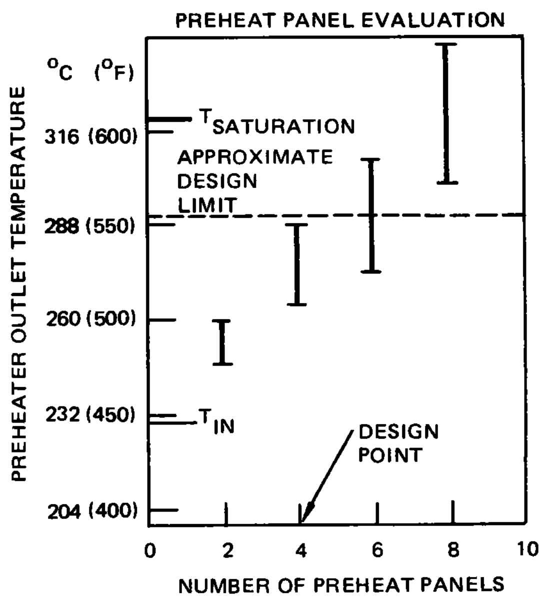


Figure 3-6. Receiver Panel Configuration — Commercial System

The relative makeup of receiver panels between the preheat and single-pass-to-superheat type can be seen from the data presented on the right side of Figure 3-6. The predicted variation in preheat panel outlet temperature over the course of the year is indicated by vertical bars. With the inlet feedwater and saturation temperatures as indicated, it is desirable to maintain at least 28^{o}C (50^{o}F) subcooling at the inlet to the boiler panels to permit the flow to become fully developed prior to the onset of the boiling process. In viewing the variations in preheat panel configurations considered (0 to 8 in. increments of 2), the temperature range indicated for configuration with two preheat panels indicates that they would operate substantially below the "approximate design limit." The outlet temperature range for four preheat panels represents a good design choice. By contrast, the six preheat panel configuration absorbs sufficient thermal power to cause the outlet water temperature to actually exceed the saturation value. This would imply that local boiling actually begins in the preheat panels which is an unacceptable design condition. As a result, the four preheat panel configuration has been selected as the baseline configuration with the remaining 18 panels being of the single-pass-to-superheat type. The preheat portion of the receiver would be configured into two parallel flow paths with each path containing two panels plumbed in series.

Cooling Circuit Analyses

Receiver cooling is based on the heat flux profile shown in Figure 3-7. Wall temperatures calculated for the receiver are shown in Figure 3-8. Detailed temperature distributions for two axial locations are shown in Figures 3-9 and 3-10. A thermal fatigue life analysis was conducted based on the temperature distributions shown in these figures. Details of the calculation technique are contained in the Pilot Plant discussion as is the data base used in the evaluation. Briefly stated, for the temperature distributions shown in Figures 3-9 and 3-10, the calculated fatigue life is in excess of 10,000 cycles.

Thermal Losses

Performance of the commercial receiver has been calculated considering reflected insolation, infrared radiation losses as well as convective losses. The techniques for performing the calcuations are described in detail in Section 4.3.2. The results are shown in Table 3-1.

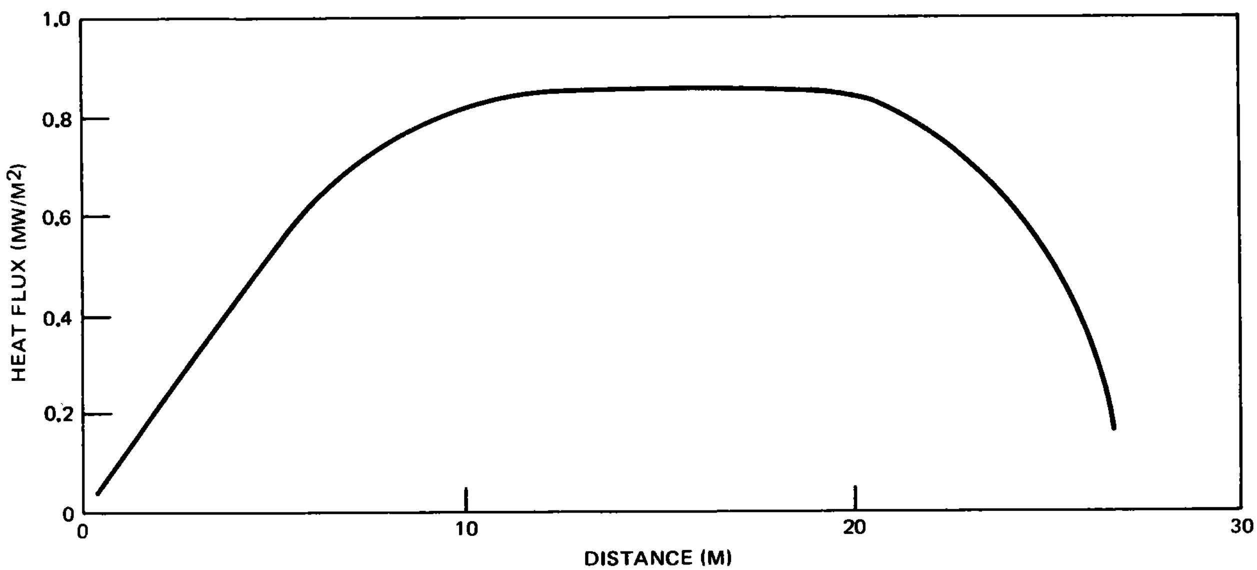


Figure 3-7. Commercial Receiver Heat Flux, Equinox Noon, North Panel

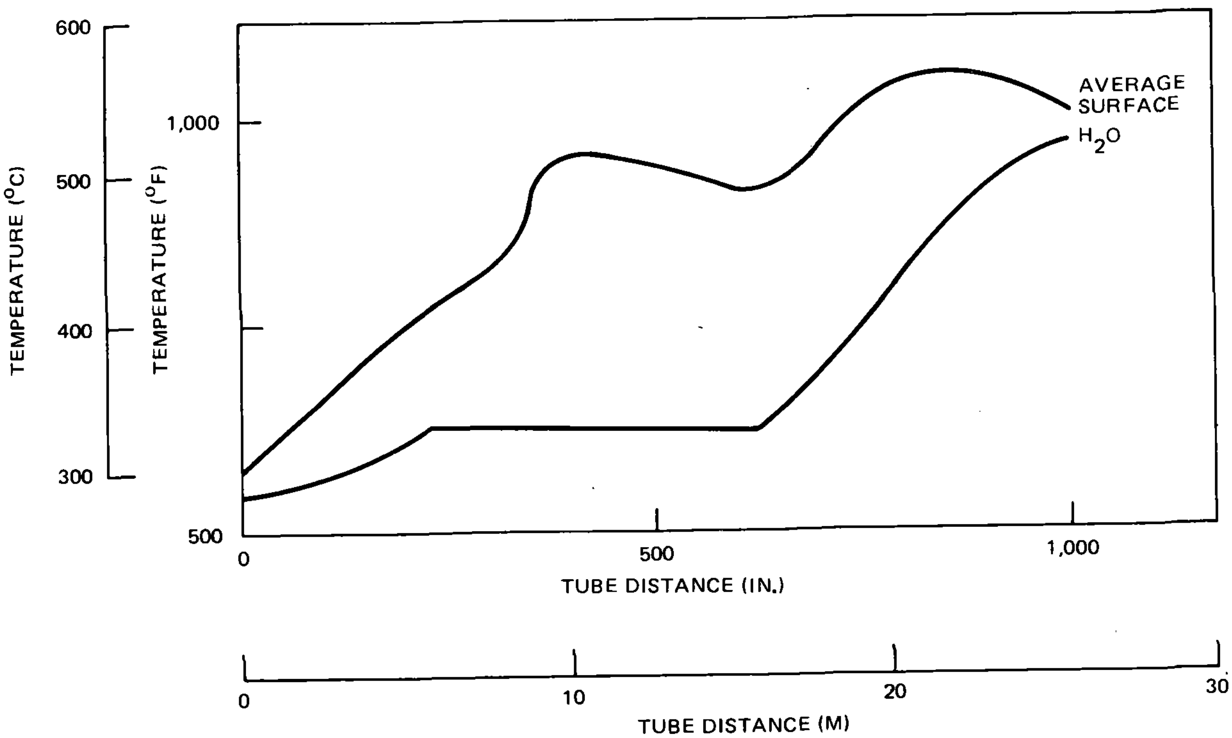


Figure 3-8. 100-MW Temperature Profiles, Equinox Noon, North Tube

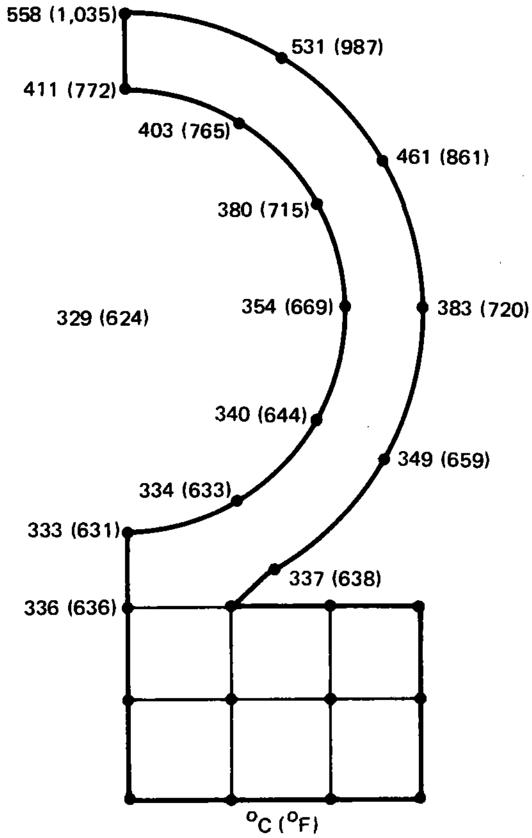


Figure 3-9. Commercial Receiver Tube Temperature 10.2M (400 in.) (Maximum Strain Point)

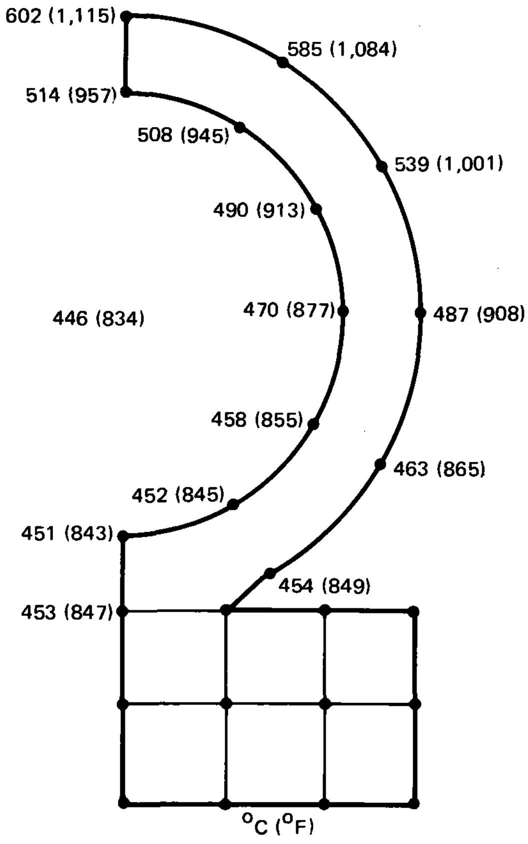


Figure 3-10. Commercial Receiver Tube Temperature 21M (830 in.) (Maximum Temperature Point)

Table 3-1

COMMERCIAL RECEIVER LOSSES

Type of Loss	Values - MW Rated Steam	Derated Steam
IR Radiation	20.6	14.3
Convection	5.4	4.5
Reflected Insolation	28.0	14.4
Total	54.0	33.2
Absorbed Energy	506.4	254.2*
Percent	9.6	11.5

*Absorbed power limited by thermal storage sizing requirement per Sandia guideline.

The convective losses were based on correlations contained in a recent German paper (E. Achenbach, "Heat Transfer From Smooth and Rough Surfaced Circular Cylinders in a Cross-Flow," Kernforschungasanlage Jülich GmbH, Germany). Documented therein are data for cylinders having relative roughness values of 0, 0.001, 0.003, and 0.009 at Reynolds numbers up to 4×10^6. These test were performed in air with knurled surfaces (pyramidal) in a high-pressure wind tunnel, thus the combined forced and natural convection effects are similar to that present in the receiver (Figure 3-11).

For the commercial receiver, the case of 0.001 relative roughness was used since that was the data case closest to the receiver situation. (The receiver has a relative roughness of approximately 0.0004.) The results of that calculation indicated a loss under rated steaming conditions of 5.4 MW_t. It is felt that this represents an upper bound on the convective loss. This is due to the following:

A. A roughness value 2.5 times the actual was used in this calculation.

B. The roughened surface area with pyramidal knurls is far greater than that due to the actual rippled tube surface.

Due to the exposed nature of the heat absorptive surfaces of an external receiver unit, it must necessarily experience somewhat greater thermal losses than a more enclosed concept. This difference in thermal losses will

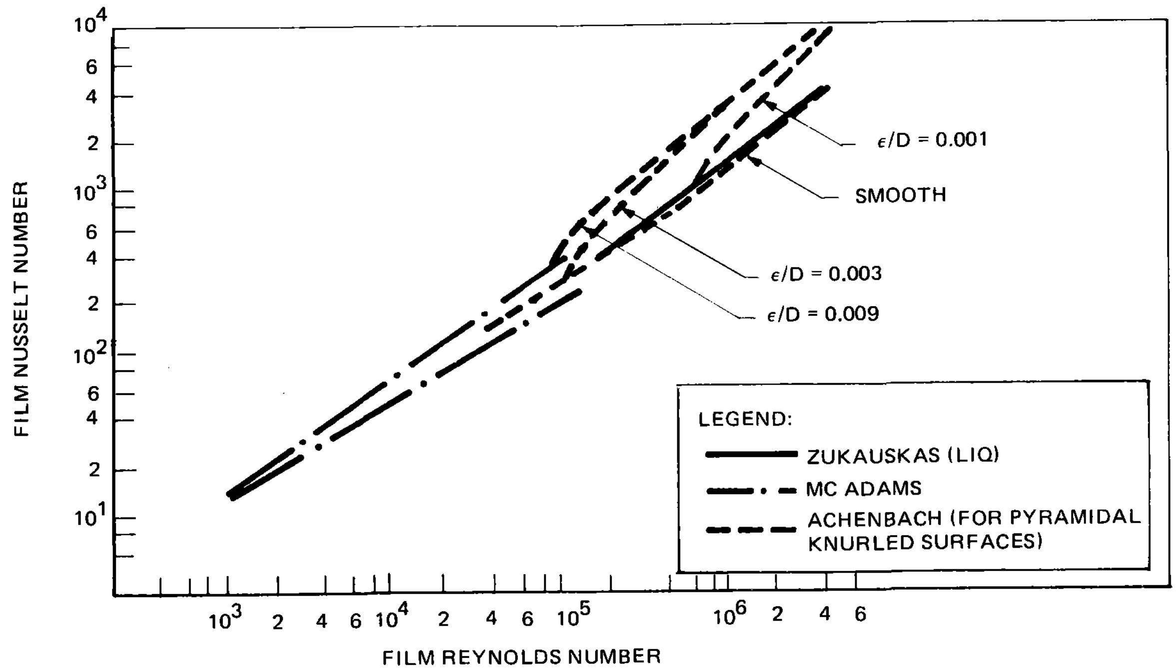


Figure 3-11. Heat Transfer to Cylinder in Cross Flow

be more pronounced in Pilot Plant scale receivers where the flux levels are purposely held down to minimize the technical risk of the first solar plant. Since the termal efficiency of an external receiver tends to increase as the incident energy flux level increases, the thermal efficiencies become competitive at the higher Commercial Plant flux levels and the choice between the two concepts must consider other overall system related issues. For example, as noted earlier in the discussion of optimum collector field shape (Section 1.2), although a north field receiver superficially appeared to be the most efficient design at the Pilot Plant scale, when the concept was applied to the Commercial scale, the complex piping network required to join the modular fields resulted in a cost penalty equivalent to a 20% loss in receiver unit efficiency.

Thermal responsiveness must also be considered as a measure of receiver thermal efficiency. Clearly, a lower thermal efficiency receiver concept which starts up faster each day, recovers more quickly from insolation transients, scavenges the maximum heat from low-quality solar insolation and thereby produces the maximum energy output per year per dollar is superior to less responsive receiver with a higher thermal efficiency.

Finally, it should be noted that the geometric flexibility and lightweight inherent in the multipanel external receiver concept provide the design freedom during the Pilot Plant development phase to investigate the cost-effectiveness of various means of improving thermal efficiency such as shown in Figure 3-12.

During the conceptual design phase of the present program, an analysis was made to determine the relative cost and performance benefits of a "shrouded" receiver concept (Figure 3-12) on both the Pilot and Commercial Plant subsystems.

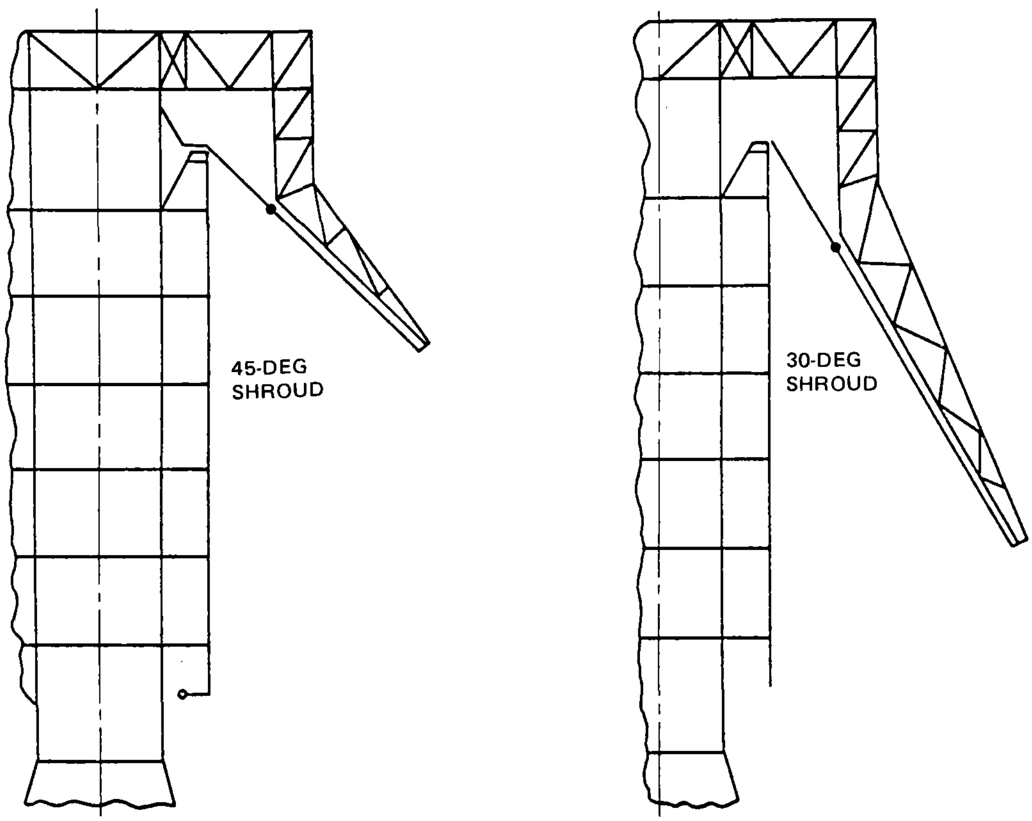


Figure 3-12. Shrouded Receiver Concepts Considered

The purpose of the shroud was to protect the upper high-temperature portion of the receiver from excessive convection and radiation losses. The shrouds would not be subjected to direct reflected energy from the collector field on a steady-state basis and therefore would not require active cooling. Clearly, as the length of the shroud increases or the shroud angle decreases, the anticipated receiver heat losses would be reduced. However, a negative effect related to the interaction with the collector field occurs. This effect involves the limit on collector field size or receiver look angle. To overcome this restriction, a taller tower would be necessary to permit the heliostats to redirect their power up under the shroud without a direct impingement. Trade studies carried out for the Pilot Plant indicated that the losses could be reduced with a shroud by as much as 15-20%, depending on the time of year and ambient conditions. However, when the cost penalties associated with shroud and increased tower structure required to support the added hardware were considered, a net savings of less than $0.5 million was predicted for the Pilot Plant while the effects essentially cancelled out for the Commercial design. Since the Commercial Plant did not seem to obtain a substantial benefit from the shroud, it was not considered further for the Pilot Plant in order to maintain configuration symmetry between the two designs.

<u>Tubing Material Selection</u>

Incoloy 800 (ASME boiler code designation = nickel-iron-chromium Alloy 800) is the baseline material for the receiver subsystem.

Table 3-2 lists the materials considered for use in the receiver. All are basically iron-base alloys and most contain similar alloying elements. However, insofar as Section 1 of the ASME code is concerned, Incoloy 800 is considered as nonferrous since normally it contains less that 50% iron. (This requires the addition of 0.065 in. to the wall thickness determined from hydraulically induced stresses when designing to Paragraph 27.2.5 of Code Section I.)

Table 3-2

RECEIVER ALLOY COMPOSITION COMPARISON

Alloy Designation	Nominal Composition*
Incoloy 800	32 Ni - 20 Cr
Low Alloy Steel	2 1/4 Cr - 1 Mo
Stainless** 304	18 Cr - 8 Ni
Stainless** 316	16 Cr - 13 Ni - 3 Mo
Stainless** 321	18 Cr - 8 Ni - 1 Ti
Stainless** 347	18 Cr - 8 Ni - 1 Cb

*Remainder Iron
**Austenitic Stainless Steels

Upon the basis of mechanical properties listed in the boiler code, all the materials in its Table 1 (except 304) have characteristics which would allow its use in the receiver. This pertains to tensile strength. Additionally, the ductilities (area reduction) are close enough such that predicted fatigue lives based on thermostructural interaction would also be similar.

The other characteristics of interest are general corrosion (rusting) resistance, chloride stress corrosion cracking, and thermal sensitization (intergranular precipitation). General discussions with vendors, as well as a Rocketdyne-sponsored test program, indicated that the low-alloy steel (2-1/4 Cr-1 Mo) had high corrosion rates. Table 3-3 shows the results of these tests.

Table 3-3

COMPARISON OF CORROSION OF TUBE ALLOYS

Material	Corrosion Rate* (mills/yr)
2 1/4 Cr, 1 Mo	130
Stainless 304	13
Incoloy 800	10

*170 fps steam, 50% quality at 310 psia

Reference 1 discusses the use of Incoloy 800 in a Commonwealth Edison Plant. It was installed originally in conjunction with 347 stainless and was shown to yield more favorable performance. Based on these data, complete superheater units were installed using Incoloy 800H (same composition as 800, slightly different heat treat).

References 2 and 3 document other applications of Incoloy 800. The former describes satisfactory performance in a superheated steam environment at temperatures up to 1,150°F. Reference 2 documents a study performed by the ASME Research Committee on High Temperature Steam Generators. This was an extensive test program on alloys for superheater tubes in fossil fuel power plant boilers. In a series of tests up to 1,500°F, four austenitic and seven ferritic alloys were tested for periods up to 18 mo. Incoloy 800 exhibited the best resistance to the environment. Incoloy 800 has been extensively used in boilers/superheaters. Table 3-4 lists several experiences drawn from users.

Tube Geometry

Using the heat flux generated by the heliostat aim strategy for the Commercial Plant, tube geometry variations were studied. The study initially considered a boiler panel constructed of 114 tubes of Incoloy 800 with 19.1 mm (3/4 in.) OD and a wall thickness required by the boiler code of 3.55 mm (0.14 in.). Calculations indicated that the temperature at the exposed tube crown in the peak strain region would be 667°C (1,230°F). On the coolant side wall the temperature would be 480°C (895°F). In the peak temperature region, the exposed tube crown temperature would be 680°C (1,255°F), which is beyond the recommended operating temperature for the tubing.

Tube size was then reduced to 12.7 mm (OD) with a 2.92 mm (0.115 in.) wall thickness to provide the same level of stress. For a panel of 170 tubes, the coolant mass velocity and corresponding heat-transfer coefficients would approximately double. The effect would be to reduce the exposed tube crown temperature in the peak strain region to 558°C (1,035°F) and the coolant side wall temperature to 403°C (756°F) (see Figure 3-9). The maximum exposed tube crown temperature in the maximum temperature region would be likewise reduced to 602°C (1,115°F), which is within acceptable material limits.

Table 3-4

STEAM SERVICE CORROSION DATA (SUMMARY) INCOLOY 800

Location	Steam Temp	0_2 Content	0_2 Removal Method	Results
Ohio Power Beverly, Ohio	(1,025°F)	0.2 ppm	Mechanical dearation Only	30 mo, no scaling or oxidation
So. Calif. Edison Hermosa Beach, CA	565°C (1,050°F)	5 ppb	Dearation; hydrazine and ammonia	22 mo, nonspalling oxide (0.004 in.) 0.1 mm
Commonwealth Edison	565°C (1,050°F)	---	Hydrazine	24-48 mo, no scaling
Electric Energy, Inc. Joppa, Ill. Boiler No. 2	570°C (1,055°F)	0.003-0.007 ppm	Hydrazine and sulfite	32 mo, tight adherent scale (0.004 in.) 0.1 mm
Electric Energy, Inc. Joppa, Ill.	570°C (1,055°F)	0.003-0.007 ppm	Hydrazine and sulfite	66 mo, tight adherent scale (0.004 in.) 0.1 mm
Electric Energy, Inc. Joppa, Ill. Boiler No. 1	540°C (1,005°F)	0.003-0.007 ppm	Hydrazine and sulfite	42 mo, tight adherent scale (0.004 in.) 0.1 mm

Based on the foregoing, the 12.7 mm (0.5 in.) OD 6.88 mm (0.269) ID tube geometry was selected for the Commercial Plant boiler tubes.

Because the preheater panels are subjected to a much less severe heat flux environment, the tubing dimensions were chosen as 19.0 mm (0.75 in.) OD x 13.2 mm (0.52 in.) ID to reduce the pressure drop through the series preheater panels.

Codes for Panel Design

The solar receiver is nominally a forced-flow steam generator. As such, it would normally be designed to Section I of the ASME boiler code. However, it would be desirable that the panel be designed using Section VIII, Division 2 (ASME code) analysis techniques using Section I material allowable strengths. This approach is proposed because Division 2 of Section VIII offers techniques for structural design by analysis; whereas, Section I contains only minimal analysis. This proposed approach to structural design has been successfully used at Rocketdyne for a compact steam generator design. Since Section I of the code does not, in general, allow for advanced concepts, it is suggested that a code case be initiated to incorporate structural design by analysis into Section I. This might take the form of either a code case or an Appendix to the code section.

Section VIII, Division 2, was derived from the work done on nuclear vessels for Section III of the code. At present, the maximum allowable working temperature in Division 2 is 430°C (800°F); however, at that temperature, higher allowable stresses are used than are used in Section I. Factors on strength are outlined and compared for the two code sections in Table 3-5. The reason for these greater allowables in Section VIII is the degree of analysis provided for in that section. Thus, the proposed approach of analysis from Section VIII, plus lower working strengths from Section I, should provide a conservative design.

Because Section I is more of a handbook approach, factors are introduced into the design formulas that are not considered applicable to the design of new concepts, such as the receiver panels. For example, the panel tube material is nickel-iron-chromium alloy 800, seamless tubing, per

Table 3-5

COMPARISON OF FACTORS ON MATERIAL STRENGTH BETWEEN SECTIONS I AND VIII OF THE ASME BOILER AND PRESSURE VESSEL CODE

Code Section	Reference	Factor on Material Strength	
		Ultimate	Yield
Section I	Appendix Para A-150	1/4	5/8
Section VIII Division 2	Appendix 1, Para 1-110	1/3	2/3

Notes: 1. The allowable stress is the lower of the factor yield times the yield strength or the factor on ultimate times the ultimate strength.

2. Since yield governs for the Incoloy 800 alloy, the difference in working strength is relatively small.

Specification SB-408. Since this material is classified as "nonferrous," Paragraph 27.2.4 of Section I would have to be used in this design. Using the paragraph, the tube OD must be used in the stress calculation, and, in addition, a constant thickness of 1.65 mm (0.065 in.) for "structural stability" is added (and not counted for strength) to the calculated value. The Pilot Plant baseline tube design satisified this requirement as does the Commercial Plant; however, future applications where a higher heat flux would be desirable may not be able to satisfy both strength and life requirements because of the larger temperature differentials that the excessive tube thickness would impose. Thus, using Section I, both the cost (excessive weight) and technical viability (reduced life) of the panel are adversely impacted. For these reasons, it is suggested that the combination of Section I and Section VIII, Division 2, be used as an interim approach (perhaps making it necessary to run the Pilot Plant as a "State Special"), until a code case can be evolved with the Section I Committee of the ASME for design by analysis.

Detailed Panel Design Description

With the exception of the larger scale and the tubing size difference between the boiler and preheater panels, the construction, absorptive coating, backup structure and thermal expansion designs of the Commercial receiver panels are similar to the Pilot Plant panels. Details concerning these areas may be found in Section 4.

3.2.2.2 Controls and Instrumentation

Requirements

The basic requirements for the controls and instrumentation subassemblies are to provide the control and information necessary to (1) produce the directed steam outlet conditions notwithstanding the highly transient diurnal and seasonal variations in solar insolation, (2) evaluate receiver performance, (3) to protect the receiver, and (4) to provide filtration, flushing, and purging functions as required. Receiver operating conditions are described in Section 4.4.

Controls Analyses and Design Description

The control and instrumentation assembly includes data sensors, control electronics and a flow distribution network that includes flow control valves, stop-check valves, safety relief and vent valves, purge valves, drain valves and filters. A schematic showing the arrangement of components is presented in Figures 3-5 and 3-13. All valves and their functions are described in Table 3-6. In general, components are commercially available items.

The control systems were designed to accomplish the necessary functions in the simplest manner possible and at the lowest cost. Safety, reliability, and response to off-design conditions were also major considerations. Economy and reliability were achieved by designing valves to be manually operated rather than remotely operated wherever feasible. Only those valves which may be required to operate when the receiver unit is being subjected to radiation are remotely controlled.

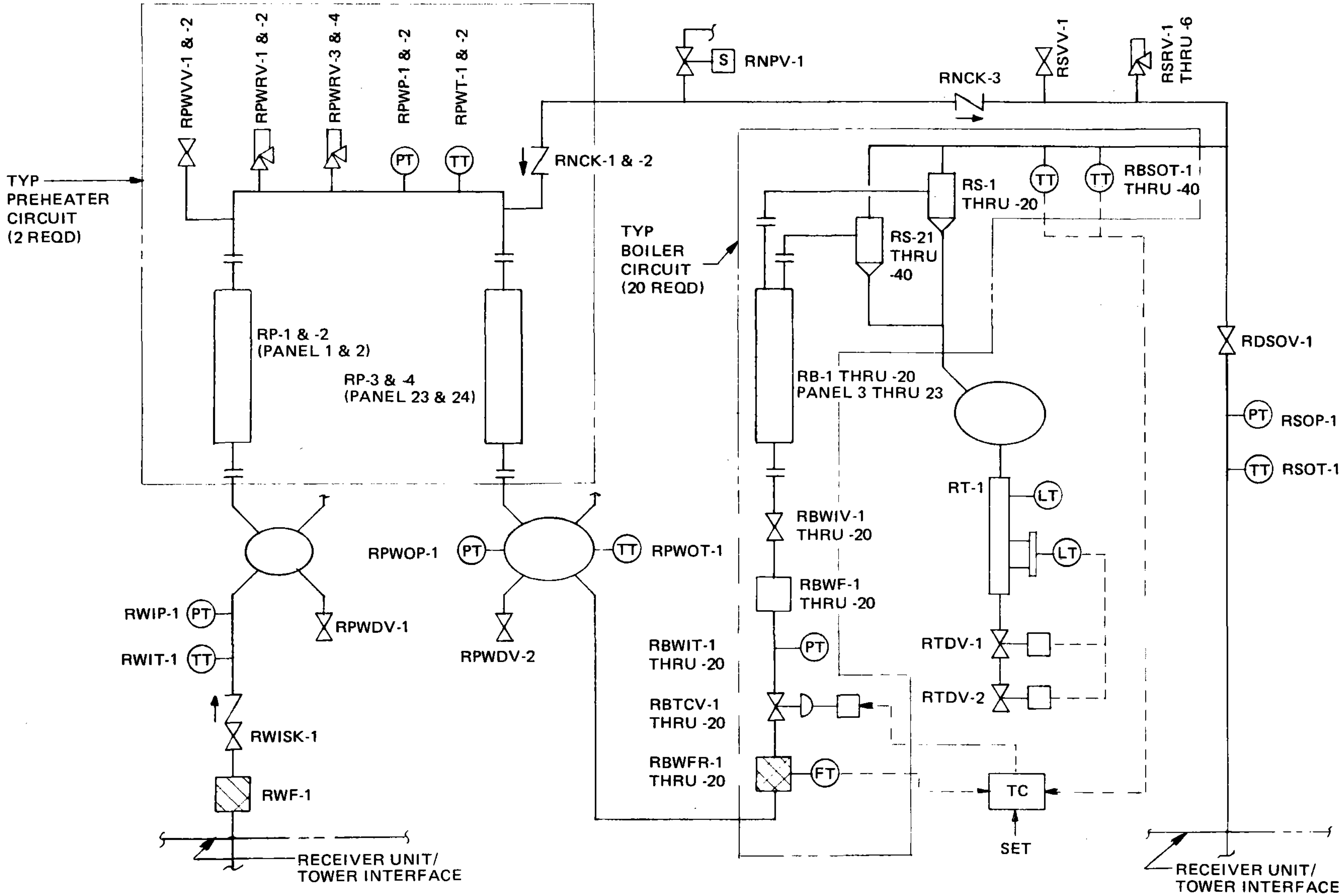


Figure 3-13. 100-MW Receiver Schematic

Table 3-6.
VALVE LIST, 100-MW RECEIVER

Valve	Symbol	Qty	Nom. Size (In.)	Control	Function
Receiver Water Inlet	RW1SK-1	1	10	Manual	Isolate receiver and limit preheaters
Receiver Water Drain	RPWDV-1	1	1 1/2	Manual	Drain first pass preheaters
Receiver Water Relief	RPWRV-1 through -4	4	3	Spring	Prevent preheater over-pressure
Receiver Water Vent	RPWVV-1 & 2	2	1	Manual	Vent preheaters during fill
Receiver Nitrogen Charging	RNCK-1 & 2	2	1	Spring	Backfill preheaters during drain
Receiver Water Outlet	RPWOV-1 & 2	2	6	Manual	Limit of preheater panels
Receiver Water Drain	RPWDV-2	1	1	Manual	Drain second pass preheaters and boiler panels
Receiver Water Flow Control	RBTCV-1 through -20	20	3	Pneumatic	Control boiler panel flowrate
Receiver Water Inlet	RBWIV-1 through -20	20	3	Manual	Limit boiler panels
Receiver Nitrogen Charging	RNCK-3	1	1	Spring	Backfill boiler panels and downcomer
Receiver Water Vent	RSVV-3	1	1	Manual	Vent boiler panels during fill
Receiver Steam Relief	RSRV-1 through -6	6	3	Spring	Prevent boiler overpressure
Receiver Steam Outlet	RDSTOV-1	1	16	Manual	Isolate receiver and limit boiler panels
Receiver Water Drain	RTDV-1 & 2	2	1 1/2	Power	Drain off water from accumulator
Receiver Nitrogen Charging	RNPV-1	1	2	Manual	Charge nitrogen system for backfill during drain

The function of the receiver control electronics is to receive command signals from an operator or the master controller and translate these signals into specific actions in the receiver. The controller also monitors the receiver conditions and sends status signals and activates alarm signals when critical operation parameters indicate abnormal conditions. The controller performs these functions during prestart checks, startup, operation, shutdown, emergency operation, and standby.

Since the controls for both receivers are nearly identical in function, further details of the controller analyses, function and hardware are described in the Pilot Plant control section (4.3.2.2).

3.2.2.3 Receiver Unit Support Structure

The receiver structure must withstand the following loads:

Sustained Wind (at 280 m)	65.6 m/s (215 fps) (40 m/s (90 mph) at 10m elevation)
Seismic	Horizontal 0.25g at ground level Vertical 2/3 of horizontal

The following ground rules were used in the evaluation:

1. Load occurs during operation.
2. Absorber and structure remain in place.
3. Only minor repairs are required.
4. Quake and wind do not happen simultaneously.

For the primary structure, quake accelerations are the critical loads. Expected column loads due to quake accelerations are an order of magnitude larger than loads due to wind or dead weight alone.

The tower weight was based on quake loads supplied by Stearns-Roger Inc., and on equipment weights as summarized in Table 3-7. Columns were selected from the AISC Steel Construction Manual and the analysis iterated until an optimum carbon steel weight was found. To simplify the analysis, transition section members were sized as being main vertical columns and diagonals.

The Commercial structure is similar to the Pilot Plant structure. There are 24 panels each 25.5m long and 2.18m (86 in.) wide, and assorted piping and valves. Accessory equipment includes a crane of 18.2MG (20 tons) capacity, flooring, and items such as ladders and railings. Components along with their weights and cg locations are summarized in Table 3-7. The carbon steel weight includes primary and secondary structural steel.

The receiver unit should withstand quake, wind, and thermal distortion loads. Panel thermal loads are accommodated by allowing free panel growth in the plane of each boiler and preheater panel. Tube-to-header joints in each panel are provided with sufficient flexibility to prevent unacceptable thermal and mechanical strains. Receiver tower columns and cross bracing are strong enough to withstand quake loads.

Table 3-7
COMMERCIAL RECEIVER WEIGHT SUMMARY
(AT 0.25g GROUND LEVEL SEISMIC INPUT)

Item	Weight (Kg x 10^{-3})	(kips)	Assumed cg Location* (Meters,	ft)
Carbon Steel** (ASTM A-572, Grade 50)	653	(1,437)	25.91	(85) (conservative)
24 Panel Assemblies	155	(340)***	25.91	(85)
Piping	307	(675)	18.59	(61)
Crane	42	(92)	44.20	(145)
Other Components	73	(160)	20.88	(68.5)
Total Weight	1,229	(2,704)	*Above tower interface.	

**50,000-psi yield
65,000-psi ultimate
30,000-psi allowable

***Preheater panel = 19,000 lb
Boiler panel = 13,200 lb

Heating of an individual absorber panel by the heliostat field causes large thermal growth in the plane of the panel. Restriction of this growth would result in large longitudinal and transverse thermal strains rapidly leading to buckling of the solar absorber panel. Panel heating also causes out-of-plane distortion which would cause large bending moments at the inlet and outlet manifolds unless the panel were held flat. These requirements are met by a backup structure similar to that used in the 10-MW Pilot Plant.

The steam manifold is attached to the tower at the top of the absorber panel and the water manifold is attached at the bottom of the panel. As in the Pilot Plant, both manifolds were analyzed to the criteria of Section I of the ASME code where applicable. Offset bending between the growing absorber surface and the fixed manifolding must be taken primarily through bending of an absorber water manifold transition section. To avoid overloading the absorber surface, this transition section will be flexible at the bottom end of the panel. To allow the required longitudinal growth of the absorber panel, the transition section is nearly 3m long (9 ft).

Preheater panels used in the 100-MW Commercial Plant are similar to boiler panels except for number and OD of tubes. Backup structure is the same as for boiler panels. Manifolds are similar to boiler manifolds, being fixed in the same manner, and also have been evaluated using ASME Section I code techniques where applicable.

3.2.3 Commercial Plant Receiver Tower Assembly

3.2.3.1 Requirements

Primary requirements for the Commercial Plant receiver tower are:

- Provide means for attachment, support, and operation of the receiver assembly.
  - Receiver design weight (wet) = 1,462,836 kg (3,225,000 lb)*
  - Maximum allowable sway at top of tower during operational wind or seismic conditions = 0.67m (2.2 ft)
- Provide means for attachment and support of riser and downcomer assembly.

*Actual receiver weight and survival ground level seismic acceleration requirements were 1.229×10^6 kg (2.704×10^6 lb) and 0.25g, respectively, so the following structural analysis is believed to be conservative.

- Maintain structural integrity during postulated survival seismic and wind environmental conditions.
- 0.33 g horizontal acceleration at ground level. *
- 40.2 m/s (90 MPH) winds.
- Provide a 30-yr life.
- Provide access and capability for inspection, maintenance, and repair of receiver assembly and riser/downcomer assembly.
- Provide for lightning protection and aircraft warning.
- Assumed soil bearing capacity = 48,820 kg/m^2 (10,000 psf; Barstow data).

Loads

Static loads include the weight of the receiver, tower, and foundation. Wind loads on the tower are based on a velocity profile obtained by using the following formula:

$$V_h = V_{10} \left(\frac{h}{10}\right)^{0.15}, \quad h \geq 10_m$$

where V_h = wind velocity at height, h, above ground

V_{10} = wind velocity at 10m above ground

For the operational wind condition, V_{10} = 16.1 m/s (36 mph), including wind gusts. For the maximum survival wind condition, V_{10} = 40.2 m/s (90 mph), exclusing wind gusts.

Based on results obtained from the analysis of the Pilot Plant concrete tower, namely that wind forces are negligible in comparison to seismic forces, it was decided to omit the analysis of the response of the Commercial Plant concrete tower to wind forces. Seismic loads were calculated using the ground response spectra given in the NRC Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants." These

*Actual receiver weight and survival ground level seismic acceleration requirements were 1.229 x 10^6 kg (2.704 x 10^6 lb) and 0.25g, respectively, so the following structural analysis is believed to be conservative.

spectra were normalized to 0.165g maximum ground acceleration for the operating basis earthquake (OBE) and to 0.33g maximum ground acceleration for the safe shutdown earthquake (SSE) through which the structure must survive. A vertical component of two thirds the intensity of the horizontal earthquake is assumed to act concurrently with the horizontal earthquake. For each selected mode of vibration, the structural response to the concurrently acting components was calculated by taking the square root of the sum of the squares of the response caused by each of the components of motion. The total structural response was then formed by a square root of the sum of the squares summation over all the selected modes of vibration. Damping values were selected from the NRC Regulatory Guide 1.61, "Damping Values for Design of Nuclear Power Plants." Damping ratios for reinforced concrete structures are given as 4% of critical for the OBE and 7% of critical for the SSE.

Stresses

Allowable stresses for concrete are in accordance with the strength design provisions of ACI 318-71. A load factor of 1.25 was applied to dead load in combination with the SSE. For dead load in combination with the OBE, allowable stresses are in accordance with the working stress provisions of ACI 318-63 with a one third increase in allowable stresses.

Materials

Materials are those which are customarily found in conventional concrete construction. The concrete must meet ACI standards for ultimate compressive strength of 4,000 psi at 28 days. Reinforcing must meet ASTM A615-72 Grade 60.

3.2.3.2 Analysis Studies

The STARDYNE Structural Analysis System was used to perform the analyses of the concrete tower. The modal analysis was made using the STAR program. The dynamic earthquake analyses were made using the DYNRE 4 program. A fixed base model was employed.

Tower Deflections

Tower deflections are shown in Table 3-8 for seismic conditions. Table 3-8 shows that the concrete structure will easily meet the 2.2-ft sway limit when

Table 3-8
COMMERCIAL PLANT TOWER DEFLECTIONS*

Condition	Deflections
EARTHQUAKE	
1. Operating Basis Earthquake 0.165g (4% damping)	24.64 (9.70 in.)
2. Safe Shutdown Earthquake 0.33g (7% damping)	41.68 cm (16.41 in.)

*Deflections indicated are at top of tower (height, 242m, (794 ft)

experiencing the operational earthquake. Refer to Figure 3-14 for plots of concrete tower and receiver deflections vs. tower height.

A similar analysis indicated that a steel commercial tower could not satisfy the maximum deflection requirement.

Tower Base Shears and Moments

Tower base shears and moments are shown in Table 3-9 for seismic loading conditions.

Tower Accelerations

Tower accelerations for the dynamic earthquake conditions are shown in Table 3-10 at several reference points. Refer to Figure 3-15 for plot of tower and receiver acceleration vs. tower height.

The first few natural frequencies of the concrete tower are shown in Table 3-11.

3.2.3.3 Design Description

As shown in Figure 3-16, the concrete tower developed in the preliminary design studies extends approximately 242 meters (794 feet) above grade. The top of the concrete has an outside diameter of 15.3 meters (50.25 feet) with a nominal 0.305 meter (12 inch) wall thickness. The base of the tower has an outside diameter of 45.7 meters (150 feet) with a 0.46 meter (18 inch) wall thickness.

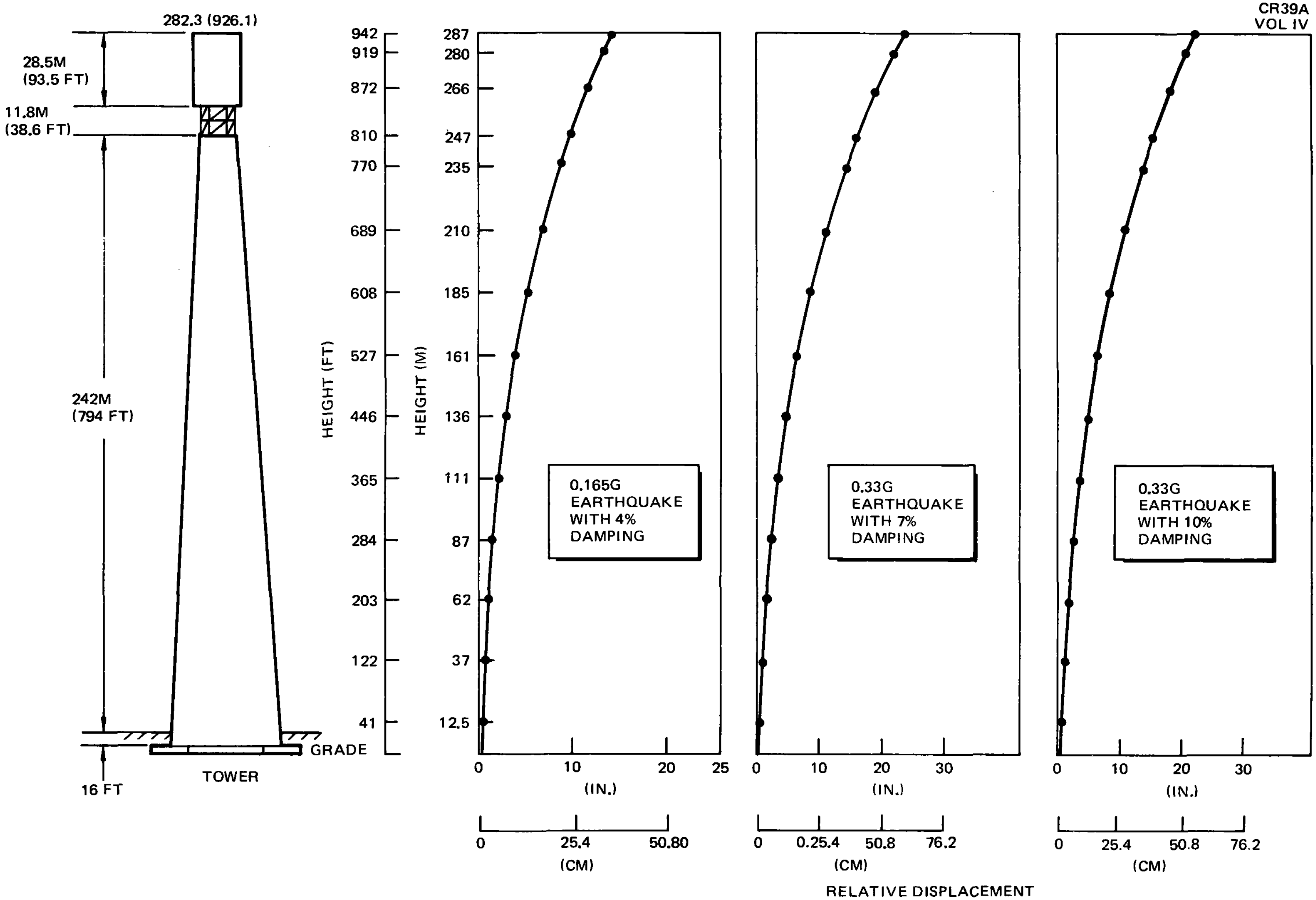


Figure 3-14. Commercial Tower Displacements (Concrete Tower)

Table 3-9

COMMERCIAL PLANT TOWER BASE SHEARS AND MOMENTS*

	Condition	Base Shear	Base Moment
	EARTHQUAKE		
1.	Operating Basis Earthquake 0.165g (4% damping)	3.03×10^5 kg (6,686 kips)	2.91×10^8 m-kg (2,104,700 ft-kips)
2.	Safe Shutdown Earthquake 0.33g (7% damping)	4.93×10^6 (10,865 kips)	4.85×10^8 m-kg (3,508,400 ft-kips)

*Concrete Tower Height = 242m (794 ft)

Table 3-10

COMMERCIAL PLANT TOWER ACCELERATIONS*

	Location	Operating Basis Earthquake	Safe Shutdown Earthquake
1.	Top of Tower Structure 242m (794 ft)	0.66g	1.08g
2.	Center Line of Receiver 268m (879 ft)	0.65g	1.08g
3.	Top of Receiver 282.2m (926 ft)	1.20g	1.95g

1g = 9.81 m/sec^2 (32.17 ft/sec^2)

*Concrete Tower Height = 242m (794 ft)

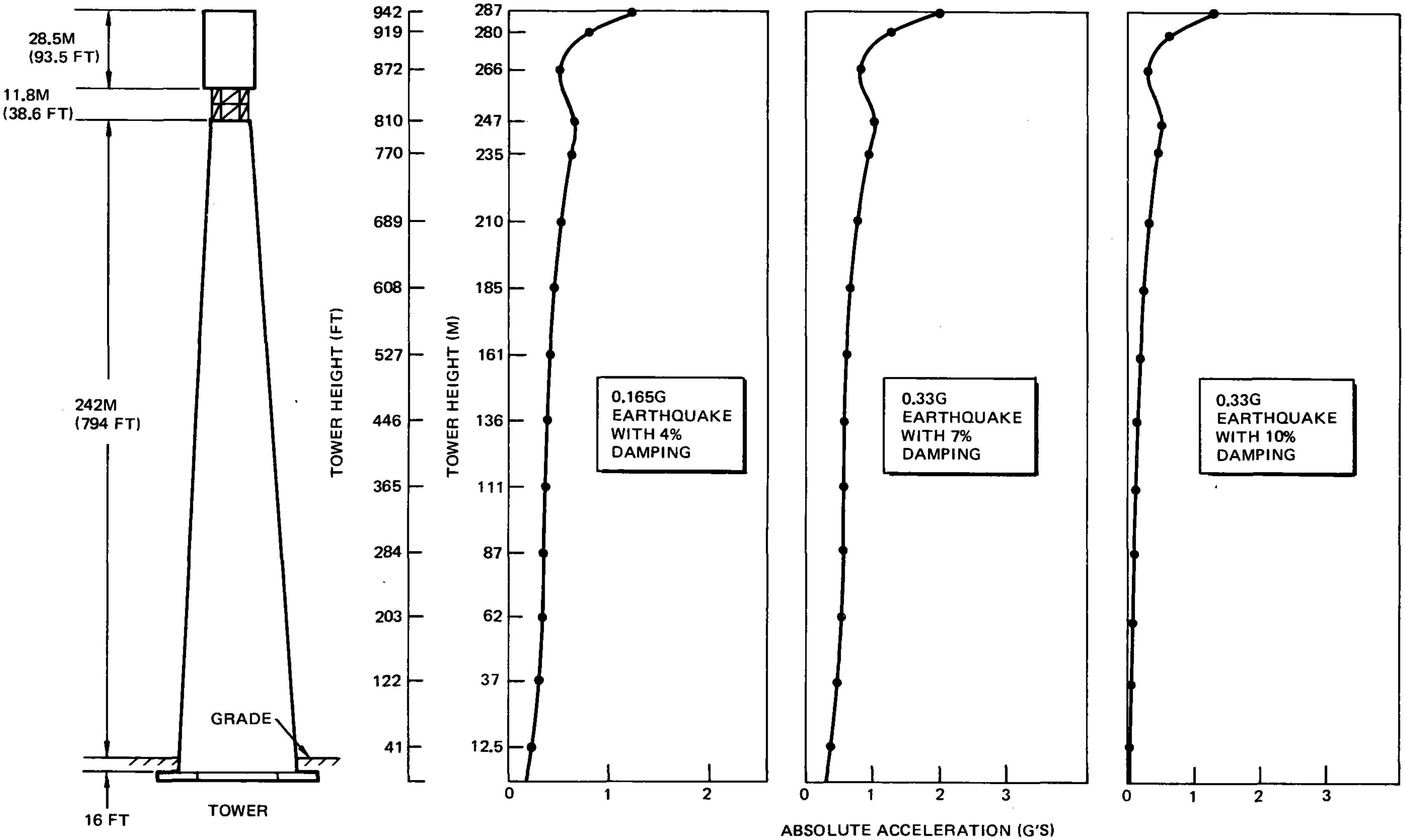


Figure 3-15. Commercial Tower Accelerations (Concrete Tower)

Table 3-11

COMMERCIAL PLANT TOWER NATURAL FREQUENCIES*

Mode Number	Frequency (cps)
1	0.425 cps
2	1.309 cps
3	2.748 cps
4	3.711 cps (vertical mode)

*Concrete Tower Height = 242m (794 ft)

The foundation, which is located 4.9 meters (16 feet) below finished grade, is a 61 meter (200 feet) outside diameter annular circular mat with a 30.5 meter (100 feet) inside diameter. The foundation thickness is 3.8m (12.5 ft). All reinforcement is A615 Grade 60.

3.2.3.4 Receiver Tower Auxiliaries

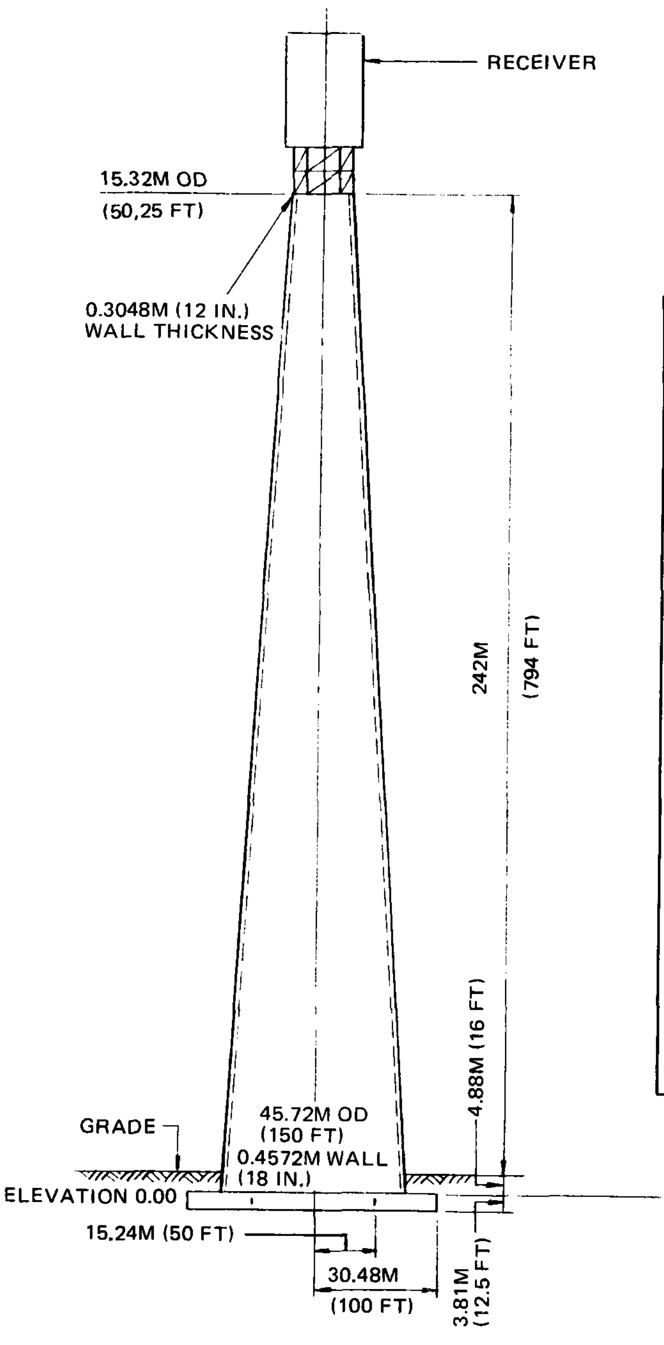
The receiver tower auixiliaries include equipment and materials necessary to provide access to the receiver from grade elevation, to facilitate installation and maintenance functions, aircraft obstruction lights, lightning protection, access platforms, lighting, and piping and electrical supports and attachments to the tower. The Commercial Plant receiver tower auxiliary equipment arrangement is shown in Figure 3-17.

Receiver Access

Access from grade elevation to the top of the tower is provided by both an elevator and a caged ladder. The elevator will be provided with stops at each intermediate platform level for maintenance and repair operations as required. A service lift and caged ladder are also provided from the top of the tower to the top of the receiver structure.

Installation/Service Crane

An installation and service crane of 18.14T (20 ton) capacity is located at the top of the receiver support structure to facilitate initial installation of the receiver panels and to assist in maintenance functions of the receiver and



MATERIAL QUANTITIES

1) CONCRETE TOWER
   CONCRETE = 9,203.83 CU M (12,038 CU YD)
   REBAR = 967T (1066 TONS)

2) FOUNDATION MAT
   CONCRETE = 8,339.85 CU M (10,908 CU YD)
   REBAR = 363T (329 TONS)

3) SOIL EXCAVATION
   VOLUME = 35,026.92 CU M (45,813 CU YD)

NOTES:

1) MIN CONCRETE STRENGTH SHALL BE 27.6 MPa (4,000 PSI) COMPRESSIVE STRENGTH AT 28 DAYS

2) REINFORCING BARS SHALL BE NEW INTERMEDIATE GRADE DEFORMED BARS WHICH SHALL CONFORM TO ASTM 615 GRADE 60

Figure 3-16. Commercial Plant Concrete Receiver Tower

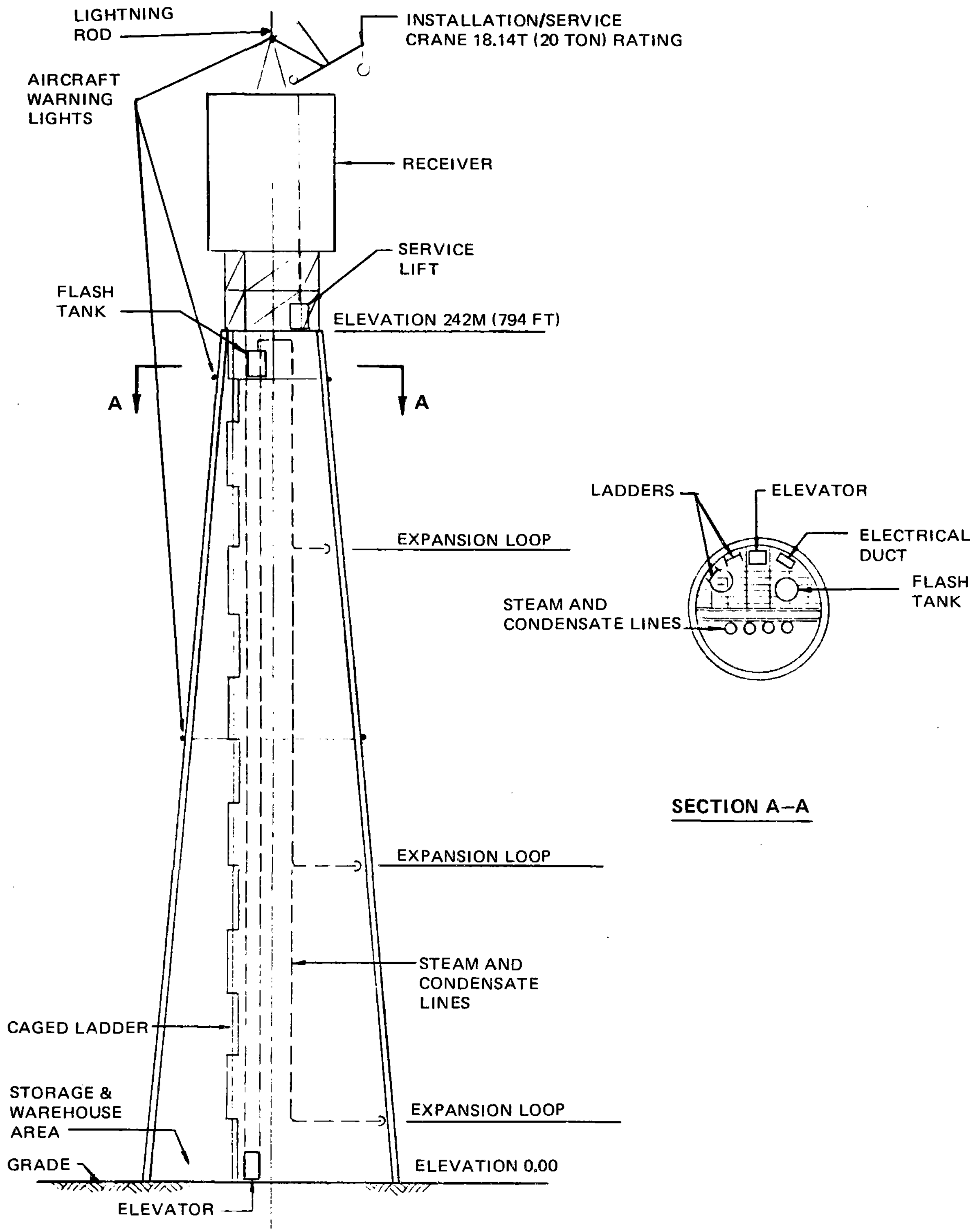


Figure 3-17. Commercial Plant Concrete Receiver Tower with Auxiliary Equipment

supporting equipment during the plant life. The proposed installation/service crane for the Commercial Plant is shown in Figure 3-18.

Aircraft Obstruction Lights

Aircraft obstruction lights will be located at the highest point of the receiver structure and on the tower in accordance with FAA regulations. White, high-intensity obstruction lights will be provided. Safe access will be provided to each obstruction light to facilitate maintenance.

Lightning Protection

The tower will be shielded from lightning strokes by air terminals (masts) on top of the receiver structure. The terminals will be insulated from the tower with porcelain insulators. The terminals will be grounded with copper cables. The copper cables will be insulated from the tower with porcelain insulators. The method of grounding will be reviewed, based on the location (isokeraunic level) of the plant.

The tower will provide protection for the heliostat field in close proximity to the tower. Protection for the outer areas will be determined base on the location (isokeraunic level) of the plant.

Access Platforms and Guard Rail

Access platforms and guard rail will be provided for maintenance and repair of receiver components, pipe supports, instrumentation, valves, lights, service crane, etc., in accordance with OSHA regulations.

Lighting

Lighting will be provided as required at grade elevation and in the tower interior at the various access and operating platforms. Convenience outlets (115v a-c, single phase) will also be provided for small tools and convenience lighting.

Piping and Conduit Supports

Miscellaneous steel and embedded items will be provided for supporting piping and electrical power, control, and instrumentation conduits as required.

CRANE RATING:	20 TON AT 40 FT
BASE:	CIRCULAR WITH 360-DEG ROTATION
LIFTING SPEED:	TO BE DETERMINED
OVERALL WEIGHT:	92,000 LB

NOT TO SCALE

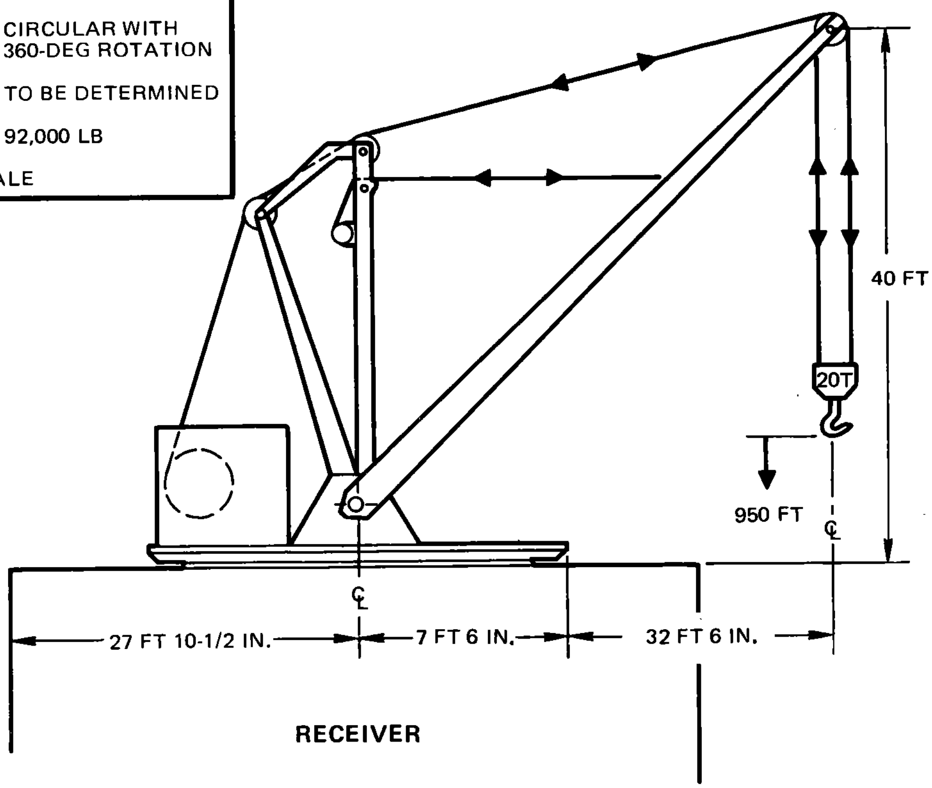


Figure 3-18. Commercial System Installation/Service Crane

3.3 SUBSYSTEM FABRICATION/INSTALLATION

This section describes the fabrication and installation of the subsystem. Overall commercial schedules are presented in Figures 3-19 and 3-20.

3.3.1 Receiver Unit

The receiver unit consists of the insolation absorbers, feedwater and steam piping with all filters, instrumentation and control, flow control, safety relief and servicing valves, and the structural steel supporting structure.

3.3.1.1 Absorber Fabrication

A manufacturing flow diagram is shown in Figure 3-21. The process used is identical to that used during SRE. The tubes are drawn and delivered in 100-ft straight lengths. The tubes are initially formed, trimmed, and welded into approximately 10 tube bundles. The bundle ends are folded over and then welded into full-width panels. The end manifolds are installed and the tubes expanded and seal-welded in place. The remainder of the manifolds are welded into place and the assembly pressure-tested. The backup structure is added and a handling fixture attached so the assembly can be raised to a position where it can be grit-blasted and coated. The fixture will also stabilize the assembly during shipment and field installation.

3.3.1.2 Controls Fabrication and Integration

The piping, pipe fittings, servicing valves, flow control valves, safety relief valves, instrumentation, etc. are delivered directly to the field site from suppliers. The pipe, fittings, valves, etc. are then integrated (welds inspected and X-rayed as required) into reasonable assemblies for raising and welding into place in the receiver. The welds in the receiver are inspected and X-rayed as required. Then the system is pressure-tested, leak-checked, and insulated.

3.3.1.3 Structure Fabrication

Generally, it is more economical to use welding instead of bolting for in-shop fabrication, but at the field site the reverse is generally true. The design will be done so that fabrication of welded assemblies in the shop and the other assemblies would generally be joined at the field site with high-strength bolts.

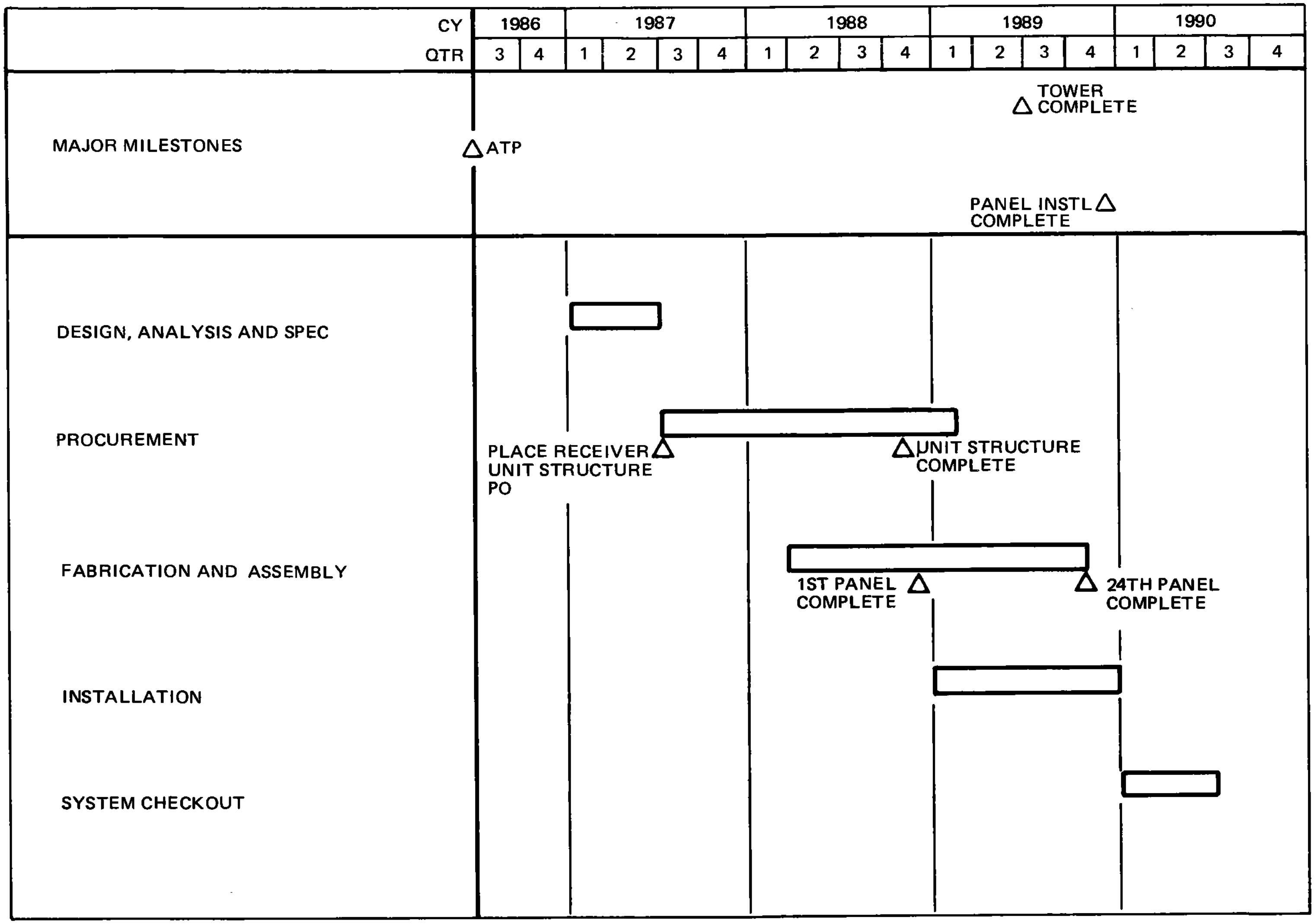


Figure 3-19. Receiver Subsystem First Commercial Plant

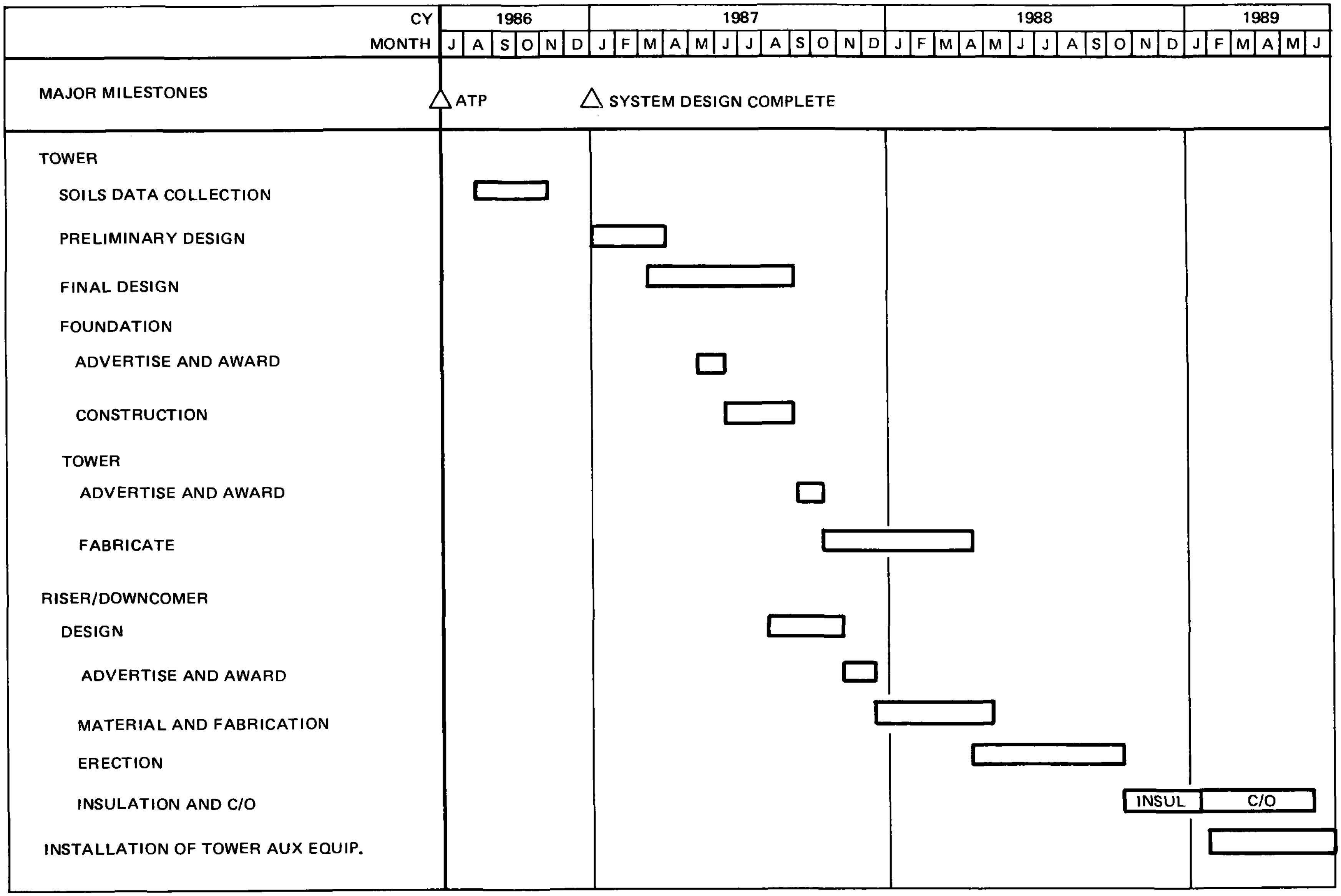


Figure 3-20. Tower – Riser/Downcomer Schedule – Commercial Plant

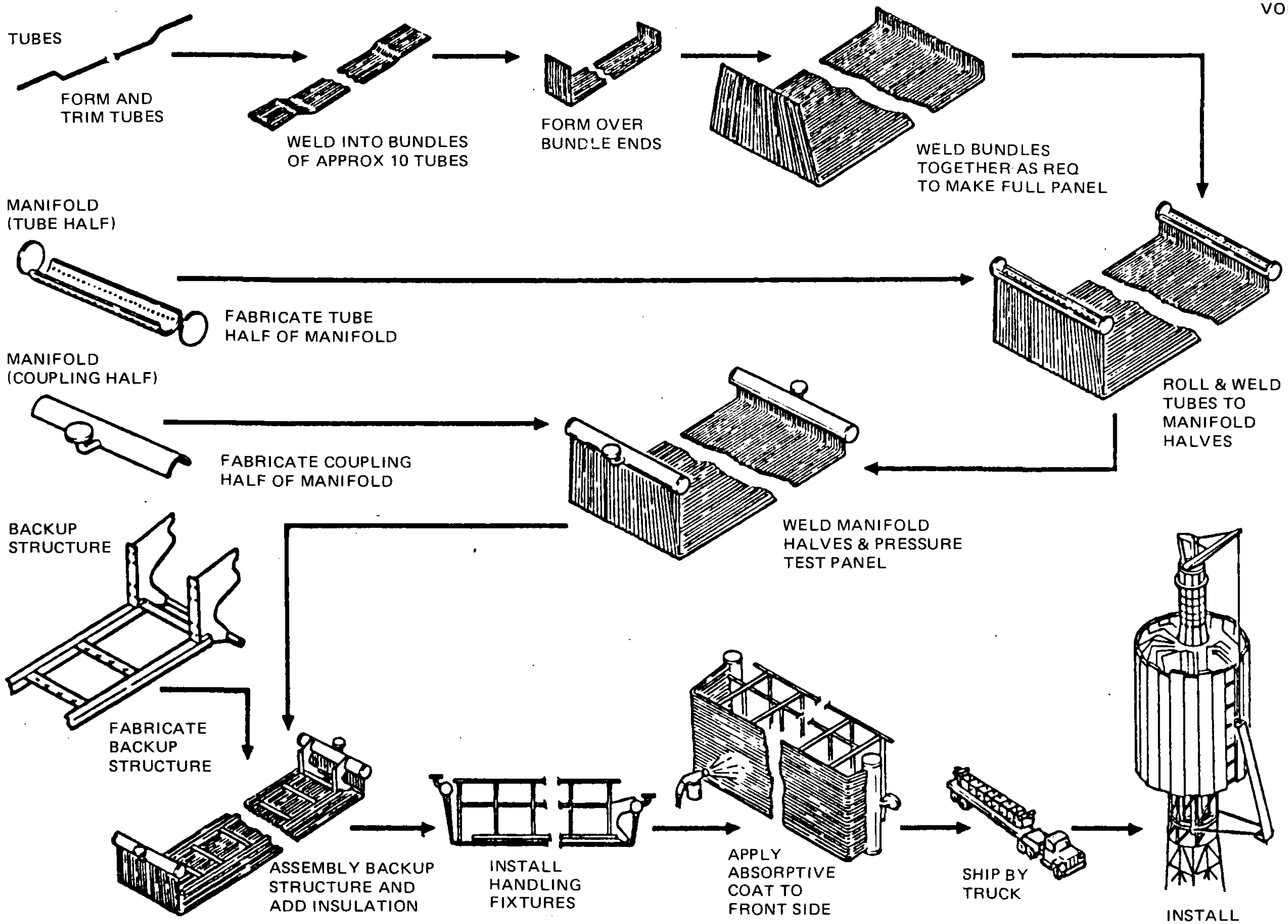


Figure 3-21. Receiver Panel Manufacturing Flow

Welding will be used at the field site only when it is more desirable or economical to do so. The fabricated assemblies would be trucked to the site. The crane used for the erection of the base tower will be used for the erection of assemblies. Crane capacity will determine the size and weight of shop-fabricated assemblies. Final painting will also be accomplished in the shop with only touchup after erection.

3.3.1.4 Subsystem Installation

The absorbers, controls, instrumentation, etc. are installed after fabrication of the supporting structure and the feedwater and steam systems are complete. The sequence of operation to install the absorbers is shown in Figures 3-22 and 3-23. The only attachments to be made are the bolted inlet and outlet flanges and bolts securing the absorber backup structure to the receiver structure. The steps are as follows:

A. Hoist panel to top of tower.
B. Disconnect from hoist truck, raise to intermediate position, and attach swing arms.
C. Raise panel to full height.
D. Rotate panel to position for installation.
E. Install positioning guides and remove swing arms.
F. Install inlet, outlet, and structure attachment bolts.
G. Disconnect and stow crane. Panel is ready for checkout and operation.

All instrumentation and electrical and pneumatic controls are connected after the absorbers are installed. The final checkout is now to be accomplished and the receiver made ready for integration with the other subsystems.

3.4 OPERATIONAL CHARACTERISTICS

The operational characteristics of the 100-MW receiver are essentially identical to those of the 10-MW receiver, which are discussed in detail in Section 4.4. These characteristics encompass the startup, normal operation, emergency, shutdown, and nonoperating modes.

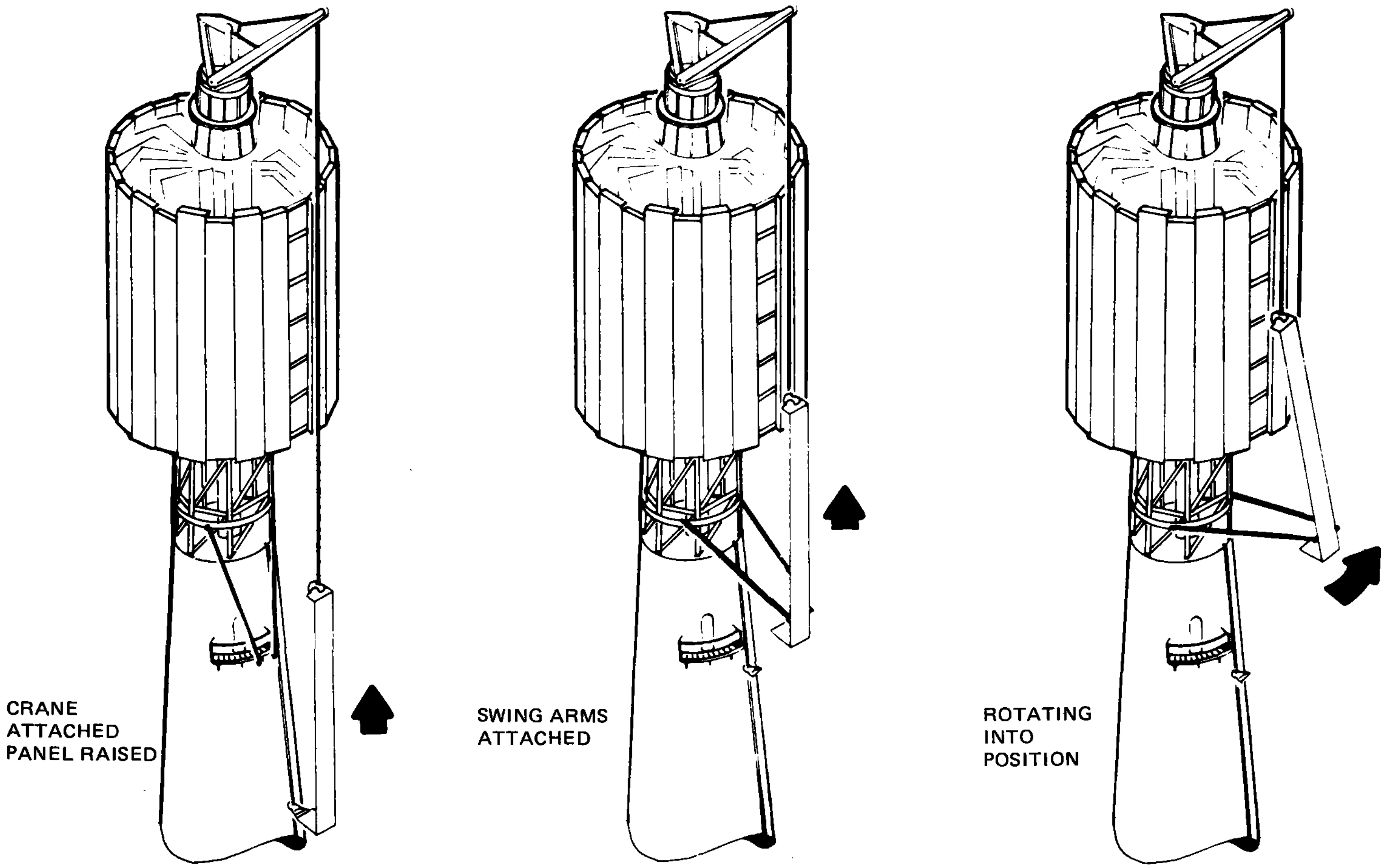


Figure 3-22. Panel Installation — Part 1

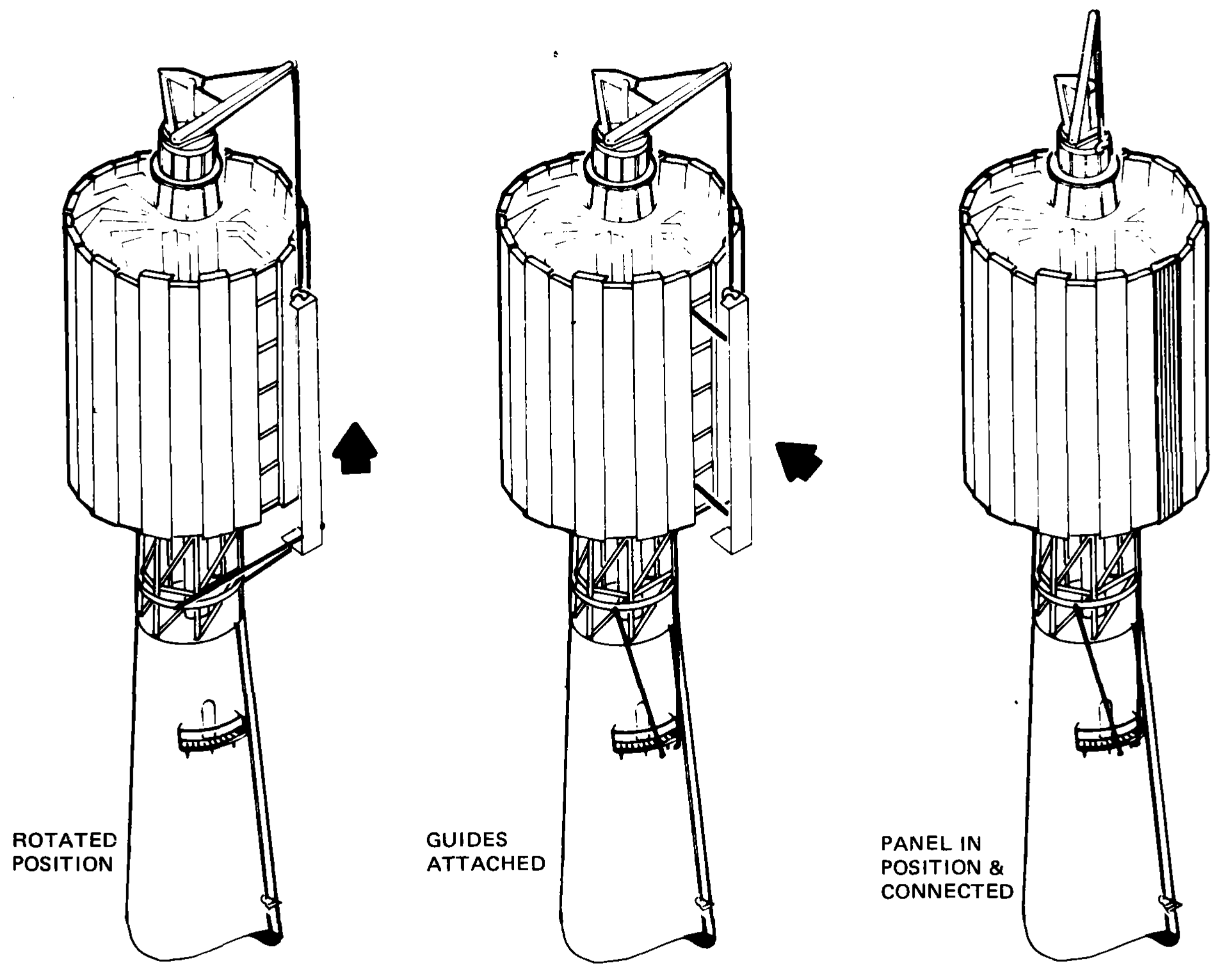


Figure 3-23. Panel Installation – Part 2

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3-2. Incoloy 800 for Nuclear Fuel Sheaths. GEAP-4633 compiled by C. Spalaris General Electric Atomic Laboratory, San Jose, California, July 1964.

