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ERDA CONTRACT NO. E(04-3)-1109

SOLAR PILOT PLANT

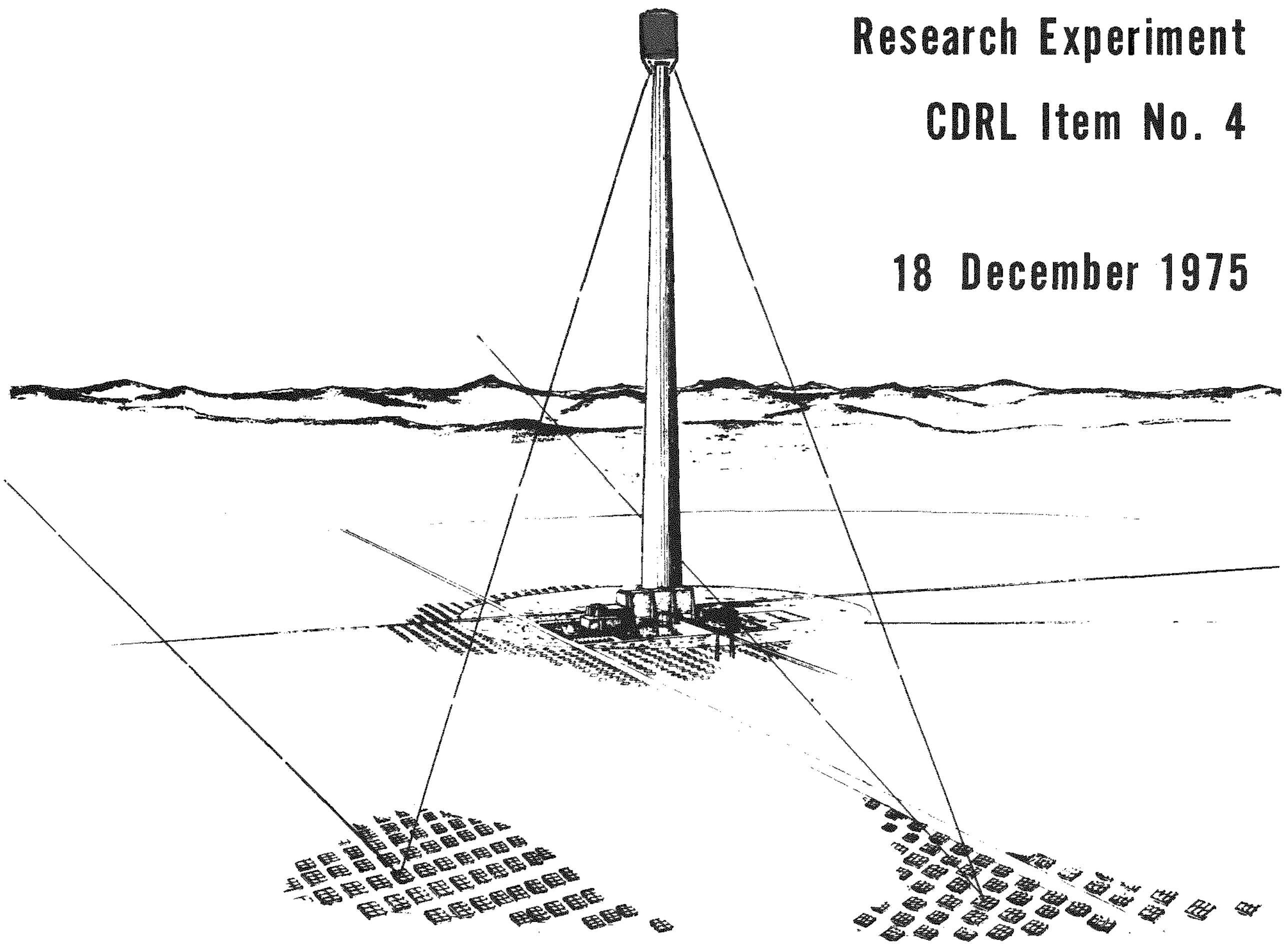
Phase I

CONCEPTUAL DESIGN REPORT

Steam Generator Subsystem Research Experiment

CDRL Item No. 4

18 December 1975



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Systems & Research Center
2600 RIDGWAY PARKWAY,
MINNEAPOLIS, MINNESOTA 55413

40290 Printed in U.S.A. F3419-DR-103

FOREWORD

This is the first submittal of the Solar Pilot Plant Steam Generator Subsystem Research Experiment Conceptual Design Report per CDRL No. 4 under ERDA Contract E (04-3) 1109. This study report was written in a form that documents the concurrent oral presentation. This report is submitted for review and approval by ERDA.

AGENDA

SOLAR POWER PLANT PROGRAM

CONCEPTUAL DESIGN REVIEW - STEAM GENERATOR SUBSYSTEM SRE

18 December 1975

Minneapolis, Minnesota

Thursday - 18 December 1975		Honeywell SRC G&APD Executive Conference Room
8:30 AM	CONCEPTUAL DESIGN REVIEW - STEAM GENERATOR SRE	
	• Program Overview	R. Stiles
	• Steam Generator Configuration	G. Watson
	• Steam Generator Design	G. Watson
	• Steam Generator Test Requirement	G. Watson
	• Test Facility and Operation	B. Bursack
	• Data Acquisition System	B. Harris
	• Simulator	B. Harris
	• Test Schedule	R. Stiles
11:00 AM	ERDA COMMENTS/APPROVAL	
12:00 N	LUNCH	

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ILLUSTRATIONS

TABLES

SECTION I
PROGRAM OVERVIEW

SUBSYSTEM RESEARCH EXPERIMENT PROGRAM OBJECTIVES

A 5 MW(th) model of the steam generator will be constructed and tested to ascertain with a high degree of confidence that future larger-scale units are feasible and practical.

The primary objective of the subsystem research experiment is to validate the pilot plant concept and to gain knowledge and experience which can be applied to the pilot plant preliminary design. Consideration is also given to the characteristics implied for larger commercial systems.

The feasibility of generating steam as a working fluid in a steam generator heated by redirected and concentrated solar flux from a collector field will be verified. The working fluid must be conditioned and provide the required flow, pressure, and temperature conditions required for efficient operation of a turbine-generator set operating with a Rankin cycle.

The construction and test of a small-scale steam generator will provide a base of technical knowledge which, with the application of valid scaling judgments, can be directly applied to geometrically and capacity wise larger units.

Experience gained from the operation of scaled and similarly controlled equipment is directly applicable to larger sizes of equipment. Procedures found necessary to successfully determine performance under various operating conditions will become acceptable and safe operating procedures for subsequent and larger steam generators.

Fabrication techniques employed during the fabrication of equipment which is geometrically scaled from other sizes with similar design configurations will remain essentially the same. Construction methods could be reasonably expected to be different because of physical size and its implication to transportation and handling requirements.

Extensive use of standard components and material during the construction of scaled models, which are subsequently operated and perform satisfactorily, will verify the selection of parts and materials selected for larger equipments.

Empirical data derived from scale model testing can be used to verify predicted performance based on design analysis. Analytical methods can be modified on the basis of test results to enhance their use in future designs.

Controllability of larger scale units can be verified by testing small models with identical control equipment. It is also economically feasible to design the scaled units for greater range and with more controllable elements to ascertain operational limits before commitment to equipment with superfluous requirements.

Test experience with a model will provide reliability and maintainability which can be applied to effectiveness studies of future equipments.

SRE Program Objective

Validation of Pilot Plant Preliminary Design

- Prove technical feasibility
- Provide technology base
- Identify operational procedure
- Confirm fabrication techniques
- Verify applicability of standard components and material
- Verify structural, thermal, and hydraulic analysis with empirical data
- Verify controllability
- Provide data in support of system effectiveness studies.

HIGHLIGHTS OF THE STEAM GENERATOR SUBSYSTEM RESEARCH EXPERIMENT

A proper approach toward the design, fabrication, and test of the 5 MW(th) steam generator research experiment will reduce to a minimum the uncertainties existing at the completion of the program.

The steam generator design approach selected will meet the objectives of the program with low technical risks, an assurance of a timely program completion, and a maximum value to future central receiver solar power development plans.

Centuries of experience have been accumulated in arriving at the present state of the art in fossil fueled steam generators and, in more recent years, the consideration of peaking power plants to handle the peak demands of grid loads. Design analysis and fabrication techniques gained over these years is in many cases directly applicable to the design consideration required for the development of a solar flux powered steam generator. Of particular value is the design assurance now possessed by steam generator suppliers that their equipment can survive the cyclic operation typical of solar operation.

Critical design parameters are held the same for the research model as for the pilot plant. Among these parameters are boiler and superheater tube dimensions, pressure drop across the superheater, flow circuitry configuration, boiler and superheater tube temperatures, flux profiles and peaks, steam cycle conditions, boiler circulation ratio, superheater combined stresses and life requirements. Standard fabrication techniques will be used in the construction of the steam generator.

Control of the steam generator during the test program is designed to be identical to that planned for the pilot plant.

The design selected for the SRE is a simple design with a right circular cylindrical cavity with the boiler in the high flux area and the superheater in the lower flux areas.

The SRE steam generator will be constructed in accordance to the same ASME code and other applicable requirements as the Pilot Plant.

The design of the 5 MW(th) steam generator will consider future adaptability for use at the National Test Facility. The delivered hardware will not require redesign or modification for future planned testing.

The approach selected for testing the steam generator will maximize knowledge for further developing solar steam generators.

A solar flux simulator is selected which will simulate the flux peaks and profiles experienced during normal operation of the generator, while mounted on a central receiver tower and heated by solar flux from a collector field.

All testing will be done using working fluid which meets the requirement for water chemistry qualifications to assure valid testing as it relates to long term performance and life requirements.

The testing will be performed under utility plant operating practices and the steam generator will be operated by utility operators, thus assuring evaluation of operating practices which will be imposed on pilot and commercial plant operation.

Data taken during the test operation will be of sufficient quantity to evaluate the design parameters and to correlate actual performance to predicted performance under normal and abnormal operating conditions.

Selective test data will be processed in real time to assure safe operating procedures and to allow for a timely sequencing of test conditions.

Highlights of the Steam Generator Subsystem Research Experiences

- Steam Generator Design Approach
  - Extensive use of fossil steam generator technology
  - Critical design parameters are held constant
  - Design implies standard manufacturing techniques
  - Control design philosophy held constant
  - Design simplicity
  - Code compliance
  - Provisions made for subsequent testing at the National Test Facility
- Test Approach
  - Simulated solar flux input
  - Quality water chemistry
  - Test control under steam plant operational constraint
  - Test conducted with utility plant operators
  - Test conducted in compliance with standard utility requirements (code and ordnances)
  - Sufficient data collection to verify design
  - Test data reduction in real time to expedite test program

SRE Steam Generator

Program Overview

INTRODUCTION

A Subsystem Research Experiment (SRE) design concept has been selected which will verify the performance of the key features of the steam generator proposed as the preliminary design baseline for the 10 MW(e) Pilot Plant.

The preliminary design baseline solar steam generator is a pump-assisted, recirculating drum boiler with a helical superheater. A review of key features of the generator are:

- A recirculating drum boiler, rather than a once-through boiler, because it will be easier to control during daily startup and shutdown
- Pump-assisted circulation allows the use of smaller boiler tubes than natural circulation, thus reducing weight and thermal stress
- A helical superheater, because its flexibility will allow relatively free radial thermal expansion and because the helical flow circuitry will average out the effect of heat flux maldistribution in the superheater
- Steam temperature will be controlled by spray attemperators between the two stages of the superheater

Existing fossil boiler technology will be fully applied to reduce risks of failure in design areas requiring a high degree of technology.

This report describes the SRE steam generator concept. Scaling relationships are presented which will verify the key features of the Pilot Plant steam generator by the successful operation of the SRE steam generator.

Objective of SRE

Verify key features of Pilot Plant steam Generator

Key Features

- Recirculating drum boiler
- Pump-assisted circulation
- Helical superheater
- Spray attemperator

Existing technology applied to reduce risk

Scaling relationships will be presented

STEAM GENERATOR REQUIREMENT

The proposed Subsystem Research Experiment will meet the requirement established by ERDA: Validation of the baseline design of the solar steam generator for the Pilot Plant.

The SRE steam generator can provide data for verification of the Pilot Plant steam generator because both

- Have the same flow circuitry and physical arrangement
- Match fluid and metal temperatures at all points in the flow circuit
- Have the same tube dimensions and materials
- Are designed using the same methods

The measured performance of the SRE steam generator will be compared to predictions. This comparison will either verify the design methods, or show where modifications will be necessary. The design methods can then be confidently applied to the Pilot Plant steam generator.

SRE data applies to Pilot Plant steam generator

- Flow circuitry and physical arrangement
- Fluid and metal temperatures
- Tube dimensions and materials
- Design methods

Design method verification by comparison of measured and predicted performance

SECTION II

STEAM GENERATOR CONFIGURATION

SRE Steam Generator

Steam Generator Configuration

PUMP-ASSISTED RECIRCULATING DRUM BOILER

The pump-assisted recirculating drum boiler, as recommended for the Pilot Plant solar steam generator at the PDBR, will be used for the SRE steam generator.

Figure 2-1 is the flow schematic for the pump-assisted recirculation drum boiler. This concept consists of a boiler section and a two-stage helical superheater with an interstage spray attemperator for steam temperature control.

The flow schematic applies to both the Pilot Plan and the SRE steam generators. Referring to Figure 2-1, the drum receives feedwater from the plant's feedwater system and a steam-water mixture from the boiler section. Mechanical separators in the drum separate the steam fromthe steam-water mixture flowing into the drum from the risers. The saturated steam leaves the top of the drum and flows through the saturated steam lines to the first-stage superheater. The steam exiting from the first-stage superheater passes through a spray attemperator where additional feedwater is injected for superheat control. From the attemperator, the steam flows into the second-stage superheater where the desired superheat is reached. The saturated water separated with the mechanical separators mixes with the feedwater and exits from the bottom of the drum through a downcomer pipe connected to the recirculating pump. This pump discharges to the boiler where steam is generated.

The Pilot Plant steam conditions to be modeled by the SRE are presented in Table 2-1.

Table 2-1. Solar Steam Generator Steam Conditions

	PDBR Pilot Plant 1450 psig/950 F 55 MWt PDBR Maximum Capability Summer Solstice @ 12:00 Noon
Steam Pressure @ Outlet of Second-Stage Superheater, bars	103 (1500 psig)
Steam Temperature @ Outlet of Second-Stage Superheater, °C	513 (955 F)
Drum Operating Pressure, bars	117 (1700 psig)
Boiler and Superheater Design Pressure, bars	124 (1800 psig)
Feedwater Temperature @ Inlet to Drum, °C	271 (520 F)

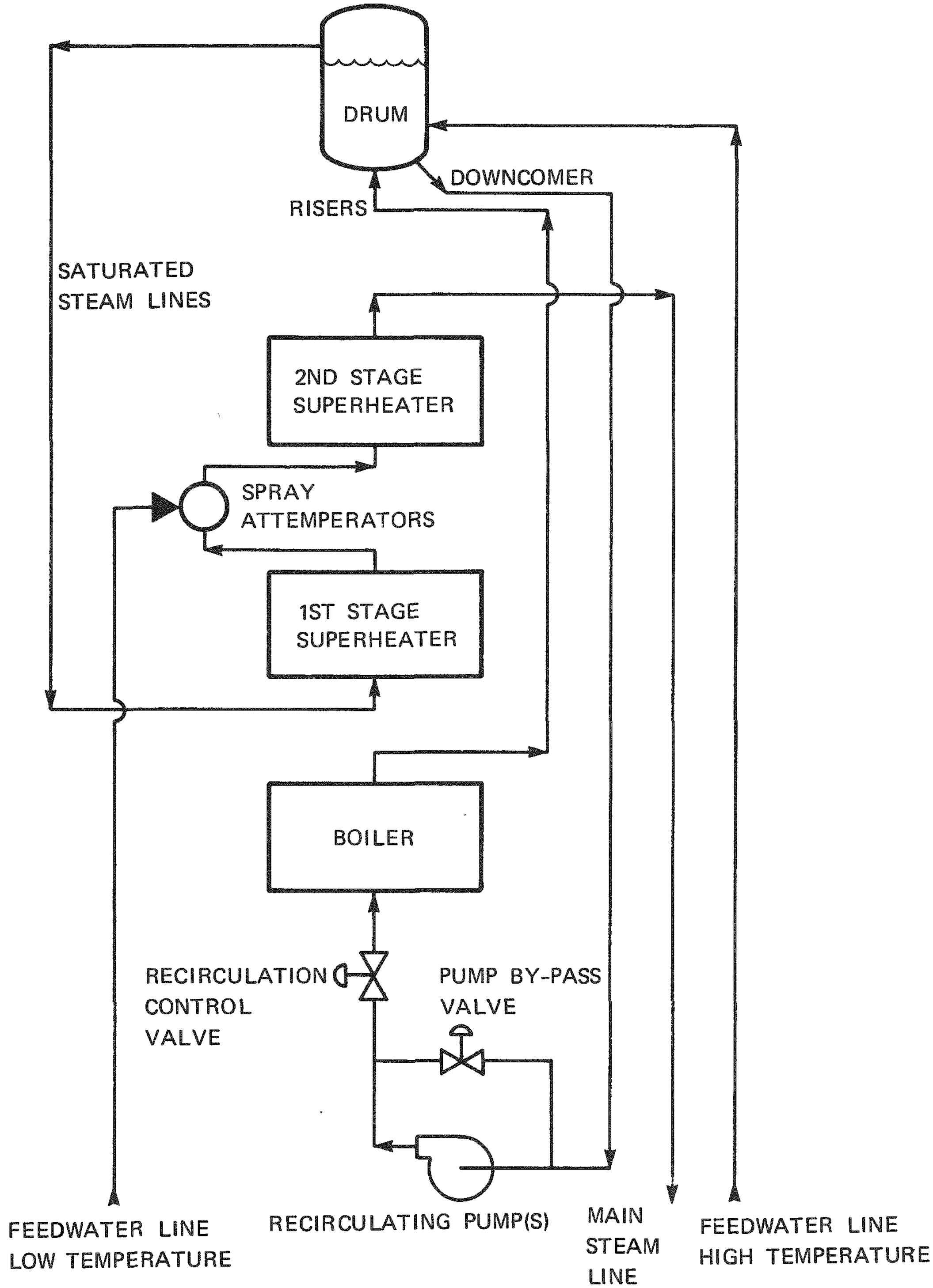

Figure 2-1. Solar Steam Generator - Flow Schematic

SRE Steam Generator

Steam Generator Configuration

REVIEW OF PILOT PLANT ARRANGEMENT

It is appropriate to review the arrangement of the Pilot Plant steam generator because it is the basis for modeling the SRE steam generator.

Presented in Figure 2-2 is the Pilot Plant steam generator arrangement using the pump-assisted recirculating boiler. The boiler, first-stage superheater and second-stage superheater heat transfer surfaces cover the surface area of the right circular cylinder of the cavity. The boiler section, which has the relatively cool heat transfer surface, is on the bottom portion of the cavity; there the reradiation losses through the cavity aperture are reduced. The first and second stages of the superheater are arranged on the remaining upper portion of the cavity such that the second-stage superheater will be in the lowest heat input zone for metal temperature protection.

The drum, piping and headers and spray attemperators will be placed outside the thermal insulation and lagging covering the heat transfer surface. All these components will be enclosed by the steam generator housing.

The headers for the heat transfer surface will be hung from the structure by supports which allow for thermal expansion.

The recirculating pump will be located in an equipment room on the top of the tower immediately below the aperture. The downcomer and the return line, as well as the feedwater line, attemperator water supply line, and main steam lines will be routed through the cavity supports (corbels).

Although the basic arrangement of the Pilot Plan design concept has not changed since the PDBR, several refinements have been made which reflect the development process:

- The ceiling of the cavity will not be arranged with a heat transfer surface but will be insulated.
- The arrangement of the external piping has been changed to reflect recent design considerations which will be presented in this report.

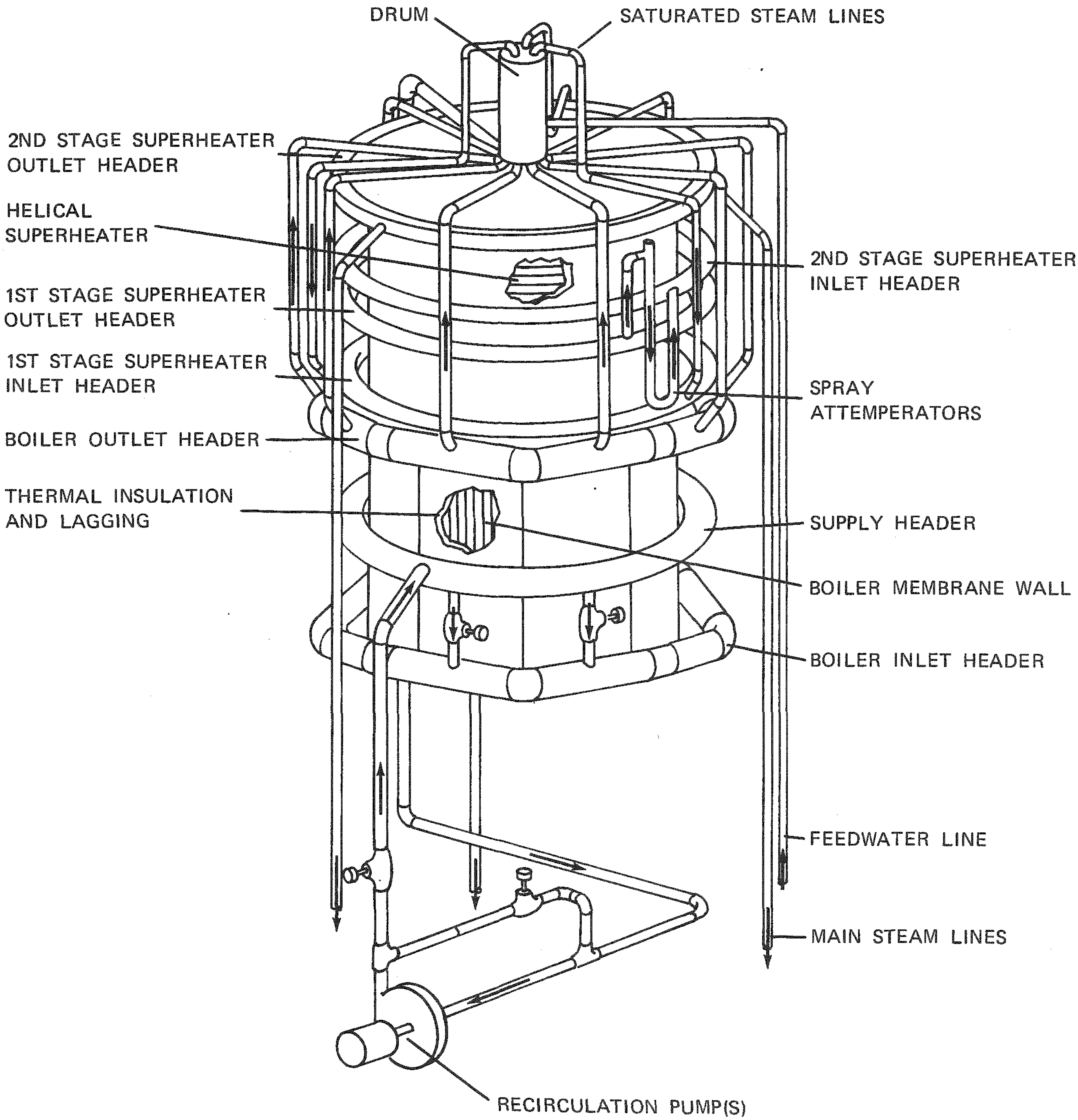

Figure 2-2. Pilot Plant Design Arrangement

SRE Steam Generator

Steam Generator Configuration

ARRANGEMENT OF THE SRE STEAM GENERATOR

The arrangement of the SRE steam generator is the same as the Pilot Plant arrangement except for minor modifications required for testing at the Riverside Facility.

The SRE physical arrangement (Figure 2-3) represents the same arrangement shown previously for the Pilot Plant, except for the relocation of the boiler recirculating pump to the side of the steam generator.

The support structure for the SRE (Figure 2-4) will be a nine-sided frame consisting of welded channels. This frame will be positioned on the outside of the piping and headers as arranged in Figure 2-3. All of these components will be supported from the structural frame. There will be three support legs which are flanged to the structural frame. These legs will be removed for shipping and installed at the test site.

In the design of the structural supports the following factors were considered:

- Support of steam generator for the Pilot Plant
- Installation and removal of the solar simulator into the cavity of the SRE
- Installation of the SRE steam generator on a tower at the National Test Facility.

All supports, piping, etc., are in multiples of three to correspond to the position of the corbels and to effect symmetry of the system, minimizing the design analysis complexity.

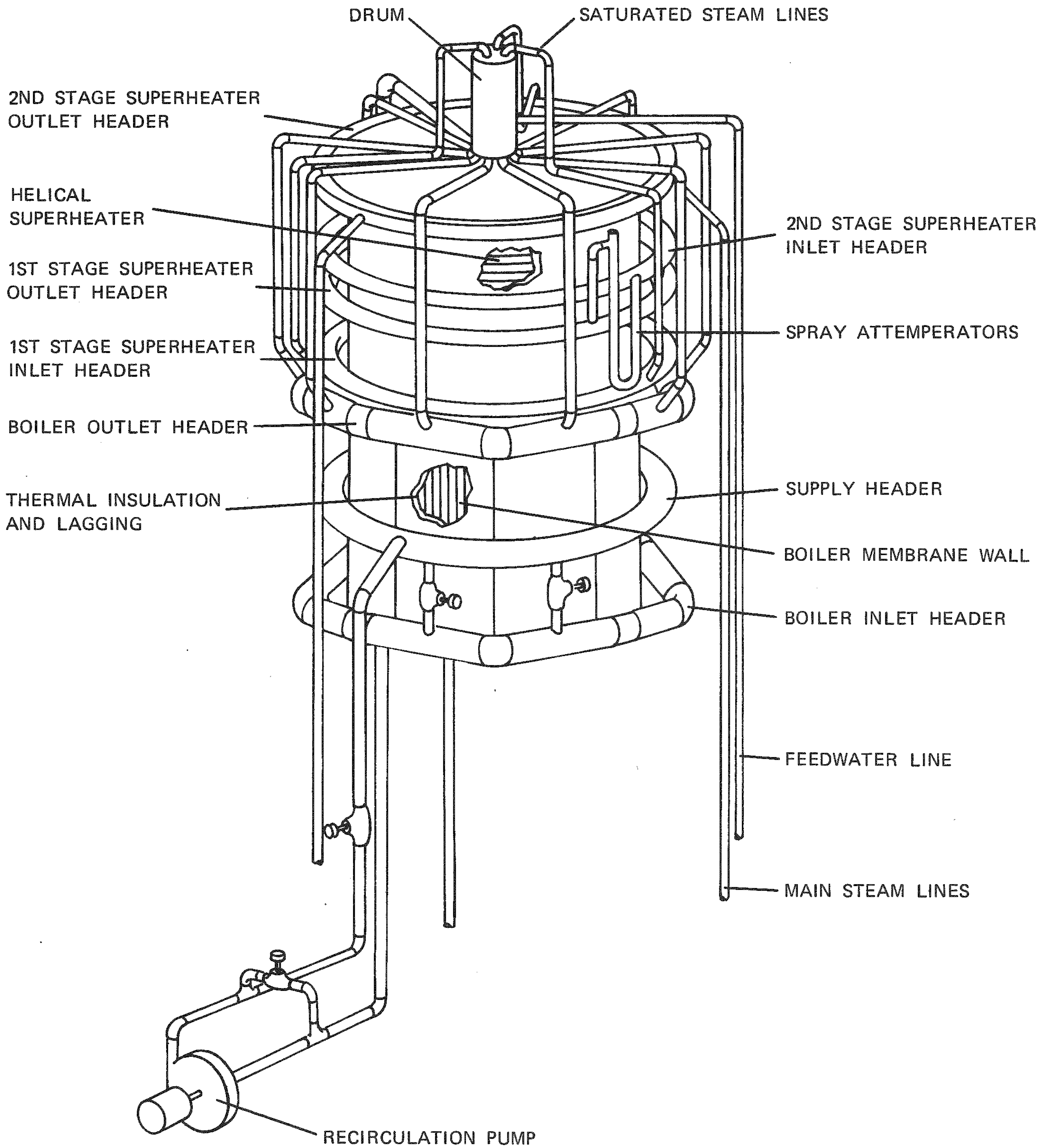

Figure 2-3. SRE Design Arrangement

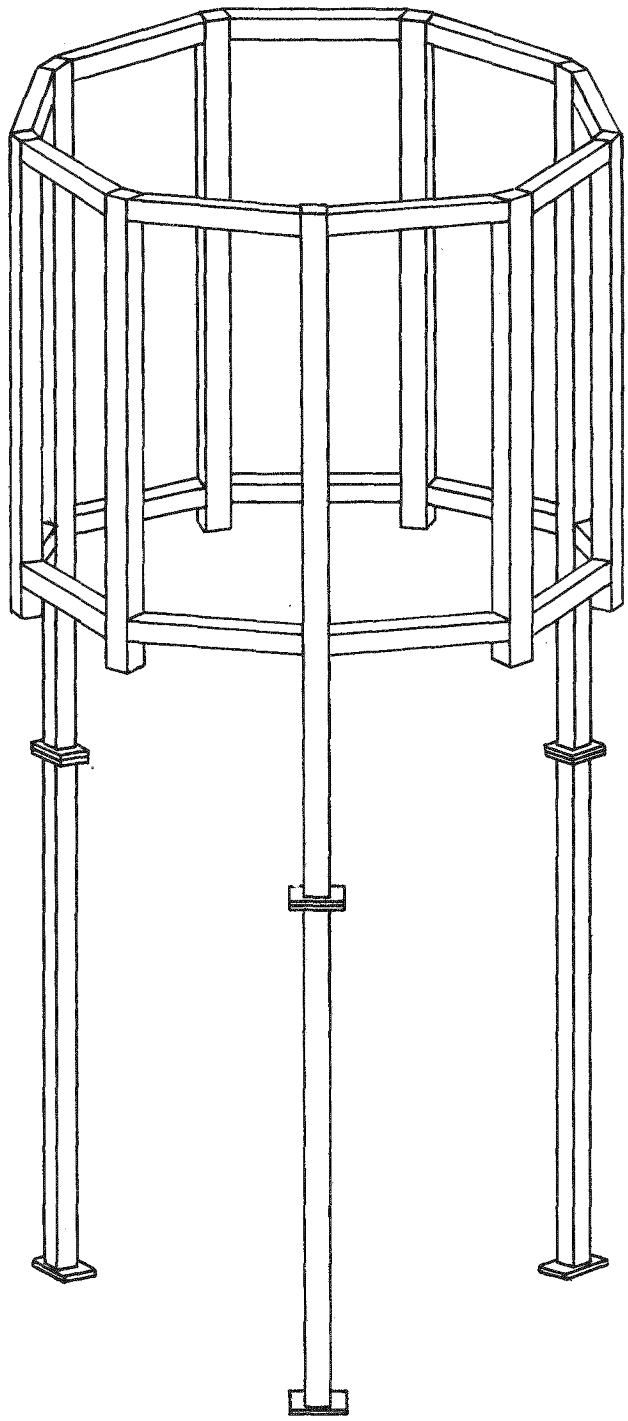

Figure 2-4. SRE Structural Support Frame

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SRE Steam Generator

Steam Generator Configuration

SCALING CRITERIA

The cavity dimensions of the SRE steam generator are scaled from the Pilot Plant using the square root of the power ratio; flow is scaled directly by the power ratio.

The criteria that determine the scaling law for cavity dimensions are that the magnitude and distribution of the absorbed heat flux be identical for the Pilot Plant and SRE steam generator. These criteria were selected because thermal stress, tube metal temperatures and other important design parameters are directly dependent on heat flux. To meet these criteria the cavity surface area scales directly with the power ratio while maintaining the cavity height to diameter ratio. Thus, the linear cavity dimensions scale with the square root of the power ratio.

The power ratio between the 55 MWt Pilot Plant and the 5 MWt SRE steam generator is 11. The scaling factor for cavity dimensions is 3.32.

The structural integrity and the service life of the steam generator depend to a great extent on the local fluid and metal temperatures. To meet the criteria that these temperatures be equal in the Pilot Plant and the SRE steam generator, the flow circuitry of the two generators must be identical and the fluid flow scaled directly with the power ratio. Steam flow at noon summer solstice is 80,150 Kg/hr (176,700 lb/hr) for the Pilot Plant and 7286 Kg/hr (16,064 lb/hr) for the SRE.

Figure 2-5 presents the Pilot Plant steam generator dimensions used as the basis for scaling the SRE. The cavity height is 14 meters (46.1 feet), and the diameter is 12 meters (39.4 feet). The boiler height is 7.31 meters (24 feet) established by the criteria discussed in the next paragraph.

The ratio of energy absorbed in the boiler section to the energy absorbed by the superheater must match the requirements of the steam cycle.

The height of the boiler is selected to absorb the energy required to produce saturated steam from the feedwater. Actually, the boiler surface is slightly undersized, and the extra energy absorbed by the superheater is balanced by the energy required to vaporize the spray attemperator flow. As the sun changes position, causing slight variations in the vertical distribution of absorbed energy, steam temperature control is maintained by the spray attemperators. (The calculation procedure is presented in Appendix A.)

The two stages of the superheater are placed on the upper portion of the cavity walls. For simplicity and to reduce design costs, the first and second stage superheaters are the same size.

The dimensions of the SRE shown in Figure 2-5 were obtained by applying the scaling laws to the dimensions of the Pilot Plant steam generator, as presented at the PDBR.

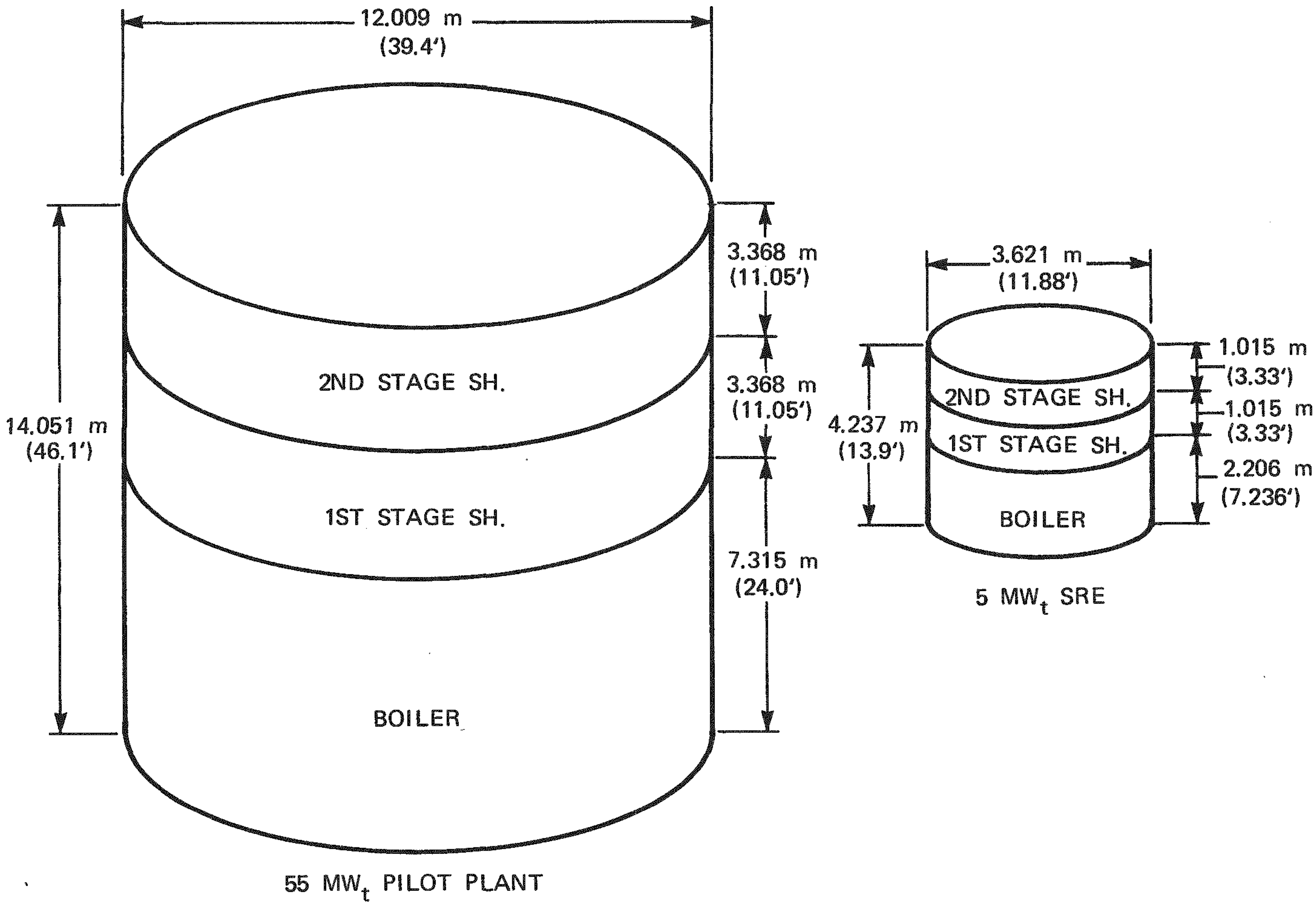

Figure 2-5. Cavity Size

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SECTION III
STEAM GENERATOR COMPONENTS

FLOW CIRCUIT FOR THE BOILER SECTION

The boiler section will have nine parallel flow circuits so that flow distribution can be adjusted to match the hot spots caused by the corbels.

The heat flux maps from the Ray Trace analysis show, that as a result of the corbels, there are three hot spots on the lower portion of the cavity. There are also three regions of average heat input and three of lower-than-average heat input. Therefore, nine parallel flow circuits will be used so three circuits can have a higher flow than the remaining six circuits.

The nine boiler flow circuits are shown schematically in Figure 3-1. The feedwater and saturated water exiting from the cyclone separators mix and exit the steam drum. This mixture flows through the downcomer to the inlet of the recirculating pump(s). The boiler flow is then controlled by the valve at the exit of the pump and flows to the supply header. Connected to the supply header will be nine boiler flow circuits. Each circuit will be similar and consists of a flow meter, pressure drop (valve), inlet header, a membrane wall panel, outlet header, and a riser to the steam drum. With the exception of the membrane wall panels, all of the flow circuitry will be external to the ID of the cavity.

With nine individual flow circuits the flow into each circuit can be varied depending upon the circumferential heat flux distribution on the lower portion of the cavity. Here, by the proper setting of the inlet valves of each circuit, the flow rate in each can be changed such that the circuits with the highest heat flux will receive the highest flow.

A circulation ratio (boiler inlet flow/steam flow) must be selected which will reduce flow maldistribution so that the heat transfer effectiveness of the boiler section will not be impaired.

Individual boiler flow circuits also have the following advantages:

- The header sizes required for a balanced flow both on the inlet and outlet are reduced due to the reduced tube flow area served by each header.
- The inlet and outlet headers can be attached to the membrane panels in the shop, thereby reducing the number of field welds which have to be inspected.

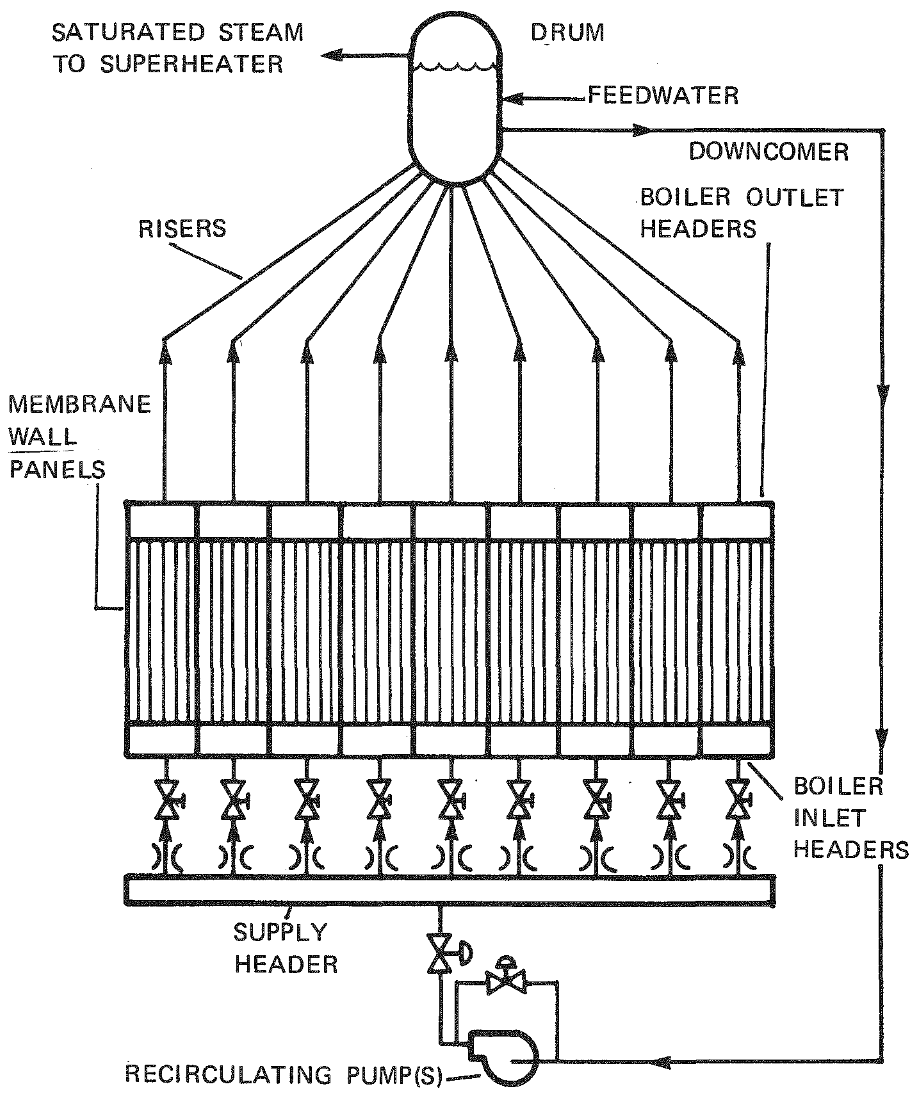


Figure 3-1. Boiler Flow Circuit

SURFACE ARRANGEMENT FOR THE BOILER SECTION

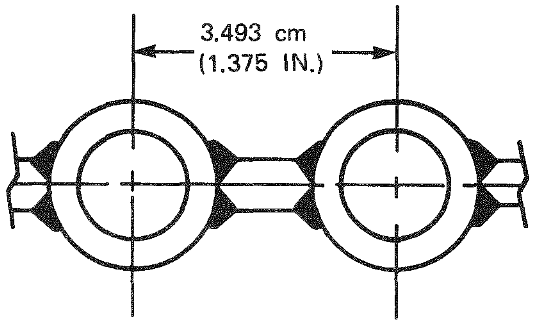
The nine-sided boiler section is fabricated from membrane wall panels because this construction has proven to be most economical for similar fossil boiler applications.

The membrane wall specifications shown in Figure 3-2 will be used both for the Pilot Plant and the SRE steam generators. The tube dimensions and the centerline spacing are the same. The tube material will be Croloy 1/2 (SA 213 Grade 2) with a carbon steel web welded to adjacent tubes.

For the SRE steam generator, each of the nine flow circuits will be composed of a membrane panel connected to an individual inlet and outlet header. The arrangement of an individual membrane panel is shown in Figure 3-3. In each membrane panel (per flow circuit) there will be 38 tubes for a cavity diameter of 3.621 meters (11.88 feet).

The nine membrane panels will be arranged on the circumference of the lower portion of the cavity such that the OD's of the center two tubes of each panel are tangent to the circumference of the cavity. The arrangement is shown in Figure 3-4.

In the furnace zones of fossil boilers and in the membrane hoods used in the steel industry the membrane panels are joined by a complete weld to form a relatively rigid structure. The solar steam generator membrane panels will be welded together along with the inlet and outlet headers to achieve rigidity. A flow boundary plate will be inserted and welded at the ends of the inlet and outlet headers before the final pressure weld is made.



SPECIFICATIONS:

TUBE:

O.D.	2.223 cm	(.875 IN.)
MIN. WALL	0.376 cm	(0.148 IN.)
MAT'L.	CROLOY 1/2 (S.A. 213 GRADE 2)	

WEB:

THICKNESS	0.635 cm	(0.25 IN.)
MAT'L.	CARBON STEEL (C1015 C.F.)	

Figure 3-2. Membrane Wall

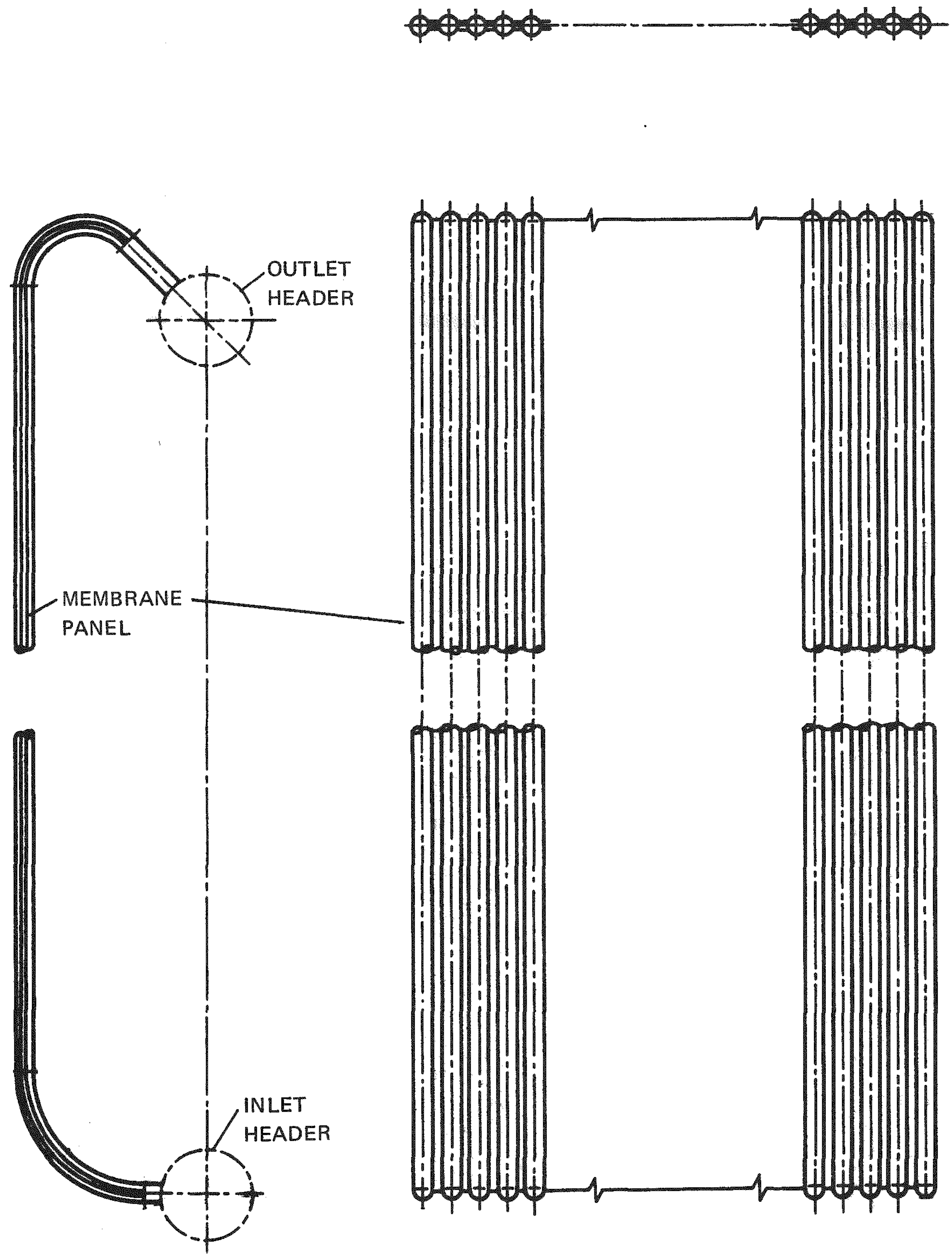


Figure 3-3. SRE Membrane Panel Arrangement

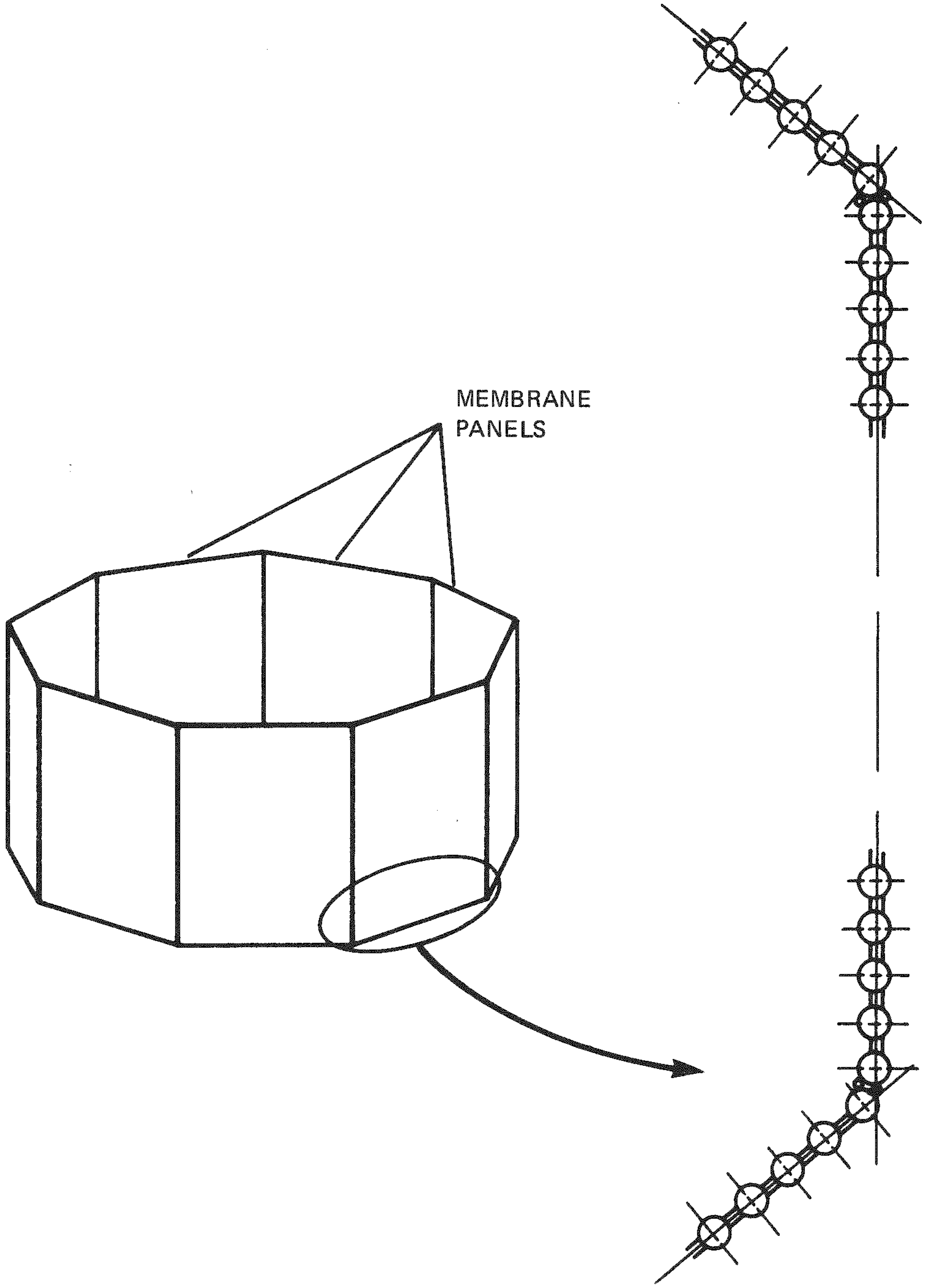


Figure 3-4. SRE Boiler Surface Arrangement

THERMAL AND HYDRAULIC ANALYSIS OF THE BOILER SECTION

The integrity of the boiler section is maintained by avoiding tube failures due to departure from nucleate boiling (DNB).

DNB occurs when the heat transfer mechanism in the tubes changes from nucleate boiling with a high heat transfer coefficient to film boiling with a low heat transfer coefficient. If operating conditions exeeed the DNB limit, an excessive tube temperature can result which will then be followed by a tube failure.

Presented in Figure 3-5 is the DNB limit for the boiler tube in the membrane wall of the solar steam generator. Any operating condition of absorbed heat flux and quality which exceeds this limit could result in a tube failure. The safe operating conditions are the range of absorbed heat fluxes and qualities below and to the left of this limit. This DNB limit was derived by considering the following:

- Pressure and Tube ID
- Nonuniform Axial Heating
- Nonuniform Circumferential Heating
- Boiler Flow Rate

For a fixed heat input to the boiler section, the local steam quality along the length of the tube is inversely proportional to the boiler flow rate. Steam quality must be kept on the safe side of the limit curve shown by maintaining a sufficiently high boiler flow rate.

The inlet flow to the boiler tubes must be large enough so that local steam quality does not exceed the limit curve shown on Figure 3-5.

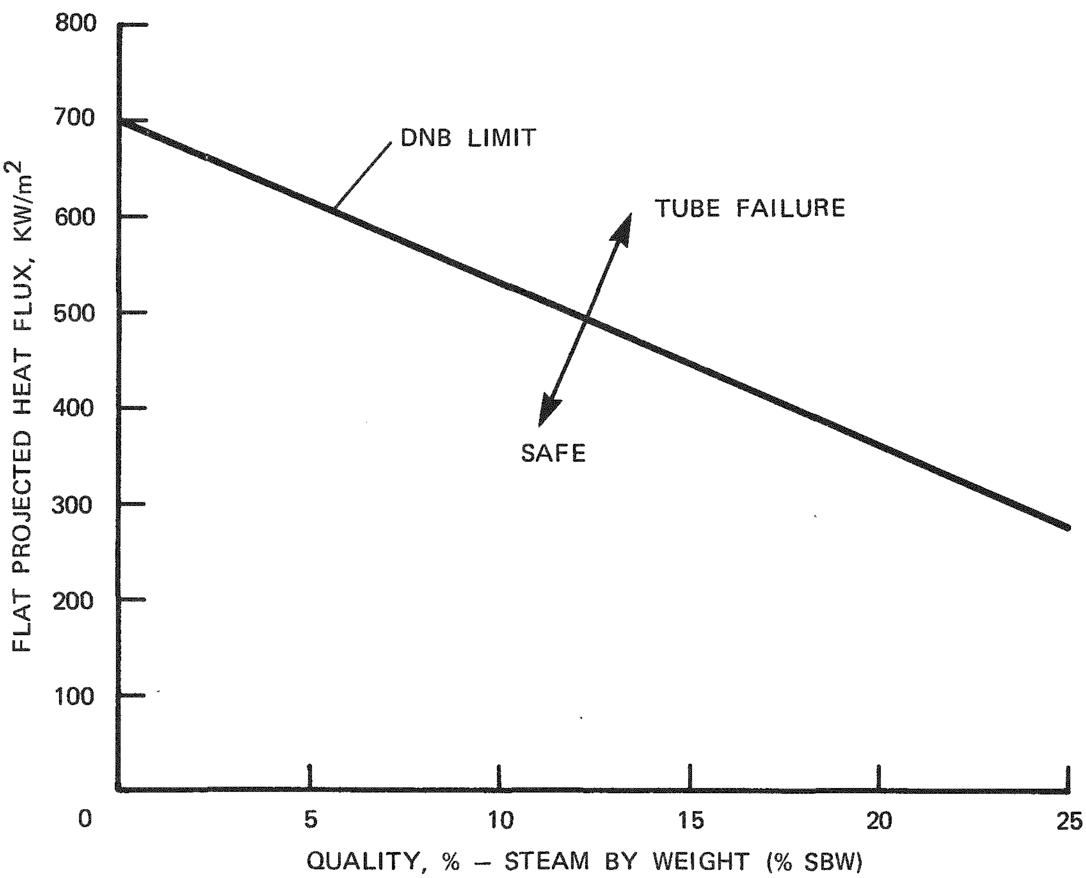


Figure 3-5. DNB Limit for the Boiler Section

COMPARISON OF AN OPERATING CONDITION TO THE BOILER DNB LIMIT

The boiler tubes in the Solar Steam Generator operate with a sufficient safety margin (DNB ratio).

The results presented in Figure 3-6 show that an inlet velocity of 2.05 m/sec to the Pilot Plant boiler tubes provides a safety margin (DNB ratio) of 1.24 at noon summer solstice. The safety margin must account for:

1. Flow redistribution due to varying heat input, tube-to-tube and membrane panel-to-panel

2. Flow maldistribution due to the header arrangement

The criterion that determines the scaling law for boiler flow rate is that the DNB ratio be equivalent or greater for the Pilot Plant than for the SRE steam generators. The cavity dimensions are scaled to obtain equal local heat fluxes and the boiler flow rate is scaled to obtain equal local steam qualities. Identical steam quality is achieved by maintaining the same circulation ratio* in the Pilot Plant and the SRE steam generators.

*Circulation ratio is the ratio of boiler flow to steam flow.

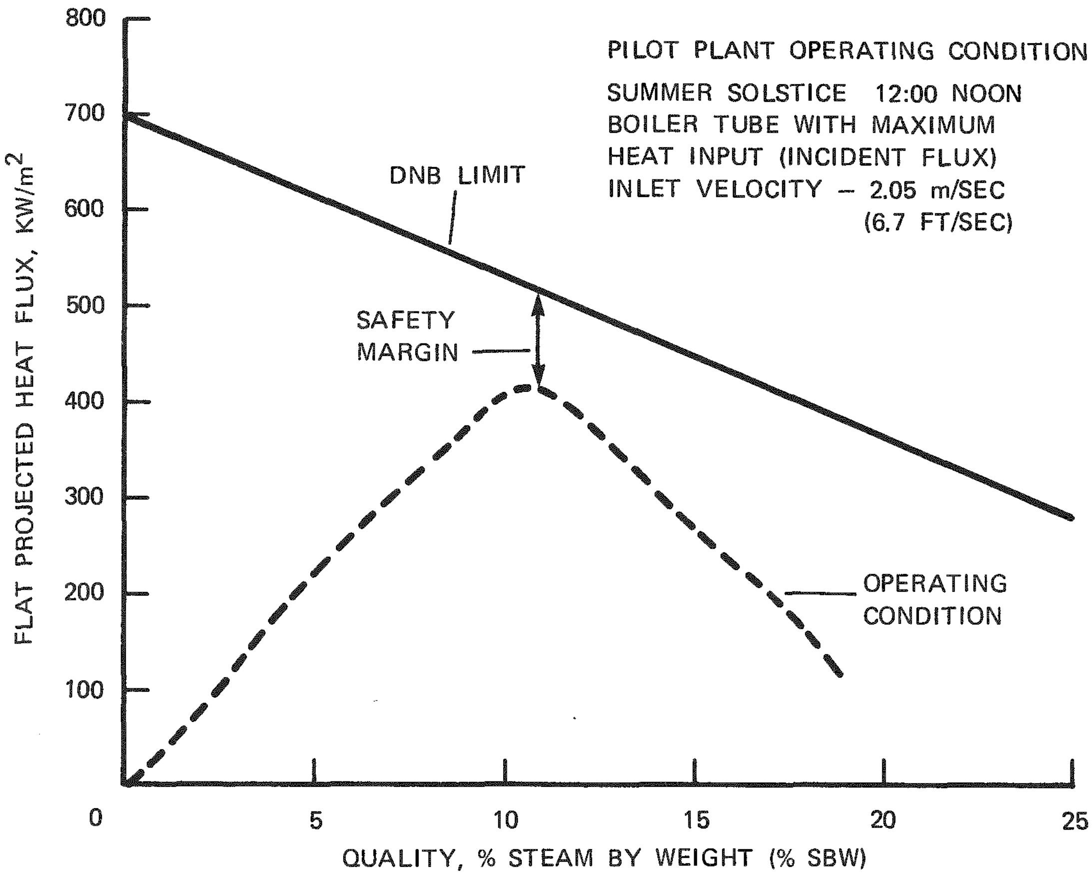


Figure 3-6. Comparison of an Operating Condition to the DNB Limit

STRESS ANALYSIS OF THE BOILER SECTION

The criteria of Section III will be used to assure sound structural design of the boiler section.

The major analysis requirements for the boiler section are outlined in the Boiler Section Stress Analysis flow chart (Figure 3-7). The initial tube sizing will be done per Section I using the design pressure and temperature. This will implicitly assure that the Section III allowable on primary loads (namely internal pressure) will be satisfied, although the pressure stress is calculated for later use. The total thermal stress state is obtained by combining the results of two analyses. A two-dimensional generalized plane strain model is used to obtain the thermal stresses due to the uniform heat flux on the boiler section. Thermal stresses due to flux differences on adjacent locations on the panel are evaluated by using an equivalent orthotropic finite element plate model. After combining the stresses due to the temperature and pressure, the cyclic part of the combined pressure and thermal stresses is then compared to the allowable of 3 S_m (which is equivalent to twice the yield stress). The satisfaction of this allowable will guarantee that the elastically calculated stresses are adequate for determining the fatigue life. The fatigue evaluation is then made in accordance with the procedures of Section III. If either the limit of 3 S_m or the fatigue damage limit is exceeded, then the thermal stress calculations and thermal analysis must be refined.

Results of the preliminary analysis are shown in Figure 3-8. In the first figure, the calculated stress due to the pressure loading is compared to the appropriate allowable stress. In this figure, heat fluxes and ensuing temperatures much in excess of what are anticipated are included. Above approximately 750 F, creep becomes important and invalidates the method of analysis previously discussed. This point will be discussed in more detail with regard to the superheater stress analysis in Appendix D. In the second figure, the combined pressure and thermal stress (computed by considering only a uniform heat flux) are compared to the 3 S_m allowable up to approximately 750 F. Above 750 F, the allowable is much reduced because of the creep effects. The purpose of limiting the stress to the yield above 750 F is also discussed in Appendix D. It should be pointed out that the comparison with 3 S_m should be made on the basis of the cyclic part of the combined pressure and thermal stress range. After satisfaction of the allowables shown in these two figures, the fatigue evaluation would be made.

Based on the stress analysis results previously discussed and the Babcock and Wilcox experience with fossil boilers with membrane panels operating at similar conditions, the boiler design is feasible from a stress standpoint.

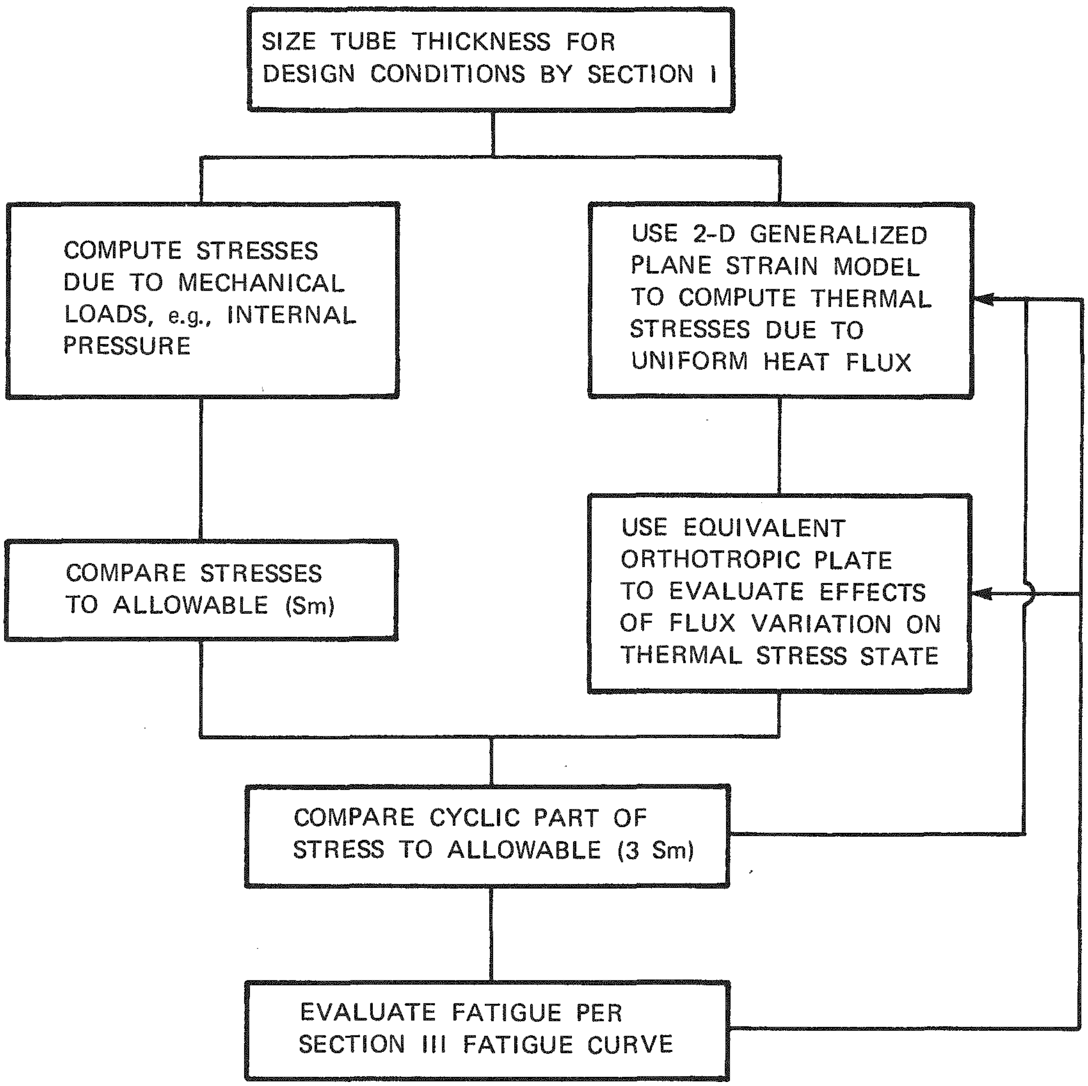
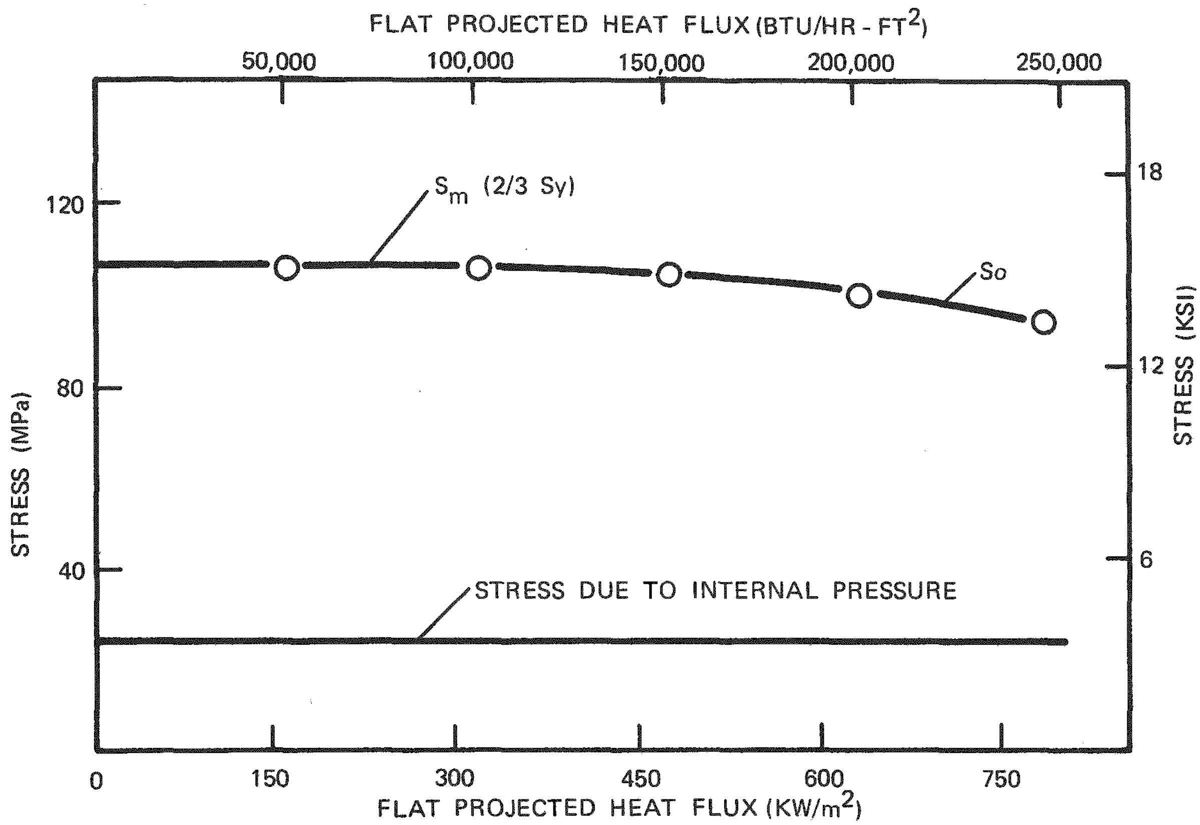
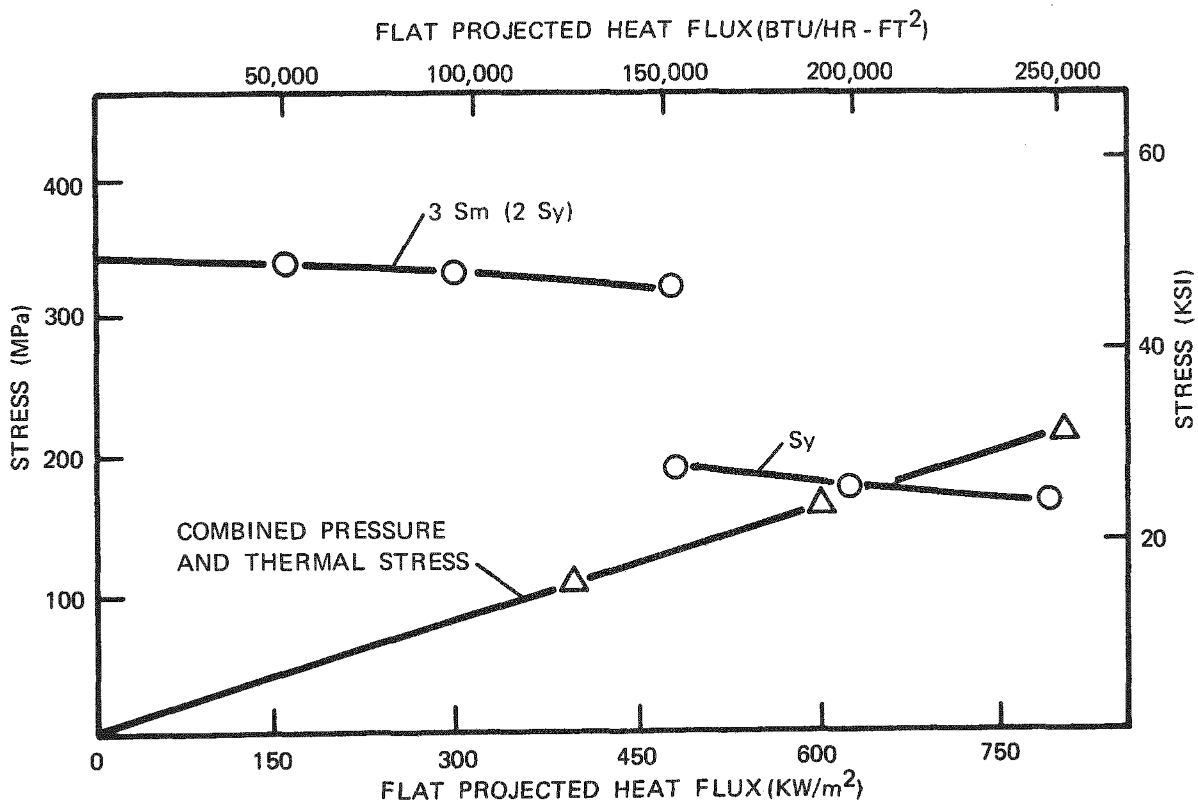


Figure 3-7. Boiler Section Stress Analysis



COMPARISON OF STRESS DUE TO PRESSURE IN THE BOILER SECTION TO THE ALLOWABLE STRESS



COMPARISON OF THE COMBINED PRESSURE AND THERMAL STRESS IN THE BOILER SECTION TO THE ALLOWABLE STRESS

Figure 3-8. Stress and Pressure Comparisons

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COMPARISON OF THE PILOT PLANT AND SRE BOILER SECTION

A comparison of configuration, metal temperatures and stresses shows that the SRE boiler section has been successfully scaled to the Pilot Plant.

Table 3-1 compares the Pilot Plant and the SRE design conditions for the boiler membrane wall. The same tube and web dimensions will be used for both the Pilot Plant and SRE. Overall length and width of the panels are scaled by the square root of the power ratio.

The safety margin with respect to tube burnout is scaled by maintaining the same circulation ratio in both the Pilot Plant and the SRE steam generator.

The Pilot Plant and the SRE have the same membrane wall configuration (tube OD, wall thickness, and material) and the same local heat flux. Therefore, the local pressure and thermal stresses will be the same. The stresses due to the heat flux gradients within a panel, and from panel-to-panel, will be somewhat greater for the SRE because the heat flux gradients are larger. Therefore, a design that maintains a safe stress level in the SRE will be conservative for the Pilot Plant.

The boiler support system will be designed to minimize stresses caused by restraints on radial and longitudinal expansion of the boiler section.

Table 3-1. Comparison of the Pilot Plant and SRE Boiler Design Conditions

Concept - Membrane Wall	PDBR Pilot Plant 55 MWt	SRE 5 MWt
Flow Circuits	9	9
Membrane Wall Panels	TBD	9
Tubes, OD x Min Wall, cm (inches)	2.223 x 0.376 (7/8 x 0.148)	2.223 x 0.376 (7/8 x 0.148
Centerline Spacing, cm (inches)	3.493 (1-3/8)	3.493 (1-3/8)
Tube Material	Croloy 1/2	Croloy 1/2
Length, Meters (feet)	7.315 (24)	2.206 (7.24)
Number of Tubes	1080	342
Thermal - Hydraulic		
Pressure, bars (psig)	117 (1700)	117 (1700)
Temperature, °C (°F)	322 (612)	322 (612)
Avg and Max Heat Flux	Same	Same
Enthalpy Change	Same	Same
Circulation Rate	10	10
Flow Rate per Tube, Kg/hr (lb/hr)	742 (1636)	213 (470)
Inlet Velocity, m/sec (ft/sec)	2.05 (6.7)	0.59 (1.93)
Tube Pressure Drop, Kg/cm^2 (psi)	0.60 (8.5)	0.12 (1.7)
Local Pressure Stress	Same	Same
Local Thermal Stress	Same	Same
Stress Due to Supports	TBD, Small	TBD, Small
Stress Due to Heat Flux Distribution Within a Panel, and Panel-to-Panel	TBD	TBD, Higher

HEAT TRANSFER SURFACE FOR THE SUPERHEATER

The helical superheater has sufficient flexibility and thermal averaging capability to withstand the temperature stress cycles imposed during daily startup and shutdown.

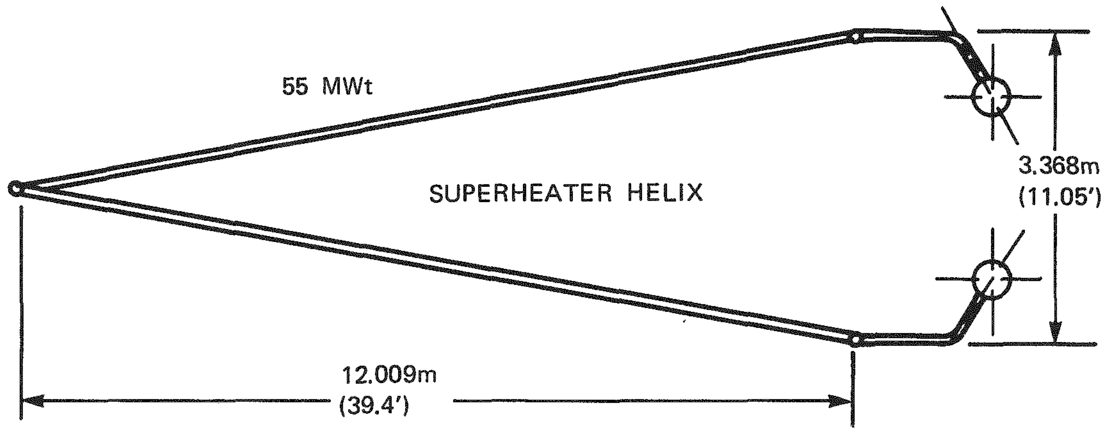
Helical flow circuits are used in European fossil steam generators to reduce the effect of heat flux variations. Since every tube passes completely around the circumference and through each azimuthal heat flux zone, the effects of the heat flux maldistribution caused by the tower supports and cloud coverage will be averaged out. In addition, the superheater has been designed to

- Reduce thermal stress by allowing relatively free radial expansion
- Cover the receiver cavity surface and minimize reradiation losses
- Achieve a high superheater heat transfer coefficient by providing a low ratio of steam flow area to heat transfer surface area

The superheater will be on the upper portion of the cavity because the heat fluxes are lower and the circumferential variation less than in the lower boiler section.

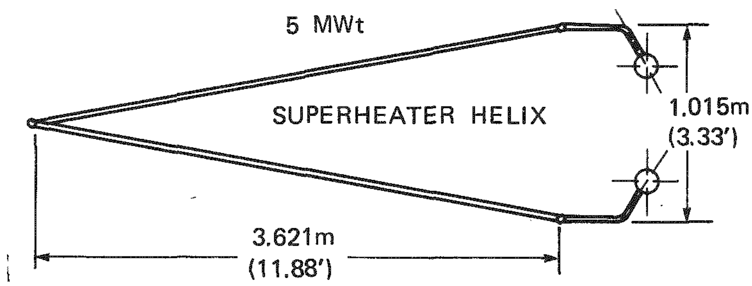
The superheater is divided in two stages to permit interstage spray attemperator control to equalize steam temperature before entering the higher temperature region of the superheater.

Each stage of the helical superheater has one turn. A comparison of the tube specifications for the Pilot Plant and SRE is presented in Figure 3-9.



SPECIFICATIONS:

TUBE O.D.	2.54 cm (1.0") (132 TUBES REQ'D)
MIN. WALL	0.279 cm (0.11")
MAT'L.	CROLOY 2 1/4 (S.A. 213 GRADE T-22)



SPECIFICATIONS:

TUBE O.D.	1.27 cm (.50") (80 TUBES REQ'D)
MIN. WALL	0.274 cm (.108)
MAT'L.	CROLOY 2 1/4 (S.A. 213 GRADE T-22)

Figure 3-9. Superheater Heat Transfer Surface

FLOW CIRCUITRY FOR THE SUPERHEATER

The superheater tubes and headers are designed to minimize flow maldistribution while keeping header thickness small to minimize thermal stresses.

The flow resistance of the superheater tubes is designed to be large compared to the resistance of the inlet and outlet headers. The tube resistance is kept uniform from tube-to-tube by proper specification of tolerances. In this way the superheater tubes control flow distribution.

The flow resistance of the inlet and outlet headers is reduced by increasing the header diameter. The headers are split into three equal segments with individual inlet and outlet pipes. The diameter of the segmented header is reduced. Wall thickness is also reduced, reducing thermal stresses during fluid temperature transients. The flow circuitry for the superheater is presented in Figure 3-10.

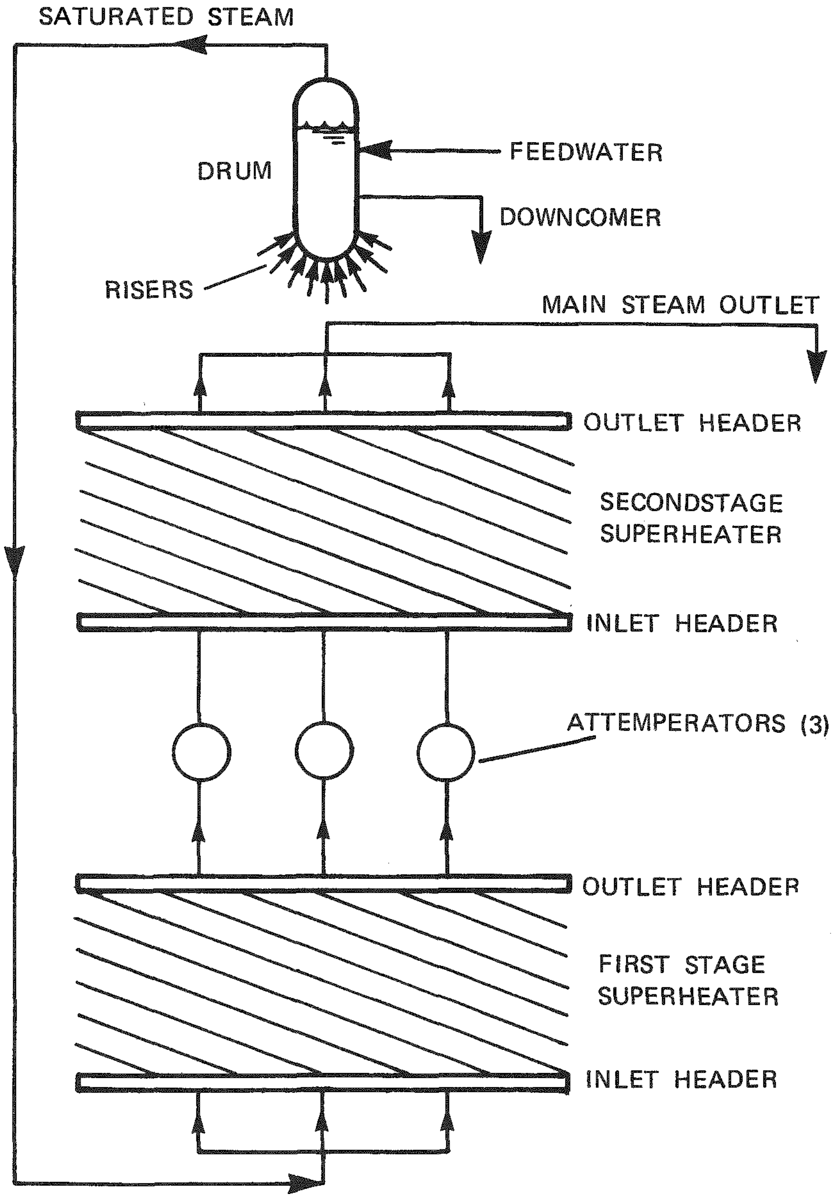


Figure 3-10. Superheater Flow Circuit

THERMAL AND HYDRAULIC ANALYSIS OF THE SUPERHEATER

The superheater tubes and flow distribution headers have been sized so that the temperature limits of the superheater materials will not be exceeded.