3-3. F. Eberle and C.H. Anderson. Scaling Behavior of Superheater Tube Alloys in ASME High Temperature Steam Research Tubes at 1100-1500 F. Paper No. 61-PWR-3, presented at AIEF-ASME National Power Conference, Septebmer 1961.

4 PILOT PLANT RECEIVER DEFINITION

Section 4
PILOT PLANT RECEIVER DEFINITION

This section describes the analyses and design of the Pilot Plant receiver subsystem for the 10-MWe solar power plant and the plans for its fabrication, installation and operation (Figure 4-1).

4.1 FLOWDOWN FROM COMMERCIAL PLANT

Since the basic mission of the Pilot Plant is to demonstrate the validity of the Commercial Plant design concept, the Pilot Plant receiver design is dictated by a flowdown from the Commercial receiver concept. The Pilot Plant receiver design is therefore necessarily a scaled-down version of the Commercial receiver.

The flowdown from the commercial system to the Pilot Plant receiver is basically one of scale. All processes from fabrication through installation are identical. The operational aspects are likewise identical. The only areas with distinct differences lie in the design requirements for heat flux and power level. These differences are shown in Table 4-1, which describes the receiver parameters to be scaled.

Table 4-1
RECEIVER PARAMETERS

Item	Commercial	Pilot Plant
Power MW_e	100	10
Peak Incident Heat Flux MW/m^2	0.85	0.30
Diameter - M	17	7
Length - M	25.5	12.5

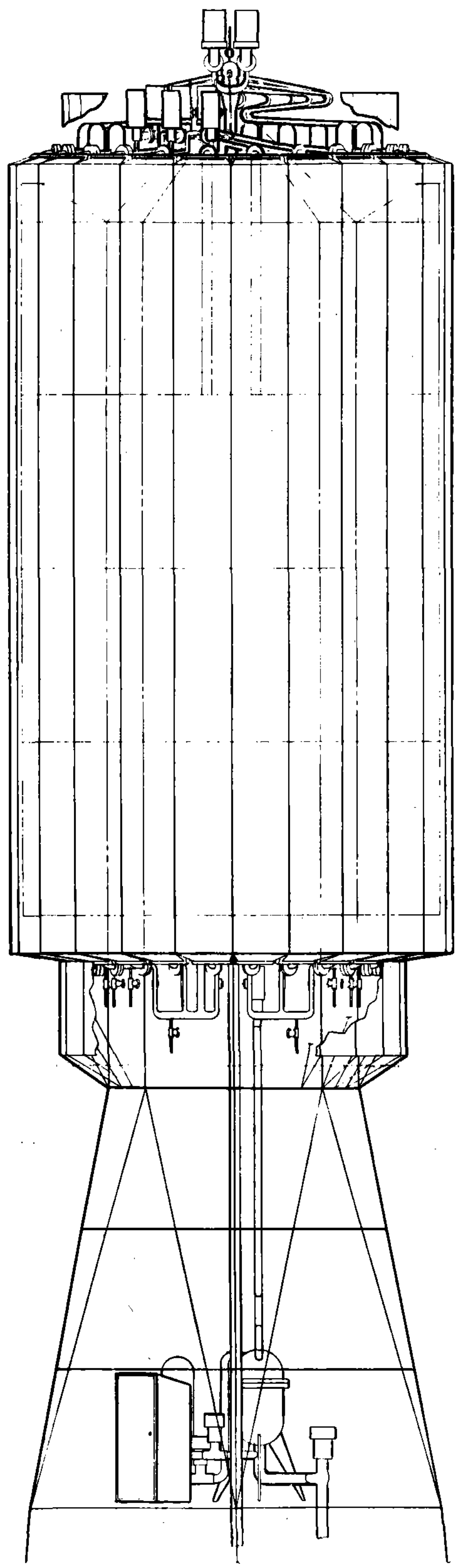


Figure 4-1. Pilot Plant Receiver Unit External View (Looking North)

Since the Pilot Plant receiver must provide for maximum technology transfer to the Commercial device, the heat-transfer scaling analysis is highly pertinent to the Pilot Plant configuration selection. It can be shown that the temperature drop in the receiver cooling tube film is given approximately by:

$$\Delta T \sim \frac{q_p d W^{0.8}}{Q^{0.8}}$$

where

q_p = Peak Heat Flux

d = Tube Diameter

W = Receiver Circumference

Q = Power

The foregoing relationship was developed from single-phase flow equations; however, it is only used for rough scaling and is considered sufficient for that purpose.

From this, we may gather the following significant points about cooling receivers:

A. For constant power and peak heat flux, a smaller heated width will result in larger tubing.

B. If the peak heat flux remains constant and power is reduced at the same rate as the width, then tube size does not change.

C. If power reduces faster than width, then tube size will reduce if the peak heat flux remains constant.

Considering the latter case for the relationship between a Commercial (100 MW_e) receiver and the Pilot Plant (10 MW_e), a scale reduction (S) is required under the condition of constant peak heat flux. If the temperature difference across the coolant film is constant, the above becomes:

$$\frac{d_2}{d_1} = \left(\frac{W_1}{W_2}\right)^{0.8} \left(\frac{Q_2}{Q_1}\right)^{0.8}$$

If power scales by a factor S and the surface area of the receiver by the same factor, then

$$Q \sim S$$

$$W \sim S^{1/2} \quad \text{since } WL \sim S$$

The tube size reduction becomes

$$\frac{d_2}{d_1} = \frac{1}{S^{0.4}}$$

In the case of the Pilot Plant to Commercial receiver where the scale factor, S, is 10, the tubes must reduce as follows:

$$\frac{d_2}{d_1} = \frac{1}{2.5} = 0.4$$

Now in the case where the inside diameter is between 1/4 to 1/2 in., the resulting fluid passages would be extremely small.

Assuming that such is the case, in order to keep d_2 equal to d_1, we determine what reduction of peak heat flux is necessary. This may be simply shown to be

$$\frac{q_{p_2}}{q_{p_1}} = 0.4$$

This design approach will yield the same size tubes and identical temperature drops across the coolant film, and consequently the similar risks in terms of sensitivity to flow maldistribution and inaccuracies in the cooling calculation. As wall temperatures are similar and the hydraulic stress is the same, the design margin is similar in both cases. Naturally, using identical tubes gives good manufacturing experience. The only item missing is the question of the tube fatigue life; however, that item is not and cannot be demonstrated by the Pilot Plant program, but rather is a calculated item. It is of necessity calculated in accordance with procedures set forth in the ASME boiler code. Because of the code's conservative design approach, life is not viewed as an item of technical risk. In the case of both the Pilot Plant and Commercial Plant, life has been calculated in excess of the 30-year (10,000 cycles) requirements.

It should be noted that the results of the prior calculations only approximate the actual relationship between Pilot Plant and Commercial receivers. The actual temperatures and tube sizes for both applications were rigorously determined with detailed computer programs. This discussion is only intended to provide a succinct indication of scalability.

Once the design aspects are seen to flow, confidence in the Pilot Plant lends similar confidence to the Commercial Plant because all processes are identical. The tubes are the same as are the construction techniques. No risk is involved in fabrication, installation, and final implementation.

4.2 REQUIREMENTS

The mission of the Pilot Plant receiver subsystem is to efficiently transfer energy from the concentrated solar radiation reflected from the mirrors of the collector subsystem into the water supplied by the electrical power-generation subsystem and to deliver steam, at precisely controlled superheated conditions, to the plant turbine generator and/or the thermal storage subsystem.

The receiver subsystem design will also minimize complexity and cost, and ease fabrication and maintenance within the limitations permitted by performance requirements.

4.2.1 Fluid Conditions

Nominally, the receiver will be required to accept water from the flow distribution system at 13.8 MN/m^2 (2,000 psia) and 205°C (401°F) and deliver superheated steam at rated conditions of 10.4 MN/m^2 (1,515 psia) and 516°C (960°F) to the electrical generation subsystem. Rated steam generated in excess of turbine power requirements will be diverted to the thermal storage subsystem.

The receiver subsystem must also be capable of delivering steam at 10.4 MN/m^2 (1,515 psia) and 349°C (660°F) when it is required to charge the total receiver energy output into thermal storage.

The receiver will accept feedwater of the following quality:

Factor	Maximum Limit*
Total solids	0.050 ppm
Silica as SiO_2	0.020 ppm
Iron as Fe	0.010 ppm
Copper as Cu	0.002 ppm
Oxygen as O_2	0.007 ppm
Hardness	0.0 ppm
Carbon dioxide	0.0 ppm
Organic	0.0 ppm
Lead	0.0 ppm
pH	9.3 - 9.5

*Steam, Its Generation and Use. Babcock and Wilcox, 38th edition (1972).

4.2.2 Power

The peak incident power to which the receiver is designed is naturally dependent on the mirror field design. For the collector subsystem considered here, it is 43.4 MW_t. Other power requirements are as follows:

	Rated	Derated
• Maximum Absorbed Power	37.1 MW_t	32.8 MW_t
• Minimum Absorbed Power	10.0 MW_t	7.26 MW_t

The peak heat flux associated with the thermal environment influenced by the collector is 0.3 MW_t/m^2. Diurnal variations in receiver power are shown in Figure 4-2. The need for efficient capture and utilization of solar insolation requires a high solar absorptance value on the external surface of the receiver of not less than 0.9. The value must exist regardless of degradation as may be expected in a desert environment. The surface must be also easily refurbished.

4.2.3 Geometry

The geometric requirements for receiver design are as follows:

• Tower Height		65m (213 ft)
• Receiver Centerline Elevation		80m (262 ft)
• Receiver Envelope	Dia.	7m (23 ft)
(Absorbing Surface)	Ht.	12.5m (41 ft)

4.2.4 Structure

The structural requirements to which the receiver are designed are made up of two parts. The first refers to those areas of concern relative to internal pressure and temperature distribution. The second refers to external influences, namely wind and seismic loading.

As a forced flow steam generator, the receiver will be designed and certified to the requirements of Section I of the ASME boiler code and local and state piping codes. The receiver shall also be designed for a 30-year (10,000 cycle) fatigue life.

The second requirement, external influences, is covered by the following:

• Receiver Centerline Sway (with 16 m/s (36 mph) sustained wind at 10m)	0.18m (0.6 ft)
• Tower Survival (sustained wind at 10m)	40 m/s (90 mph)
• Receiver Weight Limit	0.227×10^6 KG (0.50×10^6 lb)
• Seismic Load	0.25g lateral acceleration at tower base

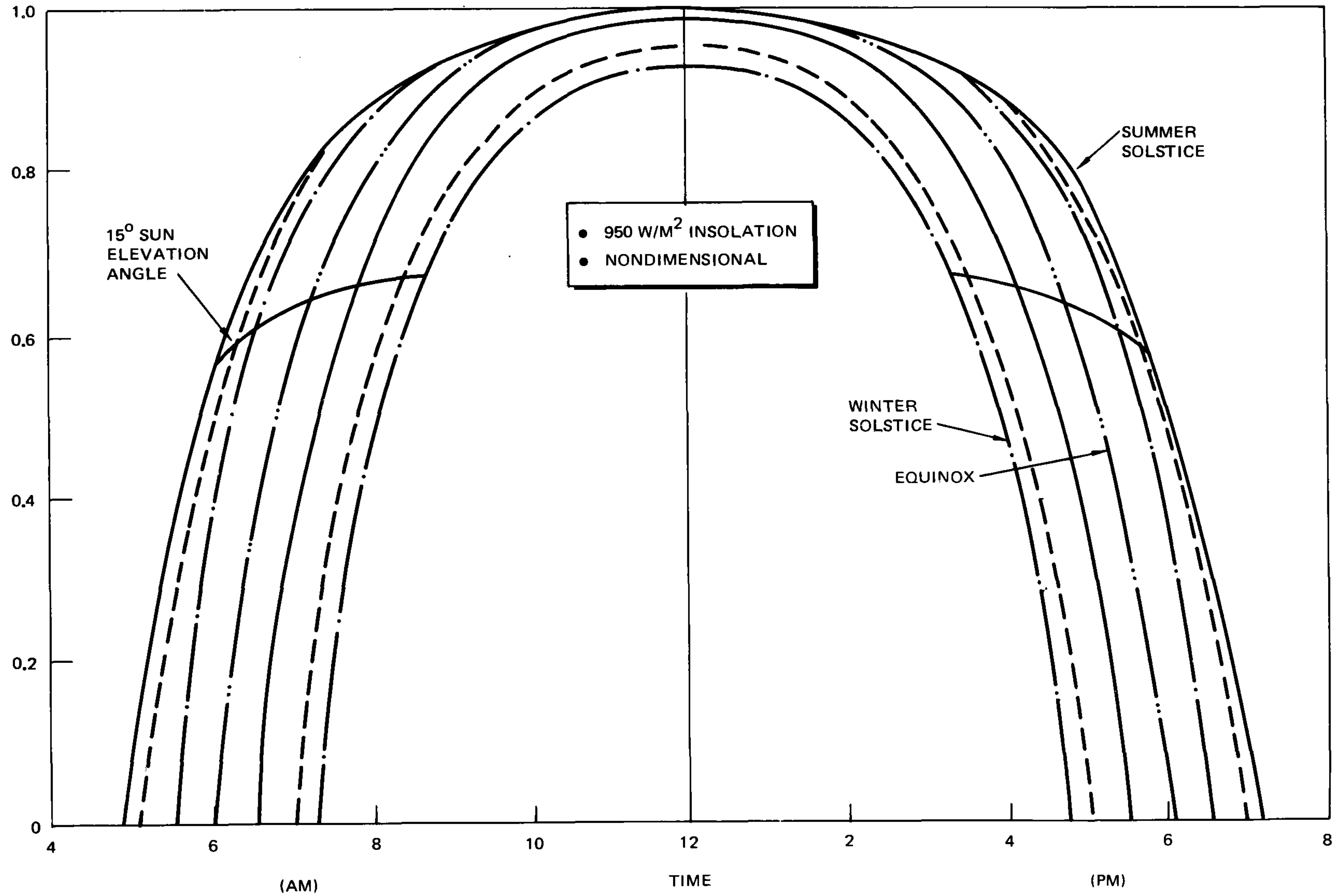


Figure 4-2. Monthly Diurnal Variations in Absorbed Thermal Power, Pilot Plant

4.2.5 Environmental

This set of requirements refers to the set of conditions that govern the heat losses to which the receiver is designed:

- Ambient Temperature — $28^{o}C$ ($82.6^{o}F$)
- Wind Speed at 10m Elevation — 3.5 m/s (8 mph)
- Velocity Profile — $V_H = 3.5\ m/sec\ (H/10m)^{0.15}$

Nighttime conditions governing design requirements are:

- Ambient Temperature — $5^{o}C$ ($41^{o}F$)
- Wind Speed at 10m Elevation — 3.5 m/sec (8 mph)

4.2.6 Operational

The receiver must operate throughout the day within the envelope of power and fluid conditions described in earlier sections. Table 4-2 summarizes the operational conditions for the following conditions:

Case 1. Design point operation (Winter 2 pm) 10 MW_e net, no flow to storage, rated steam.

Case 2. Equinox noon maximum power collection, rated steam, no flow to storage, all flow to turbine (12.82 MW_e gross – within 10% overflow capability).

Case 3. Equinox noon maximum power collection, rated steam, 10 MW_e net turbine-generator output, excess power to storage.

Case 4. Maximum charging of thermal storage, derated steam (30 MW_t into storage tank).

Case 5. Intermittent cloud operation combines maximum charge of thermal storage (Case 4) with turbine operation off thermal storage at maximum flow.

The receiver design must provide for smooth and stable transition from one operational mode to another. Additionally, the receiver must distribute fluid internally to ensure safe operation and be capable of starting and shutting down in a safe and stable manner. The receiver must be available for 96.7% of the sunlight exposure time (including 1.61% forced and 1.42% planned planned outages).

Table 4-2

RECEIVER OPERATIONAL CONDITIONS

Item	Case 1	Case 2	Case 3	Case 4	Case 5
Absorbed Power	32.64 MW_t	37.1 MW_t	37.8 MW_t	32.8 MW_t	32.8 MW_t
Receiver Exit Conditions	516°C	516°C	516°C	349°C	349°C
	(960°F)	(960°F)	(960°F)	(660°F)	(660°F)
	10.45 MPa	10.45 MPa	10.45 MPa	10.45 MPa	10.45 MPa
	(1,515 psia)	(1,515 psia)	(1,515 psia)	(1,515 psia)	(1,515 psia)
	12.9 Kg/sec	14.8 Kg/sec	14.8 Kg/sec	16.5 Kg/sec	16.5 Kg/sec
	(102,400 lb/hr)	(117,570 lb/hr)	(117,570 lb/hr)	(130,500 lb/hr)	(130,500 lb/hr)
Receiver Inlet Conditions	205°C	210°C	210°C	211°C	211°C
	(401°F)	(410°F)	(410°F	(412°F)	(412°F)
	13.79 MPa	13.79 MPa	13.79 MPa	13.79 MPa	13.79 MPa
	(2,000 psia)	(2,000 psia)	(2,000 psia)	(2,000 psia)	(2,000 psia)
	12.9 Kg/sec	14.8 Kg/sec	14.8 Kg/sec	16.5 Kg/sec	16.5 Kg/sec
	(102,400 lb/hr)	(117,570 lb/hr)	(117,570 lb/hr)	(130,500 lb/hr)	(130,500 lb/hr)

4.2.7 Functional and Physical Interfaces

The receiver interfaces optically with the collector subsystem, mechanically and hydraulically with the riser and downcomer of the electrical power-generation subsystem, and electronically with the master control subsystem. Interface requirements with the collector, thermal storage, and electrical power subsystems were covered in terms of fluid conditions and thermal power requirements in Sections 4.2.1 and 4.2.2.

The interface with master control requires that the receiver be capable of responding to commands from master control and be able to furnish input data to master control for use in Pilot Plant status reporting or control.

4.3 DESIGN CHARACTERISTICS

4.3.1 Subsystem Design Summary

The major hardware assemblies that comprise the Pilot Plant receiver subsystem are the receiver unit, the tower on which the receiver unit is mounted above the collector field, and the supporting control and instrumentation equipment.

The receiver has 6 modular preheater panels and 18 boiler panels, flow control and instrumentation equipment, and the supporting structure.

Panel subassemblies are structurally identical, built of 70 tubes of high-strength, corrosion-resistant Incoloy 800 laid side-by-side and joined together thermally and structurally and made opaque to incident light by full-length longitudinal welds. Incoloy 800 has high conductivity and excellent ductility for long life and resistance to thermal shock.

An Incoloy 800 water manifold at the lower end of the panel assembly equally distributes water to all panel tubes. An Incoloy 800 steam manifold, also at the upper end of the panel subassembly, acts as a collector manifold for the effluent steam from all tubes. To ensure leak integrity, all panel tubes are welded to both the water and steam manifolds.

Each tube is 12.7 mm (0.50 in.) OD x 6.8 mm (0.269 in.) ID. The exposed length is 12.5m (41 ft). Additional length provides for folding over at the bottom to protect the inlet water manifold and lower support structure from radiation and folding over on top to protect the outlet steam manifold from insolation. The actual Pilot Plant scale panel fabricated for SRE testing is shown in Figure 4-3.

The surfaces of the tubes exposed to solar radiation are coated with Pyromark paint which has demonstrated an absorptivity of 95% over a wide range of wavelengths. The coating is resistant to weathering and was tested for long-term compatibility with high-intensity solar radiation during SRE.

Each panel tube bundle is mounted to a panel backup structure to maintain the panel shape and hold it to the receiver tower structure properly while allowing for thermal growth and providing support for wind and seismic loads. A series of sliding clips and channels permit unrestrained lateral and vertical thermal expansion of the panels to prevent the buildup of thermal stresses. Each panel is insulated on the backside to reduce thermal loss and protect the support structure and control components.

The individual tubular panel assemblies of the receiver unit are mounted on a central core steel support structure to form a single large and essentially circular (24-sided) cylinder 7m (23 ft) in diameter by 12. 5m (41 ft) long. The heliostats surrounding the receiver tower direct their collected insolation onto the full 360-deg external surface of the receiver unit.

The receiver tower is of steel construction and extends 65m (213 ft) above grade to the interface with the receiver unit steel support structure which continues up through the receiver unit to an elevation of 86m (283 ft) where it is crowned with a crane of 5-ton capacity. Midpoint of the receiver unit is 80 mm (262 ft).

The base of the tower is 12. 2m (40 ft) square, tapering to 4. 6m (12 ft) at 65m elevation. The square concrete foundation is composed of a mat 0. 61m (2 ft) thick which is 15. 2m (50 ft) on a side and located 3. 96m (13 ft) below finished grade. Concrete wall and pedestals extend 5. 48m (18 ft) up to meet the steel structure at an elevation of 1. 52m (5 ft) above the grade.

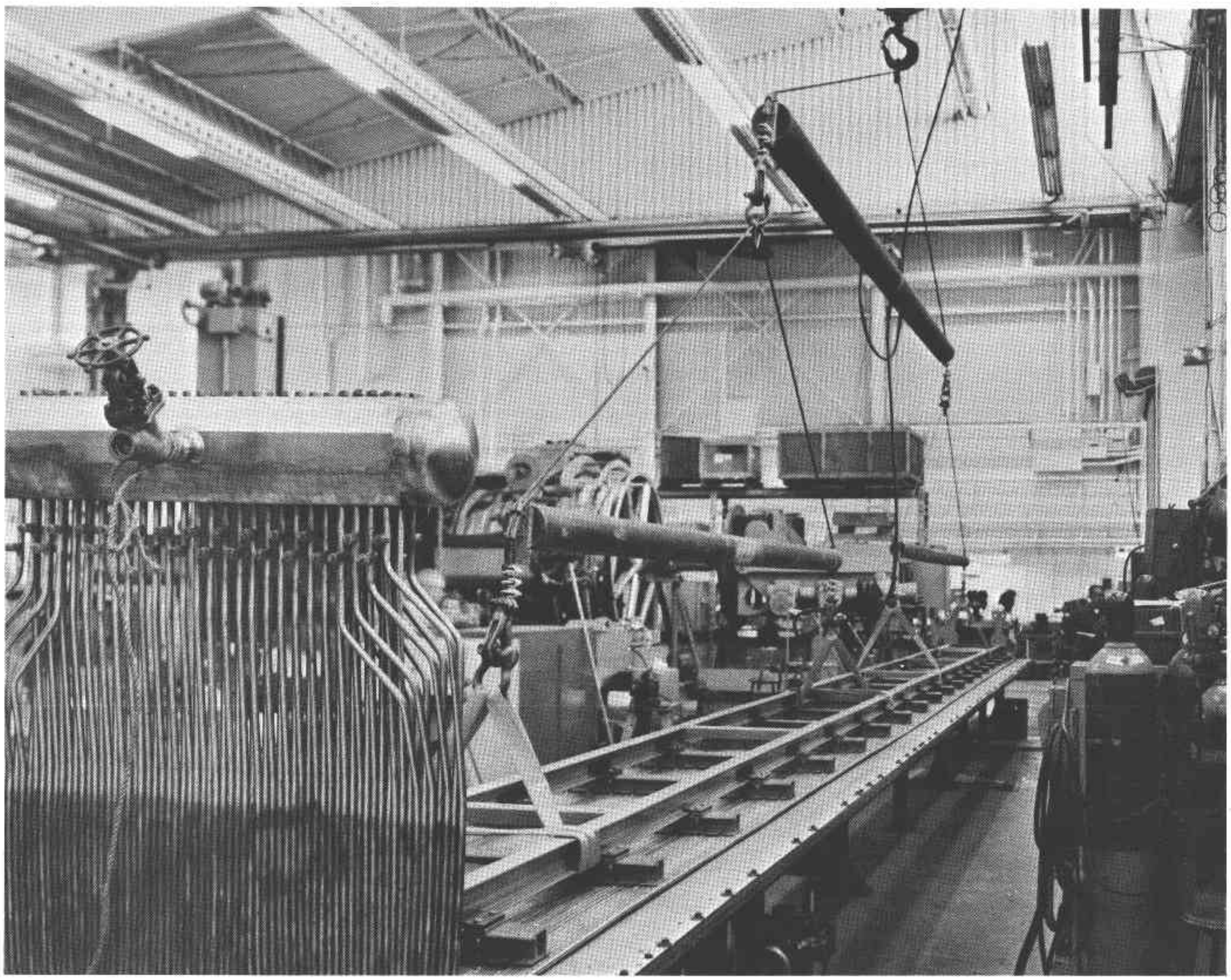


Figure 4-3. Completed Pilot Plant Panel

The flow control and instrumentation subassembly includes sensors, signal conditioning, control electronics, valves, filters, and plumbing (Figure 4-4). The function of the subassembly is to direct and control the flow of water to the various parts of the receiver as directed by the plant operator or master control.

To initiate startup, water from the water treatment equipment of the electrical power-generation subsystem is forced up the tower riser by feed pumps and into the receiver inlet filter assembly. The water then enters a manifold, which distributes the flow to the inlets of three parallel sets of two panels in series located on the south side of the receiver and designed to function as preheaters. The water absorbs heat as it flows through the first panel of each set and down through the second panel, where it joins the flow from the other preheaters in a ring manifold that supplies the remaining 18 panel assemblies designated as boiler panels. Passing through a modulating flow control valve at the inlet to each boiler panel, the water flows vertically upward again, absorbing heat from the incident solar insolation and leaving the upper end of the boiler panels as superheated steam. The individual boiler panel inlet valves provide the flow control necessary to maintain constant outlet temperature despite diurnal and seasonal variations in heat load at each panel. The control valves also control cloud-induced transients and regulate startup and shutdown sequences. Thus, active control of the water flow through the preheater panels is not required.

As steam exists from each panel discharge manifold, it passes through a cyclone type water separator as a precautionary measure to ensure absolutely dry steam. The steam enters the steam downcomer collection manifold. There it is mixed with the discharge flow from the other boiler panels and is carried away by the downcomer to the turbine of the electrical power-generation subsystem or the thermal storage subsystem or both as directed by master control.

During startup or other conditions, when solar insolation is too low to produce the proper superheat conditions, a combination of valves divert receiver discharge flow away from the downcomer and into a receiver flash tank assembly until proper superheat conditions are achieved.

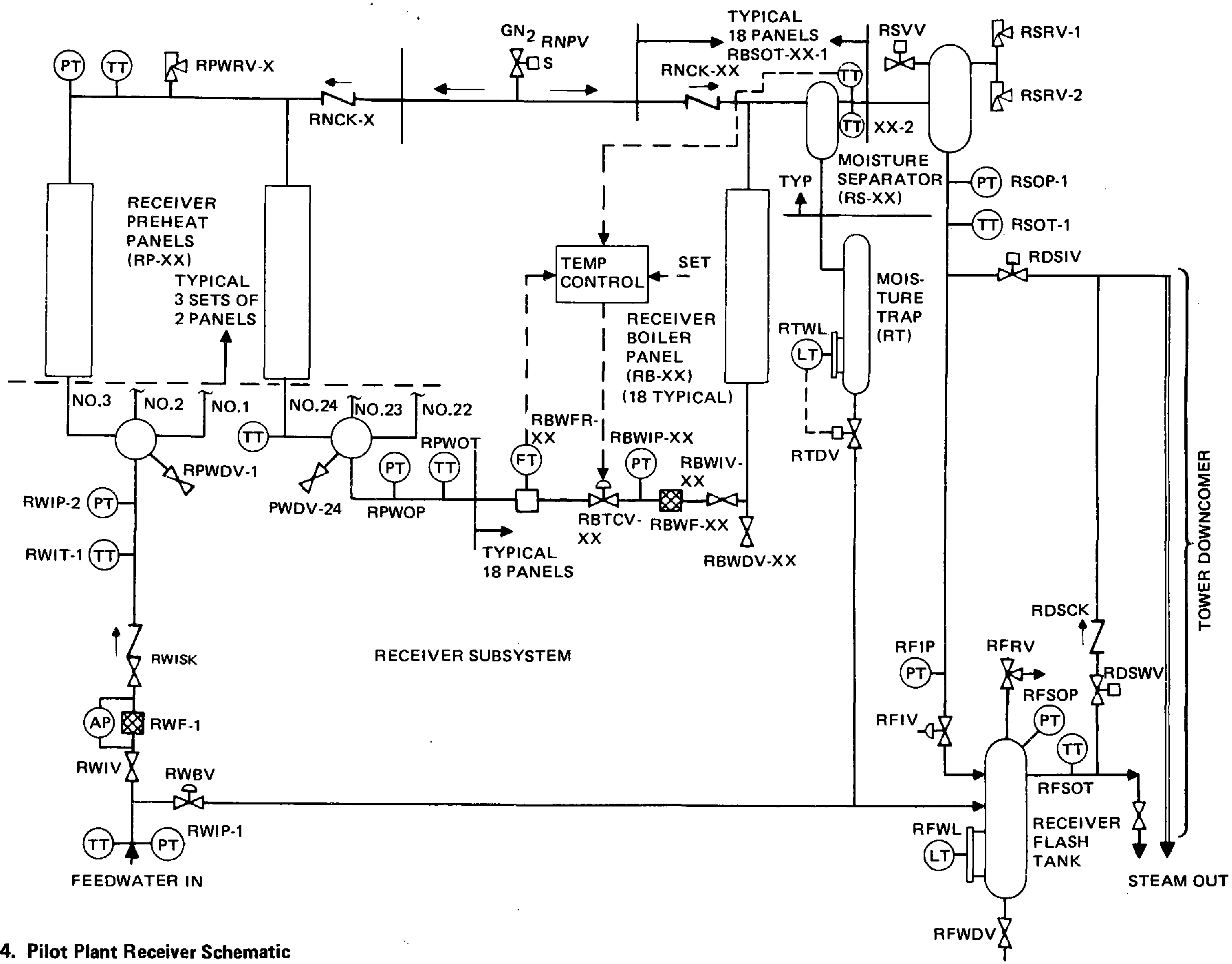


Figure 4-4. Pilot Plant Receiver Schematic

A drawing of the overall receiver unit is shown in Figure 4-5. An elevation view of the exterior of the receiver is also shown. The apparatus at the center base of the receiver is the main filter element, which contains provisions for automatic backwashing at night. The requirement for filtration will depend on a final selection of material for the riser pipe line. A line is shown leading from the filter to the inlet manifold for the three preheaters. Two boiler relief valves (code requirement) are on top of the receiver, and three preheater relief valves are to the right of center near the top. Portions of the passive radiation shield are shown which protect the central top portion of the receiver from spillover radiation. Portions of a lower shield are shown at the bottom of the panels. Various sectional views of the receiver are shown, and the configuration of the preheater crossover lines is shown in the top sectional view.

(The manifolding and feed system components are discussed in Section 4.3.2.2 and are shown in Figure 4-35. The steam lines, with expansion sections which conduct steam from the separators of each panel to the downcomer are shown at the top of Figure 4-35. The water drain lines from each of the separators and the drain line manifold are also shown. The drain line feeds into the receiver moisture trap, which is equipped with remotely operated blowoff valves and level sensors. The blowoff valves operate in conjunction with the level sensors to maintain a specified water level in the tank. If the level exceeds the control level, a sensor higher up in the tank sends an alarm to master control. The manifold in the center of Figure 4-35 is the boiler feed manifold or the preheater discharge manifold.)

4.3.2 Pilot Plant Receiver Unit

The pilot plant receiver unit is composed of 6 modular preheater panels, 18 modular boiler panels, flow control and instrumentation equipment, and the supporting structure. Drawings of the receiver unit are provided in Figure 4-5.

4.3.2.1 Preheater and Boiler Panels

This section describes the requirements, supporting analyses, and calculations supporting the preheater and boiler panel designs. Panel design predictions are supported by SRE data, independently conducted test programs, and other Government-supported programs.

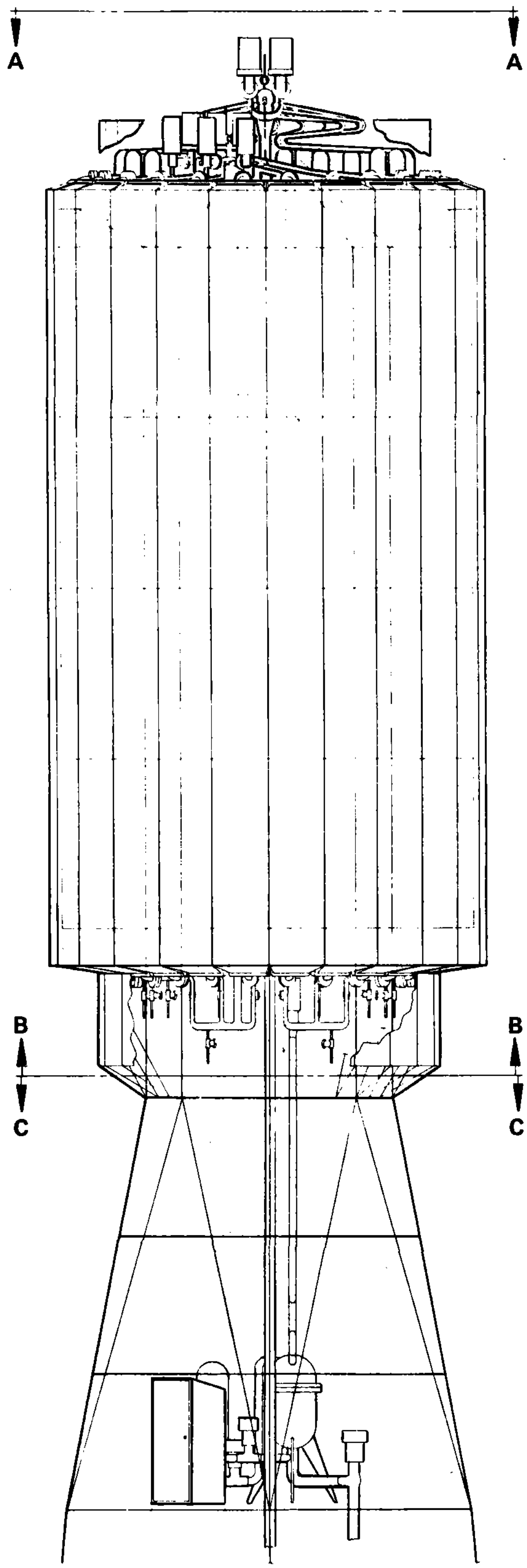
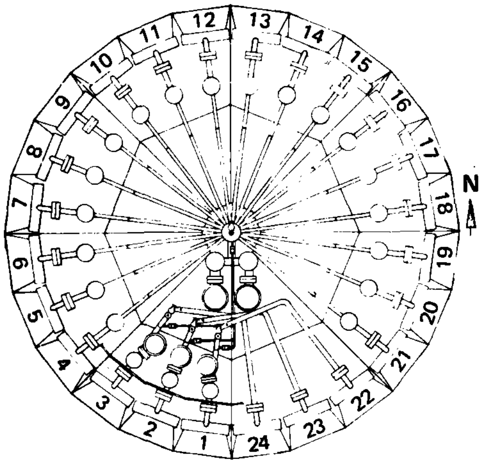
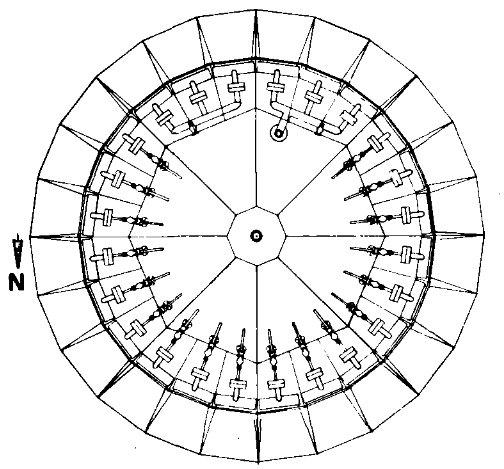


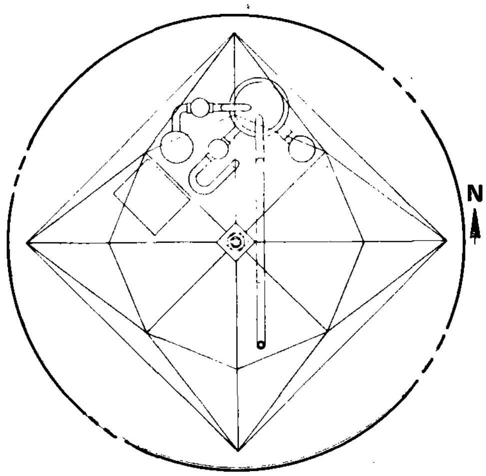
Figure 4-5. Pilot Plant Receiver Unit External View (Looking North) (Page 1 of 2)



VIEW A–A



SECTION B–B



SECTION C–C

Figure 4-5. Pilot Plant Receiver Unit Cross Sections (Page 2 of 2)

As noted in Section 4.3.1, water entering the receiver unit passes first through the preheater panels for initial heating before it enters the boiler panels and is converted into superheated steam. Although the preheater and boiler panels are different in their functions, they are structurally identical.

Requirements

The basic requirement driving the receiver design is contained in Figure 4-6, which is the incident heat flux profile on the north side of the receiver. Since this is the highest heat flux to which the receiver is subjected, it follows that this will be the limiting condition insofar as fatigue life is concerned since this phenomenon is governed by gradients within the metal. The relative absorbed power distribution on the receiver is shown in Table 4-3 for various times of the year throughout a diurnal cycle. These requirements then drive the absorber panel design.

Analysis and Supporting Data

This section describes the design of the panels from the point of view of configuration, cooling, thermal losses, fatigue, stability, and nighttime thermal control.

Tube Geometry, Materials, and Design Codes

The analyses leading to the selection of the basic receiver configuration, materials of construction, and governing design codes have been discussed in detail in Section 3. The flowdown requirements setting the Pilot Plant tube geometry was discussed in Section 4.1.

Collector Aim Strategy

The Pilot Plant collector (heliostat) aim strategy has a significant effect on receiver tube design. Of major importance is the heat flux value in the film boiling region where the strains within the cooling tubes are maximized due to the relatively inefficient cooling mechanism.

The temperature distributions (results are shown in Figures 4-19 and 4-20) were based on the selected customized 3 point high-low aim strategy and resulted in a peak heat flux of 0.30 mw/m^2 (Figure 4-6). An evaluation of the effect of using a single aim point strategy was performed, however,

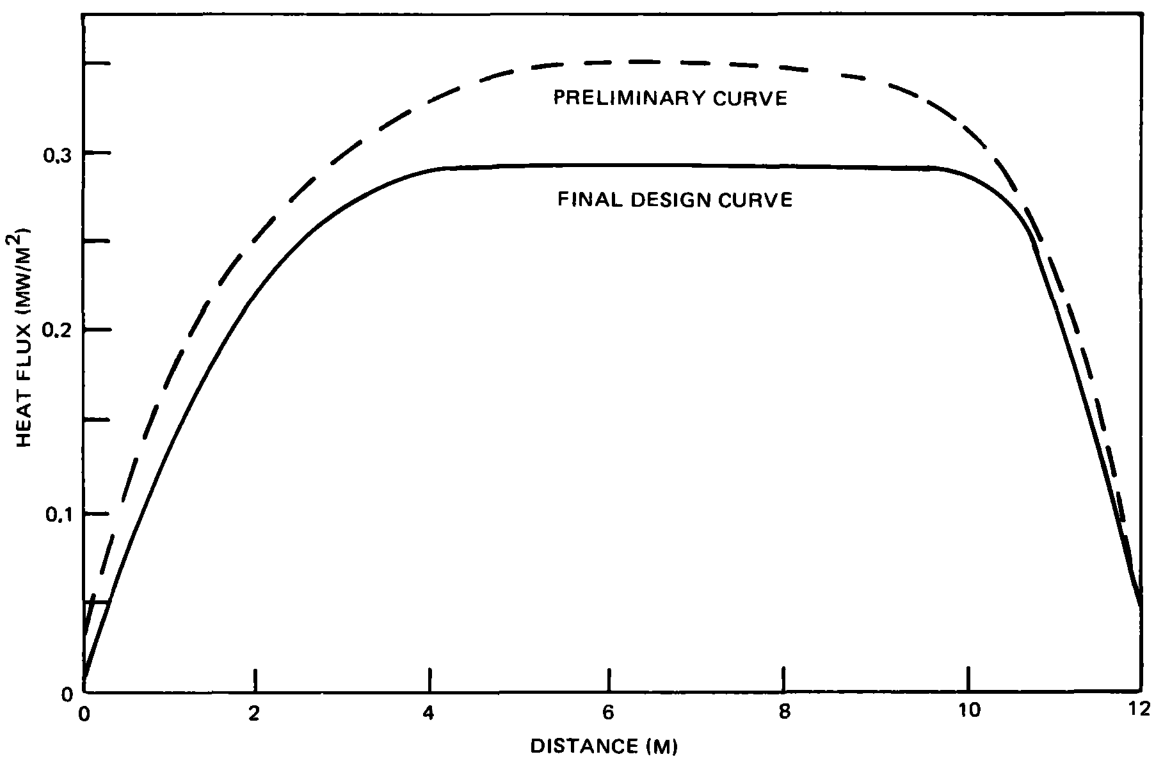


Figure 4-6. Pilot Plant Receiver Incident Heat Flux Profile, North Panel, Equinox Noon

Table 4-3

RECEIVER ABSORBED POWER DISTRIBUTION - PERCENTAGE OF TOTAL RECEIVER POWER

		Panel Location			
		East	North	West	South
Day	Hr.				
Jun 21	12 Noon	4.63	5.92	4.63	2.00
	2 PM	5.36	5.97	3.85	1.98
	4 PM	6.00	5.48	2.54	2.12
	6 PM	6.47	5.55	2.51	1.98
Mar 21	12 Noon	4.62	6.40	4.62	1.65
Sep 21	2 PM	5.38	6.48	3.11	1.64
	4 PM	6.28	6.52	2.42	1.74
Dec 21	12 Noon	4.67	6.78	4.67	1.34
	2 PM	5.16	7.05	3.04	1.30
	4 PM	6.22	5.98	2.48	1.16

the peak heat flux for that case was in excess of 0.5 mw/m^2. Using the same tubes as in the Commercial receiver, 12.7 mm (0.5 in.) OD, the resultant wall temperatures were 528°C (1,000°F) in the film boiling region but 631°C (1,166°F) in the superheater region. The former point would meet the life requirements; however, the latter implies sufficiently high temperatures that could impact material capabilities. The alternative to this would be to reduce tubing size to improve cooling (higher velocity); however, this is viewed as unattractive because of a greater tendency for contamination and added fabrication costs due to additional welds and more parts.

Cooling Circuit Design

The original data base for cooling calculations emanated from an independently funded research and development program. (Ref.: Rocketdyne IR&D Technical Report 1TR-75-044-C, "Heat Flux Demonstration for Solar Tower Receiver," by R.D. Tobin, 10 November 1975.) Based on data derived from a Department of Energy program. E(04-3)-1103 (Ref.: R9958, "Solar Receiver Heat Flux Capability and Structural Integrity," May 1976;

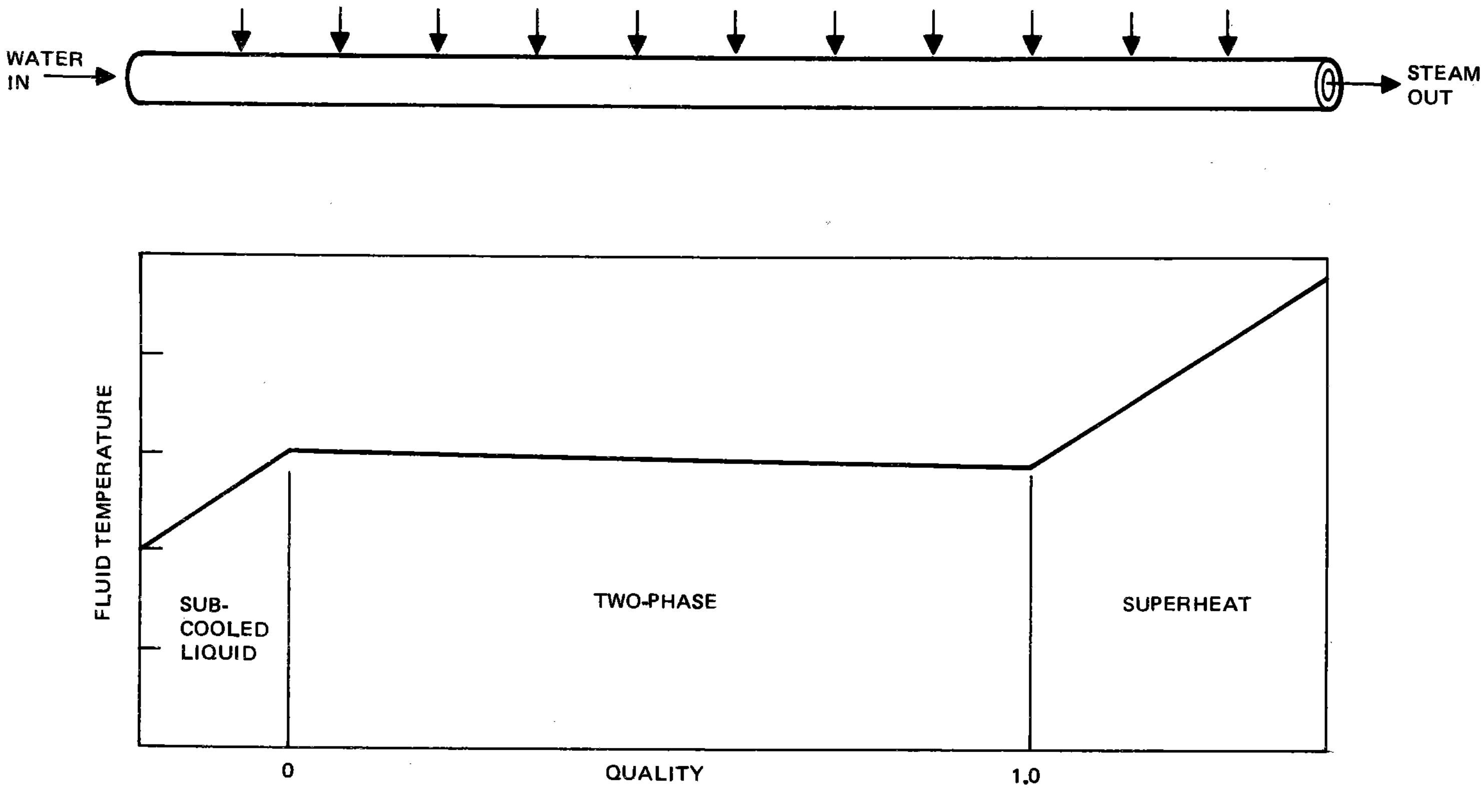
Rocketdyne) and the results derived during this program, the data base has been improved and allows the design of the Pilot Plant receiver with a high degree of confidence.

Original Data Base — The primary objective of the independently funded program was to determine the cooling feasibility of the once-through boiler concept at conditions consistent with Commercial receiver conditions. The concept of a once-through boiler is shown in Figure 4-7. The major objective was to measure cooling heat-transfer coefficients to be used for design purposes.

The technical approach used in this experimental test program consisted of first determining the range of operating conditions and candidate tube designs commensurate with Commercial receiver requirements. An evaluation was then performed to select an electrically heated tube configuration compatible with facility capabilities to simulate the receiver operating range. The electrically heated tube was then tested over a range of heat flux, flowrate, outlet temperatures, and outlet pressures.

The testing conducted under this task differs in two primary respects from actual solar tower receiver application. First, the test section used herein was mounted horizontally rather than vertically to minimize the cost of facility activation. Second, the use of electrical resistance heating provided a uniform heat flux profile both circumferentially and longitudinally rather than the asymmetric profile encountered in a solar tube panel.

The use of a horizontally mounted test section was presumed acceptable because the relatively high coolant velocities required to handle the high heat flux levels result in inertia forces much greater than the gravity forces (i.e., high Reynolds number flow). Also, the use of a horizontal tube is conservative in terms of flow stability. That is, if the horizontal position results in stable flow, then a vertical tube would tend to be even more stable due to the additional benefit of gravity forces. The use of electrically heated tubes is, however, an accepted technique for obtaining basic cooling data and is believed satisfactory for this task.



CONCEPT ADVANTAGES

- SIMPLE MANIFOLDING
- LIGHT-WEIGHT
- LOW-COST
- COMPACT

AREAS OF INVESTIGATION

- WALL TEMPERATURE PREDICTION
- PRESSURE DROP
- FLOW STABILITY

Figure 4-7. Once-Through Boiler Concept

The selection of the tube geometry for use in this task was based on consideration of receiver operating conditions, facility capabilities (i.e., electrical power), and available in-house tubing. The resulting test section consisted of a 0.64-cm OD 91/4 in.) x 0.17 cm (0.065 in.) wall 347 stainless steel tube with copper buss bars brazed to either end to facilitate electrical power connections. The electrically heated length was selected to be 15.75 ft to match the facility power capability of 500 amps at 100 V. At this maximum power condition (50 kw), the maximum internal heat flux was about 1 MW/m^2 (0.67 $Btu/in.^2$-sec) neglecting losses.

The tube (5.2m long) was instrumented with 17 chromel-alumel thermocouples at 0.3m intervals. Insulation was wrapped around the tube at the thermocouple attachment locations to minimize the effect of ambient air conditions on temperature measurements.

The tests were conducted at the Rockwell B-1 Division Thermal Lab. A facility schematic denoting instrumentation locations is presented in Figure 4-8. Deionized water was stored in a tank pressurized up to 21 MN/m^2 (3,000 psia) with gaseous nitorgen. A control valve was used to establish the required flowrate as measured by the pressure drop across a calibrated orifice. An in-line heater (25 kW) upstream of the test section provided the required water inlet temperature. Downstream orifices of various sizes were used to achieve the back pressure based on desired steady-state flowrate and steam outlet temperature.

An eight-channel dynograph recorder was used to record test section inlet and outlet pressure and temperature and the calibrated orifice pressure drop. The 17 wall temperature measurements were recorded on a Leeds & Northrup 24-channel multipoint recorder. The inlet and outlet temperatures, and an additional wall temperature measurement, were monitored on a Doric digital readout device.

Prior to initiation of testing, heat-loss calibrations were obtained as a function of tube temperature. This was accomplished by applying electrical power to the test section without coolant flow. The power required to

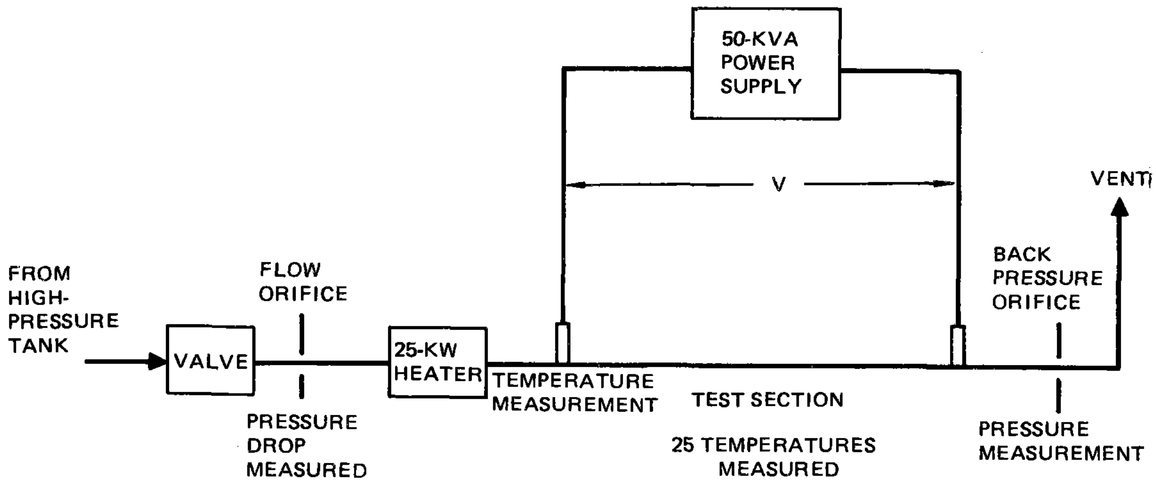


Figure 4-8. Flow Schematic of Electrically Heated Tube Test Facility

maintain the tube at a steady temperature level without flow is essentially equivalent to the losses from convection and radiation.

The basic test proceures were straightforward. The water flowrate was established at the desired test level with the flow control valve. The in-line heater was then adjusted to provide the required inlet temperature of 204° to 260°C (400° to 500°F). Electrical power to the test section was then gradually increased to the desired level. Final adjustements were then made on flowrate and inlet temperature. Steady-state conditions were maintained for approximately one minute, which permitted two complete cycles of the multipoint wall temperature recorder.

The data reduction technique used is summarized in Table 4-4. The computer model used was developed originally based on studies related to Rocketdyne's compact steam generator. For this task, the model was modified to simulate electrical resistance heating, including the effect of electrical resistance variation with wall temperature.

The temperature differential through the tube wall was calculated from a closed-form solution to the radial heat conduction equation with internal heat generation.

A series of 22 tests was conducted in the electrically heated, horizontal tube test section with an average heat balance of 7.3%. The range of test parameters evaluated exceeded the Commercial solar receiver heat flux level. Heat fluxes to 1.5 MW/m^2 were tested at pressures between 10 and 18 MN/m^2. Satisfactory steady-state operation was obtained over this entire range of operating conditions without sustained flow instabilities. It is believed that the lack of flow instability is due to the relatively high coolant mass flux and heat flus levels in conjunction with this coolant pressures.

A comparison of outer surface wall temperature profiles as a function of pressure is presented in Figure 4-9. Note the typical peak that occurs in

Table 4-4

DATA REDUCTION TECHNIQUE

- Measure
  - Outer Surface Wall Temperature Profile, T_{w_o}
  - Electrical Power Input, Q_{in}
  - Coolant Flowrate, $\dot{W}$
  - Coolant Inlet and Outlet Temperature, T_{c_i} and T_{c_o}
  - Coolant Inlet and Outlet Pressure, P_i and P_o
- Calculate
  - Water Enthalpy Rise, ΔH
  - Heat Balance - Q_{in} vs $\dot{W}\Delta H$
  - Inner Wall Temperature, T_{w_i} = F (Geometry, Heat Flux)
  - Coolant Temperature Profile, T_c
  - Coolant Film Coefficient Profile, $h_c = \dfrac{Q/A}{T_{w_i} - T_c}$
- Compare With Computer Model
  - Outer Surface Wall Temperature Profile
  - Coolant Film Coefficient Profile

the two-phase region. This peak is due to a dry-out condition. The most interesting aspect of these data is the effect of coolant pressure on the two-phase temperature peak.

The pressure effect is more pronounced when considered in relation to the minimum (two-phase region) convective film coefficient as shown in Figure 4-10. The higher mass flux levels appear to be significantly affected by coolant pressure variations. The pressure effect on film coefficient is greater than can be accounted for in terms of coolant property variations in a typical forced convection correlation.

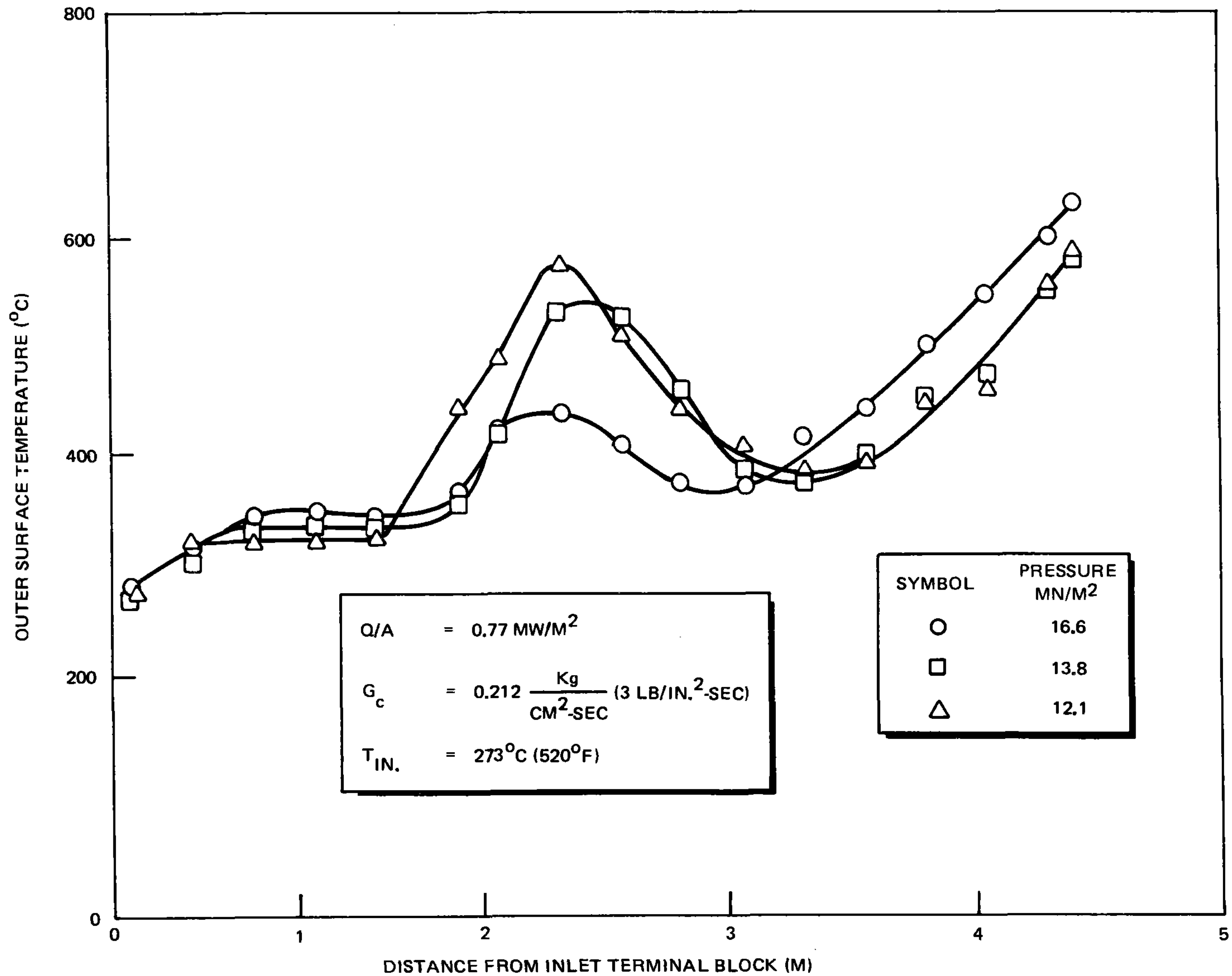


Figure 4-9. Coolant Pressure Effect on Tube Wall Temperature

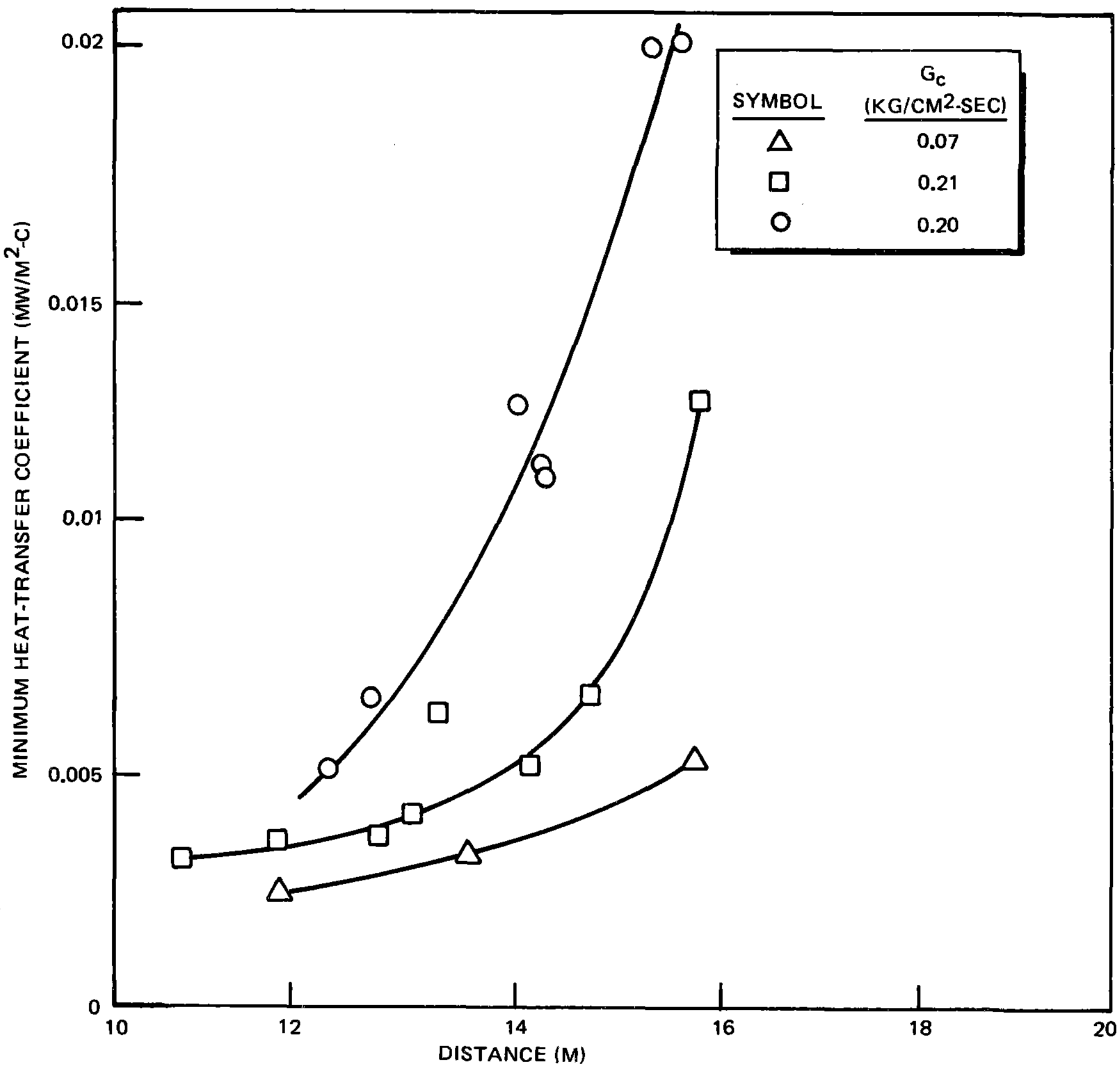


Figure 4-10. Coolant Pressure and Mass Flux Effect on Minimum Heat-Transfer Coefficient

The location along the tube where the minimum film coefficient occurs is also of importance. Two factors, heat flux and quality, appear to affect the location of the minimum cooling point. In general, the higher the heat flux level, the lower the steam quality at which film boiling occurs. The minimum cooling point was therefore correlated as a function of these two parameters.

Lastly, these data were correlated in a computer program used to predict wall temperatures. Program elements were as follows:

1. The computer program performs unidimensional heat-balance calculations at stations along the tube. Using calculated heat-transfer coefficients, the balances allow determination of tube wall temperatures. Heat loads were used to determine the fluid enthalpy and temperature rise for the next station. In addition, pressure drops were determined. At particular locations, a two-dimensional calculation is performed.
2. The two-dimensional analysis used Rocketdyne's differential equation analyzer program (DEAP). This program solves second-order partial differential equations using distributed network models in steady-state and transient modes. It considers variable thermal properties.
3. Steam and water heat-transfer coefficients are calculated from the classical McAdams equation.
4. In the low quality region, nucleate boiling provides for excellent heat transfer. The equation in this region used correlations from UCLA/Purdue experiments. The empirical equation used was:

   $$h = 0.04\ (Q/A)^{3/4}\ e^{P/6.2}$$

   where

   $h = MW/m^2\text{-}K$

   $Q/A = MW/m^2$

   $P = MN/m^2$

or

$$h = 0.02\,(Q/A)^{3/4}\,e^{P/6.2}$$

where

$h = \text{Btu/in}^2\text{-sec-F}$

$Q/A = \text{Btu/in}^2\text{-sec}$

$P = \text{psi}$

This equation provided satisfactory agreement with the experimental data as shown in Figure 4-11.

The film boiling regime was the most complicated region analytically. Empirical data was analytically correlated to pressure, quality, and heat flux. There are three main conditions in the film boiling region that were of interest. These were the start of film boiling, the minimum film coefficient, and the end of film boiling at unit steam quality.

The start of film boiling was correlated to quality, and heat flux as shown in Figure 4-12. The heat-transfer coefficient used in the analysis at the start of film boiling corresponded to the nucleate boiling coefficient calculated at the previous station. A polynomial curve fit was used to estimate the heat-transfer coefficient at stations between the start of film boiling and the station at which the minimum coefficient occurred.

The same type of correlation was done for the point at which the minimum film coefficient occurred. This is illustrated in Figure 4-13. The data spread for this point is greater than the previous because this point is not as well defined by the test data. The minimum film coefficient was calculated using the equation:

$$S_t = \frac{0.023}{R_e^{0.2}\,Pr^{2/3}}\,\emptyset$$

The properties were saturated steam properties and Ø was a factor dependent on pressure as shown in Figure 4-14.

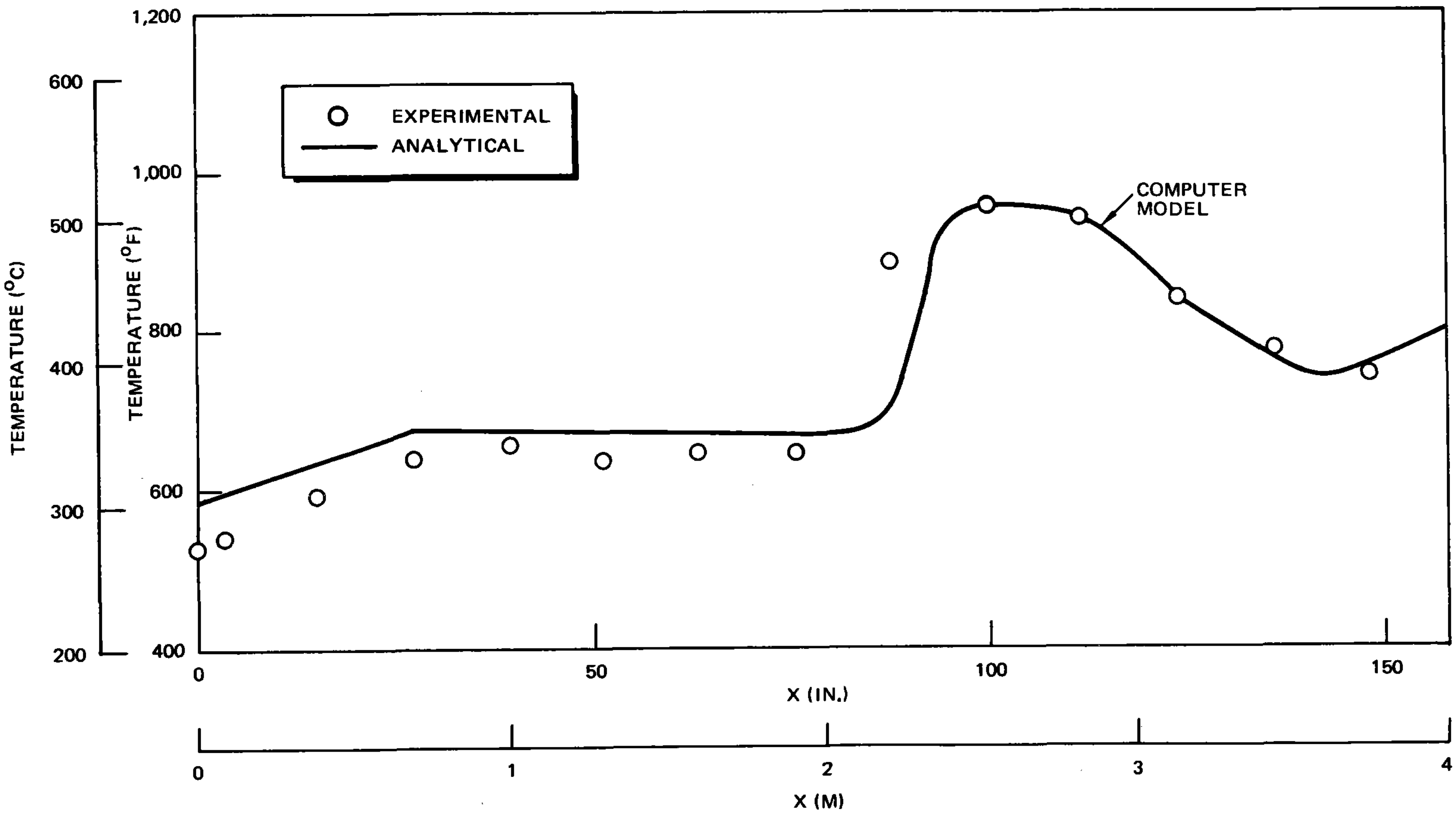


Figure 4-11. Comparison of Predicted and Measured Outer Wall Temperature Profile

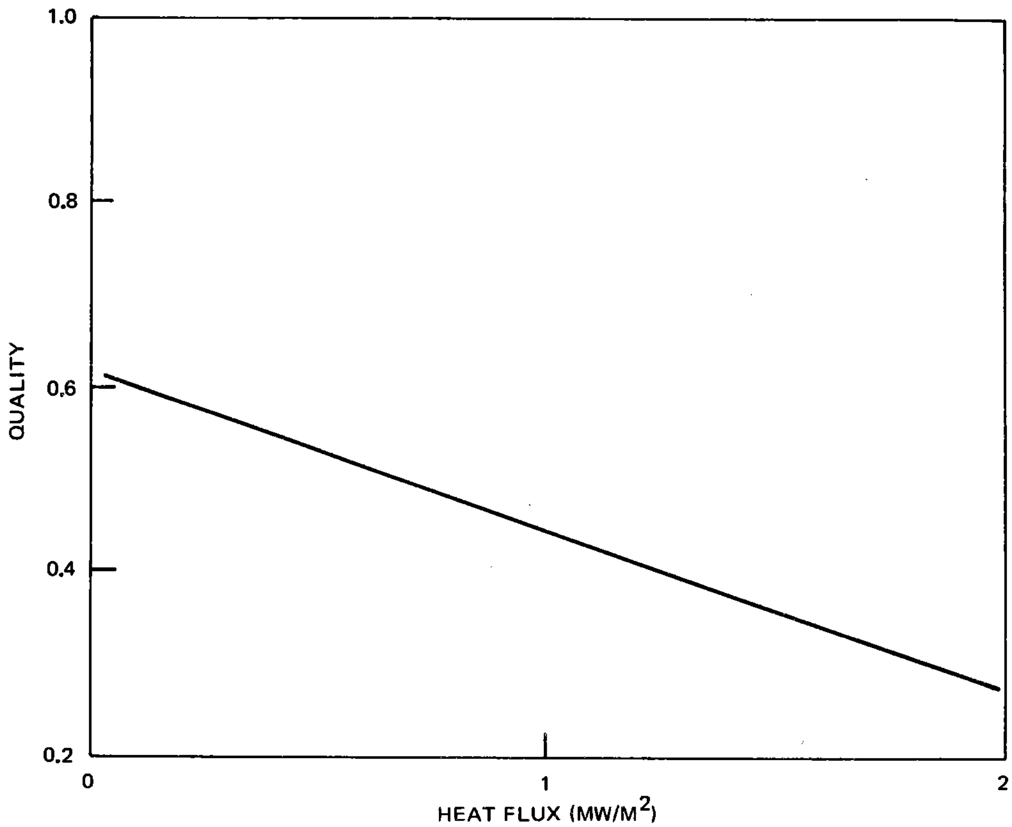


Figure 4-12. Quality at Departure From Nucleate Boiling C(DNB)

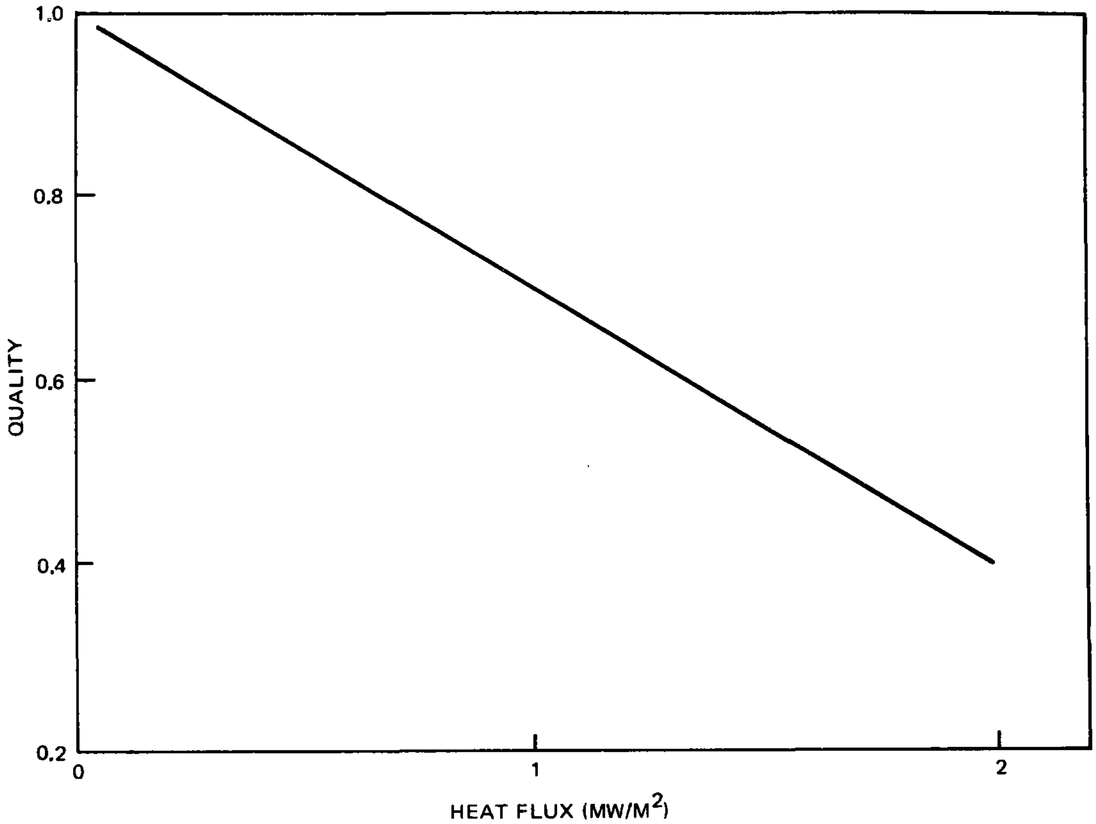


Figure 4-13. Quality at Minimum Film Boiling Coefficient

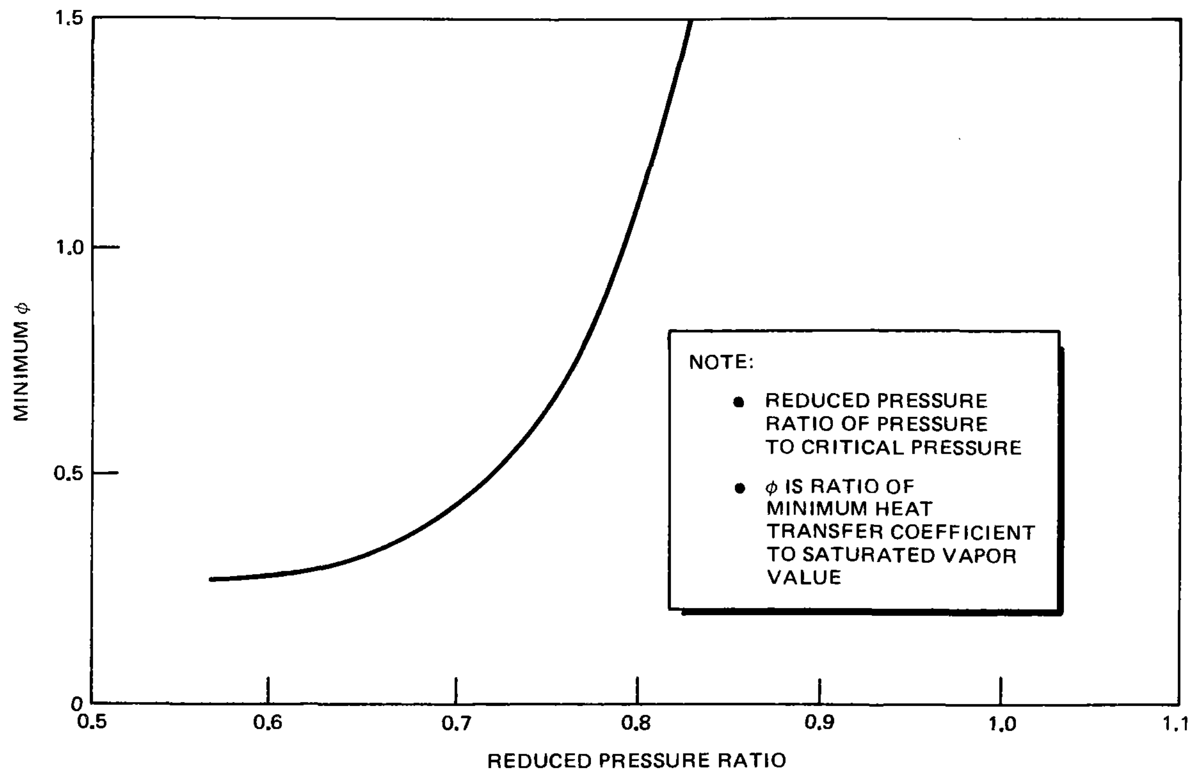


Figure 4-14. Minimum ϕ Factor in Film Boiling

The saturated steam point is well defined. The quality is 100% and the film coefficient corresponds to that of saturated steam. All other film boiling coefficients between these three points were found by interpolating between the coefficients as a function of quality.

Correlation With High Heat Flux Data — Under a separately funded activity, both single tubes and five tube panels were irradiated using graphite strip heaters to simulate conditions in the Commercial receiver. The work was performed pursuant to ERDA Contract No. E(04-3)-1103. The complete results are contained in R-9958, "Solar Receiver Heat Flux Capability and Structural Integrity," Rocketdyne, May 1976.

Single tube test sections 20m long were fabricated of 6.4 and 9.5 mm OD x 0.9 mm wall thickness stainless steel tubing. A 20m long panel was fabricated of five 8-mm OD x 1-mm wall Incoloy 800 tubes longitudinally welded together for a light-tight seal.

A series of 23 tests was conducted with the 9.5 mm OD single-tube test section in the horizontal radiant heating facility. Heat flux levels ranged from 0.2 to 1.1 MW/m^2 (absorbed) at steam outlet pressures of 7 to 16 MW/m^2. Steam exit temperatures up to 750°C (1,380°F) were achieved. The test section was undamaged at the conclusion of the test series.

Eleven tests were conducted with the five-tube panel at heat flux levels up to 1 MW/m^2 (absorbed), pressures up to 16 MN/m^2, and steam temperatures up to 540°C (1,000°F). The test section was undamaged except for three pinhole leaks which apparently resulted from electrical arcing between the panel and graphite heaters.

The flow was stable in all tests. Minor flow and pressure oscillations (< 5%) were noted during the start of four of the single-tube tests but damped out after only two to three cycles.

Measured wall temperatures in general were lower than values predicted with the computer model previously described. It was found that removal of the pressure correction factor (Figure 4-15) would adequately represent the data.

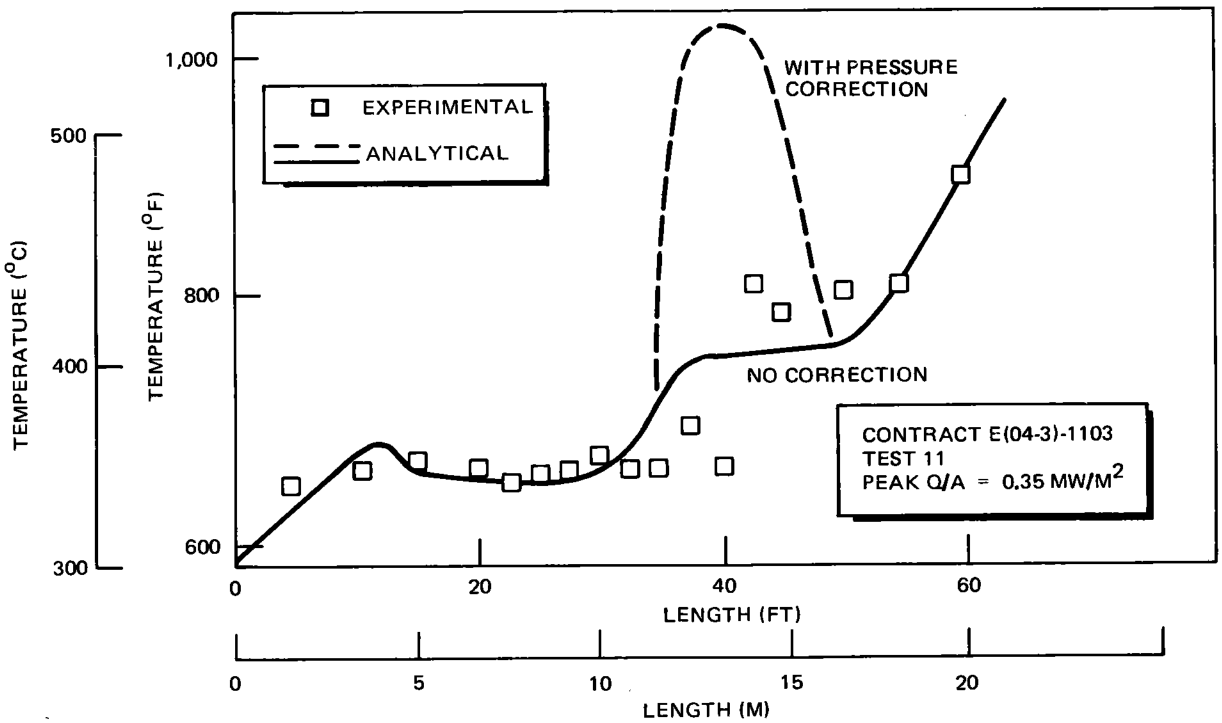


Figure 4-15. Comparison of Analytical and Experimental Wall Temperature Profiles

One particularly interesting aspect of the data is the fact that the peaking of temperature expected in the two-phase region was absent.

Data analysis for two particular heavily instrumented runs are shown in Figures 4-15 and 4-16. As indicated, therein, the original model with a pressure correction consistently predicts temperatures well in excess of experimental values. Removal of the pressure correction factor indicates good agreement generally. In general, removal of the pressure correction indicates temperatures possibly 28°C (50°F) below experimental values. This is generally acceptable since special thermocouple investigation tests documented in the referenced report indicates that most temperature readings would be biased on the high side nominally at the same order of magnitude of the 28°C (50°F) previously mentioned.

The conclusion reached by virtue of this extensive test program was that the original mathematical model derived from the independent research testing was conservative and that removal of the pressure correction term permitted a respectable correlation of the data.

Correlation With SRE Data — A complete presentation and discussion of the SRE program is contained in Section 6, however, this particular paragraph will focus on tests where the data is specifically applicable to the cooling correlation with the Pilot and Commercial Plant 12.7 mm (0.5 in.) OD x 6.8 mm (0.269 in.) ID tubing.

Absorbed heat loads for the tests (ΣQ_A) were determined by multiplying the difference in the specific enthalpy of the water at the exit and inlet of the panel by the water flowrate. Absorbed power could not be calculated for those tests where the effluent was in the two-phase condition. The range of the values of absorbed power per tube on the Pilot Plant ranges from 5.7 Btu/sec-tube for the minimum value on the southern portion of the receiver to 51.7 Btu/sec-tube for the maximum value on the northern side of the receiver.

Absorbed heat fluxes were calculated for specific tests as follows: The total incident power, ΣP_1, was determined by adding the electrical power

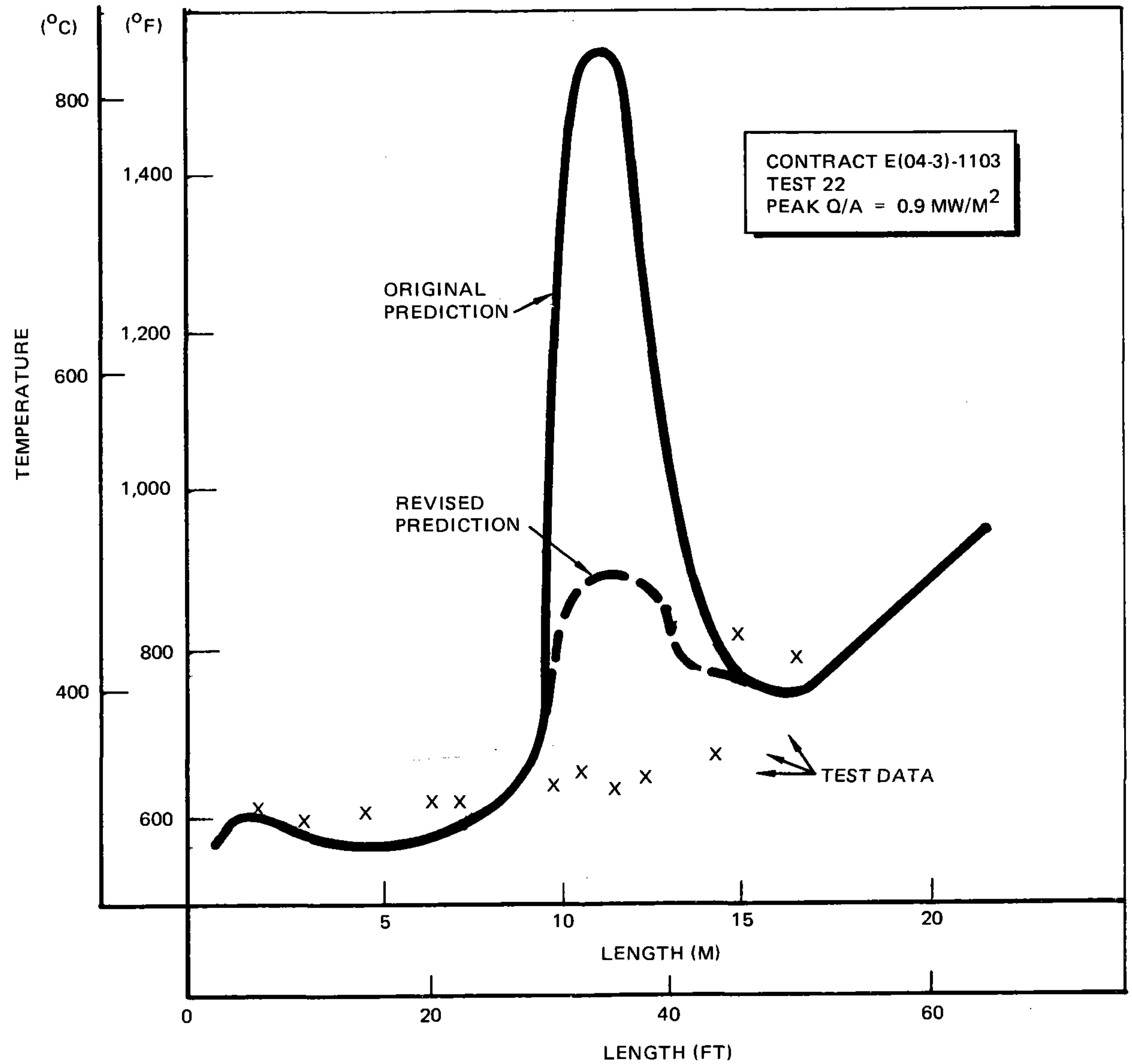


Figure 4-16. Comparison of Analytical and Experimental Wall Temperature Profiles

furnished to each of the heater elements. The power absorbed in each heating zone was determined from

$$Q_A)_n = \Sigma Q_A \left[P_1 \;_n / \Sigma P_1\right]$$

The heat flux levels were determined by dividing the values of $Q_A)_n$ by the area of the panel under the particular heater.

Maximum flux in the two-phase region occurred on Test 15. The power input to heater No. 7 during this test was 50 kW, compared to a total electrical power input of 396 kW. The total power absorbed was 0.158 MW (150 Btu/sec). Thus, the absorbed heat in the region of heater No. 7 was 21 Kw (20 Btu/sec). The effective area covered by heater No. 7 was 761 cm^2 (118 $in.^2$) so that the heat flux over this area was 0.28 MW/m^2. This represents a heat flux of close to the maximum value anticipated on the Pilot Plant. The heat flux profile for Test 15 is shown in Figure 4-17, along with the temperature profile.

Wall temperatures recorded during two tests were compared with theoretical predictions using the following method:

Reference analyses were available for Pilot Plant high and low heat flux.

The reference liquid side film coefficient, $h_c)_{Ref}$, at the crown of the tube was used to determine the coefficient under test flow conditions:

$$h_c)_{test} = h_c)_{Ref} \text{ (test flow/Ref. flow)}^{0.8}$$

The liquid side film ΔT was determined for test conditions:

$$\Delta T_{film} = (Q/A)_{absorbed,\ test} / h_c)_{test}$$

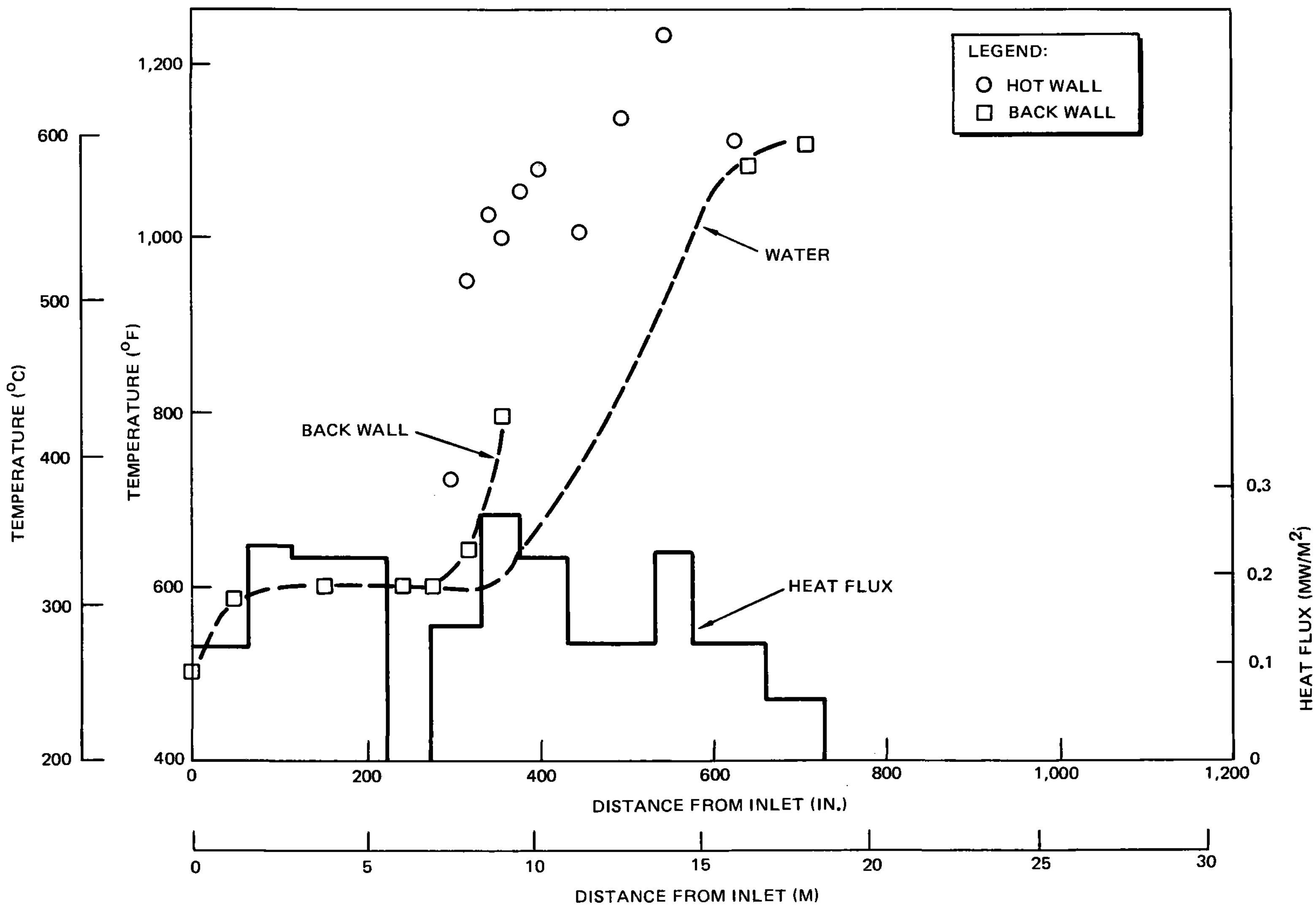


Figure 4-17. Test Data from Five-Tube Test No. 5-15

The Reference wall temperature ΔT was used to predict the test ΔT:

$$\Delta T_w\Big)_{test} = \Delta T_w\Big)_{Ref.} \left[(Q/A)_{test}/(Q/A)_{Ref.}\right]$$

The maximum wall temperature occurs in the two-phase region. The fluid bulk temperature, T_b, was taken as the saturation temperature corresponding to the experimental pressure. The hot wall temperature, T_{wh}, was predicted as:

$$T_{wh} = \left(T_b + \Delta T_{film} + \Delta T_w\right)_{test}$$

Figure 4-9 was used to estimate the steam quality at the point of maximum temperature based on $(Q/A)_{test}$. The axial location of this point was determined by integrating the test absorbed heat flux profile to the enthalpy value corresponding to the specified quality point. Hot wall thermocouples near this point were used to indicate the experimental hot wall temperature.

The results of the comparison are shown in Table 4-5. These results indicate the predicted values to be conservative over the entire range of heat fluxes.

The data from Test 15 was further evaluated by subjecting the test conditions to the previously described analysis (i.e., removing the pressure correction Ø) derived from the test program described in Section 4.3.2.1, it was found

Table 4-5

TUBE WALL MAXIMUM TEMPERATURE COMPARISONS

Test	Absorbed Heat Flux (MW/m^2)	Quality at Maximum Temperature Point (%)	Wall Temperature	
			Predicted	Measured
6	0.026	98	354°C (670°F)	332°C (630°F)
15	0.28	85	657°C (1,215°F)	554°C (1,030°F)

that the temperature differential across the tube from front to back was approximately 110°C (200°F), but the temperature level was lower than indicated by the data. Since the properties of the metal (Incoloy 800) vary little in the region of interest near 540°C (1,000°F), the effect is small. As noted in Figure 4-17, there is a significant rise in back wall temperature in the analysis region. Consequently it may be that the local bulk temperature predicted from the power, as previously described, may be slightly in error; also completion of boiling in Test 15 may have occurred slightly earlier than the 9m (350 in.) point as previously discussed. If, for example, it occurred at 8.3m (325 in.), the peak wall temperature was 496°C (925°F) with a differential across the tube of 125°C (225°F). If it occurred at 7.6m (300 in.) and the heat flux was double that indicated (locally), the wall temperature would have been 465°C (870°F) with a similar temperature differential. These latter points agree with the analysis previously discussed.

Lastly, a calculation was performed with a variable ϕ value around the tube to determine the effect of local fluid dynamic conditions. The value was varied from 0.18 at the heated crown to 0.75, 90° from there. The value of ϕ was assumed to be unity between the 150° and 180° points. This calculation showed poor agreement in terms of backwall temperature. The values of ϕ were chosen to have the hot crown temperature agree with the data, however, in order to obtain the indicated empirical result with a variable ϕ, the value of back wall temperature is suppressed far too low for the analysis to be valid. Thus, it is concluded that the previously described approach is valid.

Results — The results of the analysis for the Pilot Plant receiver are shown in Figures 4-18, 4-19, and 4-20. The first shows the average hot wall temperature along with the bulk temperature of the coolant. As noted, the temperature is not highly peaked in the two-phase region which agrees with the previously discussed data. Figures 4-19 and 4-20 show the temperature distribution at the peak strain region as well as at the peak temperature point in the superheat region. This analysis was performed on the boiler/superheater panels but not the preheater panels. The latter are so heavily

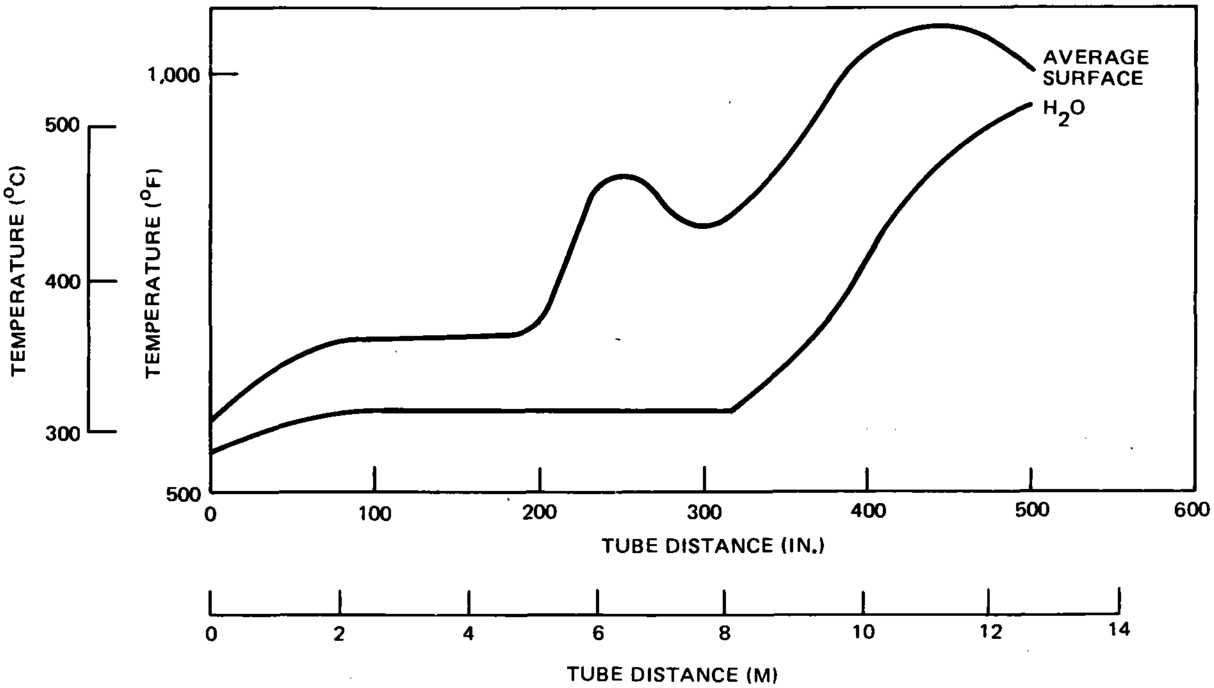


Figure 4-18. Pilot Plant Temperature Profiles, Equinox Noon, North Tube

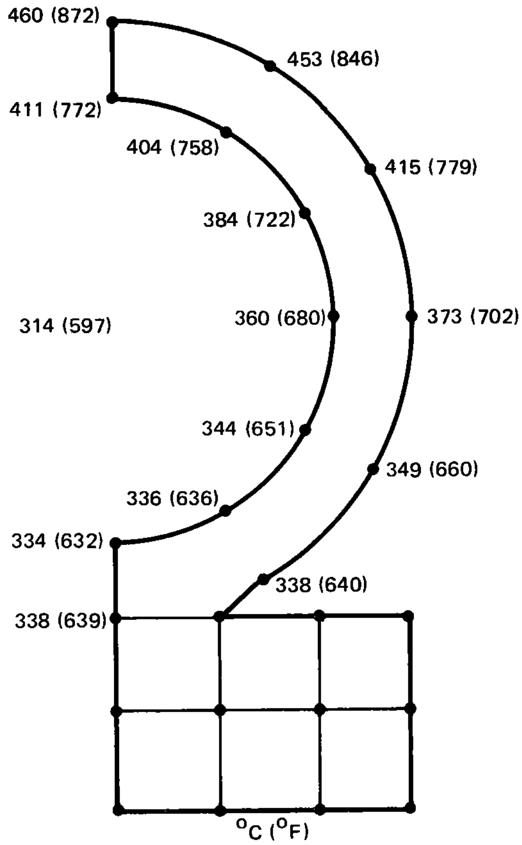


Figure 4-19. Pilot Plant Receiver Tube Temperature Profile 6.48M (225 in.)

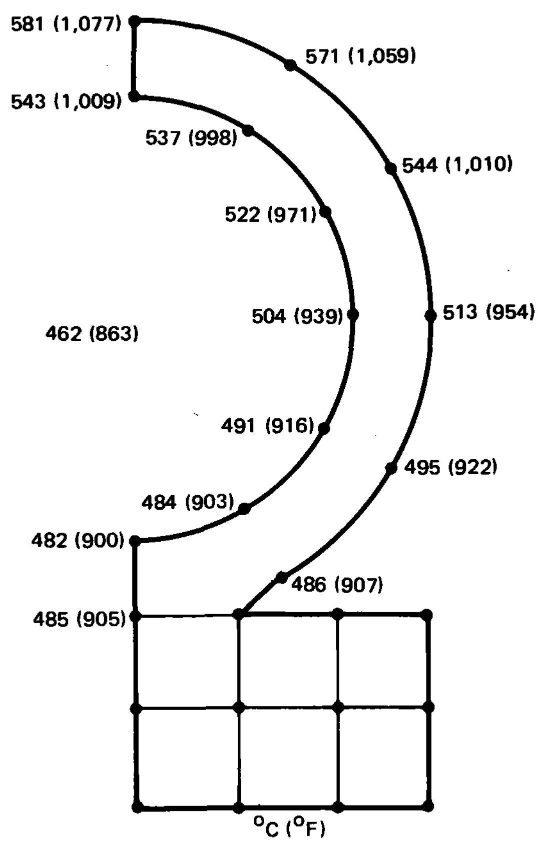


Figure 4-20. Pilot Plant Receiver Tube Temperature (Superheat Zone)

overcooled (three times as much flow per panel on the south or low heat flux region), that the wall is virtually at bulk temperature throughout.

Preheaters — The design rationale for the preheater panels was presented in the Commercial receiver discussion (Section 3.2.2.1). As previously mentioned, the preheaters simply heat the fluid prior to introduction into the boiler/superheater panels. As such, they present no controlling design impact because they are highly over-cooled. For control purposes, however, they must not allow the fluid to be heated excessively and become two-phase prior to entering the boiler panels.

An analysis was conducted to determine the temperature of the effluent from the preheaters as a function of the inlet temperature to the receiver, the fraction of the total receiver heat load incident on the preheaters (Figure 4-21), and the condition of the steam being produced by the boiler panels. Bulk temperature increase for the preheaters is shown in Figure 4-22. As noted for the range of anticipated duty conditions, temperatures will remain below 293°C (560°F), the approximate upper limit. This incidently corresponds to 50° minimum subcooling of the fluid within the boiler panel inlet heater. The results of these analyses were used, together with data relating the heat load on each panel to the time of year and time of day, to determine the number of panels which could be used as preheaters without exceeding the maximum preheater inlet temperature. These analyses resulted in selection of the southern most six panels as preheaters.

Fatigue Analysis — This section describes the fatigue life analysis conducted to evaluate the Pilot Plant absorber. The Pilot Plant panel life analysis consisted of fatigue analysis, thermal ratcheting analysis, and a creep study which indicated that the 12.5m panel design has more than adequate fatigue life.

Panel fatigue analysis showed the tube bundle and connections to have life greater than the required 10,000 cycles (daily cycling for 30 yr). Analysis shows that thermal ratcheting and creep are no problem.

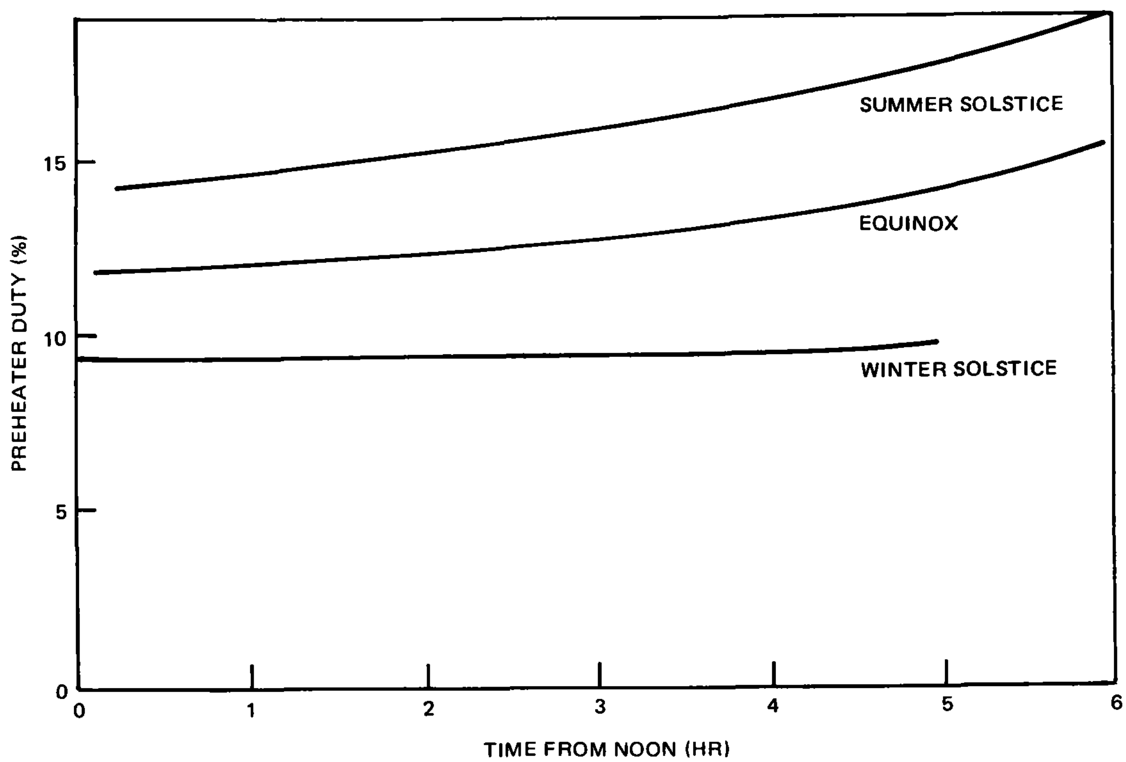


Figure 4-21. Pilot Plant Preheater Duty

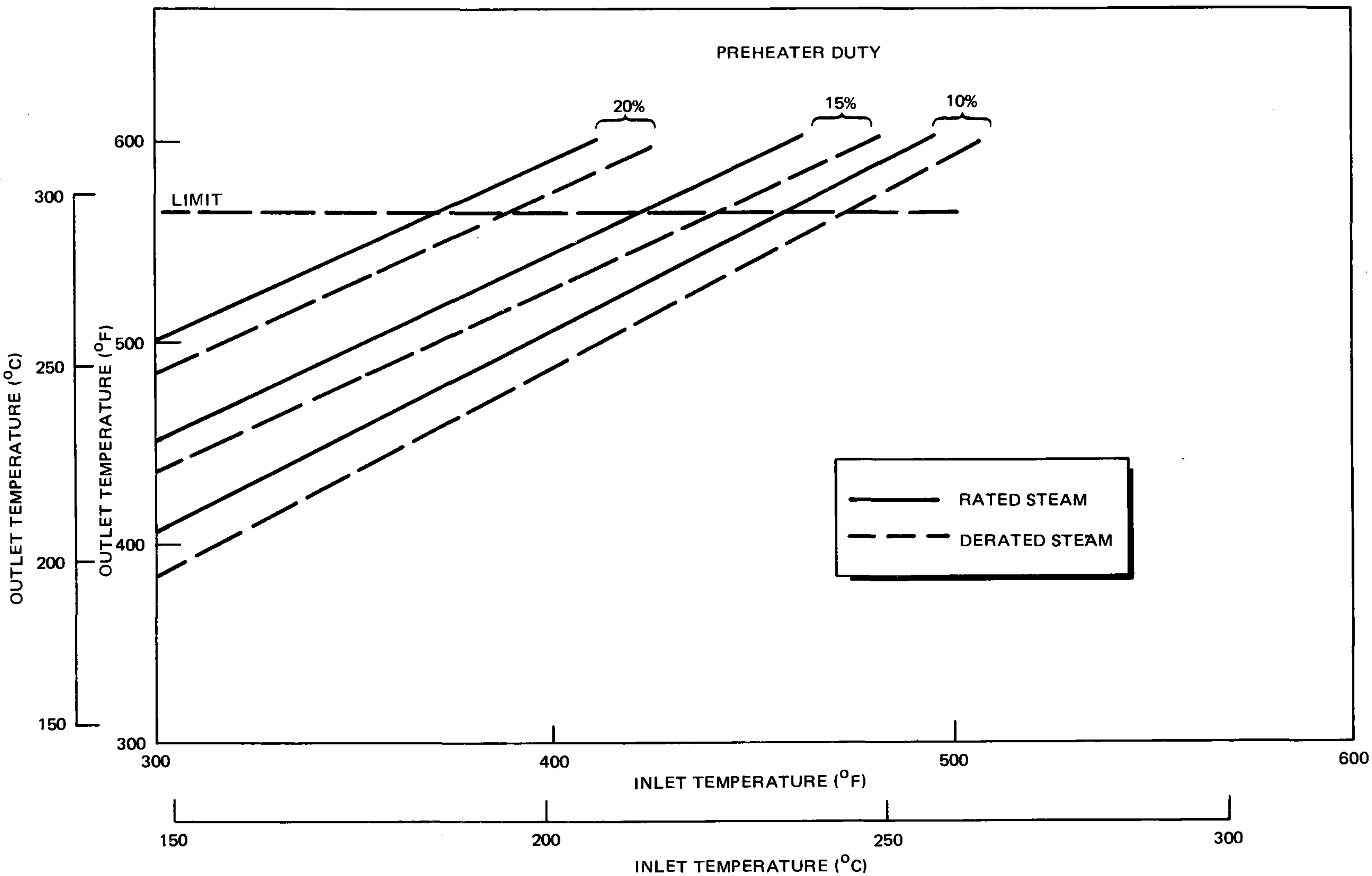


Figure 4-22. Pilot Plant Preheater Performance

The 10-MW Pilot Plant solar panel uses 1/2-in. Incoloy 800 tubing welded together to form a panel 12.5m long and 70 tubes wide. Heliostats focusing the insulation on the panel cause thermal gradients as previously discussed. The gradients used are shown in Figure 4-19 and 4-20. The life analysis was based on a higher than nominal (preliminary) heat flux profile (Figure 4-6).

Strain range/life design curves were generated for Incoloy 800 using ASME Code methods for experimental data presented in Figure 4-23. The design curve is the lower of 1/20 of experimental cyclic life or 1/2 of the experimental strain range. Figure 4-23 shows a comparison of the experimental and design curves at 583°C (1,000°F) and at 593°C (1,100°F). As may be seen, allowable strain range at 538°C (1,000°F) is 0.44% strain and at 593°C (1,100°F) is 0.38%. Interpolating gives 0.39% allowable strain at 584°C (1,083°F), the expected peak tube temperature. Both temperature distributions in fact have adequate life.

In addition to fatigue, creep and thermal ratcheting were also investigated. Huntington Alloy curves in Figure 4-24 show that for peak temperatures under 593°C (1,100°F), creep is not a problem. Code methods from Section VIII, DIVS. 1 and 2 were used to consider thermal ratcheting. Connections to the panel meet ASME Section I Code strength requirements. Life is not a problem for panel connections since strains are lower than in the hot tube bundle. Results of tube strain/life analysis for the absorber panel tube case in Figure 4-19 are in Figure 4-23.

For a 538°C (1,000°F) design curve, 0.44% strain is allowable. For a 593°C (1,100°F) curve, this strain drops to 0.38% and an extrapolation gives 0.3% strain at 721°C (1,330°F). This allowable strain drop shows that tube hot crown temperature is significant since an 18% increase in temperature causes a 90% drop in cyclic life.

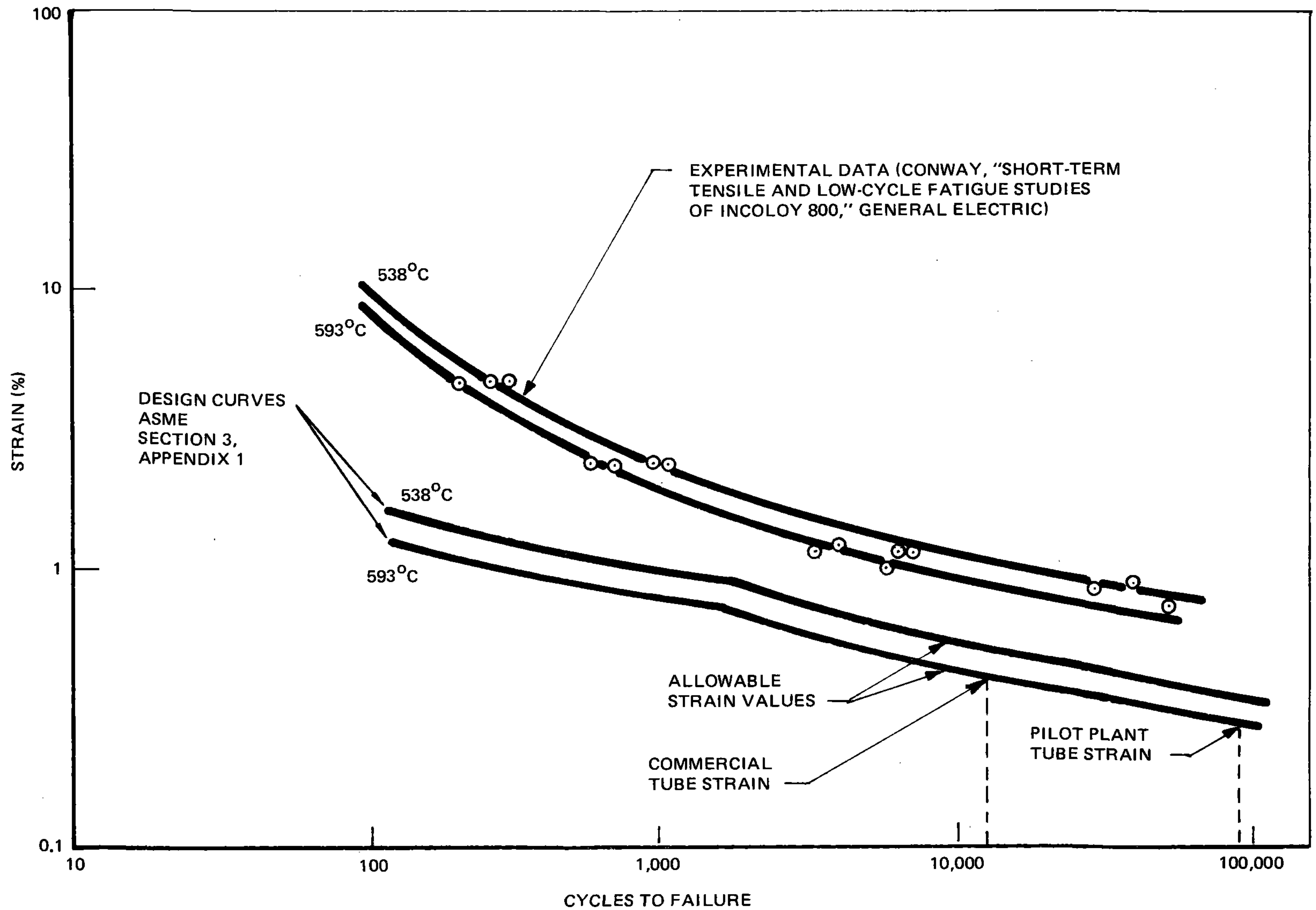


Figure 4-23. Fatigue Data and Design Curves

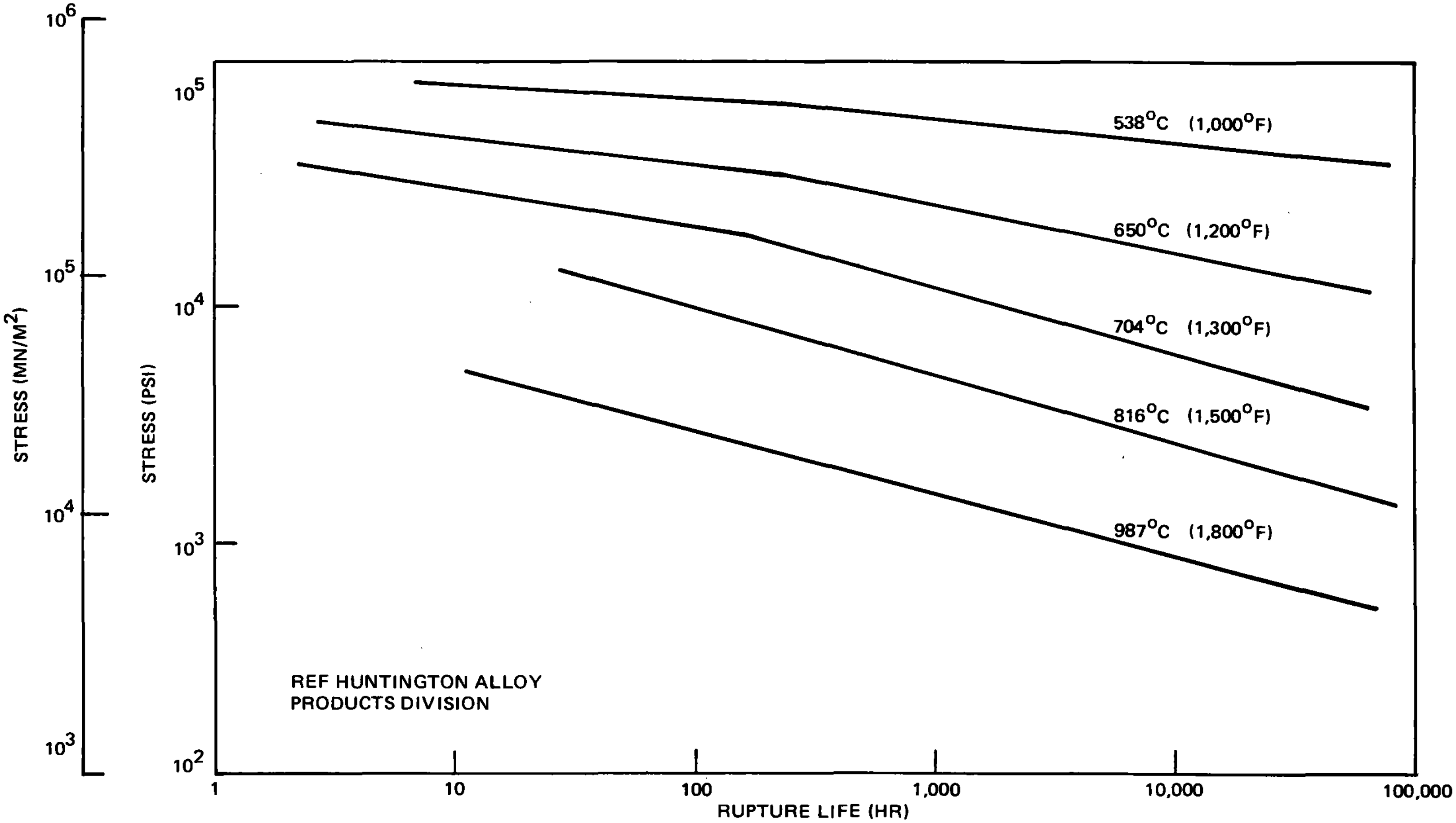


Figure 4-24. Rupture Strength of Tubing — Incoloy 800

Thermal Losses

This section presents the analysis undertaken to ascertain thermal losses from the receiver. The particular approach taken to ascertain convective losses is detailed below.

General Approach — This section describes the general approach taken to the determination of thermal losses from the receiver. There are three sources of receiver thermal losses: reflected insolation, infrared radiation, and convection. Reflected insolation is simply considered by noting that the energy absorbed by the receiver is equal to the solar absorptance of the surface times the incident energy. The solar absorptance of the Pyromark paint considered as the receiver baseline was measured by TRW during SRE. The measurement was made between wavelengths of 0.2 and 2.5 μm. The absorptance value so determined was 0.95. Testing during SRE was also accomplished to indicate the longevity of the paint, both from the point of view of thermal cycles and potential bleaching effects in concentrated sunlight. In both instances, no deleterious effects were found. Exposure up to 160 hr in the White Sands solar furnace indicated that solar absorptance did not degrade. Additionally, a tube painted with Pyromark and cured was subjected to more than 300 cycles between 200° and 1,200°F with no spalling or flaking evident.

The infrared radiation loss is calculated from the fourth power of the temperature and the receiver emissivity. The emissivity of Pyromark was measured by TRW up to wavelengths of 25 μm and found to be 0.9. The actual temperature distributions throughout the receiver were used in combination with the emissivity to determine the infrared radiation loss. Convective heat transfer loss is significantly more complicated than the radiation loss. These are covered in detail in a subsequent paragraph. However, the three losses when added together comprise a total thermal loss for the receiver and when divided by the incident energy represents the quoted receiver thermal efficiency.

The choice of a flat black paint such as Pyromark was dictated by the requirement that the receiver absorb as much insolation as is possible with a lesser regard for the question of infrared losses. If one considers that the receiver is subjected to an intensity of approximately 500 suns, one percent degradation in solar absorptance results in a five-sun loss. With a solar absorptance of 95%, the loss is approximately 25 suns. The corresponding infrared radiation loss, as will be shown subsequently, is of the same order of magnitude. If one considers selective coating (i.e., black chrome) as a viable alternative, one must inquire as to what the reduction in emittance yields in terms of benefits relative to the degradation in solar absorptance. Typically, black chrome has emittance values of the order of 0.3. Therefore, the loss can be reduced from 25 suns to 8 suns if one considers infrared radiation only. Unfortunately, black chrome in a weathered condition is hard-pressed to maintain solar absorptance above 0.9. Therefore, the insolation loss is virtually doubled to a value of 50. It was, therefore, concluded on the basis of this reasoning that a selective coating is not appropriate for this application since it could not be shielded from the atmosphere and would be subject to oxidation and general degradation.

<u>Convective Loss</u> — Convective losses are normally calculated by means of an empirical correlation which relates nondimensional parameters which are indicative of the heat transfer and dynamic head as well as fluid properties. The generalized form normally used for a cylindrical body is

$$Nu_f = K\, Re_f^{\,a}\, Pr_f^{\,b}$$

where the symbols have their usual meaning.

Here the fluid properties are measured near a mean film (f) value between the average condition between the gas and wall temperature condition. The values of K, a, and b become dependent upon the level of Reynolds number with $0.5 < a < 0.8$ and $0.3 < b < 0.4$. The value of K becomes successively smaller with higher Reynolds number, i.e., from a K value of approximately 1.0 at the lower level to about 0.02 at an elevated Reynolds number value. The combined K and a values become somewhat dependent upon the line slope drawn by the experimenter through the test data and the span of the Reynolds range tested.

An effect of higher Reynolds number values is indicated on the solar receiver wall (7m diameter) at the peak and design wind velocity conditions at the tower altitude level position. Analysis results in a freestream Reynolds number value range between 10^6 and 7×10^6 which is above the available body of data taken for cylindrical objects normal to a gas stream. Correlated data for gas conditions exists up to a 3×10^5 R_e value. Levels above this value except for Zukauskas (liquid data) and Achenbach (air) are generally unreported.

The data derived by Zukauskas (Ref.: Zukauskas, A., et. al., Local Heat Transfer of Tubes in the Critical Flow Region for Pr >1.0, Fifth International Heat Transfer Conference, Tokyo, Vol. IV, 1974) and used for the solar receiver was conducted with liquid flows at specific Reynolds numbers of

5.5×10^4 *
9.53×10^4
4.42×10^5
8.7×10^5 *
1.10×10^6
2.03×10^6 *

with the asterisked data sufficiently detailed to allow a fit to the form of the above equation. Prandtl number values ranged from 1 to 3. For these particular cases, the measured data around the circumference has been integrated in 20-degree increments from that shown in Figure 4-25, and corrected for the Prandtl number for air (0.72) to determine Nusselt number values.

The results of this analysis are shown in Figure 4-26 for the data points taken and compared to the overall data line of McAdams (Ref.: McAdams, W. H., Heat Transmission, Third Edition, pp. 266-267) for flowing gases. As shown, it is seen that a good agreement with existing gas data is shown with a coalescence at the lowest Reynolds number value. Based on the results shown, it is believed that the data shown are within ±15% of the true value which is about the heat-transfer accuracy limit for this condition and measurement procedure.

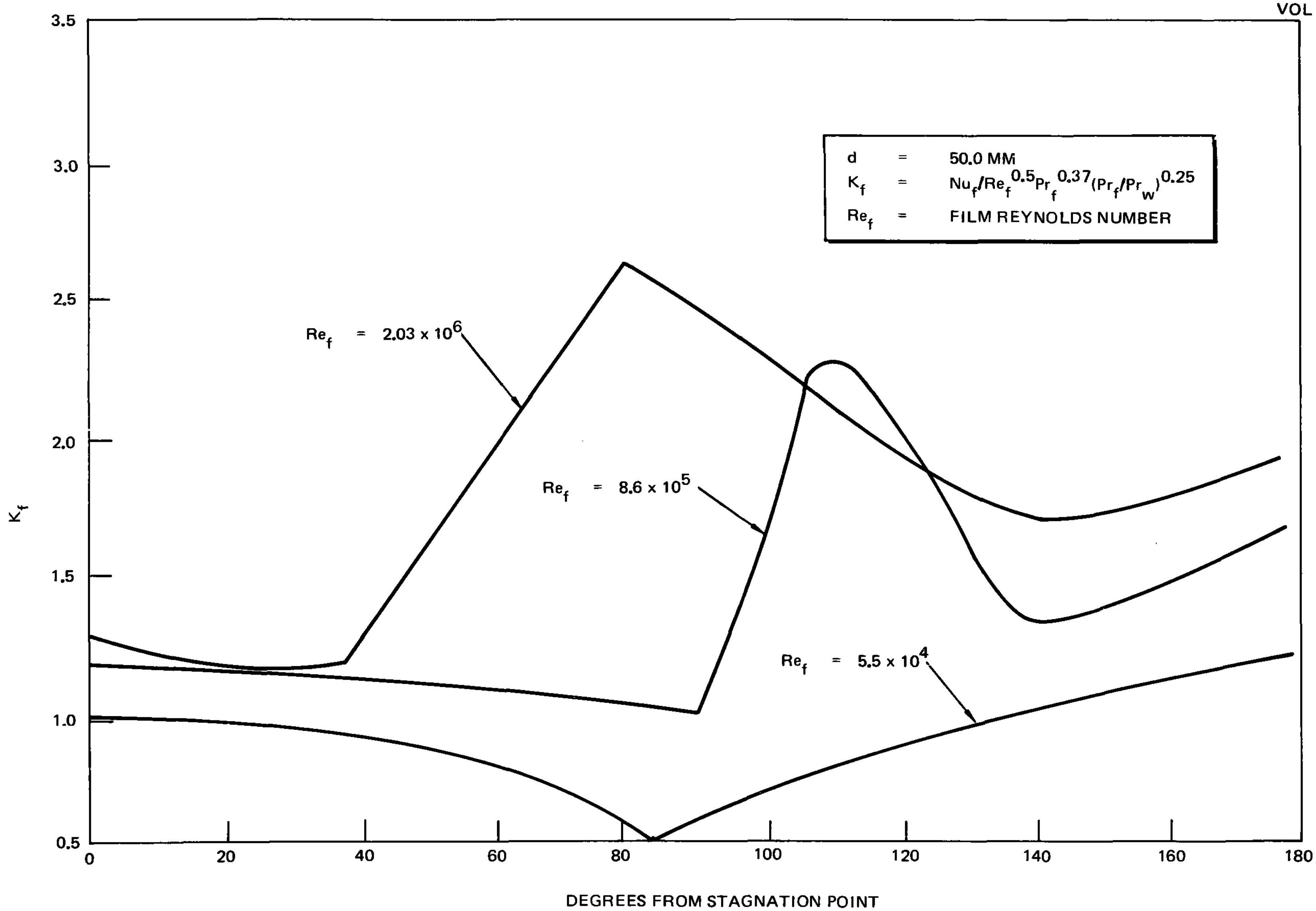


Figure 4-25. Typical Local Heat Transfer of a Tube

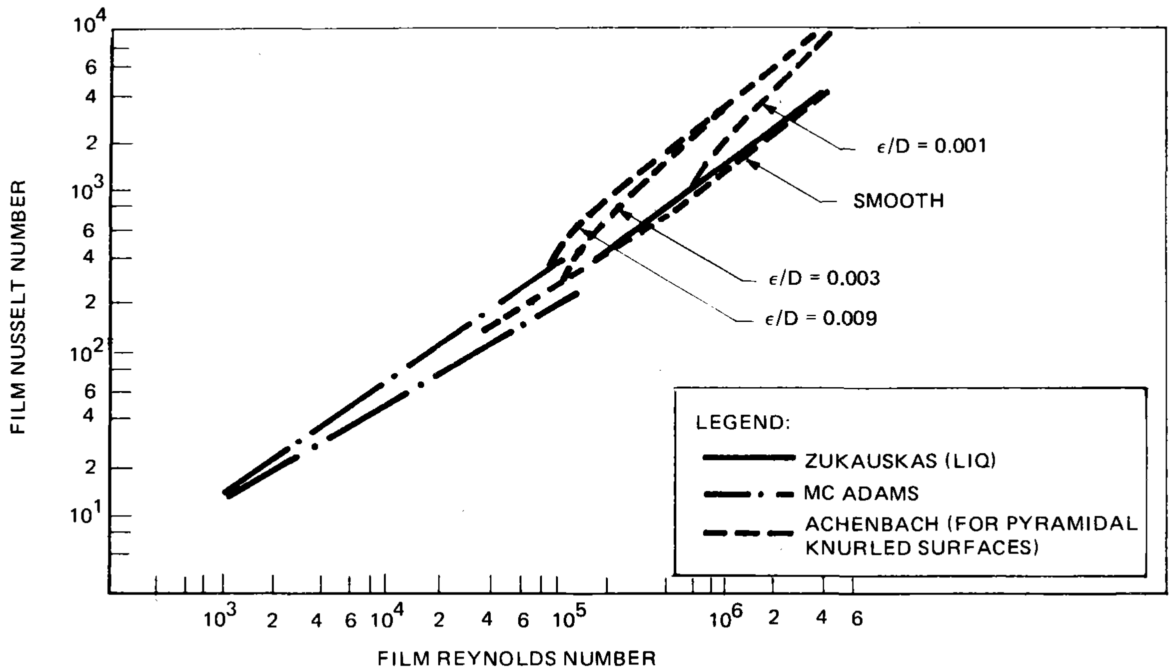


Figure 4-26. Heat Transfer to Cylinder in Cross Flow

In summary, it can be concluded that the use of the liquid correlation should be reasonably correct for the application to the solar receiver except for protuberances formed by the tubular construction of the receiver.

Schlichting (Ref.: Schlichting, "Boundary Layer Theory," 6th Edition; McGraw-Hill) discusses two particular areas that hold qualitative relationships to the phenomenon under investigation. Schlichting has shown that, for sand-type roughness (tightly spaced protuberances), if the protuberance height exceeds that of the laminar sublayer in the nominally turbulent boundary layer, then one might nominally expect an increase in frictional drag. Based upon this fact, one might be led to infer that heat-transfer rates would likewise increase. The classical Reynolds Analogy Theory qualitatively illustrates this effect, whereas data developed by Dipprey-Sabersky has been shown by Schlichting to be a valid approach to the question of determining heat transfer in roughened tubes. In activities in rocket nozzle cooling at heat fluxes as high as 100 Btu/in^2-sec, the Dipprey-Sabersky relationships have been extensively used to optimize cooling passage design.

If one uses Schlichting's approach to calculate permissible protuberance height, it is found that the laminar sublayer thickness is approximately 0.75 mm (0.03 in.) which is less than the tube radius (6.3 mm). Thus, one might consider the calculation of a so-called roughness enhancement. Direct use of the Dipprey-Sabersky formulation results in the following:

1. For a Reynolds Number of 10^6 and a smooth surface, the friction coefficient is 0.003. For a roughness of 0.25 in. on a diameter of 23 ft, the friction coefficient is 0.006. (The friction coefficients are based on flow in tubes.)
2. The roughness Reynolds Number for the smooth case is, of course, small and for a 0.25-in. roughness is approximately 2,100.
3. The Beta functions to be used in Dipprey-Sabersky were found from Figure 23.4 in Schlichting to be 9 and 21 for smooth and rough cases, respectively.
4. Use of the Dipprey-Sabersky equation indicated an enhancement of 1.78 for the roughened surface.

This, however, may be an erroneous approach to use because Schlichting indicates that the consideration of this effect is particularly for sand roughness wherein the protuberances are tightly spaced. In the receiver these are located 0.5 in. apart. Secondly, the Dipprey-Sabersky equation is strictly based on sand-roughened surfaces. The receiver surfaces can hardly be considered to be a sand-roughened surface. It can, therefore, be questioned whether the foregoing approach is valid because of the nature of the surface.

An alternate approach would be to consider the interstices between the tubes as cavities or notches transverse to the flow and inquire as to how the heat transfer within same compares to the values in the freestream (i.e., the local condition without the notch). A wealth of literature exists on this phenomenon; however, one particular paper deserves detailed evaluation in this regard: Fox (Ref.: Fox, "Heat Transfer and Air Flow in a Transverse Rectangular Notch," J. Heat Mass Transfer, Vol. 8, Pergamon Press, 1965), in addition to presenting some data of significance relative to heat transfer in transverse cavities, reviews the literature extensively. Specifically, Chapman (NACA TN3792) as early as 1956 predicted theoretically that for laminar flow, the average heat-transfer coefficient in a cutout was 56% of the average of a flat plate of the same length as the cutout. This result, Fox indicates, was verified experimentally in 1959 by Larson (J. Aerosp. Sci., 26, 731 - Heat Transfer in Separated Flows). In fact, this might be expected based on Fox's data which indicates that below the surface of the notch the ratio of local velocity to free stream velocity reduces far below unity. Data in Fox's paper indicates 0.3 near the notch mid-point.

It is of particular interest to quantitatively ascertain what the effect of the notches formed by the tube interstices might be in terms of the relationship between the heat transfer in the notch relative to the value that would exist had the notch been absent. In this regard, Fox's data was used directly for the receiver flow condition to ascertain the heat-transfer coefficients within the notches. These values were then compared with local value upstream of the notch if the receiver flow condition occurred in Fox's experimental setup. It was found in fact that the heat-transfer coefficients are far lower in the notch than they would be had the notch been eliminated from the test setup (10-70% of freestream). This is intuitively obvious because one would not expect freestream velocity to be adjacent to the wall throughout the notch which Fox demonstrates in his data.

These arguments tend to leave open the question of what the true loss is since they tend to contradict one another. The Achenbach data was taken with airflow over knurled cylinders and as such represents the closest approximation to the receiver condition. Although the test article knurls were relatively rougher than the tube interstices, the Achenbach data was used directly.

Achenbach presents heat-transfer data for air flow over cylinders with relative roughness values of 0, 0.001, 0.003, and 0.009. (E. Achenbach, "Heat Transfer From Smooth and Rough Surfaced Cylinders in a Cross-Flow," Kernforschungsanlage Jülich GmbH, Germany.) The tests were run with air in a high pressure wind tunnel. Achenbach's data is superimposed in Figure 4-26 relative to the Zukaukas and McAdams data, and indicates for the indicated roughness condition, an enhancement over that which Zukauskas indicates. The data due to Achenbach was directly used to evaluate the thermal loss due to natural convection for the indicated receiver roughness. The roughness (absolute) was assumed to be the tube radius or 6.3 mm. The cylinder diameter is 7m. Thus, the relative roughness is nearly 0.001 which corresponds almost identically to one of Achenbach's cases. Using an average wall temperature for the receiver, a film Reynolds number of 900,000 is indicated which results in a Nusselt number of 1750. Evaluating properties at the film condition yields a total convection loss of 1 MW_t. This, it is postulated, represents somewhat of an upper bound on the thermal loss because the knurled surface is unquestionably rougher than the rippled tube surface present on the receiver. This result is in reasonable agreement with the result shown in Table 4-6, and at this point represents the most valid approach to the question of convective heat loss.

Table 4-6

RECEIVER HEAT LOSSES

	Pilot Plant		Commercial	
	Rated Steam (MW)	Derated Steam (MW)	Rated Steam (MW)	Derated Steam (MW)
IR Radiation	3.2	2.5	20.6	14.3
Convection	1.00	0.87	5.4	4.5
Reflected Insolation	2.16	1.90	28.0	14.4
Total	6.36	5.27	54.0	33.2
Absorbed Energy	37.1	32.8	506.4	254.2
Percent Loss	14.6	13.8	9.6	11.5

Results — The results of the heat loss calculation are shown in Table 4-6 for both the Pilot Plant receiver and Commercial receiver. Assumed values for absorbed energy are noted therein.

Reference may be made to Commercial receiver Section 3.2.2.1 for a discussion of a shrouded receiver configuration which could provide substantial thermal loss savings in the Pilot Plant but was not selected because it was not felt to be necessary for the Commercial Plant and would therefore have compromised the configuration symmetry between the two plants.

Panel Design Description

Function

The function of the preheater and boiler panel assemblies is to contain the water/steam and to convert a maximum amount of the incident solar energy to thermal energy in the steam. A secondary, but necessary, function of the panels is to protect the structure behind them from the incident thermal solar energy. In order to minimize design and tooling costs, the preheater panels were designed to be structurally identical to the boiler panels (Figure 4-27).

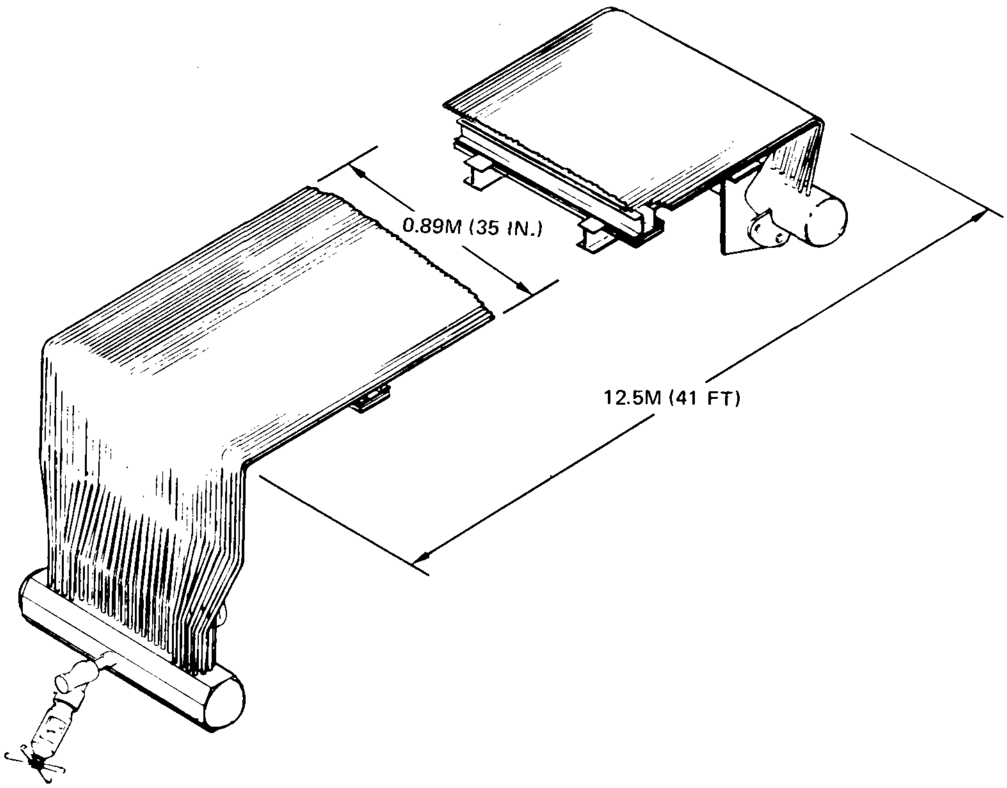


Figure 4-27. Pilot Plant Receiver Panel

Each panel assembly includes a tube bundle, inlet and outlet manifolds, backup structure and insulation as described below. Detail drawings of the full-scale Pilot Plant panel are listed in Table 6-1 of Section 6 of this report.

Tube Bundle

The tube bundle consists of 70 tubes. Each tube is 1.27 cm (0.55 in.) OD x 0.68 cm (0.269 ID). The irradiated length is 12.5m (41 ft). Additional length provides for folding over at the top and bottom to protect the manifolds and lower steel structure from insolation. The tubes are fabricated from Incoloy 800 seamless tubing and are welded together to effect mechanical and thermal integrity.

Absorptive Coating

The surfaces of the tubes exposed to solar radiation are coated with "Pyromark," a paint which has been in commercial use for various applications for many years. The coating is resistant to weathering and was successfully tested for long-term compatibility with high-intensity solar radiation during the SRE.

The Pilot Plant receiver design originally called for S-31 paint on the surface of the receiver panels. However, the continuing pursuit of innovations to reduce Pilot Plant costs showed that Pyromark has significant cost and operational advantages over S-31.

Simultaneous absorptivity comparisons of two samples of each paint showed a broadband solar absorptance of 0.954 for Pyromark (Figure 4-28) and 0.935 for S-31. The greater absorptance of Pyromark will produce significant savings in Pilot Plant collector field cost.

Tubes of Incoloy 800 painted with both S-31 and Pyromark and cured according to manufacturer's specifications have been thermally cycled between 280^{o} and $1,125^{o}F$ to simulate receiver operation for a year. The test apparatus consisted of uncooled, electrically heated tubes. Approximately 5% of the S-31 paint was lost by flaking off during 300 cycles. Initial Pyromark samples experienced approximately a 2% loss over 300 cycles. However, where the Pyromark was applied within 6 hr following grit blasting,

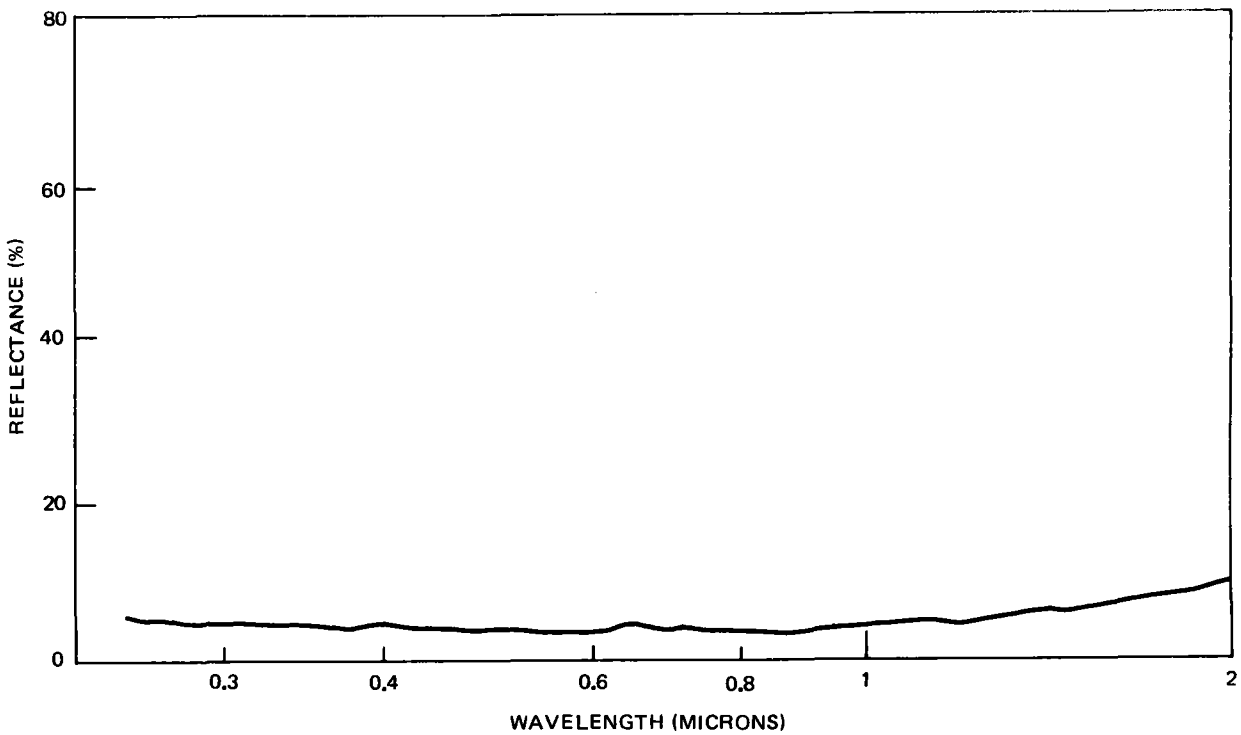


Figure 4-28. Spectral Reflectance of Pyromark

no deterioration was detected after 318 thermal cycles. All samples were subjected to water spray during the tests while at maximum operating temperature with no apparent effect on either paint.

The initial application and curing process for Pyromark also offers significant manufacturing and operational advantages over S-31. Although both paints require elevated temperature curing (600°-$1,000^{\circ}F$) to assure maximum durability, Pyromark is considerably easier to handle, since it will air dry but S-31 will not. This feature of Pyromark offers the potential of eliminating large (60 ft) paint curing ovens during manufacturing and permitting initial coating and subsequent refurbishment on the receiver tower with elevated curing provided by heliostat-directed insolation.

Consideration of the above data has resulted in the selection of Pyromark as the baseline material to provide a high solar absorptivity for the solar panels.

Manifolds (Headers)

An Incoloy 800 water manifold is located at the lower end of the panel assembly and functions to equally distribute water to all panel tubes.

An Incoloy 800 steam manifold is located at the upper end of the panel subassembly and acts as a collector manifold for the effluent steam from all tubes. To ensure leak integrity, all panel tubes are welded to the steam manifold.

Backup Structure

The function of the panel backup structure is to maintain the panel shape and hold it to the tower structure in proper location while allowing for thermal growth and providing support for wind and seismic loads.

The structure immediately adjacent to the panel and the manner of attaching the panel to the tower structure is shown in Figure 4-29. Each panel is independently mounted rigidly to the tower at the upper end. Two fixed T-beams on the tower engage sliding blocks at several axial stations on the

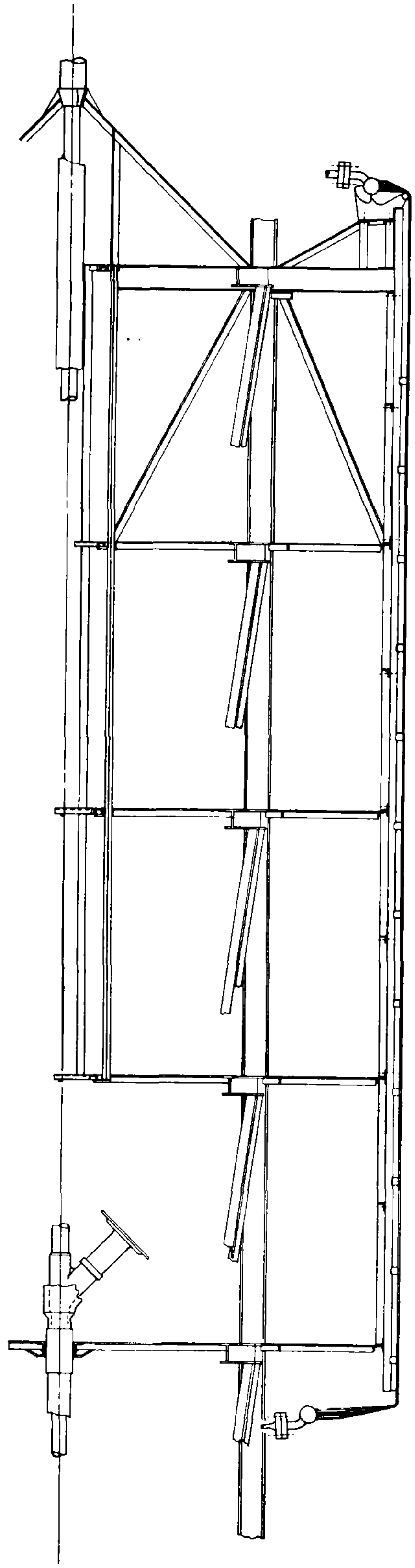


Figure 4-29. Panel Attachment

panel to allow for downward axial expansion while holding the panel in close proximity to the tower (Figure 4-30). Each pair of sliding blocks (at a given axial station) is fastened to a channel having a hat-shaped cross section. Clips welded to the tubes slide on the above-mentioned channels (hat bands) to permit lateral expansion of the panel (Figure 4-31).

In addition to providing panel support, the transverse hat bands will be used to mount bonded mineral fiber thermal insulation on the back of the panels to reduce heat losses from the back side of the tubes.

Interpanel Thermal Control

Allowance for lateral thermal growth of absorber panels requires that no concentrated sunlight impinges on structural or functional components that are not actively cooled. Two methods were evaluated: (1) overlapping the panels so that no "gap" develops between the panels and, (2) providing a passive radiation shield in the gap as shown in Figure 4-32. The overlapped panel approach results in shaded tubes near the end of the receiver panels and a major impact on tube life as a result of the large temperature differential between tubes. The second concept and the design selected for the Pilot Plant, has the advantage of nonvariant tube temperatures but requires a shield able to resist reasonably high temperatures. The shield design shown in Figure 4-32 consists of a semicircular channel of stainless steel polished on the inside surface. The shield will be insulated from the support structure at the attach points and will run the full length of the panels. The temperature on the shield surface was calculated to be below 980°C (1,800°F) and this would only exist at the north side of the receiver at summer-noon, so the condition should be acceptable because the shield would carry no appreciable load.

4.3.2.2 Controls and Instrumentation

A. Requirements.

The basic requirements for the controls and instrumentation subassemblies are to provide the control and information necessary to

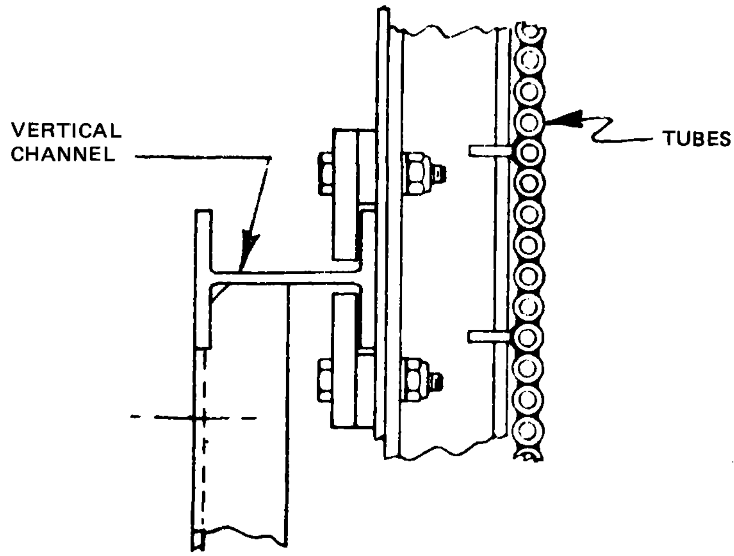


Figure 4-30. Absorber Axial Expansion Provision

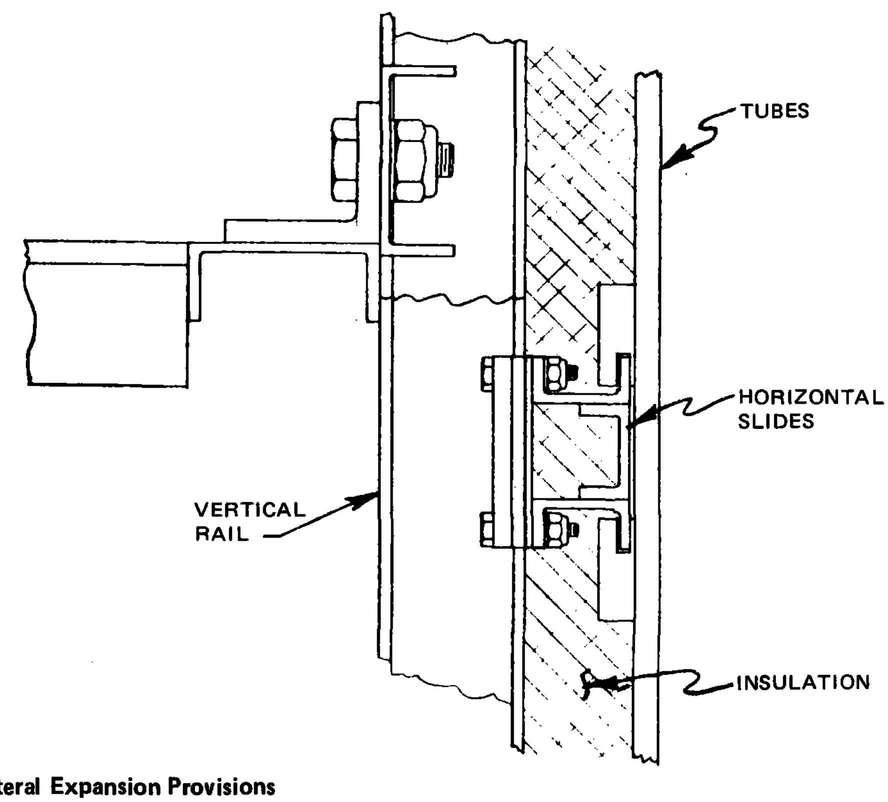


Figure 4-31. Panel Lateral Expansion Provisions

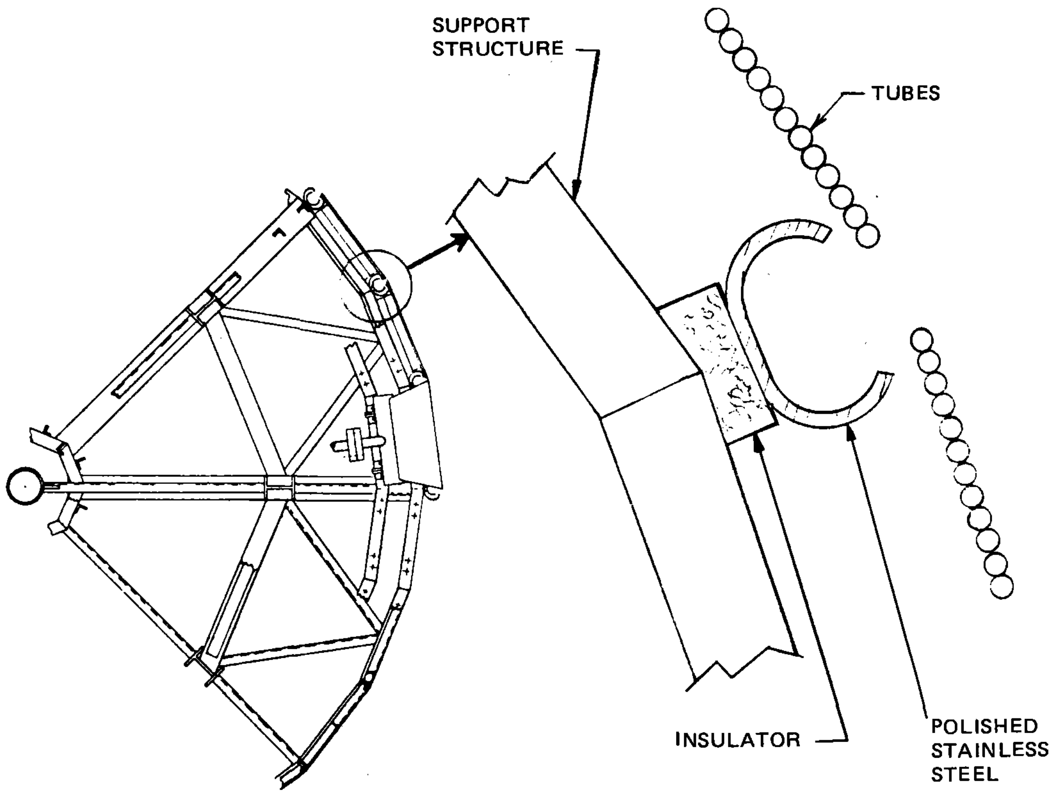


Figure 4-32. Absorber Interpanel Arrangement

(1) produce the directed steam outlet conditions notwithstanding the highly transient diurnal and seasonal variations in solar insolation; (2) evaluate receiver performance; (3) protect the receiver; and (4) provide filtration, flushing, and purging functions as required. Receiver operating conditions are described in Section 4.4.

B. Control Logic.

The function of the receiver control system during quasi-steady-state conditions (i.e., supplying rated or slightly superheated steam during the diurnal cycle) is to maintain a constant steam temperature by varying the water flowrate to follow the variation in incident energy. Control of a solar receiver differs from control of conventional power boilers in that the energy source is not regulated in the case of the solar receiver. Instead, the desired steam conditions are achieved by controlling water flow. Receiver outlet temperature is controlled by the receiver unit control system. Inlet and exit pressures and inlet temperatures are regulated by other control elements such as the turbine throttle valve, the thermal storage subsystem, feedwater heater controls, and feedwater pump speed regulators.

It would appear, at first assessment, that simply comparing the panel outlet temperature with the desired value and using the resultant error signal to control the water flowrate would not be adequate. However, thermal lags in the panel are such that a simple feedback of panel discharge temperatures using control electronics with proportional and integral logic was demonstrated during SRE as adequate to maintain individual panel steam outlet temperatures within ±28°C (±50°F) during steady-state and transient conditions.

C. Stability and Uniformity.

One of the primary concerns in operating a multitube boiler (particularly the once-through type) is that the effluent temperature be constant during intended steady-state operation. Another consideration is that the effluent temperature should be reasonably uniform in all the tubes. Excessive transients or spacial variations in effluent temperature could cause undue strains or fatigue or could result in carryover of liquid harmful to piping and the turbine.

To assure stability under operating conditions, it is necessary that an increase in flow produce an increase in pressure drop in the boiler. Figure 4-33 shows the theoretical pressure drop/flow characteristics for tubes with the nominal heatload, 40% of the nominal heatload, and 25% of the nominal heatload. The slope of these curves is an indication of flow stability within the panel. For example, on the nominal heat flux curve at rated conditions (nominal outlet temperature), the pressure drop of the tube is approximately 0.07 MN/m^2 (10 psi) and the flowrate of 0.017 kg/s (0.037 lb/sec). Increasing the flow from this point results in a fairly significant increase in pressure drop which is a requisite for a stable system. However, from 0.025 kg/s (0.055 lb/sec a flow of up to 0.07 kg/s (0.15 lb/sec), the pressure drop does not appreciably increase with flowrate. This implies that a two-fold change in flowrate can occur without a significant change in resistance to flow, which is a highly unstable condition. Only a slight amount of liquid flow resistance is necessary to improve this condition. As shown in figure 4-33, an additional pressure drop of approximately 1 psi at nominal conditions will result in a curve which has a slope on log-log paper that is always positive.

Experience in boiler operation shows that promoting flow instability are low flow, high heat flux, and low pressure. Low pressure is significant because the difference in specific volume between water and

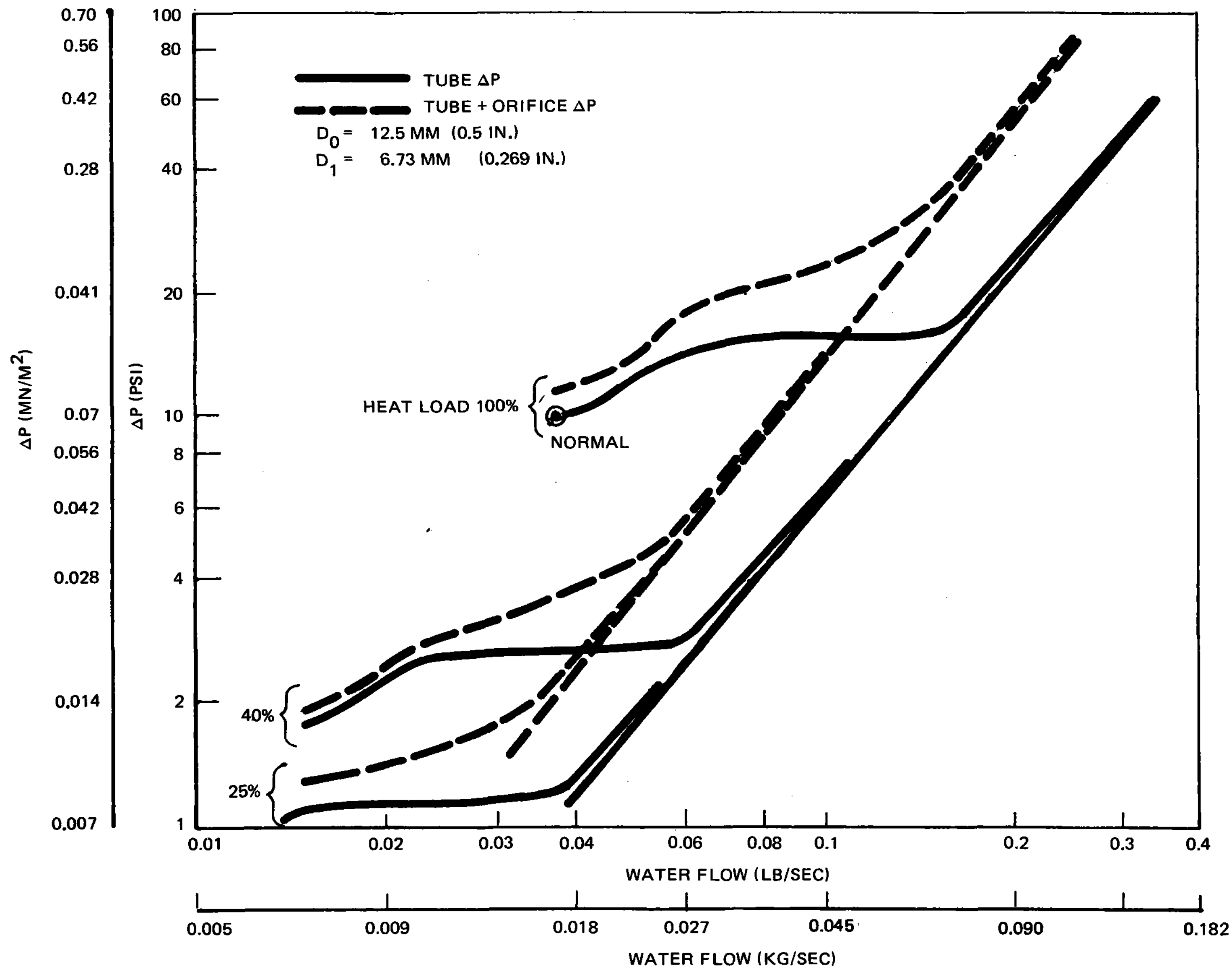


Figure 4-33. North Side Five-Point Aim Tube ΔP Characteristics

steam becomes large. Therefore, evaporation of a given mass of water results in a more significant volume change at lower pressures. This volume change tends to perturb pressures, flows, and heat-transfer coefficients, thus contributing to instability.

The same factors aggravate nonuniformity of flow from tube to tube. However, in the case of tall vertical boilers, the hydrostatic head of the fluid significantly promotes flow uniformity. In the Pilot Plant receiver, the hydrostatic head exceeds the friction drop in the tubes. Thus, if the flux on one tube is slightly high and tends to overheat and dry up that tube, the lower water level in the tube relative to the others tends to increase its flowrate and restore the original water level.

Initially the receiver was designed with provisions for orifices at the inlet to each tube. However, experience during the SRE on both the 5-tube and the 70-tube panels indicated that no orificing was necessary for stability or uniformity. The 5-tube panel exhibited insignificant instabilities and during the start transient only. The 70-tube panel was stable under all conditions including a complete simulated pilot plant start. Both panels indicated effluent temperature uniformity to be within 56°C (100°F) for all tubes during steady-state operation and within 170°C (300°F) during rapid transients.

The most rapid transients will occur in the Pilot Plant during startup, shutdown, emergency, and cloud cover conditions when steam is directed to the receiver flash tank or thermal storage rather than to the turbine. Start and shutdown heat flux transients are predicted to be much slower than those experienced during the SRE. Furthermore, a liquid detector in the steam line near the exit of the 70-tube panel steam manifold during the SRE indicated no slug flow during these transients. However, to further minimize the possibility of liquid entrainment, a cyclone separator is installed at the exit of each of the boilers in the Pilot Plant receiver. The separators are equipped with level sensors to signal excessive water or initiate shutdown.

D. Flow Control Valves.

Individual flow control valves are installed at each boiler panel to maintain constant receiver steam outlet temperature despite diurnal and seasonal variations in heat load, to control cloud-induced transients, and to regulate the receiver startup and shutdown sequences.

At this point, two control options were available. The inlet pressure to the receiver could remain constant and the diurnal and seasonal variations in heatload be followed by the control valve to maintain a constant outlet temperature. Alternately, the pump discharge pressure could be varied as well as the control valve positions. The latter strategy could result in pump power savings up to approximately 30 kW, but would result in more complex control logic to relate pump flow control with control valve positioning. It was felt at this point that the saving of 0.3% of plant output did not warrant the added control complexity. Therefore, the receiver system pressure drop was chosen to remain constant with the control valves providing flow control to each of the panels.

Consideration was given to whether the flow control valve should be located upstream or downstream of the panels. The upstream location was selected because it provided a milder and more constant environment. Flow regulation of water is much more desirable than controlling in the steam flow downstream of the panels.

The transients which occur in following a nominal diurnal cycle are slow and the control valve may be considered to be in a quasi steady-state condition. The most extreme transient probably occurs under intermittent cloud conditions. Under these conditions, the receiver can experience a change in incident heat flux from a small value to nearly 100% heatload in approximately 10 sec. The control valves selected are capable of responding to this type of variation and are not a limiting component for these types of excursions.

E. Nighttime Control

Water is maintained in the receiver at night unless repair or maintenance requires draining. The mass of the receiver is sufficient to retain adequate heat from daytime operation to prevent freezing at night during most of the year. For very cold nights, or downtimes of several days, provision is made for recirculation through the receiver unit. Provision is also made for recirculating through the riser and downcomer for maintaining these components at approximately 93°C (200°F) to reduce the morning startup time.

The recirculation water is heated in the thermal storage unit or by an auxiliary heater. A crossover line from the receiver unit inlet to the flash tank contains a throttling valve which is closed during daily operation and opened at night. With this valve fully open, and the receiver boiler temperature control valves nearly closed (against their 5% open limit stops), very little water will recirculate through the receiver so that losses will be negligible. When the receiver unit requires water recirculation to prevent freezing, the receiver controller causes the boiler temperature control valves to open and control the panel outlet temperature to a value above freezing. If the position of any of the temperature control valves exceeds 90% of full open, the controller signals the bypass valve to close, thereby forcing more water through the receiver unit.

Radiation to the clear sky will require circulation to the receiver unit when the ambient temperature drops below 10°C (50°F). Detailed meteorological data were not available for the Pilot Plant site. Available data for nearby Inyokern were used which indicated an average of 1,580 hr/yr when nighttime temperature would be below 10°C (50°F). The average temperature during this time was 5°C (41°F). At shutdown, the receiver average temperature is 370°C (700°F). The receiver will cool to 5°C (41°F) in 5-hr without water flow on a windless night with an ambient temperature of -1°C (30°F).

Thermal losses in the receiver unit for a 5°C (41°F) wind blowing at 4.9 m/s (16 fps) were calculated to be 350 MW-hr/year (1.2×10^9) Btu/year when recirculating 93°C (200°F) inlet water to prevent freezing. This represents a loss of 0.9% of the annual electrical power generated.

Under most severe conditions, the Inyoken data indicated a wind velocity of 18 m/s (60 fps) at a temperature of -18°C (0°F). Under these conditions, the heat-transfer rate is 3.5 times the average value and requires a flow of 250 kg/hr (550 lb/hr) through the coldest panel and 4,700 kg/hr (10,500 lb/hr) through the complete receiver unit. These flows are within the capabilities of the feed system and the boiler flow control valves.

Emergency Transients

Component redundancy, backup power, and filtration are being provided in the system design to eliminate loss of water flow to the receiver as a credible failure. Nevertheless, an analysis was made assuming a sudden loss of coolant water to determine the time within which emergency protective systems would be required to function to protect the receiver from damage. Since defocusing of the heliostats from the receiver is probably the slowest of the possible protective actions, the analysis investigated the impact of the high heat flux during the time lag of the mirror control system.

Temperature histories were calculated for the Incoloy 800 tube material for the condition of feedwater flow loss in an emergency situation. The following assumptions were used in this analysis:

A. Nominal tube dimensions were used to calculate temperature response.

B. Incident radiation level from the collector field is 0.30 MW/m^2 (0.184 $BTU/in.^2$ sec).

C. The mirrors will complete slew within 40 sec after the signal to begin slew is received from Master Control.

For various delay times between feedwater loss and initiation of slew, the temperature transients shown in Figure 4-34 were calculated. For the condition of 1,500 psia pressure within the tubes, the rupture times in Table 4-7 were calculated. Table 4-8 shows rupture times for only weight loading of the tubes (zero internal pressure). For reference in both cases, the typical time to 5% creep is shown. If times at temperature above the 5% creep values are encountered, distortion of a typical tube may be sufficient to preclude its further use. If creep times byond the allowable rupture time are encountered, tube failure may occur.

For the case where the mirrors are not slewed (constant heat flux incident of 0.3 MW/m^2), the tubing will reach radiative equilibrium 1,260°C (2,300°F) in approximately 400 sec (0.1 hr). Thus, with pressure in the tubes, the creep damage may be sufficient to preclude further use of the tubing in less than 4 min; however, catastrophic failure will not occur until much later.

Evaluation of the predicted values of temperature and of the creep properties of the material indicate that damage due to creep will be negligible if tube pressure is vented. Damage will be relatively small if slew is initiated within minutes after feedwater flow is lost even if pressure is maintained.

It should be noted that the present receiver panel design includes a remote controlled vent valve which could be activated in an emergency sequence.

Controls Design Description

The control and instrumentation assembly includes data sensors, control electronics, and the flow distribution network that includes flow control valves, stop-check valves, safety relief and vent valves, purge valves, drain valves, and filters. A schematic showing the arrangement of components is presented in Figures 4-35 and 4-36. All valves and their functions are described in Table 4-9. Components are generally commercially available items.