The superheater flow rate and tube diameter have been selected so that the tube outside wall temperature does not exceed the oxidation limit for the tube material (593.3 C (1100 F) for Croloy 2-1/4). The tube diameters and flow rates were chosen such that the OD tube metal temperatures are equal and less than 593.3 C (1100 F). Figure 3-11 shows that the maximum metal temperature is 12.77 C (55 F) less than the maximum allowable.

Safety margin (12.77 C) must account for:

- Heat flux tolerance
- Tube dimension tolerances
- Flow maldistribution

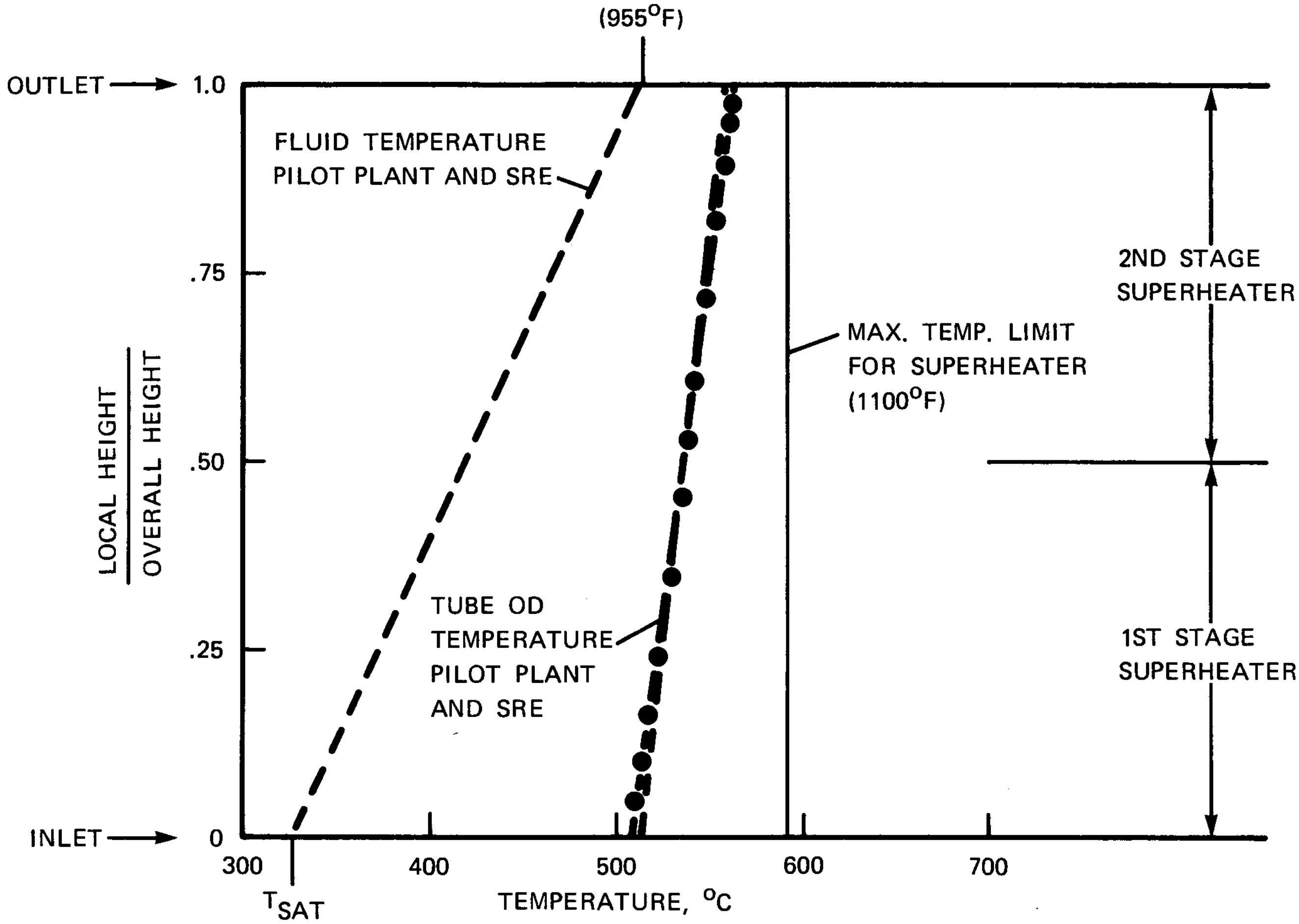


Figure 3-11. Fluid and OD Tube Temperatures - Superheater

STRESS ANALYSIS OF THE SUPERHEATER SECTION

Since the anticipated metal temperatures in the superheater are well into the creep regime, the intent of Code Case 1592 of Section III will be used to analyze the superheater section.

The major analysis requirements for the superheater section are outlined in the Superheater Section Stress Analysis flow chart (Figure 3-12). As with the boiler section, the initial tube sizing will be done per Section I using the design pressure and temperature of the superheater. The pressure stress is calculated and compared to the time-dependent (because of creep effects) allowable S_{mt} (obtained from Code Case 1592). A plane stress finite element model will be used to analyze the stress state in the superheater tubing resulting from thermal gradients and internal pressure. The plane stress assumption will later be verified with a three-dimensional finite element model which will be subjected to the superheater tubing support constraints and which will accommodate a variable temperature distribution and internal pressure.

There is no explicit allowable stress to limit the cyclic part of the combined pressure and thermal stress. Therefore, the cyclic stress will be limited to the material yield stress. A full discussion of the philosophy behind this decision will appear in Appendix C. Briefly, however, the intent of limiting the combined stress to the material yield stress is to justify the neglect of thermal stresses when later determining the creep damage, and to ensure that elastic calculations are adequate for determining the fatigue damage. After the elastic calculations are performed, the creep and fatigue damages are then individually calculated and summed for comparison with the allowable stress.

Results of the preliminary analysis of the superheater section are shown in Figures 3-13 and 3-14. For both the SRE and Pilot Plant, the calculated stress due to the internal pressure is compared to the time-dependent allowable S_{mt}. Also, for both superheaters, the combined pressure and thermal stress is compared to S_y on the figures. As in the boiler section, this conservatively shows the total combined stress as opposed to including only the cyclic portion of the stress. Satisfaction of this criterion then permits the subsequent determination of creep damage based primarily on pressure stress. The fatigue damage is then determined using elastically calculated strain ranges.

Preliminary results of the superheater stress analysis indicate that the helical superheater concept is feasible for the anticipated operating conditions.

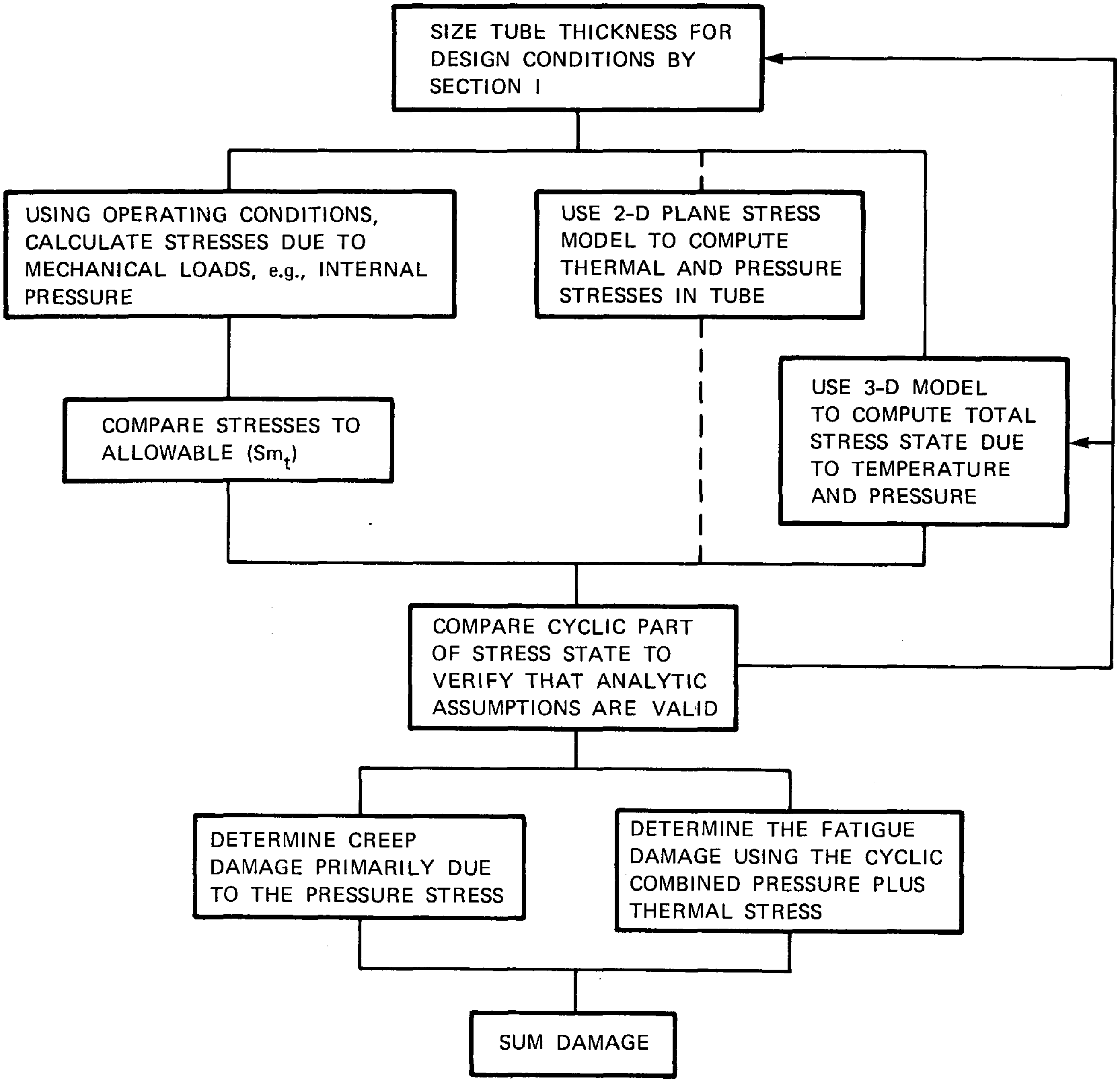
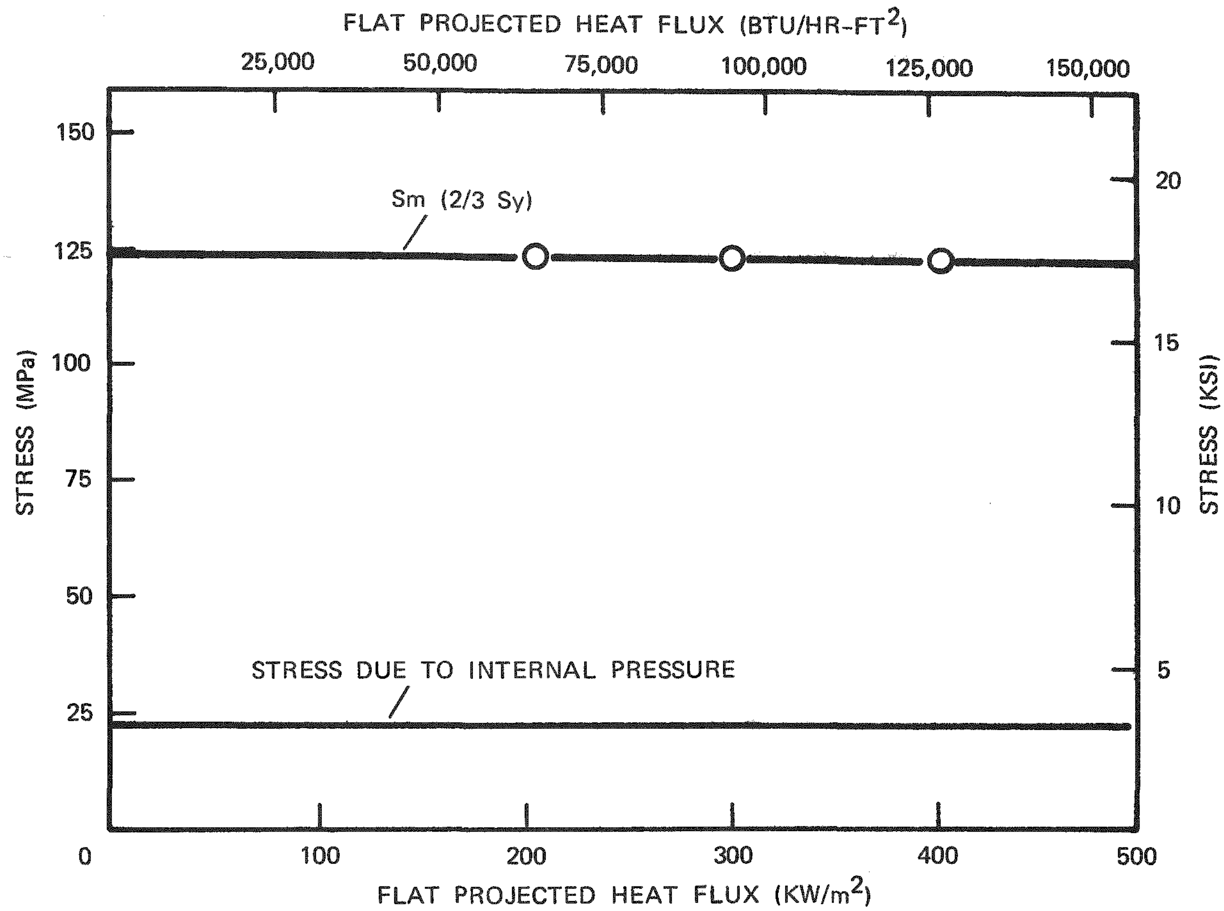
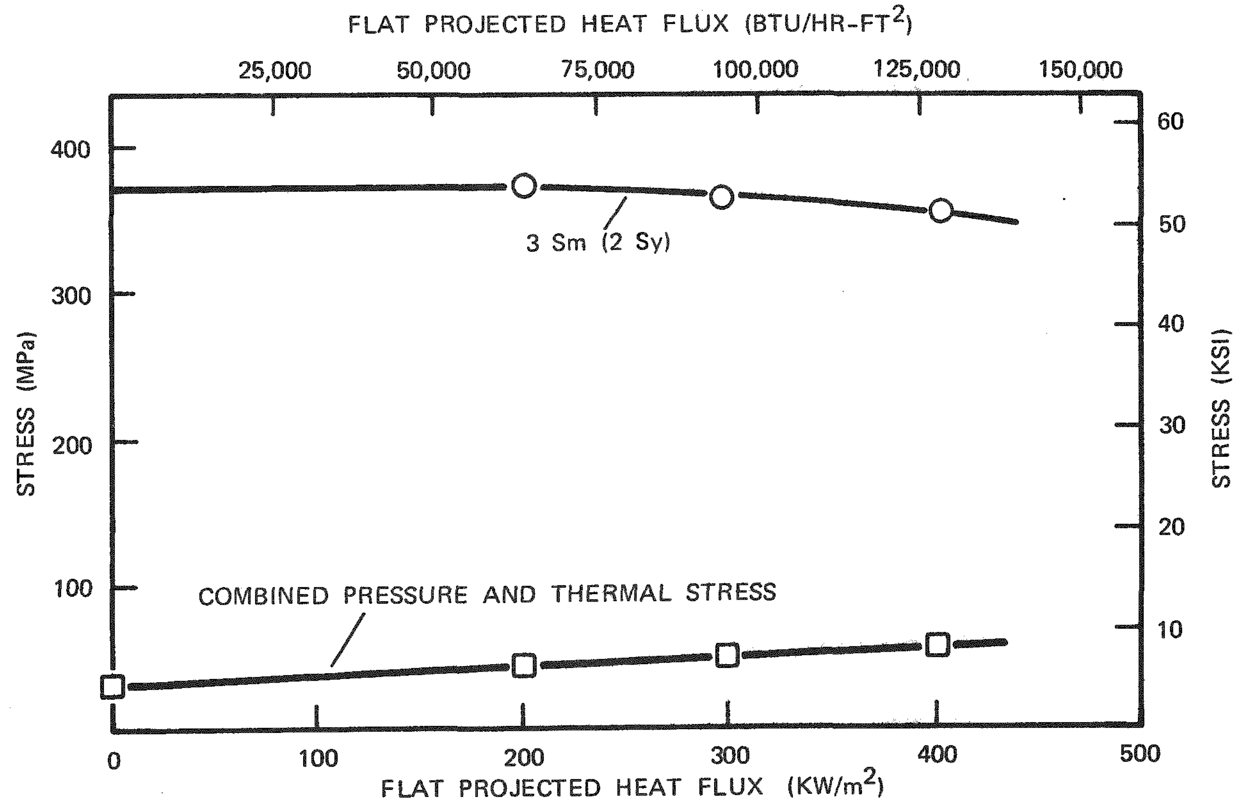


Figure 3-12. Superheater Stress Analysis

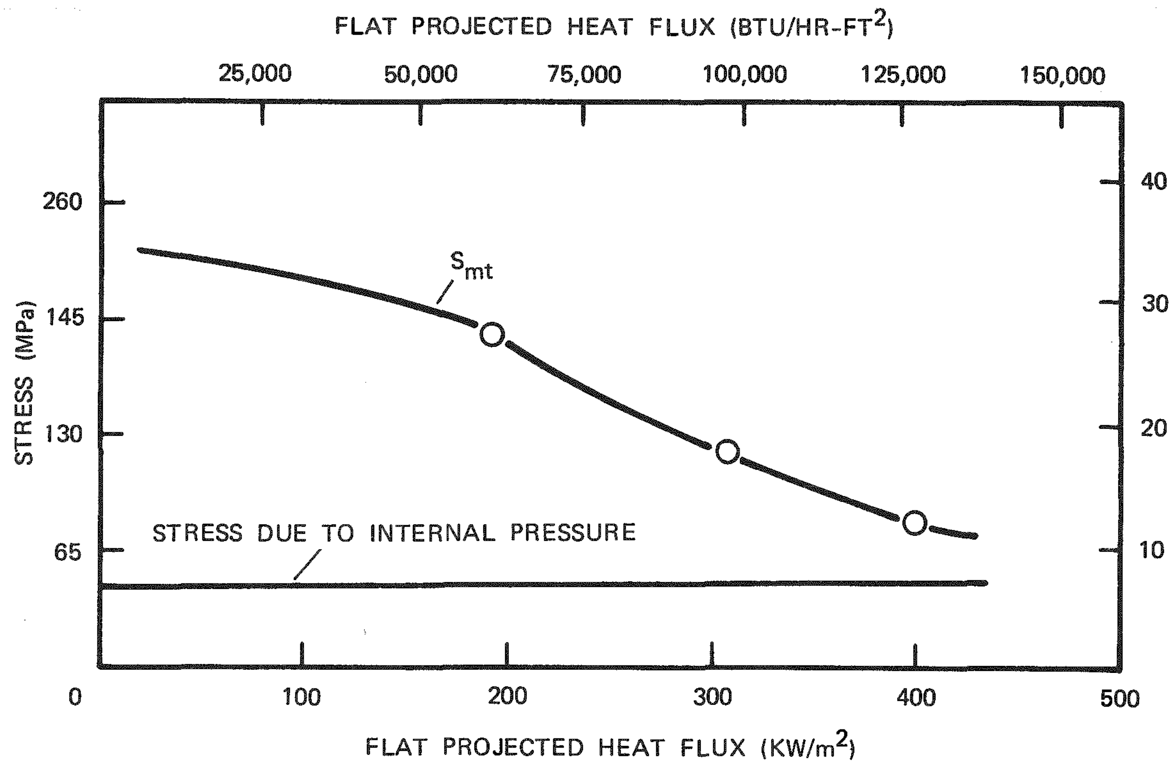


COMPARISON OF THE PRESSURE STRESS TO THE ALLOWABLE STRESS

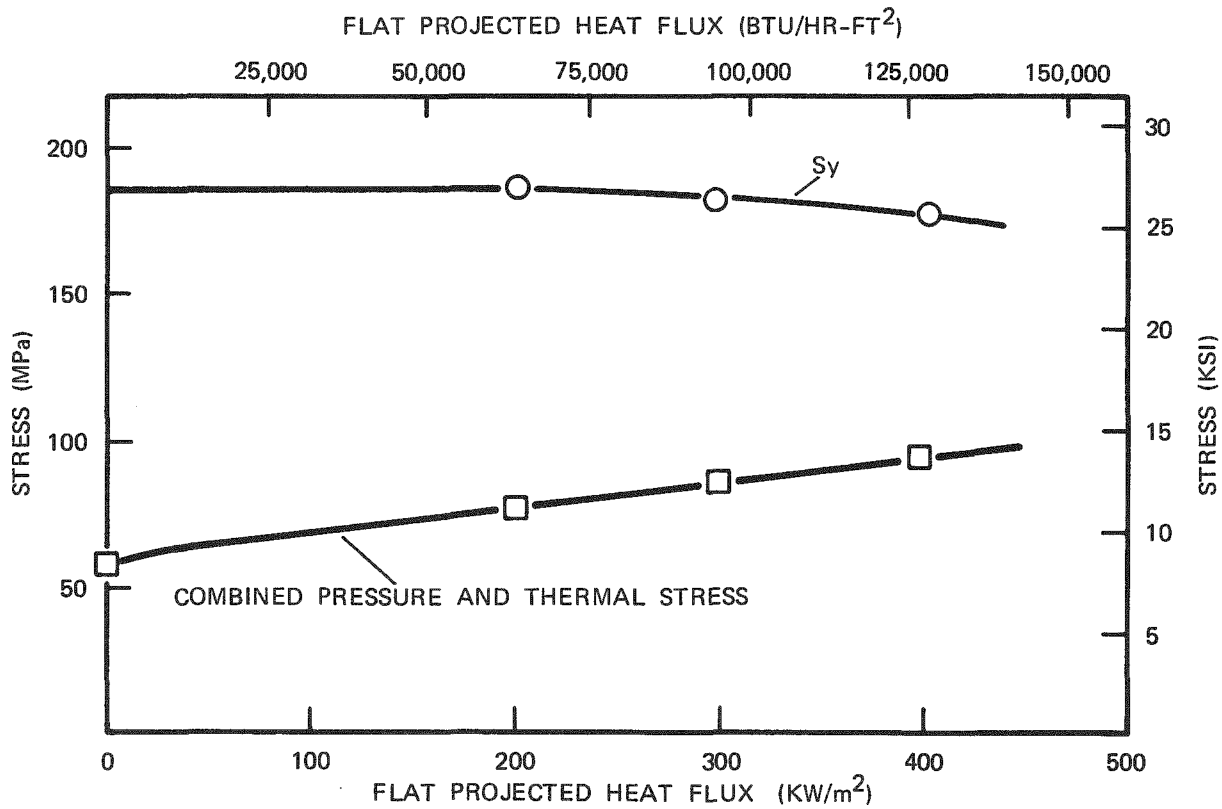


COMPARISON OF THE COMBINED PRESSURE AND THERMAL STRESS TO THE ALLOWABLE STRESS

Figure 3-13. Superheater Stress Analysis - SRE



COMPARISON OF THE PRESSURE STRESS TO THE ALLOWABLE STRESS



COMPARISON OF THE COMBINED PRESSURE AND THERMAL STRESS TO THE ALLOWABLE STRESS

Figure 3-14. Superheater Stress Analysis - Pilot Plant

COMPARISON OF THE PILOT PLANT AND SRE SUPERHEATER

A comparison of the configuration, fluid and metal temperatures and the combined stresses indicates that a new scaling concept will provide a better match of the SRE and Pilot Plant superheater.

The initial approach to scaling the superheater, and the one presented in the discussion so far, has been to maintain the same number of tube turns in both the SRE and Pilot Plant steam generators. This choice was made to duplicate the thermal averaging effect of the helical flow circuitry.

A one-turn superheater was selected for the Pilot Plant at the PDBR. Therefore, one-turn was used for the SRE. The overall length of a superheater tube is scaled by the square root of the power ratio.

The superheater tube diameters, wall thickness, and flow rate were selected to maintain approximately the same local fluid temperature, heat transfer coefficient and temperature drop across the tube wall. In this way, the tube outside surface metal temperatures can be matched along with the local thermal stress.

Table 3-2 compares the Pilot Plant and the SRE superheater design conditions. As discussed previously the tube OD temperatures and the local thermal stresses are matched by the scaling concept selected. However, Table 3-2 shows that other parameters are scaled less accurately.

- The higher fluid velocity in the SRE results in a higher pressure drop and a better flow distribution than for the Pilot Plant superheater.
- The smaller tube diameter of the SRE results in a larger safety margin when compared to either the time dependent allowable stress, S_{mt} or the yield stress, S_y.

Because the initial scaling concept results in lower combined stresses in the SRE than the Pilot Plant, a different scaling concept has been selected. The tube outside diameter and wall thickness along with the steam velocity will be identical for both the SRE and the Pilot Plant steam generators. To obtain these identities, the superheater will have more turns in the SRE than in the Pilot Plant.

The new scaling concept will match the combined stresses due to internal pressure and local heat flux. Local tube OD temperatures will also be closely matched. The major disadvantage is that the SRE steam generator will have more turns resulting in better heat flux averaging. However, this effect can be calculated and accounted for in the design of the Pilot Plant superheater.

Table 3-2. Comparison of Pilot Plant and SRE Superheater Design Conditions

Concept - Helical Coil	PDBR Pilot Plant 55 MWt	SRE 5 MWt
Flow Circuits	3	3
Superheater Stages	2 - Equal Area	2 - Equal Area
No. of Turns	1	1
Height Per Stage, Meters (feet)	3.37 (11.05)	1.01 (3.33)
Length Per Tube (Helix only), Meters (feet)	37.88 (124.27)	11.42 (37.47)
Tube: OD x Min Wall, cm (inches)	2.54 x 0.279 (1.0 x 0.110)	1.27 x 0.274 (0.5 x 0.108)
No. of Tubes	132	80
Material	Croloy 2-1/4	Croloy 2-1/4
Thermal-Hydraulic		
Outlet Pressure, bars (psig)	104 (1500)	104 (1500)
Outlet Temperature, °C (°F)	513 (955)	513 (955)
Avg and Max Heat Flux	Same	Same
Flow Per Tube, Kg/hr (lb/hr)	607.4 (1339)	91.2 (201)
Inlet Velocity, msec (ft/sec)	8.5 (28)	10.7 (35)
Pressure Drop (Tubes only - 2 Stages) Kg/cm^2 (psi)	2.53 (36)	4.43 (63)
Stress		
Internal Pressure, MPa (psi)	43 (7000)	22 (3570)
Combined Pressure and Thermal Stress @ 200 Kw/m^2, MPa (psi)	75 (11250)	40 (6000)

SUPPORT FOR THE HEAT TRANSFER SURFACES

The steam generator support concept will support the weight of the heat transfer surface and accommodate thermal expansion.

Presented in Figure 3-15 is the steam generator support concept. This concept allows for support of the weight and thermal expansion of the boiler section and the two stages of the helical superheater.

The boiler section will be top supported at lugs welded to the boiler outlet header. Attached to these lugs will be a hanger, rod, and rocker assembly. This construction will allow for radial growth to accommodate radial thermal expansion. No supports will be used on the boiler inlet header; therefore, the boiler section will be free to grow down in the vertical direction thereby reducing the tendency for buckling.

For each stage of the helical superheater, the support concept is the same. Here each header, inlet and outlet will be top supported by a "U" support assembly attached to a hanger, rod and rocker assembly. This support concept will fix each of the headers in the vertical direction, but will allow for radial expansion. The helical coils are supported by the tubes attached to the headers and the vertical support channels. These supports are unrestrained thereby permitting radial expansion growth. The double bend in each tube near the attachment to the header will permit this radial expansion growth independent of the header.

Details of the header support lugs, "U" support rods, and rocker assembly are given in Appendix F. These supports are standard in fossil boilers.

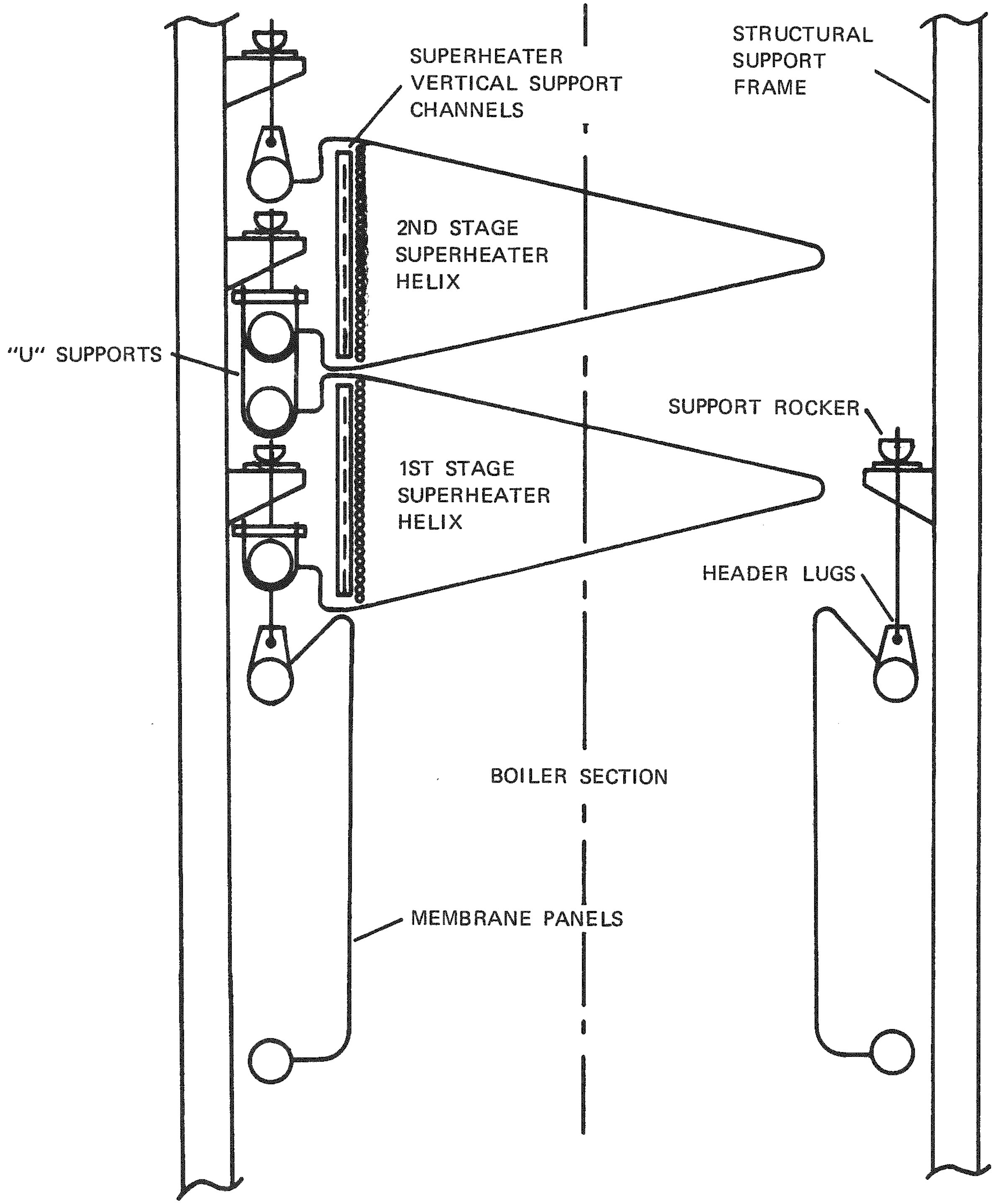


Figure 3-15. SRE Support Concept

TUBE SUPPORTS

The boiler tubes and the superheater tubes are maintained in position during temperature changes without exceeding stress limits.

The tube-to-tube spacing of the boiler heat transfer surface is maintained in the membrane wall assembly by the welded web between tubes. This support has been verified by experience with fossil boilers.

The superheater tube support concept shown in Figure 3-16 maintains the alignment of the superheater tubes while allowing free radial expansion. Vertical expansion of the helical coil tubes is accommodated by the vertical slots in each vertical support channel. The radial expansion is accommodated by the hanger and rods assembly attached to the inlet and outlet headers. Each vertical support channel will be attached to every other tube by self-welding studs at equally spaced locations on the circumference of the coil. The vertical support channels will not be fixed, but free to grow in the radial direction while maintaining the vertical alignment of the superheater tubes.

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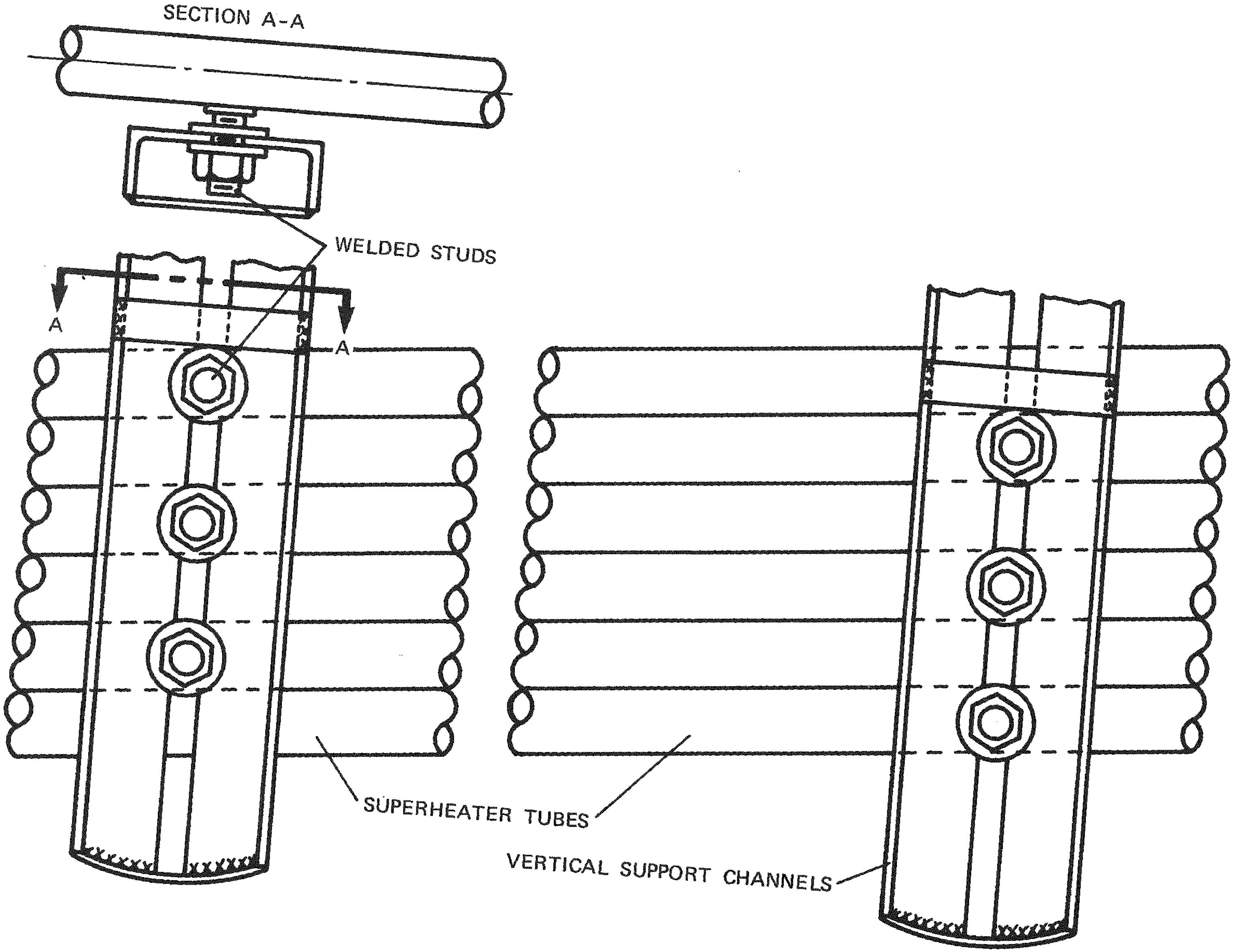


Figure 3-16. Superheater Tube Support Concept

SRE Steam Generator

Steam Generator Components

DRUM AND INTERNALS

A vertical drum configuration similar to that recommended for the Pilot Plant will be used for the SRE steam generator.

The SRE steam generator drum and internals will be similar to the drum and internals recommended for the Pilot Plant, except for the number of cyclone steam separators. Eight cyclone separators were chosen for the Pilot Plant design condition; for the SRE steam generator, only one cyclone separator is required. The drum and the arrangement of the internals are presented in Figure 3-17.

The internals will also be rearranged for the SRE steam generator. Because only one cyclone is used for the SRE, the internal shroud separating the steam-water mixture (entering the drum from the risers) from the saturated and feedwater mixture will be located against the inside diameter of the drum rather than in the central core region of the drum as recommended for the Pilot Plant. This difference does not affect separator performance.

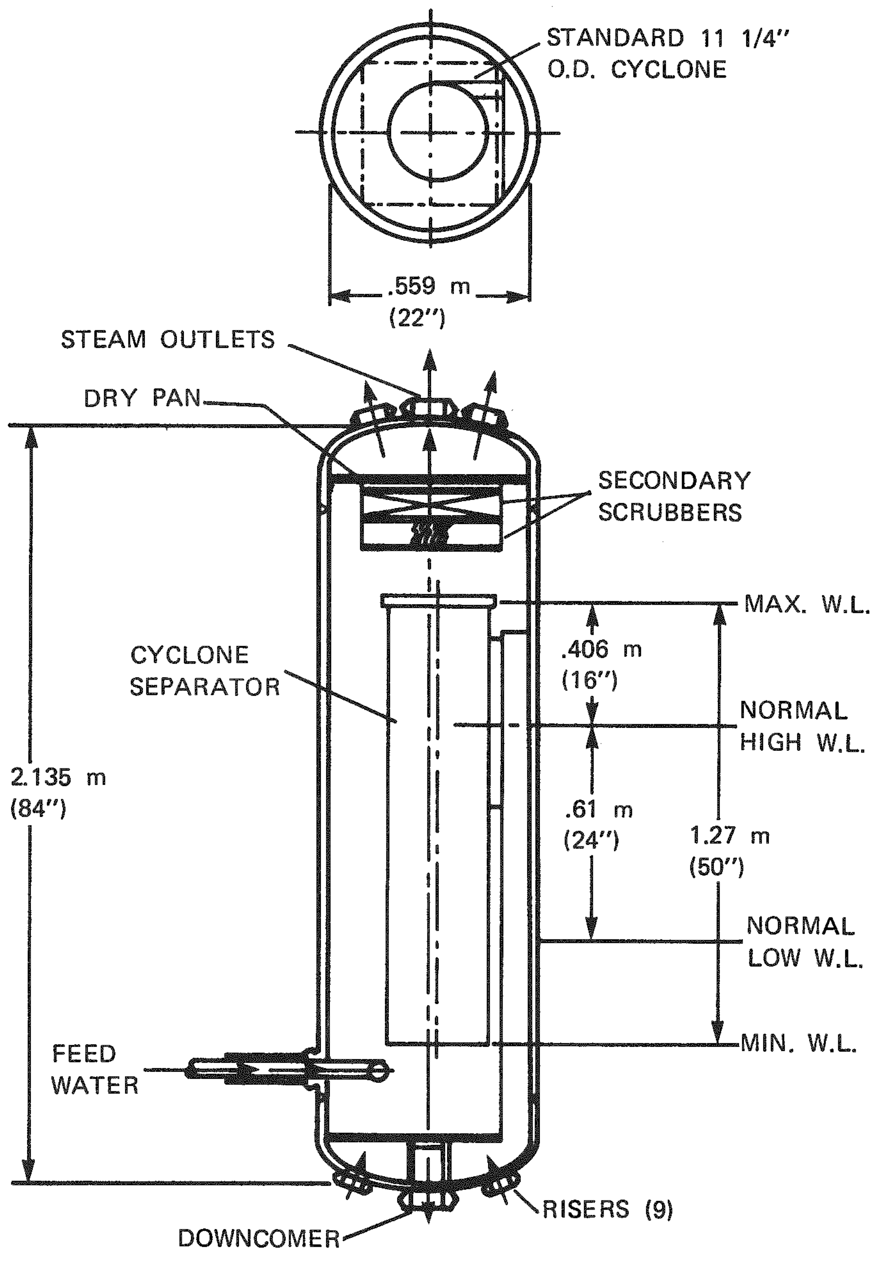


Figure 3-17. SRE Drum and Internals

SUPERHEATER MATERIALS

The material selected for the superheater must resist oxidation during the severe cyclic operation of the solar steam generator.

Oxidation and exfoliation of superheater materials are accelerated by cyclic operation. Using the model illustrated in Figure 3-18, the metal loss for various candidate superheater materials is estimated for 11,000 cycles (Table 3-3). However, it must be emphasized that the model is based on a meager amount of data and, therefore, the results could be significantly in error.