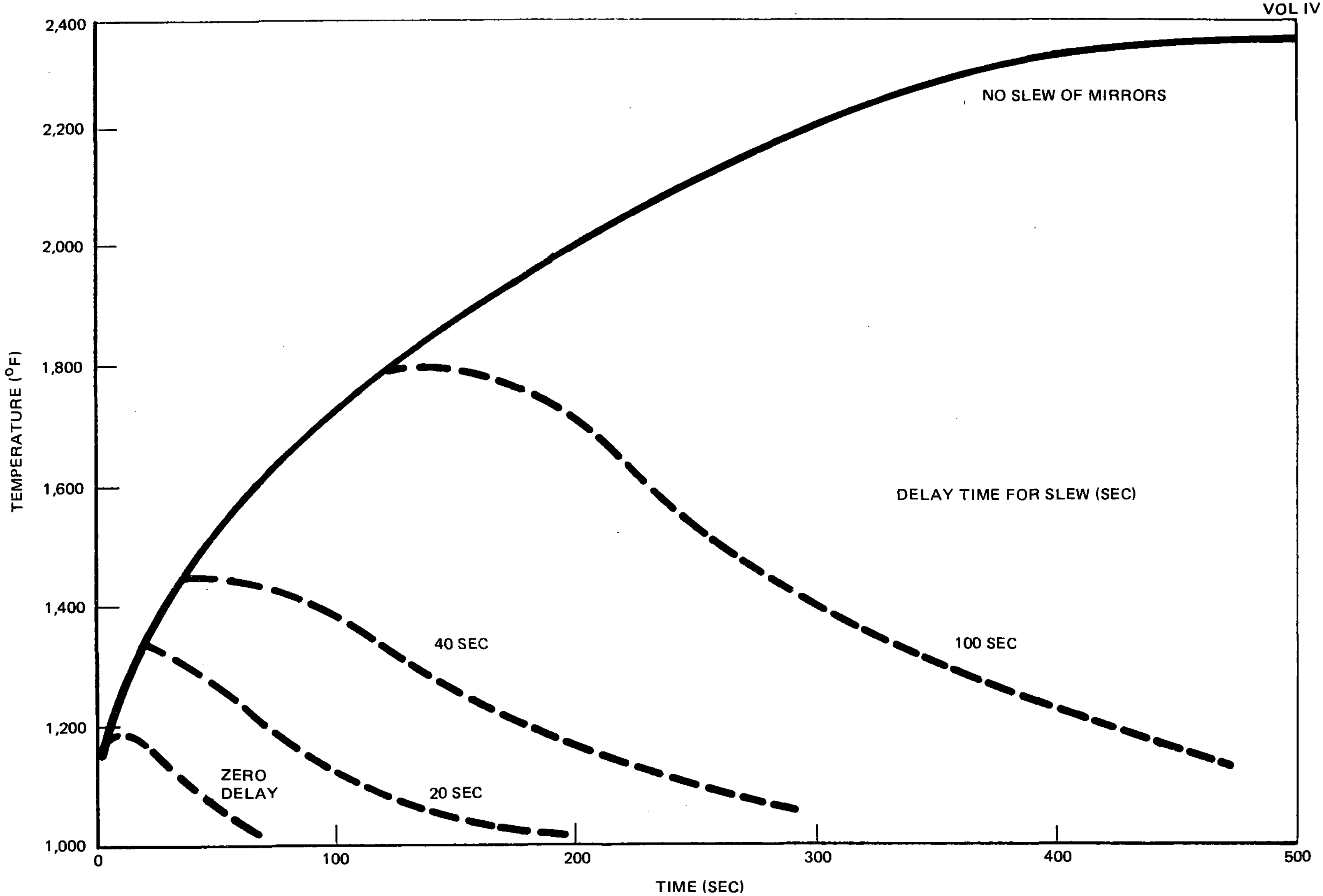


Figure 4-34. Temperature Response of Tubing After Loss of Water Flow

Table 4-7

SURVIVABILITY LIMITS OF RECEIVER TUBING
(1,500 PSIA PRESSURE IN TUBES)

Temperature (°F)	Time to Rupture* (Hr)	Typical 5% Creep Time (Hr)
1,400	18,000	25,000
1,600	1,400	167
1,800	80	42
2,000	7.5	1.72
2,200	0.7	4 min

*Typical time to rupture divided by 5.0. No fatigue damage considered.

Table 4-8

SURVIVABILITY LIMITS OF RECEIVER TUBING
(ZERO PRESSURE IN TUBE)

Temperature (°F)	Time to Rupture* (Hr)	Typical 5% Creep Time (Hr)
1,800	20,000	40,000
2,000	10,000	2,000
2,200	360	77

*Typical time to rupture divided by 5. No prior fatigue damage considered.

The control systems were designed to accomplish the necessary functions in the most simple manner possible and at the lowest cost. Safety, reliability, and response to off-design conditions were also major considerations. Economy and reliability were also achieved by designing the valves to be manually operated rather than remotely operated wherever feasible. Only those valves which may be required to operate when the receiver unit is being subjected to radiation are remotely controlled.

The function of the receiver control electronics is to receive command signals from an operator or the master controller and translate these signals into specific actions in the receiver. The controller performs these functions during the prestart checks, the startup, operation, shutdown, emergency operation, and during standby.

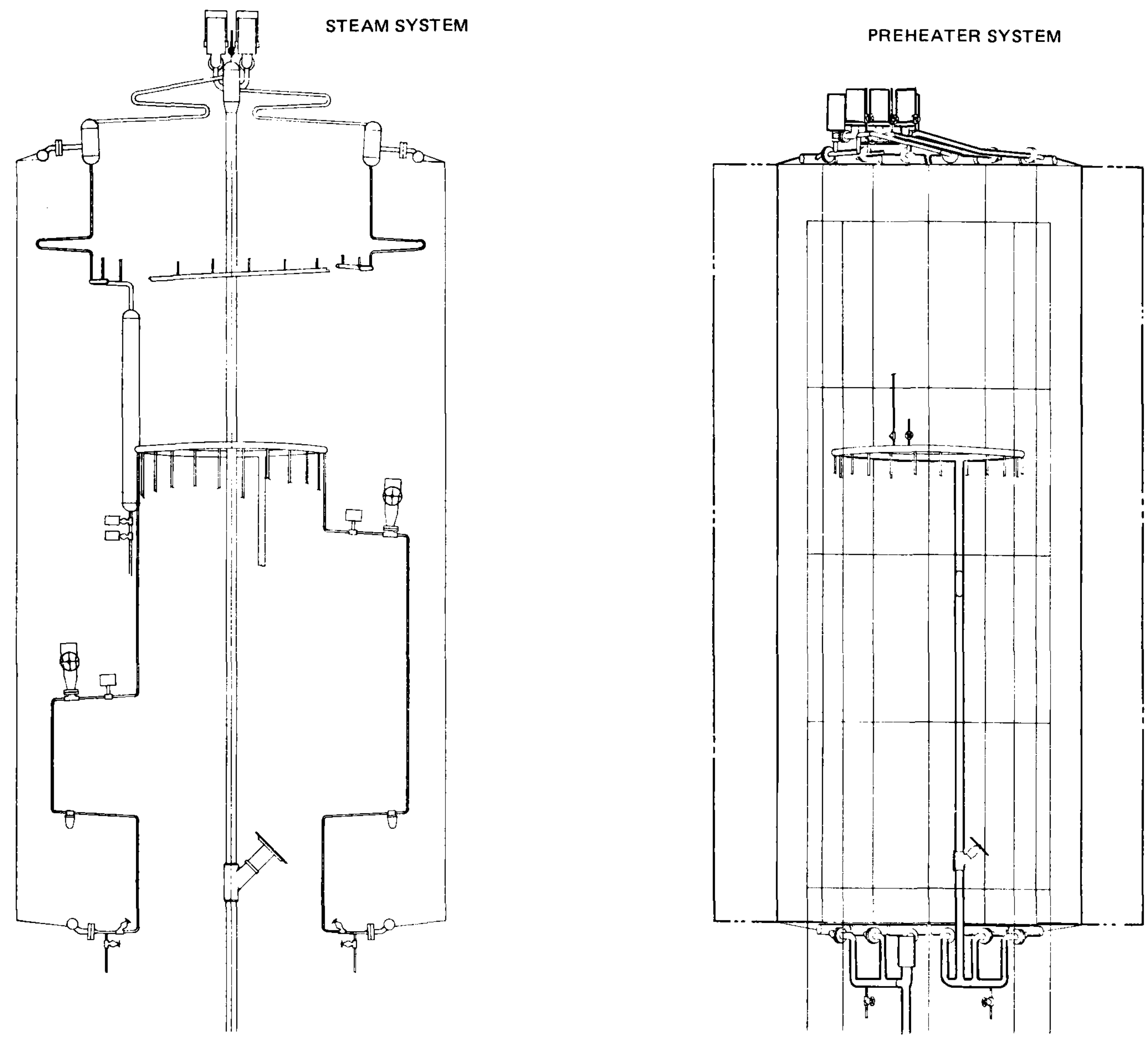


Figure 4-35. Abosrber Feed System

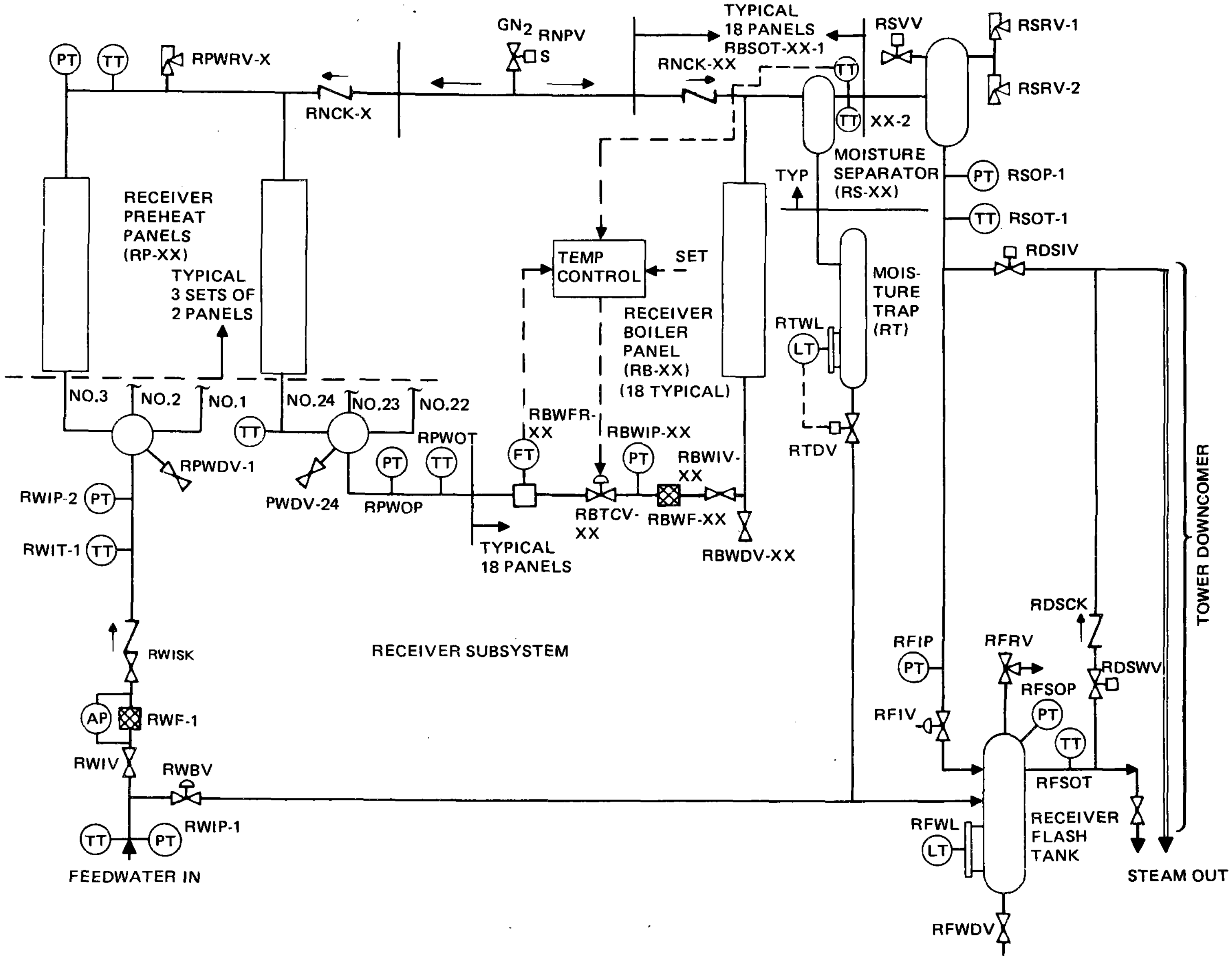


Figure 4-36. Pilot Plant Receiver Schematic

Table 4-9 (Page 1 of 2)

VALVE LIST, 10-MW RECEIVER

Valve	Symbol	Qty	Nominal Size (In.)	Control	Function
Receiver Water Inlet	RWISK-1	1	4	Manual	Isolate receiver and limit preheaters
Receiver Water Drain	RPWDV-1	1	1	Manual	Drain first pass preheater panels
Receiver Water Relief	RPWRV-1 thru -3	3	2 1/2	Spring	Prevent preheater overpressure
Receiver Water Vent	RPWVV-1 thru -3	3	1	Manual	Vent preheaters during fill
Receiver Nitrogen Charging	RNCK-1 thru -3	3	1/2	Spring	Backfill preheaters during drain
Receiver Water Drain	RPWDV-2	1	1	Manual	Drain second pass preheater panels
Receiver Water Inlet	RBWIV-1	1	4	Manual	Limit of preheater panels
Receiver Nitrogen Charging	RNCK-4	1	1/2	Spring	Backfill boiler feed lines during drain
Receiver Water Vent	RBWVV-4	1	1	Manual	Vent manifold during fill
Receiver Water Flow Control	RBTCV-1 thru -18	18	1	Pneumatic	Control boiler panel flowrate
Receiver Boiler Panel Water Inlet	RBWIV-2 thru -19	18	1	Manual	Limit of boiler panels
Receiver Water Drain	RBNDV-3 thru -21	18	1	Manual	Drain boiler panels
Receiver Nitrogen Charging	RNCK-5	1	1/2	Spring	Backfill boiler panels and downcomer during drain

Table 4-9 (Page 2 of 2)

VALVE LIST, 10-MW RECEIVER

Valve	Symbol	Qty	Nominal Size (In.)	Control	Function
Receiver Water Vent	RSVV-5	1	1	Manual	Vent boiler panels during fill
Receiver Steam Relief	RSRV-1 and -2	2	2 1/2	Spring	Prevent boiler overpressure (1,700 PSIG max at 1,000°F)
Receiver Water Drain	RTDV-22 and -23	2	1	Power	Drain of water accumulation
Receiver Steam Outlet	RDSOV-1	1	6	Manual	Isolate receiver and limit boilers
Receiver Nitrogen Charging	RNPV-1	1	1	Manual	Charge for backfilling during drain

Receiver feedwater enters the receiver at the riser interface through a large inlet filter assembly. A hand valve at the entrance to the filter and a stop check at the exit permit isolation for filter element maintenance. The stop check valve also prevents potential backflow of water from the receiver panel in the event of any failure-mode condition that results in a loss of feedwater pressure under panel operating conditions. In the event of an inadvertent loss of feedwater supply, all water that is in the panel tubes at the time of the malfunction is retained in the tubes to absorb heat influx during an emergency cutoff transient.

The feedwater from the main filter then rises through a pipe to the preheater distribution manifold located near the base of the panels and is fed into the inlets of the three sets of preheater panels. For control purposes, the inlet flow to the boilers themselves must be liquid water. To assure this, the preheaters were designed to produce slightly subcooled water as an effluent. The maximum preheater effluent temperature was selected to be 290°C (550°F).

An analysis was conducted to determine the temperature of the effluent from the preheaters as a function of the inlet temperature to the preheaters, the fraction of the total receiver heat load incident on the preheaters, and the condition of the steam being produced by the boiler panels. The results of these analyses are shown in Figure 4-22 and were used, with data relating the heat load on each panel to the time of year and time of day, to determine the number of panels which could be used as preheaters without exceeding the maximum preheater inlet temperature. These analyses resulted in selection of the southernmost six panels as preheaters.

To minimize tooling costs and to fully exploit the learning curve for fabricating the panels, the preheater panels were designed to be identical to the boiler panels. (This consideration would be less important for a Commercial Plant where large production numbers of panels are considered.)

The panel tubing size dictated that no more than two preheater panels could be arranged in series in order to maintain reasonably small pressure drops in the preheater loop. The configuration results in a pressure drop of

0.34 MPa (50 psi) in the preheater loop. The preheater interconnect lines cross the north-south axis of the receiver as shown in Figure 4-35, to provide a more uniform outlet temperature from each pair of preheaters.

Flow leaving the preheaters join in an accumulator manifold and then rises to the boiler panel distribution manifold located within the cylinder formed by the panels and about half-way to the top of the receiver. Feedwater to each boiler panel is supplied through individual lines and passes first through a flowmeter and then into the panel temperature control valve.

At any given time, the heat loads vary from panel to panel around the receiver to a considerable extent, as shown in Table 4-3. Thus, it was decided to provide individual controls for each boiler panel. By sensing the outlet temperature of each individual boiler and using it to control the water flow rate to that boiler, each panel is isolated from the remaining panels so that the interaction between panels is minimized and the stability of the overall receiver enhanced.

Feedwater flowrate to each boiler panel is controlled by a modulating throttle valve (RBTCV). This valve is pneumatically actuated with 0.7 MPa (100 psig) air or nitrogen supply pressure. The actuator positioner provides for closed-loop control of throttle valve displacement. A 0.02 to 0.10 MPa (3 to 15 psig) pneumatic input signal to the positioner is related to a mechanical feedback measurement of actuator and valve position, through a servo-valve mechanism, so that 0 to 100% valve displacement corresponds to the positioner input signal range. The actuator is a double-acting piston type, which, in combination with the actuator positioner and the relatively high supply pressure level, provides fast response to maintain steady-state fixed positions. An electropneumatic transducer converts a current signal input, typically a 4 to 20 mA or 10 to 50 mA range, to a 0.02 to 0.10 MPa (3 to 15 psig) pneumatic signal for the positioner. The displacement of the valve from its closed position is thereby controlled by electrical position-command signals from a remote source. A valve position transducer provides a position signal for monitoring and for use in control logic circuits.

The temperature control valve requires a reasonably high-pressure drop to provide for variations in inlet and outlet pressures and system resistance. A pressure drop of 2.1 MPa (300 psi) for the control valve under conditions of maximum flow results in a value of approximately 1.5 for the valve coefficient, C_v, and a nominal receiver inlet pressure of 14 MPa (2,000 psia).

Leaving the temperature control valve, the feedwater passes through the boiler panel water filter (RBWF) and the panel isolation valve which is required by the ASME boiler code to define the limits of a boiler.

Travelling upwards through the boiler panel, the feedwater is converted to superheated steam at the required conditions. Although all SRE test results have shown no tendency for the boiler panels to produce "wet" steam even under highly transient input conditions, all steam is passed through a cyclone type water separator. If any water is present in the steam, it will be drained into a moisture trap tank where level sensors will provide an early warning to the operator.

All individual boiler panel flows are finally mixed together in the steam header manifold at the top of the downcomer. The mixing process not only serves to join the individual panel flows, but also minimizes any individual panel output variations, thus stabilizing receiver output.

Redundant safety relief valves are mounted on the steam header for protection against overpressure. In addition, a remotely controlled vent valve is provided so that receiver pressure can be rapidly relieved, if necessary, due to any emergency which might arise during operation. Outflow of all safety valves are through vent stacks with conventional provisions for precluding inadvertent accumulation of water or other outflow restrictions.

Flow from the receiver during normal steady state plant operation will go directly from the steam header through the downcomer steam inlet valve and on to the electrical power generation subsystem and/or thermal storage. However, during the water cleanup mode prior to startup and during startup, before superheat conditions are achieved, receiver flow is diverted into a receiver flash tank assembly. The receiver flash tank will be sized for

3.16 kg/s (25,000 lb/hr) which corresponds to approximately 20% of maximum receiver flow at equinox noon. See Figure 4-37 for the flash tank configuration.

All panel lines are fabricated of Inconel 800 material. The diameter of the panel inlet and outlet lines are kept to a minimum to permit greater flexibility to accommodate thermal expansion. The routing is also such that thermal expansion is permitted.

Because of the high temperature and pressure, all piping and component connections are welded except for the water and steam connect points for each panel which are flanged to permit ease of assembly and disassembly. The flanges are the 2,500-lb weld neck type which are butt-welded to the pipe, thus making highly reliable joints. Seals may be "ring joint" gaskets or flexitallic gaskets, both of which are standard.

Manually operated stop check valves are provided for inflow of chemical flushing fluids to the receiver and its plumbing. Flushing fluid outflow will be through the individual panel drain valves.

A solenoid valve and in-series check valves provide for inflow of nitrogen to the panels under shutdown conditions. The nitrogen is supplied from a regulated low-pressure source to maintain an inert environment in the panels, if desired, when the receiver is not in operation.

Control Logic

The control logic for the boiler temperature control valves (RBTCV) is shown in Figure 4-38. Analog logic symbols are used to describe the actual circuitry built for the SRE. Digital control would be used for the Pilot Plant controller and would have identical operating characteristics. Operation of the circuit is as follows:

In the startup sequence of operations, solid-state electronic switch S-1 is closed to apply a preset voltage E_1 to an amplifier which then delivers a corresponding output current I_{x1} as a position-command signal to valve RBTCV. The feedwater control valve responds by moving to a partially open setpoint position.

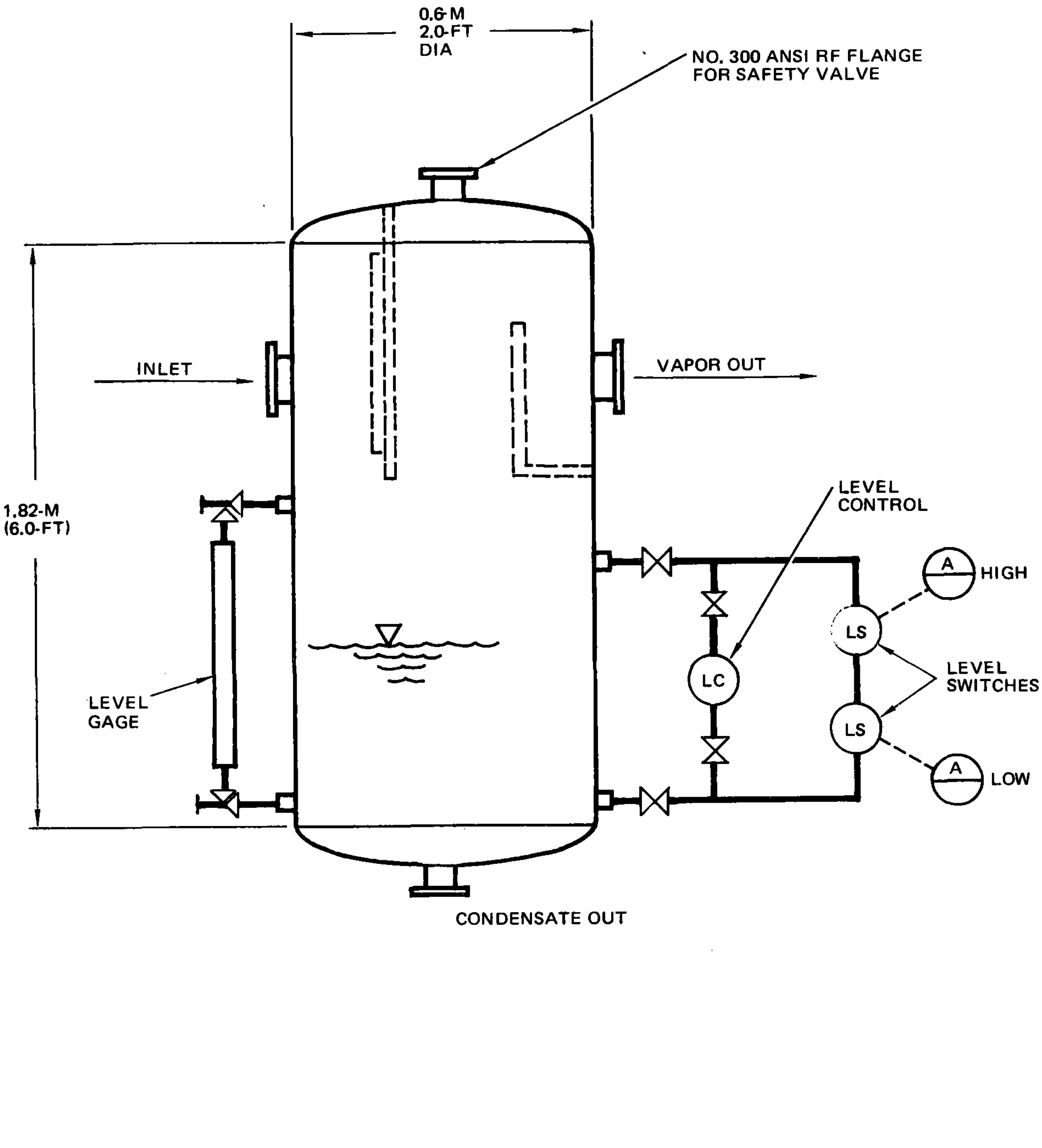


Figure 4-37. Receiver Startup Flash Tank (Pilot Plant)

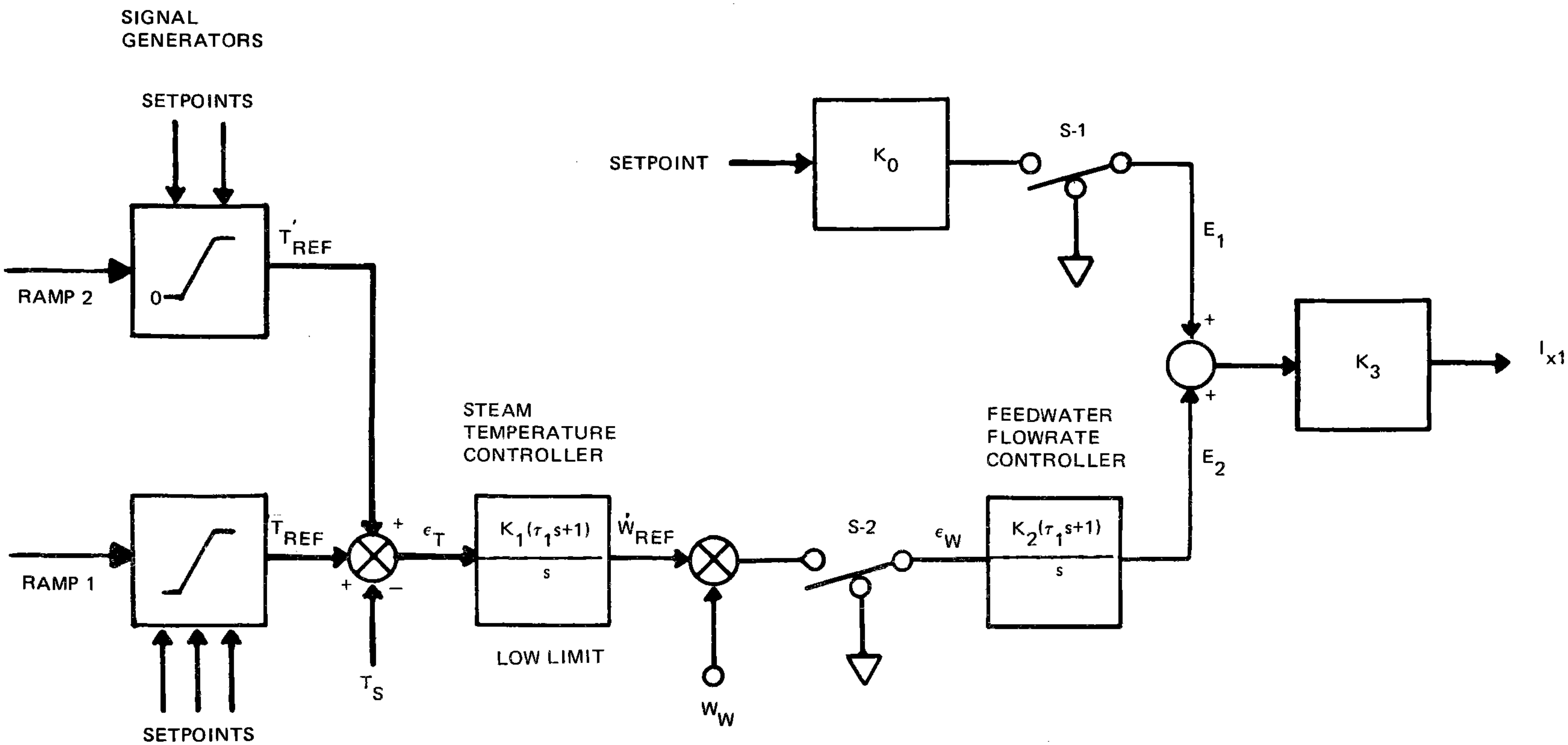


Figure 4-38. Feedwater Flowrate Control Circuit Block Diagram

Subsequently, solid-state electronic switch S-2 is closed to activate the signal generators. Initially, a T_{REF} signal is compared with a sensed steam outlet temperature signal T_S. The proportional-plus-integral steam temperature controller commands a feedwater flowrate W_{REF}, as required for elimination of temperature error, ε_T. Commanded and measured flowrates, W_{REF} and W_S, are compared, and a proportional-plus-integral feedwater flowrate controller output signal E_2 is changed from zero and is added to, or is subtracted from, E_1. The resultant valve position command signal I_{x1} changes until the error, ε_W, is eliminated. Smooth transfer from valve position control to closed-loop steam temperature and feedwater flowrate control is thereby achieved. Additionally, the steam temperature controller has a preset low limit for its output signal to limit feedwater flowrates during the start and shutdown sequences.

The signal generators in Figure 4-38 operate as follows: Signal T_{REF} has an initial value 260°C (500°F), a ramp increase, and a final value 343°C (650°F), as determined by setpoint adjustments. When switch S-2 closes, a logic signal Ramp 1 is applied to initiate the function generation. Completion of the Ramp 1 transient will result in production of superheated steam at derated temperature conditions. Upon command to produce rated steam, a logic signal Ramp 2 is applied to initiate generation of signal T_{REF} which is additive to T_{REF}. The completion of the Ramp 2 transient results in the production of steam at 516°C (960°F). The generated ramp signals reverse and return to their initial values during a transition to derated steam or a shutdown sequence of operations.

4.3.2.3 Structure

The Pilot Plant receiver structure consists of structure necessary to transmit loads from the receiver unit and service crane into the tower. The structure includes primary structural members, attachments, and clips and rails to support the absorber panels. The secondary structure includes members to transfer loads from the absorber rails into the main structural members. These members must carry static system loads as well as live loads such as thermal loads, winds, and quakes.

Requirements

The requirements for the structure are as follows:

- Static Loads

  Dead Weight of Structure and Absorber, 1g
- Live Loads
  - Seismic

    Horizontal 0.25g at Groundlevel

    Vertical 2/3 of Horizontal
  - Wind, 22 m/s with 55 m/s Gust
  - Floor, 700 lb Concentrated Weight

Ground rules used in the analysis are as follows:

A. Load occurs during operation.

B. Absorber and structure remain in place.

C. Only minor repairs required.

D. Quake and wind do not happen simultaneously.

Analysis

The analyses conducted on the Pilot Plant support structure consisted of absorber-clip thermal loads as well as nonthermal live load analysis for the clips and carbon steel structure. The resulting weight and calculations were then used in the tower main member sizing.

The clip supports for the absorber panel are loaded by restraining the absorber from thermal bowing. The free thermal distortion is calculated and input into a computer program with supports at the clip stations. This program gives reactions which are then broken down into clip loads at the various transverse locations. Clip loads at each longitudinal station sum into a net load which sum to zero over all longitudinal clip stations. However, for analysis purposes, the two longitudinal slide rails are flexible so these station loads are transmitted to the secondary structure.

The receiver structure must be able to handle loads as previously discussed. For attachment structure such as the clips and panel rails, wind loads are the critical nonthermal loading condition. For the secondary structure, seismic loads, floor loads, or wind loads are the critical load condition. These load conditions were used to obtain member sizing.

For the primary structure, quake accelerations are the critical loads. Expected column loads due to quake accelerations plus dead weight are an order of magnitude larger than loads due to wind or dead weight alone. Analysis for maximum seismic loads generated a maximum shear and column load from tower overturning bending moment and vertical accelerations. Shear diagonals and cross bracing were conservatively sized and their weights were used in the column sizing. Columns were then selected from the AISC Steel Construction Manual and the process was repeated until an optimum column size was found. The transition section members were sized similarly to the main vertical columns taking into account their slopes, and also using bracing in the weak direction.

The 10-MW Pilot Plant carbon steel structure is shown in Figure 4-39. The eight column primary structure is a truss with diagonals and cross members to carry shear with columns carrying the vertical axial loads and bending moment axial loads. The main vertical beams are shown extended to interface with the service crane used to install panels or transport equipment to the top of the tower.

The carbon steel structure and transition section consist of wide flange beams for the primary structure, with angle beams and channel sections used for the secondary structure supporting the absorber panels and flooring. Table 4-10 provides a complete parts list. Shear diagonals provide torsional stability for the main columns and for the secondary panel support structure. Secondary supports and cross members maintain the shape of the receiver.

Dimensions for the Pilot Plant structure are shown in Figure 4-40. In addition to this structure, there are 24, 12.5m panels, each 88.9 cm (35 in.) wide, and assorted piping and valves. Accessory equipment includes a 11,000-Kg (25 K-lb) crane, flooring and items such as ladders and railings. Components, and their weights and cg locations, are summarized in Table 4-11. The carbon steel weight includes primary and secondary structural steel as listed in Table 4-10.

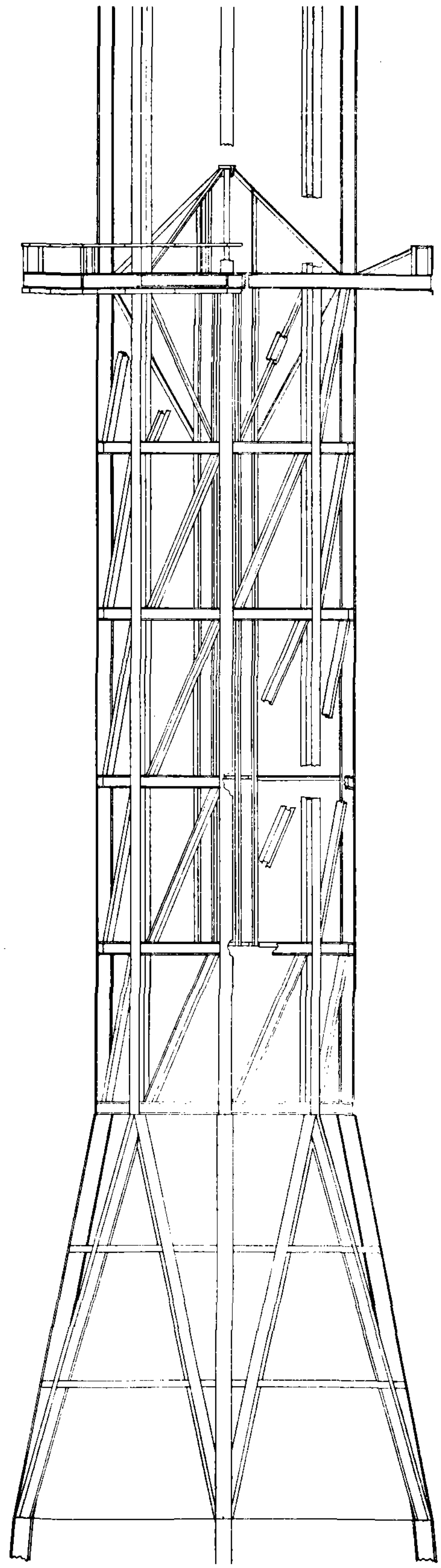


Figure 4-39. Pilot Plant Receiver Primary Support Structure

Table 4-10 (Page 1 of 2)

10-MW PILOT PLANT CARBON STEEL PARTS LIST

Item	AM Standard Size	Units: m (ft) Total Length (or Area) Req	Elevation (Above 65m Interface)
1. 8 Main Columns	W10x39	146.3 (480)	6.55-24.84 (21.5-81.5)
2. 8 Deck Beams (6th Deck)	W10x29	23.16 (76)	20.27 (66.5)
3. 8 Base Support Columns	W10x39	56.08 (184)	0-6.55 (0-21.5)
4. 4 Base Support Corner Columns	W12x65	26.82 (88)	0-6.55 (0-21.5)
5. 56 Horizontal Cross Members	W8x20	76.81 (252)	6.55-24.84 (21.5-81.5)
6. 40 Diagonal Members	W8x20	125.58 (412)	6.55-20.27 (21.5-66.5)
7. 7 Centerline Rings	C4x5.4	17.07 (56)	6.55-24.84 (21.5-81.5)
8. Intermediate Members (6th Deck)	C4x5.4	18.29 (60)	20.27 (66.5)
9. Exterior Members	C4x5.4	109.73 (360)	6.55-20.27 (21.5-66.5)
10. 4 Interior Verticals	∠3x3x1/2	73.15 (240)	6.55-24.84 (21.5-81.5)
11. Horizontal Members	∠3x3x1/2	54.86 (180)	6.55-17.53 (21.5-57.5)
12. Horizontal Members	∠3x3x1/2	38.1 (128)	6.55-17.53 (21.5-57.5)

Table 4-10 (Page 2 of 2)

10-MW PILOT PLANT CARBON STEEL PARTS LIST

	Units: m (ft)		
Item	AM Standard Size	Total Length (or Area) Req	Elevation (Above 65m Interface)
13. Cross Members	∠3x3x1/2	121.92 (400)	6.55-17.53 (21.5-57.5)
14. Connections and Miscellaneous	---	---	0-24.84 (0-81.5)
15. Expanded Metal Flooring (6 Lower Decks)	2.27 $^{kg}/m^2$ (5 lb^m/ft^2)	188.87 (area) (2033)	6.55-20.27 (21.5-66.5)
16. Top Floor Grate	6.80 kg/m^2 (15 lb^m/ft^2)	12.08 (area) (130)	24.84 (81.5)
17. Horizontal Members on 6th Deck	<3x3x1/2	41.45 (136)	20.27 (66.5)
18. 24.38m (80 ft) Ladder	---	---	0-24.38 (0-80)
19. 45.72m (150 ft) Handrail	---	---	0-20.27 (0-66.5)
20. 16 Exterior Vertical Members	∠3x3x1/2	195.07 (640)	6.55-20.27 (21.5-66.5)
21. Cross Bracing at 5th Bay	∠3x3x1/2	43.89 (144)	17.53-20.27 (57.5-66.5)
22. Horizontal Bracing at Transition	∠3x3x1/2	35.36 (116)	0-6.55 (0-21.5)
23. Horizontal Members on Top Deck	W10x39	13.41 (44)	24.84 (81.5)

Total Carbon Steel Mass is 42.4 x 10^3 kg (93.4 K-lbm)

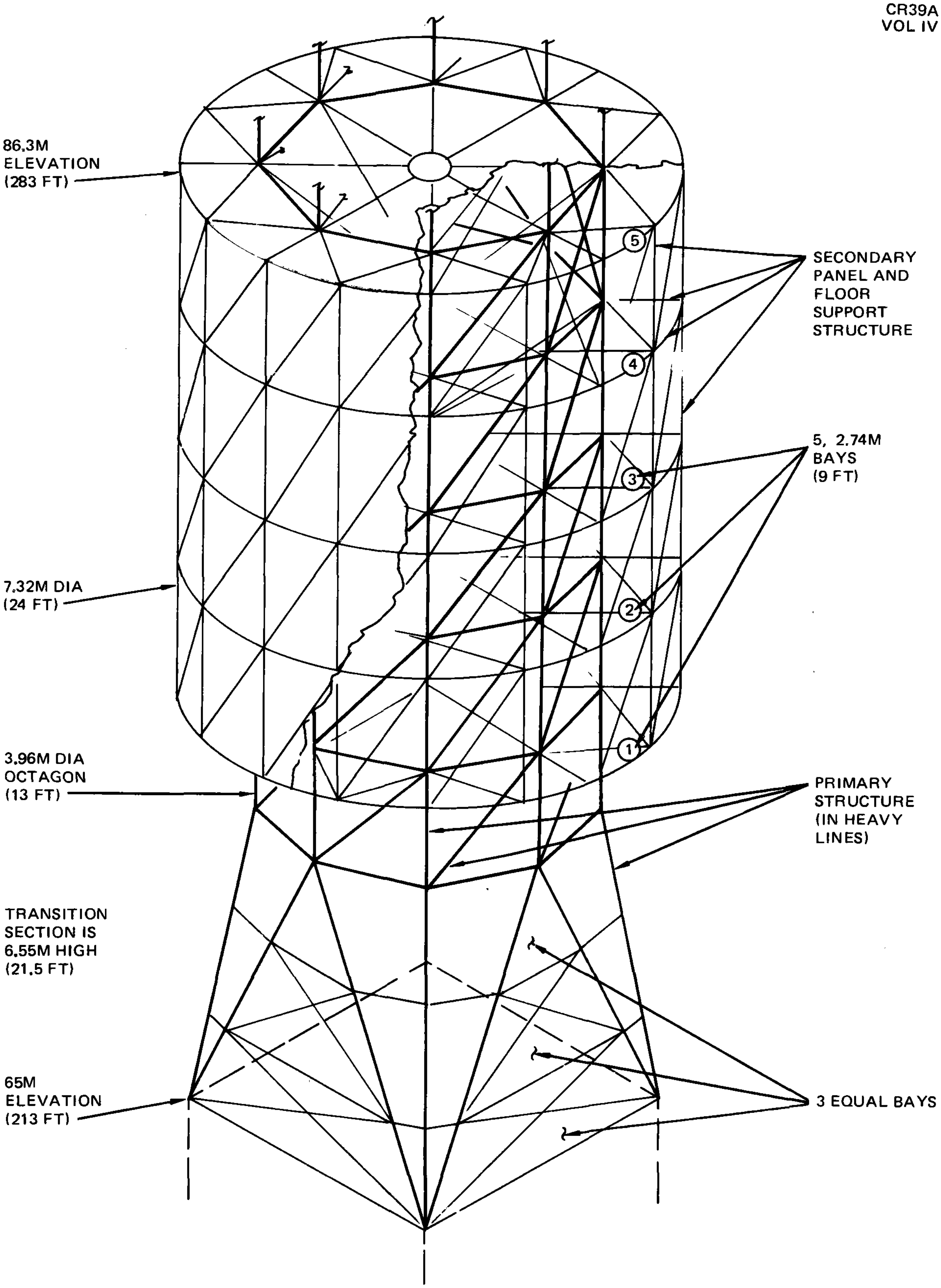


Figure 4-40. Pilot Plant Receiver Structure

Table 4-11

10-MW SOLAR RECEIVER DRY WEIGHT SUMMARY***

Item	Weight in in Kg x 10^{-3} (kips)	Above Interface (65m) in Meters (ft)
Carbon Steel* Listed in Figure	93 (205)	15.09 (49.5)
24 Panel Assemblies	38 (84)**	15.09 (49.5)
Piping, Valves, Filters, Flash Tank, etc	21 (45)	11.89 (39)
Crane	11 (25)	26.21 (86)
Total Weight	163 (359)	

*Using ASTM A-36 Steel
57,200-PSI ultimate
22,000-PSI allowable
Contingency factor of 1.4
Seismic input = 0.25g

**Each panel = 3,500 lb as installed
= 4,000 lb with handling fixtures attached

***For wet weight: add 1,500 lb (operating)
add 4,000 lb (full of water)

4.3.3 Pilot Plant Receiver Tower Assembly

4.3.3.1 Requirements

The primary requirements for the Pilot Plant receiver tower are:

- Provide means for attachment, support, and operation of the receiver assembly
  - Receiver design weight (wet), 226,800 kg (500,000 lb)*
  - Maximum allowable sway at top of tower during operational wind or seismic conditions, 0.18m (0.6 ft)
- Provide means for attachment and support of riser and downcomer assembly
- Maintain structural integrity during postulated survival seismic and wind environmental conditions

*Actual receiver weight and survival ground-level seismic acceleration requirements were revised downward following the analysis to 163,000 kg (359,000 lb) and 0.25g, respectively, so the following structural analysis is believed to be conservative.

- 0.33g* horizontal acceleration at ground level
- 40.2 m/s (90 mph) winds
- Provide a 30-yr lifetime
- Provide access and capability for inspection, maintenance, and repair of receiver assembly and riser/downcomer assembly
- Provide for lightning protection and aircraft warning
- Soil bearing capacity = 48,820 kg/m^2 (10,000 psf) (Barstow Data)

Loads

Static loads include the weight of the receiver, tower, and foundation. Wind loads used for the tower analysis were based on a velocity profile obtained by using the following formula:

$$V_h = V_{10} \left(\frac{h}{10}\right)^{0.15}, \quad h \geq 10_m$$

where

V_h = wind velocity at height, h, above ground

V_{10} = wind velocity at 10m above ground

For the maximum operational wind condition, V_{10} = 16.1 m/s (36 mph), including wind gusts. For the maximum survival wind condition, V_{10} = 40.2 m/s (90 mph), excluding wind gusts. Gust factors were calculated for the maximum survival wind condition using the provisions of ANSI A58.1-1972, "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," Section A6.3.4.1. The calculated gust factors of 1.0605 and 1.1851 were applied to the resulting pressure diagrams for the concrete tower and steel tower, respectively. Shape factors and wind pressure used are in accordance with Section 6 of the aforementioned reference.

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*Actual receiver weight and survival ground-level seismic acceleration requirements were revised downward following the analysis to 163,000 kg (359,000 lb) and 0.25g, respectively, so the following structural analysis is believed to be conservative.

Seismic loads were calculated using the ground response spectra given in the NRC Regulatory Guide 1.60, "Design Response Spectra for Seismic Design of Nuclear Power Plants." These spectra were normalized to 0.165g maximum ground acceleration for the operating basis earthquake (OBE) and to 0.33g maximum ground acceleration for the safe shutdown earthquake (SSE) through which the structure must survive. A vertical component of two-thirds the intensity of the horizontal earthquake is assumed to act concurrently with the horizontal earthquake. For each selected mode of vibration, the structural response to the concurrently acting components was calculated by taking the square root of the sum of the squares of the response caused by each of the components of motion. The total structural response was then formed by a square root of the sum of the squares summation over all the selected modes of vibration. Damping values were selected from the NRC Regulator Guide 1.61, "Damping Values for Design of Nuclear Power Plants." Damping ratios for bolted steel structures and reinforced concrete structures are given as 4% of critical for the OBE and 7% of critical for the SSE.

Note: Subsequent to the seismic analysis using the above maximum ground acceleration for SSE of 0.33g, it was determined from the Pilot Plant site selection at Barstow, that a more likely maximum ground acceleration of 0.25g could be expected. This lowering of the maximum ground acceleration will reduce the tower and receiver seismic forces by approximately 25%. However, an offsetting factor is the expected increase in seismic forces (approximately 15%) due to the inclusion of the soil flexibility in the dynamic model. For this preliminary design analysis, it was decided to assume a fixed base condition for both the concrete and steel towers. The analysis was repeated on the steel tower using the smaller acceleration of 0.25g and a revised receiver weight, including crane, of 166,364 kg (366,000 lb). It was determined that a reduction of approximately 20% tower structure weight [i.e., down to 94,545 kg (104 tons)] could be realized for a fixed base condition.

Stresses

Reinforced Concrete — Allowable stresses for concrete are in accordance with the Strength Design provisions of ACI 318-71. A load factor of 1.25 was applied to dead load in combination with the safe-shutdown earthquake. For dead load in combination with the operating basis earthquake, allowable stresses are in accordance with the working stress provisions of ACI 318-63 with a one-third increase in allowable stresses.

Structural Steel — Structural steel stresses meet AISC requirements without an allowable increase for dead load in combination with the operating basis earthquake. A one-third increase in allowable stresses is assumed for dead load in combination with either maximum wind or the safe shutdown earthquake.

Soil — Soil bearing capacity was based on allowable values for the soils at Barstow.

Materials

Materials are those which are customarily found in conventional concrete and steel construction. The concrete must meet ACI Standards for 4,000-psi ultimate compressive strength at 28 days. Reinforcing must meet ASTM A615-72 Grade 60. Structural steel is specified in ASTM A36. Field bolted connections using ASTM A325 high-strength bolts will be used to facilitate steel tower construction.

4.3.3.2 Analyses/Trade Studies

The STARDYNE Structural Analysis System was used to perform the analyses of both the concrete and the steel towers. The modal analyses and the steady-state wind and dead load analyses were made using the STAR program. The dynamic earthquake analyses were made using the DYNRE 4 program. Fixed-base models were employed in each case.

Results of the analyses indicate that the steel structure is more flexible than the concrete structure. Deflections under the specified wind loads are greater for the steel tower, but still within acceptable limits. The response of the steel structure to earthquake loading is less than that for the concrete structure. This is due largely to the fact that the more flexible steel structure has a lower fundamental frequency with a correspondingly smaller spectral acceleration. Earthquake loads on the receiver and appurtenant equipment, if mounted on a steel tower, would be less than those for the concrete tower with a commensurate reduction in cost for the receiver structure. This cost savings would extend to all of the equipment, piping, etc., which is mounted in the upper portion of the tower. Foundation requirements for the much lighter steel tower are not as great as those for the heavier concrete tower, with accompanying additional cost savings.

Tower Deflections

Detailed tower deflections are shown in Table 4-12 for the concrete and the steel structures under several loading conditions. The table shows that either structure will easily meet the 0.18m (0.6 ft) sway limit when experiencing the operational conditions. Refer to Figures 4-41, 4-42, 4-43, and 4-44 for plots of tower and receiver deflections vs tower height, for concrete and steel towers respectively.

Tower Base Shears and Moments

Detailed tower base shears and moments are shown in Table 4-13 for the concrete and the steel structures under several loading conditions.

Table 4-12

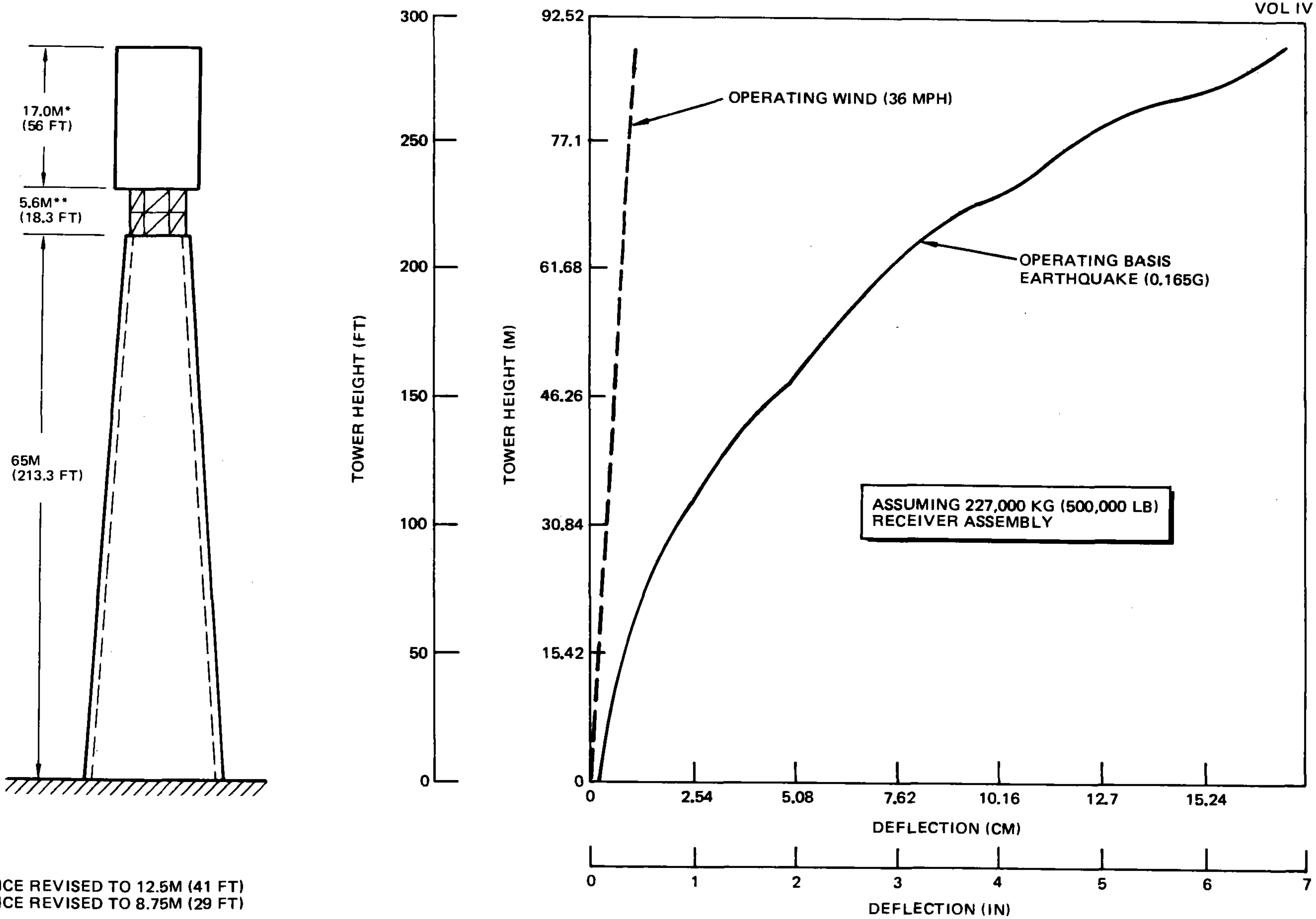
PILOT PLANT TOWER DEFLECTIONS*

Condition	Concrete	Steel
Wind		
Operational Wind V_{10} = 16.1 m/s (36 mph)	0.44 cm (0.17 in.)	1.64 cm (0.64 in.)
Maximum Wind with Peak Gust V_{10} = 40.2 m/s (90 mph)	2.92 cm (1.15 in.)	12.03 cm (4.73 in.)
Earthquake		
Operating Basis Earthquake 0.165g (4% damping)	8.38 cm (3.30 in.)	10.21 cm (4.02 in.)
Safe Shutdown Earthquake 0.33g (7% damping)	13.92 cm (5.48 in.)	17.22 cm (6.78 in.)

*Deflections indicated are at top of tower.

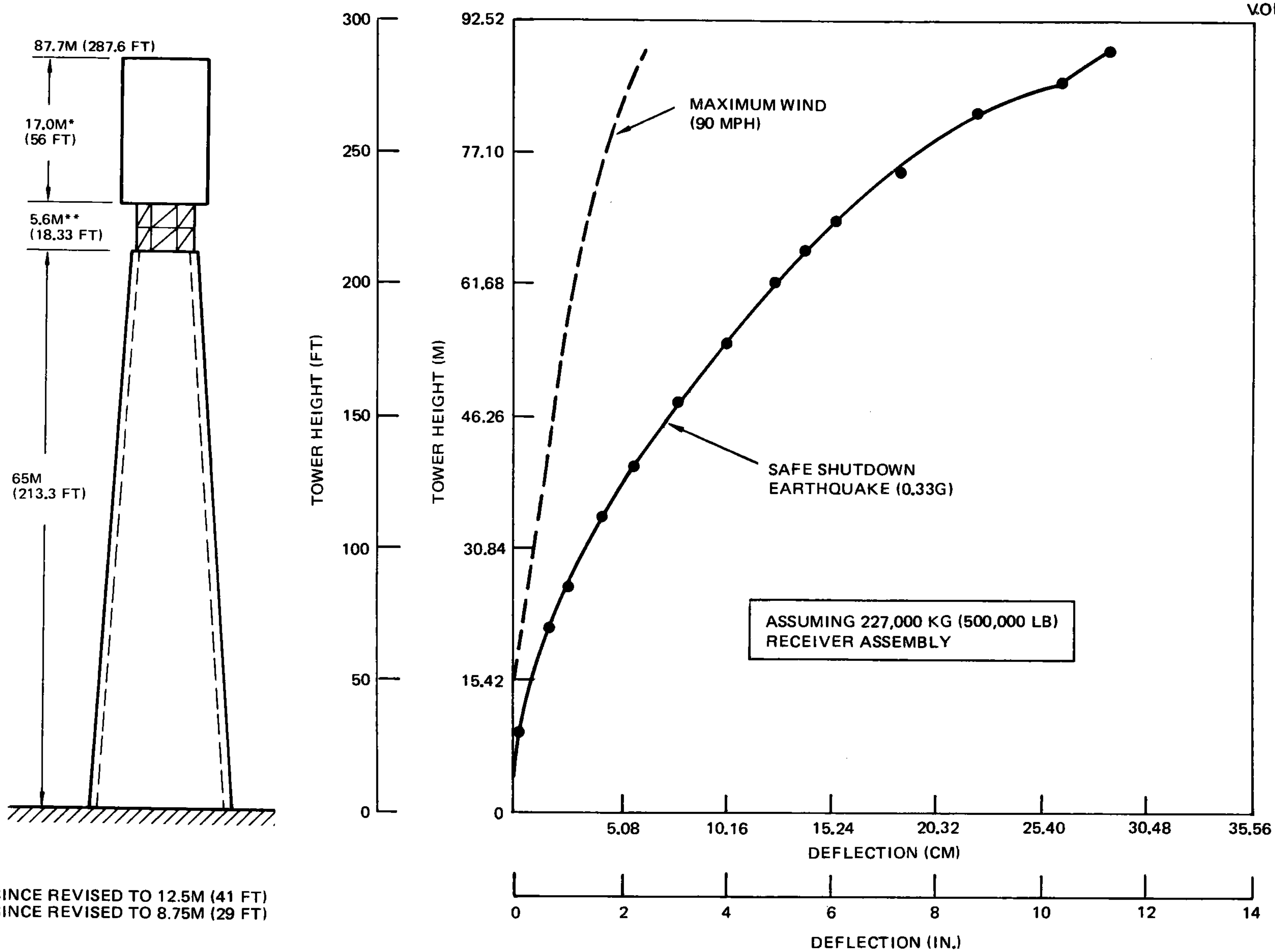
Notes:

1. Assuming 227,000 Kg (500,000 lb) receiver assembly
2. Concrete vs Steel — Tower Height = 65m (213 ft)



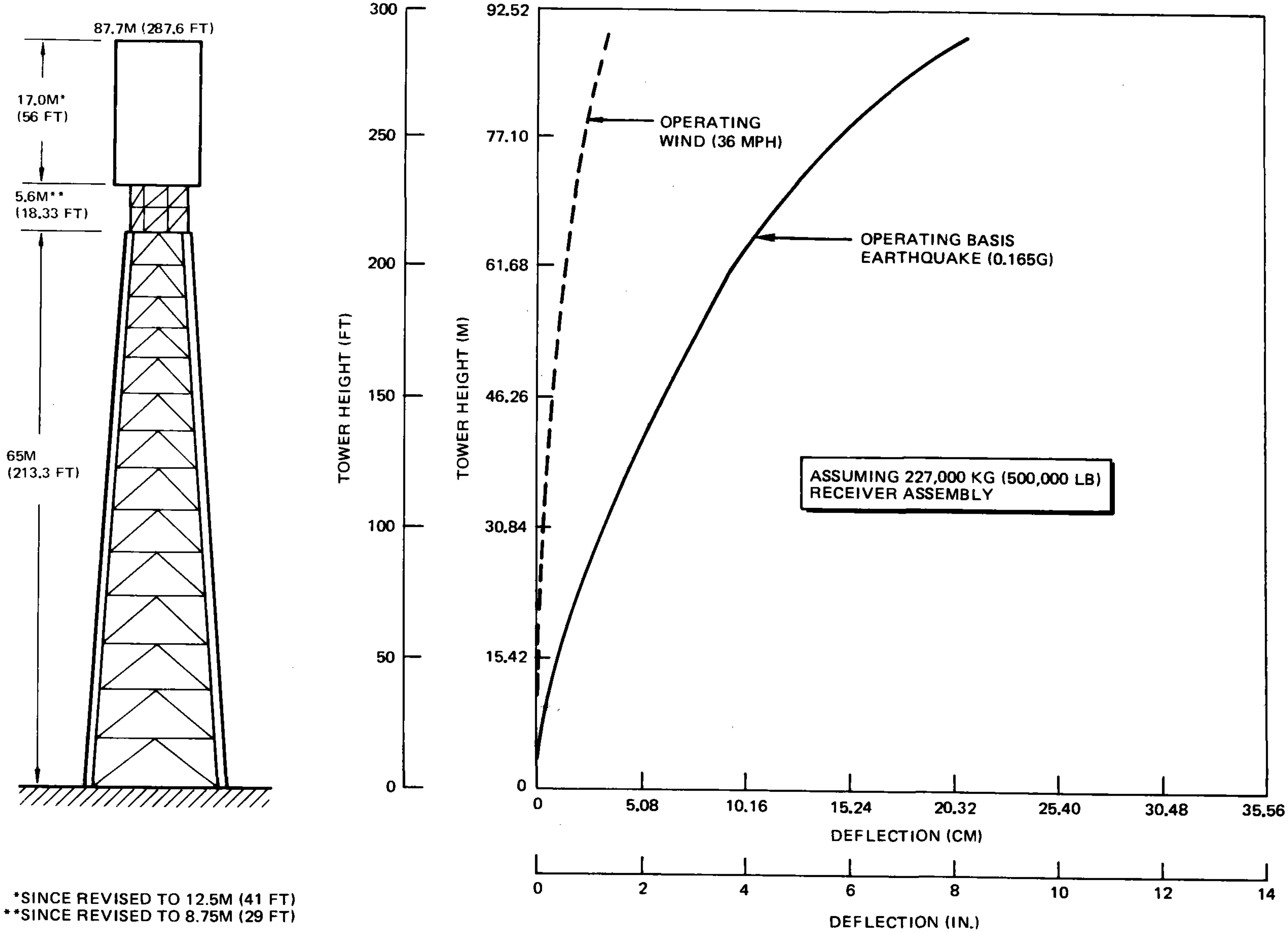
*SINCE REVISED TO 12.5M (41 FT)
**SINCE REVISED TO 8.75M (29 FT)

Figure 4-41. Pilot Plant Operating Deflections (Concrete Tower)



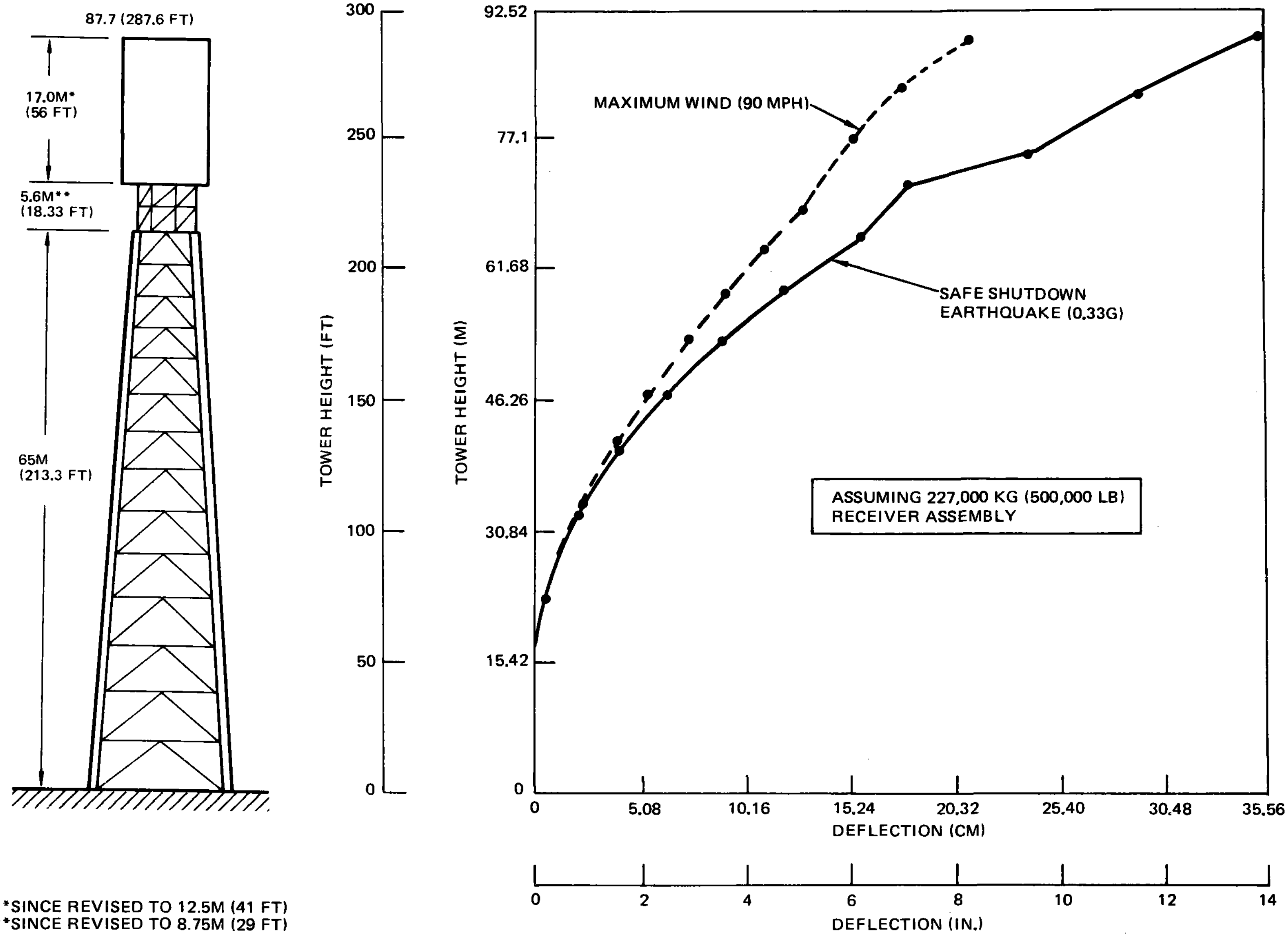
*SINCE REVISED TO 12.5M (41 FT)
**SINCE REVISED TO 8.75M (29 FT)

Figure 4-42. Pilot Plant Safe Shutdown Deflections (Concrete Tower)



*SINCE REVISED TO 12.5M (41 FT)
**SINCE REVISED TO 8.75M (29 FT)

Figure 4-43. Pilot Plant Operating Deflections (Steel Tower)



*SINCE REVISED TO 12.5M (41 FT)
**SINCE REVISED TO 8.75M (29 FT)

Figure 4-44. Pilot Plant Safe Shutdown Deflections (Steel Tower)

Table 4-13

PILOT PLANT TOWER BASE SHEARS AND MOMENTS

Condition	Base Shear		Base Moment	
	Concrete	Steel	Concrete	Steel
Wind				
Operational Wind Including Gust V_{10} = 16.1 m/s (36 mph)	9.48×10^3 kg (20.9 kips)	1.04×10^4 kg (23 kips)	4.69×10^5 m-kg (3,395 ft-kips)	4.87×10^5 m-kg (3,524 ft-kips)
Maximum Wind with Peak Gust V_{10} = 40.2 m/s (90 mph)	6.29×10^4 kg (138.7 kips)	7.62×10^4 kg (168 kips)	3.11×10^6 m-kg (22,486 ft-kips)	3.61×10^6 m-kg (26,100 ft-kips)
Earthquake				
Operating Basis Earthquake 0.165g (4% damping)	2.44×10^5 kg (537 kips)	4.35×10^4 kg (96 kips)	9.61×10^6 m-kg (69,518 ft-kips)	2.69×10^6 m-kg (19,468 ft-kips)
Safe Shutdown Earthquake 0.33g (7% damping)	3.94×10^5 kg (869 kips)	7.26×10^4 kg (160 kips)	1.58×10^7 m-kg (114,040 ft-kips)	4.54×10^6 m-kg (32,800 ft-kips)

Notes:

1. Assuming 227,000 Kg (500,000 lb) receiver assembly)
2. Concrete vs Steel — Tower Height = 65m (213 ft)

Tower Accelerations

Tower accelerations for the dynamic earthquake conditions are shown in Table 4-14 for the concrete and the steel structures at several reference points. Figures 4-45 and 4-46 show plots of tower and receiver acceleration vs tower height for concrete and steel towers, respectively.

The first few natural frequencies of the concrete and the steel structures are shown in Table 4-15.

4.3.3.3 Pilot Plant Tower Selection and Description

On the basis of the foregoing analyses, the free-standing steel tower is the preferred structure for the Pilot Plant. The main advantages of the steel structure are as follows:

- Deflection. Higher deflections than the concrete tower but within acceptable limits.
- Seismic Response. Lower response to earthquake loading, resulting in lower earthquake loads on the receiver and appurtenant equipment, piping, etc., with commensurate reduction in cost.
- Cost. Tower, including foundation, will result in a lower total installed cost over the concrete tower, including foundation, based on the design requirements used in this analysis.
- Operational Flexibility. Tower lends itself to Pilot Plant because of the relative ease of attachment of piping, conduit, etc., to the tower structure, such as may be expected subsequent to plant startup.

Steel Tower Description

As shown in Figure 4-47, the structural steel tower has a height of 65m (213 ft) to the receiver support. It is composed of square cross-section, K-braced frames supported on a square concrete footing. The width of the tower at the top is 4.6m (15 ft) while the base dimension is 12.2m (40 ft). The square concrete foundation is composed of a 0.61m (2 ft) thick mat which is 15.2 m (50 ft) on a side and located 3.96m (13 ft) below finished grade. Concrete walls and pedestals extend 5.48m (18 ft) upwards to meet the steel structure at an elevation 1.52m (5 ft) above the grade.

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Table 4-14

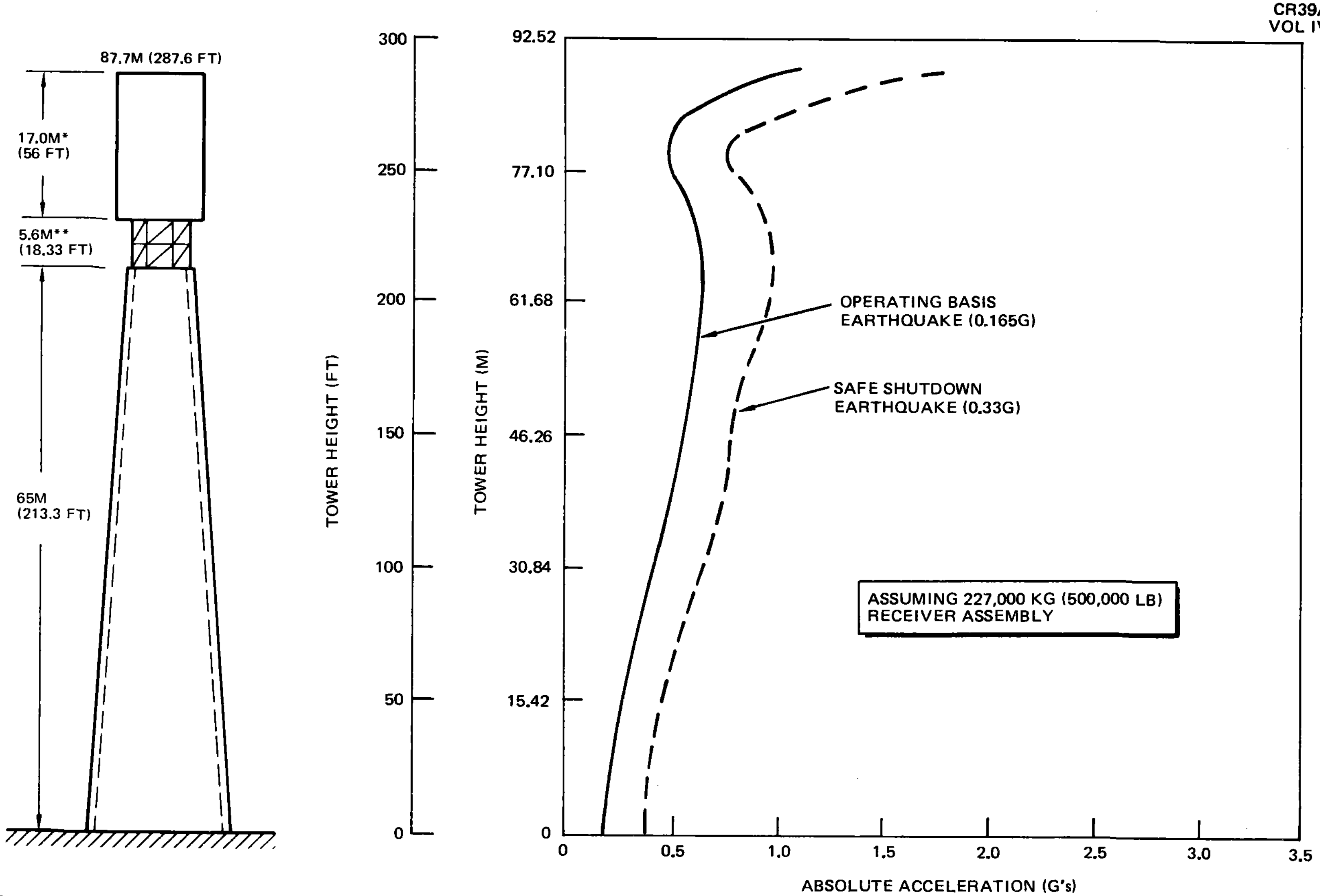
PILOT PLANT TOWER ACCELERATIONS

Location	Operating Basis Earthquake		Safe Shutdown Earthquake	
	Concrete	Steel	Concrete	Steel
Top of Tower Structure 65m (213 ft)	0.59g	0.35g	0.98g	0.60g
Center Line of Receiver 80m (263 ft)	0.44g	0.25g	0.75g	0.45g
Top of Receiver 87.7m (287 ft)	1.07g	0.39g	1.75g	0.66g

1g = 9.81 m/s^2 (32.17 bps^2)

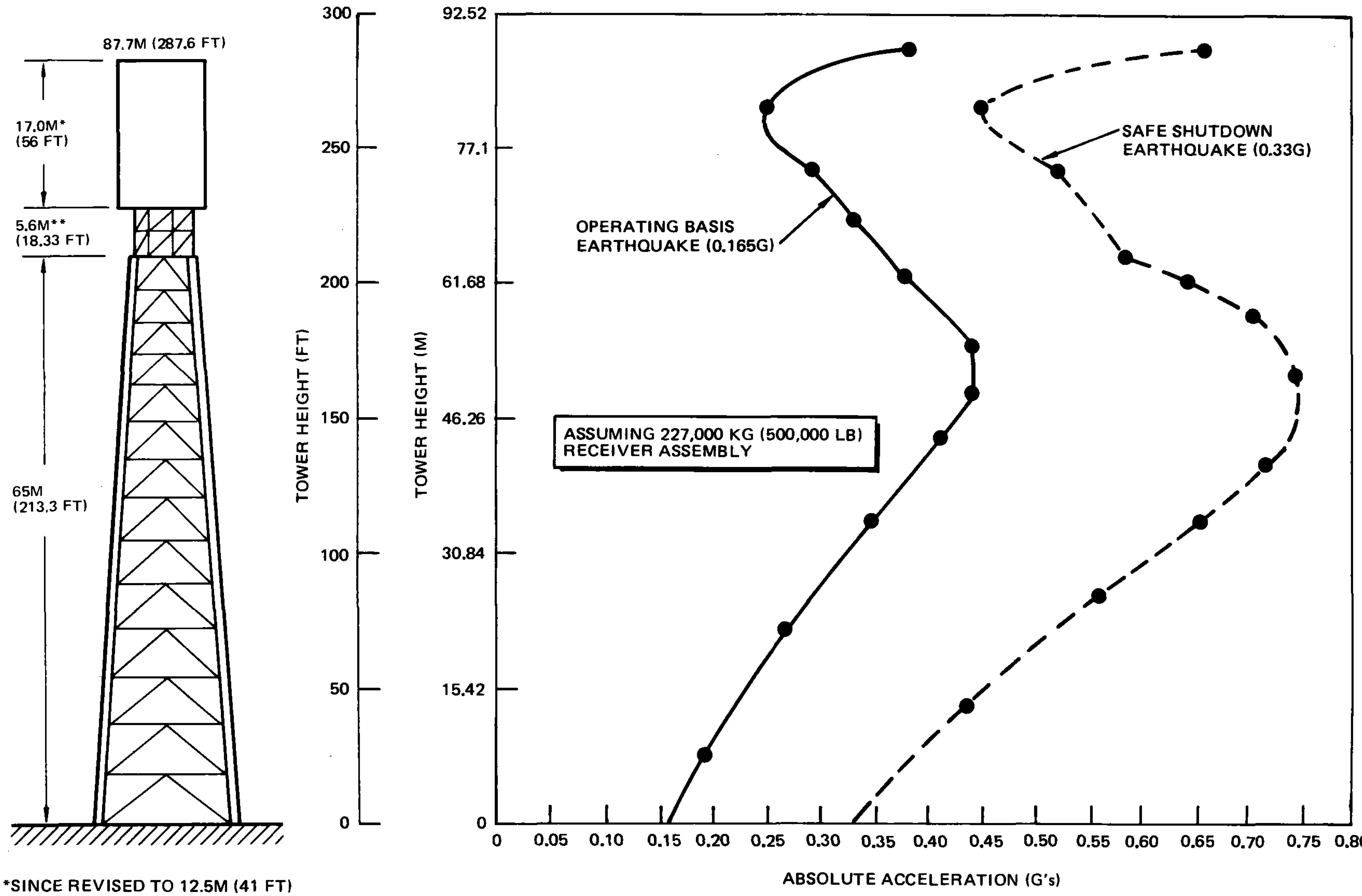
Notes:

1. Assuming 227,000 Kg (500,000 lb) receiver assembly
2. Concrete vs Steel — Tower Height = 65m (213 ft)



*SINCE REVISED TO 12.5M (41 FT)
**SINCE REVISED TO 8.75M (29 FT)

Figure 4-45. Pilot Plant Accelerations (Concrete Tower)



*SINCE REVISED TO 12.5M (41 FT)
**SINCE REVISED TO 8.75M (29 FT)

Figure 4-46. Pilot Plant Accelerations (Steel Tower)

Table 4-15

PILOT PLANT TOWER NATURAL FREQUENCIES
(Concrete vs Steel; Tower Height = 65m (213 ft)

Mode Number	Concrete	Steel
1	0.725 cps	0.455 cps
2	2.509 cps	2.710 cps
3	5.960 cps	4.335 cps*
4	10.122 cps*	5.319 cps

*Vertical mode.

Receiver Tower Auxiliaries

The receiver tower auxiliaries includes that equipment and materials necessary to provide access to the receiver from grade elevation, to facilitate installation and maintenance functions, aircraft obstruction lights, lightning protection, access platforms, lighting, and piping electrical conduit supports and attachments to the tower structure. The Pilot Plant receiver tower auxiliary equipment arrangement is shown in Figure 4-48.

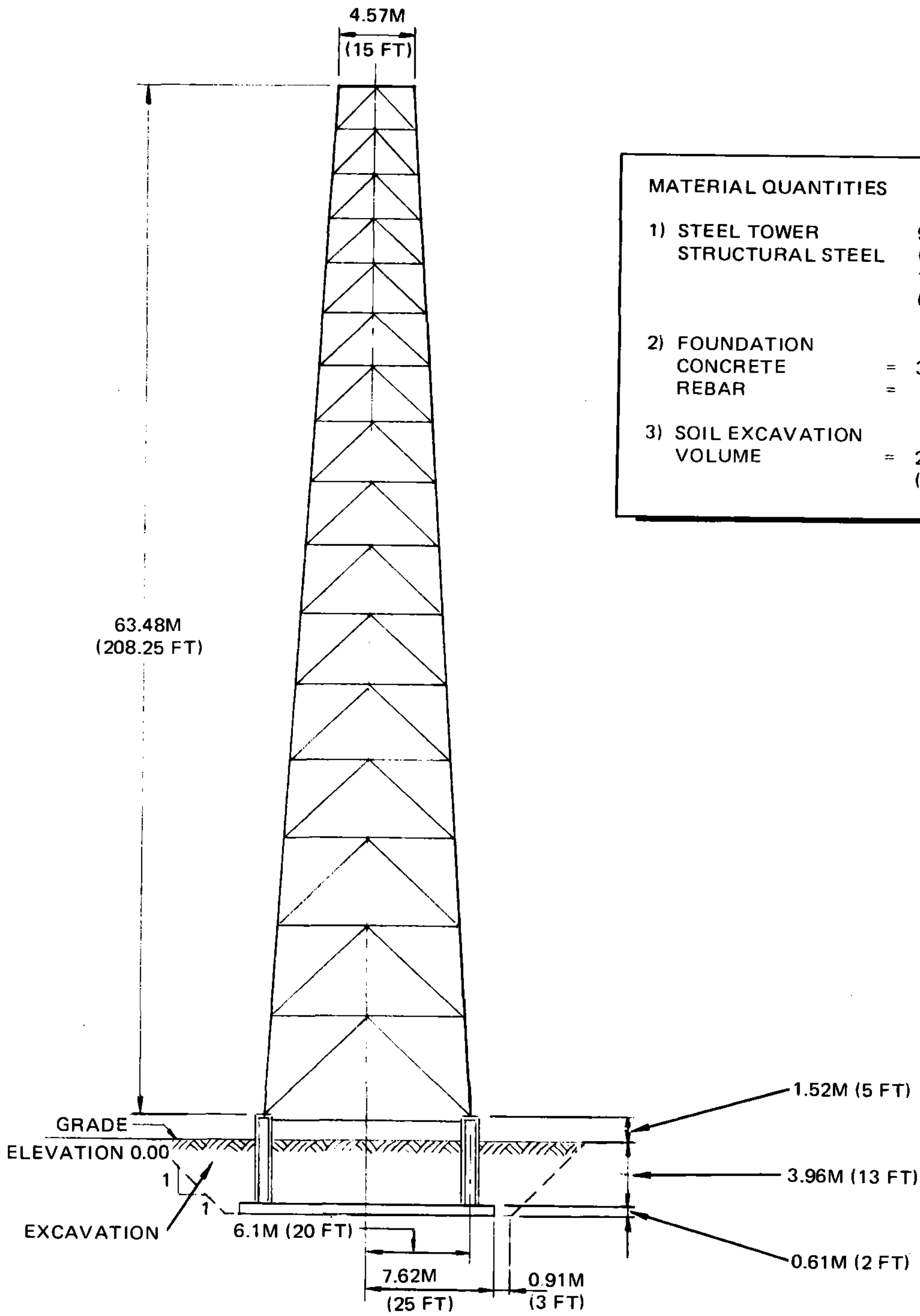
Receiver Access

Access from grade elevation to the top of the tower is provided by an elevator and a caged ladder. The elevator will be provided with stops at each intermediate platform level for maintenance and repair operations as required. A service lift and caged ladder are also provided from the top of the tower to the top of the receiver structure.

The tower elevator proposed for the Pilot Plant is of the enclosed type with rack and pinion-type drive. This type of elevator is widely used on tall powerplant chimneys as a permanent installation for access to gas sampling and monitoring equipment and aircraft obstruction lights.

Installation/Service Crane

A 4.54T (5 ton) installation and service crane at the top of the receiver support structure facilitates initial installation of the receiver panels and assists in maintenance functions of the receiver and appurtenances during the plant life (Figure 4-49).



MATERIAL QUANTITIES

1) STEEL TOWER STRUCTURAL STEEL		94.5T (104 TONS) (FOR 0.25G SEISMIC) 117.94T (130 TONS) (FOR 0.33G SEISMIC)
2) FOUNDATION		
CONCRETE	=	305.83 CU M (400 CU YD)
REBAR	=	27.22T (30 TONS)
3) SOIL EXCAVATION VOLUME	=	2,140.78 CU M (2,800 CU YD)

Figure 4-47. Pilot Plant Steel Receiver Tower

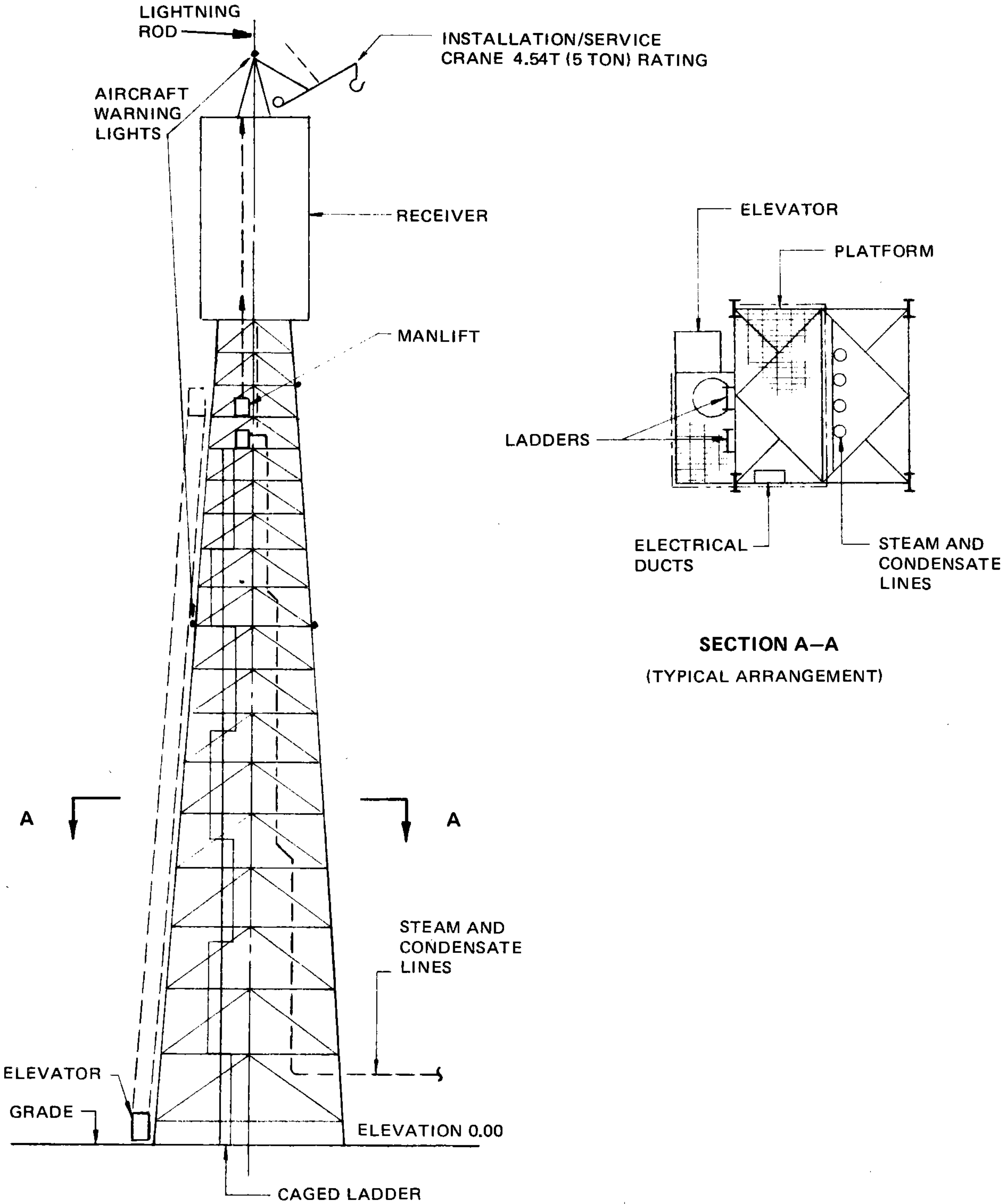


Figure 4-48. Pilot Plant Steel Receiver Tower with Auxiliary Equipment

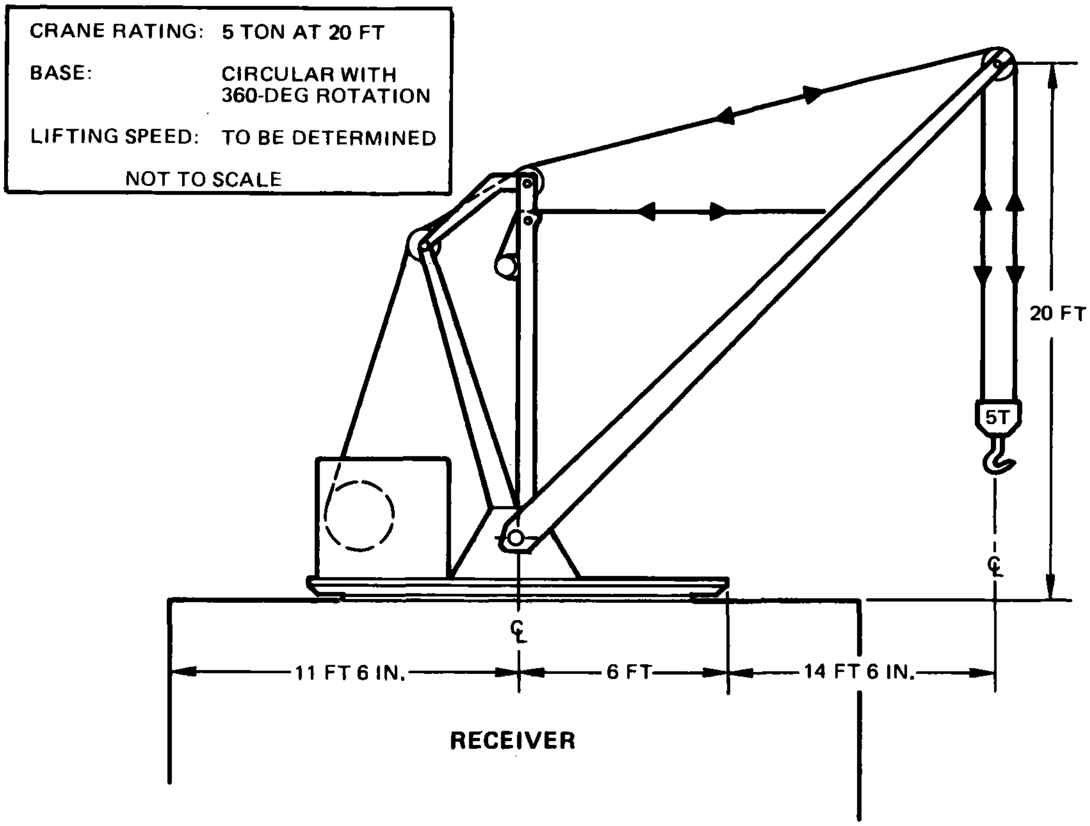


Figure 4-49. Pilot Plant Installation/Service Crane

Aircraft Obstruction Lights

Aircraft obstruction lights will be located at the highest point of the receiver structure and on the tower structure in accordance with FAA regulations. White, high-intensity obstruction lights will be provided. Safe access will be provided to each obstruction light to facilitate maintenance.

Lightning Protection

Lightning protection is provided by an air terminal at the top of the receiver structure. The air terminal will be grounded to a counterpose at the base of the tower by two 1/0 bare copper cables. The counterpoise will consist of a loop around the base of the tower of 1/0 bare copper cable. The counterpoise will be connected to ground rods or be extended as required by soil conditions. The counterpoise will be interconnected with the plant and heliostat field ground grid.

Cables, terminals, and equipment have 600V insulation which is tested for breakdown with 2, 200V AC for 1 min. The resulting impulse voltage capability is at least double or 4, 400V. If a stroke occurs to the tower, a voltage considerably higher than 4, 400 may be expected. Therefore, surge protection (arresters) are recommended on all leads to the receiver. Surge arresters may momentarily interrupt (ground) the circuit, but this should not interfere with satisfactory operation.

Access Platforms and Guard Rail

Access platforms and guard rail will be provided for maintenance and repair of the receiver components, pipe supports, instrumentation, valves, lights, service crane, etc., as required, and in accordance with CAL-OSHA regulations.

Lighting

Lighting will be provided as required at grade elevation and in the tower at the various access and operating platforms. Convenience outlets (115V AC, single phase) will also be provided for small tools and convenience lighting.

Piping and Conduit Supports

Miscellaneous steel will be provided for supporting piping and electrical power, control and instrumentation conduits, as required.

Alternate Concrete Tower Description

As shown in Figure 4-50, the concrete tower developed in the preliminary design studies extends approximately 65m (213 ft) above grade. The top of the concrete has an OD of 4.3m (14 ft) with a nominal 0.305m (12 in.) wall thickness. The base of the tower has an OD of 9.1m (30 ft) with a 0.46m (18 in.) wall thickness.

The foundation, which is 3.05m (10 ft) below finished grade, is a 21.3m (70 ft) diameter circular mat. The foundation thickness varies from 1.2m (4 ft) at the outer edge to 2.4m (8 ft) at a distance of 5.2m (17 ft) from the center of the tower. All reinforcement is A615 Grade 60.

4.4 OPERATIONAL CHARACTERISTICS

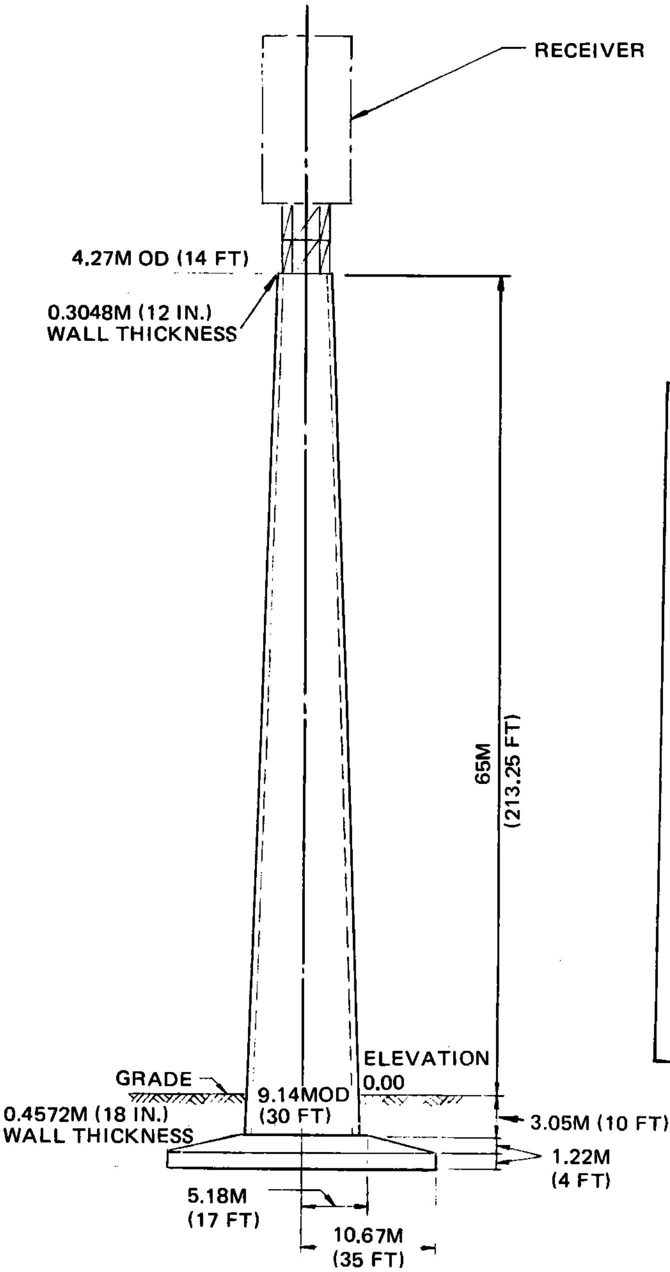
There are eight basic operating modes: prestart, startup, constant steam temperature, transition, clouds, normal shutdown, emergency shutdown, and nighttime operation.

4.4.1 Prestart

Upon receipt of a signal from master control or the operator, the receiver controller initiates a series of prestart receiver checks. Electrical signals representative of out-of-normal operating conditions are sent to the various alarm and shutdown circuits to verify their effectiveness. A signal is sent to each of the boiler valves commanding each valve to a specific position. Transducers on each valve signal the actual position back to the controller where it is compared with the referencing signal for accuracy. Any negative results of the above checks are communicated to master control, otherwise a "ready-to-start" signal is sent to master control.

4.4.2 Startup

It will be assumed that under normal conditions the receiver will stand by overnight with the receiver downcomer steam inlet valve (RDSIV) closed and the receiver unit filled with water, circulating if necessary as described in Section 4.4.8. Upon receipt of the "start" signal from master control, the receiver controller signals the following events. The receiver recirculation valve (RWBV) is closed. The flash tank drain valve (RFDV) is opened and the receiver back pressure valve set to maintain a value of 2.91 MPa (423 psia).



MATERIAL QUANTITIES

1) CONCRETE TOWER
   CONCRETE = 528.31 CU M (691 CU YD)
   REBAR = 53.43T (58.9 TON)

2) FOUNDATION MATERIALS
   CONCRETE = 685.81 CU M (897 CU YD)
   REBAR = 32.48T (35.8 TON)

3) SOIL EXCAVATION
   VOLUME = 3,580.45 CU M (4,683 CU YD)

NOTES:

1) MIN CONCRETE STRENGTH SHALL BE 27.6 MPa (4,000 PSI) COMPRESSIVE STRENGTH AT 28 DAYS

2) REINFORCING BARS SHALL BE NEW INTERMEDIATE GRADE DEFORMED BARS WHICH SHALL CONFORM TO ASTM 615 GRADE 60

Figure 4-50. Pilot Plant Concrete Receiver Tower (Alternate)

The receiver feedwater pumps are commanded to provide a receiver inlet pressure of 3.45 MPa (500 psia). Each boiler temperature control valve is signaled to a position which will provide a predetermined flow rate at the above pressure levels. Flow is initiated with the temperature control valves commanded to a fixed position to minimize transients which would occur if the control loop were closed initially. The commanded position is that which, together with the other component resistances and the specific inlet and outlet pressures, will provide approximately the desired flowrate for the next phase.

After obtaining a satisfactory comparison of the predicted and the measured individual boiler flows, controls are commanded to provide a specific flowrate to each boiler. (The reason for the specific backpressure and various flowrate set points is discussed in the following paragraphs.) The purposes of this phase are: (1) to initiate closed-loop control of the temperature control valves, and (2) to heat the panel and associated components to the inlet water temperature prior to solar heating. The flow and temperature control logic for temperature control valves are interrelated so that a specific flowrate set point is commanded subject to the overriding command that the steam discharge temperature may not exceed 260°C (500°F). With no external heating and an inlet temperature of approximately 93°C (200°F), the flowrate set point prevails.

At this point, a signal is sent to master control that the receiver is ready for solar radiation. The purpose of this phase is to limit the temperature of the steam effluent to 260°C (500°F) during the first approximately 20-min sunlight period and to control the start transient with water, two-phase, and steam effluents. The control set points are maintained as in the previous phase.

Different panels on the receiver receive different solar energy levels. These transient heat loads can be predicted and the fixed flowrates which were set for each panel in the previous phases on a given day or month are those which will result in approximately 260°C (500°F) steam in all panels approximately 20 min after the heliostats are slewed onto the receiver.

The back pressure control valve will be set to provide a pressure of 2.91 MPa (423 psia) for two reasons. First, this pressure prevents vaporization of the inlet water during start-up to maximize the heating effect on the components. Furthermore, the saturation temperature which corresponds to 2.91 MPa (423 psia) is 232°C (450°F), which provides for 28°C (50°F) superheat at the end of this phase. As the panels are heated, the temperature of the effluent from each panel will rise from the initial temperature of 93°C (200°F) to 232°C (450°F) and remain at this value while the quality of the steam varies from 0 to 100%. This small temperature rise will prevent thermal shocking of the steam system components.

The panels with the highest heat loads will produce 100% quality effluent first. The effluent temperature will subsequently rise until the commanded 260°C (500°F) limit is reached, at which time the temperature control valves will operate to maintain this temperature. The difference between this temperature and that of the least heated panels (which will be at 232°C (450°F) at that time) is small enough to preclude significant thermal strains, and to eliminate problems which might occur in the nonequilibrium of flow of liquid in a highly superheated gas stream. The total rise (from 93°C (200°F) to 232°C (500°F) in 20 min should be sufficiently slow to avoid thermal shocking of the steam system components.

Preheat steam flow to the main receiver steam downcomer will begin through the flash tank downcomer steam warmup valve (RDSWV) when system temperatures and pressures ensure good quality steam flow.

When the effluent temperature of all of the boilers has reached 232°C (500°F), the receiver controller commands the set point of all the boilers to 349°C (660°F). When the effluent temperatures of all of the panels have reached 349°C (660°F), and the main steam downcomer temperatures are acceptable, the back pressure control valve set point is ramped to the nominal operating pressure of 10.45 MPa (1,515 psia) and steam flow is begun through the main downcomer steam inlet valve (RDSIV). By delaying the ramping of the pressure set point until this time, the sequence assures continuous production of superheated steam into the downcomer.

This start sequence has been accomplished during the SRE and smooth transition was demonstrated through the various phases. The set points for temperature and pressure were actually stepped during the SRE with temperature overshoots of less than 30°C (50°F). This step-type sequencing will result in transients in the order of 3 to 20 min, depending on the heat flux level at which the sequence takes place. When the temperature of the effluent from each of the boilers has stabilized at 349°C (660°F), the pressure at 10.4 MPa (1,515 psia), and the level indicator in the receiver moisture trap indicates that no liquid water is being carried over, the startup phase is concluded and a status report is sent to master control.

4.4.3 Constant Steam Temperature

Production of derated steam continues with the flow to the boilers increasing as insolation increases during the day.

4.4.4 Transition

The receiver controller directs a change in the set points simultaneously to each of the boiler temperature controllers to 516°C (960°F) upon receipt of a command from master controller. During the SRE, a step change in the command signal again resulted in overshoots of less than 30°C (50°F). However, thermal shock considerations for the remainder of the plant may dictate that a ramp change from one set point to another be effected.

4.4.5 Clouds

With static clouds which form fairly uniformly and do not restrict the thermal input to values below ~25% of the maximum solar input, the receiver control system will remain in normal operation. As the cloud density increases, the receiver controller will reduce the amount of water flowing through the receiver in a manner which will maintain a rated receiver outlet temperature as long as possible to supply the turbine. When reduced insolation no longer permits rated output conditions, the total receiver flow will be directed to thermal storage and, if cloud conditions are stable, the receiver will be switched to derated operation to eliminate the heat loss due to desuperheater (DSH) operation.

To avoid imposing transient steam input conditions on the turbine under conditions where a fast-moving cloud front of fairly high density is approaching, turbine steam demand will again be totally assumed by the thermal storage steam generators and receiver output flow will be directed to charging thermal storage. If the peak (noncloud cover) solar energy is high, selected heliostats will be stowed if necessary to avoid exceeding thermal storage charging limitations. Even though all receiver output will be directed to thermal storage, the receiver steam output temperature control set point will remain at the rated level of 516°C (960°F) to permit large swings in outlet temperature without losing superheat conditions. When cloud conditions no longer permit receiver output conditions to stay above the superheat line, the receiver will be shut down.

Startup after a passing cloud cover will follow the normal startup procedure, except that, if the start occurs under conditions of high solar insolation, the heliostats may have to be slewed onto the receiver over a longer time period to avoid thermal shocking of the system.

4.4.6 Normal Shutdown

The purpose of this phase is to provide a controlled shutdown which will avoid thermal shocking of the components or ingestion of water into the downcomer. This mode is usually initiated from the derated steaming condition. The derated steam temperature set point is maintained and the flow to each panel decreases as the heliostats are sequentially slewed away from the receiver and the energy level decreases.

When the insolation energy onto the receiver approaches the point where the lowest power panel is unable to maintain 349°C (660°F) outlet conditions at 10.45 MPa (1,515 psia), receiver pressure will begin a controlled reduction to 2.91 MPa (423 psia). In a coordinated manner the receiver downcomer steam inlet valve will close and the receiver flash tank inlet valve (RFIV) will begin to open, diverting all receiver flow to the flash tank before the first panel begins to discharge two-phase fluid. As insolation energy continues to drop, all receiver boiler panel control valves will eventually reach their minimum flow positions and the receiver will fill with subcooled water and enter the nighttime phase described in Section 4.4.8. Filling the receiver unit with water has been chosen for night standby to prevent oxygen intrusion and to eliminate the procedural steps necessary to remove an inert blanketing gas from the system during the next day's startup. However, if gas blanketing of the receiver unit were desired, nitrogen purge provisions exist to permit this option.

4.4.7 Abnormal Operation/Emergencies

In the event of abnormal operation of the receiver as indicated by low or high flowrates, pressures, temperatures, etc., the receiver control system must first detect the abnormality and alert the plant operator. The operational monitoring system will be designed wherever possible so that the operator will be warned about non-nominal conditions sufficiently in advance to permit him to take corrective action and prevent trip-off of the receiver. If operator or master control remedial actions cannot resolve the problem before actual trip limits are exceeded, the control system will automatically function to protect the receiver subsystem while not imposing excessive conditions on interfacing subsystems.

Since trip signals tend to occur in bunches due to the cascade effect of the system shutdown on other parameters, the monitoring system will be designed to discriminate and record the actual sequence of events for diagnostic purposes.

The receiver contains multiple control sensors at critical control points. For example, each boiler panel outlet temperature is monitored by two thermocouples. One thermocouple normally sends its signal to the receiver controller and is used for normal control. The second temperature sensor is located close to the first and is normally used to actuate the alarms. Its wiring is separated from the wiring of the first thermocouple but also goes to the control room where an operator can manually select either of the two temperatures to use to direct the control valve.

Typical conditions which could result in emergency shutdowns are: a loss of receiver water at the inlet, a large leak in the receiver, failure of one or more of the boiler temperature control valves, or significant loss of incident radiation through heliostat failure or unexpected cloud cover. These failures result in two basic types of conditions: too little water with high-intensity insolation which could thermally damage components; or too much water at reduced insolation which could cause carryover of water into the downcomer. Emergency procedures are initiated which would rapidly protect both the downstream components and the receiver components without requiring diagnosis of the particular failure mode. The receiver trip procedure is to (1) immediately begin emergency slewing of the heliostats off the receiver to remove the heat, (2) when the receiver flow has dropped sufficiently, open the receiver flash tank inlet valve (RFIV), and (3) close the receiver downcomer steam valve to prevent water ingestion into the downcomer. If panel temperatures continue to rise due to loss of water, the receiver steam vent valve (RSVV) and the receiver boiler temperature control valves (RVTCV) are opened to vent the pressure in the receiver and maximize receiver flow to cool the panels. The receiver components thus affected are sufficiently lightweight that no danger of thermal shocking exists from this procedure.

Component redundancy, backup power, and filtration are provided in the system design to eliminate loss of water flow to the receiver as a credible failure. Nevertheless, a "maximum credible incident" analysis was made assuming a sudden and total loss of coolant water to the receiver during maximum power operation to determine the time within which emergency protective systems would be required to function to protect the receiver from damage (see Section 4.3.2.2). Since defocusing of the heliostats from the receiver is probably the slowest of the possible protective actions, the analysis investigated the impact of the high heat flux during the time lag of the mirror control system. The emergency slew rate of the heliostat field was found sufficient to protect the receiver even in the event of a complete and instantaneous loss of water.

For the case where the mirrors are not slewed (constant heat flux incident of 0.30 MW/m^2, or 0.18 $Btu/in.^2$-sec), the tubing will reach radiative equilibrium of 1,260°C (2,300°F) in approximately 400 sec (0.1 hr); however, catastrophic failure will not occur for 0.7 hr. Evaluation of the predicted values of temperature, together with the creep properties of the material indicate that distortion damage due to creep will be negligible if tube pressure is vented, and relatively small if slew is initiated within minutes after feedwater flow is lost even if pressure is maintained. It should be reemphasized that an RSVV is included in the design to permit emergency venting of the receiver.

4.4.8 Nighttime Operation

During nighttime, hot water is provided to maintain the temperature of the riser and receiver flash tank at approximately 93°C (200°F) to prevent freezing in the receiver unit. One of the boost pumps is used to recirculate heated water up the riser, to the receiver flash tank, down the small drain line from the receiver flash tank, and into the de-aerator.

To prevent excessive thermal losses from the receiver at night (see Section 4.3.2.2), the RWBV is normally fully opened and the RFIV is closed so that circulating water bypasses the receiver panels. If the ambient temperature drops below 10°C (50°F), the flash tank inlet valve is opened, the RWBV is throttled toward closed and the receiver controller is activated with a steam discharge temperature set point of 28°C (37°F) to force warm flow through the receiver panels. The control signals are inverted for this mode of operation with respect to the normal signal condition for daytime. That is, when a panel outlet temperature falls below the set point, the temperature control valve opens. If under conditions of extreme cold and wind any of the temperature control valves reach 80% of their maximum open value, the receiver water bypass valve will be throttled further closed to force more water through the receiver to insure sufficient warming flow.

4.4.9 Receiver Availability

The results of the availability analysis for the receiver is shown in Table 4-16. The receiver components are shown in Figure 4-36. The analysis assumed an operating time of 3,300 hours per year based on an average 10-hr day and 330 days of favorable weather. The failure rates were obtained from standard reference data. The repair time estimates were obtained by considering the time to locate the failed component, waiting time to obtain parts, for the receiver to cool down, etc., time to repair or replace the component, and time to adjust and check out the repaired component.

MCDONNELL DOUGLAS

Table 4-16 (Page 1 of 2)

AVAILABILITY ANALYSIS OF PILOT PLANT RECEIVER

Operation (Hr/Yr)	Item No.	Component	Mean Time Between Failure MTBF (Hr)	Failures/Yr	Mean Time to Repair MTTR (Hr)	Component Failure Outage FO Unavail (Hr/Yr)	Component Planned Outage PO (Hr/Yr)	System Unavail (Hr/Yr)	Comments
3300	RPWDV-1	Manual Valve	250,000	0.01	8.5	0.09	0	0	*
	RPWDV-24	Manual Valve	250,000	0.01	8.5	0.09	0	0	*
	RP	Preheater Panels	62,500	0.32	14	4.5	47	4.5	
	RPWRV-1 -2 -3	Relief Valves	100,000	0.09	9	0.81	0	0.81	
	RWIP-1	Pressure Sensor	1,000,000	0.003	6	0.018	0	0	**
	RWIT-1	Temperature Sensor	1,000,000	0.003	6	0.018	0	0	**
	RPWOP	Pressure Sensor	1,000,000	0.003	6	0.018	0	0	**
	RPWOT	Temperature Sensor	1,000,000	0.003	6	0.018	0	0	**
	RBTC-XX	Temperature Controller	27,400	2.17	6	13.0	0	0	**
	RBSOT-XX-1 -2	Temperature Sensor	1,000,000	0.12	6	0.72	0	0	**
	RBWFR-XX	Flowmeter	83,000	0.71	9	6.39	0	0	**
	RBTCV-XX	Control Valve	24,000	2.5	9	22.5	0	22.5	
	RBWF-XX	Filter	125,000	0.48	9	4.32	0	4.32	

*Not used during operations.
**Control component — non-critical.

Table 4-16 (Page 2 of 2)

AVAILABILITY ANALYSIS OF PILOT PLANT RECEIVER

Operation (Hr/Yr)	Item No.	Component	Mean Time Between Failure MTBF (Hr)	Failures/Hr	Mean Time to Repair MTTR (Hr)	Component Failure Outage FO Unavail (Hr/Yr)	Component Planned Outage PO (Hr/Yr)	System Unavail (Hr/Yr)	Comments
3300	RBWIV-XX	Manual Valve	250,000	0.24	8.5	2.04	0	0	*
	RBWDV-XX	Manual Valve	250,000	0.24	8.5	2.04	0	0	*
	RB	Boiler Panel	62,500	0.96	14	13.44	47	13.44	
	RNPV	Manual Valve	250,000	0.24	8.5	2.04	0	0	*
	RNCK-XX	Check Valve	250,000	0.01	8.5	0.09	0	0	*
	RSRV-1, 2	Relief Valve	100,000	0.07	9	0.63	0	0.63	
	RSVV	Manual Valve	250,000	0.01	8.5	0.09	0	0	*
	RFIV	Control Valve	24,000	0.14	9	1.26	0	1.26	
	RDSIV	Shutoff Valve	24,000	0.14	8.5	1.26	0	1.26	
	RFWDV	Shutoff Valve	24,000	0.14	8.5	1.26	0	1.26	
	RDSCK	Check Valve	250,000	0.01	8.5	0.09	0	0.09	
	RDSWV	Shutoff Valve	24,000	0.14	8.5	1.26	0	1.26	
	RFRV	Relief Valve	100,000	0.03	9	0.27	0	0.27	
	RFWL	Level Sensors	1,000,000	0.003	6	0.018	0	0	**
	RTWL	Level Sensors	1,000,000	0.003	6	0.018	0	0	**
	RFSOP	Pressure Sensors	1,000,000	0.003	6	0.018	0	0	**
	RFSOT	Temperature Sensors	1,000,000	0.003	6	0.018	0	0	**
	RSOP-1	Pressure Sensors	1,000,000	0.003	6	0.018	0	0	**
	RSOT-1	Temperature Sensors	1,000,000	0.003	6	0.018	0	0	
	RWBV	Control Valve	24,000	0.14	9	1.26	0	1.26	
	RWIV	Manual Valve	250,000	0.01	8.5	0.09	0	0	*
	RWISK	Stop Check Valve	250,000	0.01	8.5	0.09	0	0.09	
	RWF-1	Filter	125,000	0.02	6	0.12	0	0.12	
	RWIP-2	Pressure Sensor	1,000,000	0.003	6	0.018	0	0	**

*Not used during operations.
**Control component — non-critical.

The major failure items in the receiver are the 21 control valves with an estimated MTBF of 27,000 hr and predicted failure rate of about three per year. The 18 electronic temperature controllers are next with an estimated MTBF of 27,400 hr and an estimated failure rate of two per year. The preheater and boiler panels are next with a predicted one failure per year.

The calculations of system unavailability assume that if a failure occurs in one of the control valves, a remote shutoff valve, one of the relief valves, a check valve, or a filter on one of the preheater or boiler panels, the receiver must shut down for repair (a forced outage). However, a failure of one of the temperature or pressure sensors or temperature controller will not necessarily require a receiver shutdown. This is consistent with fossil powerplant experience and assumes that manual control of the control valves or an alternate sensor is available and feasible. It is also assumed that the only applicable failure mode of the manual valves is failure to close (or open) when required and thus will not affect system availability. The external (and internal) leak failure mode is neglected.

The results of the receiver availability calculations show a total of 53.07 hours per year of forced outages. It is assumed that if any of the 24 panels have a failure, all panels must shut down. An operating time of 3,300 hours per year results in a forced outage of 1.608%. The planned outages are 47 hours per year, or 1.424%. That figure is consistent with the receiver subsystem availability goal of 96.7%.

5 PILOT PLANT PLANS

Section 5
PILOT PLANT PLANS

This section describes the plans for implementation of the powerplant: the anticipated schedule, and production plan, including procurement, installation checkout and maintenance.

5.1 MASTER SCHEDULE

The master schedule showing the major activity breakouts is shown in Figure 5-1. Design will be complete by the end of 1978 with material procurement starting early that year, principally because of the large amounts of tubing required for the absorber. Informal discussions with Huntington Alloys, Inc., a division of International Nickel Company, have indicated the need for early tubing procurement. Fabrication starts late in 1978 with all absorber panels being delivered to the site by the end of 1979. Field installation and checkout would be complete by the first quarter of 1980.

5.2 PRODUCTION PLAN

This section describes the production plan. Production is defined as procurement, manufacturing, transportation, and quality assurance.

5.2.1 Procurement

Rocketdyne's procurement plan encompasses all purchasing activities required to obtain hardware, equipment, supplies, and services to support program requirements. The plan provides for the coordination with other Rocketdyne functions to ensure the purchase, schedule, quality, and delivery of all items to satisfy all contract requirements.

5.2.1.1 Make or Buy

The Rocketdyne Material Procurement organization has the responsibility and authority to ensure the successful attainment of customer and program objectives.

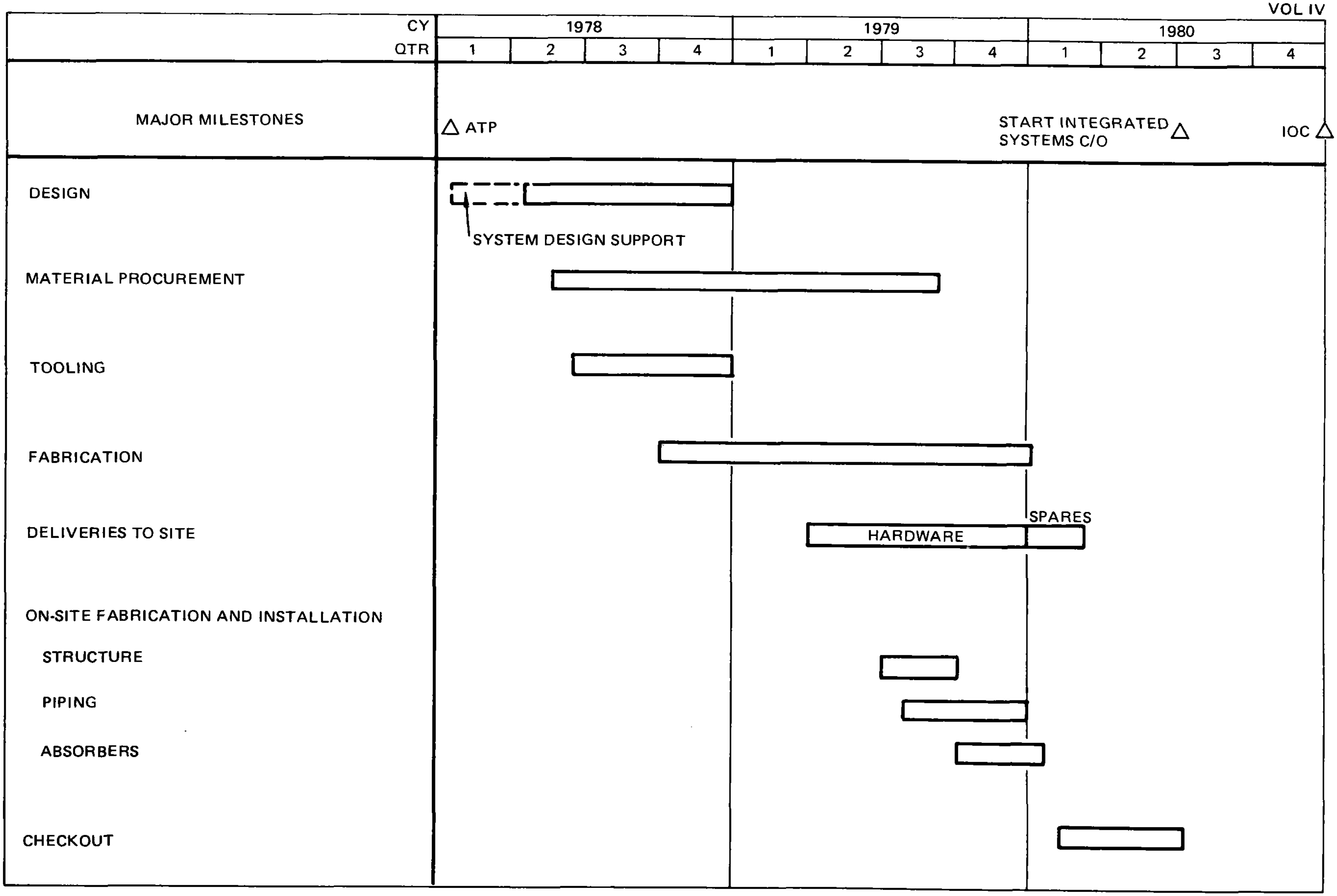


Figure 5-1. Receiver Schedule — Pilot Plant (Page 1 of 2)

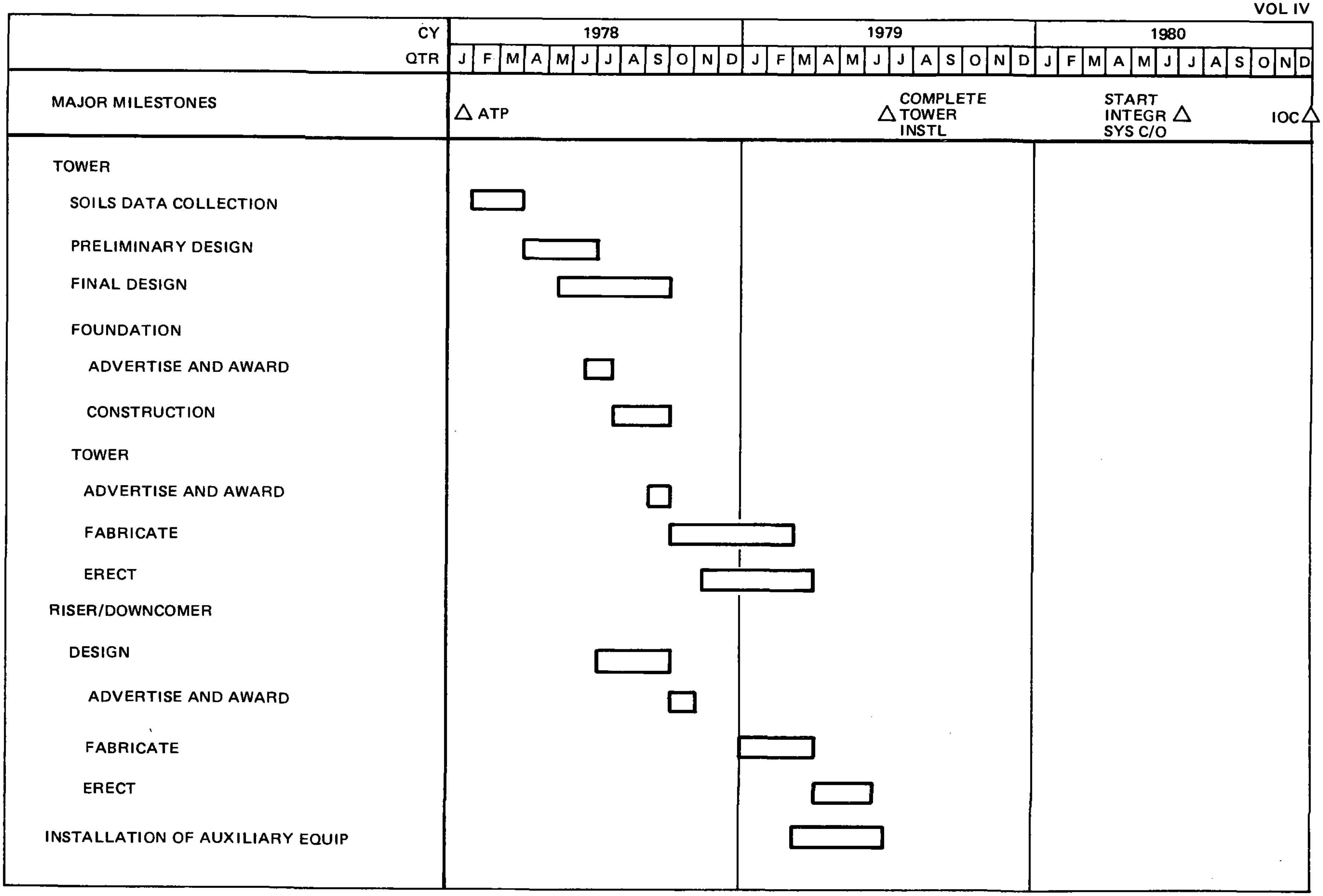


Figure 5-1. Tower — Riser/Downcomer Schedule — Pilot Plant (Page 2 of 2)

The Material Director is responsible for ensuring the procurement of contract requirements in the most efficient and cost-effective manner. Reporting to him is a Purchasing Manager, responsible for buying activity, and a Program Representative, who also reports to the Program Manager and is responsible for interface activities with other company functions.

In support of management are such support functions as material estimating, cost/price analysis, contract review, specification control and supplier distribution, purchase order typing and distribution, central files, supplier claims, receiving, warehousing and issuing material, and traffic operations.

Rocketdyne's policy is to make all purchases on the basis of quality, schedule, and price. Maximum consideration will be given to the Government's small business, minority business, and labor surplus area programs. Under certain circumstances, and in accordance with prime or subcontract requirements, prior approval from the Government may be required prior to placing purchase orders. This approval will be obtained in compliance with the requirements of the contract and permit procurement action to continue.

Sources selected to bid on procurement packages are determined by a continuing program of preaward surveys by Purchasing and Quality Assurance personnel, assisted when necessary by Engineering and Manufacturing personnel. These surveys determine potential source capabilities in facilities, equipment, finances, and desire to perform to Rocketdyne requirements. In addition, Rocketdyne uses a supplier performance rating system. It evaluates previous supplier performances by product category, measuring quality performance, and analyzing delivery performance. Based on these surveys and the rating system, a list of capable and acceptable sources is developed for the various commodities to be procured. The list is the basis for selecting sources to bid on the procurement package. Sufficient sources are maintained on the list to permit adequate and effective competition for award selection.

Once the subcontractor is selected in accordance with the preceding source selection steps, formal technical, management, and business communications are direct between the responsible Rocketdyne Program Representative and/ or Buyer and the subcontractor. All communications are documented, with copies directed to all appropriate and affected functions, both at Rocketdyne and the supplier.

Under the direction of the Purchasing Manager, items of technical, management, or business nature impacting purchase orders will be coordinated with the supplier involved by the responsible buyer assigned that commodity. The buyer will negotiate formal changes and document his file to justify such actions. Liaison personnel are assigned to coordinate and monitor the progress of the supplier to ensure performance.

Information regarding purchase order status, performance, and problems are reported weekly to the Buying Manager. He prepares a weekly report to the Material Director and the Program Representative on the basis of the buyer's report. Thus, the Director, and through him all functional managers, will have sufficient visibility to ensure that procurement objectives are maintained. Upon identification of any problems, the Buying Manager or responsible buyer immediately reviews the situation, considering the supplier's recommendation and its probable impact on the program. Under the guidance of the buyer or Manager, technical assistance from Rocketdyne will be made available to the supplier.

Changes to the subcontract or purchase order work statement require written expression in the subcontract or purchase order. Technical changes will be specified by the responsible Rocketdyne Engineer by release of an Engineering Order. The responsible buyer will negotiate the cost and schedule effect of this change, and process a formal change notice.

In a critical schedule condition, a change may be implemented unilaterally. The change clause calls for purchase order adjustment to be filed with Rocketdyne within 30 days subsequent to the change direction. After the receipt of the supplier proposal, the change is completed within 30 days.

The make-or-buy plan for Rocketdyne is to make in-house the assemblies which best capitalize on Rocketdyne's expertise and economics to fabricate. The insolation absorber panel assemblies and the steam separator assemblies will be make items. All the commercial and specialty hardware such as computers, controls, valves, fittings, and instrumentation will be buy items. The fabrication and erection of the receiver structural steel tower will be buy.

5.2.1.2 Material Purchases

The material purchase plan (parts or minor assemblies not part of the make-or-buy plan) is in accordance with the following:

A. Normal Company Capability. Work performed regularly at Rocketdyne within the scope of its normal capabilities, i.e., ability to effectively perform operations to satisfy contractual obligations.

B. Manufacture Capabilities. Comparison between Rocketdyne and outside sources regarding (1) availability of manufacturing, test, and development facilities, (2) quality, (3) schedule and ability to absorb changes within program limitations, (4) present and future capacity in relation to requirements, and (5) work which is not clearly defined.

C. Technical Capabilities. Comparison between Rocketdyne and outside sources regarding (1) specific product experience and experience of organization and technical concept (simplicity of operation, maintainability, and reliability), (2) present and future capacity in relation to requirements, (3) ability to comply with schedules and absorb changes within program limitations, (4) experience of personnel, (5) availability of adequate test and development facilities, and (6) ability to blend an assigned responsibility into overall program accomplishment.

D. Overall Cost. Includes (1) normal direct and indirect cost to make or buy, including added costs such as transportation, coordination, program delays, added facilities, etc., (2) procurement of individual components vs whole articles, (3) absorbing a temporary workload reduction to retain specialized skills and organization capacities, (4) using existing skills and facilities, and (5) placement of work at sources capable of producing follow-on requirements.

5.2.1.3 Delivery Plan

The delivery plans for all purchased parts and materials is to be shipped by the most economical commercial carrier or by Rocketdyne directly to the fabrication or use site. Generally, limited dimension parts 50 lb or less are shipped by United Parcel. A routing guide will be developed for larger parts when final purchase locations are established.

5.2.2 Manufacturing Plan

This section describes the manufacturing plan and includes the major receiver unit assemblies.

5.2.2.1 Schedule

The schedule for absorber and steam separator fabrication is shown in Figures 5-2 and 5-3, respectively. As such, they are the only major items fabricated in-house. All other items are purchased parts as previously discussed, and will in general be delivered to the factory or to the construction site for assembly.

5.2.2.2 Flow Chart

The manufacturing flow chart is shown in Figure 5-4. The procedure is identical to that used during SRE and as such involves no procedures that have not been performed previously.

5.2.2.3 Absorber Fabrication

The absorber fabrication plan is to fabricate all absorber panels at the Rocketdyne Canoga Park manufacturing facility. Figure 5-4, absorber fabrication flow chart, defines major steps of the manufacturing process. The absorber panels will be complete assemblies pressure-tested, certified by the State Division of Industrial Safety (DIS), and readied for installation in the receiver before delivery. In general, the exact procedure used during SRE will be followed.

The fabrication process begins with the receipt of raw tube stock from the mill. The tubes are booked, formed, and assembled on the automatic welding table for longitudinal seam welds. One of the primary features of the fabrication process is the seam welding between tubes that provides a

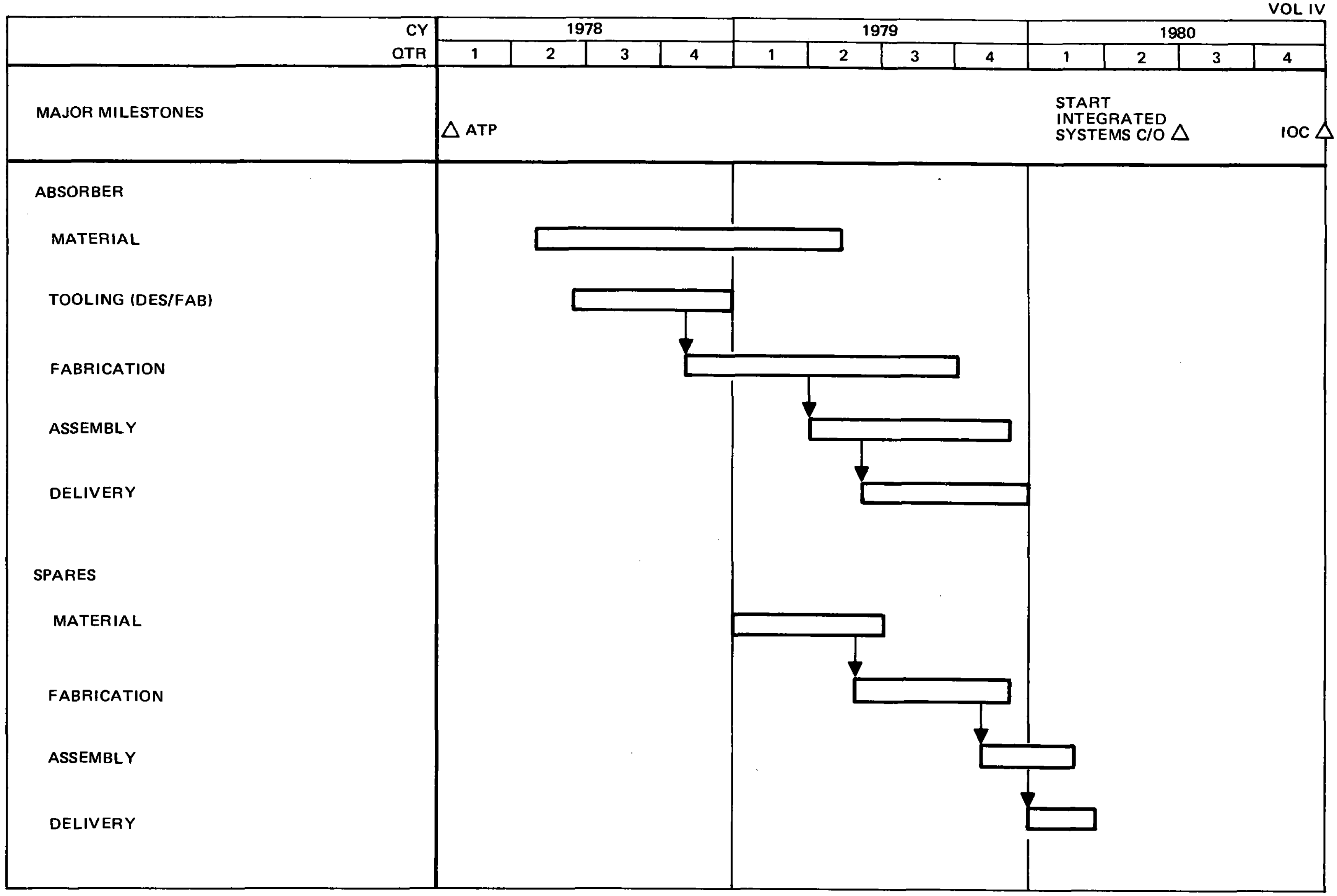


Figure 5-2. Absorber Manufacturing Schedule

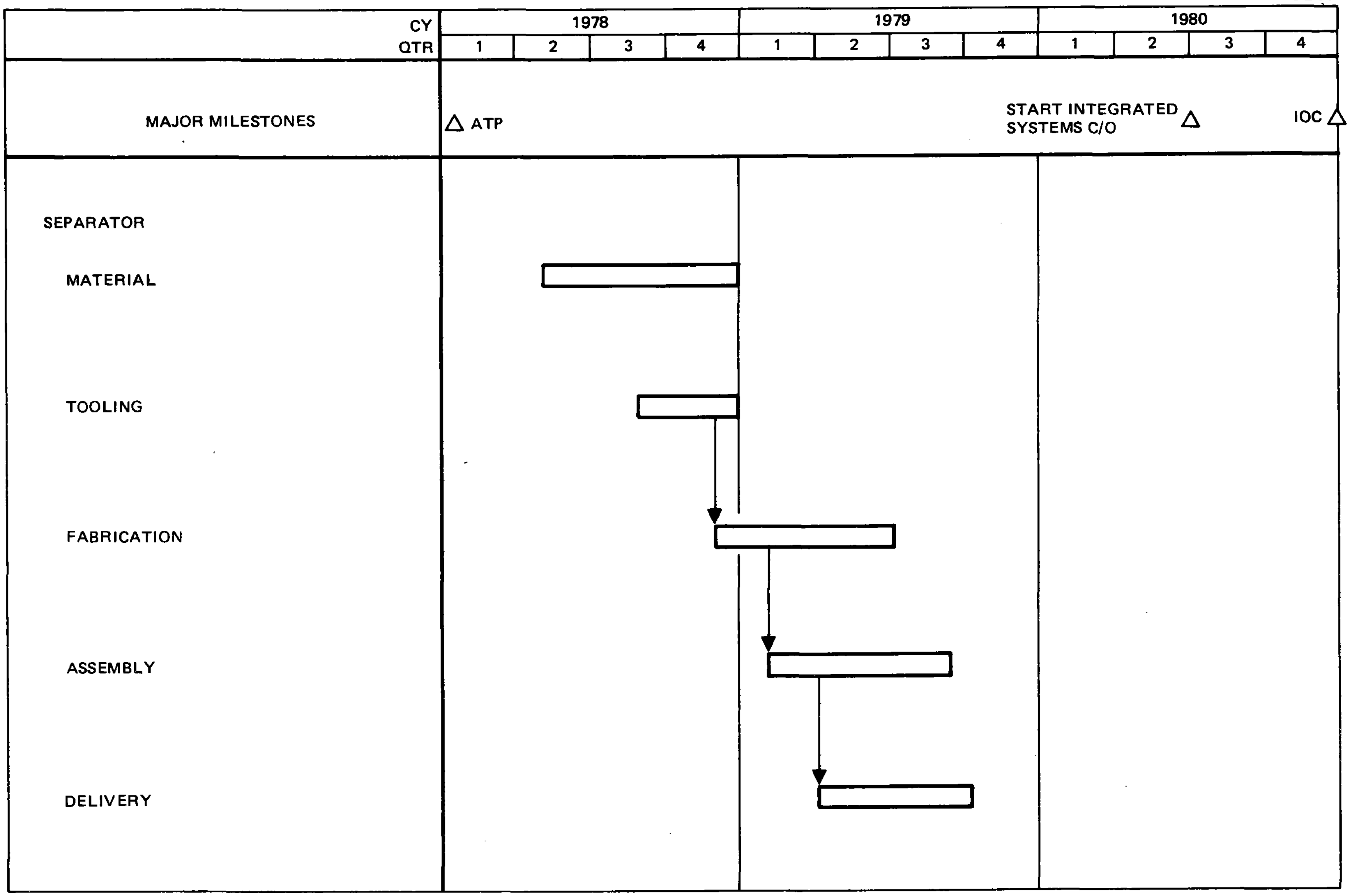


Figure 5-3. Steam Separator Manufacturing Schedule

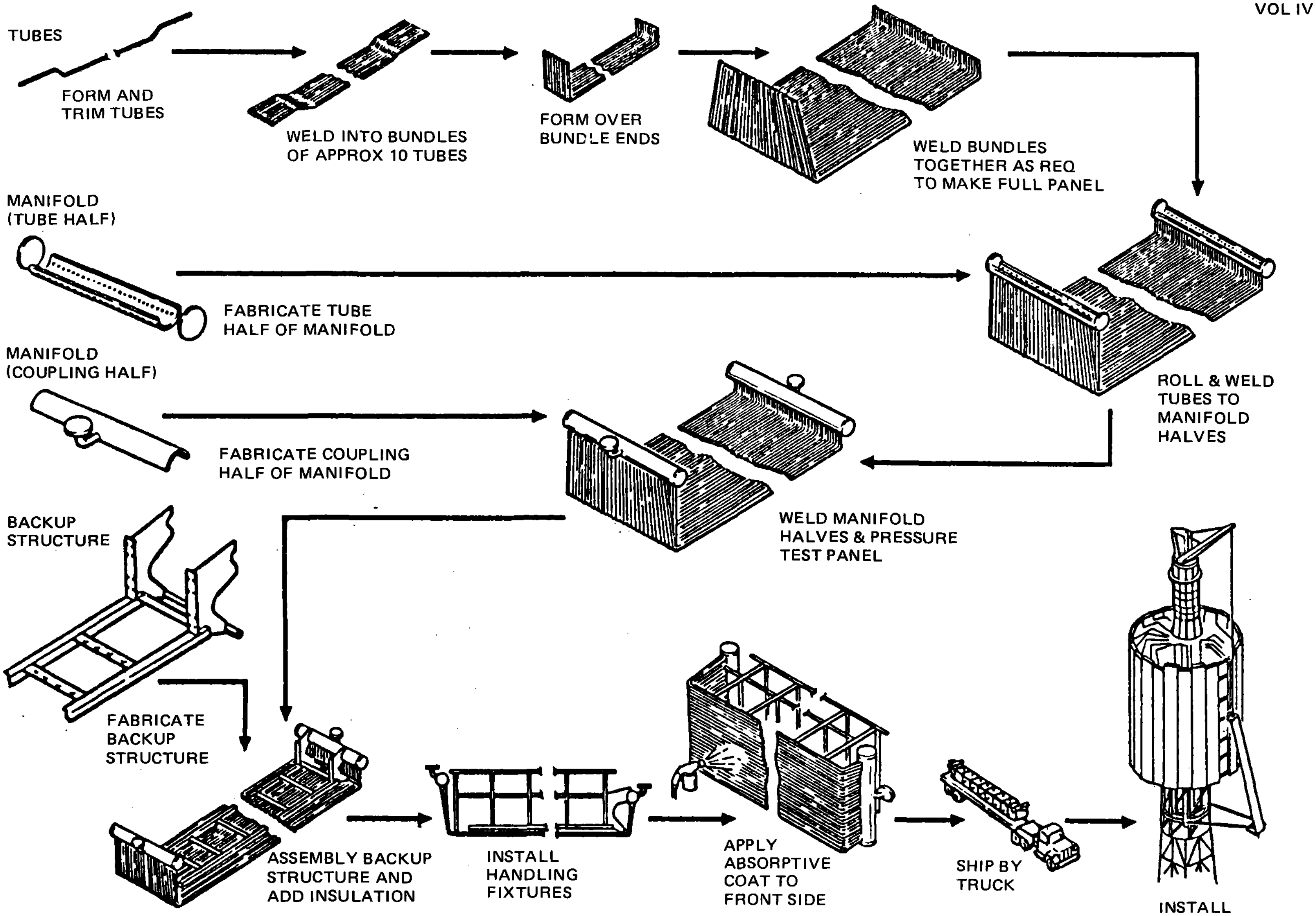


Figure 5-4. Receiver Panel Manufacturing Flow

light-tight seal such that no structure or functional components located within the receiver will be damaged. This weld is performed at 100 cm/min (40 in./min) on an automatically tracked welding table developed for SRE fabrication. The MIG weld head tracks with a wheel which rolls in the tube interstices while the weld wire feeds automatically concurrent with an inert purge which blankets the general area. An excellent quality weld was obtained during SRE when a complete Pilot Plant panel was fabricated. Fourteen panels of five tubes each were joined together in an identical manner to form the full-scale Pilot Plant panel.

Coincident with this operation, the manifold (header) fabrication takes place. Piping is cut in half and holes are drilled in locations wherein the tubes will be seal-welded to the manifold. End caps are machined and welded in place on the half manifold. At this point, the parts are ready for insertion of the tubes into the manifold and subsequent seal-welding. The tube-to-manifold joints are then made. The process starts with insertion of a tube or tubes into the drilled hole in the manifold. A special-purpose forming tool forms the tube around the hole such that a structurally sound mechanical joint exists. The joint is then sealed with a filet weld around the joint. This particular joint arrangement was used during SRE. The joint was approved for use in the receiver by the DIS. The approval was based on a test in which samples of the joint were pulled in tension to failure. The requirement was that the tube fail before the joint. On this basis, the state inspector approved the joint for use in the boiler. The identical fabrication procedure will be used for the Pilot Plant as was used during SRE.

Once the half manifolds are on and the tubes are welded in place, the manifold covers are installed. These are welded in using two weld passes, a root pass and a cover pass. The absorber assembly at this point is complete insofar as the fluid passages are concerned. The next procedure involves attachment of the backup structure. The clips are welded to the back side of the tubes and the primary support structure attached in place. The primary structure allows longitudinal expansion of the tubes during heated operation. A secondary structure which allows interface to the main receiver support structure is next attached. All these procedures were used during SRE. The final step in absorber fabrication is the application of the Pyromark paint, which does not require heat for drying. The paint is applied subsequent to sandblasting, which increases the surface area and makes paint adhere better. After the paint dries, the completed absorber assembly is mounted on a flatbed truck and transported to the field site by commercial carrier.

The quality assurance plan is discussed in Section 5.2.5. Because quality assurance is an on-going process during the manufacturing phase, it will be mentioned here to indicate that certain welds discussed herein are subjected to NDT which may be either dye-penetrant or X-ray. Many of the results of NDT are evaluated by the state inspector prior to performance of the next step in the fabrication procedure. As an example, welding of the manifold cover requires X-ray. Subsequent to the root pass, X-rays are taken and evaluated before the cover pass can be made. In a similar manner, the cover pass weld is X-rayed. The longitudinal seam welds joining the tubes are dye-penetrant inspected. The seal welds which are integral with the mechanical tube-to-header joints are not inspected since they are not structural welds. They, however, are carefully checked out during hydrostatic test of the part which requires exposure to 1 1/2 times operating pressure and full inspection for leaks under operating pressure conditions. In case of a leak, the state inspector will not allow the part to proceed to the next step in the manufacturing process until the leak is corrected.

5.2.2.3 Controls Fabrication

The controls fabrication plan includes all feedwater piping, steam piping, valves, and related components. The plan is to fabricate the steam separator at the Rocketdyne Canoga Park manufacturing facility. The assembly will be pressure-tested, certified by the DIS, and delivered to the field site for installation. All other piping and related components will be delivered directly to the field site where they will be spooled on the ground, then erected and welded into place.

5.2.3 Facilities

The production of the Pilot Plant receiver requires a leased facility primarily for fabrication of absorber panel assemblies. The facility will be capable of accomplishing tube forming, tube bundle welding, manifold welding, as well as all NDT procedures, including X-ray. Capability will include facilities for complete fabrication of the backup structure, final assembly and hydrostatic pressure test of the panels and application of the Pyromark coating. The equipment included is as follows:

A. Leasehold Improvements (Dock, Floor Preparation, Painting, Racks, Bins)
B. Tube Storage Racks
C. Structure Storage Racks
D. Backup Structure Fabrication and Assembly Table, Weld Machinery
E. Tube Preparation and Assembly Table
F. Tube Bending Table
G. Automatic MIG Weld Unit (two)
H. Hydrostatic Test Bench and Cell
I. Grit Blasting and Electrostatic Painting Cell
J. Clip and Manifold Weld Machine
K. X-ray Equipment and Enclosures
L. X-ray Processing Facility
M. Overhead Bridge Crane
N. Ten-Ton Fixture
O. Weld Station Shielding
P. Engineering and Manufacturing Support Office Areas

5.2.4 Transportation

Transportation of all hardware items to the Pilot Plant site will be by common carrier. During SRE a complete Pilot Plant panel was fabricated in-house and delivered by common carrier on a flatbed truck to the test facility some 40 mi from Rocketdyne. The delivery was made at mid-day without traffic problems. In view of this and the similar nature of the Pilot Plant hardware, no special provisions for transportation are necessary. The absorber, which is the largest single item, will simply be placed on a flatbed truck two at a time and delivered to the Pilot Plant site.

All structural steel valves, etc., that will be delivered directly to the site will be similarly carried by common carrier. It is anticipated that none of the hardware items required in the Pilot Plant will exceed the size of the absorber panel. It was found during the SRE that no special provisions for handling are necessary for the absorber and that procurement of the transportation services will simply be done by using standard commercial practice.

5.2.5 Quality Assurance

5.2.5.1 Supplier

Quality Assurance at supplier facilities is generally handled by the suppliers themselves. In general, only those firms who can deliver hardware items to ASME or ASTM specifications will be used. Piping, for example, must be delivered to ANSI specifications, whereas a structural steel must be delivered to meet AISC requirements. Therefore, quality assurance at suppliers will be handled by dealing only with those firms who can deliver hardware items to required specifications. This holds for both raw material purchases as well as for finished parts.

In those instances wherein services are being purchased, i.e., construction, only those firms who hold authorization to perform those types of construction will be used. For example, if an assembly has to be fabricated to Section VIII of the ASME boiler code, then only firms holding such authorization (U stamp) will be considered.

5.2.5.2 Receiving

All parts that come into Rocketdyne are subjected to receiving inspection procedures. These generally require that the paperwork, certifications, etc. accompanying the part or raw material be checked against the purchase order issued by Rocketdyne to procure the part. The specifications or drawings to which the part or raw material is purchased are checked against certifications accompanying the part. Only in cases where items agree will the part be accepted by receiving inspection and sent to the shop for use in the fabrication process. In the case of Section I type boilers fabricated under the ASME code, the State Department of Industrial Safety also must approve all parts and materials received from external sources prior to being used in the fabrication process. As previously mentioned, all parts and materials are bought to a specification or drawing which calls out the particular ASME, ASTM, or other specification to which the part must adhere. Receiving inspection confirms this adherence.

5.2.5.3 In Process

Quality Assurance in-house is performed during the normal fabrication process. Subsequent to design release of any hardware, it is Rocketdyne policy that in addition to the manufacturing planning tickets being written, inspection points be included and the planning approved by Quality Engineering to ensure the proper quality performance and safety. Additionally, the planning paperwork is submitted to the Inspector from the DIS for his signature and inclusion of inspections that he desires to witness or monitor prior to performing the next fabrication step. This, in fact, was done during the SRE program for the completion of both 5-tube panel and the Pilot Plant panel. In the case of the Pilot Plant, the procedure will simply be repeated many times over on a production basis. Examples are: welds of the water and steam headers, welding of tube-to-header joints, and tube-to-tube welds. Depending on the nature of the weld and code requirements which might call for X-ray or dye-penetrant inspection, the state inspector will not allow further steps to be taken prior to his approval of the nondestructive testing results. Rocketdyne has issued, as approved by the DIS, an extensive Quality Assurance manual designed specifically for adherence to Section I of the ASME boiler code. The QA manual is the authoritative document for defining procedural requirements for maintaining the controlled manufacturing system that ensures compliance with code requirements. The Director of Assurance Management has the responsibility and authority for ensuring compliance with the manual, identifying quality control problems, and initiating and recommending and assuring solutions to these problems. He has been authorized by the President of the company to comply with the system defined in the QA manual. The system cannot be changed without agreement by the ASME code authorized inspector. This manual has been used during SRE and it has been approved by the DIS.

5.2.5.4 Acceptance

Final acceptance of the receiver will be made up of two areas. In-house acceptance will be provided by the inspector from the DIS. The acceptance actually is a continual on-going following of the manufacturing and QA plans set forth in the overall manufacturing plan which has been approved by the state inspector. Upon completion of all steps, all parts of the receiver will be pressure-tested to 1 1/2 times operating pressure and carefully checked for leaks at operating pressure. Upon passing of this pressure test, the inspector accepts the hardware as meeting all requirements of the code and drawings. Field inspection of the total receiver assembly in the Pilot Plant will be done in the same way by the inspector who will inspect for leaks under hydrostatic pressure conditions and supervise applicable NDT previously described.

5.3 INSTALLATION AND CHECKOUT

5.3.1 Schedule

The installation and checkout schedule for the receiver is shown in Figure 5-5. Initial structure assembly will be accomplished during mid-1979 followed by installation of all plumbing and controls. The absorber panels will be installed in early 1980 following completion of the controls. By the end of the first quarter of 1980, checkout will be complete.

5.3.2 Installation

5.3.2.1 Structure

The structure installation plan is to start erection at the completion of the base tower. It is planned to use the base tower erection crane and equipment to erect the receiver structure which consists of welded assemblies which will be fabricated on the ground. These assemblies are then bolted together upon installation.

5.3.2.2 Absorbers

The absorber installation plan is to install the panels at completion of the piping installation. The base tower construction crane will be used for this operation. The installation method is identical to that described in the commercial system installation and as shown on Pages 1 and 2 of Figure 5-6. It is, interestingly enough, similar to the technique used during SRE when the Pilot Plant panel was installed in the test tower at the El Segundo test facility.

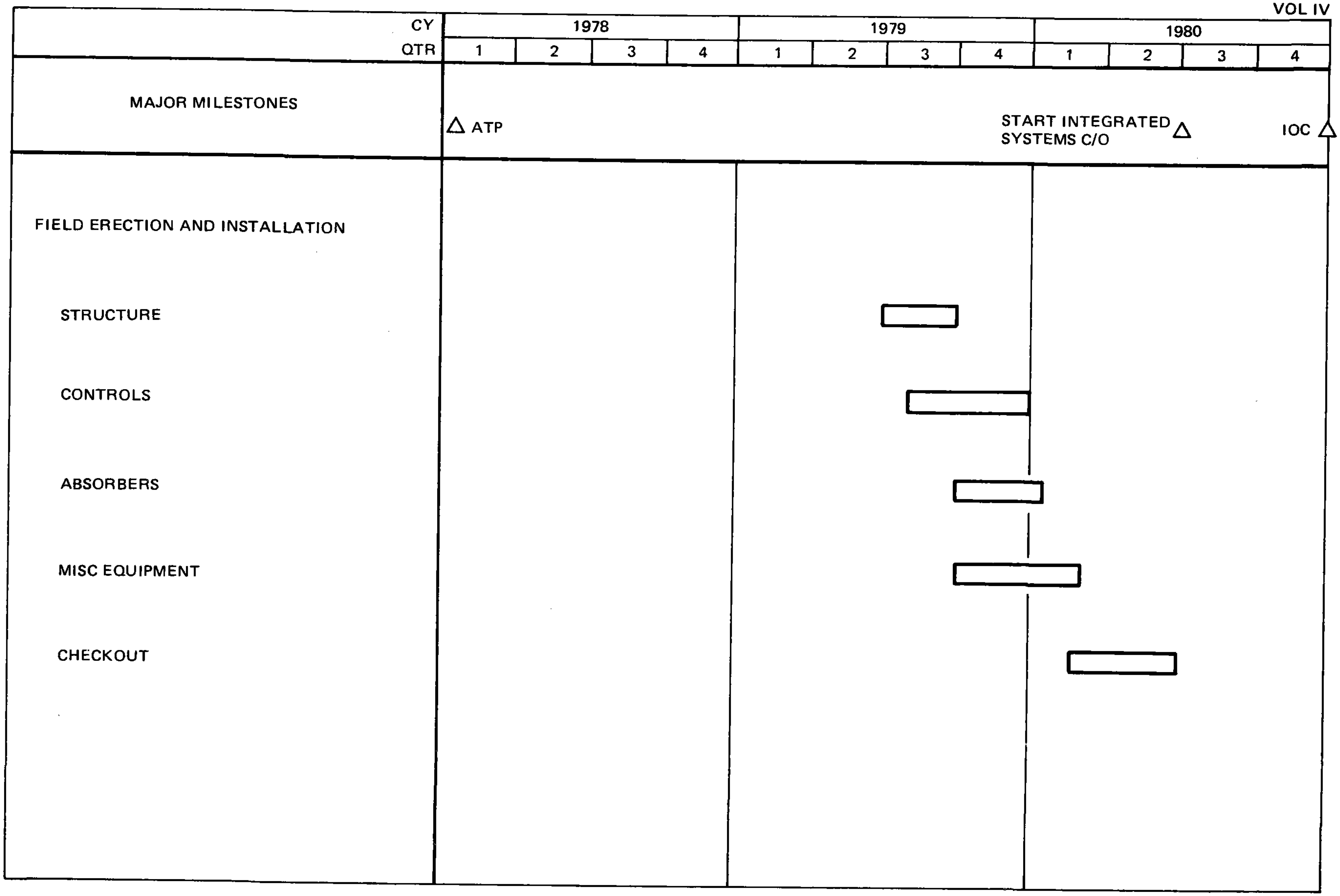


Figure 5-5. Installation and Checkout Schedule

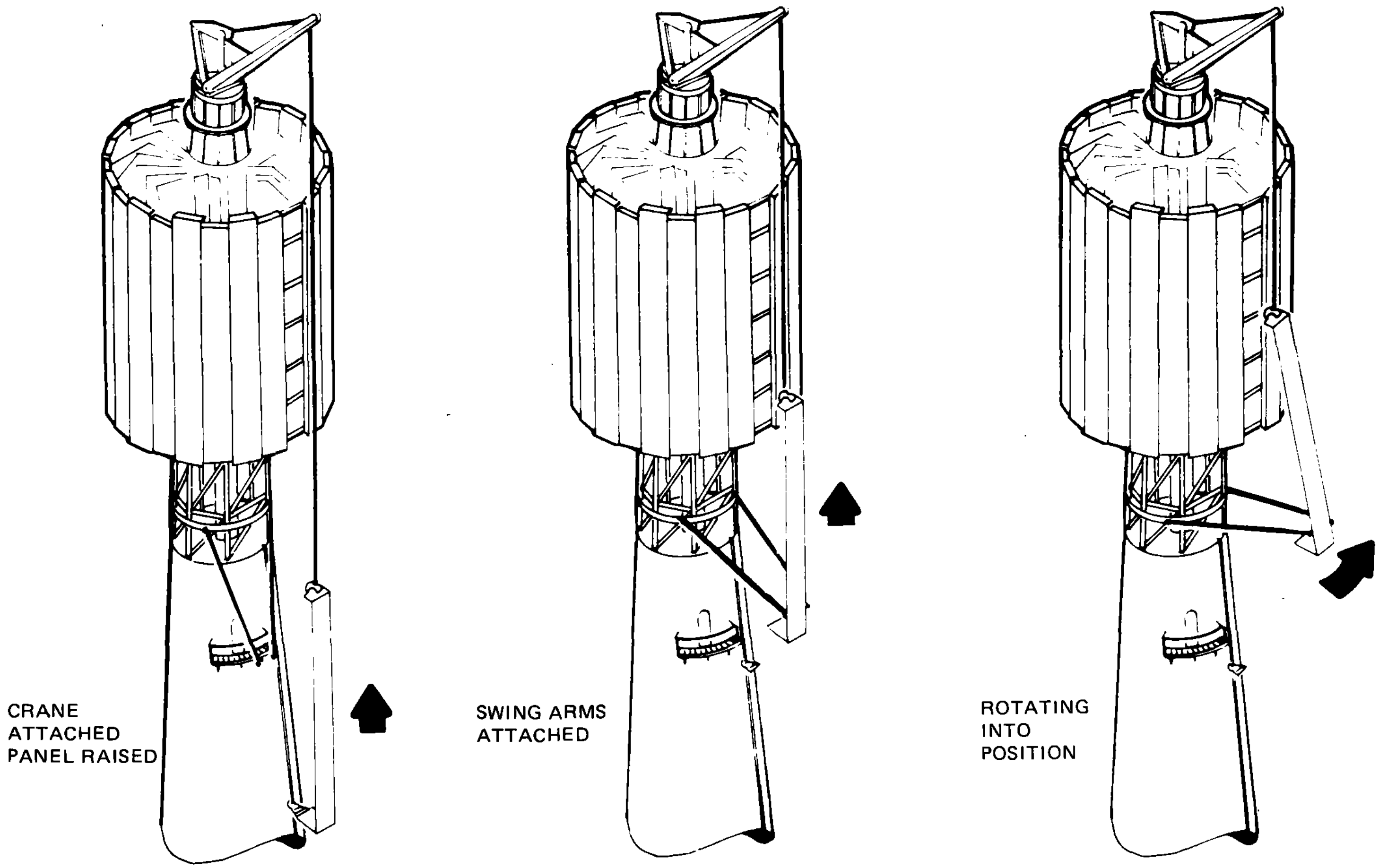


Figure 5-6. Panel Installation – Part 1 (Page 1 of 2)

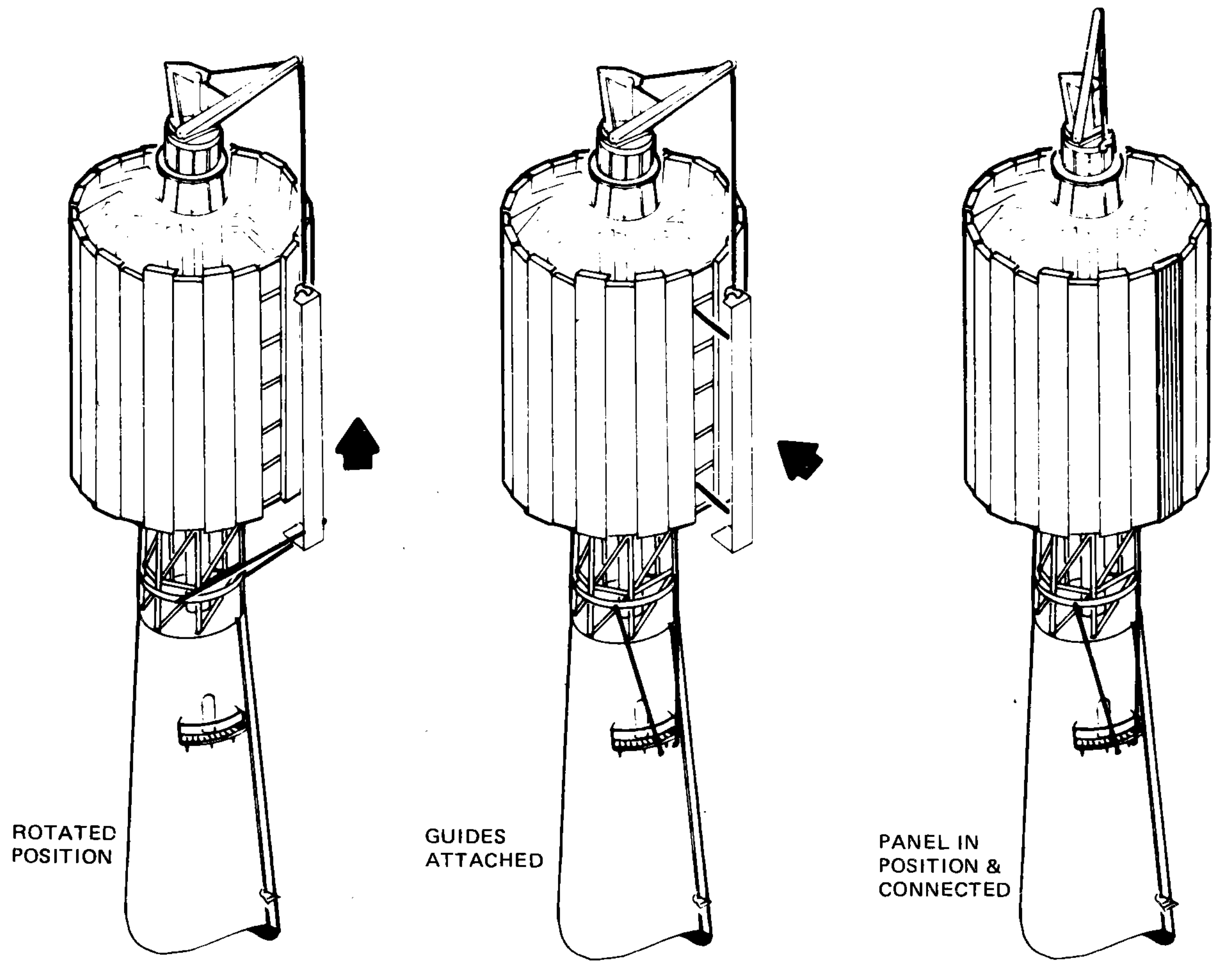


Figure 5-6. Panel Installation – Part 2 (Page 2 of 2)

5.3.2.3 Controls

The piping and controls installation plan is to start erection at the completion of the receiver structure. Spooled sections fabricated on the ground will be raised, using the base tower construction crane, and welded into place. All the miscellaneous equipment will be installed during the controls and absorber installation period.

5.3.3 Checkout Phase

The checkout phase covers the period 15 February 1980 until the beginning of the 2-yr development program on 1 January 1981.

5.3.3.1 Summary

The checkout phase covers the period 15 February 1980 to 1 January 1981 and is divided into two major tasks: Receiver Subsystem Checkout, which occurs during the first half of 1980, and Complete Integrated System Checkout, during the second half of 1980. The receiver checkout phase is further divided into preoperational and operational checkout.

The preoperational checkout period consists of verification of proper connections in the electrical and pneumatic control and power circuits, and (where possible) interconnections to the Master Controller. Preoperational checkout will be accomplished during the same time that the final installations are being completed, and will not interfere with minor changes and adjustments that may carry over from the installations. Preoperational checkout will also include verification of calibration of all mechanical and electrical components that cannot be checked with inline checkout operations. The second part of the checkout phase (operational checkout) will involve operation and verification of the fluid and the water/steam networks. When sufficient thermal energy is available from the heliostat/receiver subsystem, it will be fed to the thermal storage subsystem to verify operation under operational conditions.

The second half of 1980 will involve integrated control and monitoring operations with the Master Control. During the last quarter of 1980, the receiver subsystem will be operated in concert with the total plant, and performance will be fully documented over the complete range of operating variables. At the end of the checkout program, receiver subsystem characteristics, pressures, response times, and operation with both the subsystem controller and master control will be established for all major operating modes.

5.3.3.2 Preoperational Checkout

Preoperational checkout will occur during the first quarter of 1980 and will provide verification that critical control and operational components have been installed correctly and have been calibrated to the necessary flow, pressure, and temperature requirements. A complete record and master list will be kept of the state of calibration and verification of performance for all components. Those components that have had adequate certification will not be rechecked in the laboratory. Components that have questionable certification or that have not been calibrated or certified at the source or prior to installation will be reverified with an engineering laboratory checkout.

On-site checkout will include verification: (1) of all electrical and pneumatic circuit connections, (2) that all records and drawings showing connections are current, and (3) that all terminal box connections are well and properly marked. System checkout will be facilitated by a portable checkout module which will be described later. After circuit verification, power will be selectively applied to all circuits with verification that the appropriate activation occurs. All solenoid valves and pneumatic valves will be actuated. Normal open/normal close position of valves will be verified. Verification will be completed with all circuits, and checkout will include the responses checked at the operator's subsystem console in the control center, as well as interfacing simulating commands and responses with Master Control.

<u>Operational Checkout</u>

Receiver subsystem operational checkout will begin in the second quarter of 1980 and will include activation and control of all fluid networks at ambient temperature and to whatever extent that is possible with the heat that will be available from the collector/receiver portion of the plant.

Operational checkout will begin with verification of the operation of all manual and remote-controlled electropneumatic valves. Valves then will be set to the appropriate positions for the subsequent checkout procedures. During this period, all flanges and joints will be checked for possible leakage.

All temperature controllers and their control valves will be operated over their complete span. All instrumentation will be monitored at this time and readings will be checked against engineering estimates made during the design of the subsystem. Where deviations from performance estimates are large, a diagnostic procedure will be developed to provide insight into the anomalies.

Integrated Subsystem Checkout

Initially, the receiver checkout will interface with the Master Control, and provide signals on all circuits at the subsystem level to check response in the Master Control program. Similarly, signals generated by the Master Control will be monitored at the appropriate component to verify operation as desired. It is assumed that a checkout procedure will be programmed into the Master Control that will enable verification of the operation of all components as predicted. Checkout procedures will include simulated operation of the components with verification determined by audible, visual, or signal detection through the portable checkout module. Complete system operation will be replicated with control transferred back and forth between Master Control and the plant operation. All emergency signals and anomalous statements will be checked and displayed with simulated signals provided by the portable checkout modules.

After checking out and verifying satisfactory operation of the receiver independently and in concert with the Master Control the subsystem will then be placed in operational standby and ready to receive heat at any time. It is anticipated that initial tests will be at partial power which would be an opportune time for thermal storage bed conditioning purposes.

As the energy level increases onto the receiver unit, as well as the remaining other portions of the system, continuous monitoring of the temperature and pressure transducers will occur for verification of operation at elevated temperatures. In addition, daily monitoring of possible water or steam leaks in the system will occur. A complete log will be kept of the operational time of the units that are scheduled for periodic maintenance to provide a prediction of scheduled maintenance. When the energy level in the receiver unit reaches operational range, the system will be checked out over the complete operational heat flow and steam flow band.

As the total Pilot Plant begins to function as an integrated unit, all operational characteristics will be documented and tracked for reproducibility from day to day. Heat losses in the system will be monitored and operational characteristics will be established and included in the operations manual. During the last quarter of 1980 it is expected that the solar thermal power plant will become completely operational and demonstrate all operating modes and operate at the extreme limits as designed. During this period, the operations manual will be updated and will include all operational characteristics of the receiver subsystem. On 1 January 1981 the receiver subsystem will be completely activated and checked out and ready for a 24 hr/day operation and the 2-yr development program.

Portable Checkout Module

The receiver portable checkout module will contain those electrical sensing and power circuits necessary to check out subsystem circuit continuity, monitor signals and provide imitation signals, where necessary, to verify operation of all instrumentation and controls.

In addition, a second module may be included, depending upon the size, to provide and verify pneumatic signals. The receiver subsystem will be designed for rapid access to pneumatic and electrical transducers to facilitate initial checkout as well as subsequent periodic checkout during the life of the plant.

The checkout module will: (1) be capable of simulating signals from all instrumentation sensors to recorders or readout elements, (2) monitor commands by the operator or Master Control, and (3) provide initiation signals as required for operating control components.

Design Requirements

All sensors and checkout points will be identified with a unique coating that will provide instantly recognizable identification. Where possible, the receiver subsystem will be designed with electrical and pneumatic circuits, sensors, relays, junction boxes grouped in such a manner that checkout will be rapid and junction points will be readily identifiable and accessible. The portable modules will be designed to be self-sufficient and will include safety features that will prevent overranging of initiated or received signals where possible. Prior to checkout and periodically during the life of the plant the portable checkout module will be checked completely in the instrument calibration laboratory.

5.4 MAINTENANCE

5.4.1 Schedule

No firm maintenance schedule exists now. A schedule of frequency and type of maintenance will be developed during the checkout, integration, and 2-yr operational test program. The SRE program has demonstrated that the Pyromark paint on the receiver surface will last more than a year and industrial experience with the paint indicates many years of maintenance-free service. Acid flushing of the receiver will probably be necessary once a year; it can be done at night or during cloudy days without impact. Maintenance of electronic equipment is standard procedure and these services are normally purchased at the time the equipment is bought.

5.4.2 Types of Maintenance

Two types of maintenance, preventive and corrective, will naturally be required. The plan is to develop during the operational test phase the type and frequency of preventive maintenance and the type of corrective maintenance required. The types of preventive maintenance expected are painting, cleaning, continuity checks, functional checks, visual inspection, routine or periodic parts replacement and periodic flushing. The types of corrective maintenance expected is part replacement, part servicing or overhaul in place, flushing, and part servicing, repair, and overhaul in shope. All of these types of activities are standard for fluid systems, especially steam generation equipment operated by utilities.

5.4.3 Absorber Maintenance, Preventive

Only two preventive maintenance items are planned for the absorber assembly. The first involves repainting of the external face of the absorber to ensure the high performance discussed herein. This will be accomplished with scaffolding and spraying, identical to the means used during fabrication.

With proper flood-lighting, it is anticipated that a number of panels can be done during the night when the receiver is not in operation. This procedure can also be performed during a cloudy day when the solar system is down. The other preventive maintenance item will be periodic acid flushing of the boiler superheater and preheater panels. This will be performed normally at night or during a cloudy day. In general, neither type of receiver preventive maintenance can be expected to have any impact on completion of the Pilot Plant mission.

5.4.4 Absorber Maintenance, Corrective

Corrective maintenance insofar as the absorber is concerned will be simply to remove an affected panel and replace it. It is anticipated that a panel can be replaced overnight with no effect on the solar plant mission other than downtime immediately subsequent to the failure. Means of removing the panel will be with the crane located on top of the receiver. Removal and installation of a panel in the receiver will be essentially identical for both the Pilot Plant and the commercial receiver (see pages 1 and 2 of Figure 5-6). The only attachments which need to be broken and remade for a removal and installation are the bolted inlet and outlet flanges and the bolts securing the panel backup structure to the main receiver structure. The simplicity of the procedure provides a reasonable confidence that a panel could be changed during a nighttime down period with a zero impact on plant outage. Replacement of panels will be performed to repair or replace damaged tubes or leaks. For this purpose, in general, the panel can be returned to the factory for corrective action; however, some damage may be so slight it can be repaired on site. Tube replacement and/or repair procedures and techniques will be developed during the detailed design and fabrication of the Pilot Plant panels.

5.4.5 Controls Maintenance, Preventive

Controls maintenance is concerned with two areas: mechanical and electronic parts. Most electronic equipment is maintained routinely by the equipment supplier, normally monthly but in certain instances biweekly. This activity will be done at night with no impact to the Pilot Plant mission. Things normally done include replacement of transistors, continuity checks, and checks of computer logic. This is normal procedure in the process control industry.

Mechanical parts that will be maintained on a regular basis are the filters upstream of the absorber panels. The preventive procedure will simply involve cleaning these.

5.4.6 Controls Maintenance, Corrective

Corrective maintenance for the controls hardware also refers to the electronic and mechanical parts and in both cases involves replacement of faulty hardware. Electronics activity normally requires extensive troubleshooting using, where possible, troubleshooting routines designed into master control. Maintenance of the mechanical parts for the most part requires removal of valve components and replacement and/or repair for reinstallation into the valve.

5.4.7 Structure Maintenance

Structure maintenance consists only of periodic rust prevention painting as done on bridges.

5.4.8 Maintenance Equipment

The following equipment is required for the indicated maintenance tasks:

A. Absorber Flushing Equipment
B. Standard Hard Tools
C. Grinder, Welder, Portable X-ray Unit
D. Sand Blasting and Spray Paint Equipment
E. Power Hacksaw or Pipe Cutter
F. Panel Handling Sling
G. Standard Electronics Checkout Equipment (Digital Voltmeter, Counter, Oscilloscope, Ohm-meter, etc.)
H. Pressure Gage Calibration Bench
I. Ultrasonic Filter Cleaner

5.4.9 Manpower Requirements

Manpower skills are presented herein to document the types of personnel required. It is highly probable that a number of these skills will also be needed for standard maintenance on other parts of the feedwater/steam system of the Pilot Plant. The skills required are as follows.

A. Valve Service Mechanic (Technician)
B. Welders — Certified to Section I and Section VIII of the ASME code
C. X-ray Technician
D. Authorized Quality Assurance Inspector
E. Painter/Sandblaster
F. General Pipefitter Skilled Journeyman
G. Electronics/Instrumentation Technician
H. Crane Operator

The last skill required will probably be a purchased item to guarantee an ASME-approved third party inspection capability. Having an inspector of the DIS on hand or on call would suffice. It should be kept in mind, however, that certain utility companies, by virtue of their insurance coverage, have this function performed by insurance carriers without need for the DIS. As such, this task is not called out as a manpower requirement, but rather as an indication of what capability must be recognized.

6 SUBSYSTEM RESEARCH EXPERIMENT

6 SUBSYSTEM RESEARCH EXPERIMENT

Section 6
SUBSYSTEM RESEARCH EXPERIMENTS (SRE)

During design of the Pilot Plant receiver, several technical issues were identified that required experimental data to be obtained so that risks inherent in receiver performance, control, stability, and mechanical integrity could be eliminated. This section presents these issues, together with Experiments (SRE), facilities, and test results used to resolve these issues.

The receiver SRE included subassembly tests and tests of a complete panel of a full-scale Pilot Plant receiver. Lower level tests included single and multiple tube configurations that provided thermal, hydrodynamic, structural, and life data.

6.1 TECHNICAL ISSUES

Issues that required experimental verification or analytical verification using experimentally determined factors are as follows:

A. The ability to deliver dry steam under rated or derated temperature conditions over the required power level range.

B. The ability to withstand peak heat flux at corresponding Pilot Plant flowrates.

C. Operation with tube wall temperatures compatible with design requirements for a 30-yr life (10,000 cycles).

D. That the absorber surface maintain high absorptivity for a cost-effective period of time under conditions of thermal cycling and high-intensity solar radiation.

E. That the panel expand and contract under thermal influences so excessive stresses are prevented.

F. That the absorber operate over the required power/flow range, particularly at the lower end of the range, without excessive cycling of steam discharge temperature and without significant variations of temperature from tube-to-tube.

G. That the absorber react to passing cloud cover over the collector field without subsystem degradation.

H. That the absorber be fabricated using the procedures and materials designed, and that transportation of the absorber in urban areas is feasible.