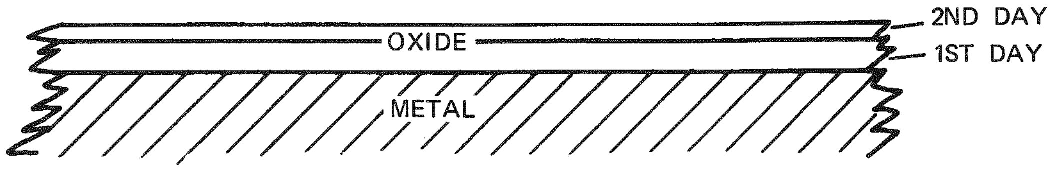
Nevertheless, we have concluded that the original choice of Croloy 2-1/4 for the superheater is not a prudent one for the solar steam generator*. As shown in Table 3-3, 304 SS would be a better choice, and other austenitic alloys are possible candidate materials.

The next step in the superheater design process will be to select a material with significantly better cyclic oxidation resistance than Croloy 2-1/4. The mechanical properties of some of the candidate materials are shown in Table 3-4.

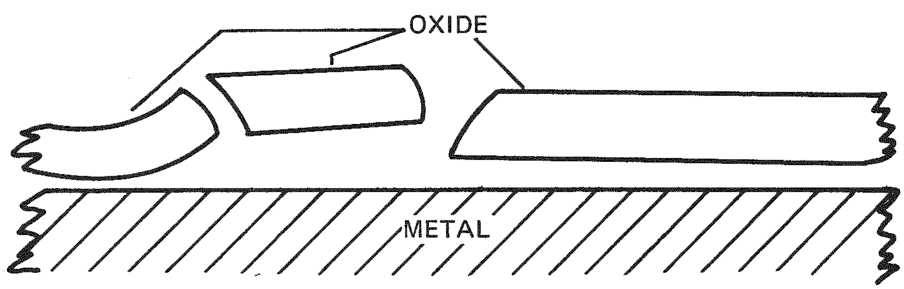
Since cyclic oxidation rate data might not be available for all candidates, selection of the superheater material might be made on the basis of its oxidation resistance at steady temperatures.

*Fossil boilers using Croloy 2-1/4 superheater tubes do not encounter the severe cyclic conditions of the solar steam generator. Operation of the fossil boilers has been entirely satisfactory.

A) THE OXIDE GROWS BY A CERTAIN THICKNESS EACH DAY IT IS CYCLED.



B) WHEN THE OXIDE REACHES A CRITICAL VALUE, IT CRACKS AND FLAKES OFF (SPALLING).



C) BARE METAL IS EXPOSED AND THE PROCESS REPEATS ITSELF.

D) TOTAL METAL LOST IS APPROXIMATELY ONE-HALF OF THE OXIDE THICKNESS LOST.

Figure 3-18. Metal Lost from Oxidation and Exfoliation

Table 3-3. Airside Oxidation

Alloy	Oxide Growth Per Day (Mils)	Spalling Thickness (Mils)	Metal Loss inches/30 yrs
	1000F		
Croloy 1-1/4	0.06	1.5	0.33
Croloy 2-1/4	0.05	2.0	0.27
Croloy 5	0.035	3.0	0.19
Croloy 9	0.025	4.0	0.14
	1100F		
Croloy 1-1/4	0.15	1.5	0.82
Croloy 2-1/4	0.12	2.0	0.64
Croloy 5	0.085	3.0	0.47
Croloy 9	0.03	4.0	0.17
304 SS	0.001	2.0	0.06

Table 3-4. Mechanical Properties of Candidate Superheater Materials

Mechanical Property @ 1100 F	Material					
	2-1/4 Cr - 1 Mo	9 Cr - 1 Mo	304 SS	316 SS	321 SS	Alloy 800 H
Minimum Yield Strength (KSI)	20.5	20.6	15.0	16.5	16.5	15.0
S_o, Maximum Allowable Design Stress (KSI)	4.2	3.3	9.7	12.4	6.9	13.5
S_t, Allowable Stress Intensity, (KSI) Based on 10^5 hr	3.3	3.5	6.8	9.5	---	11.7
Minimum Stress to Rupture (KSI) Based on 10^5 hr	5.0	3.2	10.2	14.3	8.6	18.4
Fatigue Strain Range (in/in) for $2*10^5$ Allowable Cycles	---	---	$2*10^{-3}$	$2*10^{-3}$	---	$2*10^{-3}$
Modulus of Elasticity (psi$*10^6$)	20.4	21.4	21.7	21.7	21.7	22.9
Coefficient of Thermal Expansion (in/in °F$*10^{-6}$)	7.9	7.3	10.4	10.4	10.4	9.5

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FEEDWATER AND ATTEMPERATOR WATER SPECIFICATIONS

The feedwater at the Riverside Test Facility can be used in the SRE steam generator without additional polishing systems.

Boilers used for peaking service require strict control of water quality during the transient periods to which these units are subjected. The degree of corrosion protection that can be provided is related to the ability to prevent oxygen from entering the boiler-turbine system.

Presented in Table 3-5 is a comparison of the No. 8 feedwater specifications for the Riverside Facility of Northern States Power to the feedwater specifications presented at the PDBR. Typical analyses of the water at Riverside usually fall within those listed in Table 3-5.

The conclusion drawn is that the water chemistry of the No. 8 feedwater at Riverside, because it is within the PDBR specifications, can be used for the SRE steam generator without an additional polishing system for both the feedwater into the drum and the spray attemperators.

Table 3-5. Water Specifications

	Pilot Plant PDBR Spec	Riverside - NSP No. 8 Feedwater SRE
pH	9.3 → 9.5*	9.0 → 9.5
Oxygen, O_2, ppm	0.007	0.005
Iron, Fe, ppm	0.01 max	0.01
Copper, Cu, ppm	0.005 max	0.005 max
SiO_2, ppm	0.02 max	0.02 max
Total Hardness, ppm	0.0*	Detection Limit
Organics, ppm	0.0**	Detection Limit
Total Solids, ppm	0.05 max	0.05 max
Ammonia, NH_3	As Required	TBD
Hydrazine, N_2H_4	As Required	TBD

*With carbon-steel feedwater heaters

**The specification of 0 ppm is given as a recommendation to keep these contaminants completely out of the feedwater. Special analyses for these contaminants are available. Detection limits using these special analyses are 2.0 ppm for total hardness and 0.05 ppm for organics.

TEST REQUIREMENTS

Tests will verify the predicted steady-state and transient performance of the SRE steam generator.

1. Initial checkout of the steam generator is required to assure that subsequent testing will be safe and will provide useful data. Initial checkout will include a hydrotest of the steam generator, and performance checks of all instruments, valves, and safety interlocks.

2. The test will be initially operated by circulating cold water through the system to check operation of the pump, valves, control system, and to verify that the instrumentation is functioning properly. Flow to the boiler and superheater circuits will be initially balanced at this time.

3. A hot checkout will be conducted by circulating water through the system while inputting a small amount of energy from the solar simulator. Temperature will be increased gradually and the data from the steam generator instrumentation closely observed to assure a satisfactory performance.

   When all data indications are satisfactory, power will be increased and steam generated for the first time. Instrumentation will be observed closely to determine that behavior is as expected. Control system tune-up will be conducted at this time.

4. After steam is initially generated and performance deemed satisfactory, initial calibration checks will be conducted:

   - Thermocouples will be calibrated against saturation temperature
   - Flow will be balanced to the boiler panels and the spray attemperator circuits. Feedwater flow will be checked against steam flow.
   - Heat loss data will be obtained
   - Energy input from the solar simulator will be compared to energy absorbed by the steam generator
   - The heat flux distribution within the cavity will be measured

5. After the instrumentation and the flow and energy balances are demonstrated satisfactorily, steady-state functional performance tests will begin. Test conditions will include a simulation of the solar cycle for the summer and winter solstices. The following predicted performance characteristics will be verified:

   - Steam cycle
   - Metal temperature of the boiler, superheater, drum, headers and connecting pipes
   - Displacement of the headers and the heat transfer surface
   - Strain measurement on the heat transfer surface
   - Attemperator flow required to maintain steam temperature
   - Flow stability in the boiler circuits

6. For a special test series, the steam generator will be operated with higher than design heat flux on one of the nine panels. Flow to the panel will be reduced until a DNB is detected by the thermocouples on the boiler wall. This will allow a verification of the DNB limit.

7. Another special test will be run at circulation rates less than design to determine if the steam generator performance is satisfactory. The corresponding reduction in pumping power would be a significant economic factor in the updated design of the Pilot Plant.

8. Transient tests will be initially conducted to provide data for verifying and/or tuning up the transient model of the steam generator. The tests will be conducted by ramping or stepping various inputs to the generator and determining if the response characteristics match predictions. Adjustment to the transient model input constants will be made, if necessary, to match measured and predicted response.

9. Tests will be conducted to verify transient performance predictions. The following predicted performance characteristics will be verified at summer and winter solstice conditions:

   - Startup and shutdown steam conditions
   - Steam flow variation during the diurnal cycle
   - Simulated cloud cycles

10. Tests will be run simulating system-shutdown and system-runback conditions caused by a receiver, turbine, or storage unit component failure.

Table 3-6. Test Requirements

- Initial Debugging
- Cold Checkout
- Hot Checkout
- Control System Tune-up
- Initial Calibration Tests
  - Thermocouples
  - Flow Balance
  - Heat Loss
  - Heat Balance
  - Heat Flux Distribution
- Steady-State Performance
  - Winter and Summer Solstice Cycle
  - High Heat Flux
  - Low Circulation Rate
- Transient Performance
  - Response to Ramp or Step Inputs
  - Startup and Shutdown Cycles
  - Simulated Cloud Cycles
  - Shutdowns and Runbacks

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INSTRUMENTATION

The steam generator will be adequately instrumented to verify SRE performance predictions.

The test requirements determine the type and quantity of instrumentation. At this time, the type of measurements required is relatively certain but the quantity needs further investigation during detailed design. The minimum requirements are identified in Table 3-7.

The digital data acquisition system is flexible enough to handle additional instrumentation if it is required.

Table 3-7. SRE Instrumentation

Type	Minimum Quantity
• Temperatures	200
- Headers	
- Drum	
- Boiler	
- Superheater	
- Fluid	
• Pressures	2
• Flows	9
• Drum Level	1
• Displacement	12

SECTION IV
DESIGN UPDATE

SRE Steam Generator

UPDATE

Since the PDBR, several factors have made it necessary to update the SRE design specifications.

An SRE steam generator scaled to the Pilot Plant dimensions presented at the PDBR is too large to be shipped by truck. Barge shipment, although feasible, is too risky because the 1976-77 winter freeze could delay delivery by at least three months. Therefore, the cavity size has been slightly reduced (3.62 to 3.48 meters) to permit truck shipment of the major subassemblies to the Riverside Plant of NSP for on-site erection.

The design pressures have been increased slightly to provide the capability to test at higher steam pressures.

Since the PDBR, the heliostat field has been reconfigured, changing the heat flux distribution in the steam generator cavity. As a result, the boiler height decreased from 2.21 to 1.74 meters (7.24 ft to 5.71 ft).

The scaling criteria for the superheater has been modified to result in better modeling of superheater tube stresses. The SRE superheater tube diameter will increase from 1.27 to 2.54 cm (0.5 to 1.0 inch).

Although all other material properties are satisfactory, the cyclic oxidation rate of Croloy 2-1/4 was judged to be inadequate for a solar steam generator superheater. A material with improved cyclic oxidation characteristics will be selected.

All of these changes, as summarized in Table 4-1, will improve the usefulness of the SRE steam generator.

Table 4-1. Specification Comparison

Design Specification	PDBR c SRE	Updated SRE
Cavity Size, meters (feet)	3.62 (11.88)	3.48 (11.42)
Steam Pressure at, bars Superheater Outlet (psig)	103 (1500)	109 (1575)
Drum Operating, bars Pressure (psig)	117 (1700)	122 (1775)
Boiler and Superheater, bars Design Pressure (psig)	124 (1800)	130 (1875)
Boiler Height, meters (feet)	2.21 (7.24)	1.74 (5.71)
Superheater Tube Material	Croloy 2-1/4	TBD
Superheater Tube, OD, cm (inches)	1.27 (0.5)	2.54 (1.0)

SECTION V
DESIGN SUMMARY

SRE Steam Generator

SUMMARY

The successful operation of the SRE steam generator will validate the baseline design of the Pilot Plant Steam Generator.

A comparison of the configuration, the local fluid and metal temperature distributions and the stresses indicates that the SRE steam generator concept can be successfully scaled to the Pilot Plant steam generator. Both steam generators have been shown to

- Have the same flow circuitry and physical arrangement
- Match fluid and metal temperatures
- Have the same tube dimensions and materials
- Be designed using the same methods

The data obtained from the SRE steam generator will provide a valid test of the design methods for the Pilot Plant steam generator.

Table 5-1. Summary

- SRE will validate pilot plant steam generator
  - Flow circuitry and physical arrangement
  - Fluid and metal temperatures
  - Tube dimensions and materials
  - Design methods
- SRE test will validate design methods

SECTION VI
STEAM GENERATOR TESTING

SCHEDULE OF SOURCES/SINKS

Experiment-produced steam and water will be wasted: (1) to minimize risk of upset to normal power generating operation at Riverside; and (2) to reduce test costs since demineralized water is cheaper than the conditioning equipment needed for closed cycling.

The selection of sources and sinks (Table 6-1) for water and steam for testing the steam generator and thermal storage unit has been made to minimize test expense and hazard to the power generating function of the NSP Riverside Station.

The cost of demineralized water at the station (less than $2.00 per 1000 gallons) is low enough to permit wasting (discharge to the river). Consideration was given to water recycling (e.g., by insertion either to the No. 6 unit condenser or deaerator). However, equipment costs for insertion and for pressure-temperature conditioning are significantly greater than the cost of water treatment. Moreover, risk of upset to the normal power generating operation of Riverside is minimized if the experiment-generated steam and water effluent is wasted. Demineralized water costs for the steam generator test program will be less than $600 (assuming 30, 8-hour periods of testing at conditions averaging 2/3 load). Water costs for thermal storage unit testing will be appreciably less than this.

The No. 8 unit of Riverside will provide feedwater for the steam generator, and a supply of high pressure water for interstage desuperheating for controlling temperature of the steam leaving the generator. It will also be a high-pressure water source for desuperheating the steam supply for the thermal storage unit in the charge mode. The No. 6 unit of the station will provide feedwater for the thermal storage unit in the discharge mode.

The No. 8 unit of the station will also supply the steam for the thermal storage unit in the charge mode.

All experiment-generated steam and water will be discharged to the cooling water leaving the No. 6 unit condenser. These discharges will have a non-measurable effect in raising the river temperature, even at its minimum flow stage.

Cooling water for the solar simulator will be taken from the low-service water line of the station and discharged to the No. 7 unit condenser circulating water.

SRE test program continuity is not expected to be interrupted by economic shut-down of the No. 6 or No. 8 units, but could be interrupted by equipment breakdown in those units. Such an interruption might occur four or five times a year and last that many days.

Table 6-1. Schedule of Sources/Sinks (NSP Test Site)

REQUIREMENT	SOURCE					SINK	
	NO. 8 UNIT FEEDWATER 3000 PSI 440°	NO. 6 UNIT FEEDWATER	NO. 8 UNIT MAIN STEAM 2400 PSI 1000°	LOW-SERVICE WATER 80 PSI 55°	NO. 6 UNIT CONDENSATE WATER 100 PSI 100°	NO. 6 UNIT CONDENSER DISCHARGE	NO. 7 UNIT CONDENSER DISCHARGE
STEAM GENERATOR TEST							
FEEDWATER SUPPLY	X						
ATTEMPERATOR WATER SUPPLY	X						
STEAM DISPOSAL						X	
BLOW-DOWN DISPOSAL						X	
COOLING WATER SUPPLY				X			
COOLING WATER DISPOSAL							X
THERMAL STORAGE TEST							
CHARGE MODE:							
STEAM SUPPLY			X				
ATTEMPERATOR WATER SUPPLY (INLET STEAM CONDITIONING)	X						
WATER DISPOSAL						X	
"THAW" STEAM DISPOSAL						X	
TRAP FILL (START-UP)					X		
DISCHARGE MODE:							
FEEDWATER SUPPLY		X					
STEAM DISPOSAL						X	

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RELATIVE LOCATIONS: TEST AREAS, SOURCES, SINKS

The SRE testing at Riverside will be in the vacant No. 7 Unit area with steam and water services from the adjacent No. 6 and No. 8 unit locations.

The steam generator test will be located in the vacant #7 Unit area. The steam generator will be installed through the 22' x 41' opening in the turbine room floor (Elevation 38') and mounted on the basement floor (Elevation 4').

Relative locations of test areas, sources, and sinks are shown in Figure 6-1.

The thermal storage test will be located in the vacant #7 Unit transformer vault adjacent to the station west wall. It will be mounted on the transformer pad at Elevation 13'. The exterior vault can be enclosed by erection of a single wall and roof. Provisions will be made for space heating/illumination and for drainage of condensate and molten salt.

Steam and feedwater sources and steam/water sink will be provided from the adjacent #6 and #8 Units.

The selection of steam and water services for SRE tests has been made to minimize length of and need for piping runs. Temperature conditioning is required only for the charging steam to the thermal storage unit. The #8 Unit has a sufficiently high operating pressure to derive the steam and feedwater conditions selected for the Solar Pilot Plant.

The longest pipe line distances are required for steam and water from this unit. Approximate distances from services to test areas and pipe line sizes are as follows:

	Distance (ft)	Pipe Size (in.)
Steam Generator		
Feedwater	155	2
Steam disposal	10	2-1/2
Cooling water, in	45	4
Cooling water, out	50	4
Thermal Storage (Charge)		
Steam input	117	1-1/4
Attemperator water	235	1/2
Water disposal	40	3/4
Thermal Storage (Discharge)		
Feedwater	78	3/4
Steam disposal	40	1

Pipe friction and temperature losses from source locations to the test areas are not critical since pressure and temperature reductions are deliberately made, or can be tolerated, in all cases before steam and water use. Discharge of test-generated steam and water to the #6 Unit condenser circulating water, instead of recycling via NSP power production equipment, avoids the expense of conditioning equipment and the possibility of upset to NSP operations.

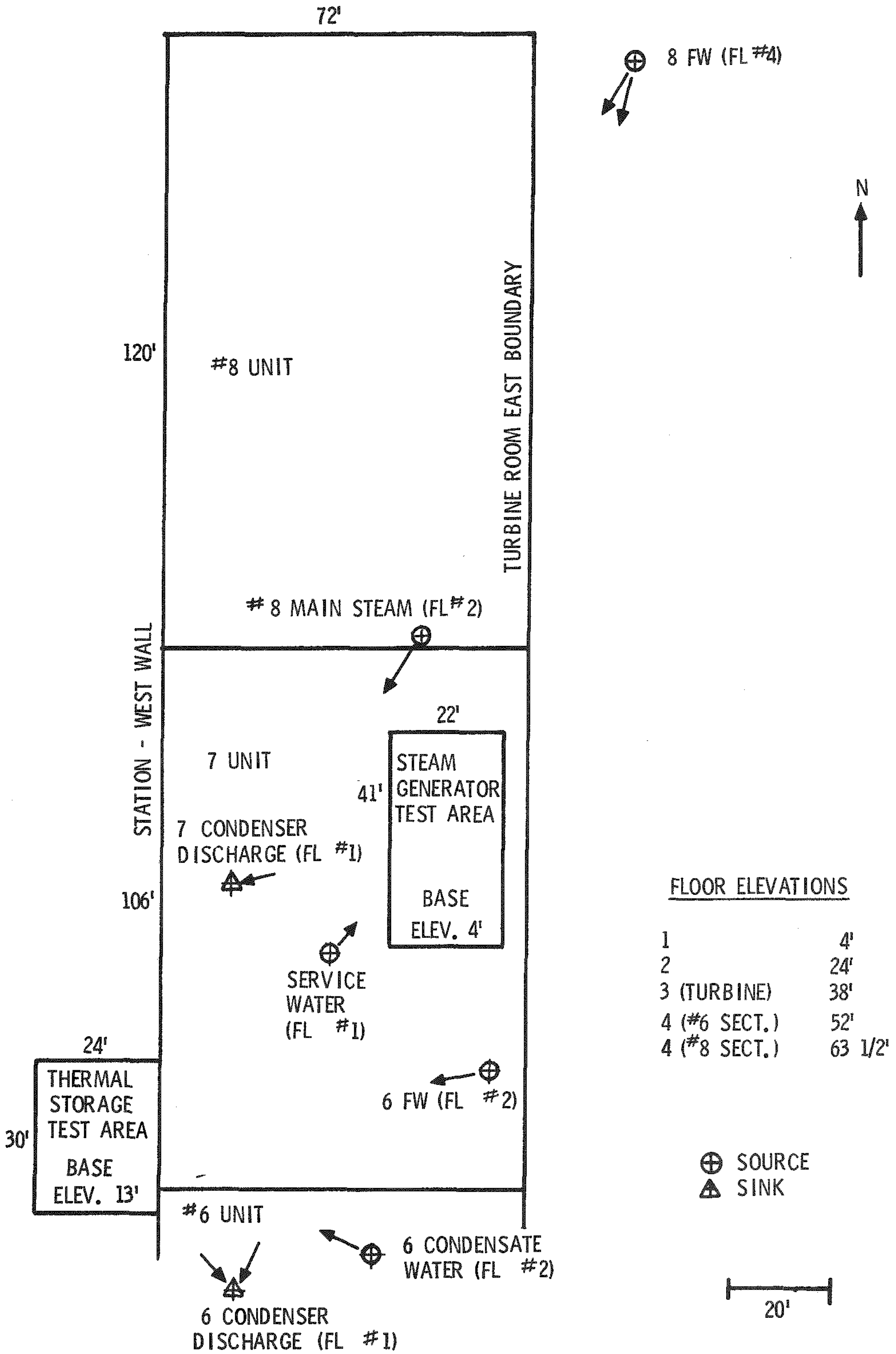

Figure 6-1. Relative Locations: Test Areas, Sources, Sink

PLAN OF TEST INSTALLATION: STEAM GENERATOR

The steam generator test arrangement provides work and rigging space without interference to station traffic patterns and minimizes the length of instrument connections.

The steam generator and solar simulator will be installed (Figure 6-2) at the basement level at Riverside (Station Elevation 4') in the vacant No. 7 Unit area. The steam generator will rise vertically through the 22' by 41' opening in the turbine floor. The transformer and power controllers for the solar simulator will also be installed at the basement level underneath the vacant No. 7 turbine location. This arrangement provides:

- Work space around equipment
- Noninterference to NSP traffic patterns
- Proximity to service water connections for the 4" cooling line to the solar simulator
- Rigging space for solar simulator installation in the steam generator

The mobile trailer housing the SRE control and data acquisition systems will be installed along side the steam generator on the turbine floor (Station Elevation 38'). The proximate location of the trailer minimizes the length of the all-electric instrument connections to the test area.

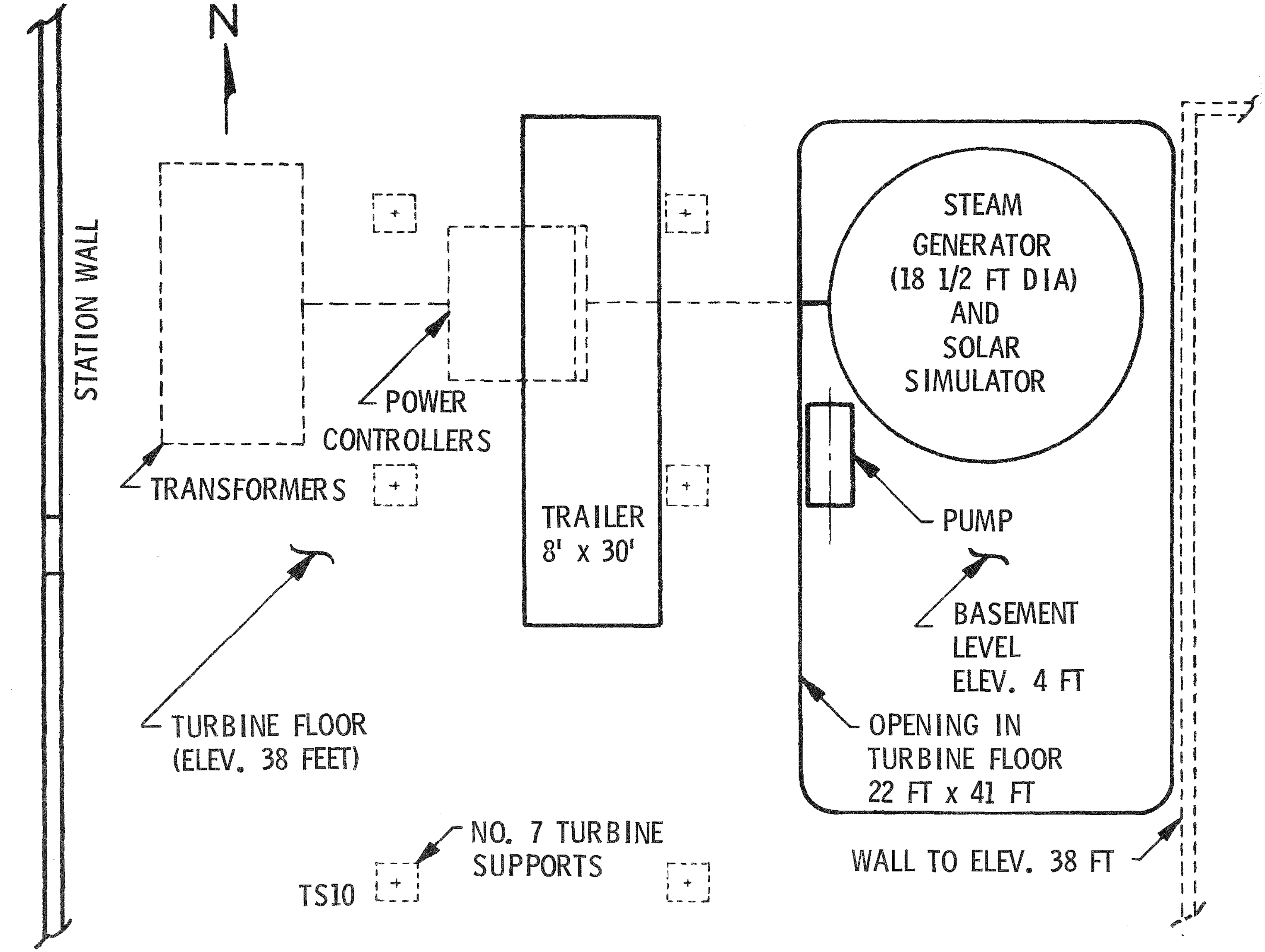

Figure 6-2. Plan of Test Installation Steam Generator

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TEST CONTROL RATIONALE

SRE testing at Riverside will be controlled from a central monitoring location in a mobile trailer adjacent to the steam generator test site.

The steam generator and thermal storage unit testing will be controlled from a central location in a mobile trailer located on the turbine floor in the vacant No. 7 Unit location. Test instrumentation will be electronic with electrical-to-pneumatic conversion for operating the control valves. This instrumentation will be selected from the standard product lines offered by instrument control manufacturers. Instrumentation of this type provides fast response and versatility as to control mode selection and range adjustment so that stable operation of the tests can be achieved. In addition, electrical transmission eliminates instrument piping between the mobile trailer and the remote test equipment.

In addition to the control system, a data acquisition system will be located in the mobile trailer. This system will accept 1-5 volt DC signals from the control system indicative of the magnitude of the controlled parameters. The data acquisition will process these signals so that real-time information is available to the test operator as regards test performance and outcome. Moreover, the data acquisiton system will provide a test supervision function to assist the test operator in the indication and control of "alarm" conditions.

While the control system will provide for maintenance of set-point accuracies typical of modern power station installations, the objective will be to provide accuracy in the "reading" of parameter values by the data acquisition system rather than by maintaining absolute values by the control system. In this connection, temperature measurements for computation of steam and water flows and enthalpies will be measured independently by the control and data acquisition systems using adjacent sensors in the flow steam. For the data acquisition system, these sensors will be thermocouples with direct millivolt outputs to the flow computation process.

For pressure and differential pressure measurements, the control system will first convert the measured value to a proportional 1-5 volt DC signal for transmission to the data acquisition system. These pressure measurements will be made by converting pressure to electrical resistance using piezoresistive sensing elements. The transmitted electrical signal will reflect pressure magnitude with an accuracy typically 0.1% of instrument span.

The steam generator and thermal storage tests can be isolated from NSP services in an emergency by actuation of an air-failure-to-close isolation valve. Typically emergency situations, resulting from equipment failure or operator error, will be presaged by audio/visual alarms to the operator followed up by automatic control action. The objective in the design of emergency controls will be to protect equipment and personnel in the event of any single component or source failure.

Table 6-2. Test Control Rationale

- Central Control of Testing

- Electronic Control:
  - Fast response
  - Versatility as to control mode selection/adjustment
  - Minimizes instrument piping

- Data Acquisition System:
  - Accepts proportional 1-5V dc signals
  - Can provide real-time test performance information
  - Provides a test supervisory function in the indication and control of "alarm" situations

- Set Point Accuracy Secondary to Readout Accuracy
  - Separate temperature measurement for control and data acquisition
  - Pressure measurement by piezoresistive sensing elements (no mechanical linkages)

- Emergency Control
  - Isolation of test sites from NSP operations
  - Automatic interlock controls

STEAM GENERATOR CONTROL

Controls are provided for maintaining steam pressure and temperature, drum level, and boiler recirculation.

The steam generator receives feedwater from the No. 8 Unit of Riverside through an air-fail-to-close isolation valve. A pressure control (Figure 6-3) then operates to reduce the pressure from 3000 psi to about 1760 psi to limit exposure of pipe and fittings to excessive pressure and to minimize sound generation through staged pressure reduction. The feedwater flow then splits going to the attemperator in the superheating section in the one case and to the steam drum in the other. Flow in both these legs is measured in respective metering sections* with outputs to indication, recorder and data acquisition system.

After flow metering, feedwater flow to the drum is regulated by the drum level control subsystem. This is a conventional three-element control by which stable drum level can be obtained using an anticipatory, or feed-forward, signal from the steam flow measurement. The level indicator-controller (LIC) maintains the selected drum level, but during flow transients its control authority is trimmed by the action of the flow indicator-controller (FIC) which endeavors to maintain a set relationship between feedwater and steam flows. The drum level control subsystem can be operated manually during start-up and shut-down of the steam generator.

Steam delivery from the drum passes through two superheater stages with interstage feedwater injection (attemperator) to control the temperature of the exiting steam. Temperature of the steam leaving the second stage superheater is measured and controlled by the master temperature controller (TIC) in conjunction with anticipatory action by the secondary temperature controller. Preliminary temperature correction is made by the secondary temperature controller which measures the attemperator exit temperature, and whose set point is positioned by a signal derived from summing the output of the master controller and the steam flow measurement (feed forward) signal. Output of the secondary temperature controller controls the valve admitting feedwater to the attemperator.

Steam pressure in the steam generator is maintained by the pressure control station downstream of the second stage superheater. The exiting steam flow is measured prior to exhausting to the No. 6 condenser circulating water discharge.

A three-channel trend recorder on the operator console indicates and records feedwater flow to the drum, steam delivery, and drum pressure.

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*Flow measurement involves inlet pressure and temperature at the primary element and differential pressure across the element.

Recirculation flow through the boiler and drum is measured and controlled by throttling. The flow controller is set by the operator to maintain a recirculation flow proportioned to the radiation level of the solar simulator. A remote controlled valve in the by-pass line of the recirculation pump is positioned at the discretion of the operator to achieve a trim control on recirculation flow rate.

Boiler blow-down is done using a remotely actuated valve. Manual control and position indication are provided at the operator console. A flow measuring station is provided in the blow-down line giving flow indication at the operator console and to the data acquisition system. Blow-down exhaust is routed to the No. 6 condenser circulating water discharge.

Some emergency control procedures are noted below:

Emergency Condition	Interlock Action
Drum:	
Low Level	- Operator warning
	- Trip solar simulator
	- Trip recirculation pump
High Level	- Operator warning
	- Shut-off feedwater supply
	- Open blow-down
	- Trip solar simulator
Low Flow:	
Boiler Water Circulation or Feedwater	- Operator warning
	- Trip solar simulator
Recirculation Pump	- Operator warning
	- Open pump by-pass

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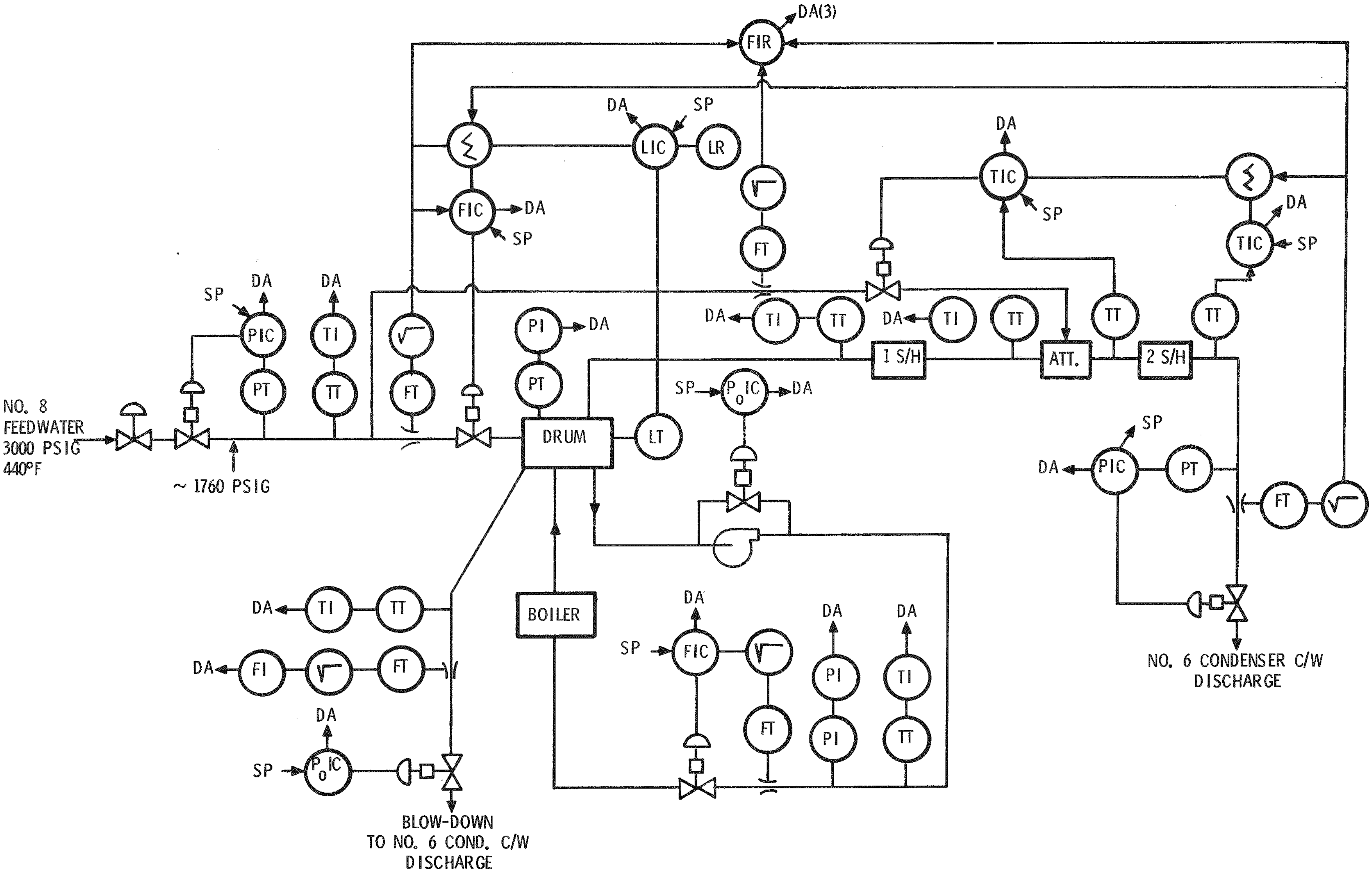

Figure 6-3. Steam Generator Control Schematic

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SOLAR SIMULATOR COOLING WATER CONTROL

Cooling water control for the solar simulator will incorporate fixed flow (to eliminate the expense of automatic control) and heat rejection measurement.

Filtered low-service (river) water at about 80 psi is to be used for cooling the solar simulator (Figure 6-4) and power controller. Spent cooling water will be routed to gravity discharge in the No. 7 condenser cooling water line.

Since the supply of low-service water is ample and its cost (pumping and filtering) is low, the cooling water system will be designed to oversupply water at partial loads and to eliminate the expense of automatic control; (i.e., outlet temperatures of the water will be monitored rather than used to effect temperature control). Manual valves in the solar simulator and power controller cooling lines will be set and locked at system startup to provide a given water temperature rise at full power to the solar simulator. Thereafter, these valves act as fixed orifices resulting in lower temperature rises at partial loads.

Visual indication of inlet and outlet temperatures, inlet pressure, and solar simulator cooling water flow will be provided at the operator console. Proportional 1-5V DC signals will also be generated for these measurements for transmittal and processing by the Data Acquisition (DA) system.

Also provided at the operator's console are the manual station (P_oIC) for remote operation of the cooling water supply valve, and alarms indicating excessively high cooling water temperature.

A local differential pressure indicator is provided for monitoring flow in the power controller cooling water circuit.

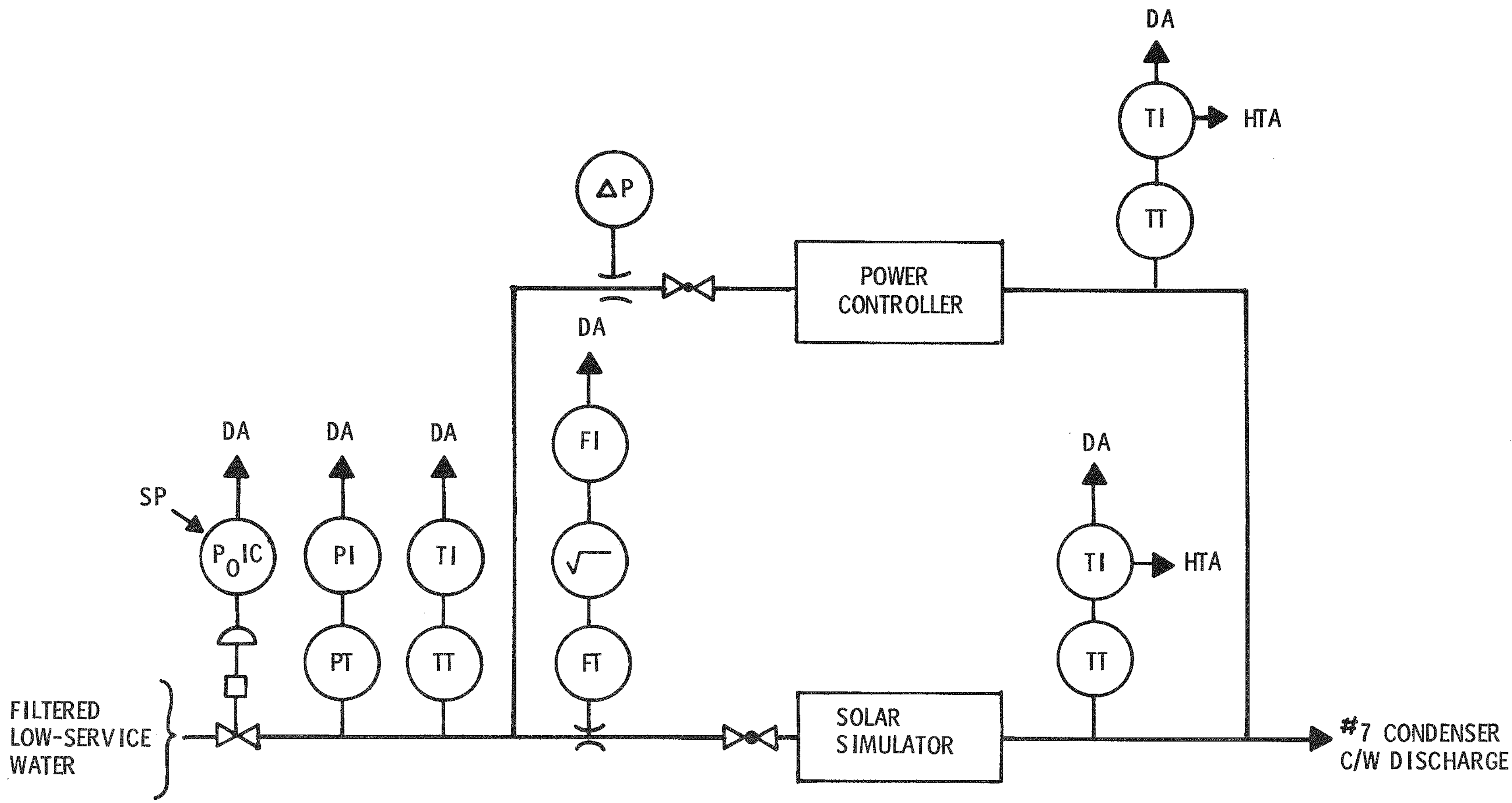

Figure 6-4. Solar Simulator Cooling Water Control Schematic

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Steam Generator

SRE Data Acquisition System

REQUIREMENTS - OPERATIONAL

The DAC system must provide engineering data in real time to facilitate efficient - safe SRE testing and permanent records to document the test results.