The experimental test results are presented in Section 6.5. Subsequent tests, defined by a contract extension, are to be performed on a full-scale Pilot Plant receiver panel at the Solar Thermal Test Facility (STTF) at Albuquerque, New Mexico. These tests will verify receiver panel performance with actual, rather than simulated, solar heat flux inputs. The test results will be reported under separate cover.

6.2 TEST PROGRAM OBJECTIVES

The objectives of the SRE program were as follows:

6.2.1 Cooling

The objective of the cooling test was to verify the cooling capabilities of the design by operating test specimens which duplicated Pilot Plant hardware at maximum heat fluxes and flowrates expected during Pilot Plant operation. The objective was also to provide experimental data on tube wall temperatures that can be compared directly with analytical predictions.

6.2.2 Panel Life

Panel fatigue life is predicted on the basis of tube wall temperatures. Therefore, the tube wall temperature data obtained during SRE provides empirical data for life calculations. Fabrication of a large-scale test specimen and the large number of required test cycles (10,000) made direct life-cycle testing unfeasible.

The relative ease of applying high absorptivity paint to the receiver surface makes a 30-yr coating life unncessary. Accordingly, short-duration subscale tests were conducted to determine if the surface could withstand significant durations of exposure to concentrated solar thermal energy, rain, and repeated thermal cycling.

6.2.3 Controls

Each receiver panel is self-contained with respect to sensors, control logic, and control valves. Panels affect each other in the receiver only as they produce pressure transients in the riser or downcomer. Therefore, the objectives on the full-scale panel SRE were to verify that the Pilot Plant control elements could maintain the panel outlet temperature within specified limits during steady-state and normal operating transient conditions, and within safe tolerances during abnormal transient conditions. The objective of the controls test was also to provide system time constants for subsequent analog modeling.

6.2.4 Flow Stability Uniformity

The objective of these tests was to use full-scale hardware to provide a final demonstration of the ability to control flow in the tubes of the once-through receiver boiler such that unacceptable excursions in panel outlet fluid temperature and tube wall temperature were prevented. The objective was also to indicate if flow orificing for each tube of the panel was required to provide a uniform distribution of discharge temperatures from tube to tube.

6.2.5 Structures

By using a full-scale Pilot Plant absorber with backup structure operating at rated temperatures, the objective of the experiment was to verify the adequacy of the thermal expansion provisions in preventing thermal stress damage. The objective was to achieve complete simulation of pressure and thermal loads on the panel and backup structure.

6.2.6 Fabrication/Transportation

The objective of this phase of the program was to verify the producibility and transportability of a full-scale Pilot Plant absorber. The objective was to be accomplished by using all the materials and processes planned for the Pilot Plant fabrication sequence. Final verification would be achieved by obtaining the ASME boiler code stamp on the completed hardware. Transportability was to be demonstrated by moving the completed panel from the manufacturing facility to the test facility, both of which are in urban Los Angeles areas.

6.3 SRE HARDWARE DESCRIPTION

The test hardware includes a single tube, a narrow panel, a full-scale Pilot Plant panel, and an absorptive surface test specimen.

6.3.1 Single Tube Test Hardware

A single tube identical to Pilot Plant panel tubing in dimensions, material (including the Pyromark high-absorptivity paint), and configuration was tested in a vertical orientation using a radiant heat input.

6.3.2 Narrow Panel

An overall view of the narrow panel is shown in Figure 6-1. This panel consisted of five receiver tubes, inlet and outlet manifolds, and backup structure that duplicates the 70-tube receiver panel in most respects.

The tubing material ID, OD, and heated length are identical to the corresponding dimension on the full panel. The method of supporting the tubing and allowing for thermal expansion is almost identical for both panels. The manner in which the tubing is joined to the manifolding in the narrow panel is shown in Figure 6-2 and is similar to the manner of joining on the 70-tube panel. As shown in Figure 6-2, the five tubes penetrate the water manifold in two rows, three tubes in one row, two tubes in another. Each tube contains provisions for a flow control restricter and a downstream pressure tap. The manifold is drilled, tapped, and plugged with a pipe plug immediately behind each of the five tubes. These plugs allow installation, removal, and inspection of each of the orifices. The two large tubes shown in the manifold in Figure 6-2 are for water inlet and for draining. The bracketry shown partially in the figure provides support for the water manifold and is attached by a sliding block, which rides along the eye beam rail, to the remainder of the panel.

Groups of bosses are provided at several locations on the 5-tube panel (Figure 6-3) to permit monitoring both fluid temperature and pressure at several locations along the panel.

A listing of the complete set of shop drawings for both the 5-tube and 70-tube panels is given in Table 6-1. The 5-tube panel was built to rigorous ASME code specifications and received the "S" stamp nameplate

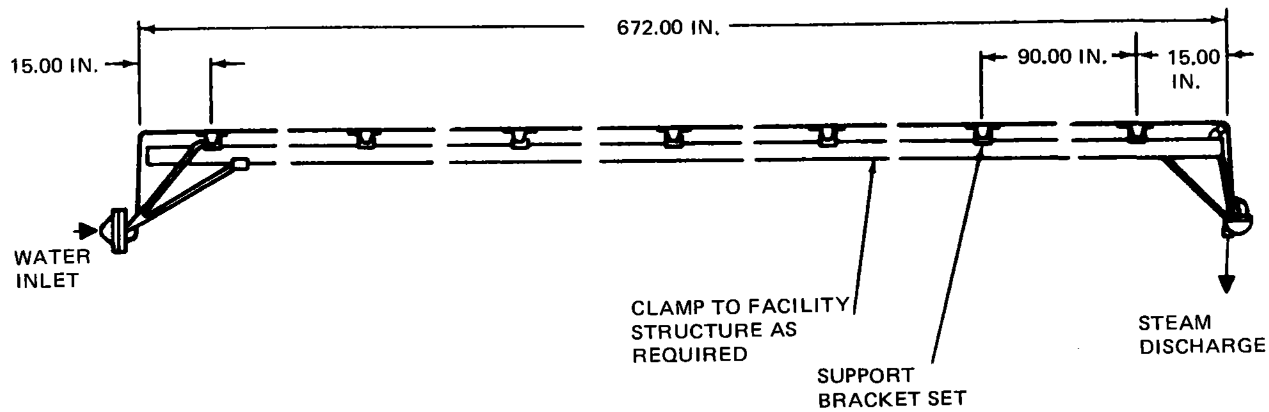


Figure 6-1. Narrow Panel

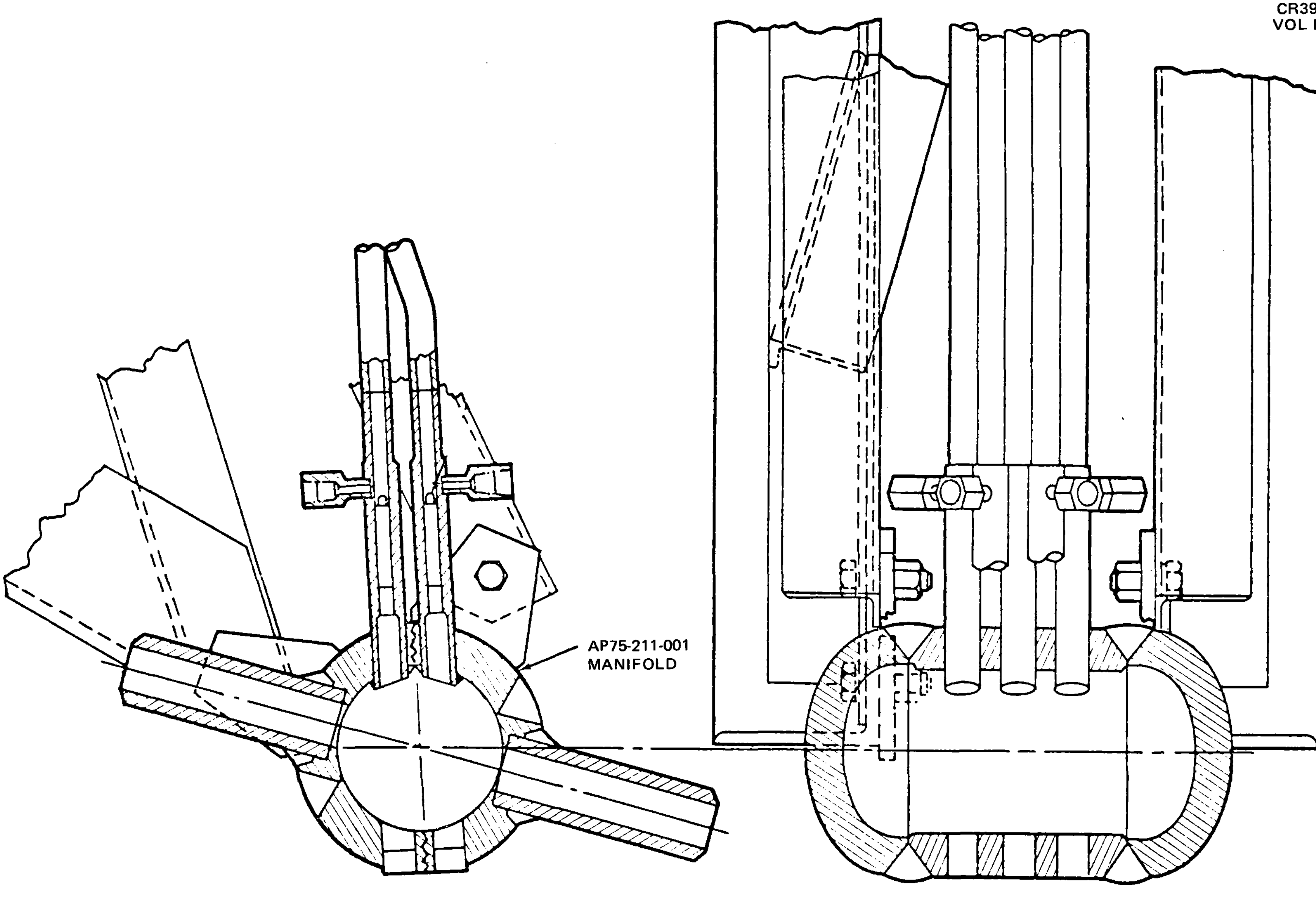
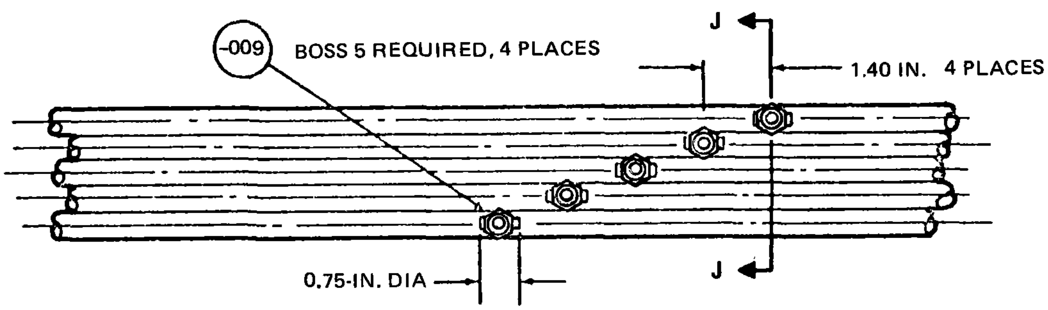
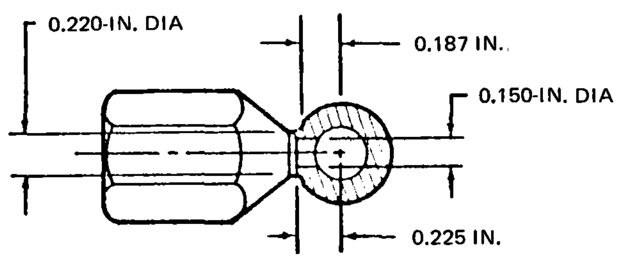


Figure 6-2. Five-Tube Panel Water Manifold





SECTION J–J

Figure 6-3. Panel Instrumentation

Table 6-1

LIST OF DRAWINGS

Drawing No.	Title
99RS010501	Panel Assembly, Solar Receiver
99RS010502	Panel, Solar Receiver
99RS010503	Tube Bundle, Solar Receiver
99RS010504	Manifold, Feedwater Inlet
99RS010505	Manifold, Steam Outlet
99RS010506	Rail, Panel Support
99RS010507	Slide and Spacer, Solar Receiver
99RS010508	Beam, Transverse, Solar Receiver
99RS010509	Beam, Intermediate, Transverse, Solar Receiver
99RS010510	Yoke, Upper, Solar Receiver
99RS010515	Block, Stand off, Feedwater Line, Solar Receiver
99RS010517	Block, Insulator, Upper, Solar Receiver
99RS010518	Block, Insulator, Lower, Solar Receiver
99RS010519	Block, Insulator, Upper Intermediate, Solar Receiver
99RS010520	Block, Insulator, Solar Receiver
99RS010521	Strap, Tie, Insulation, Solar Receiver
99RS010522	Line, Feedwater Supply, Solar Receiver
99RS010523	Coupling, Expansion, Feedwater
99RS010524	Line, Flowmeter to Throttle Valve, Solar Receiver
99RS010525	Line, Shutoff Valve to Flowmeter, Solar Receiver
99RS010526	Line, Throttle Valve to Expansion Coupling
99RS010527	Line, Steam Discharge, Solar Receiver
99RS010528	Receiver Segment Assembly
AP75-151	Panel Assembly, 5-Tube Test
AP75-211	Manifold Half, Assembly of, Steam and Water, 5-Tube Test Panel
AP76-113	Beam, Transverse, 5-Tube Test Panel
AP75-174	Beam, Tube Support, 5-Tube Test Panel

shown in Figure 6-4. Overall views of the panel are shown in Figures 6-5 and 6-6. The 5-tube panel was welded using the automatic welding machine shown in Figure 6-7, which was subsequently used in fabricating the receiver segment panel. The 5-tube panel was grit-blasted, painted with Pyromark high-absorptivity paint, and instrumented with the thermocouples on the hot wall, as shown in Figure 6-8, as well as on the back wall.

6.3.3 Receiver Panel

The SRE receiver test panel consisted of a Pilot Plant panel and associated controls. An overall view of the panel is shown in Figure 6-9. The test panel comprised 70 tubes which have a heated length of 17m (56 ft). The tubes are folded over at the top and bottom ends to protect the manifolds from the concentrated solar radiation. The panel tested for the SRE is an identical panel to that designed for the Pilot Plant in the Preliminary Design Report with the exception that the actual Pilot Plant panel length will be reduced to 12.5m (41 ft). The width of the panel is shown in Figure 6-10 to be 0.9m (35 in.). In order that the width of the manifolds not exceed this dimension (to facilitate installation and removal of the panels in the Pilot Plant), the eight tubes at each side of the panel are bent in and doubled over, resulting in the tube-to-manifold configuration shown in Figure 6-11. The similarity in the configuration between the full-panel manifold and the narrow panel manifold is evident with provisions for pipe tap plugs opposite each of the tube inlets in the manifold and water inlet and drain fittings also provided.

The manner in which the tubes are joined to the manifolds is illustrated in Figure 6-12. Dimensions are typical of the steam manifold, but the method is similar for both steam and water manifolds. The tube is inserted into the hole in the manifold and roller expanded to firm contact with the manifold. A seal weld is placed around the tube on the inside surface of the manifold (only one-half of the manifold being in place at this time) and the tube again expanded by roller into the manifold wall. This joint is a standard boiler configuration joint and has been proven to be very reliable.

The steam manifold is shown in Figure 6-13. It is quite similar to the water manifold except that only one pipe fitting is provided (there is no drain fitting) and the attachment lugs are welded onto this manifold to support the panel from the facility or Pilot Plant tower structure. The manifold is shown in this drawing without the two endcaps welded in place.

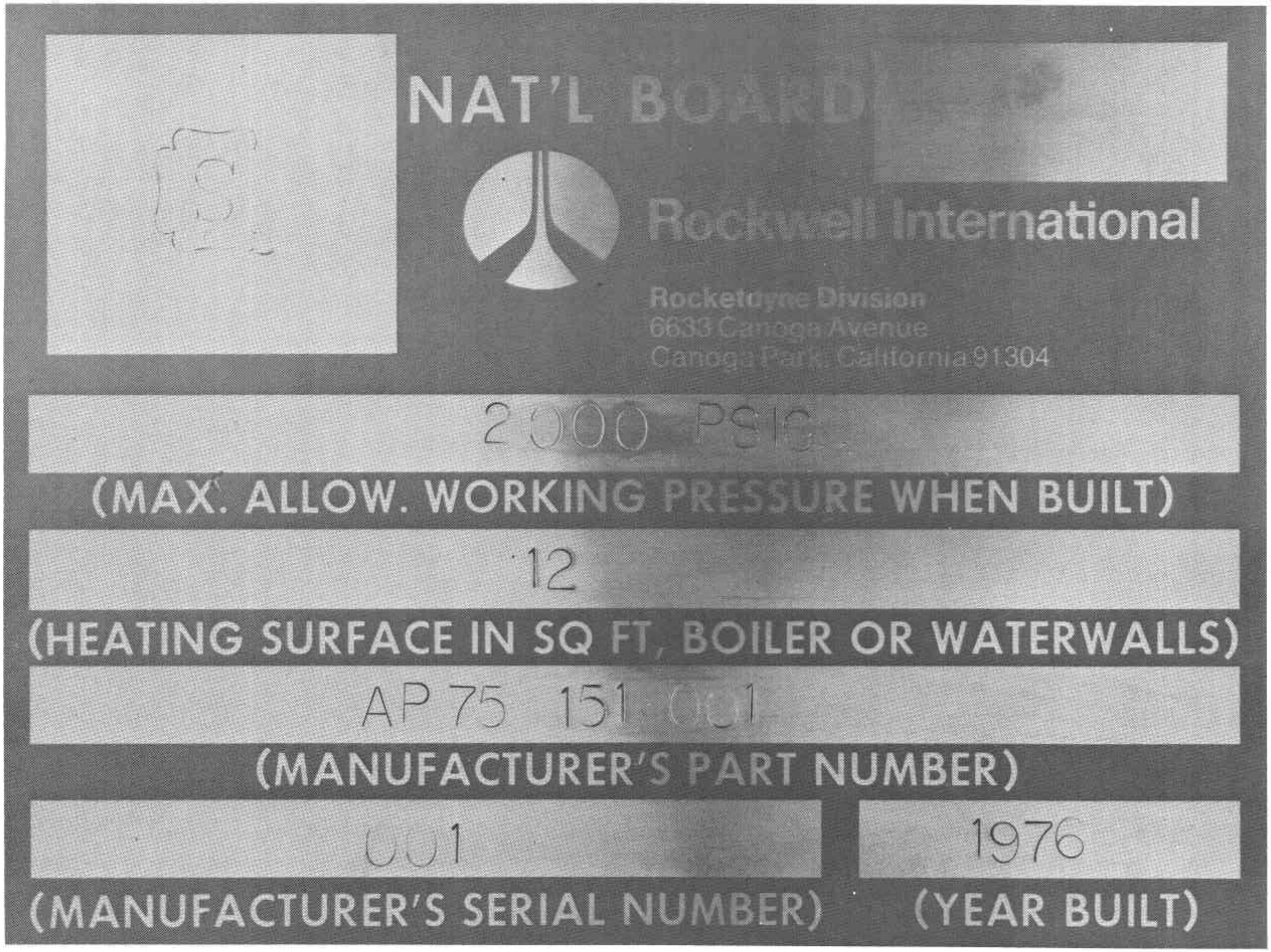


Figure 6-4. Five-Tube Panel Boiler Nameplate

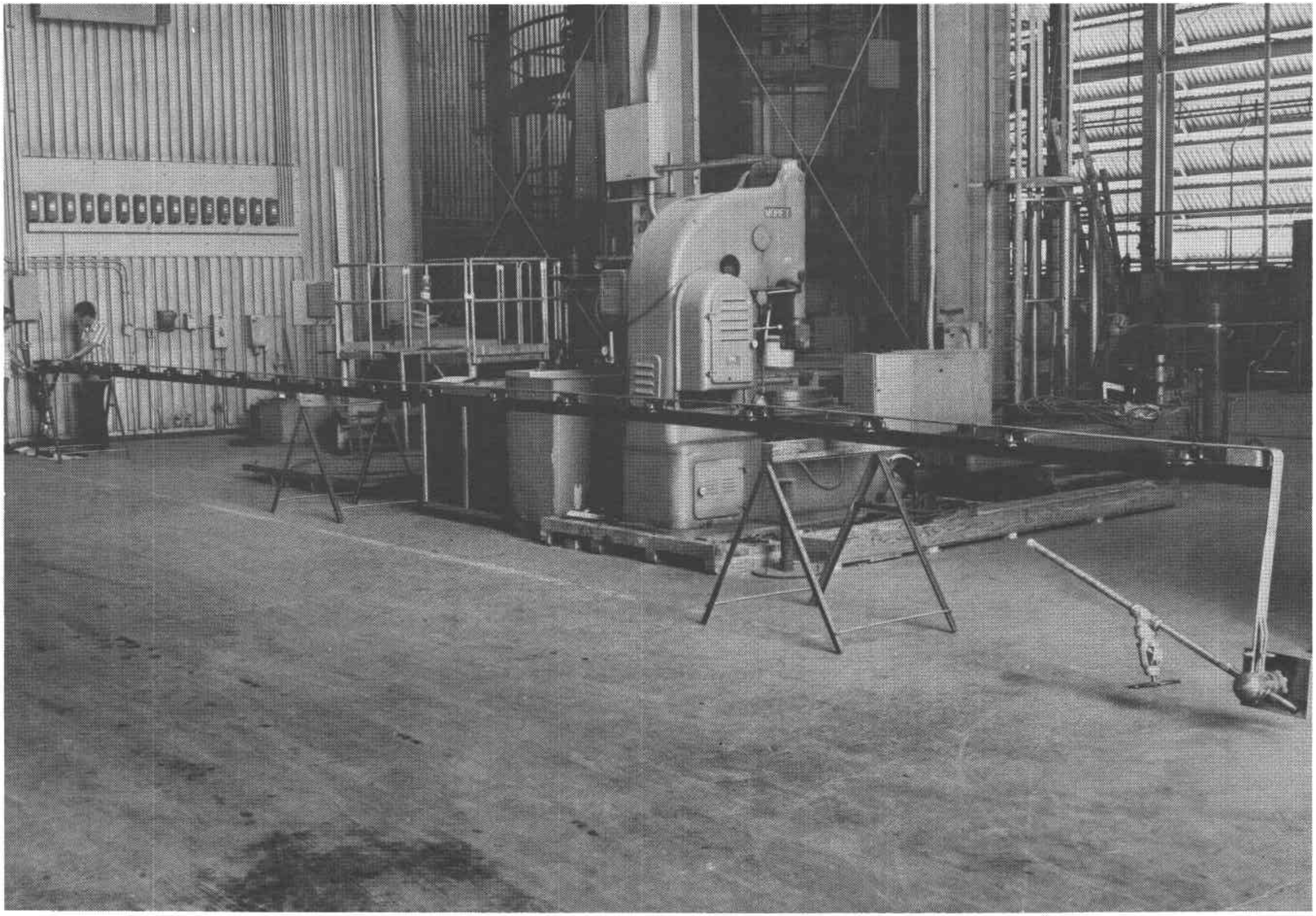


Figure 6-5. Five-Tube Panel

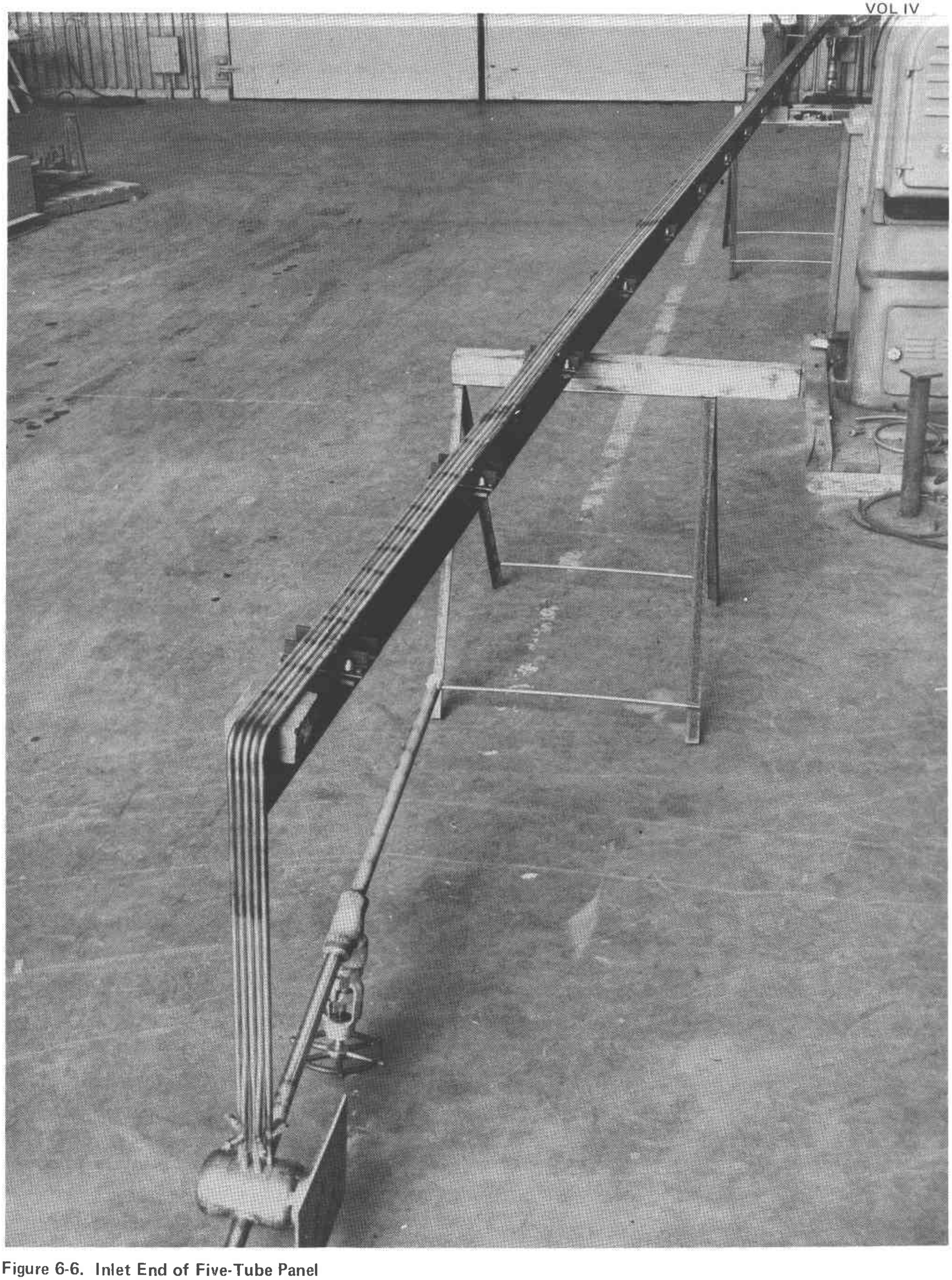


Figure 6-6. Inlet End of Five-Tube Panel

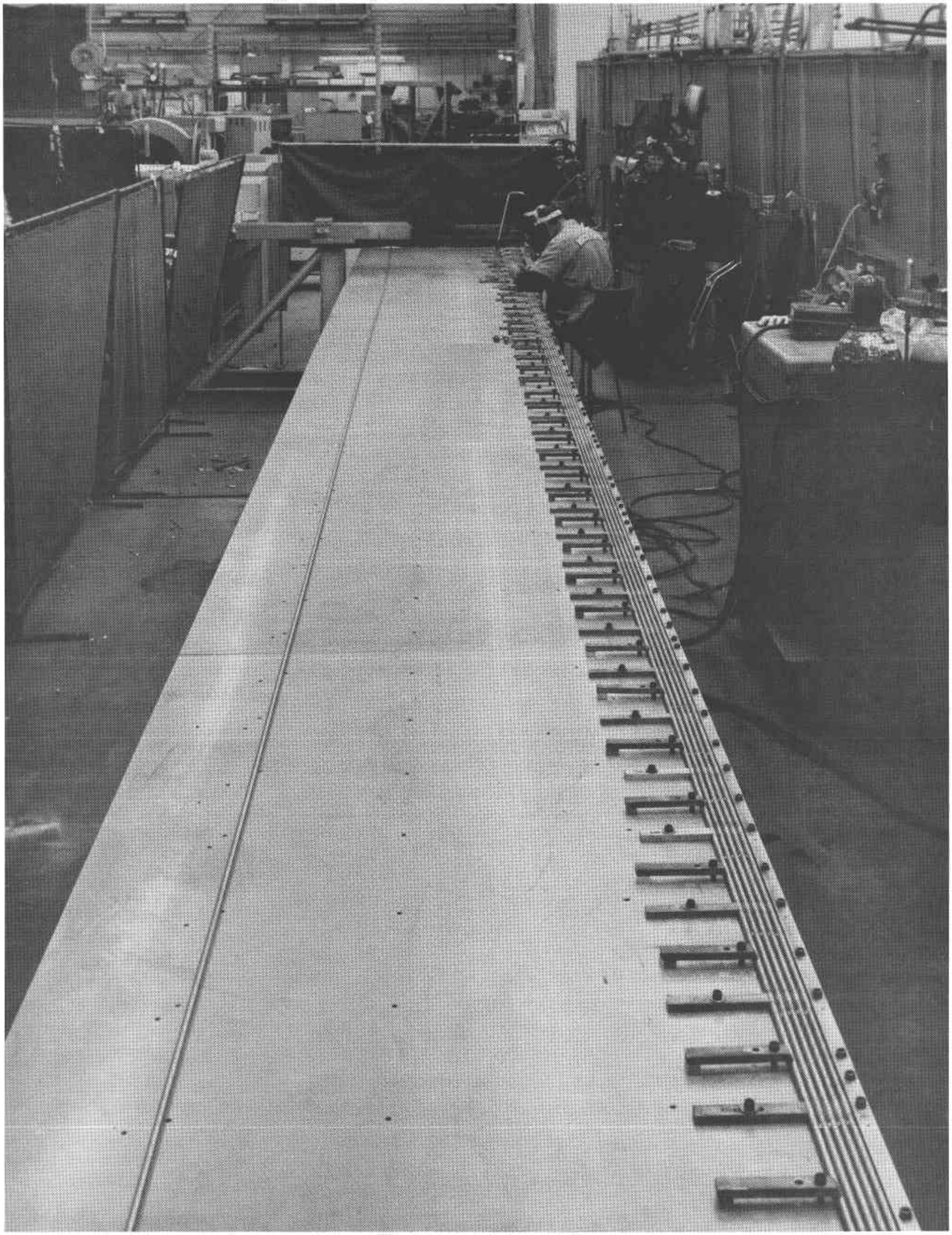


Figure 6-7. Welding Five-Tube Panel

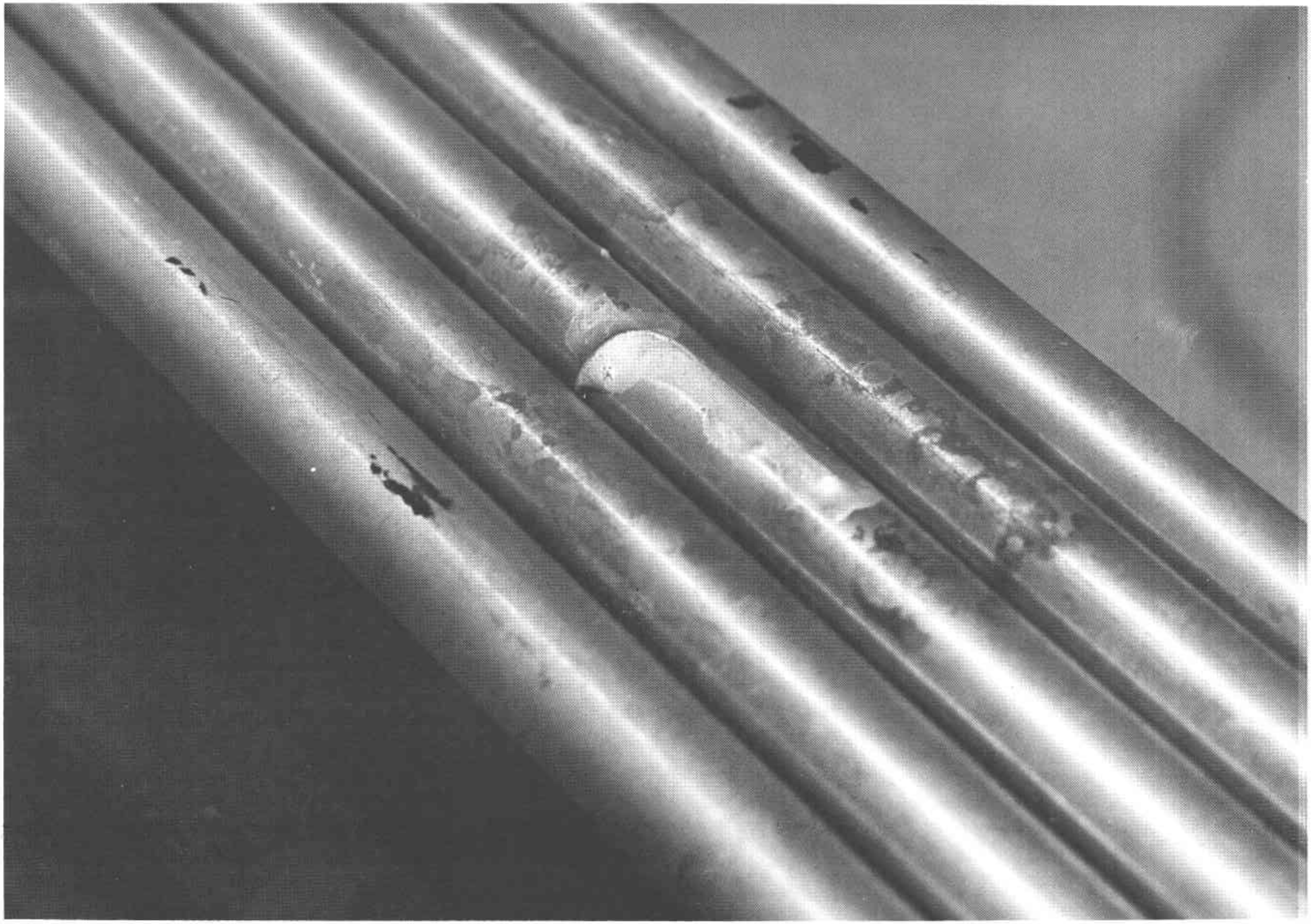


Figure 6-8. Hot Wall Thermocouple Installation

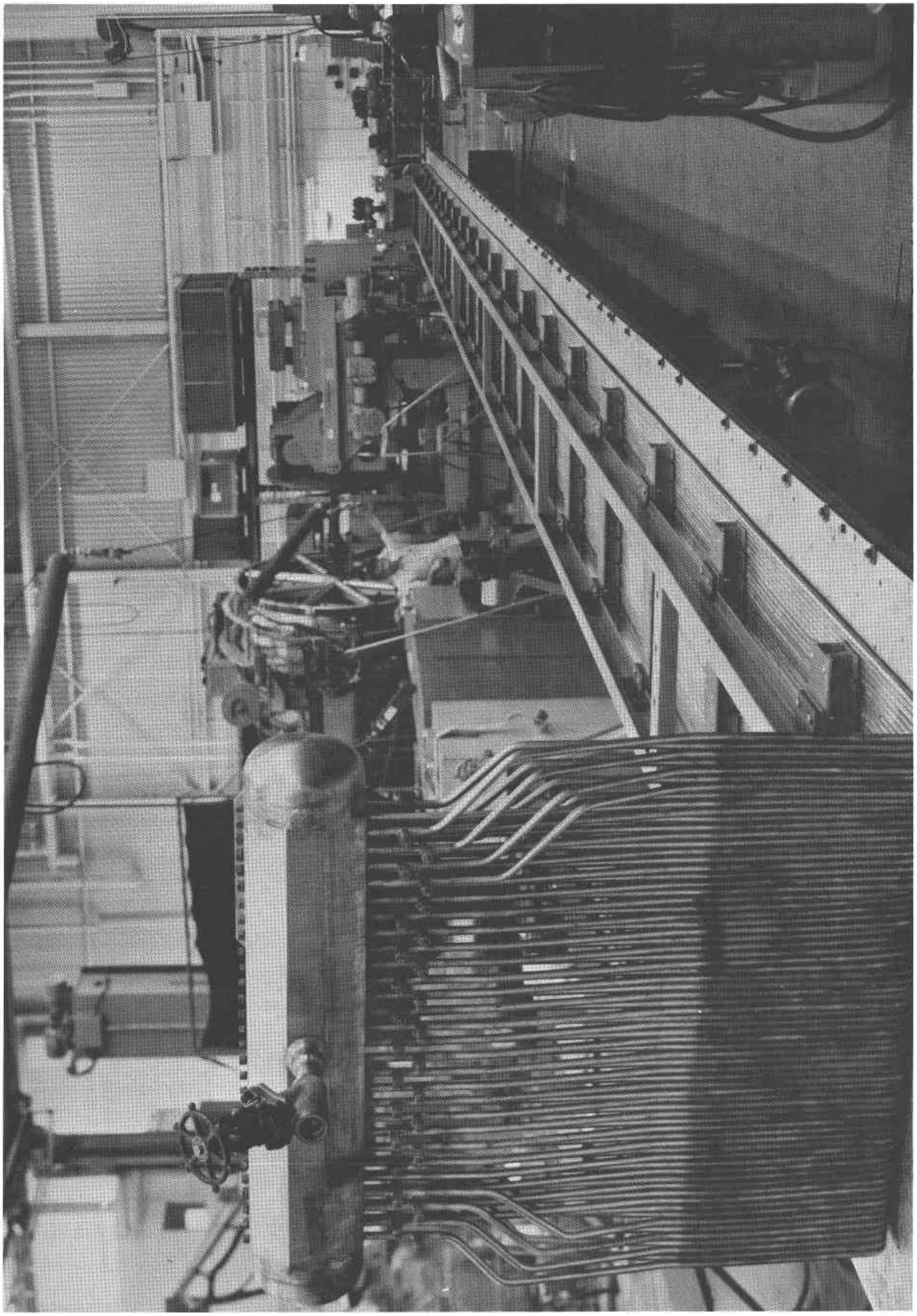


Figure 6-9. Completed Pilot Plant Panel

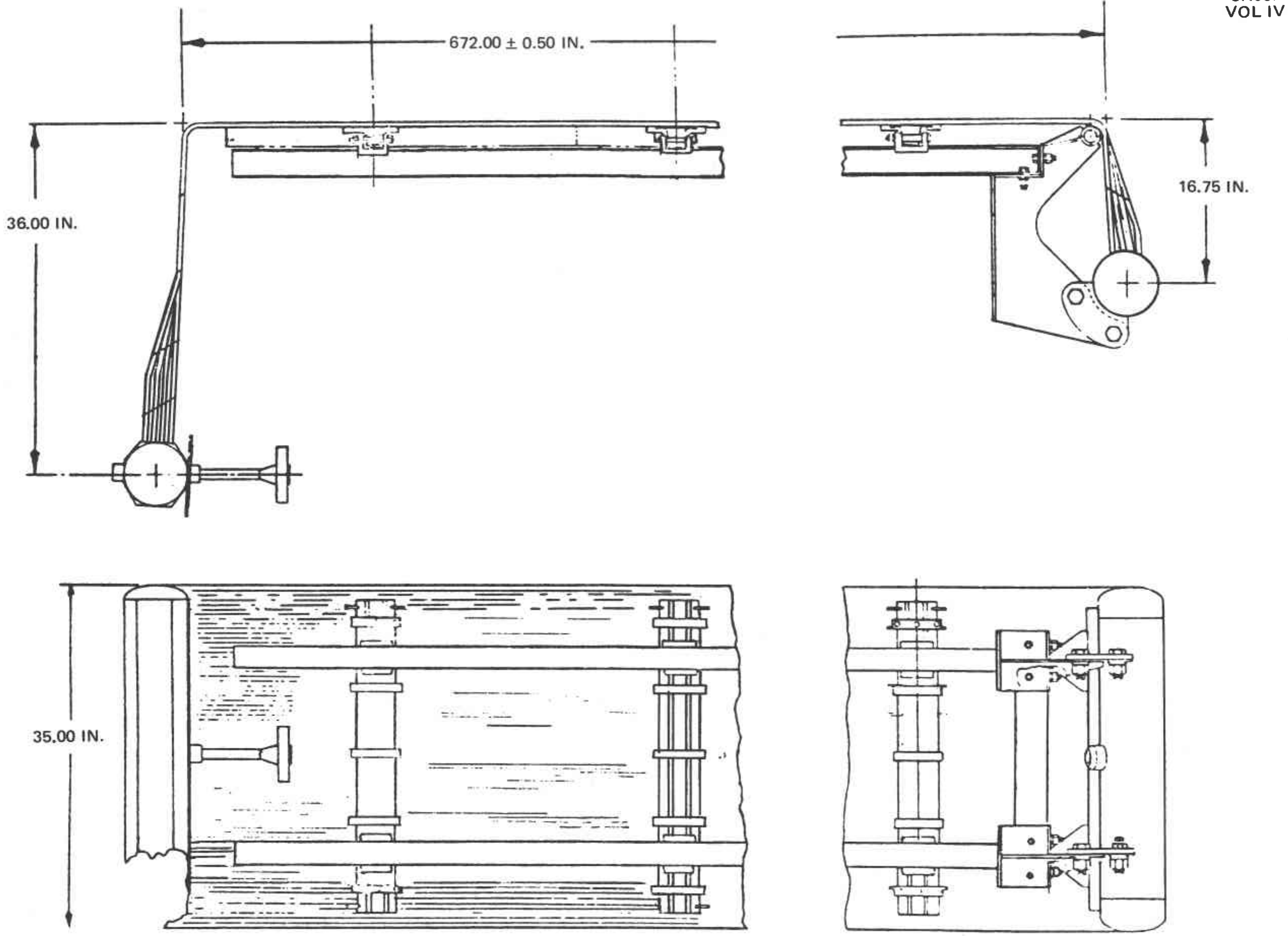


Figure 6-10. SRE Receiver Panel

CR39A
VOL IV

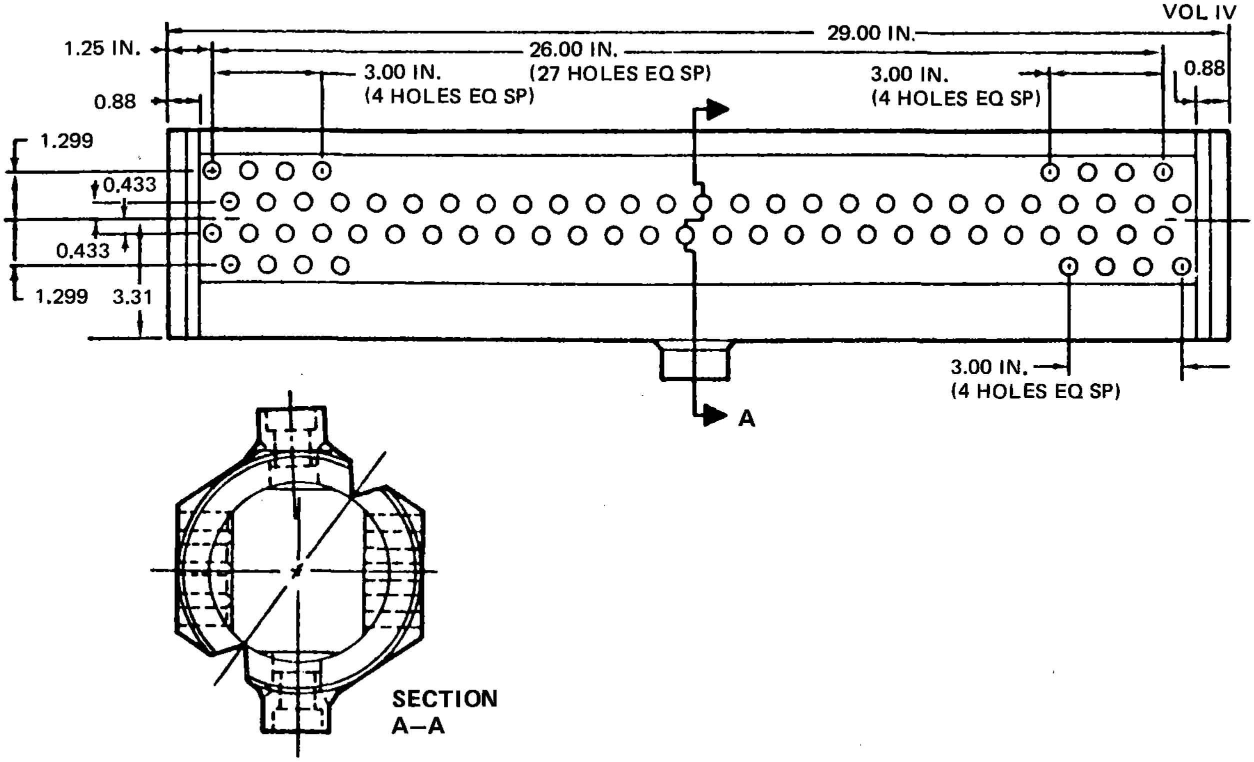


Figure 6-11. Panel Water Manifold

CR39A
VOL IV

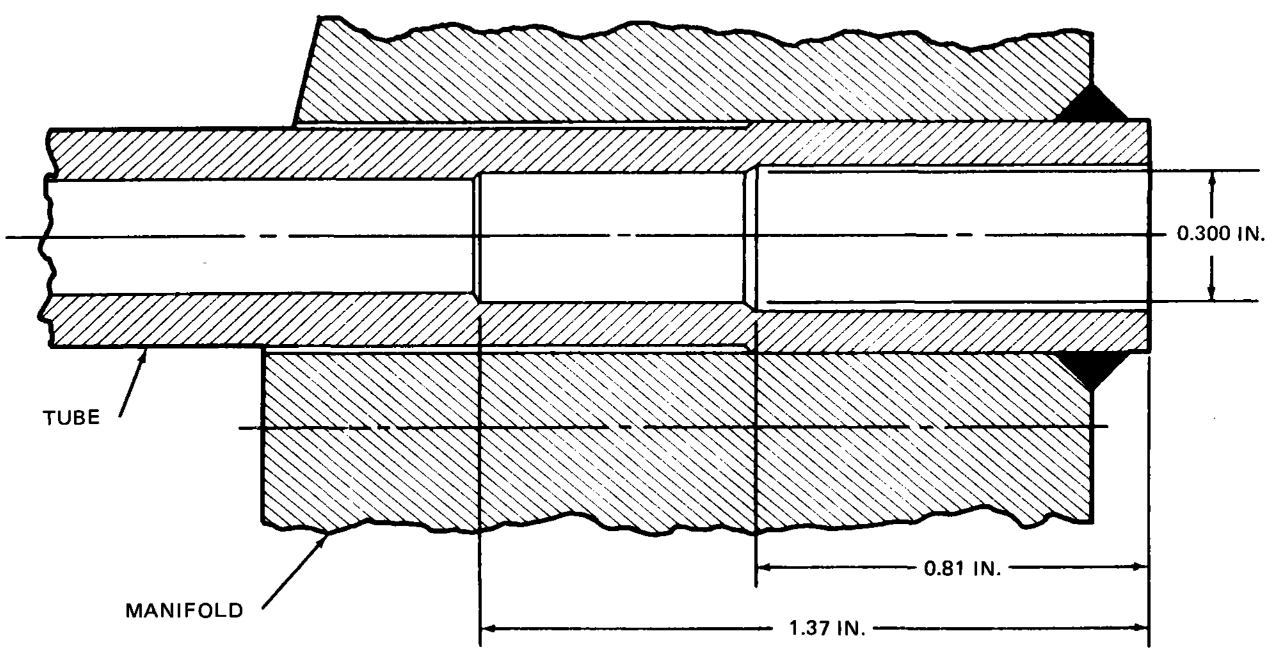


Figure 6-12. Steam Manifold/Tube Joint

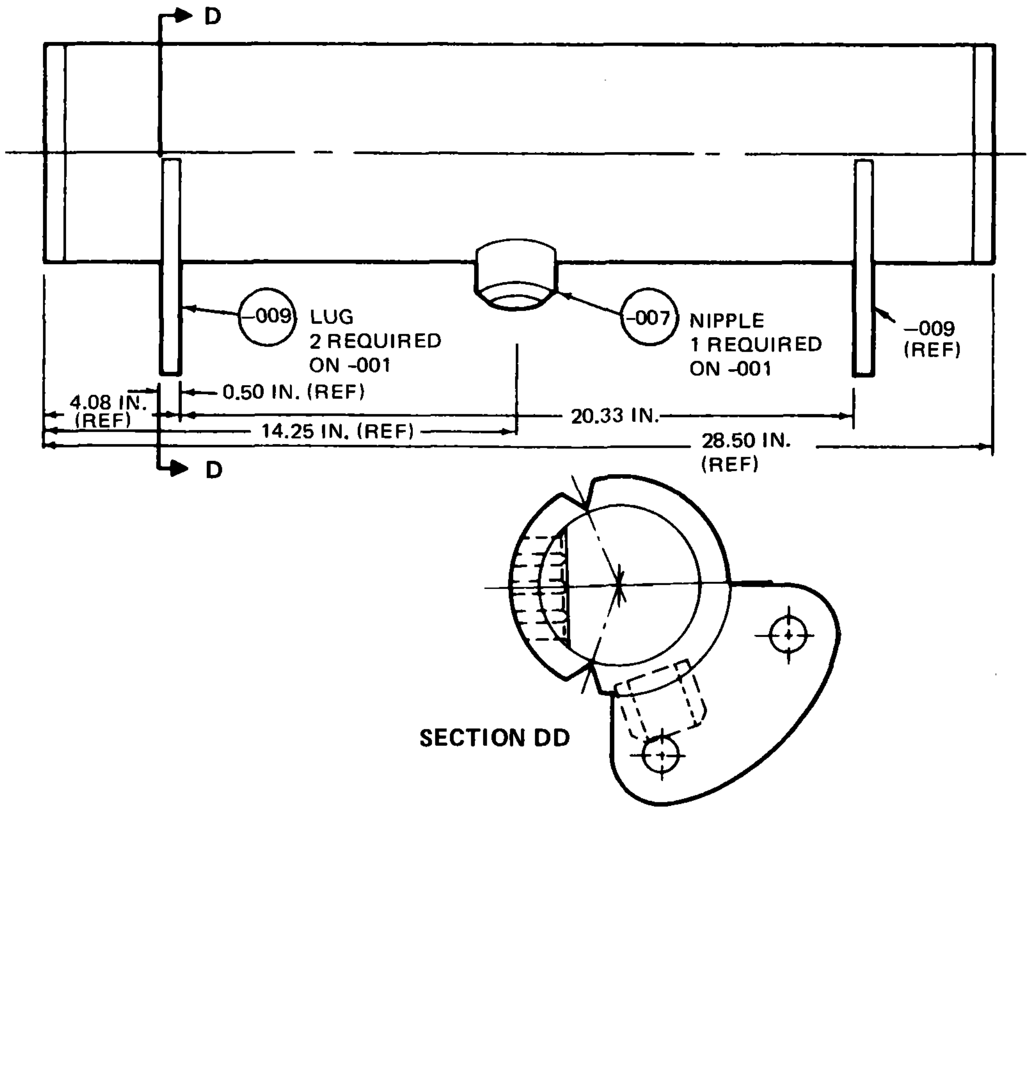


Figure 6-13. Panel Steam Manifold

The provisions for thermal expansion of the panel are shown in Figure 6-14. At numerous axial stations, several of the tubes have pairs of small clips welded to them, as shown in the upper view of Figure 6-14. These clips allow lateral expansion of the panel by sliding along the hat-shaped beam. The hat-shaped beam in turn is fastened to a sliding block which traverses along the eye beam to permit axial expansion of the panel. The panel is fastened to the two I-beams only at the top of the assembly and grows freely downward and longitudinally during the expansion and contraction. Figure 6-9 is a photograph of the completed panel.

The inlet plumbing configuration and other waterfeed systems components are shown in Figure 6-15. Water enters the segment through a shedding vortex flowmeter which features a minimum number of moving parts to enhance reliability. The next component in line is a control valve which regulates water flow through the absorber panel. The inlet piping is firmly fixed to the Pilot Plant tower or to the facility downstream of the throttle valve. An expansion joint is provided in the plumbing which provides for the thermal expansion of the panel during operation. A 100-micron filter is included in the plumbing to protect the orifices in the event of a failure of the upstream filter. A stop check valve defines the limits of ASME Section 1 jurisdiction in the boiler region. All components from this stop check valve to a stop valve on the steam discharge side of the boiler are fabricated of Incoloy 800, excluding the drain valve on the water manifold, which is of low carbon steel. The arrangement of these components is shown photographically in Figure 6-16.

6.3.4 Fabrication/Procurement

The fabrication/procurement approach is shown in Table 6-2. Both the narrow and the full-size panels were fabricated using Incoloy 800. For the narrow-panel tests, the filter and stop check valve were Pilot Plant hardware items purchased from commercial sources. The remaining feed system and controls were facility items.

For the receiver segment tests, the water throttling valve, stop check valves, relief valves, and filter were all representative Pilot Plant hardware and were commercially purchased. The remaining feed system components were

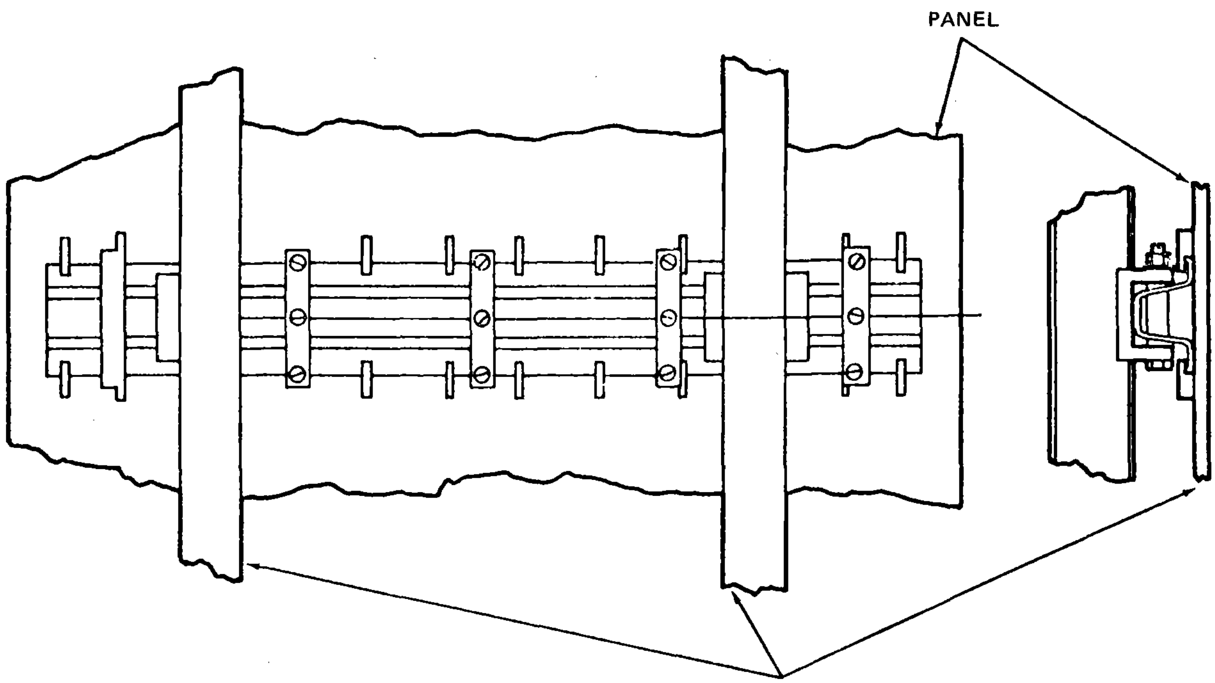


Figure 6-14. Thermal Expansion Provisions

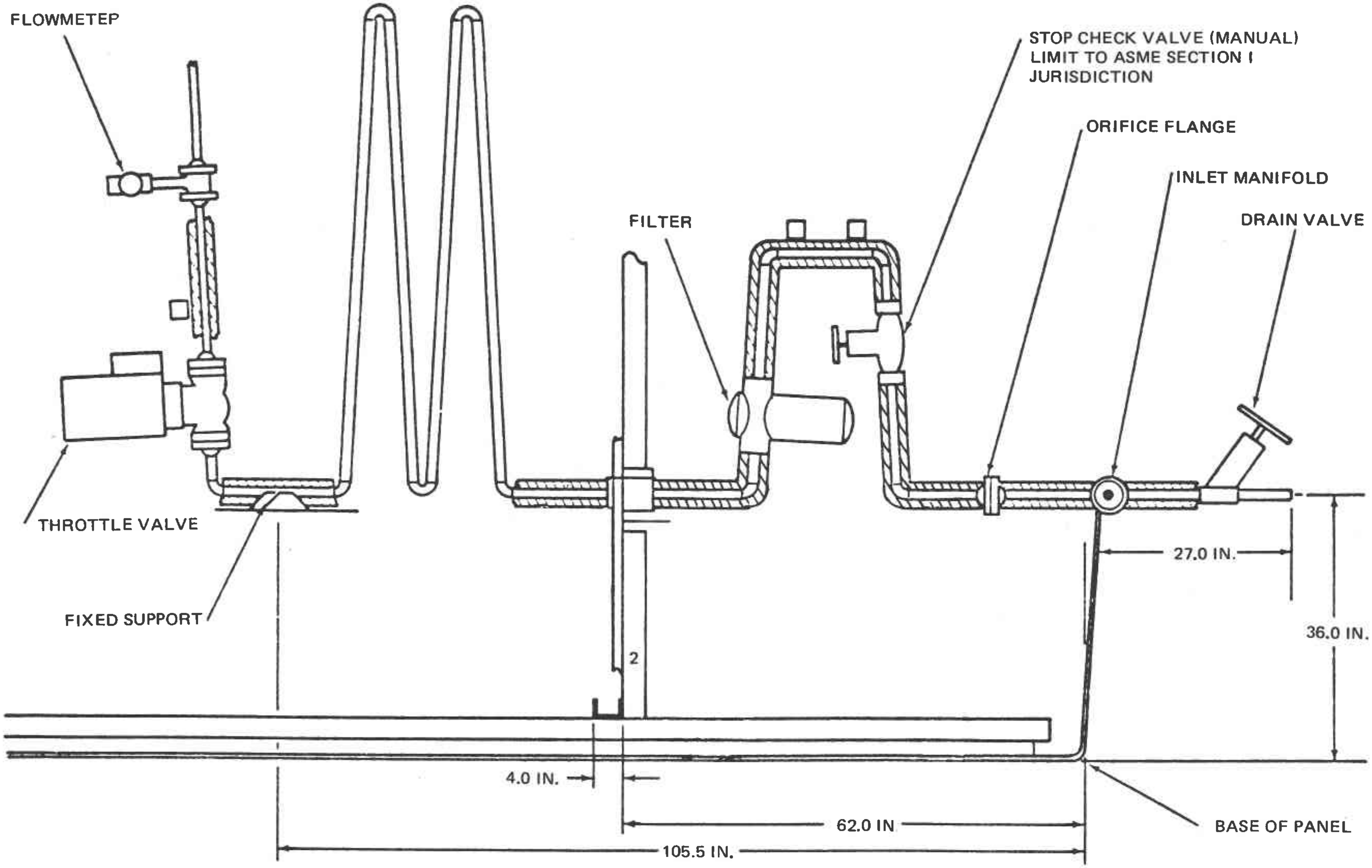


Figure 6-15. Inlet Plumbing Configuration

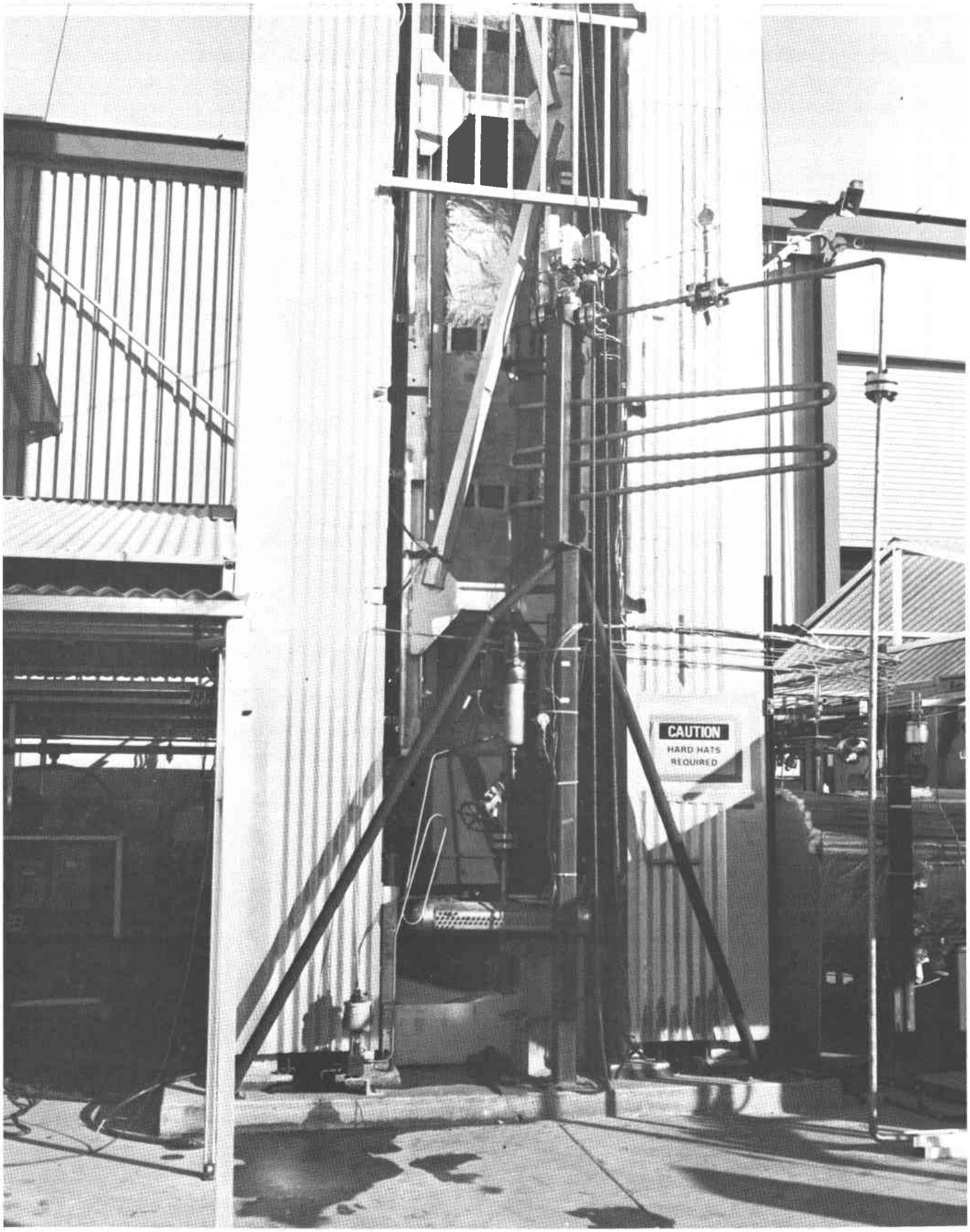


Figure 6-16. Receiver Panel Inlet Plumbing

Table 6-2

FABRICATION/PROCUREMENT APPROACH

Item	Make	Buy	Facility
Narrow panel			
Absorber materials		X	
Absorber	X		
Filter and stop/check valve		X	
Remaining feed system			X
Controls			X
Receiver segment			
Absorber	X		
Absorber materials		X	
Water control, stop/check, relief valves, filter		X	
Remaining feed system			X
Water flow control system	X	X	
Pilot Plant instrumentation			X
Remaining instrumentation			X

facility items. The water flow control system, pneumatic control, and electronic systems were purchased and fabricated to the specific requirements of the water throttling system.

The fabrication sequence is similar for both panels. Prior to beginning fabrication, the tubing and the weld procedures were certified by the ASME representative inspector. The manifold material was machined and partially welded. The tubing was trimmed to size, shaped to a configuration appropriate to each tube, and (in the case of the narrow manifold) fittings were welded to the inlet end of the tubes to contain the orifices. The partially welded manifold halves were used as part of the fixturing to hold the tubes in place while the tubes were welded together (Figure 6-17), and then welded to the manifolds themselves. The clips that retain the panel to the back of the structure were machined and welded to the tubes. At this point, the panel assembly was hydrostatically tested to 20.5 MN/m^2 (3,000 psi).

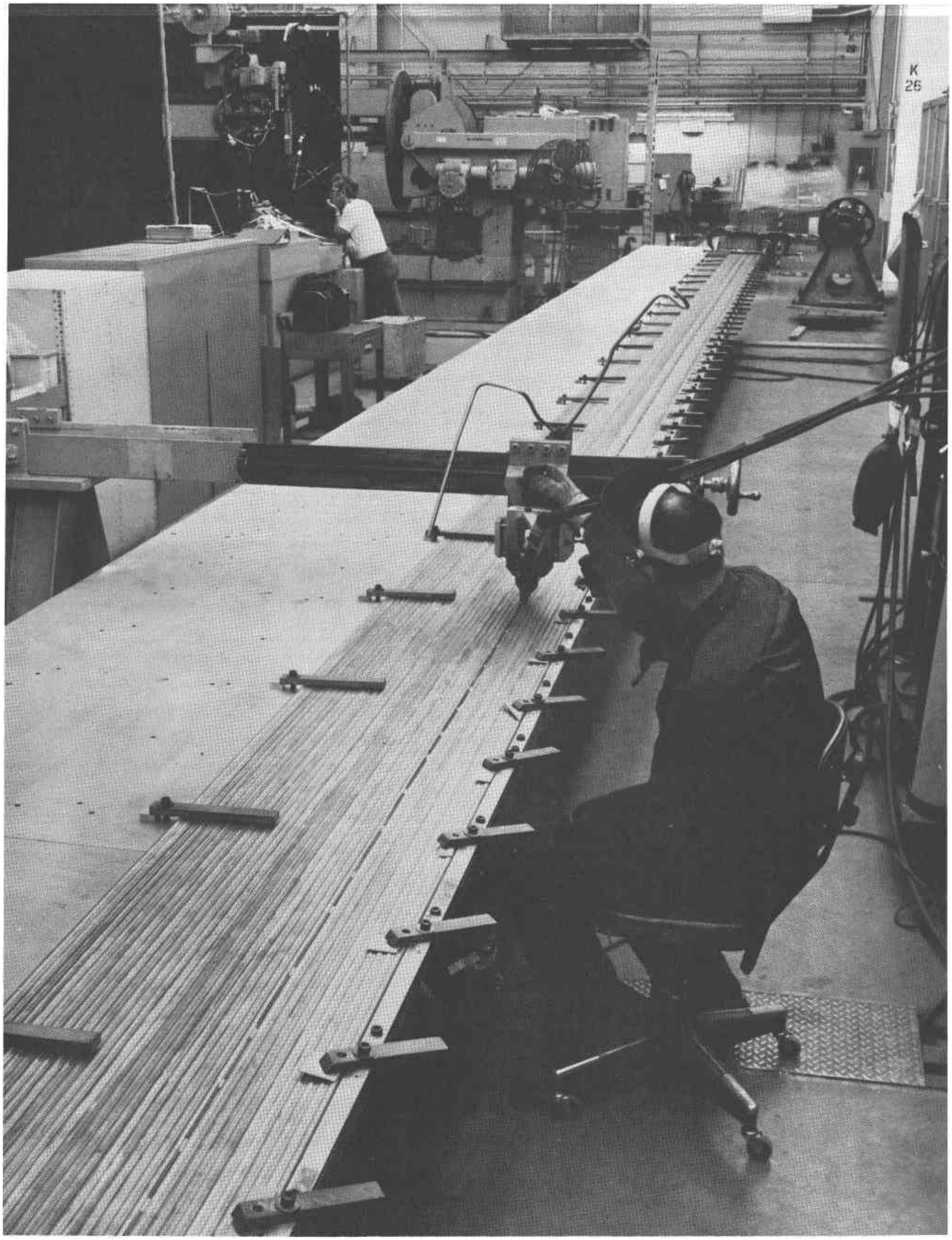


Figure 6-17. Automatic Tube Welding Operation

Following this test, the backup structure was assembled and secured to the panel assembly. Both the 5-tube panel and the 70-tube panel received the ASME code stamp (Figures 6-4 and 6-18).

6.3.5 Solar Absorptance Test Specimen

The solar absorptance test specimen is shown in Figure 6-19 and consists of a block of Incoloy with water-coolant ports and manifolds provided. Water is used to cool the surface of the Incoloy block, which is exposed to concentrated solar radiation. The test article is shown in Figure 6-19 coated with stripes of S-31 and Pyromark paints. This specimen was used to evaluate the effects of concentrated solar radiation.

The hardware used to evaluate thermal cycling effects consisted of lengths of tubing of the same cross sectional dimensions and material used in the Pilot Plant panel. The tubes were approximately 1m (3 ft) long and were grit-blasted and painted with Pyromark or S-31 paints.

6.4 TEST FACILITIES

The majority of the testing (single tube, 5-tube panel, and receiver segment) were conducted at the Rockwell B-1 Thermodynamics Laboratory. The absorptive surface tests also used at the White Sands solar furnace test facility and the TRW Thermophysics Laboratory. The special equipment required to support these tests at the Thermodynamics Laboratory consisted of the heater arrays to simulate solar energy and the flash tank assembly to simulate the bypass valve and flash tank of the Pilot Plant receiver. The existing heliostats at the White Sands facility concentrate the solar energy to simulate the function of the Pilot Plant heliostats. The facilities and hardware used to accomplish the various SRE objectives are listed in Table 6-3.

6.4.1 Thermodynamics Laboratory

The Rockwell B-1 Thermodynamics Laboratory was used as the facility to test the single tube, narrow panel, and receiver segment. All the above mentioned test hardware was oriented vertically so that proper direction of the gravity vector will be similar to that experienced in Pilot Plant operation.

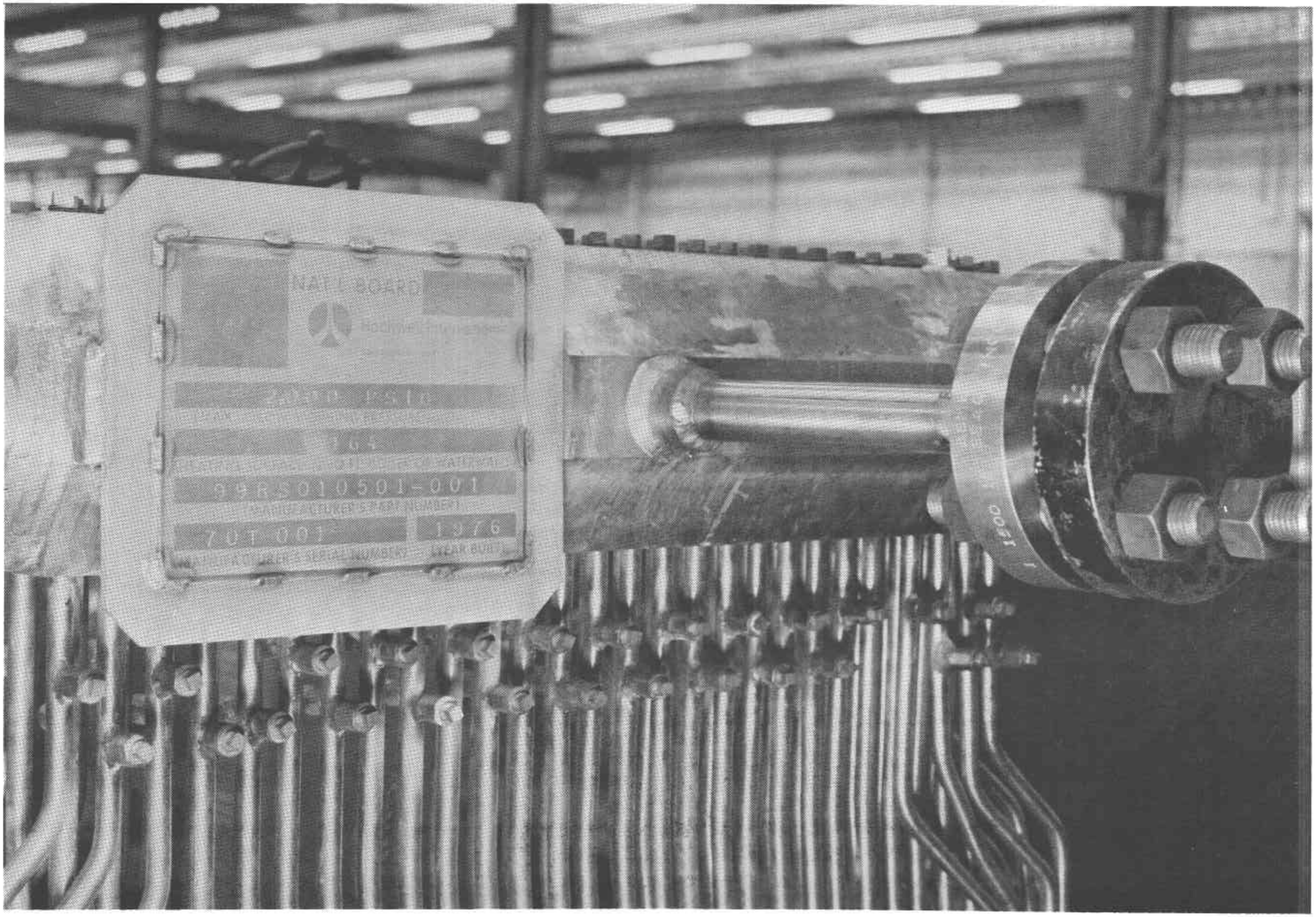


Figure 6-18. ASME "S" Stamp on 70-Tube Panel

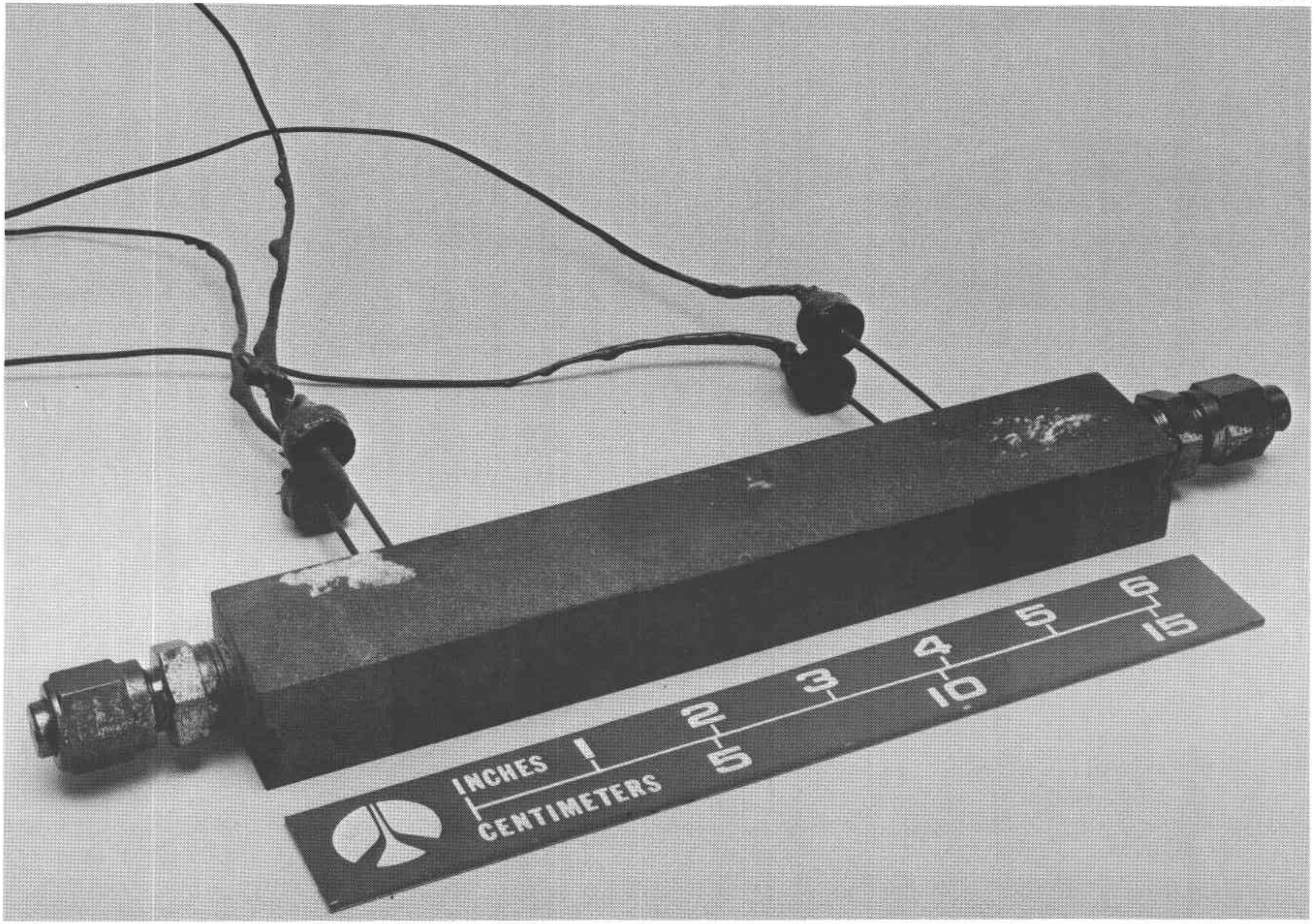


Figure 6-19. Absorptance Sample

Table 6-3

SRE HARDWARE AND FACILITIES

SRE Objective	Hardware	Facility
Cooling	1, 5, P	TL
Tube Life	1, 5, P	TL
Surface Durability	1, 5, P, A	TL, W, TRW
Control	P	TL
Stability/Uniformity	5, P	TL
Structure	5, P	TL
Fabricability	5, P	R

Hardware Symbols: 1 - Single Tube P - Pilot Plant Panel
5 - Five Tube Panel A - Absorptance Sample

Facility Symbols: TL - Thermodynamics Laboratory
W - White Sands Solar Furnacr
TRW - TRW Thermophysics Laboratory
R - Rocketdyne Manufacturing Facility

Two different heater arrays were used. One array consisted of heaters oriented along the axis of the tubes. This array was used to provide simulated solar inputs to both the single tube and the 5-tube panel. Graphite heaters were used for the single tube tests. Both graphite and metallic heaters were used for the tests on the 5-tube panel. Metallic heaters provided long-duration tests at the lower heat flux levels. The 5-tube panel installed in its tower prior to erection is shown in Figure 6-20. The width of the full panel required that the heaters be oriented normal to the axis of the tubes. The Pilot Plant panel is shown being installed in the test tower in Figure 6-21.

The flash tank separator used for the SRE consisted of 31-cm (14 in.) nominal diameter pipe approximately 4m (13 ft) long. A water level control valve drains water from the lower portion of the tank and a backpressure regulator regulates the flow of steam out of the top of the tank.

Boiler quality water as defined in Table 6-4 was used. Purification of the water to meet these characteristics was accomplished as follows: Deionized water was received and stored in a polishing unit. The water was recirculated

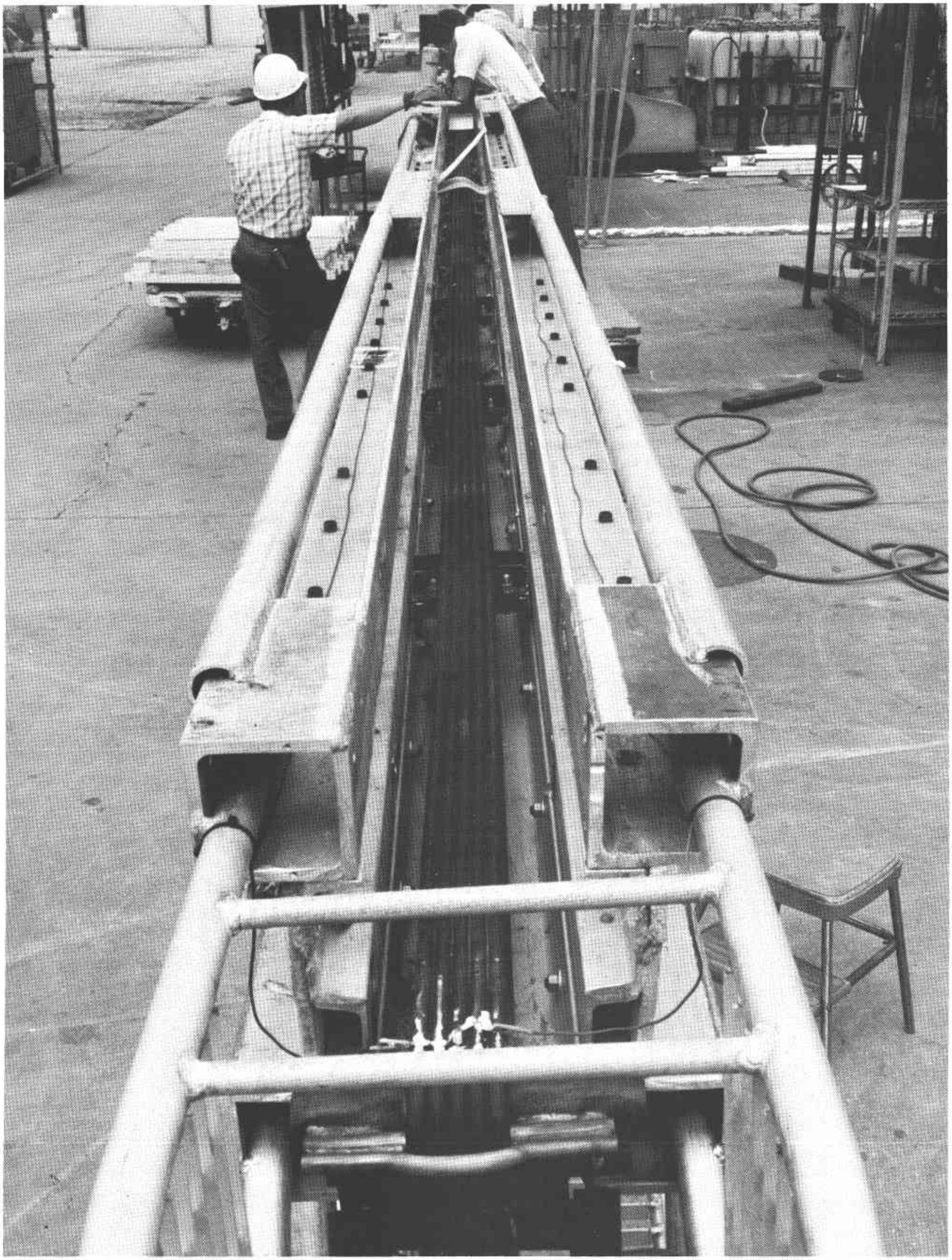


Figure 6-20. Five-Tube Panel in Tower

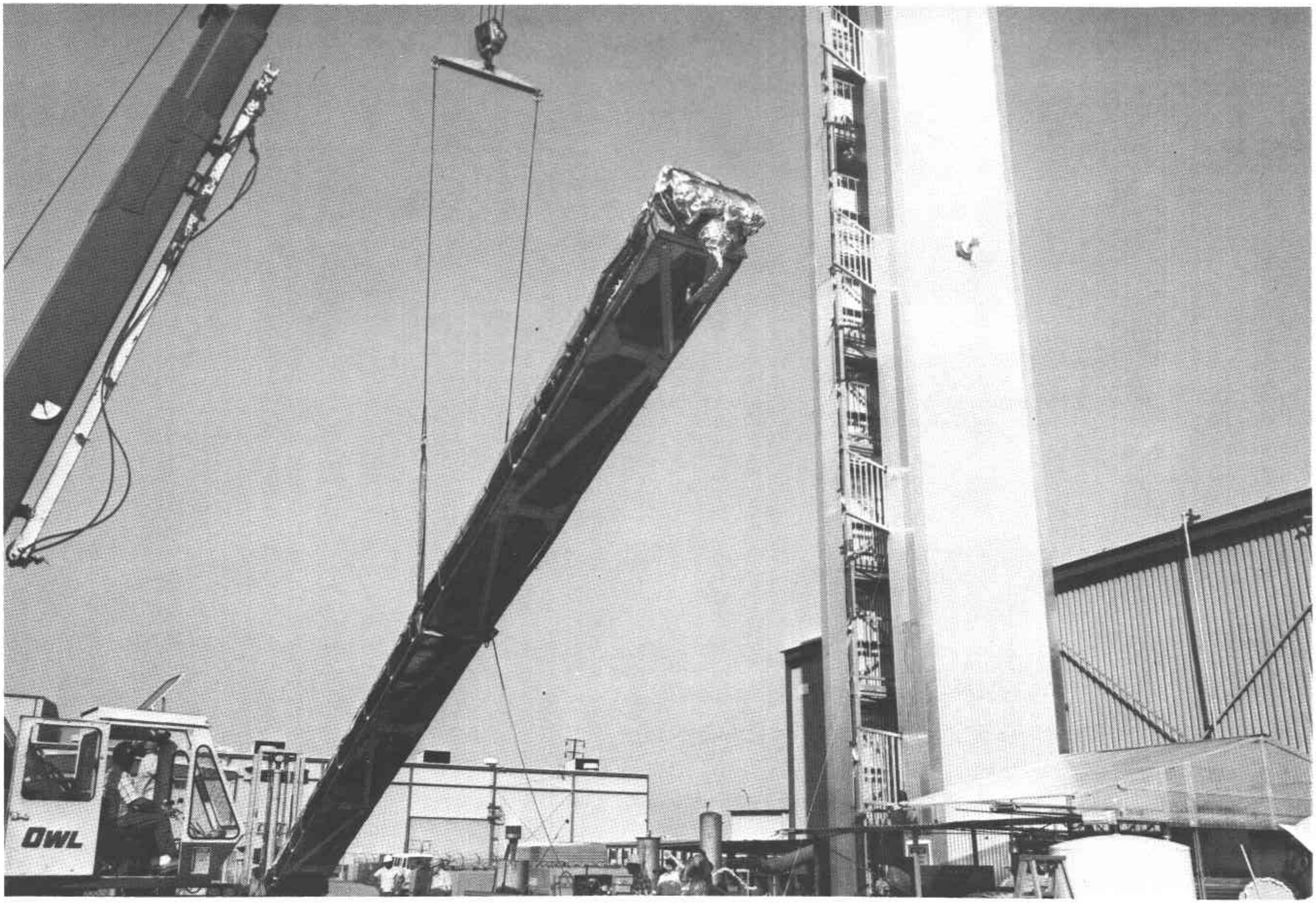


Figure 6-21. Pilot Plant Panel and Test Facility

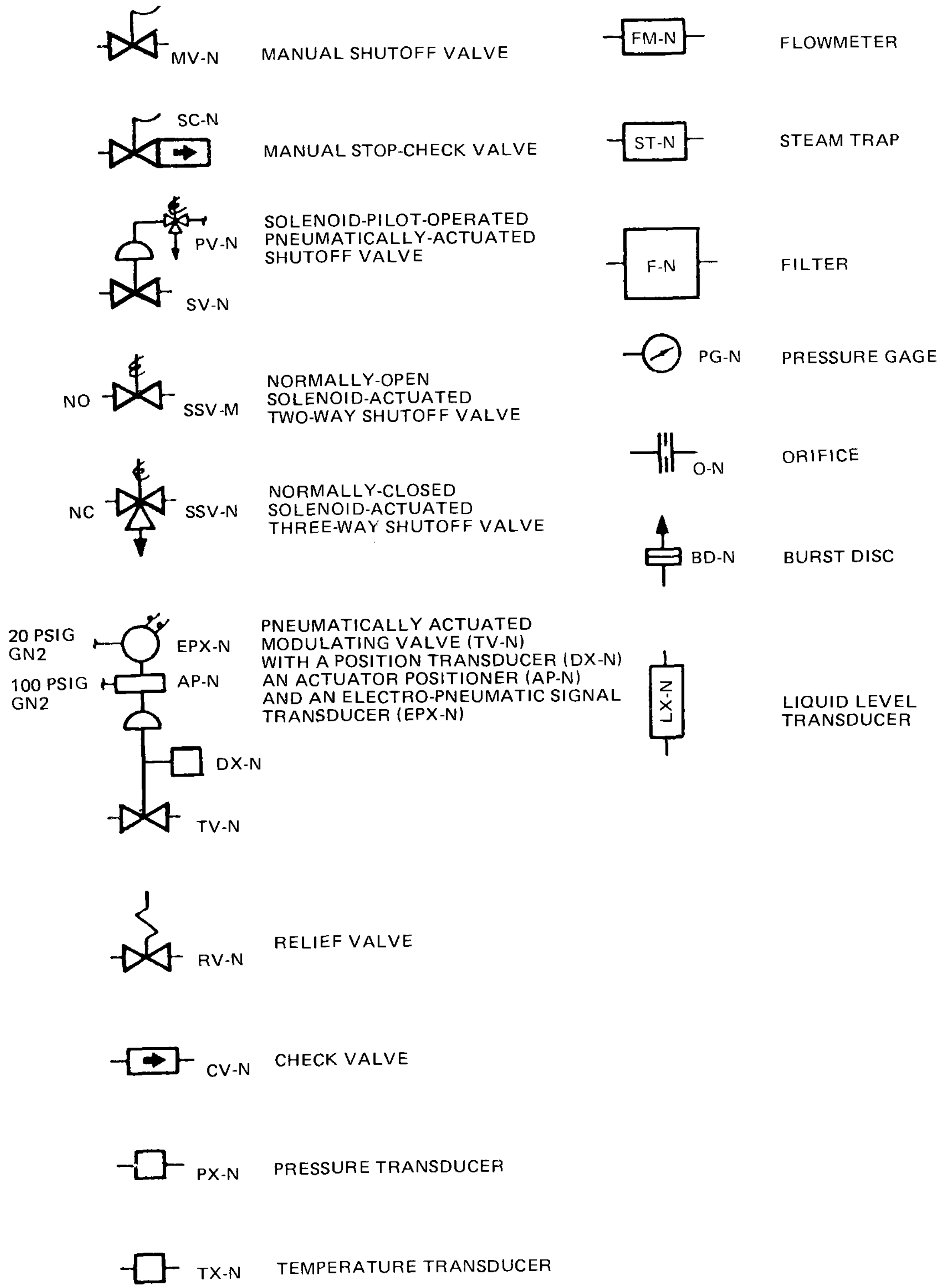
Table 6-4
BOILER WATER CHARACTERISTICS

Dissolved solids	<50 ppb
Undissolved particle size	<10
Dissolved oxygen	Trace
pH	9.5 ± 0.1

in this polishing unit to reduce the dissolved solids to the desired value. Determination of dissolved solids is made by measuring the electrical conductivity of the water and removal of the oxygen is accomplished by the addition of hydrazine. Measurement of the hydrazine content was used as an indication of the amount of oxygen present addition of hydrazine also serves to raise the pH from the original value of 7. If the pH value resulting from the hydrazine addition was not sufficient to satisfy the requirement, ammonia was added to further increase the pH. pH was measured and indicated directly. The purified water was transferred from the low-pressure, low-temperature polishing unit to a second storage vessel. When this vessel was full the pressure is raised to approximately 2.4 MN/m^2 (350 psig) and the water transferred under pressure to the facility run tank. A heating unit between the two tanks heated the water to the desired run temperature during the transfer operation. A 5-micron filter is also located between the two tanks to filter the water during the transfer.

The low-pressure GN_2 pressurizing system, shown in Figure 6-22 is used to provide an inert blanket for the system during periods of non use. The 2.1-MN/m^2 (300 psig) GN_2 system was used to provide a pressure in excess of the vapor pressure during the filling operation to prevent boiling. The GN_2 supply system indicated in the figure provides the high-pressure GN_2 to force the water through the system. Included in the GN_2 system (Figure 6-22), is a network of check valves and solenoid actuated shutoff valves for control.

Fill, vent, and drain systems are also shown on the facility tank. The level sensor indicated the water level in the supply tank. TV-2 is the backpressure regulating valve on the flash tank and SV-6 is a vent valve. The water drain valve is indicated by the symbol ST-1.



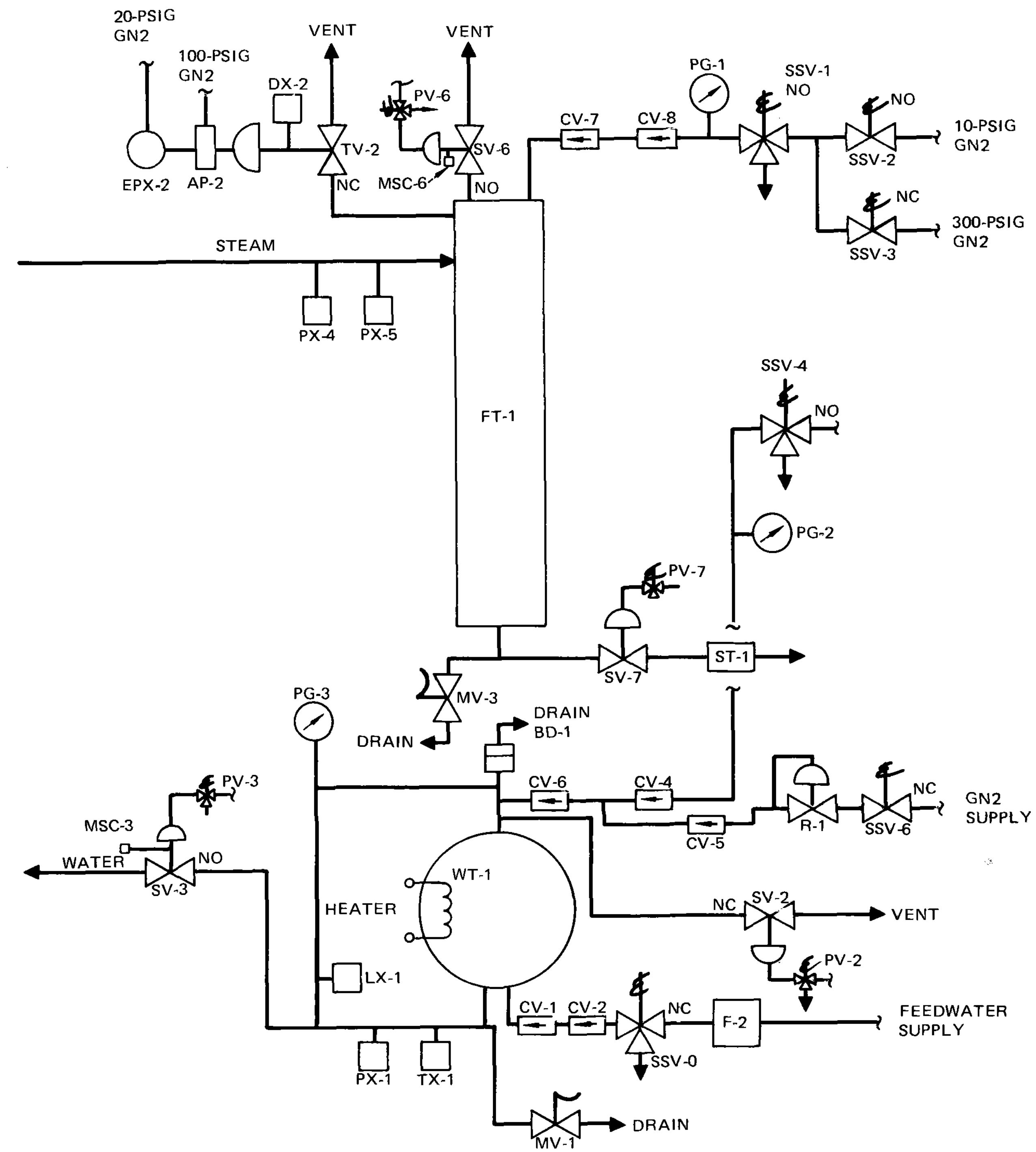


Figure 6-22. Facility Schematic for Receiver Panel Tests

The digital data acquisition facility is shown in Figures 6-23 and 6-24. The system includes multiplexors and analog/digital convertors, a double tape unit for recording the incoming data together with a programmer for organizing and formating data. Two separate analog digital convertors with visual displays are shown in the center of the lower right-hand photograph. These can be used for monitoring real-time data or tape outputs for playback of two channels of taped data. Two video display units are also available as is a printing unit shown to the left in Figure 6-24. The vertical unit in Figure 6-23 includes a programmer for converting the data into engineering units and tape recorder for storing the engineering data. Digital (numerical on paper) printout equipment is shown in the foreground of Figure 6-24. Card printout is also available.

6.4.2 TRW Thermophysics Lab

This TRW facility, in Redondo Beach, California, was used to determine the absorptivity and emissivity of several samples of Incoloy coated with various high-absorptivity paints. The facility includes a Beckman DK2A spectrophotometer with an integrating sphere which was used to determine reflectance data over the wave length region of 0.282-2.5 microns. A Gier Dunkle mobile solar reflectometer (MS 250) was used to measure reflectivity of the specimen sent to White Sands. This method was used because the sample would not fit into the integrating sphere and the Gier Dunkle instrument provided sufficient accuracy to determine whether any shift in the absorptivity resulted from the solar exposure.

6.4.3 White Sands Solar Furnace

The White Sands solar furnace, in Albuquerque, New Mexico, provided concentrated solar energy for long periods of time to determine the effect of this energy on absorptivity. This facility includes a large plain tracking mirror which directs solar energy into a test section where powers far in excess of the required 0.3 MW/m^2 can be generated.

6.4.4 Rocketdyne Manufacturing

Manufacturing facilities at the Canoga Park location include heavy-duty numerically controlled, tracer control, and conventional equipment for machining high-strength temperature-resistant materials to close tolerances.

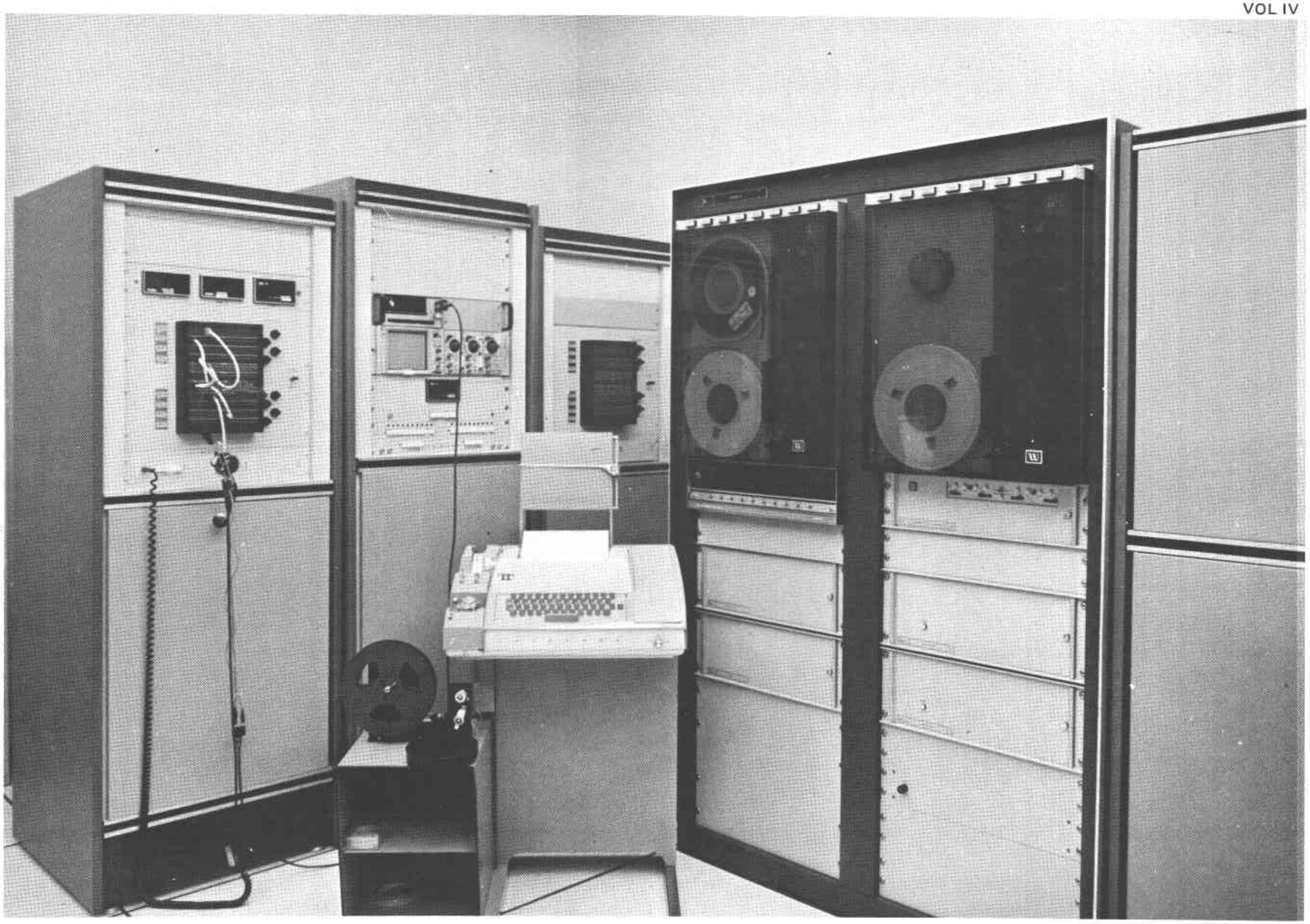


Figure 6-23. Data Acquisition Units

Figure 6-24. Data Reduction and Presentation Units

Also included are metal-forming facilities, general-purpose and specialized welding equipment, chemical processing systems, high-temperature furnace brazing facilities, and electrochemical and electrodischarge machining facilities. An area is also available for final assembly of the receiver unit. Port facilities include QA laboratories that provide metrology, equipment-calibration, and process-control support. A wide range of nondestructive testing and precision measuring equipment is available, as is a Material and Process Laboratory designed for determining properties of materials and for development of manufacturing processes and techniques.

6.5 TEST RESULTS

Test results are discussed in this section in terms of the specific technical issues for which the SRE was addressed. Summaries of the tests conducted on the tubular hardware are presented in Tables 6-5, 6-6, and 6-7 for the single-tube, 5-tube panel, and Pilot Plant panel, respectively. Single-tube, 5-tube, and Pilot Plant panel tests will be identified with the prefix 1-, 5-, or P-, respectively.

The single Pilot Plant tube was tested in the small tower which contained 13 graphite heaters and reflectors. A total of 11 tests were conducted as shown in Table 6-5. The first two tests were made to calibrate heaters which were installed in the heating system upstream of the tube to control the water inlet temperature. The tests were also used to check the expansion characteristics of the tube.

Beginning with Test 1-2A, voltages were applied to the radiant heaters to produce an incident heat flux profile (based on previous calorimeter data on the heaters) which would simulate a maximum flux profile on the south side of the receiver. Water flow conditions were adjusted to prevent steaming so that the absorbed heat flux could be determined from the water temperature measurements along the tube on Tests 1-2A and 1-3. The data indicated that more electrical power was needed so that appropriate corrections to the heater voltages were made.

Table 6-5

SINGLE-TUBE TEST SUMMARY

Test	Duration (Min)	Comment
1-1		Four in-line heaters. No radiant heaters.
1-1A		Three in-line heaters. No radiant heaters.
1-2		~10 V on each graphite radiant heater. No in-line heaters.
1-2A	8.4	High flow to maintain liquid water. Radiant heater volts based on calorimeter data. No in-line heaters.
1-3	6.0	Repeat Test 1-2A at higher power. No in-line heaters.
1-4	7.0	Same heater levels. Reduced flow. Two-phase steam produced.
1-5	7.5	Repeat Test 1-4 with 93°C (200°F) inlet water.
1-6	7.5	Same voltages: 163°C (325°F) inlet water.
1-7	9	Same voltages: 163°C (325°F) inlet water. Lower flow.
1-8	10	Same voltages: 288°C (550°F) inlet temperature.
1-9	7	Same as 1-8. No inlet orifice.

On subsequent tests, the heater voltages were unchanged while the water flow rate was decreased and the inlet temperature increased so that two-phase and, finally, superheated steam were produced. During the test series, it was noted that the absorbed power was decreasing from test to test. On the last two tests, the power had decreased to the point of simulating nearly the minimum power on the receiver.

Several of the heaters failed at the end of the last test. On disassembly of the tower, it was determined that most of the graphite heaters had been oxidized. An argon gas purge of the tower had been used but apparently there was sufficient leakage to render it ineffective in certain areas. The availability of the 5-tube panel and the encouraging stability and cooling results of the single-tube tests rendered it more desirable to begin installation of the 5-tube panel at this time.

Table 6-6

FIVE-TUBE PANEL TEST SUMMARY

Test	Duration (Min)	Purpose/Comments
5-1	17	Calibration and checkout with metallic heaters. No digital data.
5-1	13	Repeat Test 5-1. Digital data acquired.
5-3	16	Calibration at minimum heat flux profile.
5-4	30	Low-temperature steam at minimum heat flux. Facility start sequence verification.
5-5	24	Repeat Test 5-4.
5-6	29	Repeat Test 5-4.
5-7	36	Rated temperature steam at minimum flowrate.
5-8	43	Response to simulated cloud transients. Heaters turned off and on twice.
5-9	30	Response to loss of water flow. Water flow terminated for 2, 10, and 60 sec while maintaining heat flux.
5-10	20	Determine lateral uniformity of heat flux. Panel orificed at inlet for this test only.
5-11	37	High-temperature steam with moderate heat flux level.
5-12	6	Checkout test with graphite heaters.
5-13	7	Low-temperature steam at moderate power level. Produced two-phase steam.
5-14	7	Repeat Test 5-13. Produced superheated steam.
5-15	10	High-temperature steam at maximum heat flux.
5-16	7	High-temperature steam at high heat flux.

Based on these tests, the decision was made to use metallic heaters for the low heat flux tests on the five-tube panel. Methods of reducing gas purge leakage and air entrance were also implemented. Slightly over 1 hr (62 min) of operating time was accumulated during the 5-tube test program. The tests were conducted as shown in Table 6-6. A total of 16 tests were conducted for accumulative duration of 332 min. Tests 5-1 to 5-3 and Test 5-12 were conducted with ambient temperature inlet water flowing at a higher

Table 6-7 (Page 1 of 2)
PILOT PLANT RECEIVER SEGMENT TEST SUMMARY

Test	Duration (Min)	Purpose	Comments
P-1	25	Checkout, calibration, and preheater panel simulation	Successful subcooled liquid operation.
P-2	25	Preheater simulation and calibration	Repeat of Test P-1 at higher power.
P-3	23	Preheater simulation and calibration	Repeat of Test P-2 at higher power.
P-4	25	Boiler simulation	Stable operation producing two-phase steam at 1,500 psi (620 to 1,000°F).
P-5	90	Boiler simulation	Stable operation producing superheated steam at rated and derated pilot plant conditions.
P-6	61	Boiler simulation	Stable operation at derated conditions.
P-7	45	Initial (low-pressure) phase of Pilot Plant start	Stable at 2.75 MPa (400 psi) and 260°C and 370°C (500°F and 700°F) outlet temperatures.
P-8	55	Full Pilot Plant start simulation (manual)	260°C and 340°C (500°F and 650°F) at 400 psi. Then to 1,500 psi at 340°C (650°F).
P-9	35	Boiler simulation	580°C (1,100°F) at 10.3 MPa (1,500 psi). Shut-down due to burning rag on top of tower. No damage.
P-10	31	Closed-loop control	Valve closed as required by low temperature.
P-11	33	Graphite heater test	Low power on heaters.
P-12	39	Moderate heat flux	Moderate power on graphite heaters.
P-13	42	Moderate heat flux	Repeat Test P-12 at lower steam temperature.
P-14	60	Moderate heat flux	Repeat Test P-12 at lower steam temperature.
P-15	32	Closed-loop control	Demonstrated temperature control with subcooled effluent.

Table 6-7 (Page 2 of 2)

PILOT PLANT RECEIVER SEGMENT TEST SUMMARY

Test	Duration (Min)	Purpose	Comments
P-16	94	Moderate heat flux	
P-17 *	77	High heat flux and closed-loop control	Controls portion of test terminated when valve closed.

*Does not include 14 subsequent company-funded controls and high flux tests.

than normal flowrate in order to provide a subcooled effluent for purposes of calibrating the heat load and heat flux profile. The first 11 tests were conducted with metallic heaters.

The start sequence for Tests 5-4 through 5-11 was as follows: The tank pressure was set to 1.24 MPa (1,800 psig) and the backpressure and flow control valves were set to provide the required flowrate at a panel pressure of approximately 0.28 MPa (400 psig). The in-line water heaters were then energized to provide the required panel inlet temperature. Some tests were started when the inlet temperature reached the desired values; on other tests the entire system was allowed to come to nearly thermal equilibrium.

The tests were initiated by energizing the radiant heaters. This process required approximately 2 min on the initial tests to approximately 30 sec as experience was gained in controlling the power rise rate accurately. During the start transient, flow, and pressure were controlled using the backpressure and flow control valves. Generally, the flow control valve required little or no adjustment during this start transient.

The start sequence for Tests 5-12 through 5-16 was similar to that described above except that, in order to preheat the panel as much as possible (thereby minimizing the duration required with the radiant graphite heaters), the in-line heaters were set to produce a panel inlet temperature of approximately 315°C (600°F) before initiating the radiant heat portion of the test. When the radiant heaters were turned on, the in-line heater power levels were reduced to the values which would produce the required inlet temperature.

Most of the tests were conducted with metallic heaters to demonstrate flow stability and uniformity under the most critical operating conditions. During the latter tests with graphite heaters, heat fluxes up to and exceeding the Pilot Plant maximum value were reached and heat loads approaching the Pilot Plant maximum value were attained.

A total of 17 tests were conducted on the Pilot Plant segment for a duration of 792 min (13.2 hr) during the contract. Fourteen additional tests were conducted on the segment during a company-funded program, bringing the accumulated duration of test to 35 hr. Receiver segment tests are summarized in Table 6-7. Again, most of the tests were conducted using metallic heaters in order to adequately investigate stability and flow uniformity at the low heat flux regime. High heat flux tests with graphite heaters were accomplished by placing these heaters at the most critical location on the tower. Although total heat loads were fairly low on these tests, heat fluxes up to the Pilot Plant maximum value were absorbed.

Operating conditions for the tests on the Pilot Plant receiver segment are given in Table 6-8. The first three tests were conducted at high water flowrates to maintain liquid water conditions throughout the panel. This was done to simulate preheater operation and to calibrate the absorbed power vs the applied electric heater voltage. In order to obtain maximum power from the system, the power dropoff at the top and the bottom of the panel which occurred during Pilot Plant operation was not simulated. The first 10 tests were conducted with metallic heaters used to heat the entire panel. The water flowrate was reduced on Test P-4 to produce two-phase steam. Superheated steam was produced for the first time on Test P-5. Steam temperatures approximating both derated and rated Pilot Plant operating temperatures were produced on this test. A small facility backpressure valve with no flash tank was used to control backpressure on the first five tests. Prior to the sixth test the 2-in. (nominal) backpressure valve and the flash tank were plumbed into the system. Test P-6 was conducted to check out the operation of these components at approximately derated Pilot Plant superheat conditions. Operation was stable and satisfactory.

The panel was usually preheated by the radiant heaters prior to initiating flow because of the critical water supply capacity. The first stage of a Pilot Plant start was simulated using manually operated steam temperature and backpressure control valves on Test P-7. This sequence simulated the low-pressure portion of the start sequence with superheated steam temperatures of approximately 260°C and 370°C (500°F and 700°F) steam being generated.

Table 6-8 (Page 1 of 2)

RECEIVER SEGMENT OPERATING CONDITIONS

Test	Flowrate kg/sec	(lb/sec)	Inlet Temperature °C	(°F)	Outlet Temperature °C	(°F)	Outlet Pressure MPa	(psia)	Absorbed Power MW	(Btu/Sec)
P-2	0.48	(1.06)	14	(58)	90	(190)	-	0	0.04	(37)
P-3	0.50	(1.1)	12	(54)	195	(380)	-	-	0.27	(253)
P-4	-	-	225	(440)	325	(620)	10.9	(1,575)		
P-5	-	-	160	(320)	330	(630)	11.7	(1,705)		
	-	-	160	(320)	530	(990)				
P-6	0.14	(0.31)	160	(320)	375	(710)	9.8	(1,425)	0.33	(315)
P-7	0.18	(0.39)	150	(300)	300	(570)	2.9	(425)	0.42	(395)
P-8	0.18	(0.39)	140	(280)	380	(540)	3.1	(445)	0.42	(395)
	0.17	(0.37)	150	(300)	325	(620)	2.9	(420)	0.41	(390)
	0.17	(0.37)	165	(330)	350	(660)	9.5	(1,385)	0.37	(353)
P-9			130	(270)	625	(1,160)	8.7	(1,265)		
P-10**	0.15	(0.33)	100	(210)	330	(660)	10.0	(1,445)	0.37	(355)
P-11	0.16	(0.35)	100	(210)	315	(600)	10.4	(1,505)		
P-11*	0.16	(0.35)	100	(210)	390	(730)	10.4	(1,505)	0.42	(395)
P-12	0.15	(0.32)	120	(250)	345	(650)	9.6	(1,395)	0.35	(330)
P-12*	0.14	(0.31)	120	(250)	440	(825)	10.4	(1,510)	0.38	(360)

*With graphite heaters
**Before control

Table 6-8 (Page 2 of 2)
RECEIVER SEGMENT OPERATING CONDITIONS

Test	Flowrate kg/sec	(lb/sec)	Inlet Temperature °C	(°F)	Outlet Temperature °C	(°F)	Outlet Pressure MPa	(psia)	Absorbed Power MW	(Btu/sec)
P-13	0.16	(0.35)	95	(200)	310	(590)	9.6	(1,400)		
P-13*	0.15	(0.33)	95	(200)	380	(720)	10.1	(1,465)	0.40	(375)
P-14	0.15	(0.33)	110	(230)	415	(775)	10.2	(1,485)	0.40	(380)
P-14*	0.19	(0.41)	115	(235)	375	(710)	10.0	(1,445)	0.47	(450)
P-15	0.35	(0.78	125	(260)	260	(500)	10.1	(1,465)	0.22	(205
P-16	0.16	(0.35)	105	(216)	335	(635)	10.8	(1,565)	0.39	(365)
P-16*	0.15	(0.33)	105	(216)	390	(730)	10.8	(1,565)	0.39	(370)
P-17	0.15	(0.33)	200	(390)	310	(590)	10.7	(1,550)		
P-17*	0.15	(0.32)	200	(390)	320	(610)	10.7	(1,550)	0.52	(495)

*With graphite heaters

This same start sequence was repeated in Test P-8. On this test, the sequence was continued to include the transition from low pressure up to rated operating pressure.

Maximum allowable voltage was applied to the metallic heaters on Test P-9. This test was terminated prematurely because of a burning rag on the top floor of the tower. Post-test examination of the area indicated no damage.

Test P-10 was the first test attempted with closed-loop control on the steam temperature-control valve. The control circuit compared the indicated discharge temperature with a set temperature and, using proportional and integral control logic, directed the valve to maintain a constant temperature. The transient which resulted in transitioning from manual to automatic control resulted in a high water flowrate and low temperature. Responding to this temperature, the valve went fully closed to restore the temperature to its nominal value. Shutdown was initiated when the valve closed. Had the test been continued, it is probable that the valve would have opened again as the temperature exceeded the set point. The results of this test also indicated that the valve was responding too rapidly and the gain constants were changed accordingly.

The six metal heaters at the top of the tower (the steam discharge end of the panel) were replaced with high flux graphite heaters prior to Test P-11. The graphite heaters were operated at relatively low voltage on this test. The voltage to the graphite heaters was increased for Test P-12. Approximately the same power level was maintained during Tests P-13 and P-14. On these tests the flowrate was varied in order to determine heat-transfer characteristics with various liquid side flow conditions. Changing the flowrate varied the thermodynamic properties as well as the fluid velocity.

It had come apparent at this point that the temperature control valve was too large for the system. There was insufficient time remaining during the contracted test program to provide reduced size trim for the valve. (This was subsequently done under a company-sponsored test program.) Thus, in order to demonstrate control with the valve in a more opened position, Test P-15 was conducted with a high water flowrate which resulted in subcooled water effluent. The valve controlled satisfactorily to the subcooled set temperature during this test. An alternate approach to forcing the steam temperature control valve to a more open position was attempted on Test P-16. The system pressure drop was reduced to 0.34 MPa (50 psi). However, the system proved to be too sensitive to variations in the backpressure valve position, which was being controlled manually.

Test P-17 included a controls test using the metallic heaters only, i.e., no power was supplied to the graphite heaters at the steam end of the panel. During the transient which resulted from the transition from manual to closed-loop control, a high water flowrate again signalled the valve to go closed. Since it was not possible to prevent full closure of the valve (no mechanical stop was installed as would be the case in the pilot valve), and a significant unheated length of panel intervened between the temperature-sensing thermocouple, the closed valve resulted in the thermocouple sensing an even cooler temperature which maintained the valve in a closed position until manual control was restored. A final graphite heater test was made with the water valve in manual control.

6.5.1 Cooling

Tests on the tubular hardware produced data indicating the conservatism of the cooling analyses used in the Pilot Plant receiver primary design.

6.5.1.1 Single-Tube and 5-Tube Panel Tests

Due to the degradation of the graphite heaters during the single-tube tests, quantitative data relating hardware temperature to heat flux was not obtained. However, the axial temperature profile shown in Figure 6-25 for Test 1-9 indicates the absence of the high temperature condition analytically predicted to occur near the end of the two-phase steam region.

Absorbed heat loads (ΣQ_A) were determined for the 5-tube panel by multiplying the difference in the specific enthalpy of the water at the exit and inlet of the panel by the water flowrate. These data are presented in Table 6-9. Absorbed power could not be calculated for those tests (5-12 and 5-13) where the effluent was in the two-phase condition. The range of the values of absorbed power per tube on the Pilot Plant ranges from 0.006 MW/tube

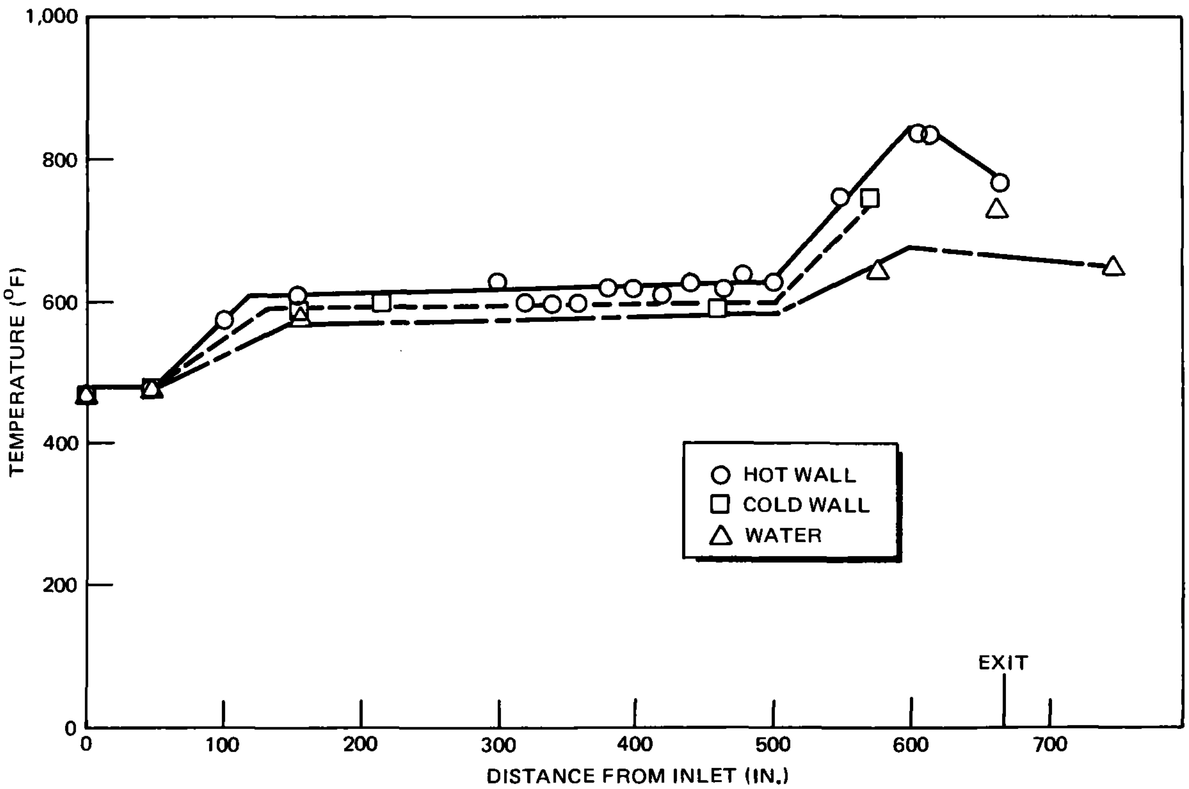


Figure 6-25. Temperature Profiles, Single Tube Test 1-9

Table 6-9

ABSORBED POWER LEVELS

	T_{in}		T_{out}		Δh		Flow		ABSORBED POWER Panel		ABSORBED POWER Tube	
Test	°C	(°F)	°C	(°F)	J/kg $\times 10^{-3}$	(Btu/lb)	kg/sec	(lb/sec)	MW	(Btu/sec)	MW	(Btu/sec)
5-1	21	(70)	235	(460)	930	(400)	0.030	(0.066)	27.9	(26.4)	5.6	(5.3)
5-2	24	(75)	245	(470)	939	(404)	0.030	(0.065)	27.7	(26.3)	5.6	(5.3)
5-3	21	(70)	260	(500)	1,010	(435)	0.040	(0.089)	40.8	(38.7)	8.1	(7.7)
5-4	225	(440)	430	(810)	2,200	(947)	0.014	(0.0305)	30.4	(28.9)	6.1	(5.8)
5-5	150	(305)	445	(835)	2,560	(1,100)	0.014	(0.0305)	35.4	(33.6)	7.1	(6.7)
5-6	130	(265)	385	(725)	2,460	(1,060)	0.014	(0.030)	33.7	(31.9)	6.8	(6.4)
5-7	200	(390)	525	(980)	2,580	(1,110)	0.013	(0.0295)	34.7	(32.9)	7.0	(6.6)
5-8	145	(290)	415	(780)	2,510	(1,080)	0.014	(0.0305)	34.8	(33.0)	7.0	(6.6)
5-9	170	(340)	460	(860)	2,530	(1,090)	0.014	(0.0305)	34.9	(33.1)	7.0	(6.6)
5-10	21	(70)	304	(580)	1,270	(547)	0.024	(0.052)	30.0	(28.4)	6.0	(5.7)
5-11	170	(340)	640	(1,180)	1,860	(1,280)	0.018	(0.040)	53.9	(51.1)	10.8	(10.2)
5-14	180	(360)	435	(820)	2,420	(1,040)	0.027	(0.059)	64.6	(61.2)	12.8	(12.2)
5-15	230	(450)	595	(1,100)	2,600	(1,120)	0.063	(0.14)	166	(157)	33.1	(31.4)
5-16	160	(320)	620	(1,150)	2,980	(1,280)	0.043	(0.094)	128	(121)	25.4	(24.1)

(5.7 Btu/sec-tube) for the minimum value on the southern portion of the receiver to 0.042 MW/tube (40.6 Btu/sec-tube) for the maximum value on the northern side of the receiver.

Absorbed heat fluxes were calculated for specific tests as follows. The total electrical power (ΣP_1) was determined by adding the electrical power furnished to each of the heater elements. The absorbed power in each heating zone was determined from

$$Q_{A_n} = \Sigma Q_A \left[P_{1_n} / \Sigma P_1 \right]$$

The heat flux levels were determined by dividing the values of $(Q_A)_n$ by the area of the panel under the particular heater.

Maximum flux in the two-phase region occurred on Test 5-15. The heat flux absorbed at heater No. 7 during this test was 0.28 MW/m^2 (0.17 Btu/in.^{2}-sec). This represents a heat flux of approximately 88% of the maximum value anticipated on the Pilot Plant. The heat flux profile for Test 5-15 is shown in Figure 6-26. The heat flux profile for Test 5-6, one of the low heat flux tests, is shown in Figure 6-27.

Maximum predicted and experimental wall temperatures were compared for a high heat flux test and for a low heat flux test. The predicted values were determined using the methods described in the Preliminary Design Baseline Report,* based on experimental heat fluxes, flowrates, and pressures.

The results of the comparison are shown in Table 6-10. These results indicate the predicted values to be conservative over the entire range of heat fluxes.

*MDC G6040, January 1976.

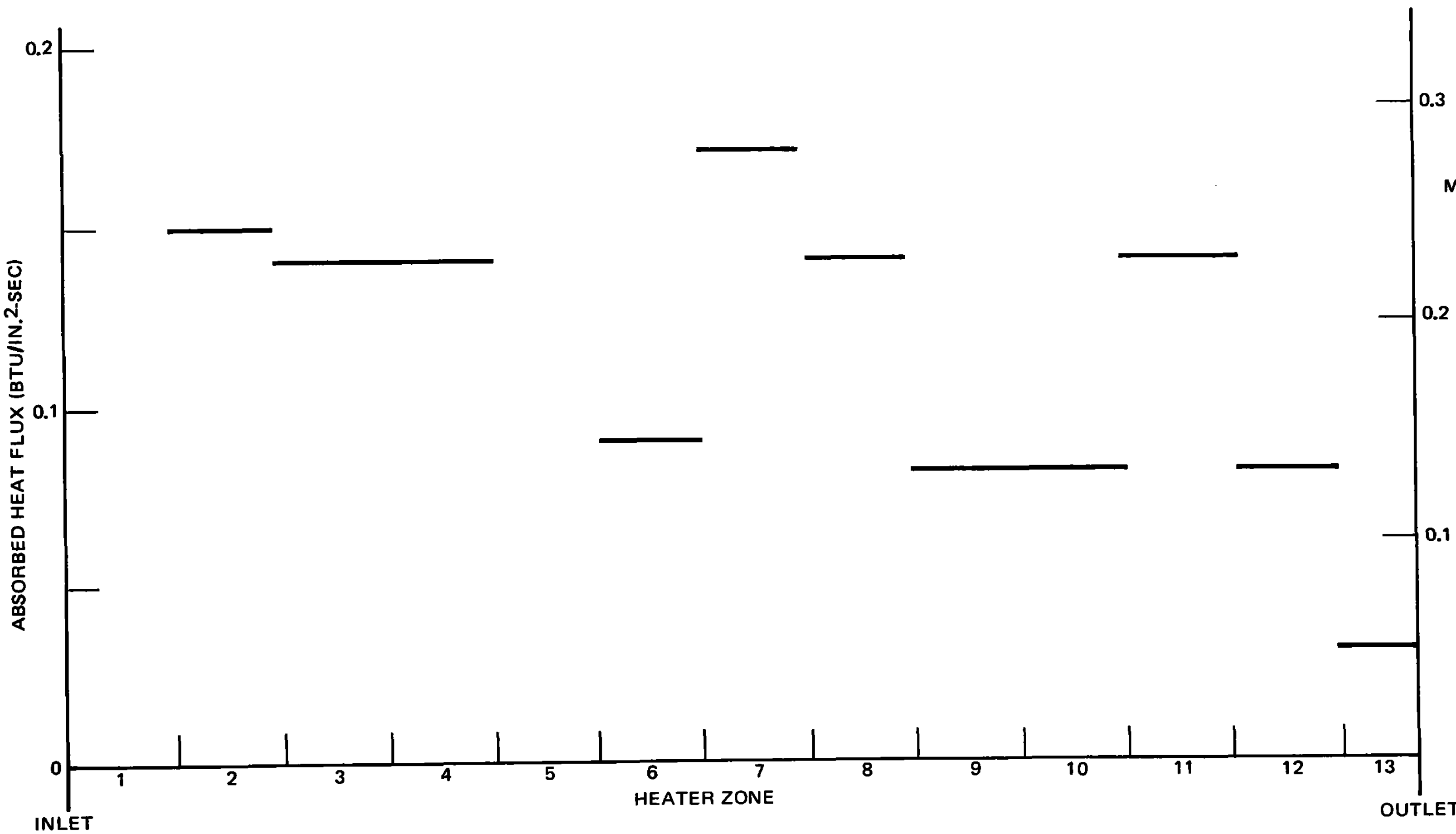


Figure 6-26. Heat Flux Profile – Test 5-15

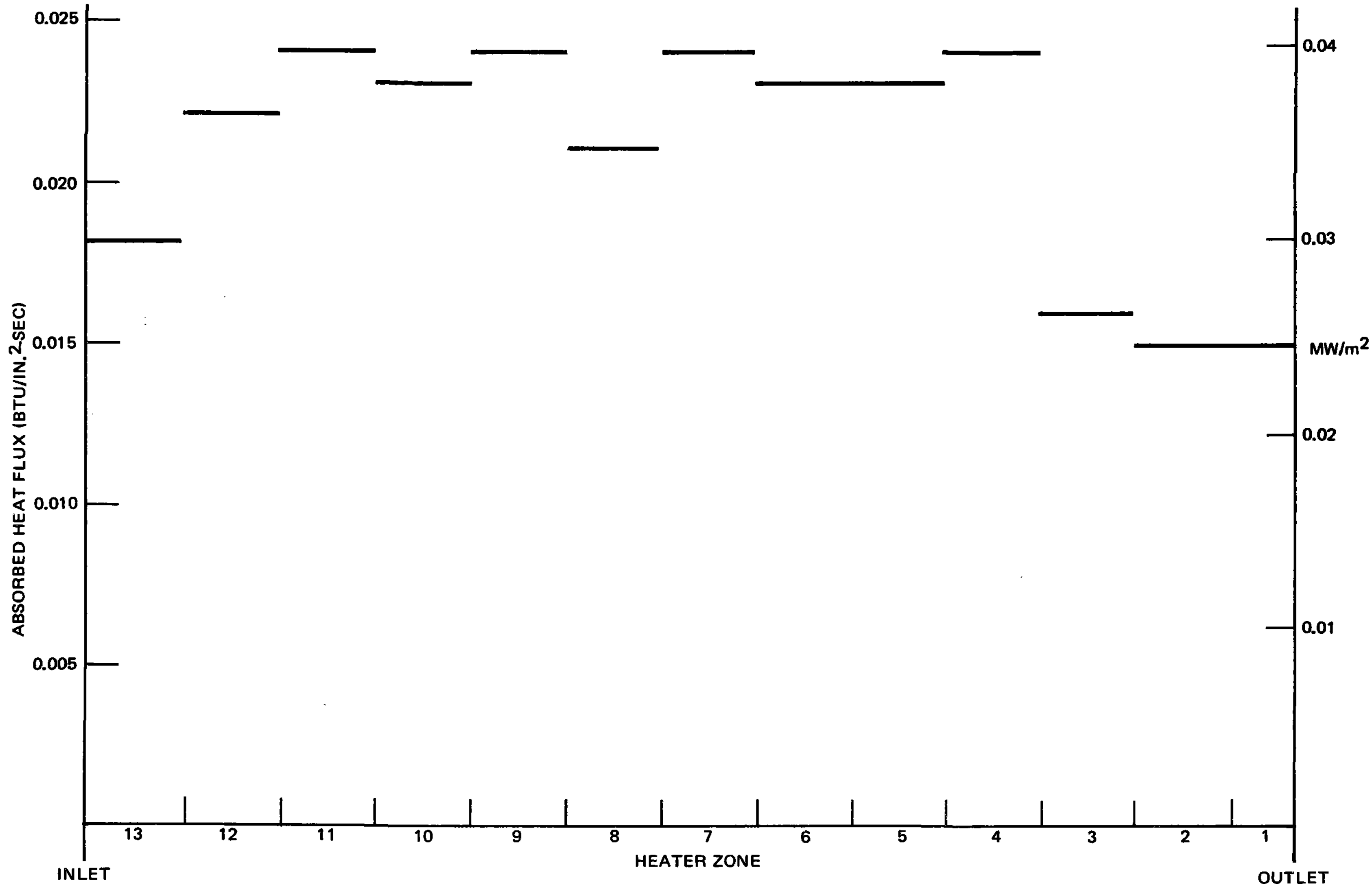


Figure 6-27. Heat Flux Profile — Test 5-6

Table 6-10

TUBE WALL MAXIMUM TEMPERATURE COMPARISONS

Test	Absorbed Heat Flux MW/m^2 (Btu/in.^{2}-sec)	Quality at Maximum Temperature Point (%)	Wall Temperature, °C (°F) Predicted	Wall Temperature, °C (°F) Measured
5-6	0.026 (0.016)	98	355 (670)	330 (630)
5-15	0.28 (0.17)	85	655 (1,215)	555 (1,030)

6.5.1.2 Seventy-Tube Panel Tests

The steam discharge temperatures and absorbed power levels for the 70-tube tests were presented in Table 6-8. A maximum power level of 0.52 MW (21% of the maximum power on Pilot Plant panel which receives the most insolation and 68% of the maximum power on the southern panels) was absorbed by the panel due to facility limitations.

The ratio of absorbed heat flux to flowrate is a more significant indication of the severity of the test conditions. Six graphite heaters were installed (replacing the metallic heaters) at the steam end of the panel prior to Test P-11. The heater at the extreme end of the panel had a higher heat flux capability than the other five heaters. A thermocouple measured the tube wall hot-side temperature under the high flux heater. The heat flux for each heater was determined by multiplying the measured electrical power by the efficiency determined by calibrating the heaters (Figure 6-28).

Power and heat flux data for the graphite heater area is summarized in Table 6-11. Heat flux vs flowrate is plotted in Figure 6-29. Heat fluxes approaching the Pilot Plant maximum value have been demonstrated. More significantly, these fluxes occurred at flowrates which were considerably lower than the flowrates which will occur in the Pilot Plant at corresponding heat flux levels. Measured hot wall temperatures are generally (except Test P-12) of the same magnitude as the maximum predicted for the Pilot Plant even though the experimental heat flux-to-flowrate ratios are much higher.

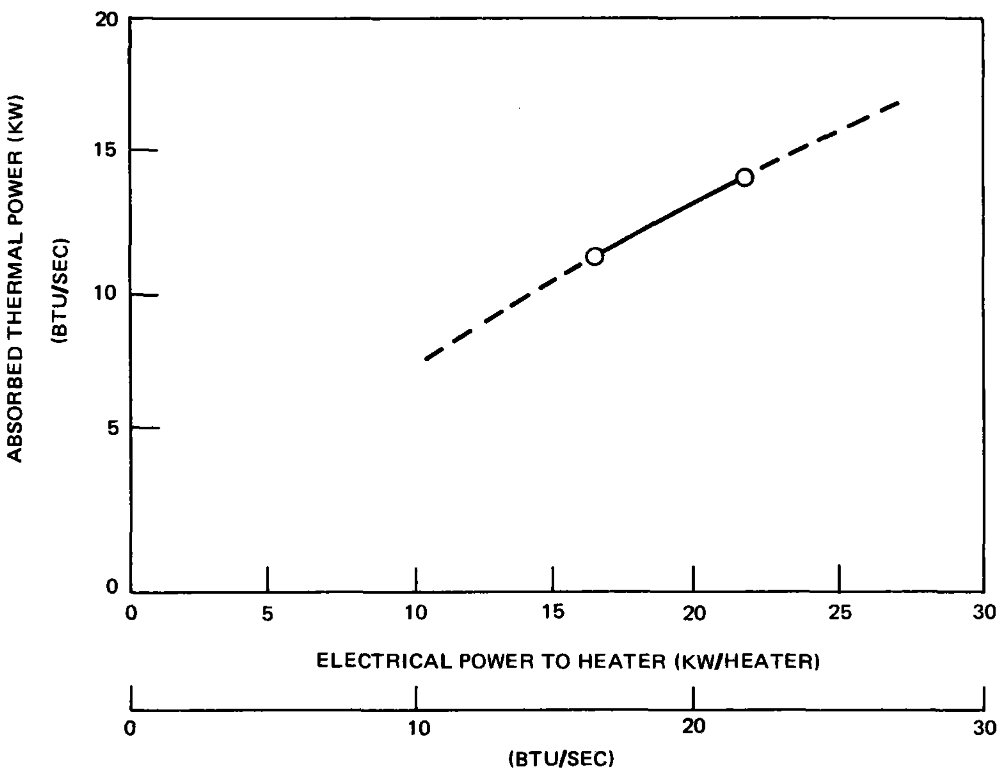


Figure 6-28. Typical Graphite Heater Assembly Calibration

Table 6-11

HIGH FLUX TEST CONDITIONS

Test	Electric Power*	Thermal Power*	Max. Absorbed Heat Flux	Flowrate	Max. Flux/Flow	Max. Wall Temperature,
	MW (Btu/sec)	MW (Btu/sec)	MW/m^2 (Btu/in^2-sec)	kg/sec (lb/sec)	$\frac{MW\text{-}sec}{kg\text{-}m^2}\left(\frac{Btu}{(lb\text{-}in^2)}\right)$	°C (°F)
P-12	0.101 (96)	0.071 (67)	0.16 (0-10)	0.14 (0.31)	1.14 (0.32	660 (1,220)
P-13	0.113 (107)	0.077 (73)	0.22 (0.13)	0.15 (0.33	1.47 (0.39)	593 (1,100)
P-14	0.083 (79)	0.057 (54)	0.23 (0.14)	0.19 (0.41)	0.21 (0.34)	577 (1,070)
P-16			0.25 (0.15)	0.15 (0.33)	1.67 (0.46	571 (1,060)
P-17	0.058 (55)	0.044 (42)	0.22 (0.13)	0.15 (0.32)	1.47 (0.41)	
Pilot Plant Panel at Maximum Flux			0.31 (0.19)	1.40 (3.09)	0.22 (0.06)	582 (1,080)

*In region of high flux heaters.

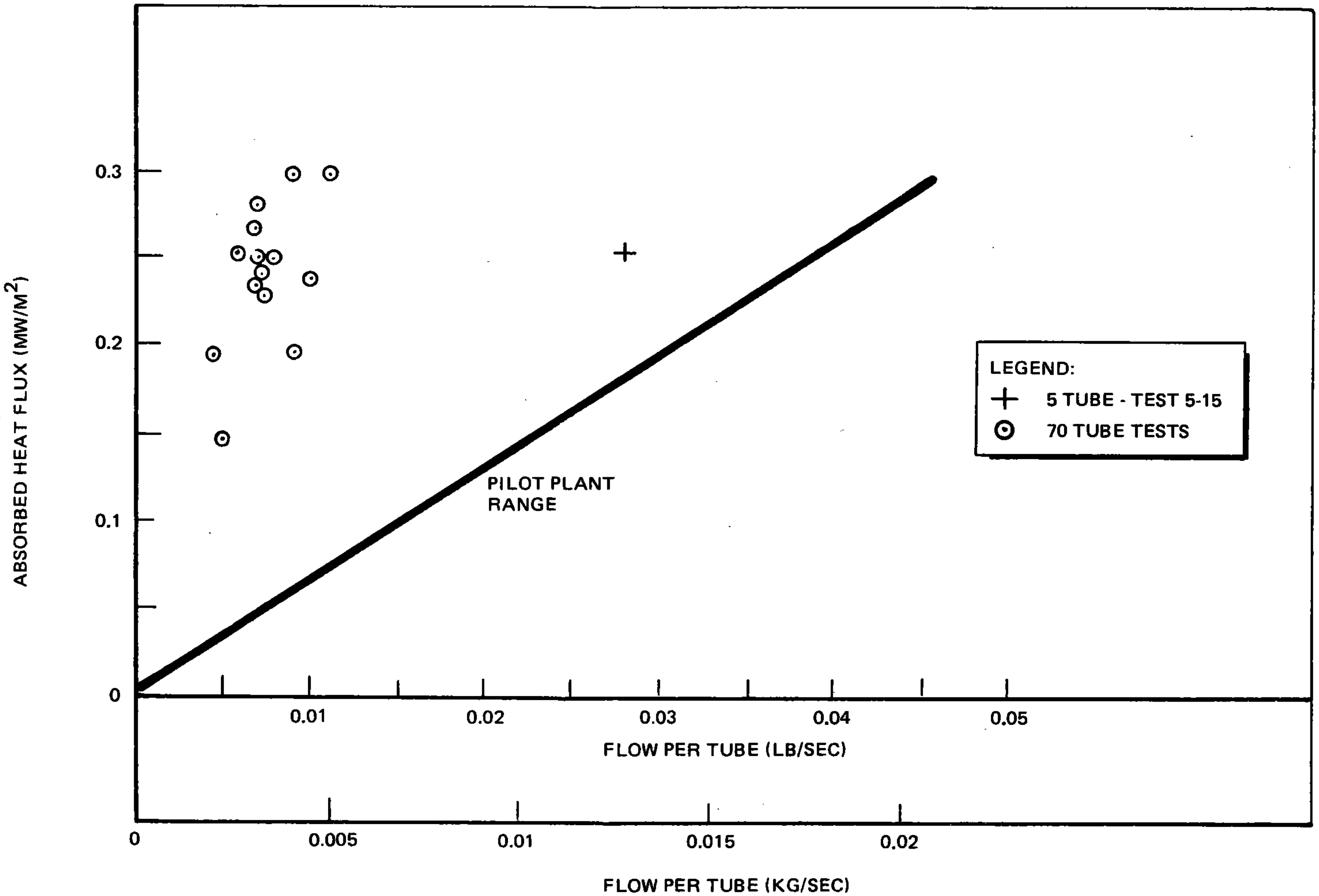


Figure 6-29. Pilot Plant Panel High Heat Flux Test Conditions

With permission of the Department of Energy, a company-funded test program was subsequently conducted with the panel adding six more graphite heaters to the outlet region of the panel. The results of these tests are shown in Table 6-12. A maximum total power of 0.51 MW (535 Btu/sec) was absorbed. Heat fluxes up to the maximum Pilot Plant design value of 0.31 MW/m^2 (0.19 $Btu/in.^2$-sec) were absorbed. Panel outlet steam temperature was measured by thermocoupled welded to the tubes approximately 10 cm (4 in.) downstream of the last heater. Steam conditions ranging from two-phase through superheat intermediate between rated and derated conditions were achieved.

The tube hot wall temperature was measured at the centerline of the last heater at the 16.8m (663 in.) axial station. These temperatures were approximately 50°C (100°F) lower than measurements taken at the same location during the contract tests. Either set of data (especially considering the low flowrate compared to Pilot Plant flows for these heat flux levels) indicates a comfortable thermal margin for the tubes. The values of the ratio of heat flux to flowrate per tube shown in Table 6-12 are considerably above the maximum Pilot Plant value of approximately 15 $MW\text{-}sec/m^2\text{-}kg$.

The thermal environment of the panel for the SRE is different from that of an actual receiver. Radiation and convection losses are small for the SRE. A test was conducted in which sections of the dry panel were heated and allowed to cool. The resulting temperature decay rates were used to estimate the losses which were primarily due to conduction to the supports and some natural convection. The results, summarized in Table 6-13, indicate these losses to be small. Actual conduction losses would be less than those which occurred during the experiment because of the warmer structure in the former case.

6.5.1.3 Overall Conclusions

The results of the SRE data indicate that the test hardware had absorbed heat loads approaching the maximum Pilot Plant value. Flux levels during the SRE program exceeded the values anticipated on the Pilot Plant receiver. Heat flux levels are meaningful only in connection with the associated coolant

Table 6-12

EXTENDED HIGH FLUX TESTS

Flow/Tube		Total Panel Power		Peak Heat Flux		Location of Peak Q/A		Q/A at 16.8m (663 in.)		Tube Temp at 16.8m (663 in.)		Steam at Panel (Tube) Outlet			Max
kg/sec	lb/sec	MW_t	Btu/sec	MW/m^2	$Btu/in.^2$-sec	m	in.	MW/m^2	Btu/m^2-sec	°C	°F	°C	°F	Quality %	$\frac{MW\text{-}sec}{m^2\text{-}kg}$
0.0050	0.0110	0.51	535	0.31	0.19	16.2	639	0.20	0.12	345	650	315	600	65	62
0.0045	0.0100	0.44	450	0.24	0.145	16.2	639	0.23	0.14	355	675	315	600	65	53
0.0041	0.0091	0.51	535	0.21	0.13	16.5	649	0.20	0.12	345	650	315	600	90	49
0.0031	0.0069	0.51	535	0.23	0.14	15.8	623	0.20	0.12	540	1000	420	790	-	74
0.0031	0.0069	0.50	525	0.24	0.145	15.9	627	0.19	0.115	525	975	405	760	-	72
0.0030	0.0067	0.50	525	0.28	0.17	16.2	639	0.20	0.12	490	910	375	710	-	93
0.0029	0.0064	0.48	510	0.27	0.165	16.2	639	0.20	0.12	520	965	390	730	-	93
0.0032	0.0070	0.46	485	0.25	0.15	16.2	639	0.22	0.13	495	920	365	685	-	69
0.0032	0.0070	0.43	455	0.25	0.15	16.8	663	0.25	0.15	465	870	330	630	-	69

Table 6-13
PANEL COOLING RATES

Panel Side	Initial Temp °C	Initial Temp °F	Final Temp °C	Final Temp °F	Time (Min)	Heat Loss MW/m^2 Btu/in.^{2}-sec
Hot	215	(415)	190	(375)	3.3	
Cold	175	(350)	160	(320)	3.3	
Average	195	(380)	175	(350)	3.3	0.0024 (0.0015)

flowrate. These parameters are shown in Figure 6-29 for the Pilot Plant receiver and for selected data points from the SRE. These data indicate that for a given flowrate, the SRE hardware absorbed heat fluxes far exceeding the corresponding value for the Pilot Plant receiver. Since no damage was encountered by the SRE hardware, these data indicate the excellent survivability of the Pilot Plant receiver at the imposed heat fluxes. The experimental data, when compared with the values predicted using methods similar to those used to predict temperatures in the preliminary design baseline report, indicate the conservatism of this method of analysis.

6.5.2 Life

The life of the Pilot Plant receiver tubes is calculated based on tube wall temperatures. The low values of the measured temperatures during the SRE compared to values determined using the analytical methods employed in the preliminary baseline design review to calculate temperatures indicate the conservatism of the life predictions made during the preliminary baseline design review. This indirect verification of the Pilot Plant panel life was made since testing for the entire lifetime of the panel (30 yr, or 10,000 cycles) was not feasible.

Similarly, demonstrations of the durability of the absorber surface coating for the entire Pilot Plant life was not practical. However, since refurbishment of the absorber coating is a relatively simple maintenance procedure, demonstration of the durability under conditions simulating even a short period of receiver operation was valuable.

Durability under thermal cycling conditions was demonstrated by painting Pilot Plant tubing with the candidate surface absorber materials and cycling the uncooled tubes using electrical resistance heating. The tubes were heated from 140°C (280°F) to 605°C (1,125°F) in a 2-min period and cooled by natural convection in an 11-min period. Fine and coarse grit-blasted tubes painted with S-31 (a Rockwell proprietary high-absorptance paint) were cycled 573 times. Each tube indicated a loss of approximately 5% of painted surface after the first approximately 200 cycles, with no noticeable degradation thereafter. A grit-blasted tube painted with Pyromark was cycled 318 times with no apparent surface degradation. It was determined that a coat of Pyromark simply painted over a previous coat would not last many cycles but that the old Pyromark could be readily removed by grit-blasting. In situ refurbishment of panel surface using portable grit-blasting and spray equipment, therefore, appears to be feasible.

A severe rain test was applied to the tubes painted with both S-31 and Pyromark. The tubes were sprayed with water for 30 sec at the rate of 150 cc/min over a 1-ft length of tube; spraying was accomplished during the powered portion of this cycle as well as at the moment the power was cut off. The latter is much more severe than actual operation conditions because the unheated tube quenced rapidly under the cooling effect of the water and subjected the paint to severe thermal shock. No evidence of surface deterioration, as a result of these spray tests, was found. Thus, it is not anticipated that rain on the panels during operation (as might occur during a sun shower) would have any deleterious affect on the panel surface. The durability of the absorber surface with respect to high intensity solar radiation was demonstrated by painting a water-cooled Inconel bar with stripes of the candidate materials. The absorptivity of each stripe was measured at the TRW Thermophysics Laboratory using a Gier-Dunkle reflectometer. The sample was then exposed to high intensity radiation at the White Sands solar furnace, and then returned to TRW for re-evaluation of the absorptance of the various stripes.

The Gier-Dunkle equipment was used because of the inability to fit the specimen in the integrating sphere of the more accurate device which was used on previous samples to evaluate the absorptivity of S-31 and Pyromark paints. One of the same early samples was also tested on the Gier-Dunkle instrument to verify the correlation of the Gier-Dunkle readings on the sample sent to White Sands with the early samples measured in the reflectometer. This correlation is shown together with the previous data obtained in Table 6-14. The measured reflectance of Pyromark over the solar spectral region is shown in Figure 6-30.

Table 6-14

COMPARISON OF ABSORPTIVITY DATA

Sample	Absorptivity, Percent	
	Integrating Sphere	Gier-Dunkle
S-31 on Incoloy Disc	0.93	0.86
S-31 on Absorptivity Sample (typical)	--	0.85
Pyromark on Incoloy Disc	0.95	0.88
Pyromark on Absorptivity Sample (typical)	--	0.89

PRE- AND POST-EXPOSURE ABSORPTIVITY DATA

Stripe	Surface	Measured Absorptivity Percent		Change
		Pre-Exposure	Post-Exposure	
0	Grit-blasted and oxidized Incoloy	76	76	0
1	Pyromark	89	89	0
2	S-31	84	83	-1
3	Pyromark	89	89	0
4	S-31	85	84	-1
5	Pyromark	89	89	0
6	Uncured Pyromark	88	89	+1
7	Grit-blasted Incoloy	66	75	+9

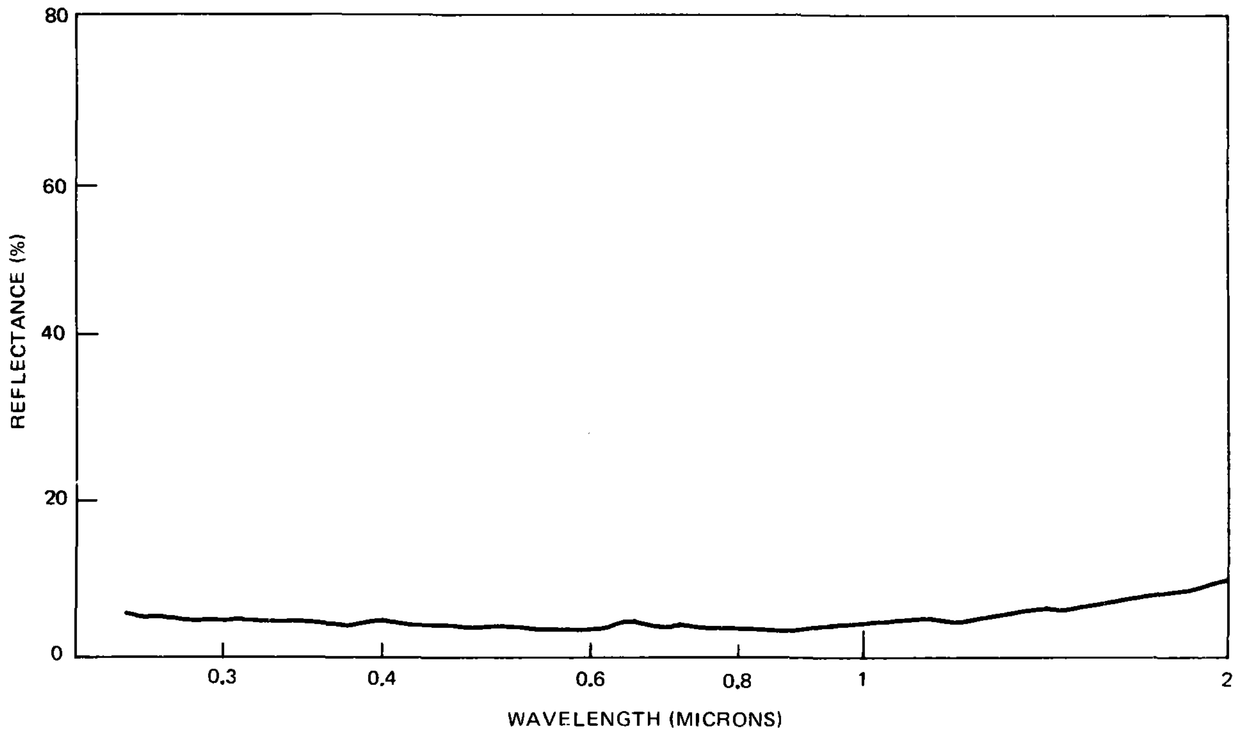


Figure 6-30. Spectral Reflectance of Pyromark

The sample was irradiated for 160 hr at the White Sands test facility. During this period, the solar energy was attenuated to near zero and re-established to provide 100 cycles of 0 to 100% power level. The intent was to expose the sample at a continuous heat flux of approximately 0.3 MW/m^2 incident to simulate the peak receiver power. However, a malfunction of the solar sensor cell resulted in heat fluxes up to 0.6 MW/m^2 being imposed on the sample for 2 days. Temperatures as high as 745°C (1,375°F) were recorded on the surface of the sample during the early exposure periods, with the average temperature being ~550°C (1,000°F). During the remainder of the test program, the average temperature was ~300°C (600°F), which is close to the average operating temperature of the pilot tubes.

Heat flux data recorded at approximately 10-min intervals were integrated over the 160-hr exposure time to yield an integrated value of 55.5 $MW\text{-}hr/m^2$. This integrated heat flux is equivalent to 1 mo of operation during summer on the most highly irradiated panel in the Pilot Plant.

The sample was then returned to the TRW facility and the absorptivity of each stripe re-evaluated. The results of the pre- and post-test evaluations are summarized in Table 6-14. These data indicate no measurable degradation in the absorptance of the Pyromark stripes on the sample, and would, therefore, imply that exposure of at least several months would be required to cause significant degradation. The S-31 absorptivity degraded by 1 point. The absorptivity of the grit-blasted surface increased as it oxidized during the test.

The SRE test results imply that the tube wall temperatures used to predict life are conservative. The data also indicates the durability of the high-absorptivity coating applied to the surface of the Pilot Plant absorber. These data imply that repainting of the absorber surface should not be required for a period of at least several months under nominal Pilot Plant operating conditions which include high temperatures, temperature cycling, concentrated solar energy, and cycling concentrated solar energy. The panel has been returned to White Sands for additional exposure to high-intensity solar radiation. The results of a re-evaluation of surface absorptivity after this exposure period will be available approximately June 1977.

Dust Effects Test

Although not originally planned nor funded as a part of the receiver subsystem research experiments, a brief lab test was run to obtain some indication of the possible effects of fine dust deposition on the receiver absorptive surface coating.

Four samples of 1/2-in. OD Incoloy 800 tubing were grit-blasted and painted with Pyromark paint. The Pyromark was cured according to the manufacturer's instructions and the average absorptivity of one side of each sample was determined by averaging multiple readings of a model MS-251 mobil solar reflectometer manufactured by Gier Dunkle Instruments, Inc. All fresh surfaces indicated average absorptivities of about 0.95 as expected.

The dust used for the tests was fine grade air cleaner test dust packaged by the AC Spark Plug Division of General Motors and consisting of natural Arizona road dust supplied by the GM Phoenix Laboratory. Particle size composition was: 0-5 microns, 39 ± 2%; 5-10 microns, 18 ±3%; 10-20 microns, 16 ± 3%; 20-40 microns, 18 ± 3%' 40-80 microns, 9 ± 3%. Dust absorptivity was measured at 0.51.

The tubing sample absorptive surfaces were dusted by hand because schedules did not permit an extended exposure to actual conditions 200 ft above the desert surface. Although the samples varied in appearance, the majority were dusted heavily enough to appear gray rather than their original dark black. It is believed that the test results are probably more severe than would be experienced under natural conditions.

After dusting, absorptivities varied from 0.94 down to 0.85 with an average of 0.88 for all four samples. Measurements made after baking two of the samples at 700°C (1,300°F) showed no change. Tap water was then allowed to run down the vertically held tubes at low velocity for approximately one minute to simulate rain effects. No rubbing or washing actions of any kind were employed. After drying, absorptivity measurements ranged from 0.93 to 0.95 showing an almost complete recovery to the pretest values.

6.5.3 Controls

The essential elements by which the outlet temperature of each of the receiver segment boilers is controlled are the sensors, the control logic, and the control valves. The sensors are standard thermocouples located at the exit of each boiler and flowmeters located upstream of each boiler. The control logic compares the set value with the sensed value of flow or temperature. The control logic generates an error signal based on the flow or temperature difference and preset proportional and integral gain factors. Electropneumatic control valves use the error to control the water flow to each boiler.

These components were tested during the SRE. The valve selected during the preliminary baseline design effort had a discharge coefficient, C_d, of 6.0. Reduction of the maximum required receiver flowrate, elimination of inlet orifices to each tube, and better definition of interface pressure tolerance, have subsequently reduced the required maximum C_V to a value of approximately 1.5. Use of this large valve, coupled with the low power levels obtained during the contract portion of the SRE, resulted in the control valve operating in the nearly closed position during the tests. As a consequence, the sensitivity of panel temperature to valve position was quite high. Furthermore, it was not possible to use a position limiting stop on the valve as would be used in Pilot Plant operation. Thus, it was possible for the valve to go fully closed in response to a low outlet temperature sensed signal. This condition did in fact occur on Tests P-10 and P-17. With the valve fully closed and the temperature sensors located downstream of the heated area on Test P-17, the sensors continued to input a low temperature to the controller even though the steam temperature within the boiler was increasing.

Operation of the sensors, control logic, and valve together were demonstrated on Test P-15 in which the set point was set to 260°C (500°F). This subcooled command temperature demanded a higher than nominal water flowrate and thus the valve operated in a more open position. The results of this test are shown in Figure 6-31, wherein the valve is shown to be responding to the temperature error signal. The amplitude of the oscillations is decreasing over approximately one and a half cycles indicating convergence and stabilization. The period of the system is shown to be approximately 12 min.

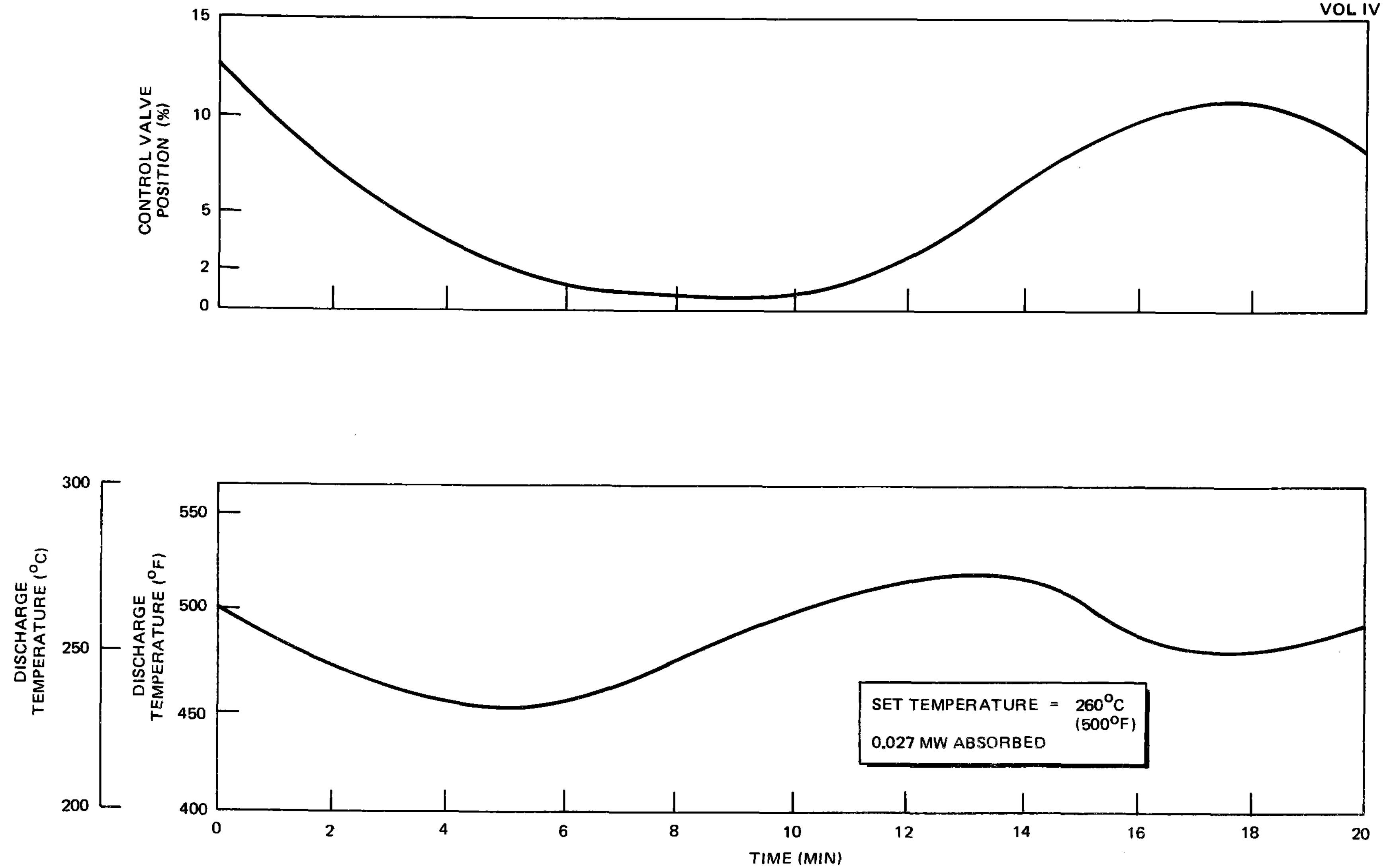


Figure 6-31. Closed Loop Control, Test P-15

Subsequent to the completion of the contracted tests, a company-sponsored program was conducted on the Pilot Plant panel with the valve retrimmed to provide a maximum C_V of 1.5. Operation at rated and derated steam temperatures, with transition from one to the other, were demonstrated as well as the effects of rapid changes in system pressure and moderate variations in thermal power load. In all normal operating cases, the controller maintained the steady-state temperature with overshoots of less than 30°C (50°F). Complete termination and rapid re-establishment of power level at rated temperature resulted in an overshoot of approximately 175°F.

A controlled transient, achieved by stepping the temperature set point from 515°C (950°F) to 365°C (690°F) and back to 510°C (950°F), is shown in Figure 6-32. The limited water supply dictated that the time spent at each operating point be limited to that which would demonstrate the maximum overshoot and convergence toward a steady value. The same limit dictated stepping rather than ramping the set point which would be done in the Pilot Plant to avoid thermal shock. Thus, the modest overshoots of less than 20°C (40°F) shown in Figure 6-32 are even greater than would be expected in the Pilot Plant. The minimum temperature during a transition from rated to derated steaming conditions would be greater than 330°C (630°F), which means that the effluent would be single-phase superheated steam even during the transient. The overshoot to less than 540°C (1,000°F) when transitioning from rated to derated steam is also acceptable.

The results of simulating a large fast cloud cover are shown in Figure 6-33 where the heaters were rapidly turned off; the panel allowed to cool for 5 min, and the heaters turned on again rapidly. The set point drifted during the downtime due to a component failure in the control electronics assembly. However, the significant point illustrated by Figure 6-33 is the smooth recovery and lack of overshoot during the rapid restart power transient. The nearly linear temperature rise during the early portion of the restart indicates that shutting down for longer time periods would affect the time to re-establish steady temperature conditions, but not the temperature rise rate or overshoot.

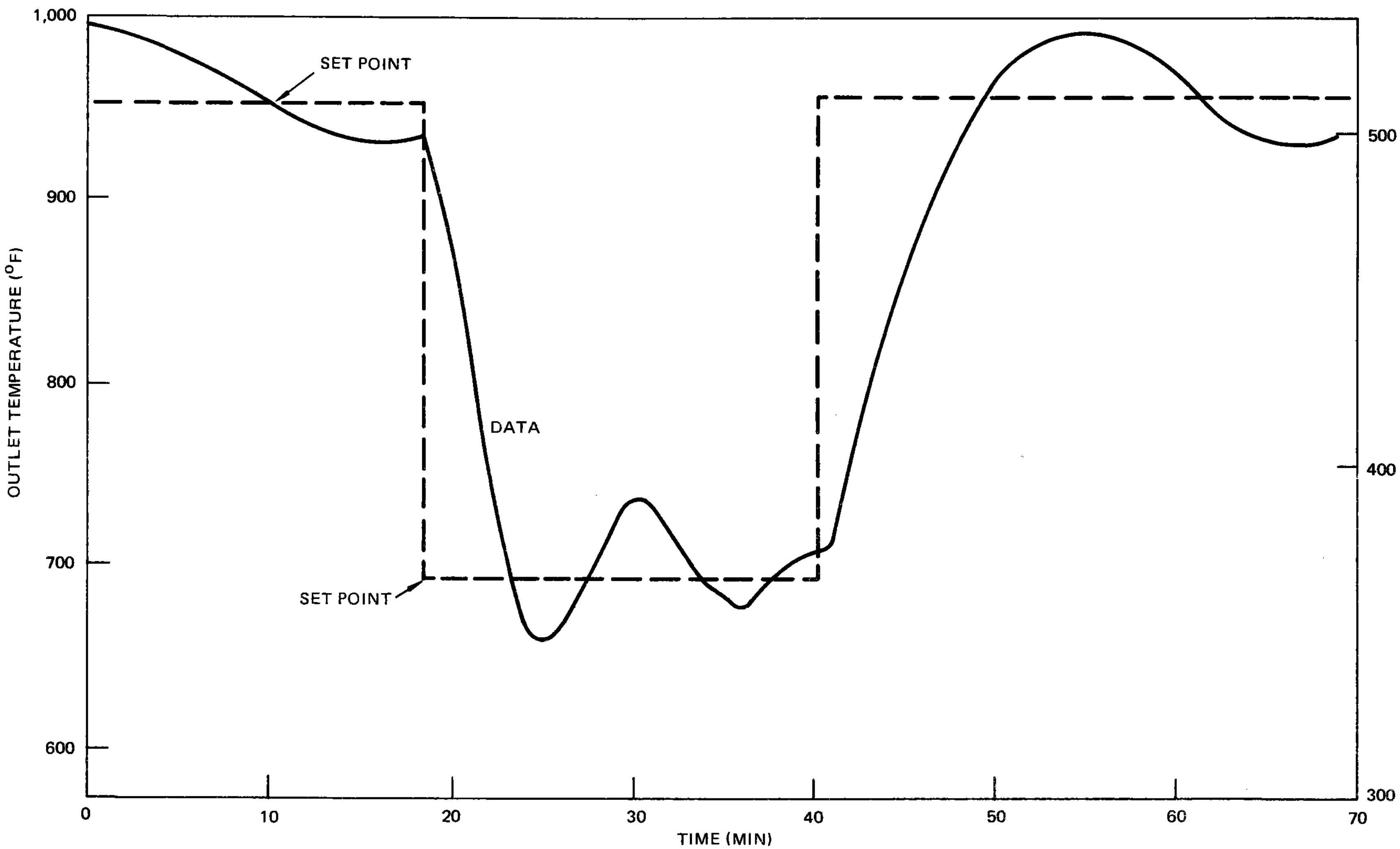


Figure 6-32. Receiver Response to Set Point Changes

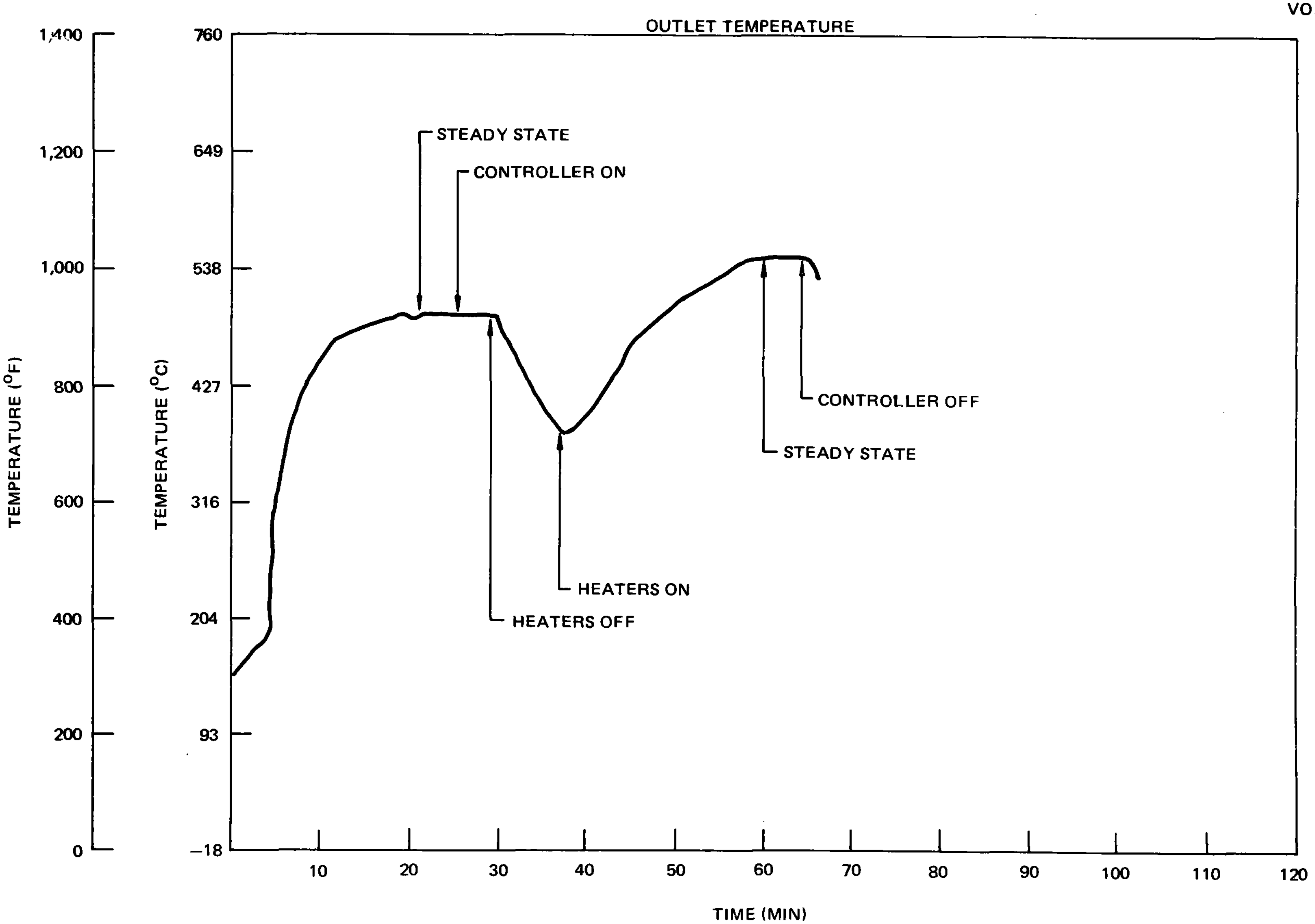


Figure 6-33. Receiver Panel Response to Cloud Passage

A vortex shedding flowmeter with no moving parts in the flow stream was installed as part of the Pilot Plant equipment. The flowmeter functioned satisfactorily over a 10:1 flow range. However, the output was severely affected by the strong electric field generated by the heaters. A low ΔP orifice was ultimately used to measure water flowrate.

The results of these tests indicate the ability of the control design approach and components to maintain receiver discharge temperatures within nominal limits under normal operating conditions and to maintain safe operating temperatures under abnormal operating conditions, such as passing cloud covers.

6.5.4 Flow Stability/Uniformity and Off-Design Operation

Uniformity of flow and temperature from tube-to-tube were demonstrated in the 5-tube panel and the Pilot Plant segment. Flow stability was demonstrated in all three pieces of tubular hardware. The most critical operating condition for flow stability and uniformity is the production of rated steam at low flowrates, i.e., low absorbed power levels. Accordingly, tests to verify the stability and uniformity of flow were conducted primarily in this low power operating regime.

6.5.4.1 Single-Tube and 5-Tube Tests

Initial tests on the single tube were conducted using a flow restrictor at the entrance to the tube. The restrictor had a diameter 15 mm (0.060 in.). Flow was stable during these tests and the jet orifice was therefore removed. Stability was then demonstrated on the last test (Test 1-9) without the orifice which produced 345°C (650°F) steam.

The outlet fluid temperature transient is shown in Figure 6-34. The initial temperature of 140°C (280°F) was provided by electrical heaters in the inlet line. The temperature trace is fairly smooth, [less than ±11°C (20°F)] with variations which were primarily caused by manual operation of the flow control valve during the test. Water flowrate, as well as back pressure, was controlled manually for all the single-tube and 5-tube tests.