The DAC system must measure all pertinent SRE operating parameters. Each measurement must be converted to process dimensions and stored. Data reduction and analysis calculations must also be performed (e.g., enthalpy and heat balance). All measured and calculated data must be available in real time and in a format easily used by test personnel. The data processing required is shown in Figure 6-5.

The DAC system measurement cycle must be short so SRE transient conditions can be defined.

The DAC system must perform limit tests on operating parameters. These limit tests must alert operating personnel when a parameter reaches its design maximum or alarm condition. Emergency shutdown independent of operator action should be considered and mechanized if feasible. Mechanization of a warning signal should also be considered. This warning would occur when a parameter deviates a significant distance from its normal operating level toward its design maximum level.

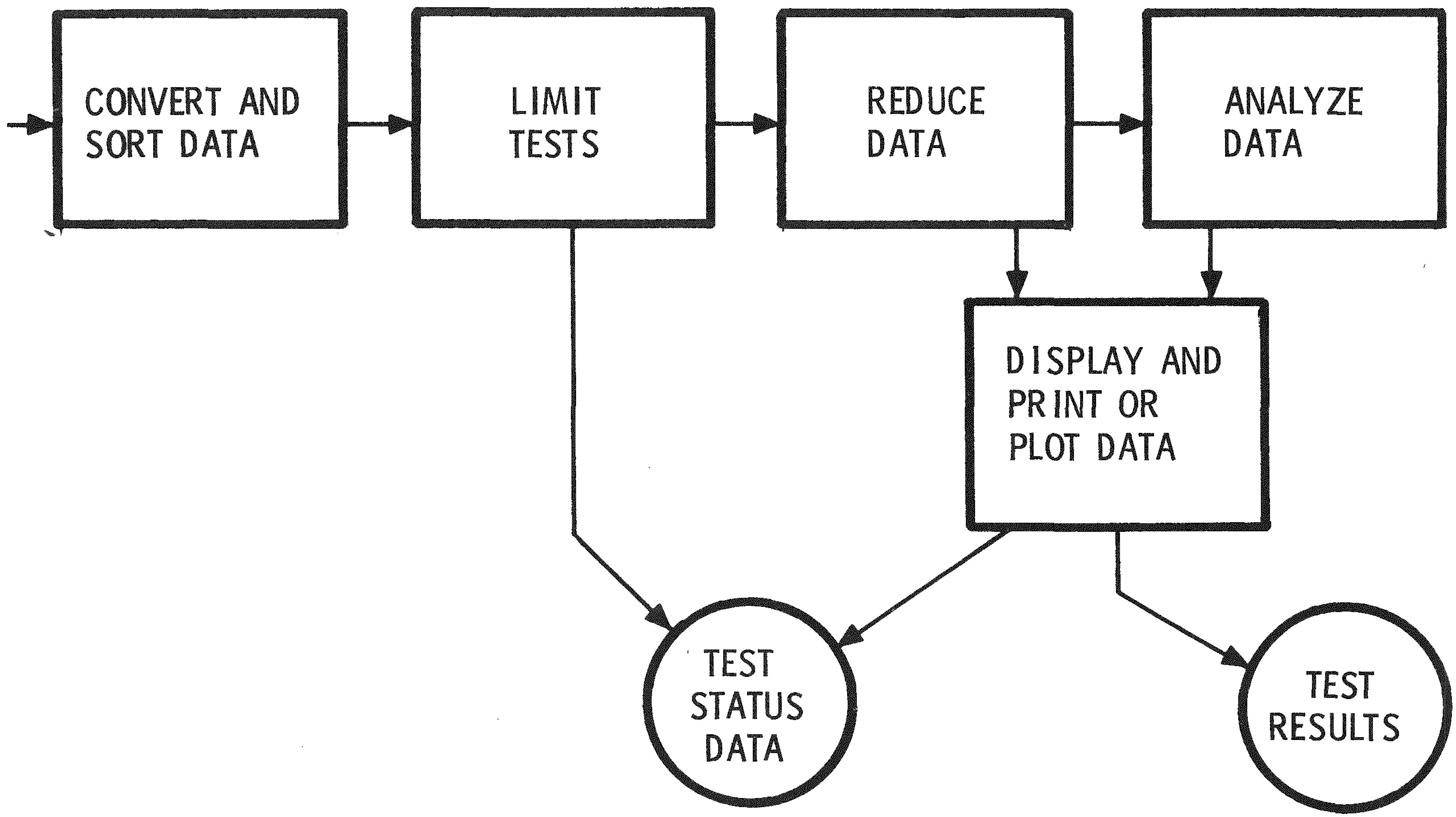

Figure 6-5. SRE Data Acquisition System Data Processing

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REQUIREMENTS - SIZE

The DAC system must be sized to process all measured data of the receiver and thermal storage SRE tests.

Receiver and thermal storage SRE testing should use the same DAC system. Receiver and storage tests will not be performed simultaneously.

Table 6-3 lists the estimated number and duration of the receiver and storage SRE tests along with the number and type of measurement points. The receiver test measurement requirements will determine the size of the DAC.

Table 6-3. SRE Measurement Estimate

Receiver SRE Tests (30-8 hr sequences)
400 temperature points
200 analog points (P, ΔP etc.)
Storage SRE Tests (30-1 to 6 hr sequences)
57 temperature points
16 analog points

CONCEPT CONFIGURATION

The system 700 Process Analyzer will meet the DAC requirements.

The greatest advantage of the System 700 Process Analyzer (Figure 6-6) is its flexibility. Input flexibility will be exploited by using some of the receiver test inputs to measure all the storage test points. Data handling flexibility will be used to get optimum reduction, analysis and display records for both the receiver and storage tests.

Test measurements are made through the real time interface-multiplexer (RT1-MUX) of the System 700. The RT1 is expandable by eight input blocks. Temperature measurements on the SRE receiver test will require 50 (T.C.) input blocks. Temperature measurements on the storage SRE tests will use eight of these same input blocks. Twenty-five input blocks will be required by the analog (flow, pressure, etc.) measurements of the receiver SRE tests. Two of these analog input blocks will be also used for the storage SRE test instrumentation.

The System 700 sample rate is 125 points/sec. In the receiver SRE test, the measurement cycle time can be less than five seconds and the storage SRE measurement cycle can be less than one second. A five-second measurement cycle will be used for the shorter SRE test sequences. If the SRE response time constants are long enough, a "wait time" will be inserted between measurement cycles. The flexibility of the System 700 timing will also allow zero wait time during transient testing (power on, shutdown, load transients, etc.) and a nonzero wait time during steady-state tests.

Limit tests will be performed on all data taken. Rates of change as well as operating levels will be checked as part of each measurement cycle. Warning and alarm messages can be shown on the teleprinter, plotter-line printer and/or CRT display. The plotter-line printer will have a usage priority of: first-alarm messages, second-warning messages, and third-real time data display. Appropriate emergency action independent of operator action may be mechanized through relay contacts.

All measured data will be converted to process dimensions and stored. During each measurement cycle data reduction and analysis will be performed. All the measured and calculated data will be available for display. The display output format can be plots on the CRT or plotter (subject to the warning/alarm priority limitation) or tabulated on either of the three output media.

Permanent test history records will be made after each test sequence by the plotter-line printer. All data outputs will be in process dimensions. It will be desirable to have a complete tabular listing of some data. Other data will be more conveniently used in a reduced/analyzed and plotted format.

The DAC system will be controlled by a minicomputer. The computer software specification (SK133245) is included as Appendix H.

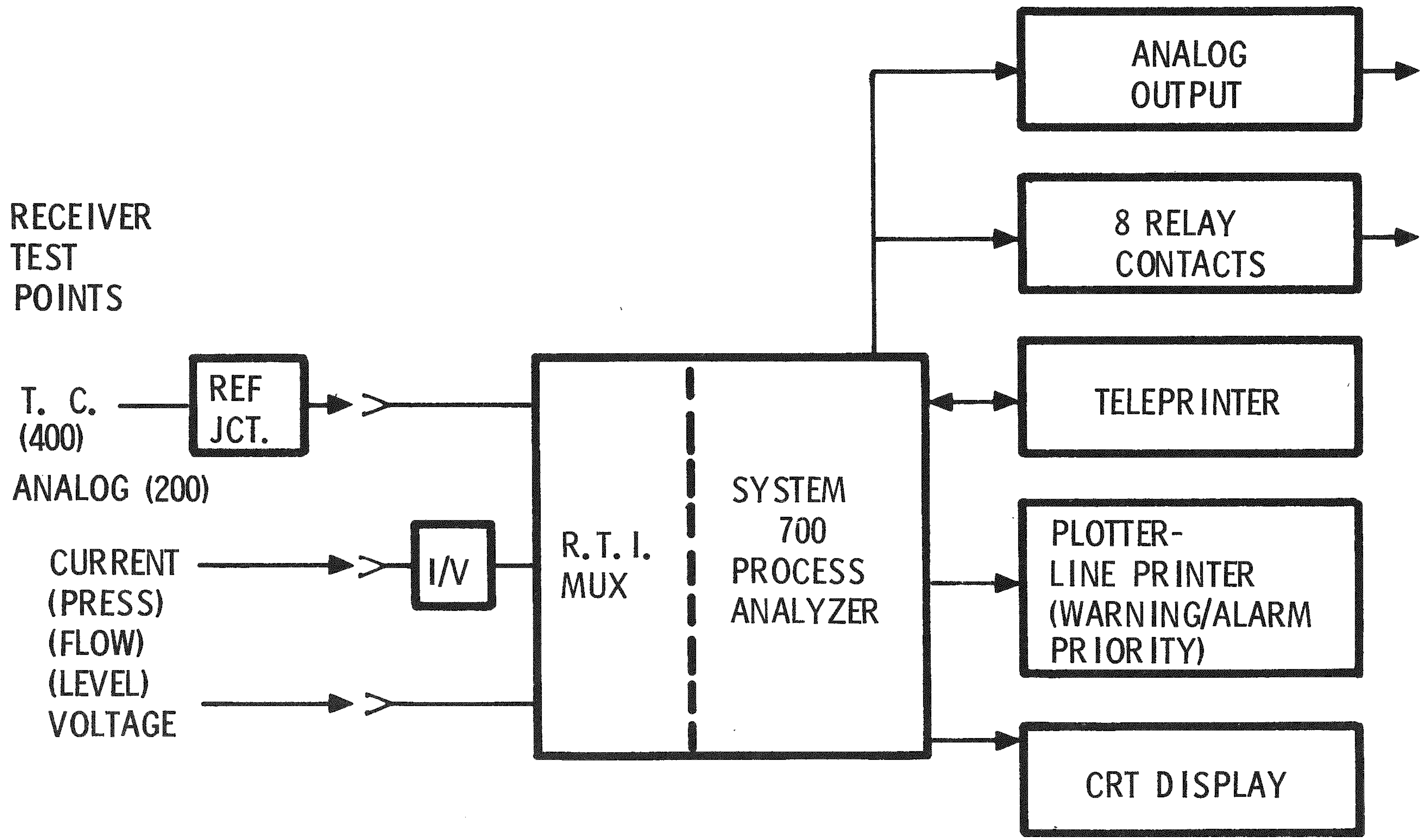

Figure 6-6. SRE Data Acquisition System Configuration

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Steam Generator

Solar Simulator

CONCEPT

The Solar Simulator will provide controlled radiant heat inputs to the SRE Receiver.

The Solar Simulator has three parts: a lamp array tower, a power controller and a control console (Figures 6-7, 6-8, 6-9, 6-10). The lamp array tower is inserted in the receiver cavity. The power controllers will be located adjacent to the base of the receiver. The control console will be inside the control center trailer.

A cover plate will be mounted at the base of the array. This plate will cover the opening in the bottom of the receiver when the array structure is inserted to prevent excessive flux leakage.

Cooling water will be required for the power controllers and the array tower-cover plate assembly.

The control console has three separate manual/automatic programming sections. Each control section corresponds to one power controller section-array zone. Thus the output of each array zone can be independently set.

The controller input power comes from the SRE substation. The low-voltage circuit breaker on the substation will have a remote trip switch located on the simulator control console.

The power controller consists of nine Research Inc. Model 650 full-wave bridge controlled rectifier assemblies. Three rectifier assemblies are controlled by each control console programmer.

The lamp array tower is a 27-facet cylinder. The facets will be positioned so the flux peaks are located in the azimuthal center of each three-section boiler membrane wall segment. The lamps are horizontally mounted in front of a water cooled reflector. The lamp leads are inserted from the outside through the insulated mounting block to the electrical terminals inside the array structure.

Flux profile distributions will be set by lamp placement densities. Azimuthal and vertical flux variations from less than 50 suns to more than 350 suns are required. The array is divided into nine equal power dissipating subzones. Each subzone is powered by one controlled rectifier assembly. Two zone orientation configurations will be used: cylindrical zones where the corresponding horizontal subzones are controlled from the same programmer; and vertical zones where the three subzones in one partial arc of the array are controlled by the same programmer. The zone incident powers are independently controllable from 5MW total down to zero.

Detail specifications for the solar simulator (SK133244) are included as Appendix G.

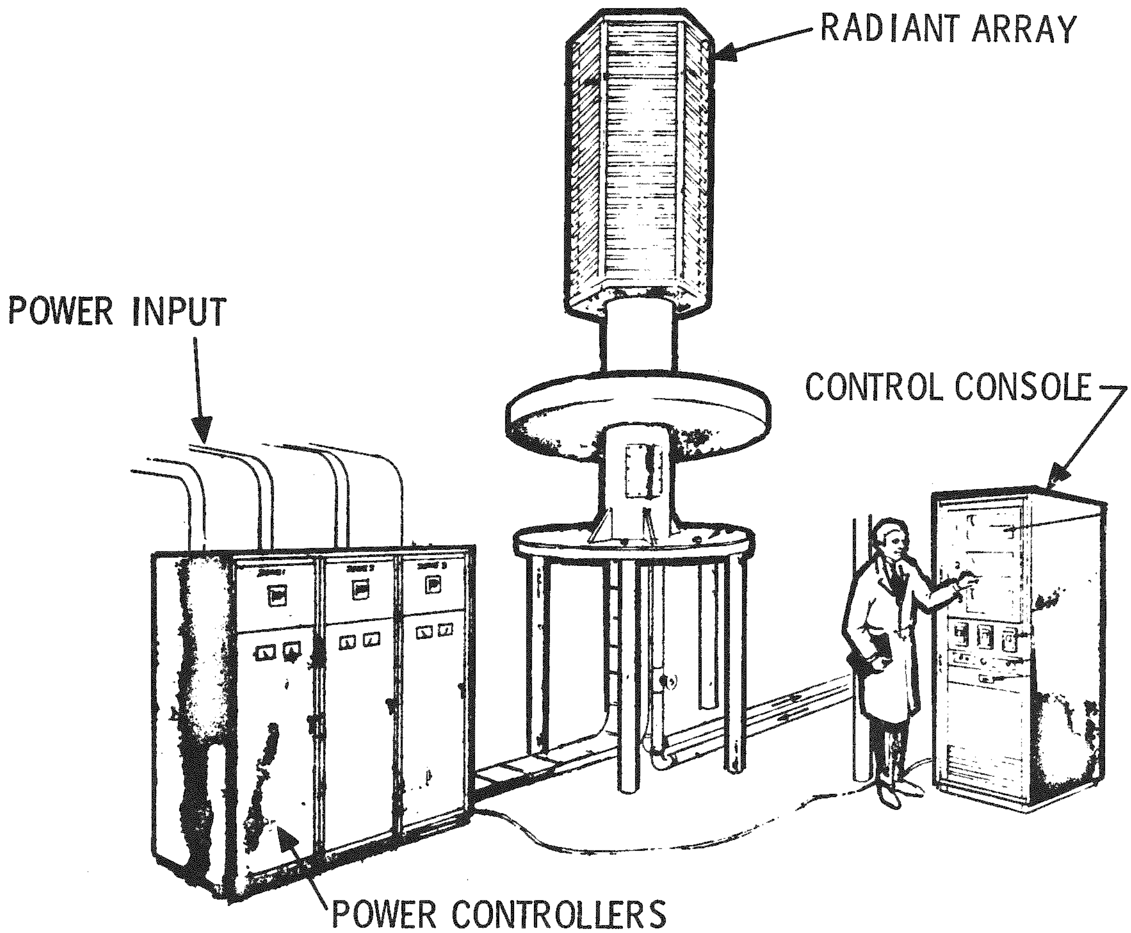

Figure 6-7. Solar Simulator System

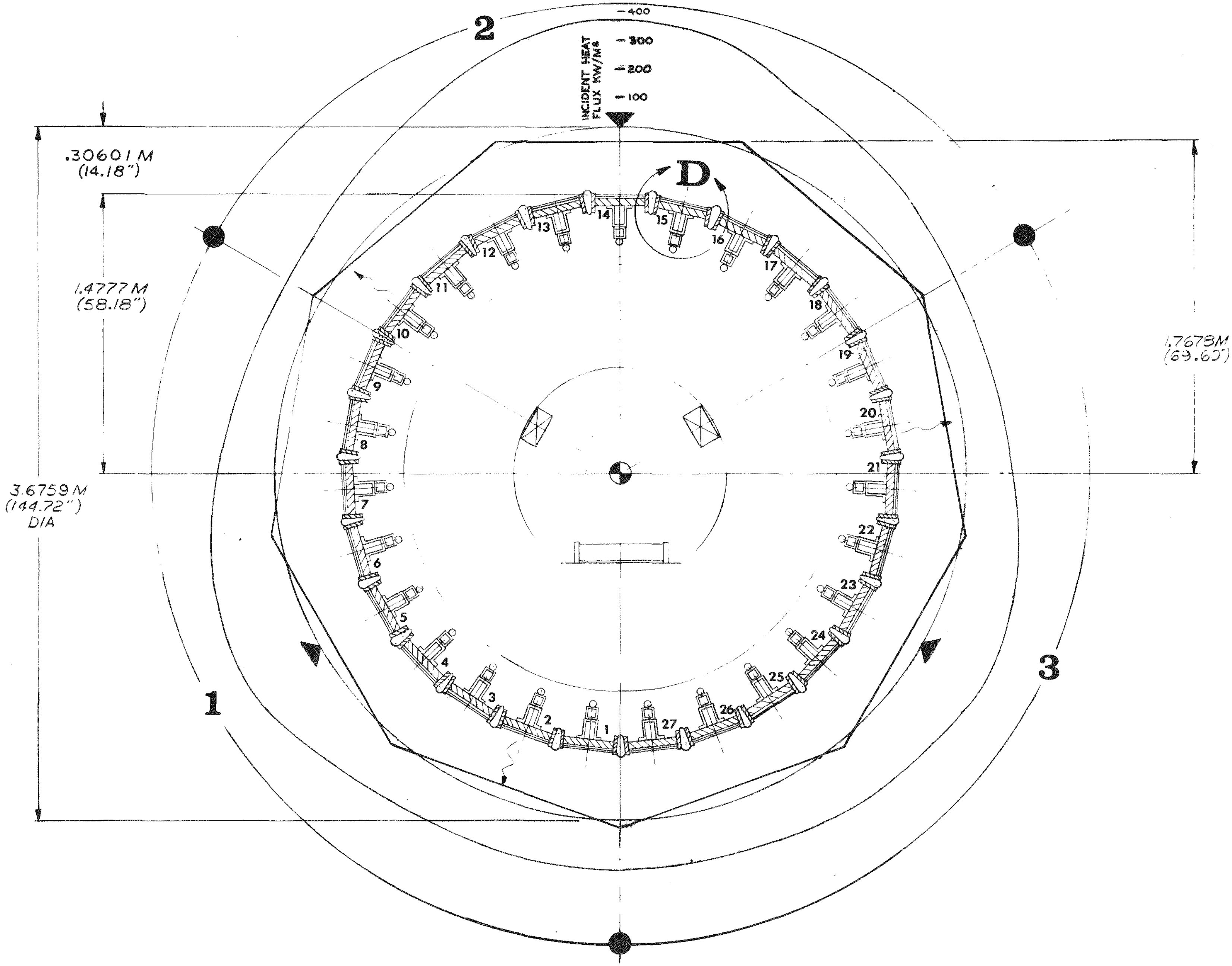

Figure 6-8. Array Horizontal Section

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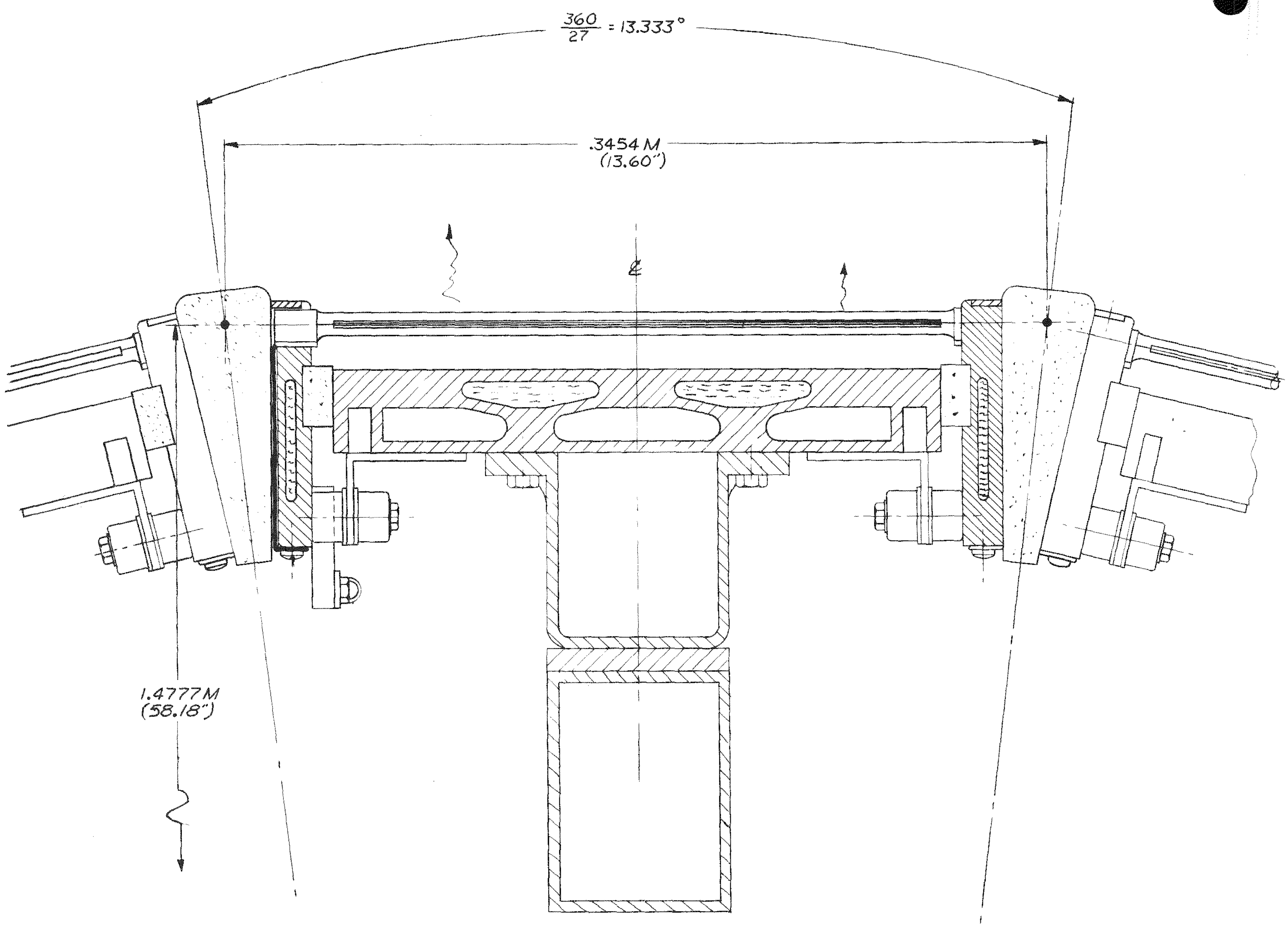

Figure 6-9. Lamp and Facet Detail

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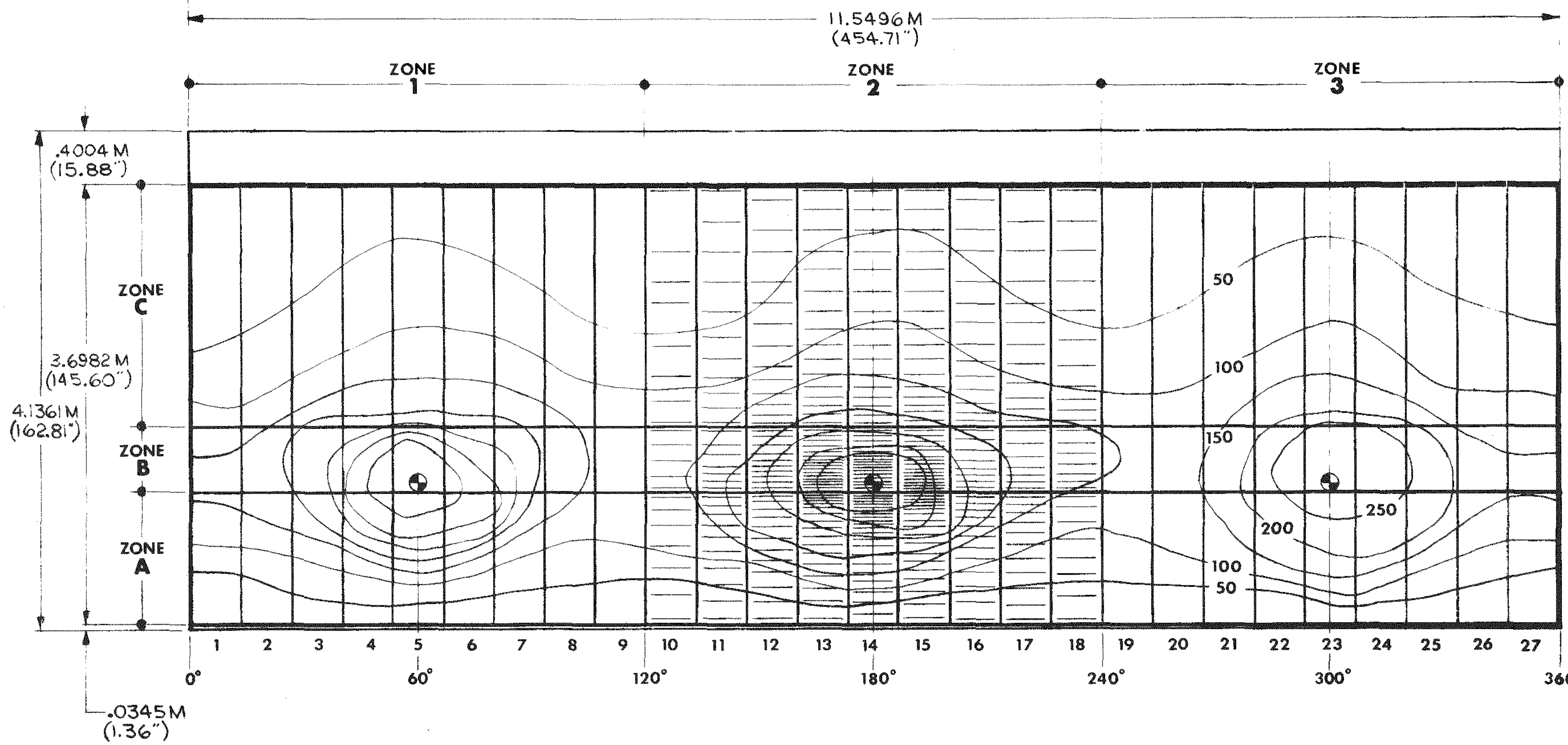

Figure 6-10. Zone Configuration

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Steam Generator

Solar Simulator

POWER SUBSTATION

Each Solar Simulator power controller will require one substation section.

The Solar Simulator power controllers require 310 VRMS - 3 phase (Δ) 60 Hz power inputs. A transformer substation with suitable switch gear will be required to get these voltages from the 13.8 KV available at the NSP Riverside plant.

The input to the substation is through the lightning arrestor. The 13.8 KV - 3 phase (Δ) is connected to a high voltage fused switch. Circuit breakers could be used instead of the high-voltage fused switch but the cost and delivery time would increase by a factor of three.

The transformer in the substation is rated for 8.5 MVA. Dry and pyronal transformers are both available in this range. Both types will be considered during detail design as well as the possibility of forced air (fan) cooling to increase the rated capacities and/or decrease the local ambient temperature rise.

The low-voltage circuit breakers (Figure 6-11) may be tripped in three ways. The first is overload sensing. The second is manned switching or local shut-off at the circuit breaker cabinet. The third is a remote trip by a low voltage (24 VDC) source such as may be mechanized as part of the Data Acquisition System and will be included on the simulator control console.

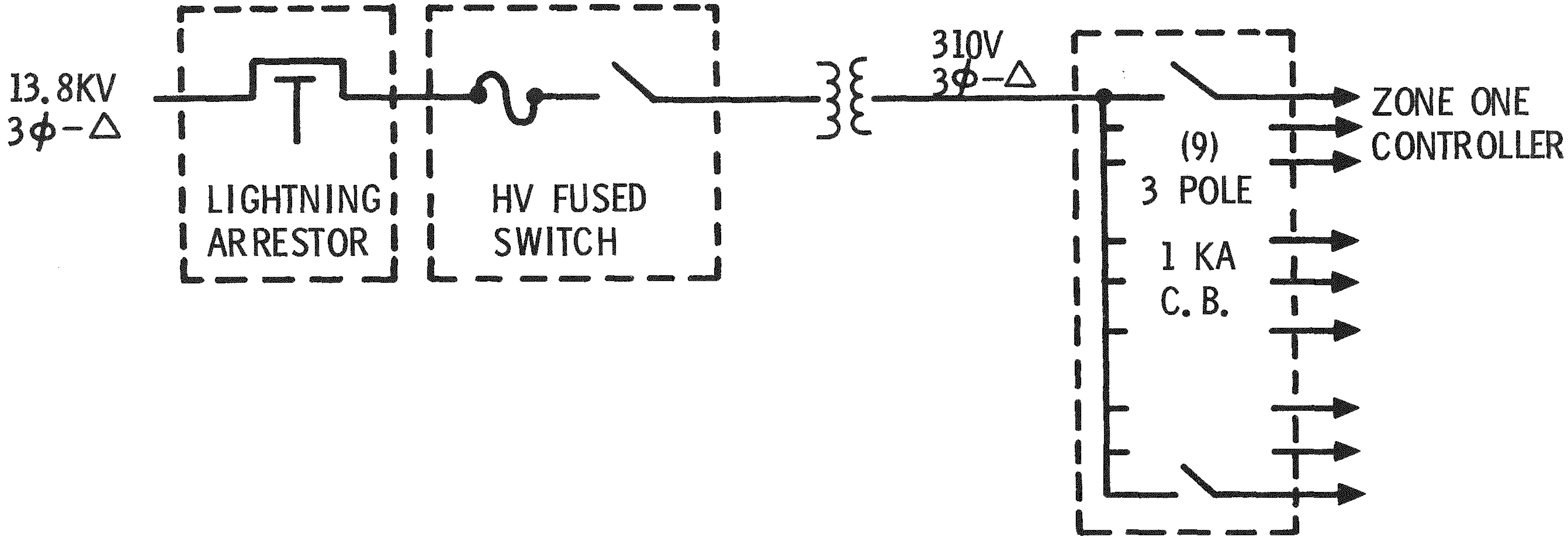

Figure 6-11. Solar Simulator Substation

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Steam Generator

Test Control Center

CONCEPTUAL CONFIGURATION

The SRE test control center will contain the display and control elements required to conduct the SRE test sequences.

The test control center will contain the SRE control panel and the simulator control panel. The SRE control panel will have the operational controls for the receiver and storage SRE tests.

The Data Acquisition System (DAC) will also be located in the instrumentation trailer. The DAC consists of the system 700, magnetic tape unit, plotter/printer, typer, CRT and quick disconnect assembly. An air conditioner will be required (Figure 6-12) to protect the system 700 from the high ambient temperatures of the NSP plant.

All the test control center instrumentation will be movable for installation and servicing, but will be secured during transport.

All signal lines to and from the control center will be routed through an access port located behind the quick disconnect assembly.

The power required to operate the instruments in the control center will be 230 VRMS center taped (115 VRMS) 60 Hz. One-hundred ampere service should be adequate to operate all the instruments and controls.

The test control center will include the necessary control and display equipment such that the test personnel can start, conduct and conclude a SRE test sequence without leaving the trailer.

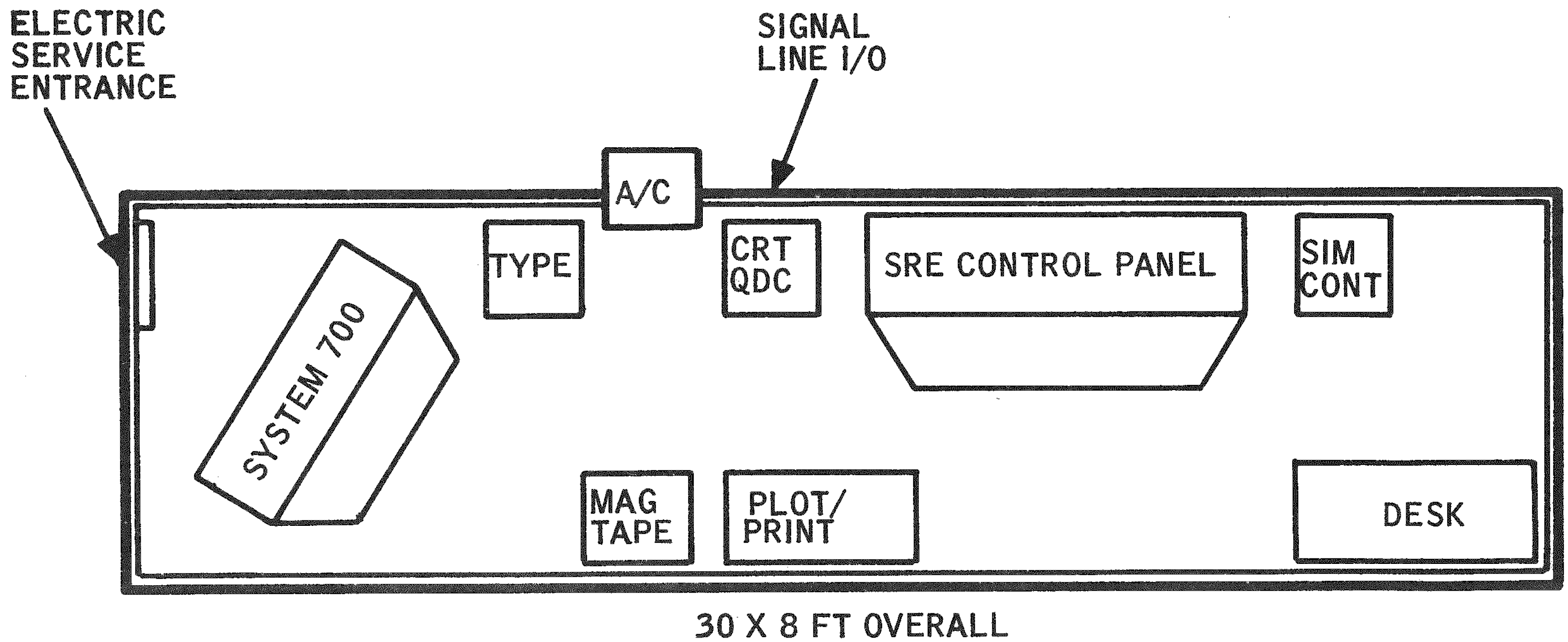

Figure 6-12. SRE Test Control Center

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SRE CONTROL PANEL CONFIGURATION

The SRE Control Panel will have the required controls and indicators to operate the SRE test items.

The receiver controls (Figure 6-13) will be on the left end of the panel. The thermal storage controls (Figure 6-14) will be the right half of the SRE control panel.

The SRE Control Panel is made up of set point controllers and indicators. The circles shown on the lower part of some items identify the set point controllers. Moving dial indicators and indicating recorders are also shown. The three larger squares are the indicating recorders.

The SRE Control Panel will resemble a conventional power plant control panel. The set point controllers and indicators will be functionally grouped.

The set point controllers are manual/automatic electrical controllers. The control signals are generated electrically and used to control pneumatic actuators on the SRE test items.

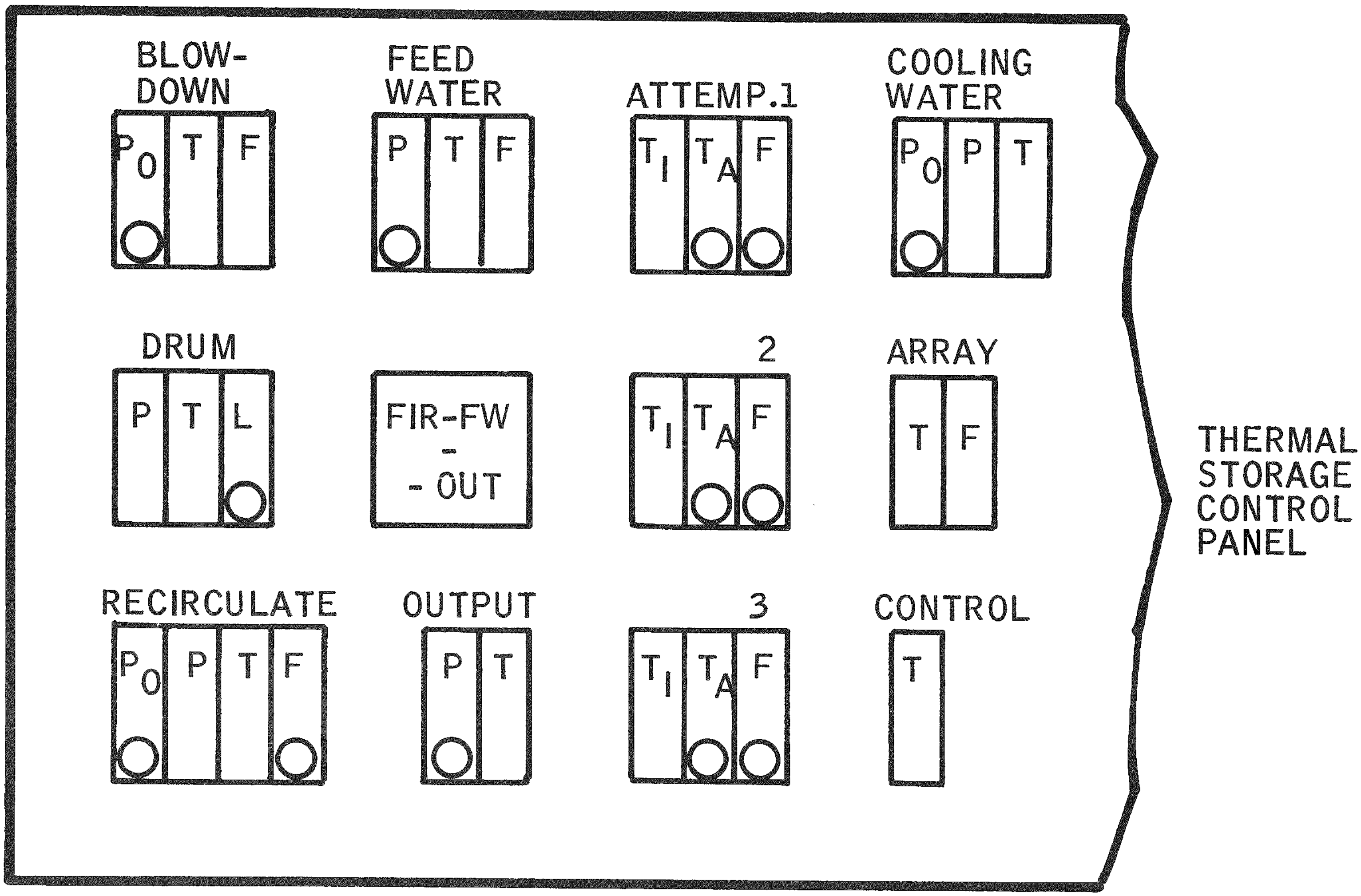

Figure 6-13. Receiver Control Panel

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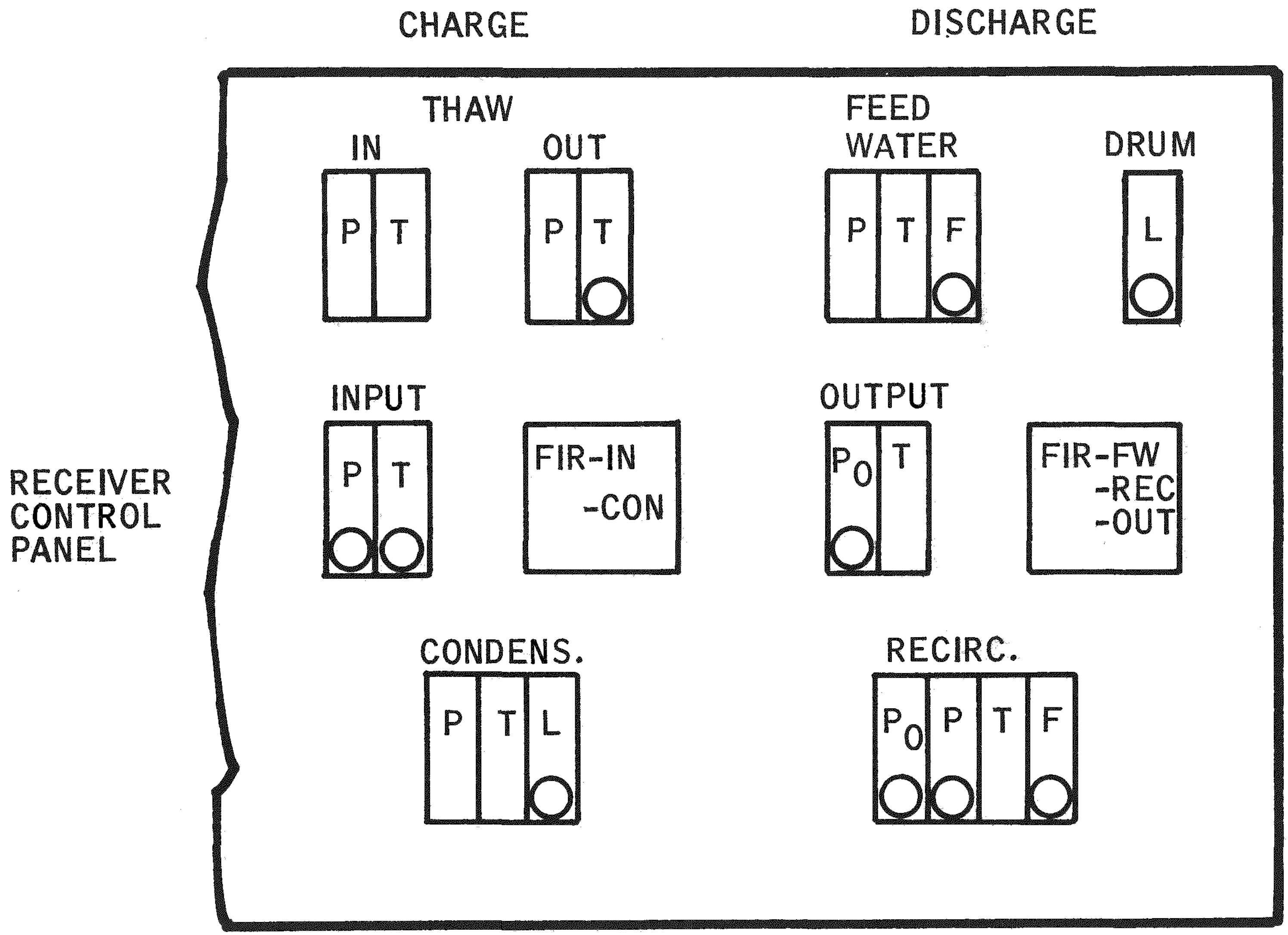

Figure 6-14. Thermal Storage Control Panel

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SET POINT/INDICATING CONTROLLER DESCRIPTION

VUTRONIK set point/indicating analog controllers will provide positive versatile control and display of the SRE test item operational parameters.