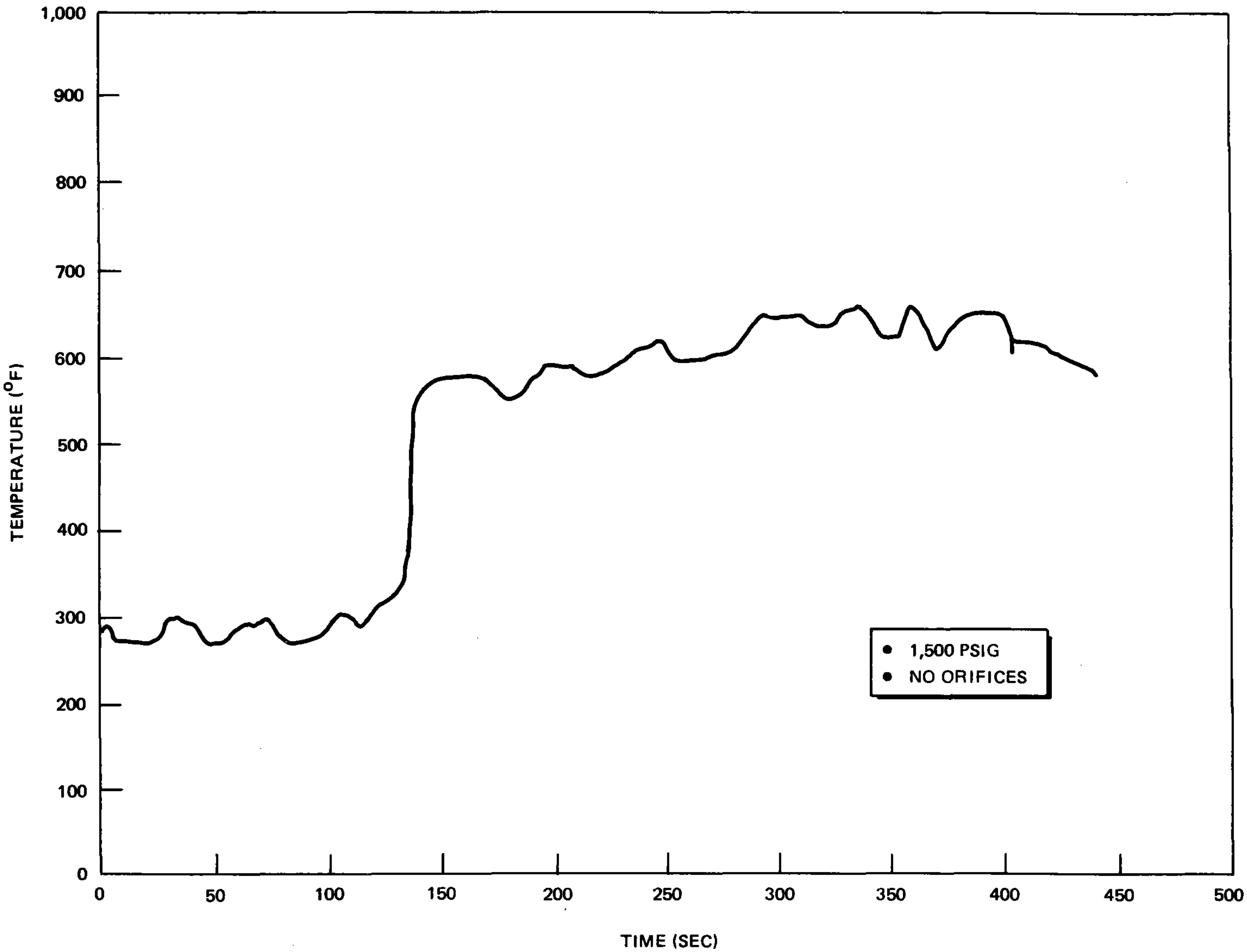


Figure 6-34. Single Tube Outlet Temperature — Test 1-9

The stable operation of the single-tube led to the decision to initiate testing of the 5-tube panel without orifices at the inlets to the tubes. Identical orifices were placed at the inlets to the 5 tubes on Test 5-10 to assure equal flow in each of the tubes. The purpose of Test 5-10 was to determine the uniformity of the heat flux from tube to tube. This was determined by monitoring the tube wall temperatures and the water temperature in each of the tubes near the exit of the panel. Data in Table 6-15 indicate the excellent uniformity of the heat flux from tube to tube.

Having established the lateral uniformity of the heat flux with controlled flow to each tube, the tube wall and water temperature were examined for other tests, all of which were conducted without inlet orifices. These data are also presented in Table 6-15. Test 5-6 was a low-heat flux test and Test 5-16 was a high-heat flux test. The Test 5-16 data is shown graphically in Figure 6-35.

Both tests indicate reasonably uniform temperatures from tube to tube which implies equal flows in each tube. The flow uniformity is enhanced by the high ratio of hydrostatic head to frictional pressure drop in the tubes. Even at the high flow and high temperature conditions of Test 5-16, the predicted frictional pressure drop is in the order of 0.069 MPa (10 psi), while the hydrostatic head is the same order of magnitude. For the low flow and low temperature conditions of Test 5-6, the frictional pressure drop decreases to less than 1 psi and the hydrostatic head increases slightly. Thus, if one tube tends to produce a higher temperature steam, the hydrostatic head will decrease causing the flow to increase, and reduce the temperature back toward the nominal value.

One of the major items to be investigated with the 5-tube panel was the ability of the panel to operate stably without inlet orifices or, if orifices were required, the minimum orificing which would permit stable operation. Start transients for Tests 5-6 and 5-16 are shown in Figures 6-36 and 6-37. These results, as well as the results of the other tests, conducted without inlet orifices in the tubes, indicate the ability of the boiler to come on line stably

Table 6-15

TUBE AND WATER TEMPERATURES

Tube No.	Test	Hot Wall Temperature at x= 1,575 cm (620 in.)* °C (°F)	Water Temperature at x= 1,676 cm (660 in.)* °C (°F)	Water Temperature at x= 1,732 cm (682 in.)* °C (°F)
1	5-10	300 (570)	-	300 (575)
2	5-10	300 (570)	305 (585)	
3	5-10	-	-	295 (565)
4	5-10	300 (570)	305 (585)	305 (580)
5	5-10	300 (575)	-	295 (565)
1	5-6	360 (680)	-	365 (690)
2	5-6	365 (690)	385 (725)	-
3	5-6	360 (680)	-	355 (675)
4	5-6	355 (670	390 (735)	345 (650)
5	5-6	350 (660)	-	355 (675)
1	5-16	615 (1,140)	595 (1,100)	600 (1,110)
2	5-16	625 (1,160)	645 (1,190)	600 (1,110)
3	5-16	620 (1,150)	630 (1,170)	620 (1,150)
4	5-16	620 (1,150	630 (1,170)	590 (1,090)
5	5-16	615 (1,140)	595 (1,100)	600 (1,110)

*x is the distance along the panel from the initial point of heating.

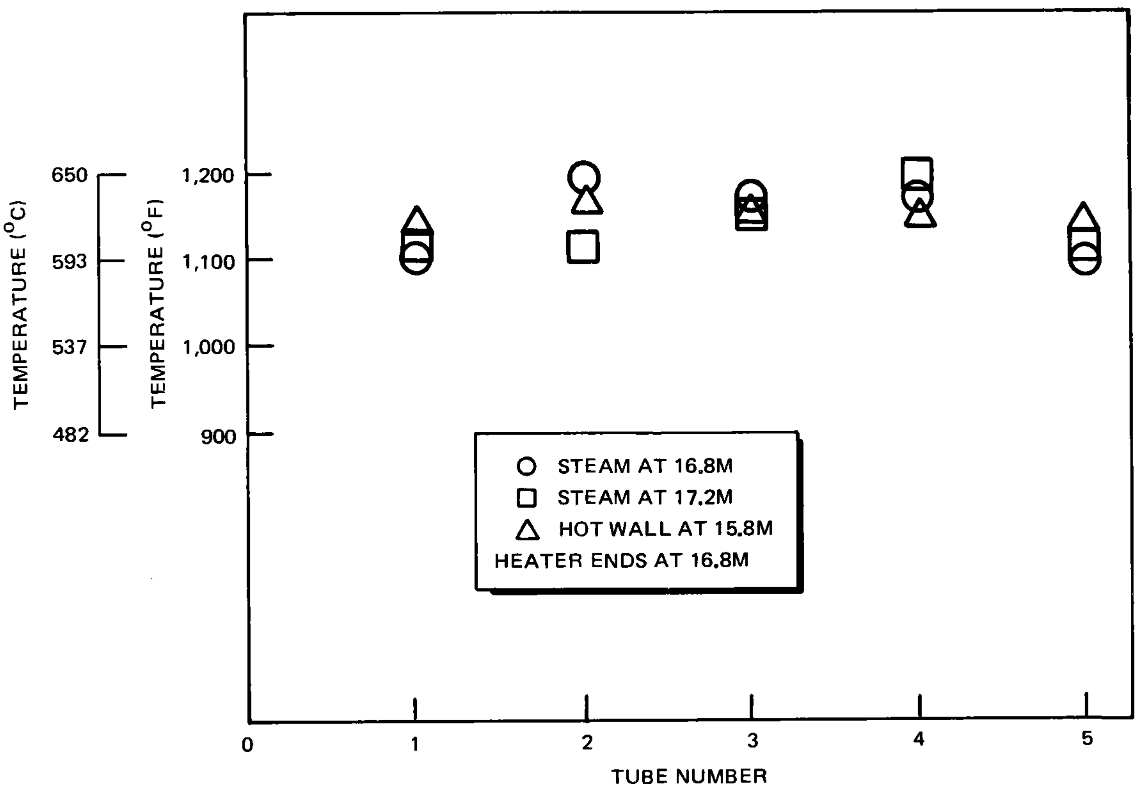


Figure 6-35. Receiver Five-Tube Test Data – Temperature Uniformity (Test No. 5-16 – 1/2 Min Before Shutdown)

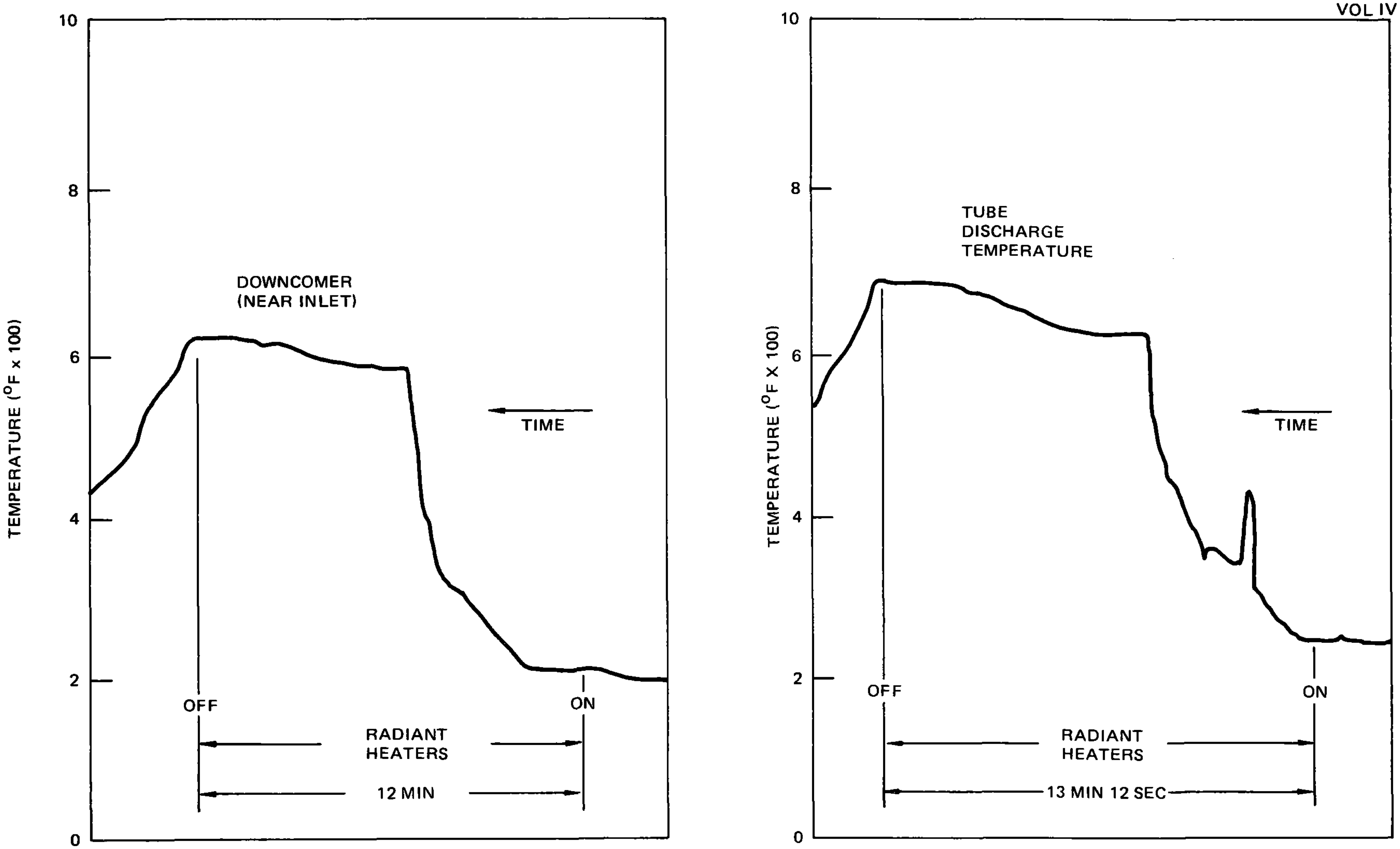


Figure 6-36. Steam Temperature Transients — Test 5-6

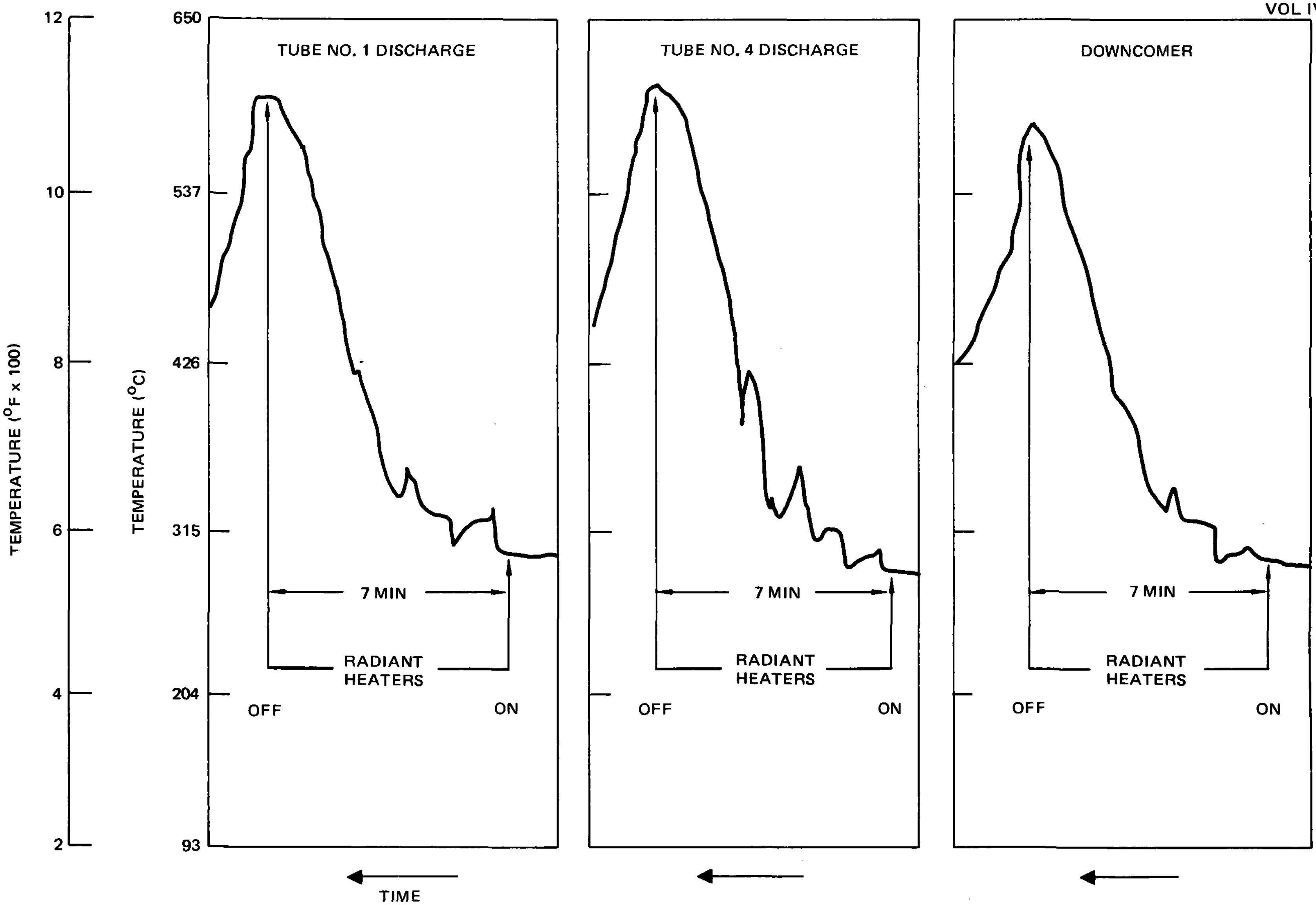


Figure 6-37. Five-Tube Test Data – Steam Temperature Transients at Start – Test No. 5-16

without orifices in the system. Temperatures at the discharge of the tubes and at the entrance of the downcomer indicated only minor oscillations during the start transients which damped out as steady-state was reached. The extremes of operating conditions are covered by these three figures. Figure 6-36 shows a start transient for a low heat flux and low discharge temperature test. Figure 6-37 shows the transient for a high flux test with a high discharge temperature.

The discharge temperatures began to respond to the radiant heat within approximately 1 min. The time to achieve steady-state conditions depends upon the heat flux level and effluent temperature conditions. The times range from a maximum of approximately 12 min for low heat fluxes with low discharge temperatures to 7 min with high heat fluxes and high discharge temperatures. The longer time period would correspond to conditions at the start of the day. The latter figures indicate the response capability of the panel to a start during mid-day in the summer.

The 5-tube panel was not insulated nor was the steam manifold and first portion of the downcomer insulated. This, together with the relatively large size of the downcomer, resulted in fairly high heat losses between the points where the tube discharge temperature and the downcomer temperature measurements were made. The lack of insulation probably also resulted in lengthening the response time, particularly at the low heat flux levels.

In order to determine the ability of the panel to survive loss of water, the water flow was terminated by shutting off the inlet valve three times on Test 5-9. The valve was shut off for 2 sec, 10 sec, and 60 sec. The effects of these transients on panel discharge temperature are shown in Figure 6-38. The 2-sec and 10-sec flow termination had negligible effects on the discharge temperature. The discharge temperature decayed approximately 50°F as the flow ceased in the vicinity of this thermocouple in the downcomer. At about the same time that the valve was being reopened during the last transients, 2 of the 13 heaters failed. This accounts for the lower outlet temperature after the transient than before. However, the absence of an overshoot after the last transient would probably not significantly be affected by the loss of the two heaters.

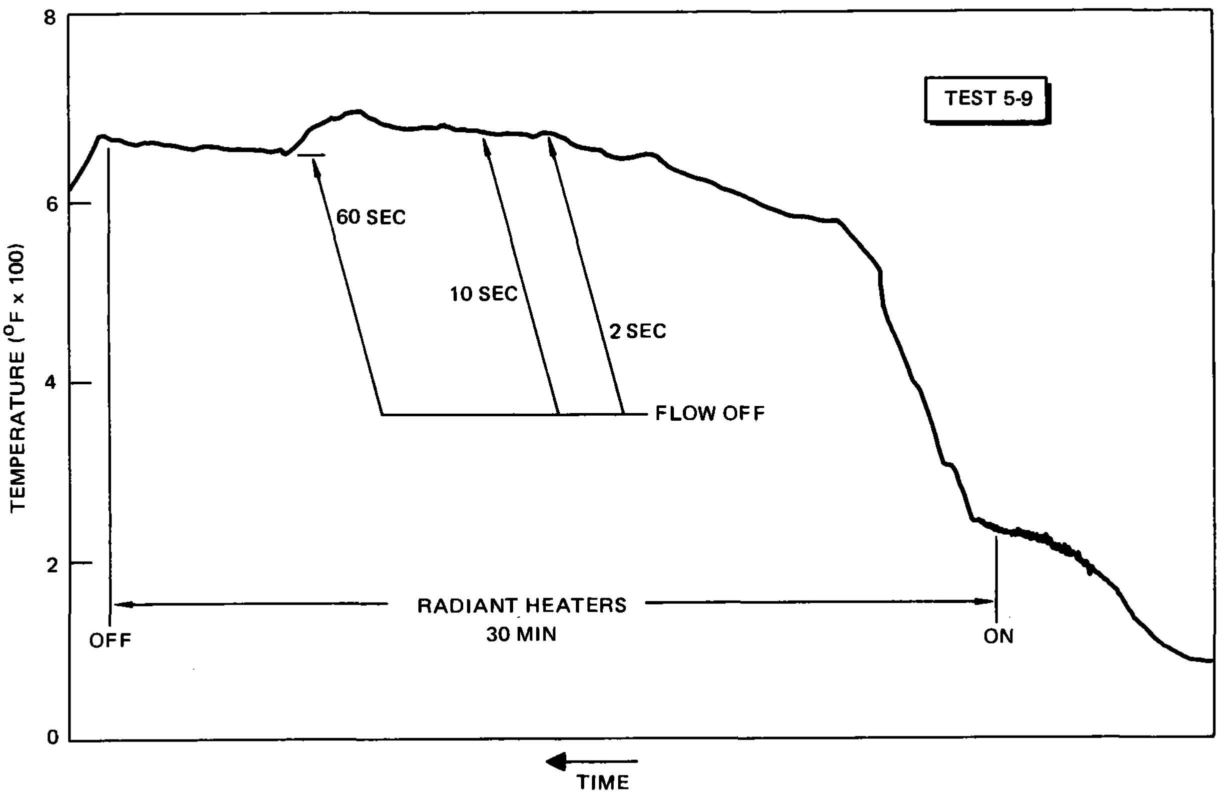


Figure 6-38. Temperature Transient – Steam in Downcomer

The maximum wall temperature during the transients was recorded by the thermocouple located at 15m (590 in.) from the inlet. The transient recorded by this thermocouple is shown in Figure 6-39, and indicates a maximum value of 470°C (880°F). Thus, it appears that stoppages of water flow for significant time periods can be tolerated by the panel without excessive wall temperatures or radical changes in effluent discharge temperature. Water temperature transients at 16.8m (660 in.) from the entrance and at the tube exit are shown in Figures 6-40 and 6-41, respectively.

Heat flux transients induced by passing clouds were simulated on Test 5-8 by reducing the electrical power to the heaters to very low values. Two transients were simulated: the first transient occurred over a period of 1-1/2 min; the second took place over a period of 1/2 min. The effect of these transients on the steam discharge (downcomer) temperature is shown in Figure 6-42. The backpressure valve was not operated to maintain constant pressure during the transient; as a result, the system produced two-phase steam at approximately 275°C (525°F) during the first transient and 295°C (565°F) during the second transient. The second transient was initiated before complete recovery from the first transient. However, the rate of recovery was slow and the shape of the curve indicates that no overshoot would probably occur. Recovery from the second transient was essentially complete without overshoot. Similar characteristics are shown in Figure 6-43 which presents the transient steam temperature at the discharge of one of the tubes. Temperatures at this point, as previously mentioned, are somewhat higher than in the downcomer, but the shape of the curves are similar indicating no overshoots. Wall temperature transient data also indicated smooth recoveries with no overshoot.

6.5.4.2 Receiver Segment Tests

Flow stability was even more evident during these than the 5-tube panel tests. The start transient for Test P-6 is shown in Figure 6-44. Note the smoothness with which the flow passes through the two-phase region when approaching the saturation temperature of 315°C (600°F) from either above or below. The "blip" from 346° to 415°C (650° to 780°F) does not occur in any of the other test records and is believed to be electrical noise.

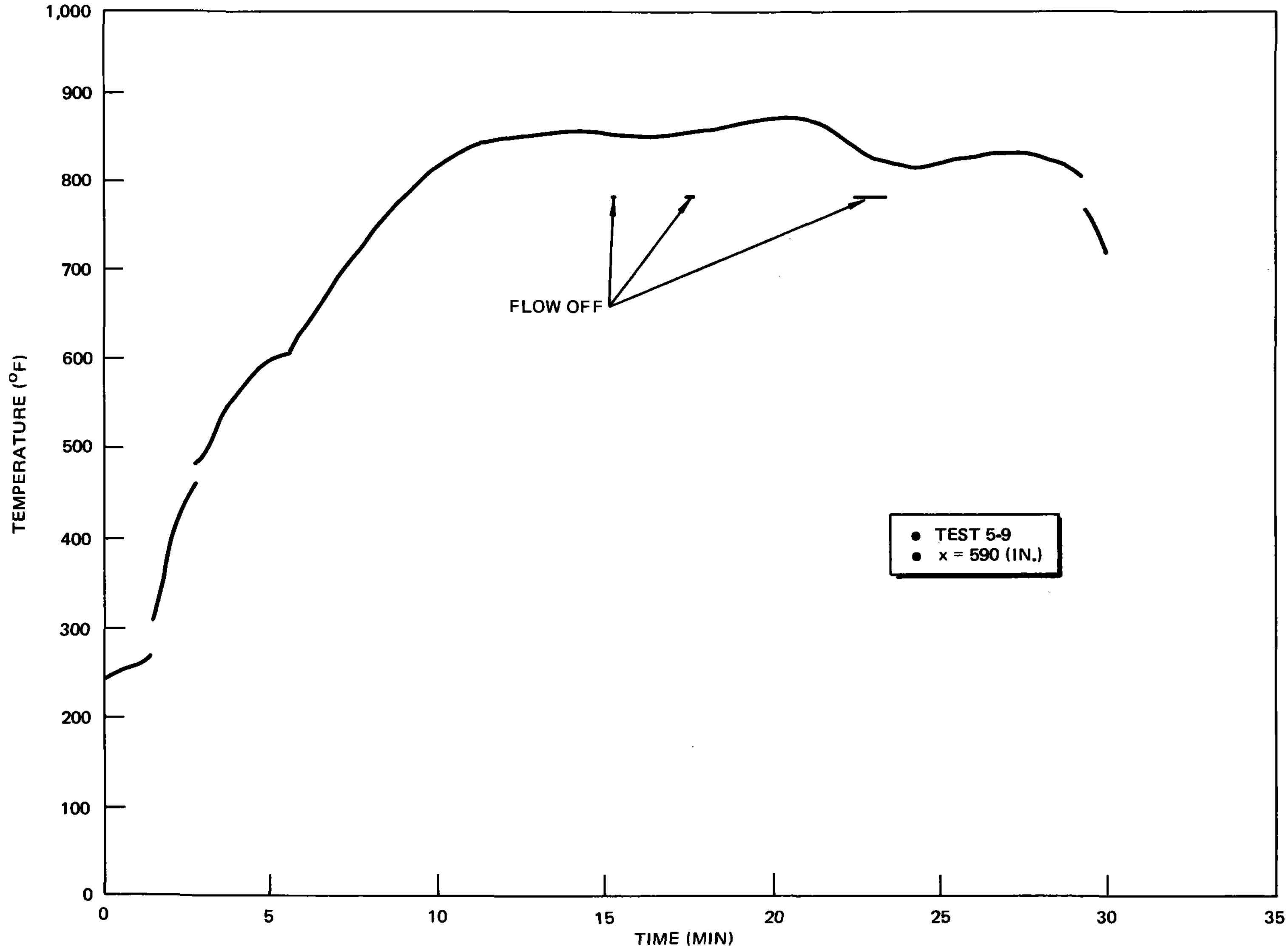


Figure 6-39. Tube Wall Temperature Transient

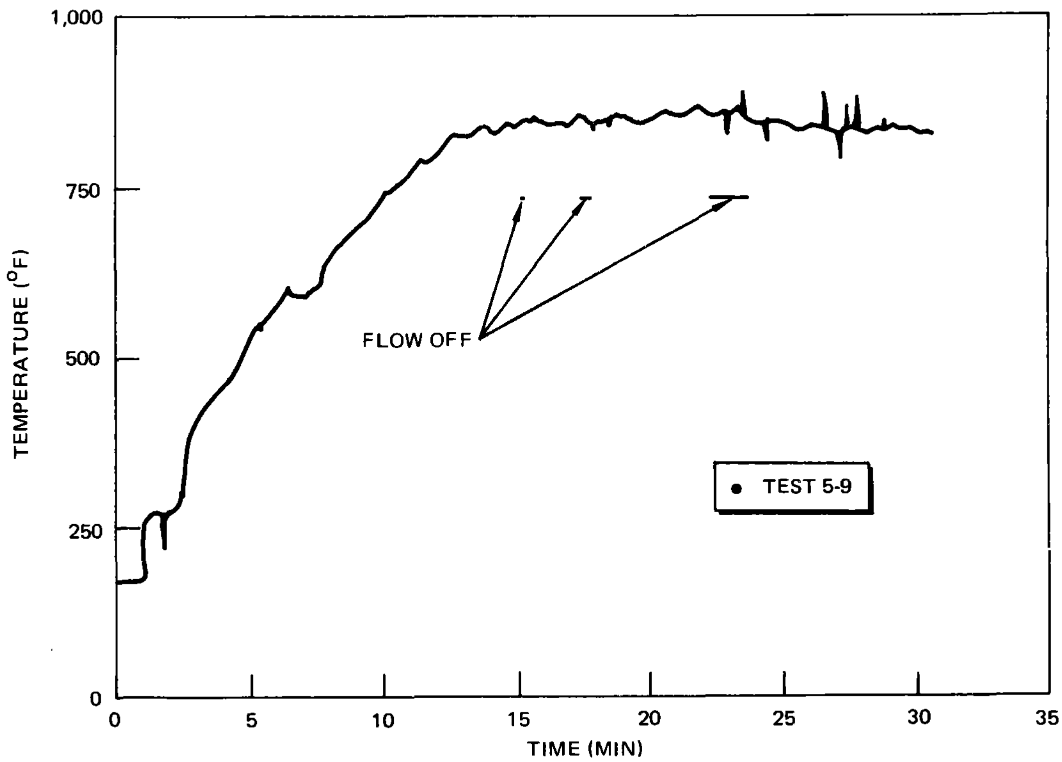


Figure 6-40. Temperature Transient – Steam at x = 1,680 cm (660-in.)

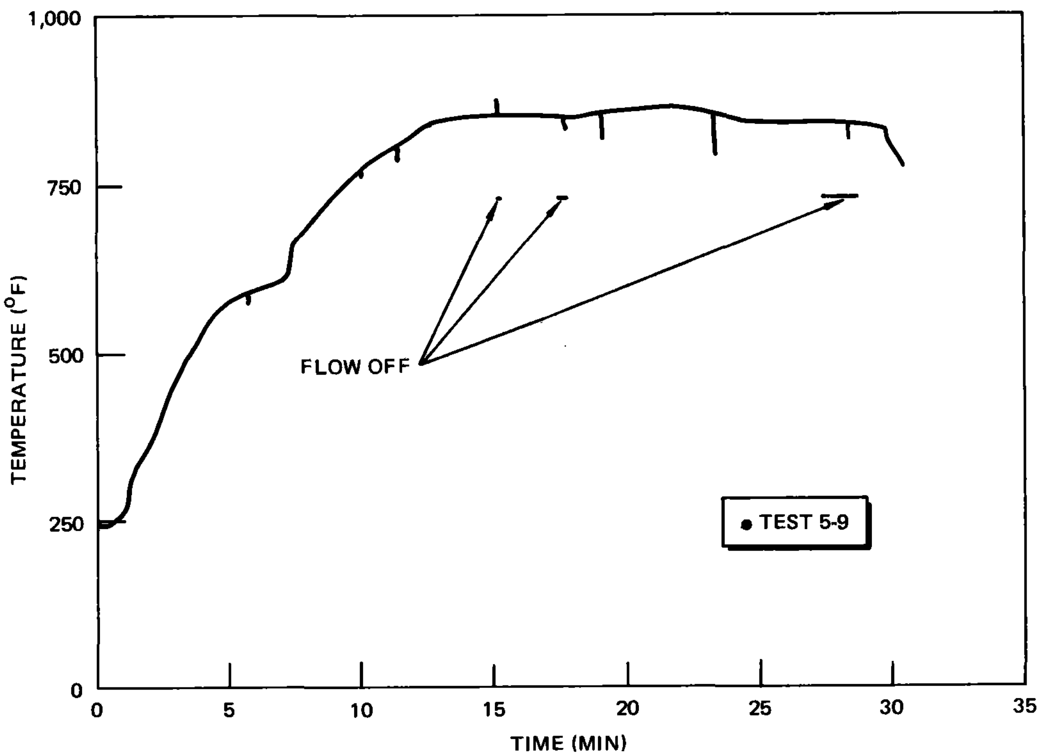


Figure 6-41. Steam Temperature Transients at Tube Discharge

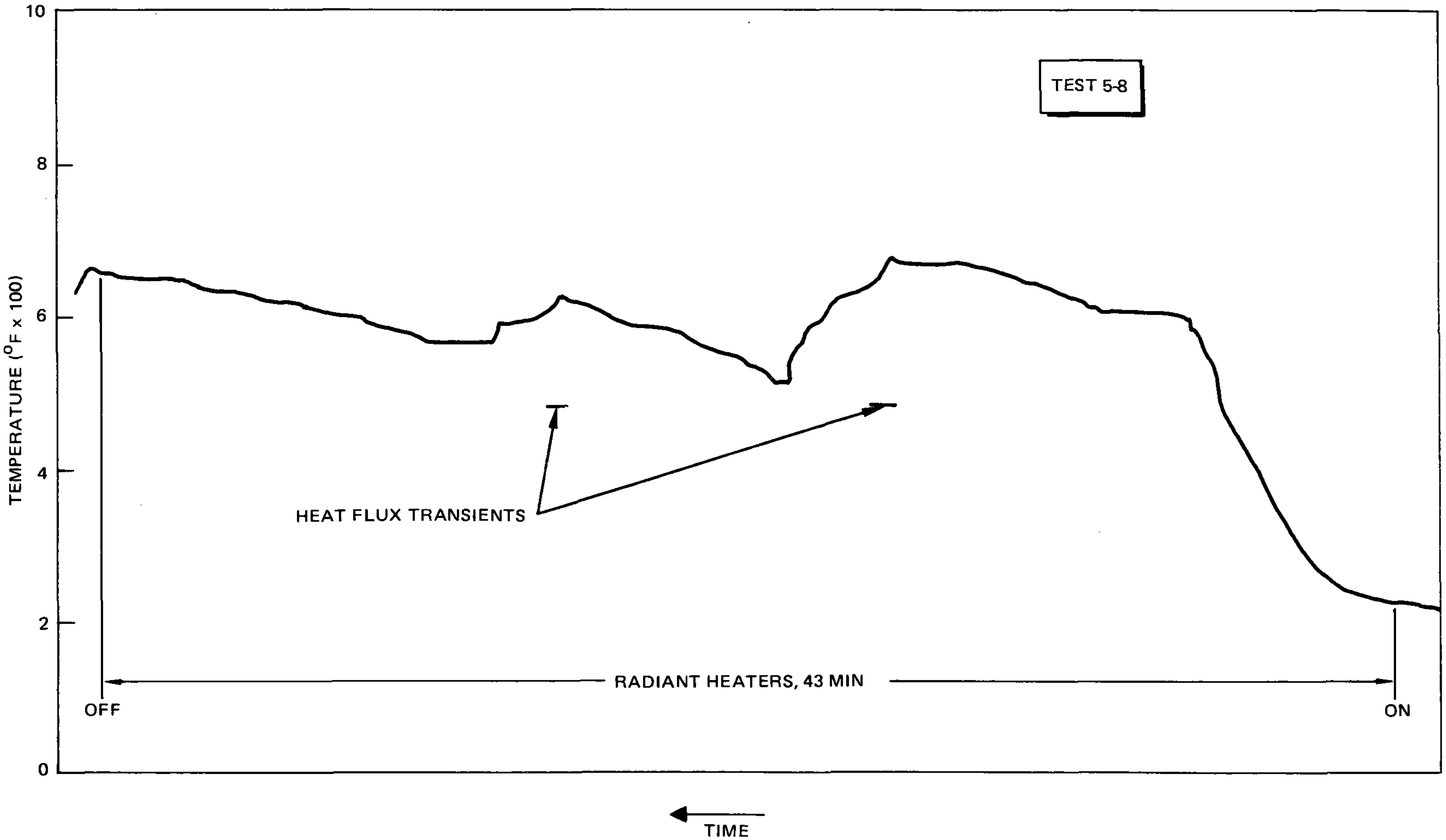


Figure 6-42. Temperature Response at Downcomer Inlet

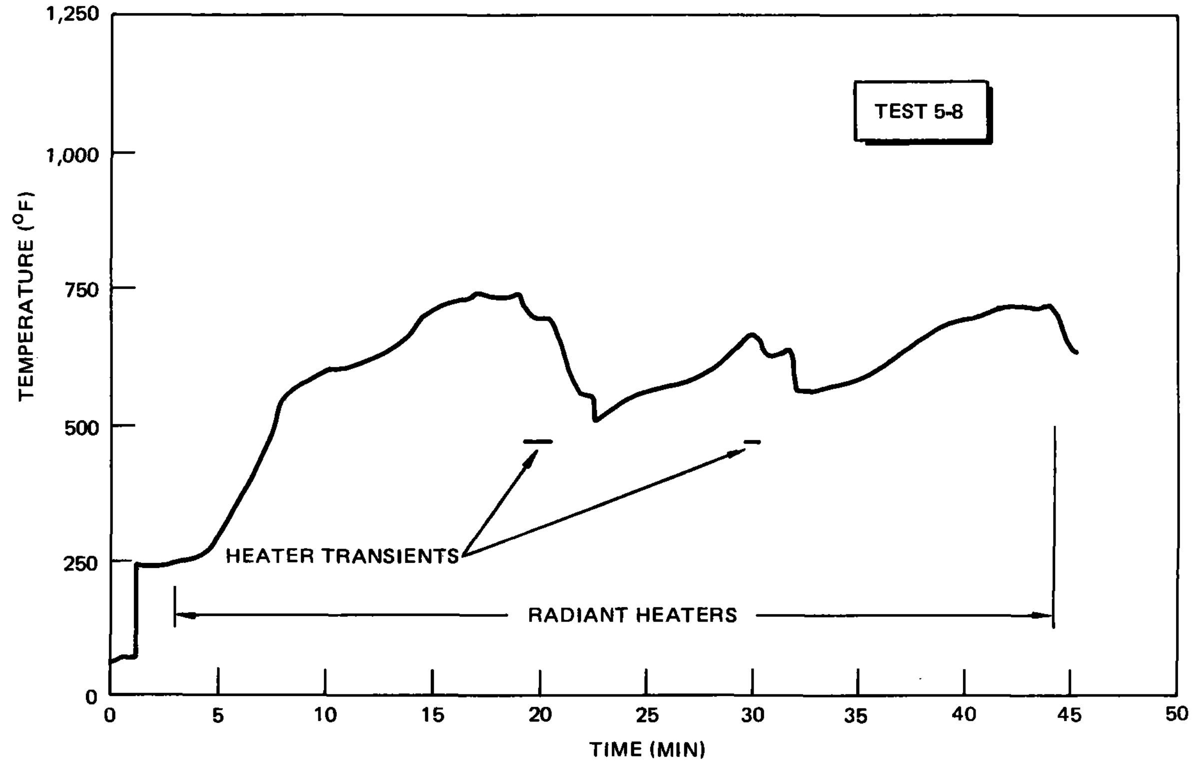


Figure 6-43. Temperature Response at Tube Discharge

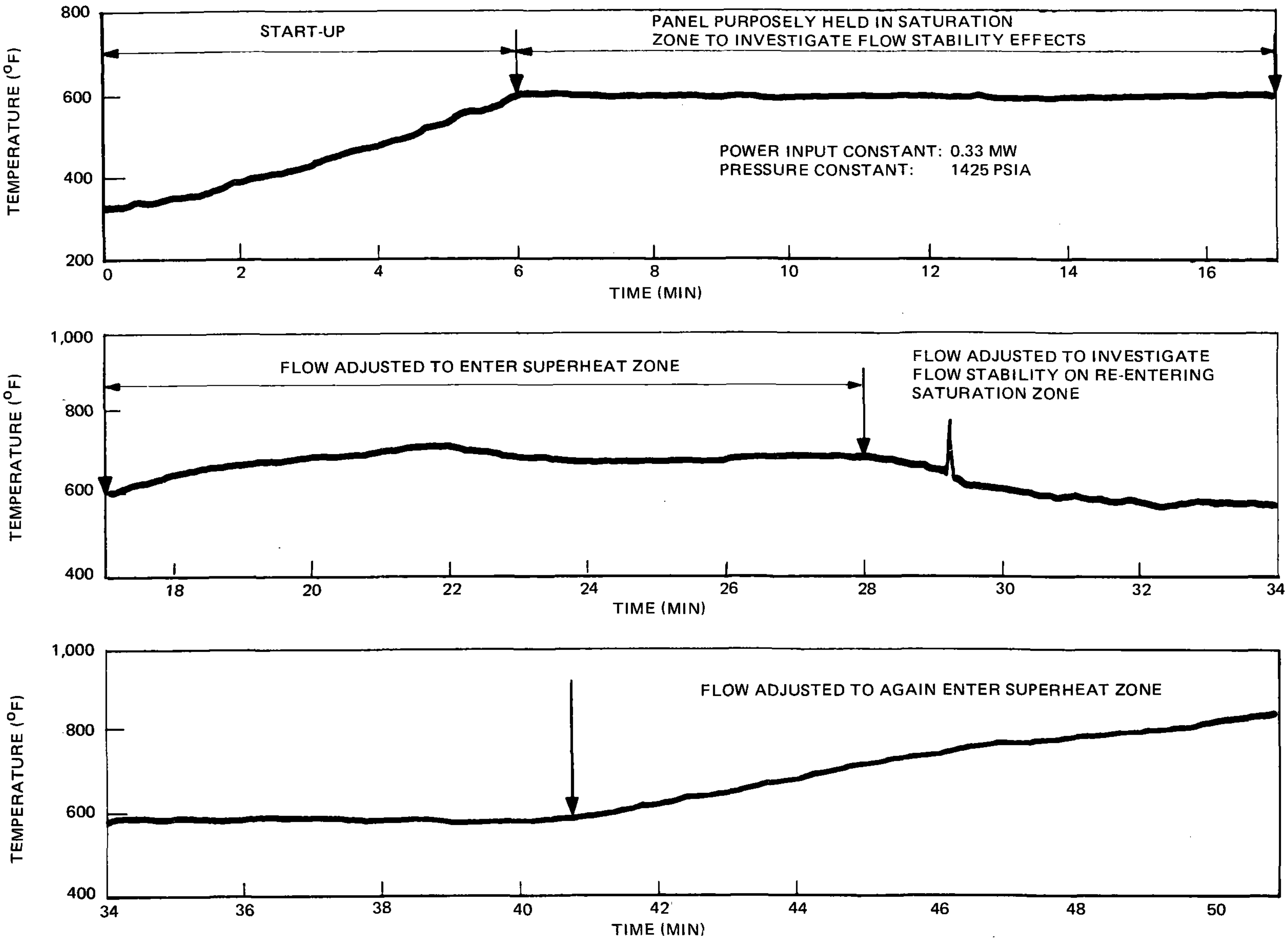


Figure 6-44. Panel Discharge Temperature (Test P-6)

Operation at low pressure tends to be destabilizing because of the large difference in density between liquid and vapor states. A complete Pilot Plant start sequence was simulated on Test P-8 using manually operated temperature control and backpressure valves. The sequence was executed as follows:

A. Flash tank pressurized to 2.91 MPa (423 psia).
B. Supply tank pressurized to 4.1 MPa (600 psia).
C. Heaters energized.
D. Flow controlled to predetermined value.
E. Flow controlled to obtain 260°C (500°F), (282°C, 540°F accepted).
F. Flow controlled to obtain 343°C (650°F), (327°C, 620°F accepted).
G. Backpressure increased to 10.5 MPa (1,515 psia). (Actual temperature and backpressure were 355°C (670°F) and 9.5 MPa (1,385 psia).

The transient discharge temperature for the test is shown in Figure 6-45. The important point is not how well the manually operated valves achieved the targeted set points but that the entire transient was accomplished smoothly with no indications of instability. The transient for the previous test, which simulated only the low-pressure portion of the start sequence, was also smooth.

A liquid slug detector was placed in the downcomer line near the boiler during the company-funded test program. The detector was simply a thermocouple in the fluid steam located as shown in Figure 6-46. The thermocouple indicates the superheated steam temperature. A slug of water entering the turn is thrown against the thermocouple which then indicates saturation temperature. The detector indicated slug-free flow at all times with smooth transitions through the two-phase region.

The wall temperatures of all 70 tubes were instrumented approximately 7.6 cm (3 in.) downstream of the end of the heated region on the panel. Not all temperature data was valid. However, sufficient data was obtained to demonstrate the uniformity of temperature across the panel. The divergence was minimum during steady-state conditions such as just before automatic control was initiated on Test P-17. The temperature profile across the panel

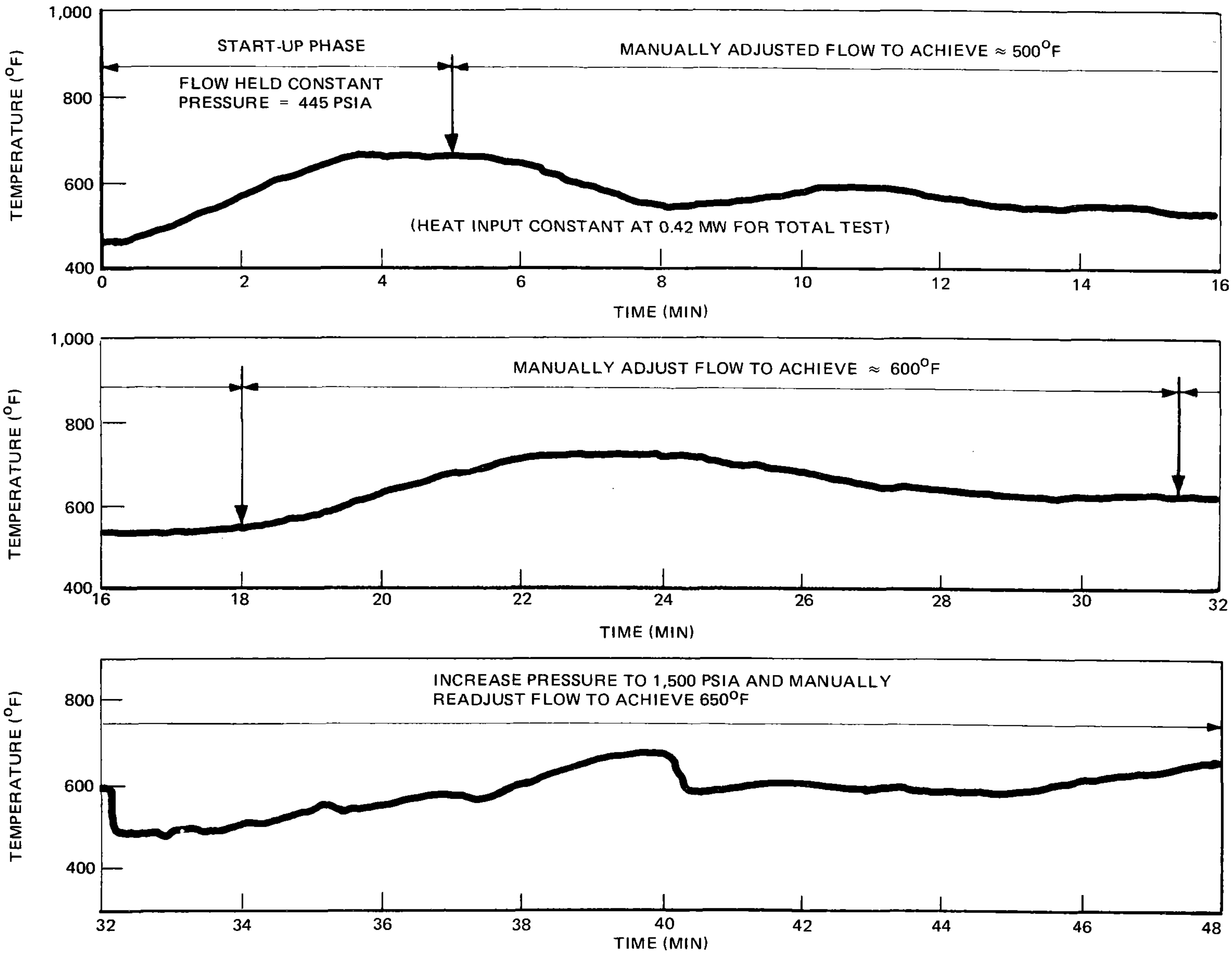


Figure 6-45. Panel Discharge Temperature During Pilot Plant Start Simulation (Test P-8)

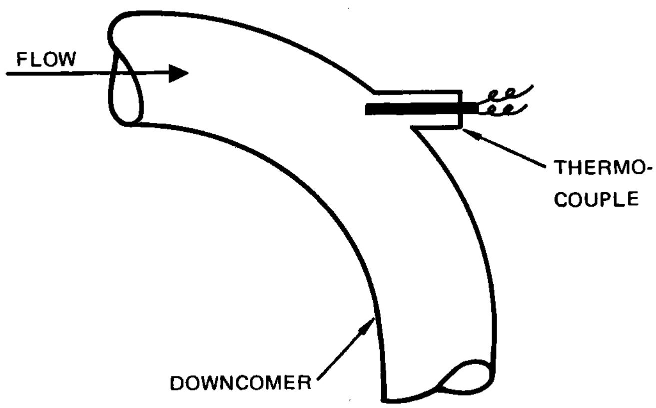


Figure 6-46. Liquid Detector

at that time is shown in Figure 6-47. The straight line between tubes 40 to 60 is indicative of lack of data in this area.

During transients, the data tended to scatter more. A significant increase in the scatter is shown in Figure 6-48 which was recorded for the same test during the start transient which had a superheat transient rate of 2,700°C/hr (4,800°F/hr). The tight pattern during steady-state operation is typical with increased divergence during the transients. Generally, the steady-state scatter was within a band of about 50°C (100°F) and increased to a maximum of 200°C (400°F) during steep transients. SRE transients were necessarily steep because of the limited water supply. The more gradual transients anticipated in the Pilot Plant will result in gradients across the panel much closer to the SRE steady-state gradients.

6.5.4.3 Overall Conclusions

The results of more than 20 hr of operating the various SRE boiler hardware under a wide range of design and off-design conditions have verified the stability and uniformity of flow for Pilot Plant operation. The ability to safely encounter water failure and cloud cover effects was also verified.

6.5.5 Structural

The structural technical issue addressed by the SRE was the verification that the provisions for thermal expansion designed for the Pilot Plant absorber would indeed function to prevent undue stress buildup as the result of asymmetrical heating (i.e., heating from one side only and to various temperatures along the panel length) of the absorber panel. Both the 5-tube and Pilot Plant panels included provisions for thermal expansion identical to that which would be used on the Pilot Plant. The design allows for both axial and lateral expansion of the absorber during heating.

6.5.5.1 Five-Tube Panel

Pilot Plant type expansion provisions were included on the 5-tube panel to provide an early verification of the adequacy of these provisions. Calculations indicated that the panel should expand approximately 8.9 cm (3.5 in.) when producing 515°C (960°F) steam with an inlet water temperature of 205°C (400°F). During the initial tests, expansions of approximately half

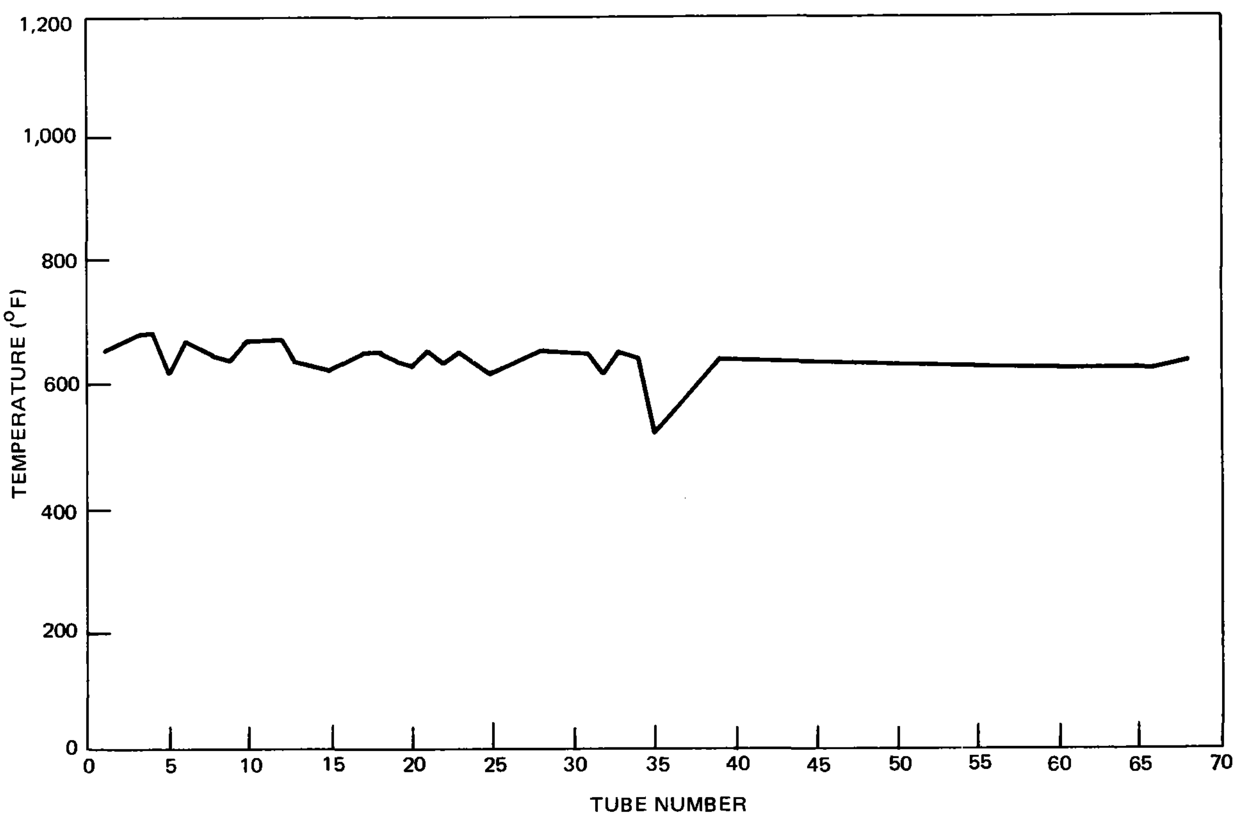


Figure 6-47. Temperature Profile Across Panel During Steady State

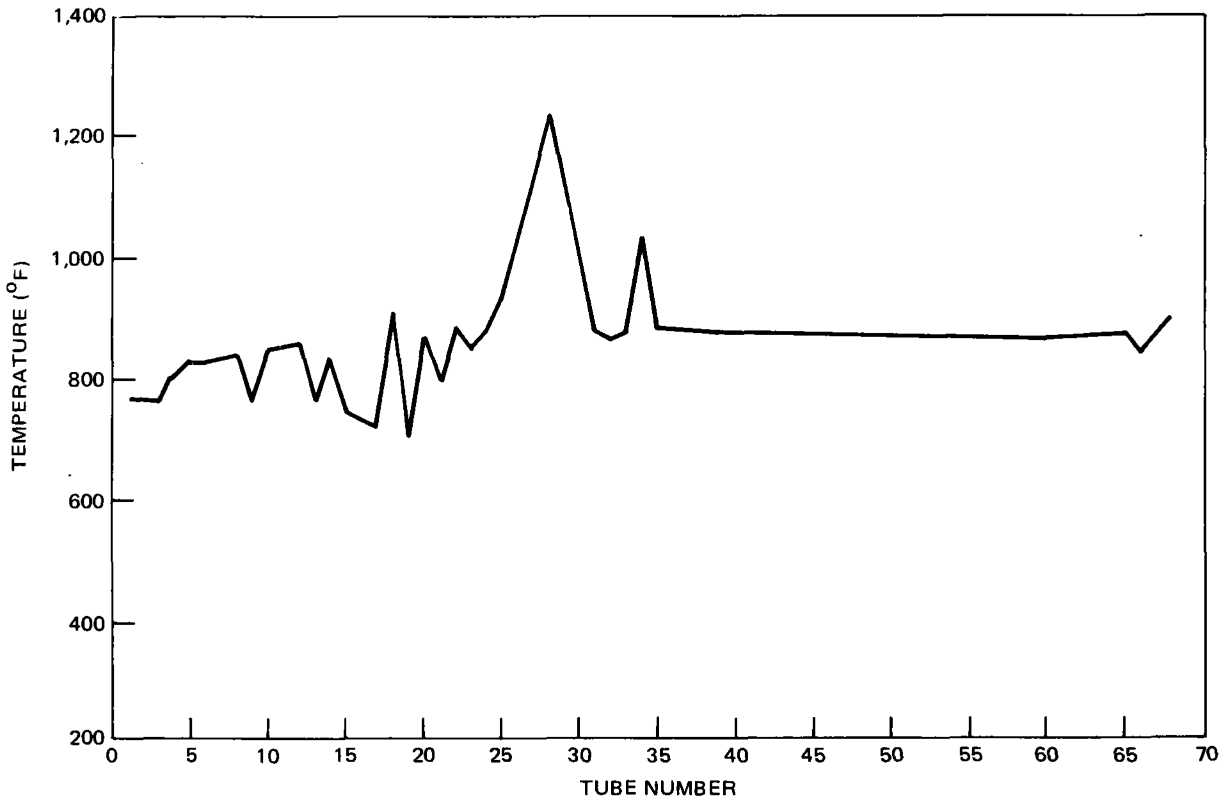


Figure 6-48. Temperature Profile Across Panel During Transient

this value were indicated. The completely enclosed nature of the tower does not permit observation of the panel except at the upper and lower extremities. After the initial tests, when the tower was disassembled, it was determined that panel growth, from approximately midpoint to the steam end, was restricted by interference with one or more of the reflector assemblies. The panel had been deformed into a wave-like shape between the support stations. Out-of-plane deformations of as much as 2 cm (3/4 in.) were measured.

The panel was straightened and the interference condition was corrected. During the subsequent Tests 5-12 through 5-16, axial growth values in excess of 7.6 cm (3 in.) were noted. Thus, the test program verified that proper expansion occurred when the sliding mechanism was unrestrained. Furthermore, the tests demonstrated the panel can withstand several cycles of deformation under restrained conditions without failure.

6.5.5.2 Seventy-Tube Panel

An initial test was conducted on the panel during which water at 270°C (520°F) inlet temperature was flowed through the panel under pressure. The resulting average temperature of the tube was 200°C (365°F) above ambient temperature. Deflections at several stations along the tube were measured and plotted in Figure 6-49. Also plotted in Figure 6-49 are lines indicating the theoretical deflections which would occur if the panel were in simple axial compression at the values indicated. The data indicate compressive loads of up to approximately 70 MPa (10 ksi) which poses no problem for operation of the Pilot Plant.

It is predicted that with heat fluxes in the order of 15% of the maximum Pilot Plant heat flux, an axial panel expansion of approximately 6.9 cm (2.7 in.) would occur. Most of the contract tests on the Pilot Plant panel and the company-sponsored controls tests were conducted at approximately this heat flux level. Visual indications and measurements during the contract tests indicated agreement with the above value. A position indicator mounted on the bottom of the panel indicated an average deflection of approximately 7.4 cm (2.9 in.) with values ranging from 6.1 to 7.6 cm (2.4 to 3.1 in.).

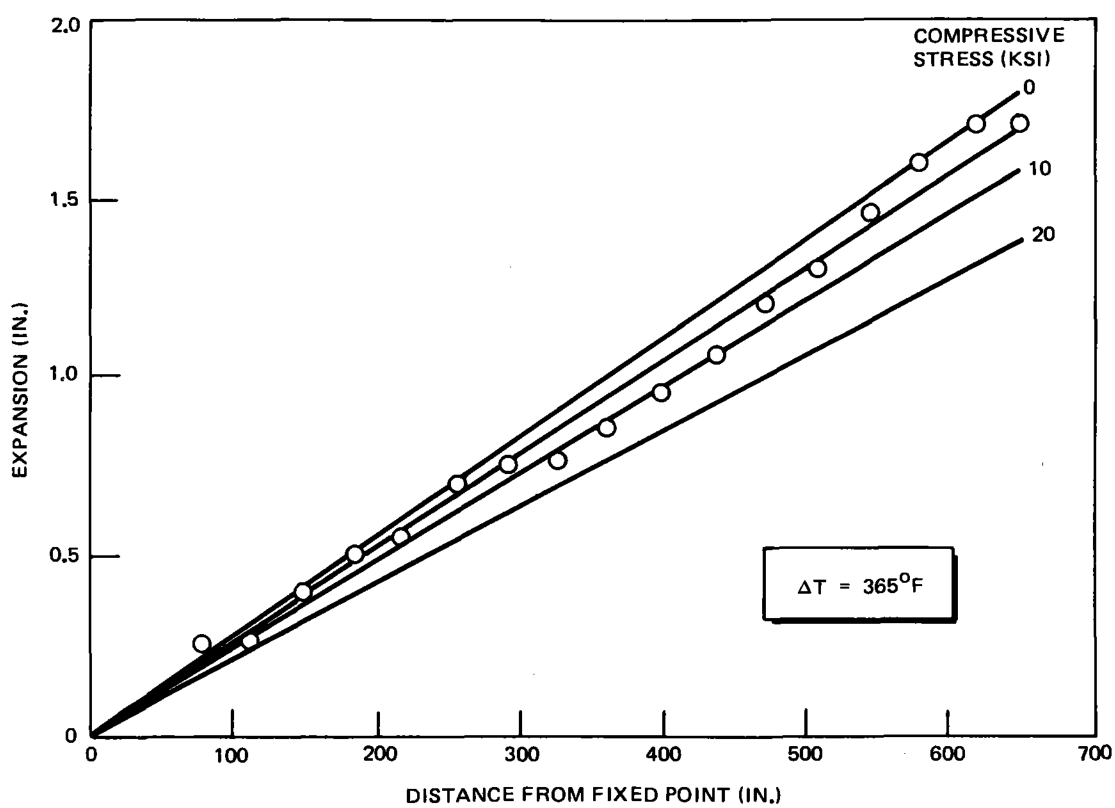


Figure 6-49. Thermal Expansion of 70-Tube Panel in Vertical Orientation

6.5.5.3 Overall Conclusions

The results of these tests verify the ability of the Pilot Plant provisions for allowing thermal expansion to occur freely. The test results also indicate that, even if the panel were completely restrained, no catastrophic failure of the panel would occur, although local buckling could be expected to take place.

6.6 RECEIVER SRE CONCLUSIONS

The results of the SRE testing conducted on the Pilot Plant receiver test articles lead to the following conclusions:

A. The fabrication methods and materials selected for the Pilot Plant receiver are compatible with the production of a boiler acceptable to Section 1 of the ASME Boiler Code.

B. Transportation and handling of the panel in both urban and business areas are practical and can be accomplished without specialized equipment.

C. The devices which provide for thermal expansion of the panel function very satisfactorily.

D. The receiver surface coating maintains its high absorptivity and structural integrity under extended exposure to cyclic and highly concentrated solar insolation.

E. The panel can operate at maximum Pilot Plant heat fluxes with tube temperatures well below the predicted values. Differential tube temperatures were such as to ensure a 30-yr panel life.

F. During steady-state operation, flow is uniform from tube to tube and is stable, even under extreme variations in pressure, flow or solar insolation.

G. The panel can survive flow cessations for significant periods without excessive temperatures or damage.

H. The panel control loop will automatically maintain steam outlet conditions within specified limits under anticipated transient conditions of pressure, flow, or insolation.

I. The panel can reach steady-state temperature conditions in 7 to 12 min (depending on the heat flux) after a constant heat load is applied.

In general, the SRE tests have resulted in a high confidence in satisfactory operation of the Pilot Plant receiver segment and thus, in the commercial receiver design concept.

APPENDIX RECEIVER SUBSYSTEM
REQ SPEC

APPENDIX RECEIVER
SUBSYSTEM
REQ SPEC

Appendix A
RECEIVER SUBSYSTEM REQUIREMENTS SPECIFICATION

1.0 SCOPE

This specification establishes the performance, design, and test requirements for the Pilot Plant receiver subsystem.

2.0 APPLICABLE DOCUMENTS

The equipment, materials, design, and construction of the receiver subsystem shall comply with all Federal, state, local, and user standards, regulations codes, laws, and ordinances which are currently applicable for the selected site and utility. These shall include but not be limited to the government and nongovernment documents itemized below. If there is an overlap in, or conflict between the requirements of these documents and the applicable Federal, state, county, or municipal codes, laws, or ordinances, the applicable requirement which is the most stringent shall take precedence.

The following documents, which were in effect on the date when the proposal was requested, form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.

2.1 GOVERNMENT DOCUMENTS

2.1.1 Specifications

- Regulations of the Occupational Safety and Health Administration (OSHA)
- Regulations of the California Occupational Safety and Health Administration (CAL/OSH) - if required.

2.1.2 Other Publications

- National Motor Freight Classification 100B - Classes and Rules Apply on Motor Freight Traffic
- Uniform Freight Classification 11 - Railroad Traffic Ratings Rules and Regulations
- CAB Tariff 96 - Official Air Transport Rules Tariff

- CAB Tariff 169 - Official Air Transport Local Commodity Tariff
- R. H. Grazlano's Tariff 29 - Hazardous Materials Regulations of the Department of Transportation
- CAB Tariff 82 - Official Air Transport Restricted Articles Tariff

2.2 NONGOVERNMENT DOCUMENTS

2.2.1 Standards

- American National Standards Institute, B31.1 Power Piping
- Manual of Steel Construction, 7th Edition, 1974, American Institute of Steel Construction
- Building Code Requirements for Reinforced Concrete, ACI 318-71, American Concrete Institute
- Uniform Building Code - 1973 Edition, Vol 1 by International Conference of Building Officials
- American Society of Mechanical Engineers, Boiler and Pressure Vessel Code:
  - Section 1, Rules for Construction of Power Boilers
  - Section 2 , Material Specifications
  - Section 5, Nondestructive Examination
  - Section 8, Unfired Pressure Vessels
  - Section 9, Welding and Brazing Qualifications
- National Electrical Code, NFPA 70-1975 (ANSI C1-1975)

3.0 REQUIREMENTS

3.1 RECEIVER SUBSYSTEM DEFINITION

The Pilot Plant receiver shall provide a means of transferring redirected radiant solar flux energy from an array of heliostats into stem (1) for generating electrical power with a conventional turbine-generator, (2) for converting to stored thermal energy in the TSS, and (3) for generating electrical power with a conventional turbine-generator using surplus thermal energy recovered from thermal energy stored in TSS. The receiver subsystem shall consist of:

A. The receiver unit (boiler/superheaters), header, drums, valves, controls, and instrumentation per ASME code, and support structure)

B. The riser piping from the ground to the receiver unit

C. The downcomer piping from the receiver unit to the ground

D. The control devices necessary to control the fluid temperature and pressure within the receiver unit

E. The required insulation and thermal protection to control thermal energy losses and provide personnel protection

F. The tower structure necessary to elevate and support the receiver unit and the riser/downcomer assembly

The receiver subsystem shall have the capability of absorbing 36.2 MWth net, and shall be capable of scaling to a larger Commercial central receiver power-generating system ranging in size from 100 to 300 MWe. The receiver shall be controlled by the master control within the Pilot Plant; however, the receiver shall also be capable of monitoring its own operation and of adjusting its own operation for time-variant insolation in order to supply rated steam conditions to the turbine-generator, and to preclude failures that would cause extensive equipment damage or be hazardous to personnel.

3.1.1 Receiver Subsystem Diagram

Figure A-1 shows the receiver, and its interfaces with the other subsystems and receiver elements.

3.1.2 Interface Definitions

3.1.2.1 Receiver/Collector Subsystem

The receiver shall have dimensions which will permit it to intercept 99% of a maximum-size image of 6.6m by 12.5m (21.6 ft by 41 ft) from the heliostat field. The receiver shall be designed to generate steam for the specified steam cycle when exposed to a programmable radiant energy flux from a 360-deg array of heliostats of the collector subsystem. The receiver shall have a minimum absorptivity of 0.9.

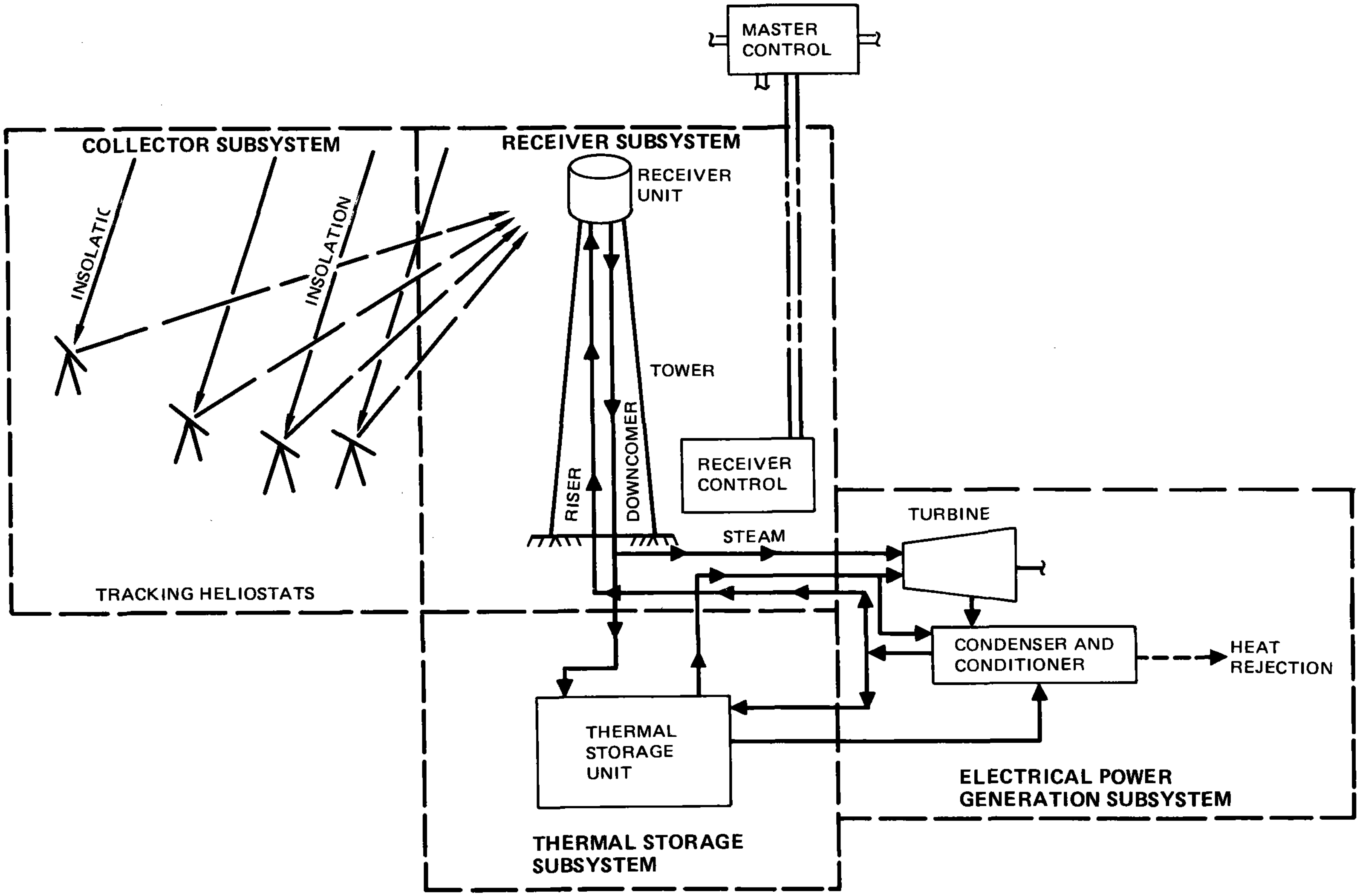


Figure A1. Receiver Subsystem Major Interfaces

3.1.2.2 Receiver/TSS/Electrical Power Generation Subsystem

The receiver shall be designed to provide for the physical connection with (and interchange of fluid with) the indicated subsystems at a flow-rate up to 16.5 kg/sec (130,500 lb/hr) at pressures and temperatures as indicated in paragraph 3.1.2.5.

3.1.2.3 Receiver/Master Control

The receiver controls shall be responsive to standard control signals (per power industry practice) from the Pilot Plant master control. The receiver internal controls shall also employ standard control signals and shall adhere to standard power industry practice.

3.1.2.4 Receiver Subsystem Internal Interfaces

Principal interfaces within the receiver subsystem include the following:

Receiver Unit/Riser/Downcomer

The receiver unit shall be physically connected to the riser/downcomer through the flow distribution assembly. The water headers shall be designed to receive water from the riser at a static pressure of at least 13.8 MN/m^2 (2,000 psia) and temperature of 205°C (401°F). The steam header shall be designed to connect to the downcomer which will carry the rated capacity at a maximum pressure of 10.4 MN/m^2 (1,500 psia) and temperature of 515°C (960°F).

Receiver Unit/Tower

The receiver unit shall be rigidly attached through its support structure to the tower top providing for the absorption of all static, environmental, and self-induced loads.

Riser/Downcomer/Tower

The riser/downcomer shall be rigidly attached to the tower at the top and through intermediate supports to provide for absorption of all environmental and thermally induced loads.

3.1.3 Major Components

The receiver subsystem is comprised of three major assemblies -- the receiver unit, the riser/downcomer, and the tower.

3.2 CHARACTERISTICS

3.2.1 Performance

The Pilot Plant receiver shall have a steam-generating capacity sufficient to produce up to 36 MWth of power. It shall be capable of absorbing a peak heat flux of 0.3 MW/m^2 (0.18 Btu/in^2-sec) without degradation in structural integrity or performance. The receiver design shall provide for maximum technology transferability to a 300- to 900-MWth receiver for a Commercial Plant.

Specific characteristics of the receiver subsystem shall be:

A. Temperature of the receiver unit shall be consistent with Section I of the ASME Boiler and Pressure Vessel Code or alternatively consistentent with the Section VIII, Division 2 analysis techniques, when used in conjunction with Section I material properties. The life of the receiver shall be 10,000 cycles when calculated in accordance with the above.

B. The effective solar absorptance of the absorber surface shall be at least 0.9 at operating temperature.

C. The total emittance of the receiver surface shall be as small as practical consistent with the maintenance of the specified solar absorptance.

D. The controls (including instrumentation) shall respond to transient and emergency conditions to provide for self-monitoring of receiver performance and to adjust flow in individual receiver parts to obtain proper performance and to avoid adverse effects on receiver components. Additionally, the controls shall monitor fluid conditions within the receiver so that the master control will be continuously apprised of the receiver conditions and performance characteristics. All instrumentation and controls wiring shall be installed per NEMA standards.

E. Startup shall be accomplished following a signal of anticipated sunrise from the master control. Following this signal, the receiver controls shall perform sufficient checks to ensure that it can operate in a manner consistent with normal safety regulations. At sunrise, the receiver shall regulate its own operation to ensure peak efficiency during all modes of operation.

F. The life expectancy of the receiver and its component parts shall be 30 yr and/or 10,000 cycles.

3.2.2 Physical Characteristics

The receiver unit shall have a maximum mass (dry) less than 500,000 kg (1,100,000 lb). The receiver unit shall have a maximum vertical dimension less than 15m (50 ft) and a maximum projected horizontal dimension less than 9m (28 ft). The receiver unit shall be designed so it can be readily erected on and removed from the tower in pieces. The receiver unit shall be designed to provide reasonable access for maintenance from permanent or temporary work platforms.

The downcomer shall be constructed of ASTM Standard A335, P11 pipe. The riser shall be constructed of ASTM Standard A106, Grade B scheduled pipe. All joints shall be of a welded construction. The pipes shall be insulated with calcium silicate insulation conforming to ASTM Standard C533. Insulation protection shall be provided in any areas exposed to the weather.

Redundant feed pumps shall be located upstream of the riser inlet. Each pump shall be capable of increasing the feedwater pressure from 3.45 MN/m^2 (500 psia) to 14.8 MN/m^2 (2,150 psia) at a maximum flowrate of 16.5 kg/s (130,500 lb/hr) and a peak power consumption of 262 kW (350 HP).

The tower structure shall be designed to withstand lateral forces caused by seismic activities, as specified in the annex, without failing. Steel components shall be designed such that yielding will not occur and concrete shall be designed to withstand failure in shear or compression. The tower shall be analyzed dynamically for resonance characteristics, pendulum effects, vibration, and whip action under seismic conditions.

A combined freight and passenger elevator shall be provided for operation and maintenance purposes. The elevator shall operate inside the tower structure for access to the inner core of the receiver.

Cantilevered and trussed supports from the tower shall carry the rails and elevator cab, and shall be designed to withstand seismic lateral loading as specified in the annex. A caged safety ladder for emergency purposes shall be installed in the interior of the tower structure for use by personnel when the elevator is inoperative.

Hinged or foldout platform sections shall extend outward at the bottom of the receiver unit for use in servicing the exterior portion of the receiver.

A crane shall be mounted to the top of the tower for use in installing the receiver unit components. The jib portion of the crane shall extend beyond the completed receiver unit space envelope so parts can be hoisted from grade to the top of the receiver unit. The crane shall be designed such that by simple dismantling or folding, it can be stored within the cone of protection provided by the receiver unit during Pilot Plant operation to protect it during heliostat misalignments. The crane shall be capable of being reactivated for maintenance of the receiver unit.

3.2.3 Reliability

High reliability shall be achieved in the receiver subsystem design by providing adequate operating margins, maximizing the use of proven standard parts, and using conservative design practices so the reliability performance shall not degrade the capability to achieve the availability specified in paragraph 3.2.5 when operated in the conditions specified in the annex.

Single-point failures that disable the automatic mode of system operation shall be eliminated wherever practical. Where it is impractical to eliminate such failure modes, suitable devices shall be used to detect and signal the occurrence of a failure. As a minimum, redundancies for the feed pumps shall be incorporated in the design.

3.2.4 Maintainability

The receiver subsystem shall be designed so that required service can be accomplished by personnel of normal skills using a minimum of nonstandard tools or special equipment. The receiver subsystem shall be designed to provide malfunction indication and fault isolation information data required by the master control. Items which do not have a redundant mode of operation shall incorporate maximum capability for on-line repair or replacement.

The receiver subsystem shall be designed so that potential maintenance points can be easily reached; so that replaceable components, such as electronic modules, can be readily replaced; and so that elements subject to wear or damage can be easily serviced or replaced. Preventive maintenance shall be designed to limit downtime to one day per month.

3.2.5 Availability

For 96.7% of its scheduled operating time, based on reliability and maintainability exclusive of isolation conditions, the receiver subsystem shall operate in accordance with the paragraph 3.2.1 performance requirements. Determinations of availability shall use 1 year as a time reference.

3.2.6 Environmental Conditions

The conditions described in Annex 1, Pilot Plant Environmental Conditions, are representative of the site characteristics and the transportation and operating environments to be encountered by the receiver subsystem. For design purposes safety margins shall be used commensurate with availability and performance requirements to ensure operation in accordance with paragraph 3.2.1 during and/or after exposure to these conditions, as appropriate, for the 30-yr life of the system.

All critical (frangible) components of the receiver subsystem shall be designed or packaged so the conditions described in paragraph 3.2 of the annex do not induce a dynamic environmental condition which exceeds the structural capability of the component. All components shall be designed to withstand handling/hoisting inertail loads up to 2 g's considering number, location, and type of hoisting points.

Practices recommended in the ASCE Paper 3269, Vol 126 and the Uniform Building Code, 1973, Vol 1 shall be employed in designing the receiver subsystem for winds.

To preclude fatigue caused by the fluctuating wind loads discussed in Annex 1, paragraph 3.3.4, the structures shall be designed such that stresses are below the endurance limits for this loading. These pressures are to be assumed in-phase over the structures.

Subsystem components shall be protected from the electrostatic charging and discharging associated with sand and dust storms.

The receiver subsystem shall be protected from the lightning threat by a 90-deg cone of protection per NFPA 78. Elements used in this design will also provide a part of the lightning protection for the collector subsystem.

The subsystem shall withstand the earthquake environment of Annex 1 without structural damage or yielding.

3.2.7 Transportability

Receiver subsystem components shall be designed for transportability within applicable Federal and state regulations by highway and railroad carriers using standard transport vehicles and materials-handling equipment. The components, in their packaged condition, shall be capable of withstanding the climatic conditions and shock and vibration environments defined in annex paragraph 3.2. Whenever feasible, components shall be segmented and packaged to sizes that are transportable under normal commercial transportation limitations. Subsystem components that exceed normal transportation limits shall be transportable with the use of special routes, clearances, and permits.

3.3 DESIGN AND CONSTRUCTION

The receiver shall be designed and constructed in accordance with the ASME Boiler and Pressure Vessel Code, Sections I (or consistent with the Section VIII, Division 2 analysis techniques, when used in conjunction with Section I material properties), II, V, and IX. Piping shall be provided as specified in ANSI B31. 1. The tower structure and associated facilities shall be designed and constructed employing the standards of the American Institute of Steel Construction, American Concrete Institute, and Uniform Building Code.

3. 3. 1 Materials, Processes, and Parts

The receiver unit and piping shall be fabricated from materials as specified in the ASME Boiler and Pressure Vessel Code, Sections I and II, and ANSI B31. 1. Materials shall be suitable for the service conditions specified in Paragraph 3. 2. 6. Except where otherwise specified, all structural materials and fabricated steel used in items of equipment shall conform to the Standards of the American Institute of Steel Construction, American Concrete Institute, and Uniform Building Code as applicable. No potentially toxic materials shall be used. Except where essential, the use of exotic or costly materials is to be avoided. All elements of the receiver unit except for absorber tubing shall be constructed from standard and/or commercial parts.

3. 3. 2 Electrical Transients

The subsystem operation shall not be adversely affected by external or internal power line transients caused by normal switching, fault clearing, or lightning. Switching transients and fault clearing functions shall require less than six cycles of the fundamental frequency (100 ms) and shall be limited to 1. 7 PU voltage (1. 7 per unit or 170%). Lightning arresters shall be installed which will limit the resultant line voltage to 5 PU on a line-to-ground basis during the interval of peak current as defined in the annex. Components of the subsystem shall be shielded from the lightning threat specified in the annex. Shielding shall protect the electrical components from both the bound charge and induced current threats.

3. 3. 3 Electromagnetic Radiation

The receiver subsystem shall be designed to minimize susceptibility to electromagnetic interference and to minimize the generation of conducted or radiated interference. The design criteria contained in the following Air Force design handbooks shall be used to assure electromagnetic compatibility: Design Handbook on Electromagnetic Compatibility (AFSC DH1-4), Checklist of General Design Criteria (AFSC DH1-X), and Instrumentation Grounding and Noise Minimization Handbook (AFRPL-TR-65-1).

3.3.4 Nameplates and Product Marking

All deliverable items shall be labeled with a permanent nameplate listing, including as a minimum, manufacturer, part number, change letter, serial number, and date of manufacture.

All access doors to replaceable/repairable items shall be labeled to show equipment installed in that area and any safety precautions or special considerations to be observed during servicing.

3.3.5 Workmanship

The level of workmanship shall conform to practices defined in the codes, standards, and specifications applicable to the selected site and utility. Where specific skill levels or certifications are required, current certification status shall be maintained with proof available for examination. Where skill levels or details of workmanship are not specified, the work shall be accomplished in accordance with the level of quality currently in use in the construction, fabrication, and assembly of Commercial Plants. All work shall be finished in a manner such that it presents no hazard to operating and maintenance personnel, is neat and clean, and presents a generally uniform appearance.

3.3.6 Interchangeability

Major components, circuit cards, and other items with a common function shall be provided with standard tolerances and connector locations to permit interchange for servicing. Components that have similar appearance but different functions shall incorporate protection against inadvertent erroneous installation through the use of such devices as keying, connector size, or attachment geometry.

3.3.7 Safety

The receiver shall be designed to minimize safety hazards to operating and service personnel, the public, and equipment. Electrical components shall be insulated and grounded. Any moving elements shall be shielded to avoid entanglements and safety override controls/interlocks shall be provided for servicing. Insulation shall be provided on all parts or components with elevated temperatures to which personnel may be exposed during routine inspection, servicing, repair, and maintenance. All pertinent OSHA rules and regulations shall be observed. The use of toxic materials is to be avoided. The tower structure and associated facilities shall be designed and constructed to assure safe and reasonable access by personnel carrying the tools, equipment, parts, and materials required to perform the necessary inspections, servicing, repair and maintenance.

3.3.8 Human Engineering

All receiver controls and mechanical details shall facilitate manual operation, adjustment, and maintenance. MIL-STD-1472, Human Engineering Design Criteria, shall be used as a guide in designing equipment layouts, controls, displays, placards, illumination, access ways, etc.

3.4 DOCUMENTATION

3.4.1 Characteristics and Performance

Equipment functions, normal operating characteristics, limiting conditions, test data, and performance curves, where applicable, shall be provided.

3.4.2 Instructions

Instructions shall cover assembly, installation, alignment, adjustment, checking, lubrication, maintenance, and operation. All phases of subsystem operation shall be addressed including startup, normal operation, regulation and control, shutdown, and emergency operations. A guide to troubleshooting instruments and controls shall be provided.

3.4.3 Construction

Engineering and assembly drawings shall be provided to show the equipment construction, including assembly and disassembly procedures. Engineering data, wiring diagrams, and parts lists shall be provided.

3.5 PERSONNEL

The Pilot Plant is to be installed, checked out, and tested by contractor personnel, then taken over and operated as a Commercial Plant by utility personnel. Operation and maintenance personnel requirements shall be satisfied by recruitment from the established utility labor pool.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 GENERAL

All quality assurance tests shall be performed by the contractor. These tests may be witnessed by the Department of Energy, ASME or their authorized representatives, or the witnessing may be waived. In either case, substantive evidence of hardware compliance with all test requirements shall be required.

4.2 SUBSYSTEM INTEGRITY

The integrity of the subsystem when installed shall be verified by subjecting it to hydrostatic pressure testing and to flow checkouts. Checkouts shall be controlled by receiver control.

4.3 STRUCTURAL INTEGRITY

Structural integrity shall be verified by inspection as specified in the Uniform Building Code and by the standards of the AISC.

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