The VUTRONIK set point controller is a deviation from set point indicating device (Figure 6-15). The thumb wheel to the right of the indicating scale moves the scale such that the set point is always under the stationary (green) pointer. A deviation from set point is indicated by a red indicator emerging from behind the stationary green indicator. VUTRONIK indicators are essentially the same except the scale is moved to position the nominal reading in the center. The red pointer indicates a deviation from nominal operating point.

VUTRONIK set point controllers are manual/automatic control loop devices. Change over from auto to manual is by a switch located under a protective bar on the front of the controller. The control constants (gain, time constants, offsets) are adjustable on the side of each controller. The controllers can be rolled out as shown and the control constants adjusted without turning off the controller power.

In the event a controller fails, the unit may be replaced with a manual controller without shutting down the control panel. The faulty controller is extended to the rail limit (about 4 inches more than shown) and a smaller manual controller is plugged in. Plugging in the manual controller disconnects the primary unit so it can be unplugged and serviced. The test sequence may now be completed with the manual controller.

A high- and low-level alarm is provided on the set point controller or indicator. The levels are adjusted on the side of the device. When an alarm level is exceeded a light behind the mylar process name label is illuminated. Relay contacts are also provided to activate a remote audio alarm.

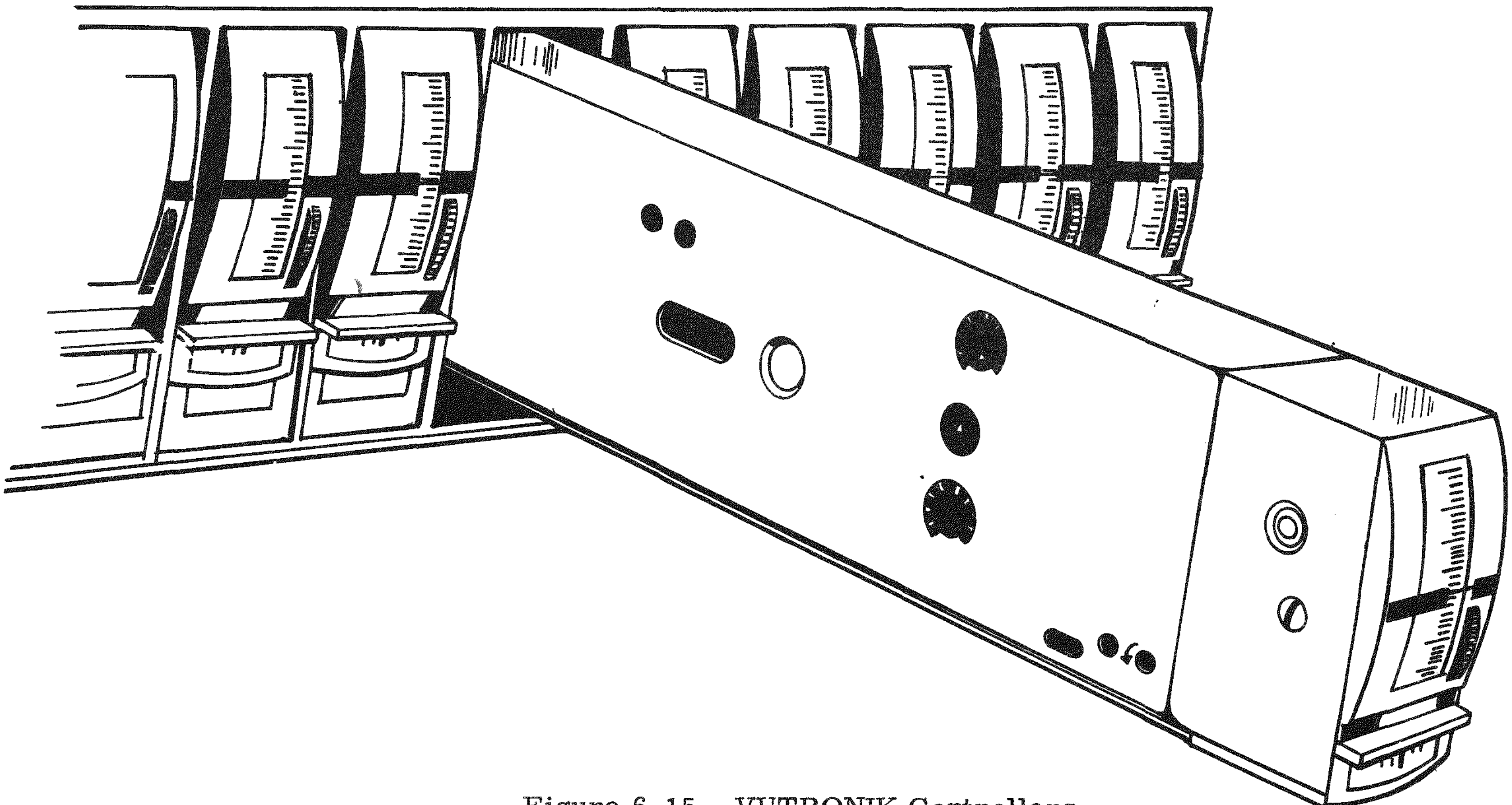

Figure 6-15. VUTRONIK Controllers

SECTION VII
TEST PLANS AND SCHEDULE

TEST SCHEDULE

The schedule for accomplishing the test program on time implies attention to the procurement of equipment and definition of events in chronological order.

The steam generator tests (Figure 7-1) will be accomplished at the NSP Riverside Plant. Preparation of the test site includes installing the required plumbing; steam lines, feedwater lines, water drain lines, vent lines, conditioning equipment, instrumentation, solar simulator and simulator power substation.

The test items will be installed following installation of the piping modifications performed in the plant. The substation will be installed prior to installing the steam generator because of installation space requirement interference. The solar simulator installation will take place after the steam generator is erected.

The control center will be assembled at the Honeywell Ridgway facility and transported to the NSP plant after construction of the pipes are modified, the simulator installed, and the steam generator erected.

The test area for the storage experiment will be prepared prior to the installation of the piping modifications required for storage test operation.

The storage tests will commence before the steam generator tests. Completion of the steam generator will be a pacing item because of the presently envisionaged long-lead time for the recirculating pump delivery. Erection of the steam generator can proceed however, with the pump installation being the last equipment to be installed.

Critical tests will be performed to meet the test requirements. It is planned to alternate test operation of the storage and steam generator on approximately a one to two day basis. Unexpected complications on one experiment should not delay operation of alternate testing.

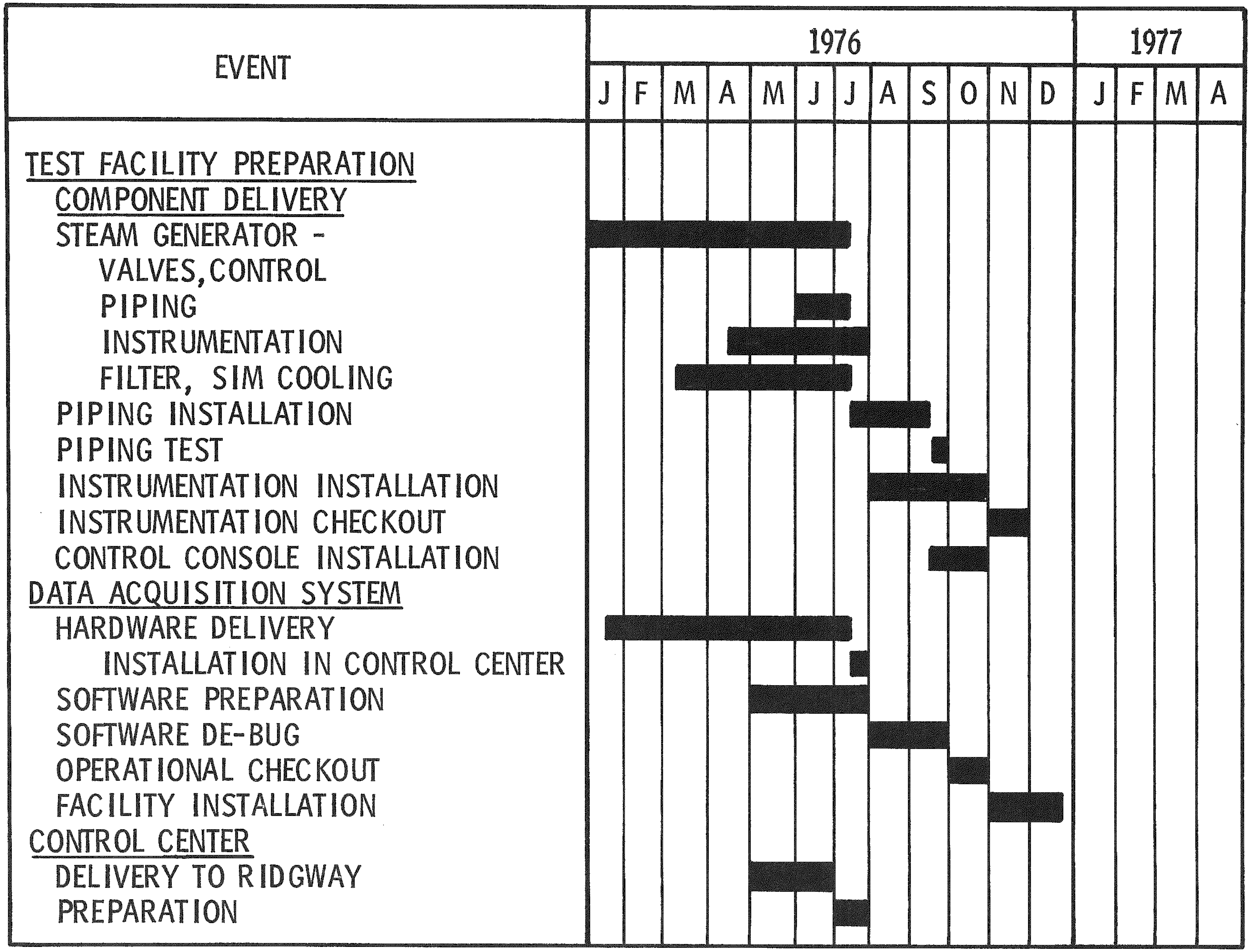

Figure 7-1. Steam Generator SRE Test Schedule

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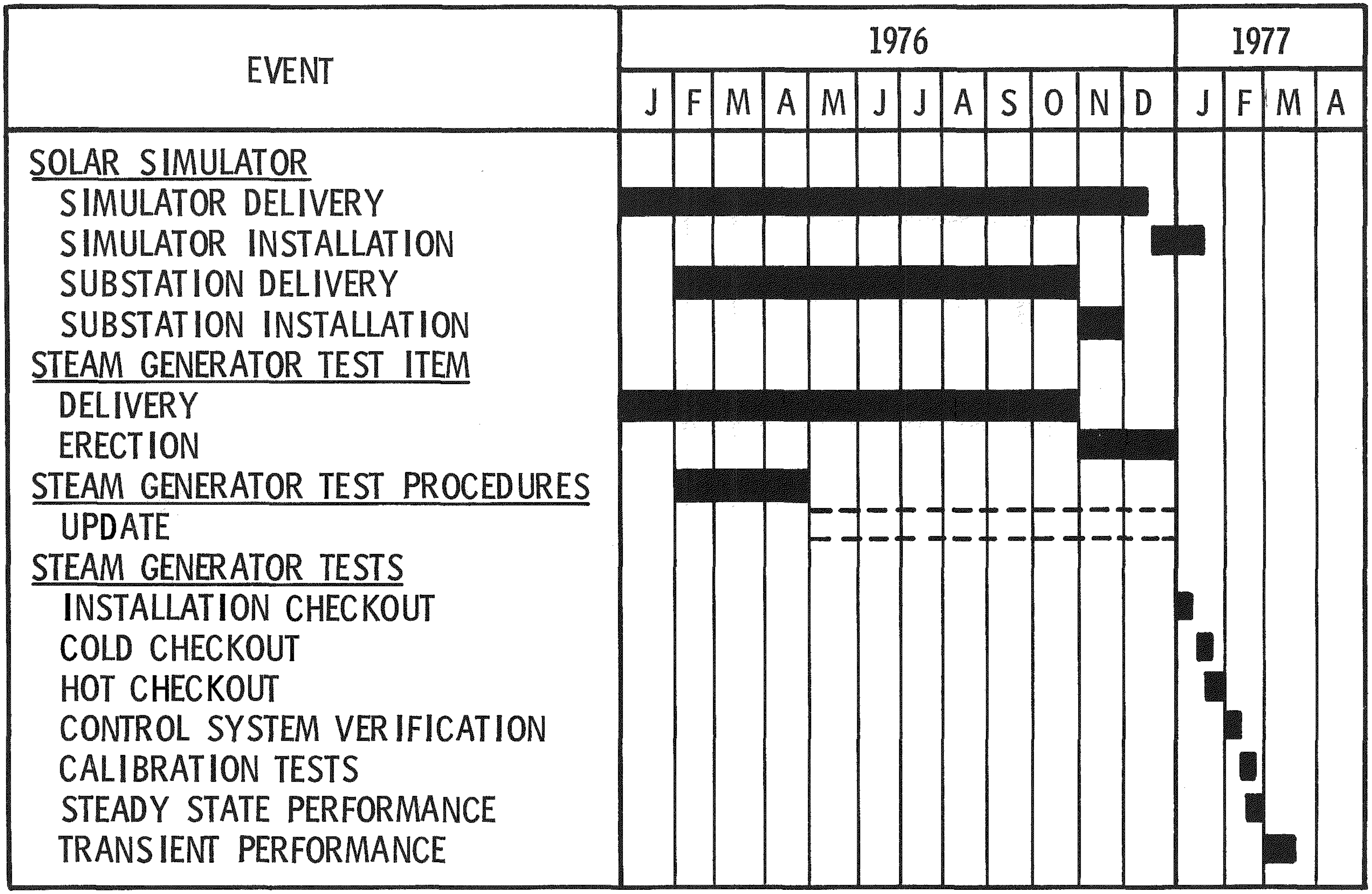

Figure 7-1. Steam Generator SRE Test Schedule (Concluded)

SECTION VIII
LONG-LEAD TIME ITEMS

TEST INSTALLATION: LONG-LEAD TIME ITEMS

A large amount of the equipment required for completing the test installation at the NSP Test Facility must be ordered prior to the Detail Design Review to allow for timely delivery.

The lead-time schedule shown is based on piping and instrument diagrams* call outs, and vendor price and delivery responses. The piping and instrument diagrams have gone through several iterations to improve design and lower costs. It is expected that further refinements will be made during the detail design period, perhaps requiring some adjustment of the cost figures shown. The total cost indicated for long-lead time items is about 85 percent of the total cost for test installation material. (The costs shown are vendor prices.)

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*See Appendix:

Piping and Instrument Diagram No. M1002 - Steam Generator, SRE

Piping and Instrument Diagram No. M1003 - Cooling Water System

Table 8-1. Steam Generator (SRE) Test Installation Long Lead Time* Items

	Order Date	Delivery Date	Cost
Valves, Control	4-15-76	7-15-76	$ 8,110
Valves, Manual	1-15-76	7-15-76	7,520
Valves, Check/Relief	1-15-76	7-15-76	2,470
Water Filter	3-16-76	7-15-76	1,200
Instrumentation	4-15-76	7-31-76	32,260
Instrument Manifolds	3-15-76	7-15-76	4,660
			56,220

*Pre-DDR

DATA ACQUISITION SYSTEM

The data acquisition hardware must be ordered prior to the Detail Design Review to permit completion and software checkout prior to its employment in the conduct of the test program.

The hardware for the data acquisition system (Table 8-2) must be ordered by 15 January, 1976. Delivery time of this item in total is presently confirmed as 6 months. After delivery, approximately one month will be required for system assembly and operational checkout. The software will be ready for running on the system by 1 August. Software "debugging" is expected to take two months and operational checkout of the system with software will require one month. The system will then be ready for starting installation at the test facility on 1 November. Installation of the system can be completed, allowing testing to start on 10 December.

Table 8-2. Data Acquisition Long-Lead Items

Item	Order Date	Delivery Date	Cost
System 700	1-15-76	7-15-76	$155,216
Plotter/Printer	1-15-76	7-15-76	5,320
CRT	1-15-76	7-15-76	1,825
Vu Pac III (Software)	2-01-76	4-01-76	5,000
Total			$167,361

Steam Generator

Long-Lead Time Items

SOLAR SIMULATOR

The solar simulator (Table 8-3) and simulator power substation must be ordered prior to the Retail Design Review.

Delivery of the solar simulator is estimated at 11 months and the substation at 9 months. The substation must be installed prior to the delivery of the steam generator and the solar simulator to prevent installation interference at the test facility. Approximately one month will be required to install the power substation.

Table 8-3. Simulator Long-Leadtime Items

Item	Cost	Order Date	Delivery Date
Solar Simulator	$765,000	1/10/76	12/10/76
Simulator Power Substation	$128,000	2/10/76	11/10/76

Steam Generator

Long-Lead Time Items

TEST ITEM LONG-LEAD TIME ITEMS

All of the major components of the steam generator test item are fabricated from long-lead time materials.

As indicated in Table 8-4, all of the materials for the major components of the SRE must be specified and ordered prior to the Detailed Design Review (DDR) scheduled for the end of April, 1976, so that they will be available at the appropriate time during the scheduled fabrication period, May - November 1976.

Contracts with the major fabricators, Patterson Industries and Roessing Manufacturing, must be signed by February 1, 1976, so that they can order long-lead time materials.

Table 8-4. Steam Generator Long Lead Time Items

Item	Cost$	Order Date	Delivery Date
Boiler Tubes and Headers	28,030	2-01-76	10-01-76
Superheater Tubes and Headers	51,729	2-01-76	6-15-76
Drum and Internals	8,371	3-15-76	7-01-76
Recirculation Pump	25,000	1-15-76	1-15-77
Piping, Valves, and Fittings	15,200	4-15-76	7-01-76
Structural Steel	10,060	3-15-76	6-01-76
Subassembly Fabrication, Patterson Industries		2-01-76	11-01-76
Superheater Tubes and Header Fabrication, Roessing Manufacturing		2-01-76	7-01-76

APPENDIX A

CALCULATIONS OF BOILER LENGTH AND ATTEMPERATOR FLOW REQUIREMENTS

APPENDIX A

CALCULATION OF BOILER LENGTH AND ATTEMPERATOR FLOW REQUIREMENTS

INTRODUCTION

This appendix describes the methodology used in the initial determination of the boiler length, power into the boiler, steam flow, attemperator flow, and maximum interstage superheater fluid temperature. These parameters were determined in the following sequence of steps for each heat flux profile:

a) sum the circumferential average wall heat flux profile

b) determine the steam flow, boiler area, boiler power, and superheater power

c) select the boiler area (i.e., boiler length)

d) calculate the attemperator flow rate and maximum superheater interstage temperature

Steps a) through d) were performed upon absorbed heat flux profiles (zero absorbed ceiling flux) for the following times and cavity sizes.

46.1' x 39.4' cavity	6/21/80,	7:00 am
"	"	8:00 am
"	"	9:00 am
"	"	10:00 am
"	"	11:00 am
"	"	12:00 pm
46.1' x 39.4' cavity	12/21/80	9:00 am
"	"	10:00 am
"	"	11:00 am
"	"	12:00 pm
45.0' x 40' cavity	6/21/80	5:30 am
"	"	6:00 am
"	"	7:00 am
"	"	12:00 pm
"	12/21/80	12:00 pm
"	Annual Average	

EQUATION SUMMARY

Presented in Figure A-1 is a simplified flow schematic of the steam generator. Table A-1 is a listing of the energy and mass balance equations that were used to make the calculations presented in the remainder of the appendix.

TABLE A-1. ENERGY AND MASS BALANCE EQUATIONS

SYSTEM ENERGY BALANCE

$$Q_{TOTAL} + W_{FW}\, h_{FW} + W_{ATT}\, h_{ATT} = W_S\, h_{S20}$$

SYSTEM MASS BALANCE

$$W_{FW} + W_{ATT} = W_S$$

BOILER ENERGY BALANCE

$$W_{FW}\, h_{FW} + Q_B = W_B\, h_{Sat\ Steam}$$

BOILER MASS BALANCE

$$W_{FW} = W_B$$

SUPERHEATER STAGE 1 ENERGY BALANCE

$$W_B\, h_{Sat\ Steam} + Q_{S1} = W_B\, h_{S1O}$$

SUPERHEATER STAGE 1 MASS BALANCE

$$W_{S1O} = W_B$$

ATTEMPERATOR ENERGY BALANCE

$$W_B\, h_{S1O} + W_{ATT}\, h_{ATT} = W_S\, h_{S2I}$$

ATTEMPERATOR MASS BALANCE

$$W_{S1O} + W_{ATT} = W_S$$

SUPERHEATER STAGE 2 ENERGY BALANCE

$$W_{S2I}\, h_{S2I} + Q_{S2} = W_{S2O}\, h_{S2O}$$

SUPERHEATER STAGE 2 MASS BALANCE

$$W_{S2I} = W_S$$

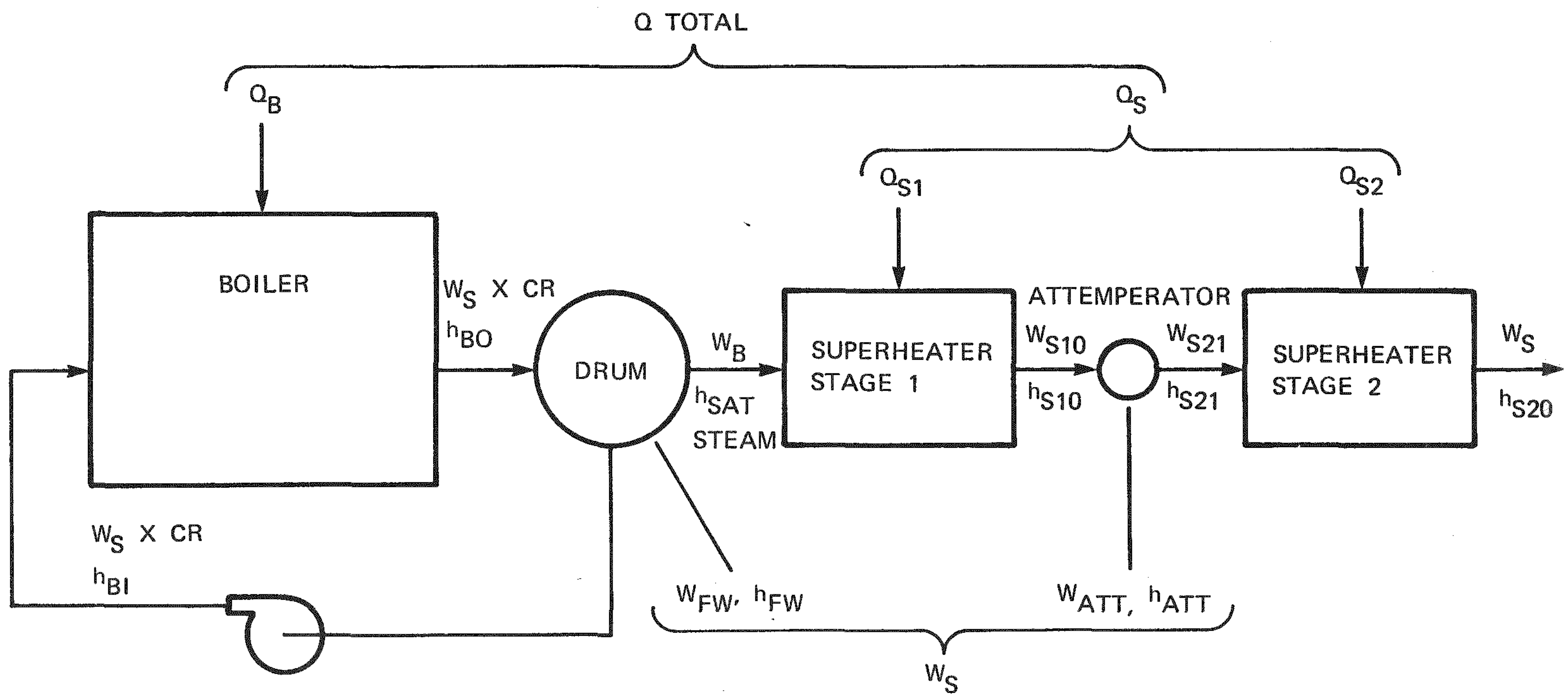

Figure A-1. Solar Boiler Flow Diagram

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CALCULATIONS

a) Summation of Cavity Wall Flux

The establishment of a cavity wall heat input summation versus cavity height curve is essential for the initial sizing of the boiler and superheater areas. The curve was made using the following equation:

$$Q_i = \Delta A \times c \times \sum_{n=1}^{i} \left| \phi_n \left(\frac{\phi_A}{\phi_I}\right)_n \right|$$

where:

Q_i ≡ summation up to and including section i (Btu/hr)

ΔA ≡ incremental cavity wall area (ft^2)

c ≡ units factor ($3.17 \times 10^5 \frac{Btu/hr\text{-}ft^2}{W/M^2}$)

ϕ_n ≡ circumferential average wall flux (MW/M^2)

$\frac{\phi_A}{\phi_I}$ ≡ $\frac{\text{absorbed heat flux}}{\text{incident heat flux}}$, Figure A-2 based on Figure A-3 obtained from RERAD Calculations

A sample summation for a 40.0' x 45.0' diameter cavity on 6/21/80 at 7:00 AM for the absorbed radiation results is presented in Table A-2.

TABLE A-2. ABSORBED HEAT FLUX, 6/21/80; 7:00 AM

Position	From	To	ϕ MW/M^2	Q 10^6 Btu/hr
Top of Cavity ———	0.0	3.0	0.012	2.60
	3.0	6.0	0.014	5.34
	6.0	9.0	0.019	8.68
	9.0	12.0	0.022	12.15
	12.0	15.0	0.028	15.88
	15.0	18.0	0.035	20.56
	18.0	21.0	0.047	26.46
	21.0	24.0	0.062	33.87
	24.0	27.0	0.084	43.60
	27.0	30.0	0.117	56.75
	30.0	33.0	0.129	70.93
	33.0	36.0	0.118	84.04
	36.0	39.0	0.081	92.75
	39.0	42.0	0.040	96.82
Bottom of Cavity ———	42.0	45.0	0.009	97.39

The corresponding Q vs Cavity Height curve was plotted on Figure A-4.

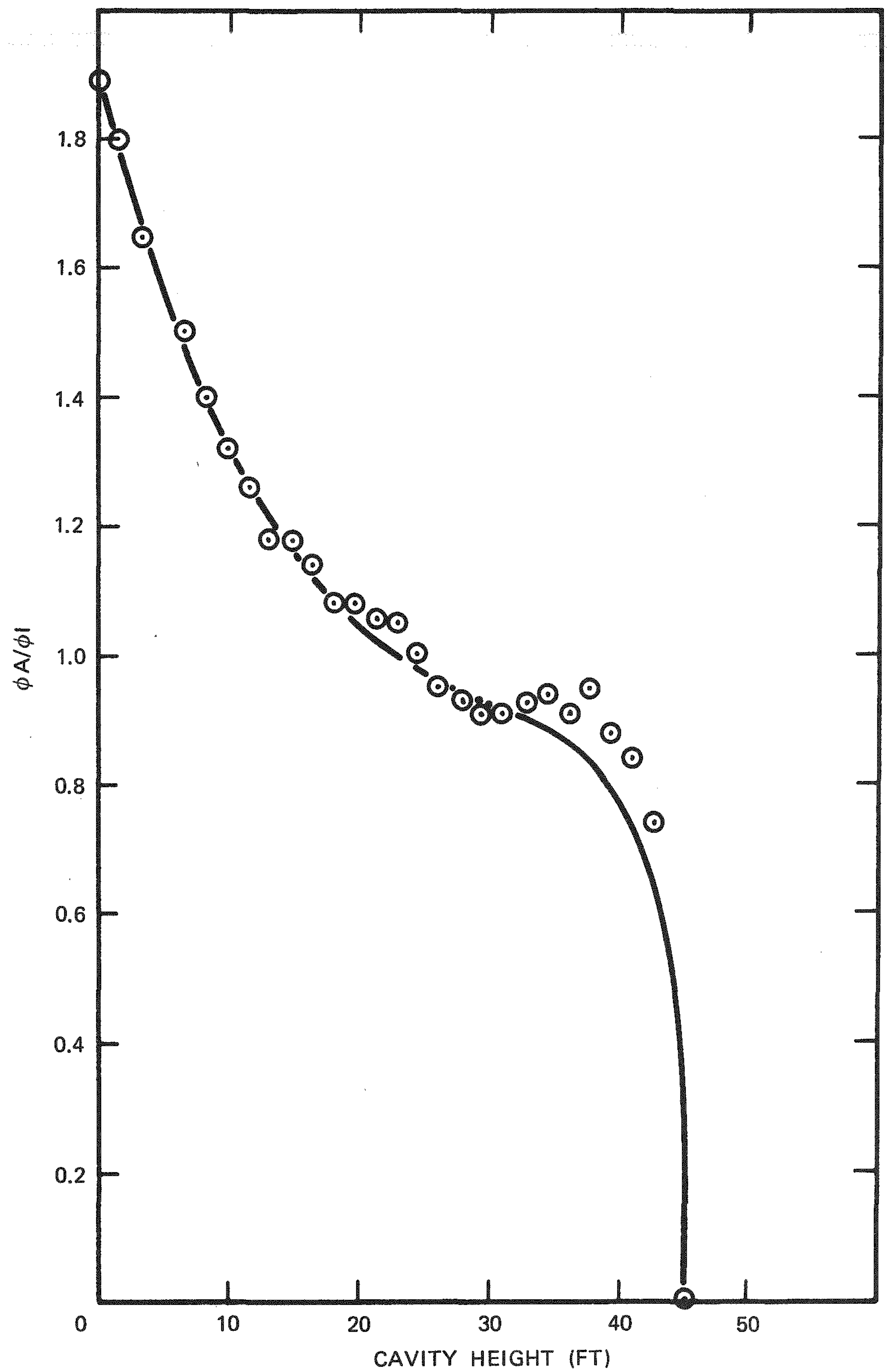

Figure A-2. ϕA/ϕI versus Cavity Height

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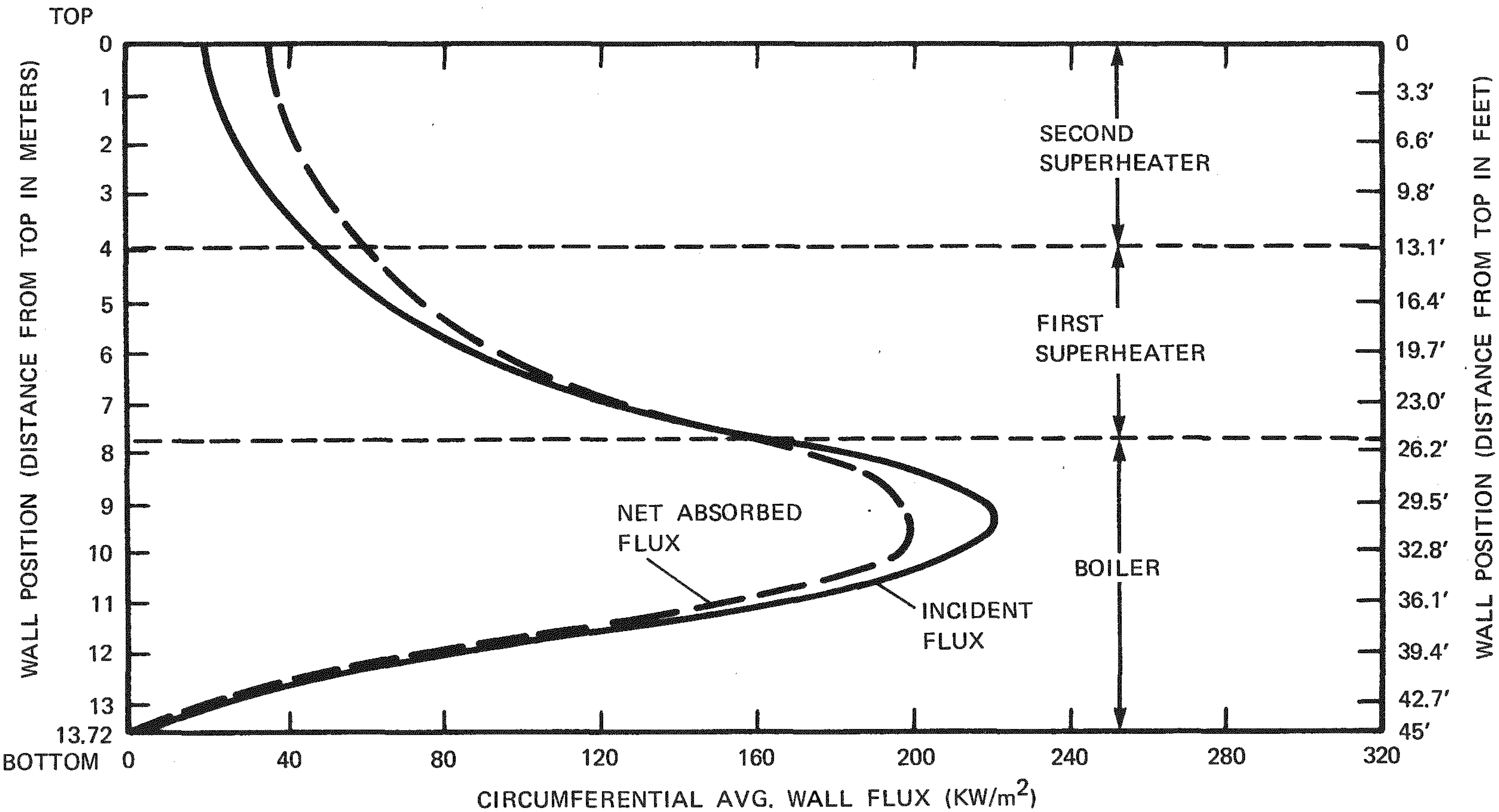

Figure A-3. Circumferential Average Flux for the Bare Ceiling Configuration at 6/21 Noon

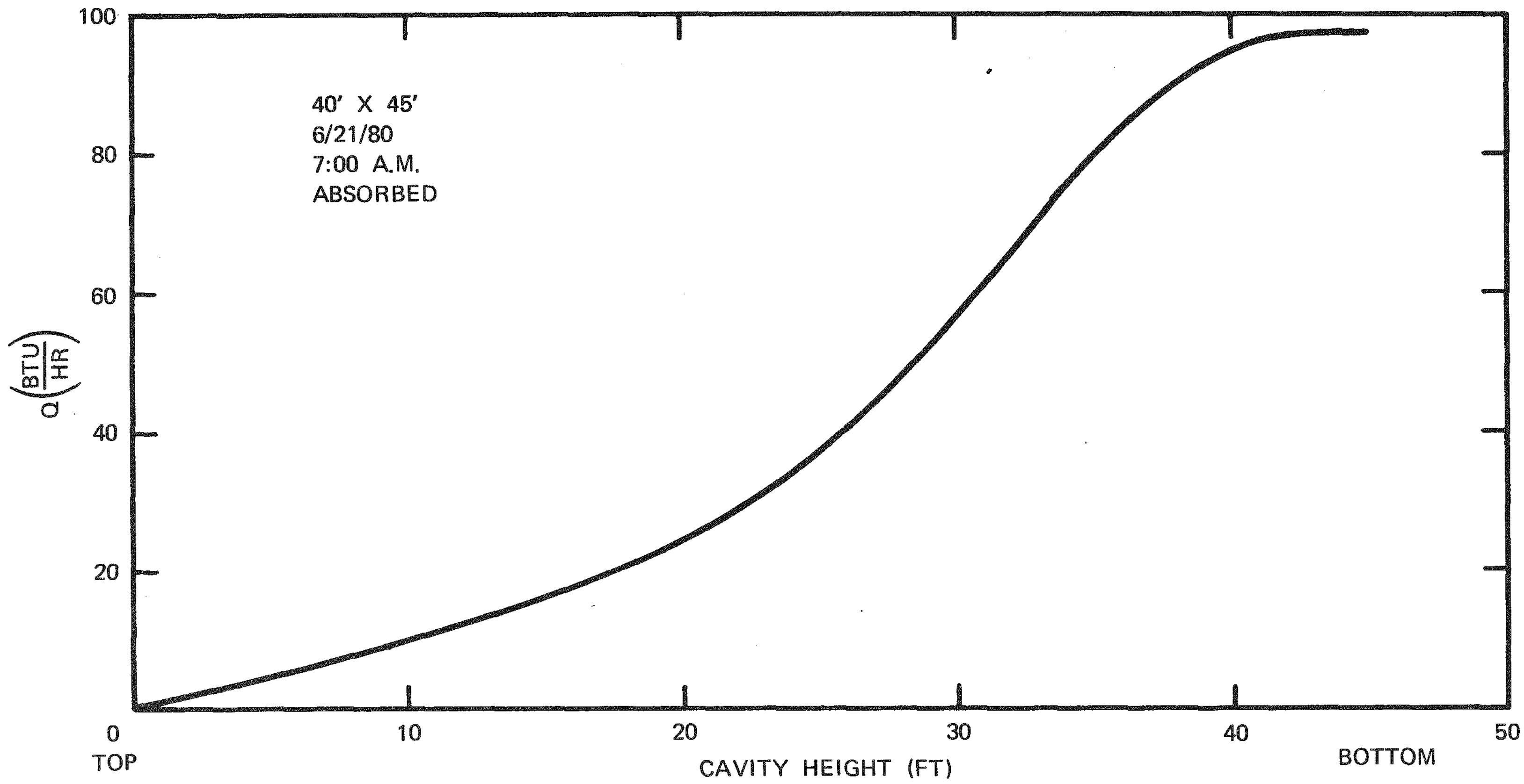

Figure A-4. Q $\left(\frac{BTU}{Hr}\right)$ versus Cavity Height (ft)

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b) <u>Determination of Steam Flow, Boiler Power, Superheater Power, and Boiler Area</u>

The total steam flow for a specific heat flux profile was determined from an energy balance on the boiler and superheater.

$$W_S = \frac{Q_{Total}}{h_{S20} - h_{FW}} \text{, assuming } h_{FW} = h_{ATT} \text{ or } W_{ATT} = 0$$

Q_{Total} ≡ total absorbed power, Btu/hr

h_{S20} ≡ enthalpy at superheater stage number 2 outlet, Btu/lb

h_{FW} ≡ enthalpy of feedwater, Btu/lb

For the 6/21/80, 7:00 AM, sample flux profile, steam flow was computed as:

$$103{,}496 \text{ lb/hr} = \frac{97.39 \times 10^6 \text{ Btu/hr}}{(1453 - 512) \text{ Btu/lb}}$$

Boiler section power corresponding to a specific heat flux profile was computed from an energy balance.

$$Q_B = W_S\,(h_{Sat} - h_{FW})$$

Q_B ≡ boiler section power, Btu/hr

W_S ≡ steam flow rate, lb/hr

h_{Sat} ≡ enthalpy of saturated steam at the steam drum pressure

h_{FW} ≡ feedwater enthalpy

For the 6/21/80, 7:00 AM sample flux profile, the boiler power was computed as:

$$Q_B = 103{,}496 \text{ lb/hr } (1157 - 512) \text{ Btu/lb}$$

$$Q_B = 66.76 \times 10^6 \text{ Btu/hr}$$

Superheater power was computed from:

$$Q_S = Q_{Total} - Q_B$$

Q_S ≡ superheater power, Btu/hr

Q_{Total} ≡ total power absorbed in the cavity, Btu/hr

Q_B ≡ boiler power, Btu/hr

For the 6/21/80 , 7:00 AM sample, superheater power was computed as:

$$Q_S = (97.39 - 66.76) \times 10^6 \text{ Btu/hr}$$

$$Q_S = 30.63 \times 10^6 \text{ Btu/hr}$$

The boiler section area for each specific heat flux profile was determined from a figure similar to Figure A-4. The boiler section area was determined by entering the required superheater power, Q_S, on the ordinate and determining the corresponding superheater length. The superheater length is then subtracted from the total cavity height of 45.0' to determine the boiler length.

For the 6/21/80, 7:00 AM sample, entering a value of 30.63 x 10^6 Btu/hr on Figure A.4 results in a superheater length of 22.7', subtracting this length, 22.7', from 45' results in a boiler height of 22.3'.

Boiler lengths vs solar times are plotted on Figure A-5 for the heat flux profiles listed in the introductory section.

c) Selection of a Boiler Area (Length)

Using the methodology presented in sections a) and b), boiler lengths were determined for the flux profiles listed in the introductory paragraph of this appendix. The boiler length was selected slightly less than the minimum calculated for a specific cavity size so that spray attemperation could be used to control steam temperatures.

For the 6/21/80, 7:00 AM example and all other 45.0' x 40.0' diameter cavity size boiler lengths plotted on Figure A. 5 a boiler length of 20.0' was selected.

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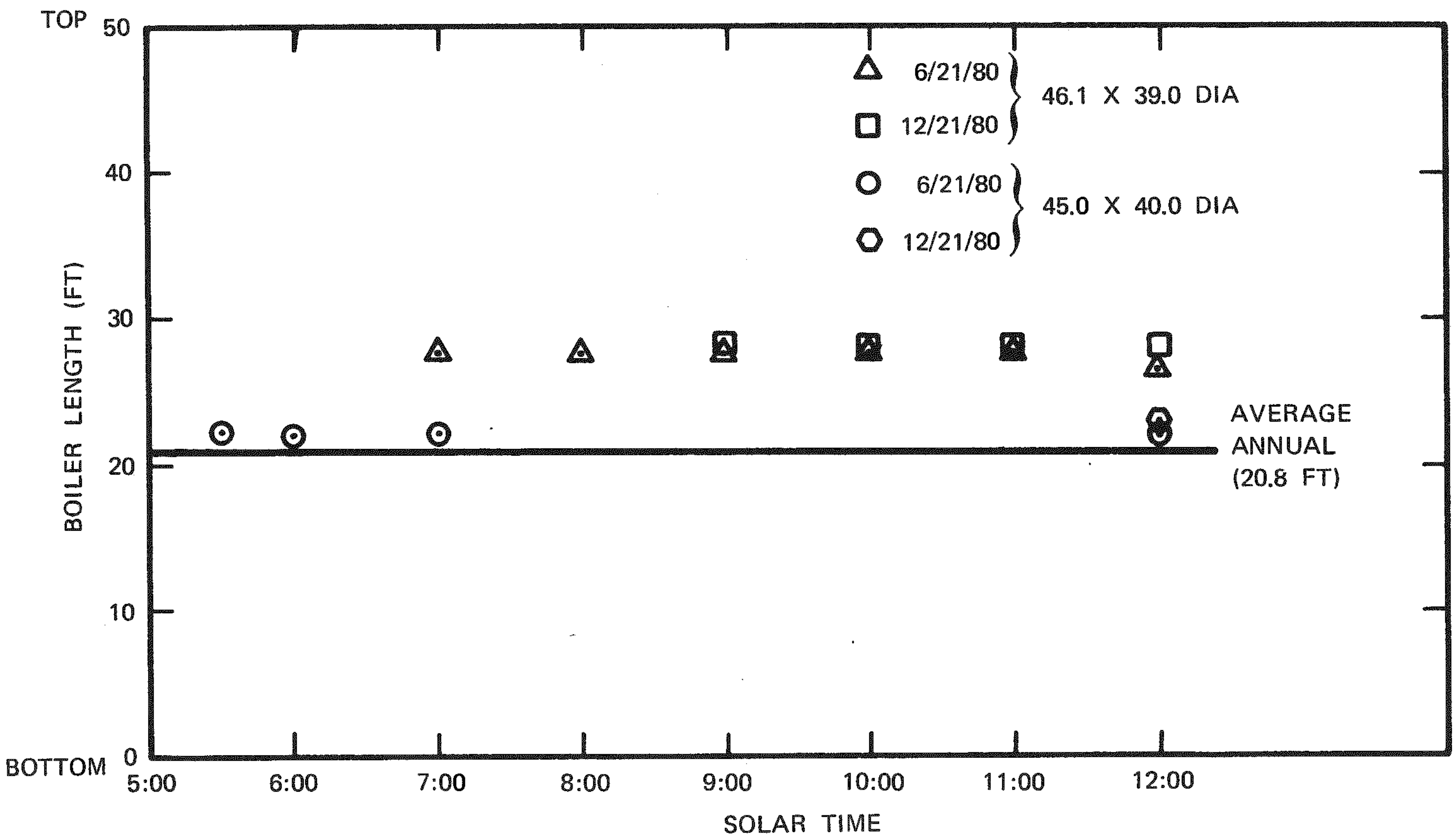


Figure A-5. Boiler Length versus Solar Time

d) Attemperator Flow Rate & Maximum Superheater Interstage Temperature

After the boiler area (length) was selected, the attemperator flow rate was computed from a mass balance

$$W_{ATT} = W_S - W_B$$

and the energy balances (assuming $h_{ATT} = h_{FW}$)

$$W_B = \frac{Q_B}{h_{Sat} - h_{FW}} \qquad W_S = \frac{Q_B + Q_S}{h_{S20} - h_{FW}}$$

which were combined and reduced to:

$$W_{ATT} = \frac{Q_B\,(h_{S20} - h_{Sat})}{(h_{S20} - h_{FW})\,(h_{FW} - h_{Sat})} - \frac{Q_S}{(h_{FW} - h_{S20})}$$

Where:

W_{ATT} ≡ attemperator flow rate, lb/hr

W_S ≡ total steam flow rate, lb/hr

W_B ≡ boiler section steam generation rate, lb/hr

Q_B ≡ boiler section power (recalculated based on the fixed boiler length), Btu/hr

Q_S ≡ superheater section power, Btu/hr

h_{Sat} ≡ enthalpy of saturated steam at the steam drum, Btu/lb

h_{FW} ≡ enthalpy of feedwater, Btu/lb

h_{S20} ≡ enthalpy of superheater outlet steam, Btu/lb

For the 6/21/80, 7:00 AM sample calculation, a 20' boiler length was selected and the attemperator flow rate computed (assuming $h_{ATT} = h_{FW}$) as:

$$W_{ATT} = \frac{60.9 \times 10^6\ (1453 - 1157)}{(1453 - 512)(512 - 1157)} - \frac{36.5 \times 10^6}{(512 - 1453)}$$

$$W_{ATT} = 9088 \text{ lb/hr}$$

Maximum superheater interstage temperature was found from a mass and energy balance.

$$h_{S10} = h_{Sat} + \frac{Q_{S1}}{W_B}$$

where:

h_{S10} ≡ enthalpy at superheater stage 1 outlet, Btu/lb

h_{Sat} ≡ enthalpy of saturated liquid at the steam drum pressure, Btu/lb

Q_{S1} ≡ superheater stage 1 power input, Btu/hr

W_B ≡ steam generated in the boiler section, lb/hr

Superheater stage 1 and superheater stage 2 areas are assumed to be equal for this analysis. The pressure used with h_{S1} to calculate superheater stage 1 was computed from

$$P_{S10} = 1500 + 14.7 + 1/2\ (200)\ \left(\frac{W_S}{176{,}700}\right)^2$$

where:

P_{S10} ≡ pressure at superheat stage 1 outlet, psia

W_S ≡ total steam flow per section b), lb/hr

For the 6/21/80, 7:00 AM example:

$$h_{S10} = 1157 + \frac{36.5 - 12.8}{94419} \times 10^6$$

$$h_{S10} = 1408 \text{ Btu/lb}$$

$$P_{S10} = 1514.7 + 1/2\ (200)\ \left(\frac{103{,}496}{176{,}700}\right)^2$$

$$P_{S10} = 1549 \text{ psia}$$

The superheater stage 1 outlet temperature is:

$$T_{S10} = 880 \text{ F}$$

Attemperator flows and superheater stage 1 exit temperatures as determined by these methods are presented for the heat flux profiles listed in the introduction section on Figures A-6 and A-7.

The heliostat field and tower height are different for the two cavity sizes presented. This change results in different flux distribution within the cavity. More heat flux is concentrated near the bottom of the 45.0' x 40.0' cavity, resulting in a shorter boiler section.

For the times investigated, spray flow required to control steam temperature varied between 4000 and 18,000 lb/hr for the 45.0' x 40.0' cavity, with an annual average value of 12,000 lb/hr.

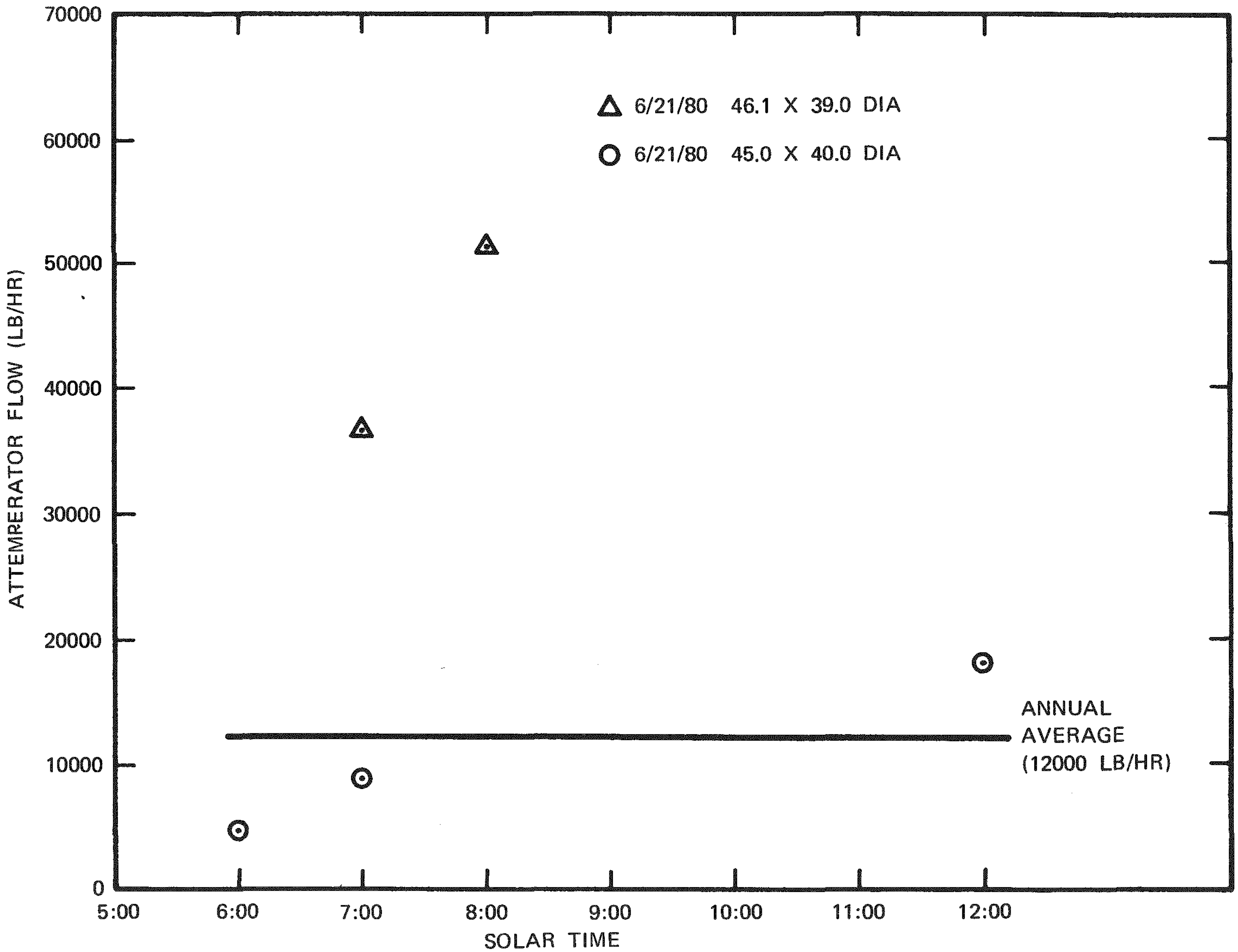


Figure A-6. Attemperator Flow versus Solar Time

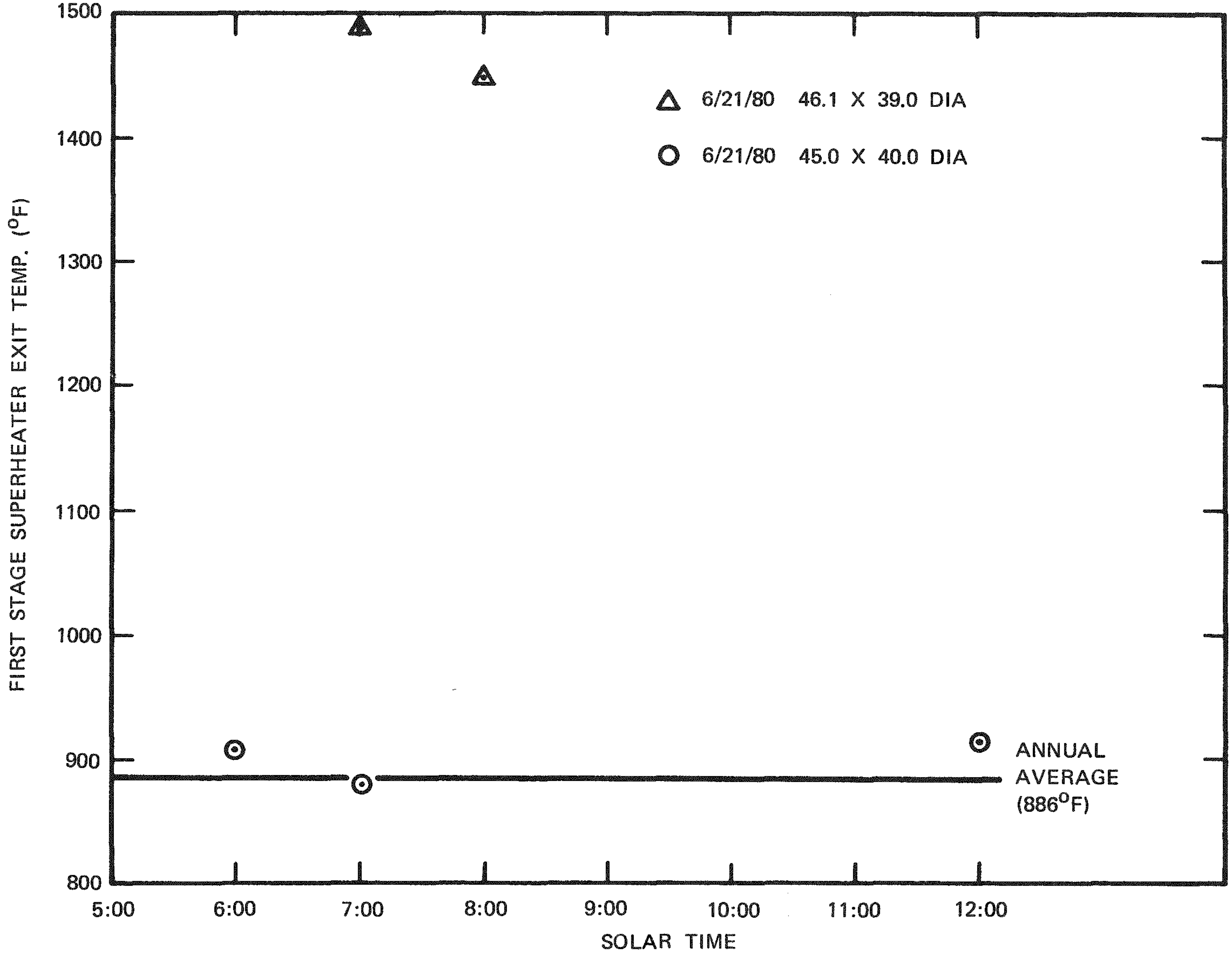


Figure A-7. First Stage Superheater Exit Temp. versus Solar Time

APPENDIX B

STEAM GENERATOR FLOW REQUIREMENTS

APPENDIX B

STEAM GENERATOR FLOW REQUIREMENTS

1. The single most important factor in the protection of the steam generator heat transfer surfaces is maintaining adequate flow or circulation of fluid through the tubes at all operating conditions.

2. In the boiler section, circulation must be maintained to avoid DNB and the resulting rapid deterioration of the tube. Boiler tube circulation is dependent on the heat flux because of the density variation of the steam-water mixture in the riser circuits.

   i. The average flow in one of the nine boiler circuits will depend on the average axial heat flux profile for that circuit compared to the circumferential average axial heat flux profile in the entire boiler section. The boiler circuit orifice valves can be used to adjust circulation distribution.

   ii. Flow to a tube within one of the nine boiler circuits depends on the axial heat flux profile to the tube compared to the average axial heat flux profile. Flow control by orificing each tube is not planned.

   iii. The ratio of the header cross-sectional area to the riser tube cross-sectional area must be selected to reduce flow maldistribution.

   iv. The tolerances on tube diameter, length and surface roughness affect flow distribution and must be considered in the design.

3. In the superheater section, the steam temperature increase in each superheater tube must be closely balanced to avoid exceeding the design temperature limit of the superheater tube material. Local heat flux must be known so that local tube temperatures can be predicted.

i. The local steam temperature depends on flow distribution and the axial heat flux profile.

ii. The metal temperature depends on the local steam temperature and the local heat flux.

iii. Average steam temperature is controlled to maintain steam line and turbine metal temperatures within safe limits. Individual tube temperatures are not controlled and the superheater must be designed to minimize flow maldistribution and tube-to-tube heat input variations.

iv. Flow maldistribution is controlled by the proper selection of the ratio of the header cross-sectional area to the riser tube cross-sectional area. Superheater tube pressure drop should be as large as practical. Tolerances on tube diameter, length and surface roughness affect flow distribution and must be controlled.

v. The interstage attemperators perform two functions.

   a. Control of final steam temperature

   b. Averaging of steam flow and temperature at the exit of the first-stage superheater so that flow and temperature are uniform entering the second-stage superheater. Three attemperator circuits are used to minimize flow maldistribution while maintaining reasonable header sizes.

SOLAR STEAM GENERATOR CIRCULATION MODEL

Figure B-1 is a flow diagram of the solar steam generator. During detailed design, this flow circuit will be mathematically modeled to verify that circulation is adequate at all times. A model of this complexity is necessary because of the ever-changing heat flux patterns in the solar steam generator.

The boiler section is represented by four parallel circuits, an average heat input circuit with 2/3 of the tubes, a low heat input circuit, a high heat input circuit, and a fourth circuit where the tube-to-tube behavior can be determined. This latter circuit is represented by a group of tubes with average heat input, a low heat input tube, a high heat input tube and a fourth tube for which the detailed local fluid and metal temperatures can be calculated.

The first and second-stage superheaters are represented by three parallel circuits. Two of the circuits will each represent a group of 1/3 of the tubes with each tube receiving the average heat input for that group. The third circuit will consist of a group of tubes at the average heat input for that group, a low heat input tube, a high heat input tube, and a fourth tube for which the detailed local and fluid metal temperatures can be calculated.

This model will allow a realistic determination of safety factors at any heat flux condition encountered by the solar steam generator.

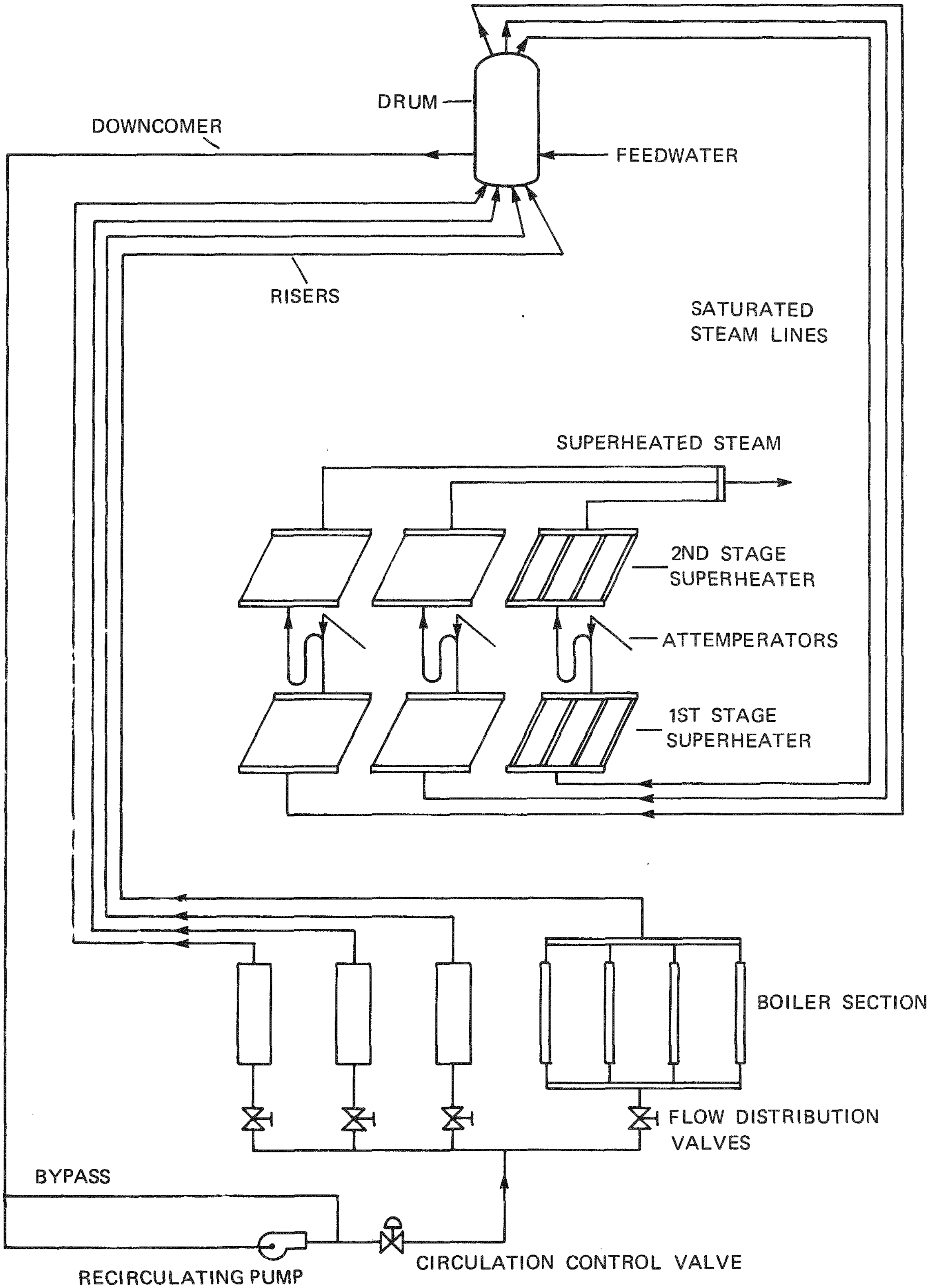


Figure B-1. Thermal and Hydraulic Model of the Solar Steam Generator

APPENDIX C

CRITERIA FOR LIMITING STRESSES IN THE BOILER AND SUPERHEATER SECTIONS

APPENDIX C

CRITERIA FOR LIMITING STRESSES IN THE BOILER AND SUPERHEATER SECTIONS

As a result of the frequent cycling of thermal stresses, the criteria of Section III will be used to assure structural integrity. In the boiler section it is expected that the temperatures will be limited such that the application of the criteria will be straightforward. However, the temperatures in the superheater will be well into the creep regime necessitating the incorporation of the principles of Code Case 1592 to assess the potential of creep-fatigue failure.

In the boiler section it is anticipated that the metal temperatures will not exceed the 700 F limit of Section III. However, it is not our intent to regard this as a rigid limitation on the applicability of Section III. In the event that metal temperatures exceed 700 F, the specific situation would be evaluated to determine if, in fact, creep is a significant design consideration. Assuming, at this point, that creep is not a significant factor the general primary membrane stress will be limited to S_m (the lesser of 2/3 the yield stress or 1/3 the tensile strength) and the primary membrane plus bending stress will be limited to 1.5 S_m. These limitations are imposed to prevent the ductile rupture and collapse failure modes and to preclude gross distortions which can all result from applied non-self-equilibrating loads (e.g., internal pressure). The range of primary plus secondary stresses ("secondary" implying self-equilibrating or deformation controlled, e.g., thermal stresses) will be limited to 3 S_m. The intent of this limit is to insure that cyclic stresses will "shake down" to elastic action such that elastically-calculated stresses remain a credible estimate of the actual structural behavior. Cyclic peak stresses (including the effects of stress concentrations and certain components of thermal stress) will be limited per the Section III fatigue curves to insure against the fatigue failure mode. Figure C-1 is a flow chart of the anticipated requirements for the boiler section.

In the superheater the design philosophy (Code Case 1592) is much the same, although additional failure modes must be considered. The allowable stresses for the general primary membrane stress and the primary membrane plus bending stress now become time-dependent because of the creep-rupture failure mode which becomes dominant at the higher temperatures. There is no explicit limitation on secondary stresses which corresponds to the 3 S_m limit at lower temperatures. Instead, the limitation is implicit in Appendix T of Code Case 1592. That appendix provides limitations on accumulated inelastic strain and addresses the creep-fatigue failure mode. Appendix T provides criteria for limiting either elastically-calculated or inelastically-calculated stresses. At elevated temperatures, in the presence of creep, the elastic calculation of any stress, other than a purely statically determinant stress,is inaccurate. As a result, the criteria for elastic calculations are frequently overly conservative. Full inelastic calculations are, however, in contrast,quite expensive. Provided that the cyclic part of the primary plus secondary stress can be limited to the yield stress and that one extreme of the cycle is at a temperature below the creep regime (as it is in this case), the adequacy of elastic calculations is assured. That is, under these conditions, the cyclic response is accurately predicted by elastic calculations regardless of the degree of relaxation of secondary stresses. Further, if one precludes a particularly detrimental state of multi-axiality (with ensuing extreme loss of ductility), the creep damage due to the secondary stress becomes negligible. More specifically, under these assumptions, any part of the secondary stress which relaxes will not reappear upon further cycling, thus this part of the creep strain is,for practical purposes, bounded by the elastically-calculated strain. In this manner the creep damage is limited regardless of the rate at which the secondary stress relaxes. If it

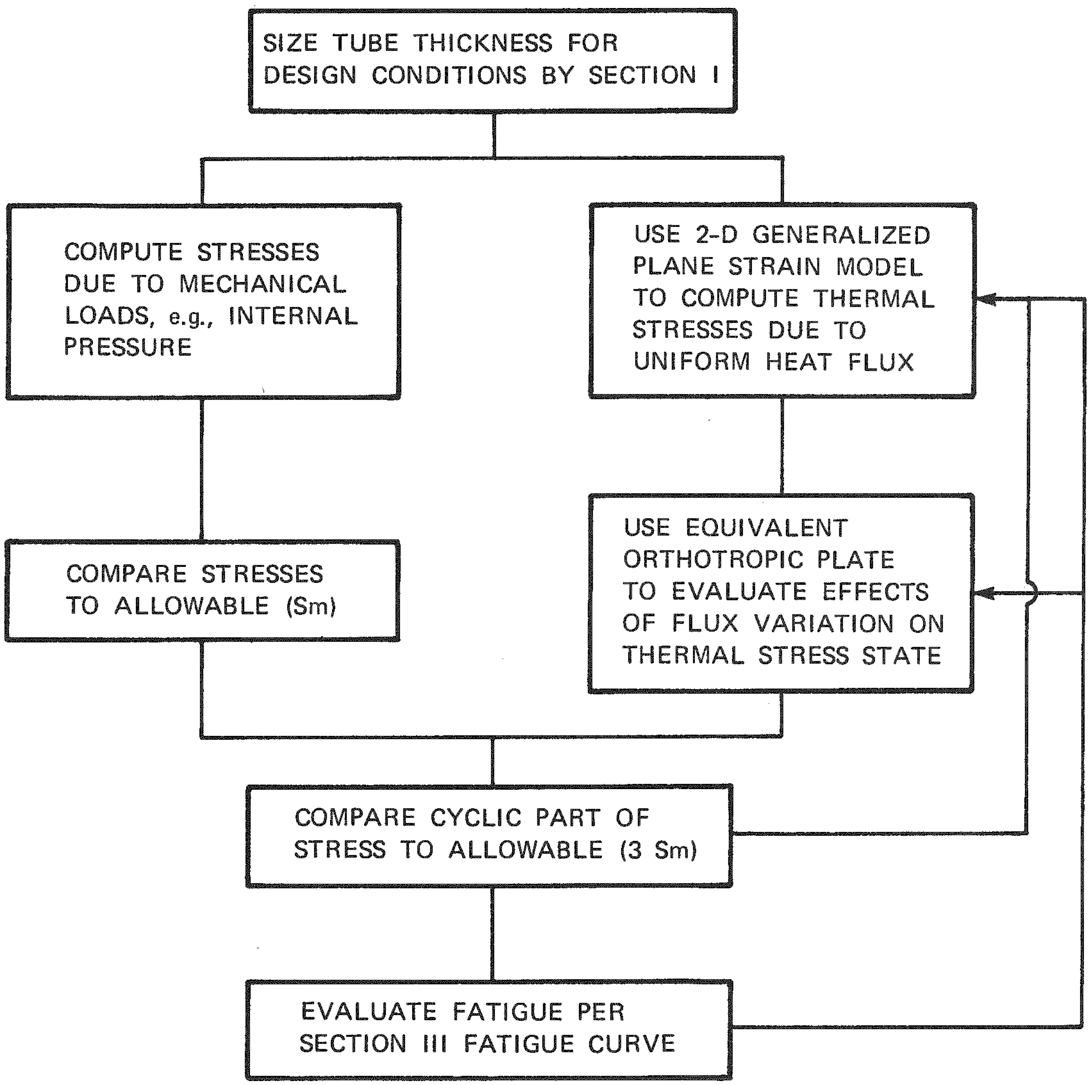


Figure C-1. Boiler Section Stress Analysis becomes necessary, it is thought that similar logic and perhaps simplified inelastic analysis could relax the yield stress limitation if the condition is encountered only infrequently and is not too severe. Even with the creep damage, due to secondary stresses, bounded,it is still necessary to limit the creep damage due to primary loading when considering creep-fatigue damage. This is done straightforwardly using the minimum stress-to-rupture data provided in Code Case 1592. With the above approach it would be permissible to use the fatigue data for continuously cycling conditions as opposed to using the hold-time fatigue data. Figure C-2 is a flow chart of the design requirements for the superheater.

In summary, in the boiler section, the rules of Section III will be used which, simply stated, require the pressure stress to be limited to 2/3 of the yield stress and the cyclic component of pressure plus thermal stress be limited to twice the yield stress. In the superheater the pressure stresses will be limited by creep-rupture and the cyclic component of pressure plus thermal stress will be limited to the yield stress. In both regions the fatigue damage will be appropriately considered.

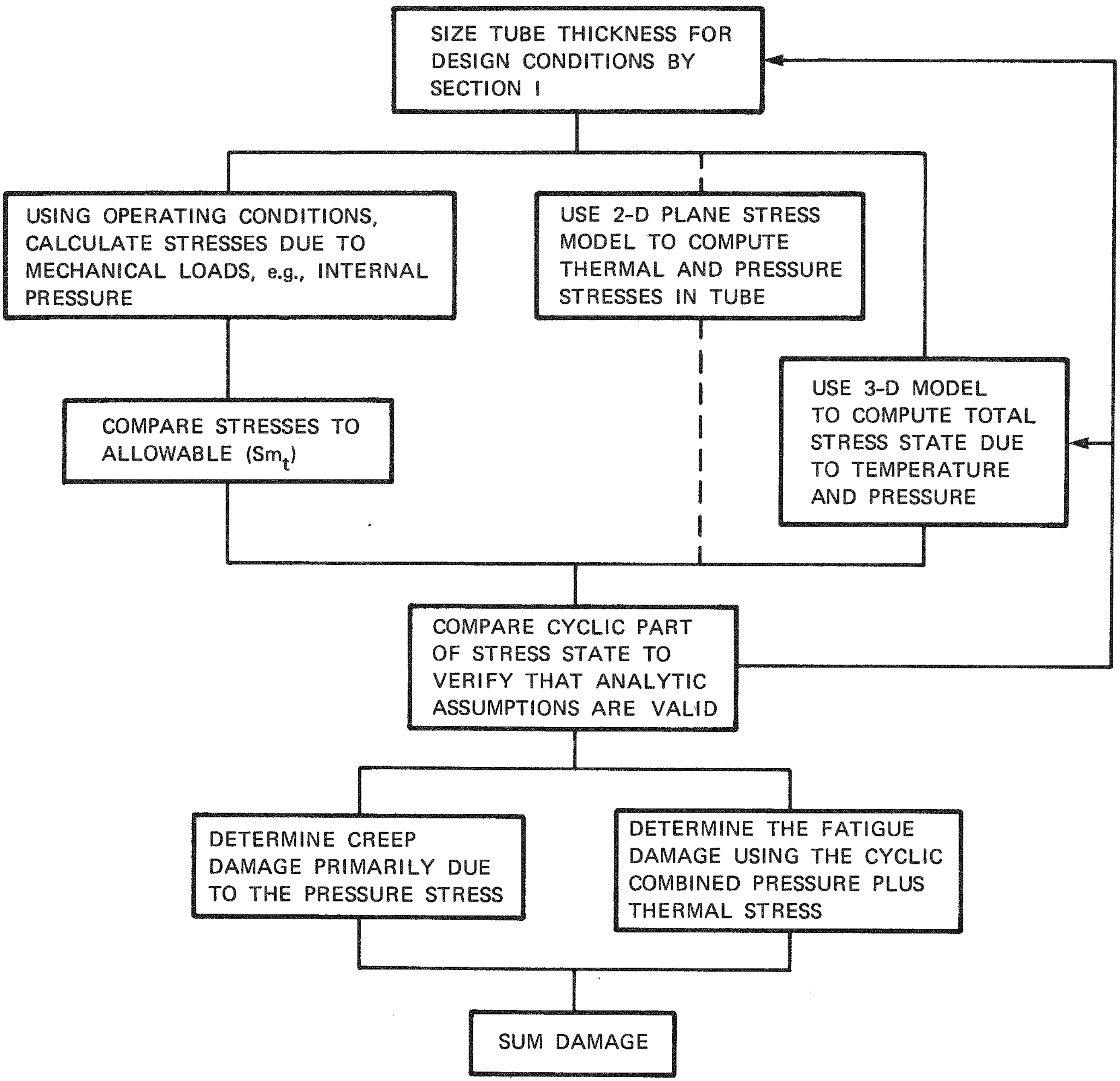


Figure C-2. Superheater Stress Analysis

APPENDIX D

BOILER AND SUPERHEATER
STRESS ANALYSIS

APPENDIX D

BOILER AND SUPERHEATER STRESS ANALYSIS

The solar steam generator is basically a cyclic operation and can experience significant secondary stresses due to asymmetrical heating of the tubes in the boiler and superheater cavity. Therefore, the structural analysis must extend beyond merely sizing the tube members for internal pressure and must include the effects of thermal gradients and fatigue due to thermal cycling. Figure C-1 in Appendix C illustrates a flow chart of the proposed method of analysis to evaluate the integrity of the boiler section membrane wall (tube-web configuration). As has been previously stated, the first step in the analysis consists of sizing the minimum tube wall thickness to accommodate the allowable working pressure in the boiler. Figure D-1 is a plot of allowable stress values for Croloy 1/2 as a function of the flat projected heat flux on the boiler section. The constant value of maximum hoop stress in the tubing due to an operating pressure of 1800 psia is also illustrated on Figure D-1 for comparison to the appropriate allowable stress. The stresses due to internal fluid pressure were computed by using Lame's equations for cylinders subjected to an internal pressure.

The second step in the analysis is to determine the thermal stresses due to a uniform flat projected heat flux on the boiler section. The steady-state thermal distribution in the tube resulting from the uniform heat flux is found by a finite difference approximation using a half-tube, half-web configuration as shown in Figure D-2. The configuration is subjected to a constant heat flux on the heated side, the other side being unheated and ambient. The steam film conductance on the inside of the half-tube is specified as are the conductivities of the tube and web materials. Figure D-3 illustrates a typical temperature distribution in the tube-web configuration when subjected to a uniform flat projected heat flux of 127,000 Btu/hr-ft^2. As can be seen from the figure, the

Flux Distribution* (QFP = 63,500 Btu/hr-sq ft)	Maximum Metal Temperature (°F)	Overall Maximum Principal Stress (psi)	Overall Minimum Principal Stress (psi)
Uniform	727	9100	-2100
Full Cosine	767	9200	-2000
Half Cosine	834	9500	-2500

*Tube characteristics and operating conditions

Tube OD	1.0 in.
Tube ID	0.78 in. (minimum wall)
Tube Material	Croloy 2-1/4
Film Coefficient	700 Btu/hr-sq ft-deg F
Fluid Temperature	622 F
Internal Pressure	1800 psia

TABLE D-1. TEMPERATURE AND PRINCIPAL STRESSES IN A PILOT PLANT SUPERHEATER TUBE AS A FUNCTION OF TYPE OF FLUX DISTRIBUTION

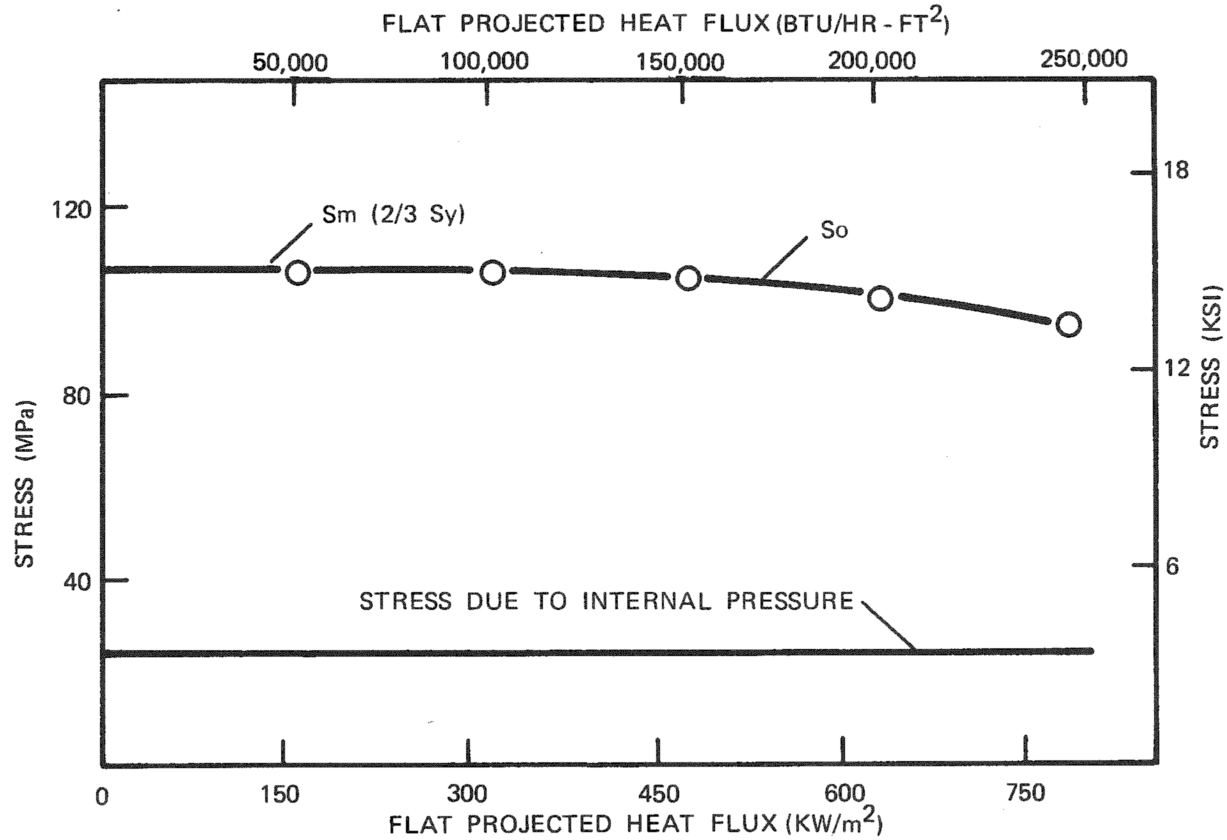


Figure D-1. Comparison of Stress Due to Pressure in the Boiler Section to the Allowable Stress

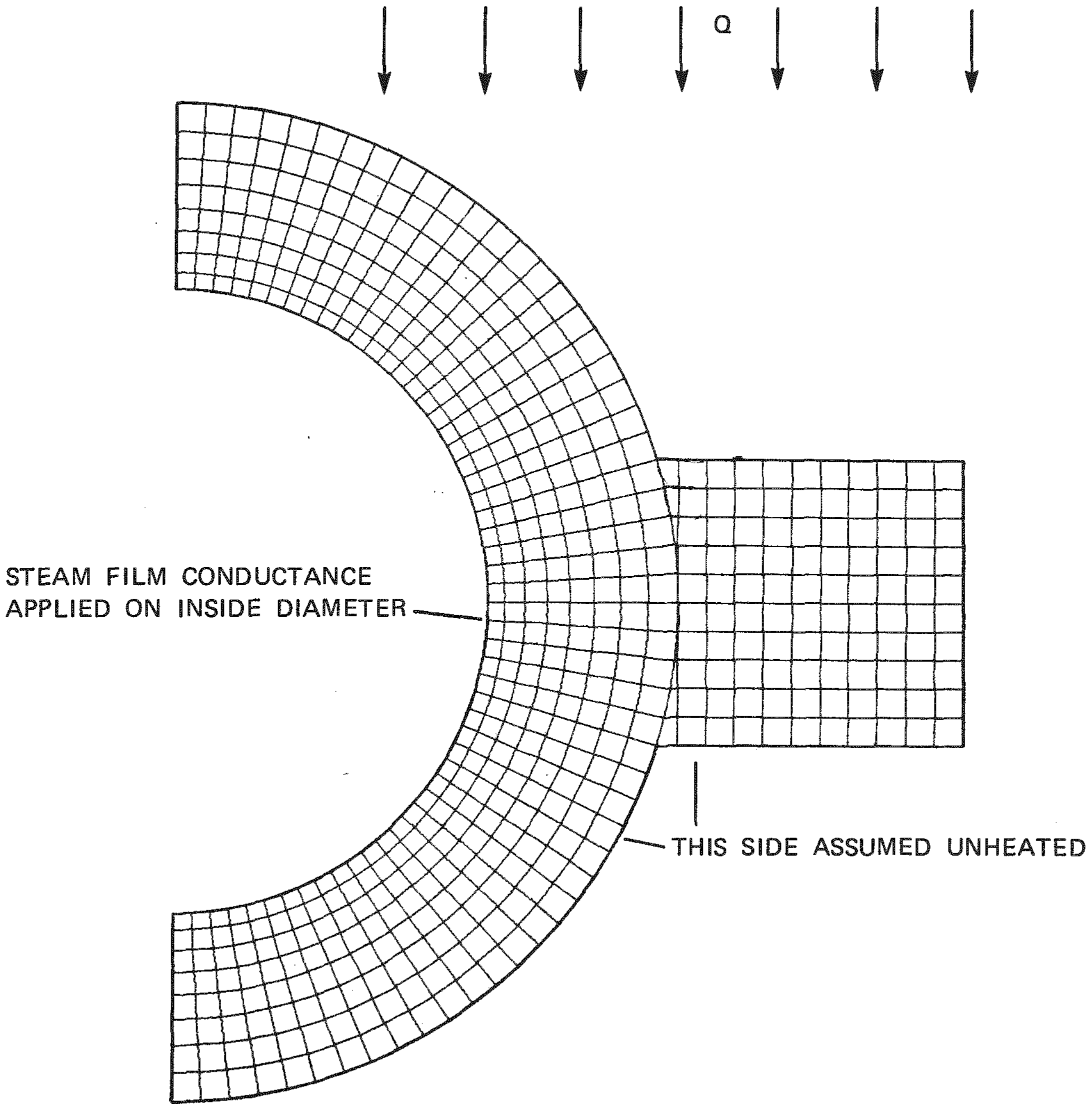
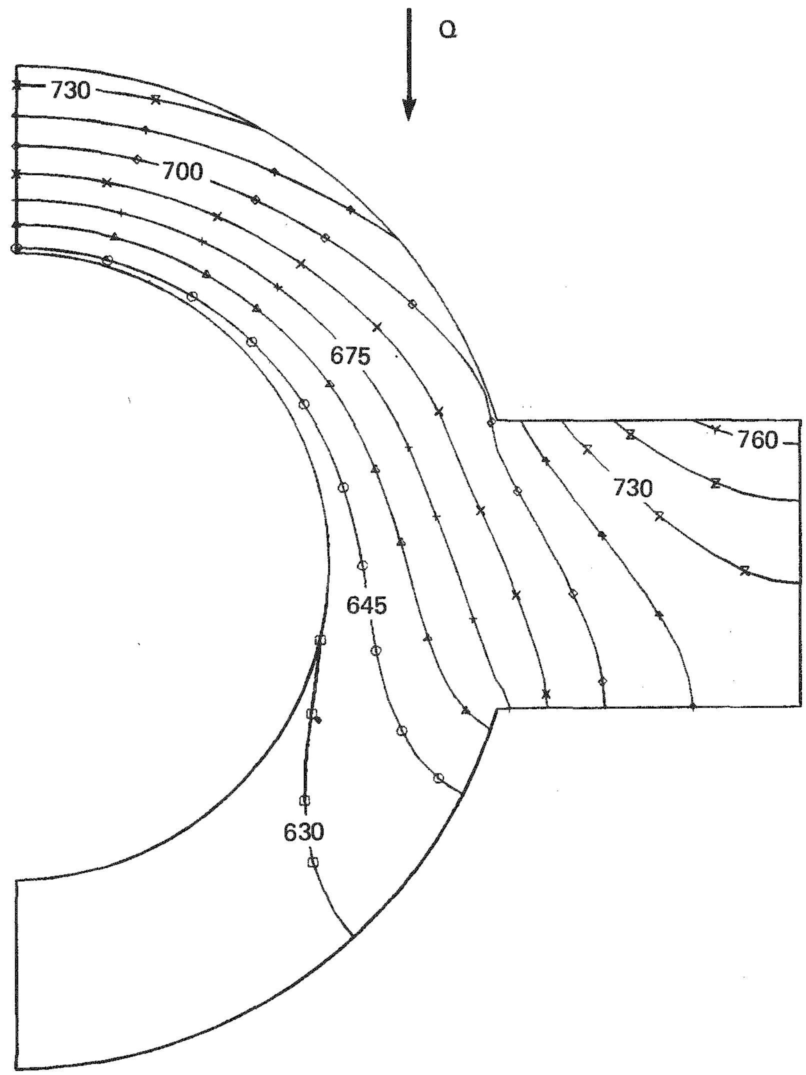


Figure D-2. Finite Difference Mesh used for Generalized Plane Strain Analysis of Boiler Section

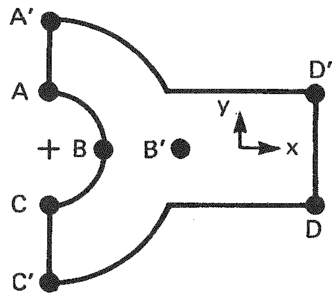


TUBE OD	0.875 IN.
TUBE ID	0.579 IN. (MINIMUM WALL)
TUBE CENTER-TO-CENTER SPACING	1.375 IN.
WEB THICKNESS	0.25 IN.
TUBE MATERIAL	CROLOY 1/2
WEB MATERIAL	CARBON STEEL (AISI C1015)
FILM COEFFICIENT	10,000 BTU/HR-SQ FT-DEG F
FLUID TEMPERATURE	622°F

Figure D-3. Temperature Distribution in Boiler Section Membrane Wall Due to a Flat Projected Heat Flux of 127,000 BTU/Hr-Ft^2

maximum temperature occurs in the web, while the rear quadrant of the boiler tube is at approximately the fluid temperature. To compute the thermal stresses due to the temperature distribution, the tube-web geometry is treated as a repetitive section. The tube and web are disjoined and each is considered independently of each other. Each is required to meet a generalized plane strain condition of ε_z = constant and $\int_{(A)} \sigma_z \, da = 0$, where A is the cross-sectional area and ε_z and σ_z are the longitudinal strain and stress, respectively. After the thermal stresses have been calculated in the separate geometries, the web is rejoined to the tube, making certain that continuity at the junction is satisfied. The stress analysis accounts for any arbitrary temperature distribution, thus the temperature distribution can vary along the radius of the tube as well as around its circumference with no requirements on symmetry. A comprehensive picture of the existing state of thermal stress in the membrane geometry is determined on a point-by-point basis because all components of the stress are determined; namely, tangential, radial, longitudinal and shear stress. The thermal stresses can then be superimposed on the stresses due to internal fluid pressure to obtain the total stress state in the generalized plane strain model.

Figure D-4 illustrates typical stress states at selected locations in the tube-web configuration due to the combination of the thermal and pressure stresses resulting from the boiler section being subjected to an internal pressure of 1800 psia and a flat projected heat flux of 127,000 Btu/hr-sq ft. The maximum stress in the configuration occurs in the web at point D' on Figure D-4. This longitudinal stress is due primarily to the restriction that the web and tube must have compatible longitudinal displacements due to the plane strain assumption. The maximum stress in the tube occurs at point A' and is a longitudinal (axial) stress which is mainly due to the asymmetrical temperature distribution.



TUBE OD	0.875 IN.
TUBE ID	0.579 IN. (MINIMUM WALL)
TUBE CENTER-TO-CENTER SPACING	1.375 IN.
WEB THICKNESS	0.25 IN.
TUBE MATERIAL	CROLOY 1/2
WEB MATERIAL	CARBON STEEL
FILM COEFFICIENT	10,000 BTU/HR-SQ FT-DEG F
FLUID TEMPERATURE	622°F
INTERNAL PRESSURE	1800 PSIA
HEAT FLUX (FLAT PROJECTED)	127,000 BTU/HR-SQ FT

LOCATION	TEMP (°F)	PRESSURE PLUS THERMAL STRESSES IN TUBE (PSI)		
		RADIAL	CIRCUMFERENTIAL	LONGITUDINAL
A	640	-1800	14804	10006
B	632	-1800	12139	10933
C	622	-1800	9415	12267
A'	741	0	-5837	-15621
B'	672	0	-3590	- 4994
C'	623	0	-1342	9516

LOCATION	TEMP (°F)	THERMAL STRESSES IN WEB (PSI)	
		σ_x	LONGITUDINAL
D	124	7975	-6993
D'	761	-7915	-19824

Figure D-4. Thermal Plus Pressure Stresses in Generalized Plane Strain Model of Boiler Section Due to a Heat Flux of 127, 000 Btu/hr-Sq. Ft.

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Figure D-5 contains two curves. The first curve is a plot of allowable stress for the Croloy 1/2 boiler tubes as a function of flat projected heat flux. The second curve on Figure D.5 is a plot of maximum calculated stress intensity due to temperature and pressure in the boiler tubes as a function of flat projected heat flux calculated using a generalized plane strain model subjected to a uniform heat flux. After satisfaction of the allowable stresses shown on Figures D-4 and D-5, one can proceed to make a fatigue evaluation.

To evaluate the effect of heat flux differences on adjacent locations on a boiler section panel at any instant of time, a boiler section panel will be modeled using equivalent orthotropic finite element plate elements (see Figure D-6). The plate elements will not be used to compute the thermal stresses or deflections due to the asymmetrical heating of the boiler section but will be used to evaluate the influence of different heat fluxes occurring on adjacent locations of a boiler section panel. The finite element model can also be used to determine the interaction of two or more of the nine boiler section panels due to flux variations between panels. The stresses computed from this analysis can be combined with the pressure stresses and stresses obtained in the plane strain analysis to yield the total stress state.

Figure C-2 in Appendix C illustrates a flow chart of the proposed stress analysis for the SRE and Pilot Plant superheater tubing. The superheater tubing has a support concept entirely different from the boiler section tubing. Each superheater tube spirals through 360 degrees as it passes from one header to the other. This helical shape was selected to accommodate radial expansion without inducing axial and bending stresses. The superheater tubes experience higher metal temperatures than do the boiler tubes, thus failure due to creep-fatigue must be given a greater degree of consideration.

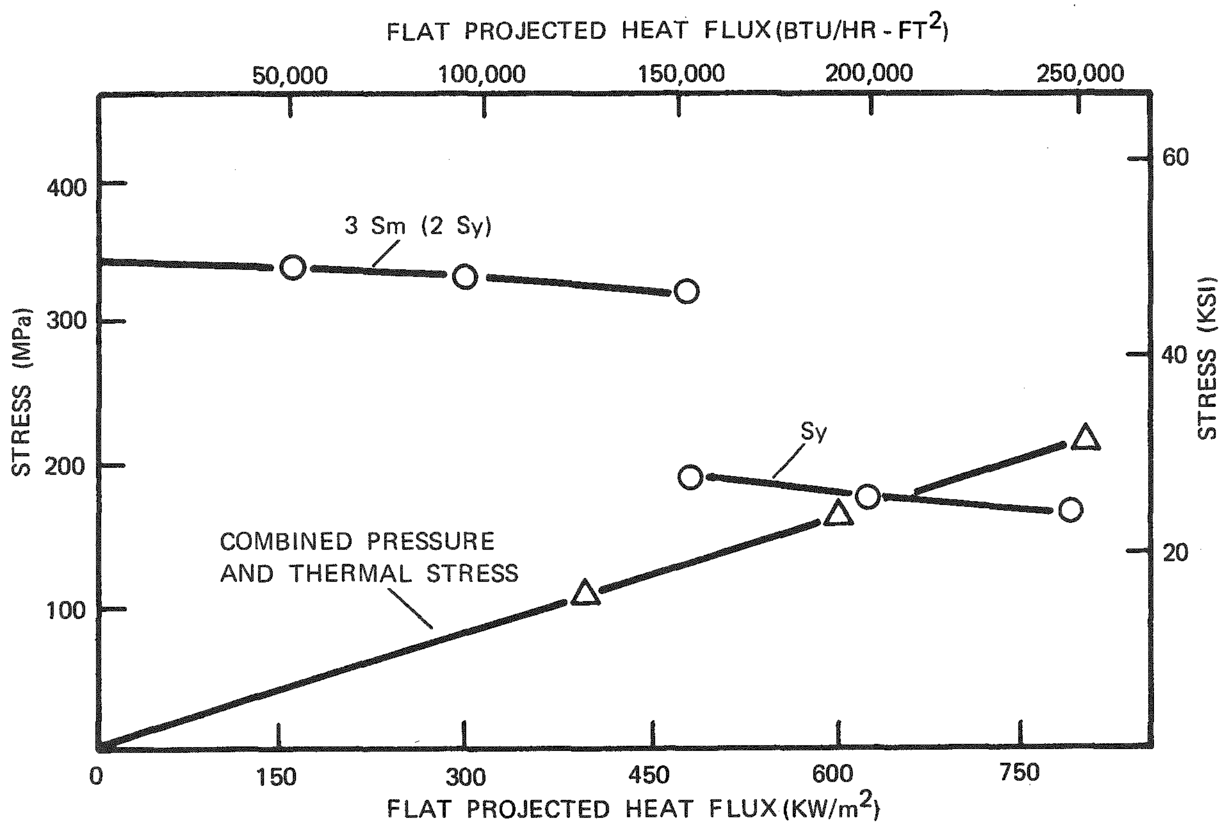

Figure D-5. Comparison of the Combined Pressure and Thermal Stress in Boiler Section to the Allowable Stress

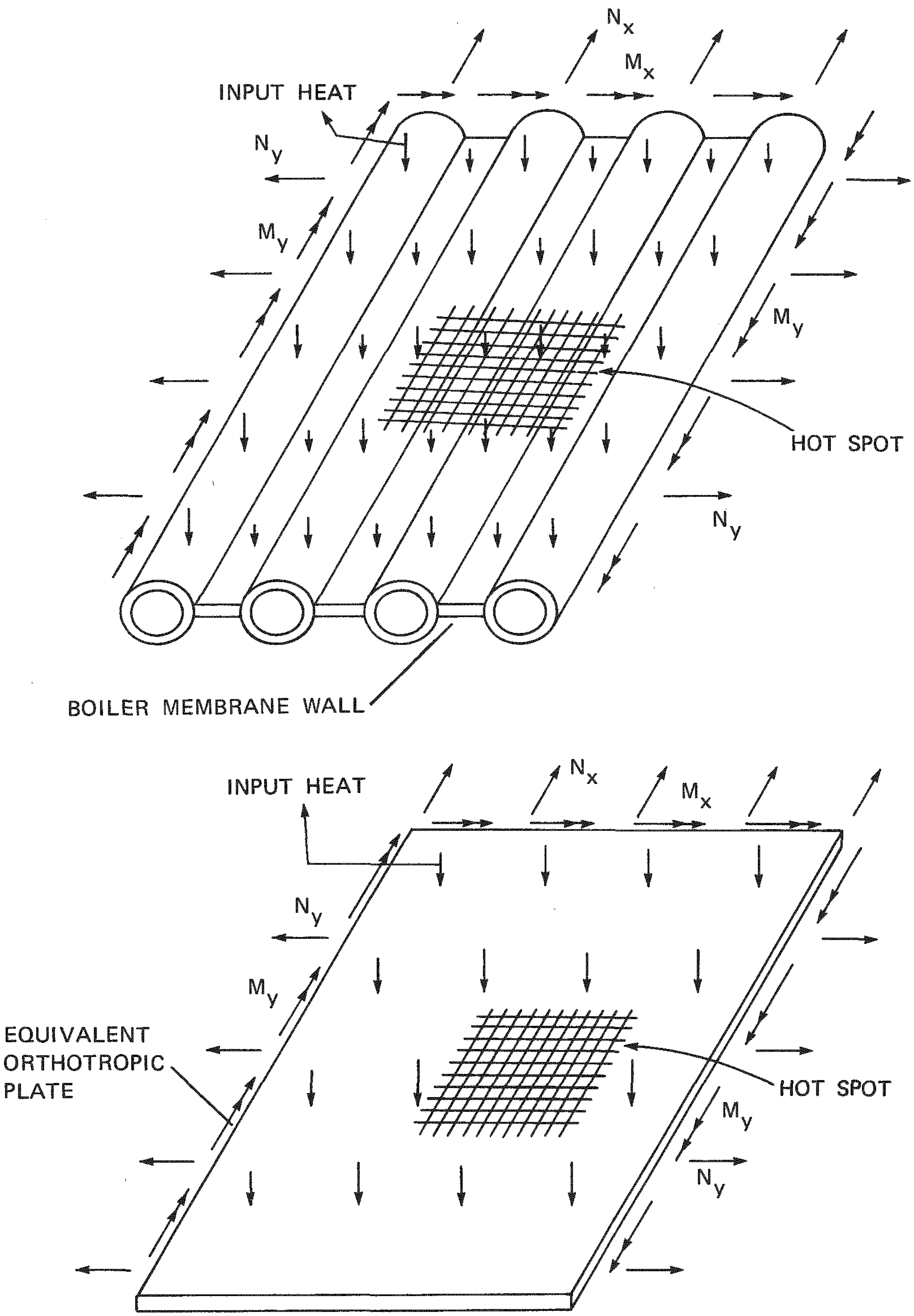

Figure D-6. Boiler Section Panel Modeling

Figure D-7 is a plot of S_m for the Croloy 2-1/4 SRE superheater tubes as a function of the flat projected heat flux. The heat flux was applied to two quadrants of the SRE superheater tubes with a full cosine distribution. Figure D-7 also illustrates the constant value of maximum hoop stress in the SRE superheater tubing due to the operating pressure of 1800 psia. Figure D-8 is an analogous graph of allowable (S_{mt}), and maximum hoop stress for the Pilot Plant superheater tubing. The Pilot Plant tubes experienced higher metal temperatures because the heat flux was applied to the tubes with a half cosine distribution. Higher metal temperatures subsequently cause the allowable stress curve to "drop off" faster for the Pilot Plant superheater tubing than for the SRE tubing for corresponding flat projected heat fluxes.

A two-dimensional stress analysis of the superheater tubing was accomplished by using finite element techniques. A steady-state heat conduction analysis with temperature dependent material properties was first performed for both the SRE and Pilot Plant superheater tubes. Figures D-9 and D-10 illustrate typical temperature profiles for the SRE and Pilot Plant tubing, respectively. Each was subjected to the same flat projected heat flux (127,000 Btu/hr-sq ft). However, the flux was applied to two quadrants of the SRE tubing with a full cosine distribution (127,000 Btu/hr-sq ft OD peak) whereas the Pilot Plant heat flux was applied to one quadrant of the tubing with a half cosine distribution (254,000 Btu/hr-sq ft OD peak).

A plane stress, $\sigma_z = \tau_{xz} = \tau_{yz} = 0$, finite element model was used to analyze the stress state in the superheater tubing resulting from thermal gradients and internal pressure. A plane stress model was selected because the basic concept behind the helical superheater design is to allow radial expansion of the superheater. Thus, longitudinal tube stresses will result only from the logarithmic and asymmetrical portion of the temperature distribution in the tube and will not be a function of the uniform temperature resulting from raising the superheater

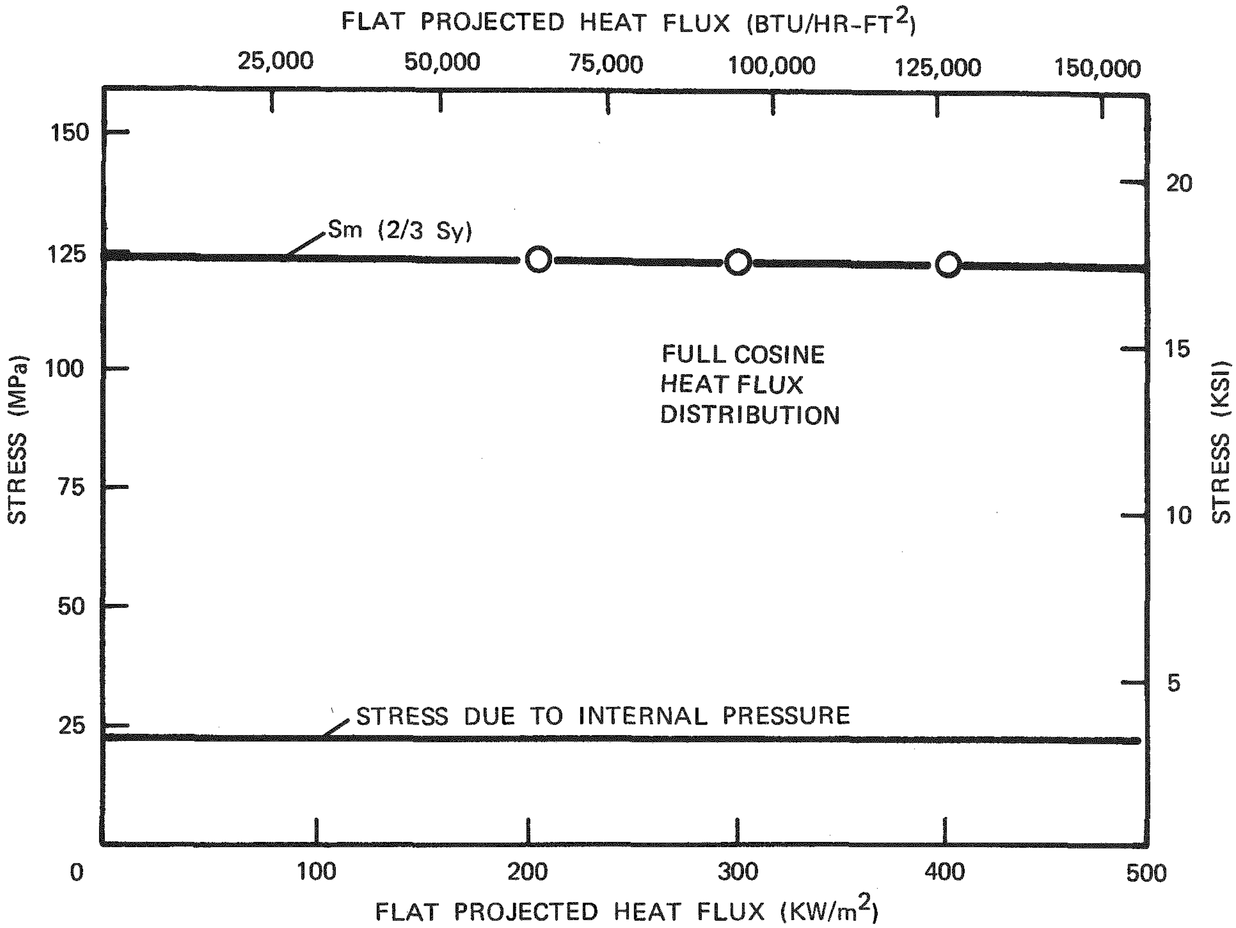

Figure D-7. Comparison of the Pressure Stress in the SRE Superheater Tubing to the Allowable Stress

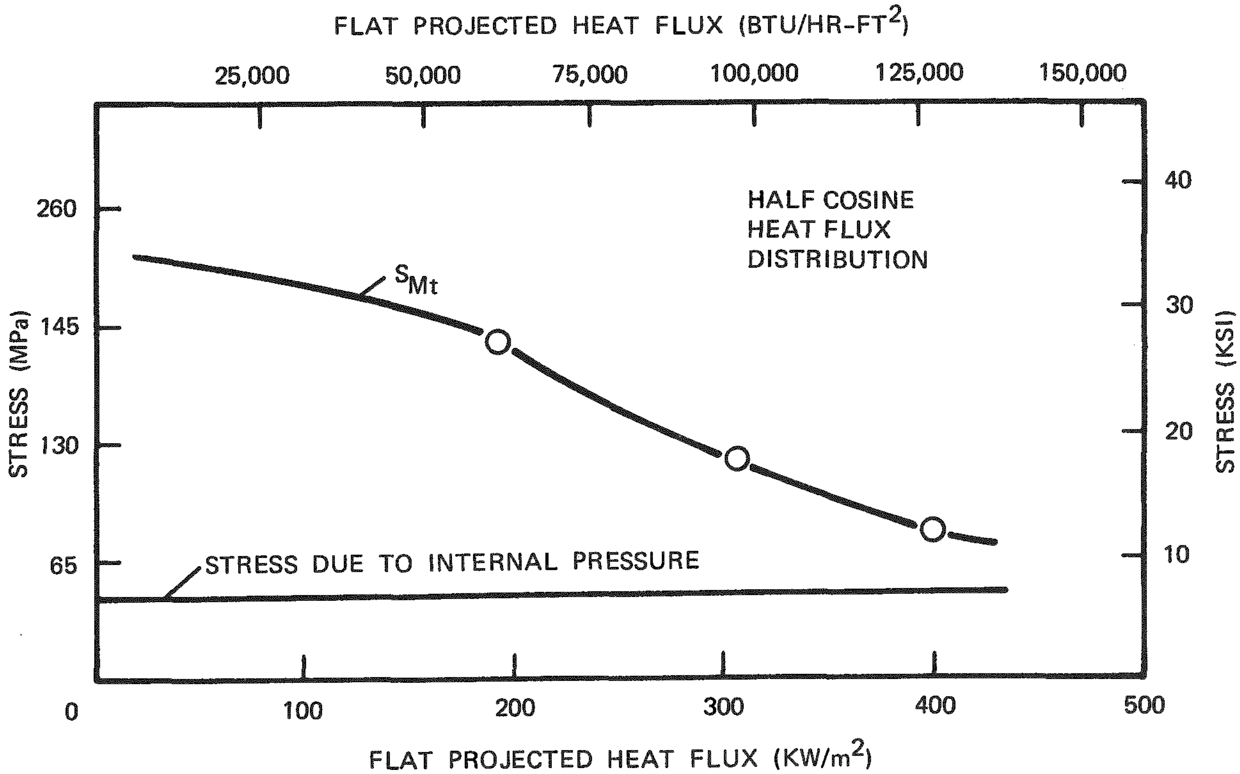

Figure D-8. Comparison of the Pressure Stress in the Pilot Plant Superheater Tubing to the Allowable Stress

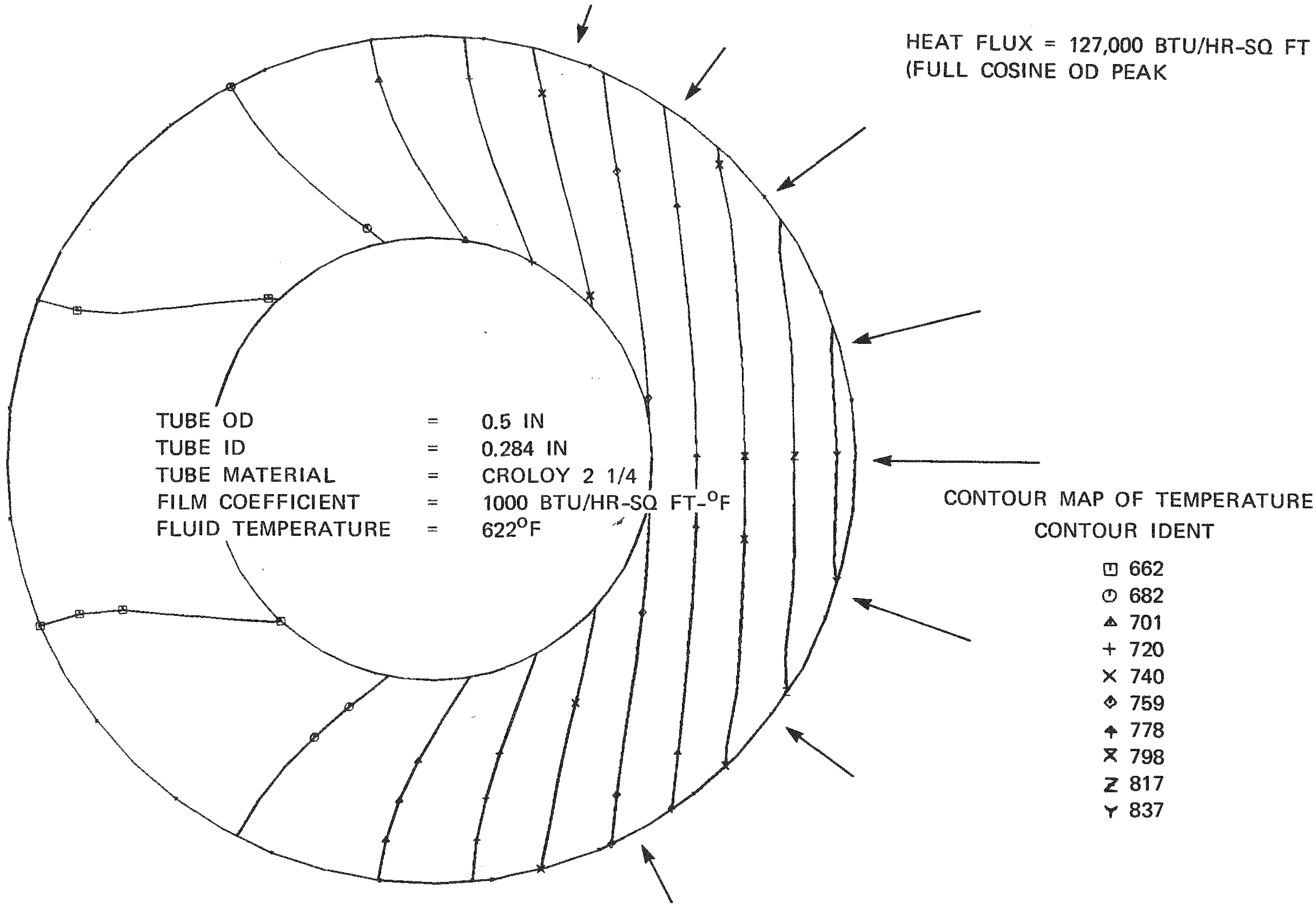

Figure D-9. Temperature Contour Lines in SRE Superheater Tubes Due to Heat Flux of 127,000 Btu/Hr-Sq Ft (Full Cosine OD Peak)

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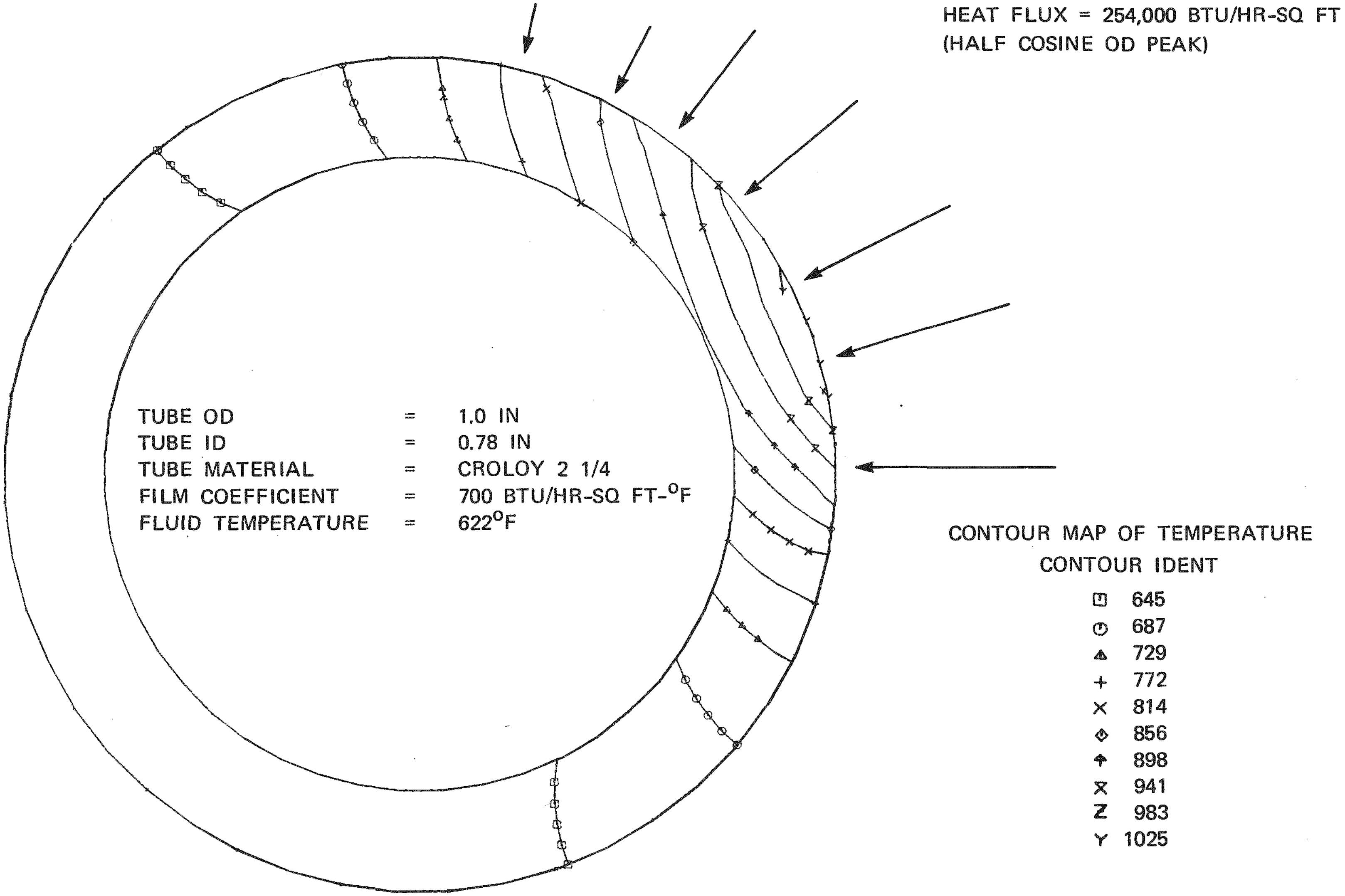

Figure D-10. Temperature Contour Lines in Pilot Plant Superheater Tubes Due to Heat Flux of 254, 000 Btu/Hr-Sq Ft (Half Cosine OD Peak) cavity from ambient to operating temperature. Both internal pressure and the thermal distribution were included in the plane stress analysis. Figure D-11 illustrates a typical maximum principal stress contour plot for a Pilot Plant superheater tube subjected to an internal pressure of 1800 psia and a heat flux having a half cosine distribution with a 254,000 Btu/hr-sq ft OD peak amplitude. The largest value of maximum principal stress occurs on the inside fibers of the tube where the internal pressure and thermal distribution both contribute to a tensile hoop stress.

The first curve on Figure D-12 is a plot of 3 S_m for the Croloy 2-1/4 SRE superheater tubes as a function of the flat projected heat flux. The second curve on Figure D-12 is a plot of the maximum calculated stress intensity in the tubes from the plane stress analysis as a function of the applied heat flux. The stress intensity includes a contribution from an internal pressure of 1800 psia. Figure D-13 contains analogous plots for the Croloy 2-1/4 Pilot Plant superheater tubes.

As has been previously mentioned, the flux distribution on the superheater tubes can vary with location in the superheater cavity. Ideally, the heat flux distribution would have a uniform intensity about the tube circumference. However, in the SRE superheater tubing, it has been hypothesized that the incident heat flux approximates a full cosine distribution over two quadrants of a tube and that the "worst case" distribution on the Pilot Plant tubing will be a half cosine distribution over one quadrant of the tube. To investigate the effect of different flux profiles on metal temperatures and stresses, a uniform, full cosine and half cosine distribution were each placed on identical Pilot Plant tubes. Figures D-14 through D-16 illustrate the difference in temperature profiles in the Pilot Plant tube due to the different heat flux distributions. The flat projected heat flux remained constant for each case; that is to say, the total heat into the tube remained constant for each case. To achieve the temperature distribution illustrated

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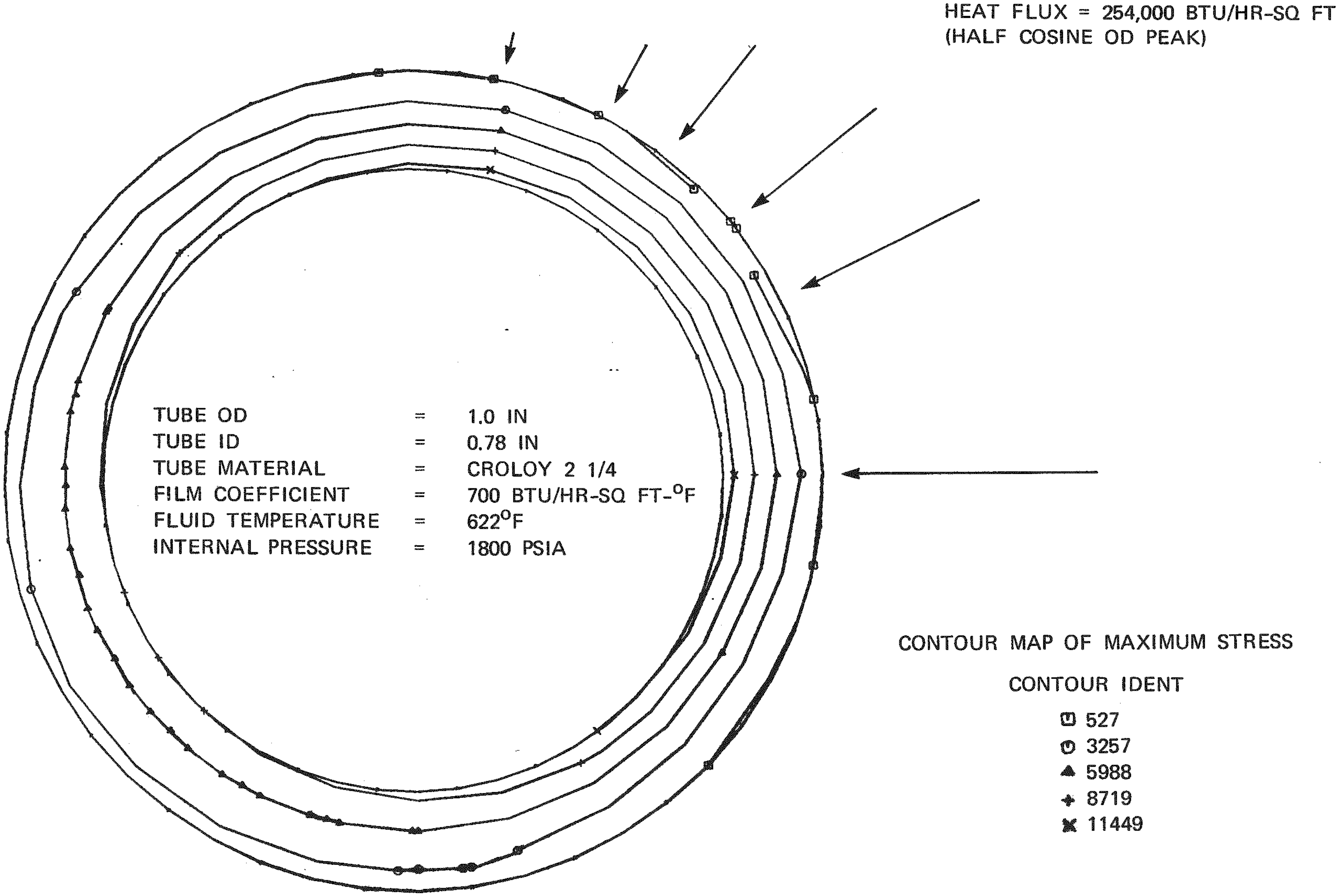

Figure D-11. Maximum Principal Stress Contour Lines in Pilot Plant Superheater Tube Due to Internal Pressure and Heat Flux of 127,000 Btu/Hr-Sq Ft

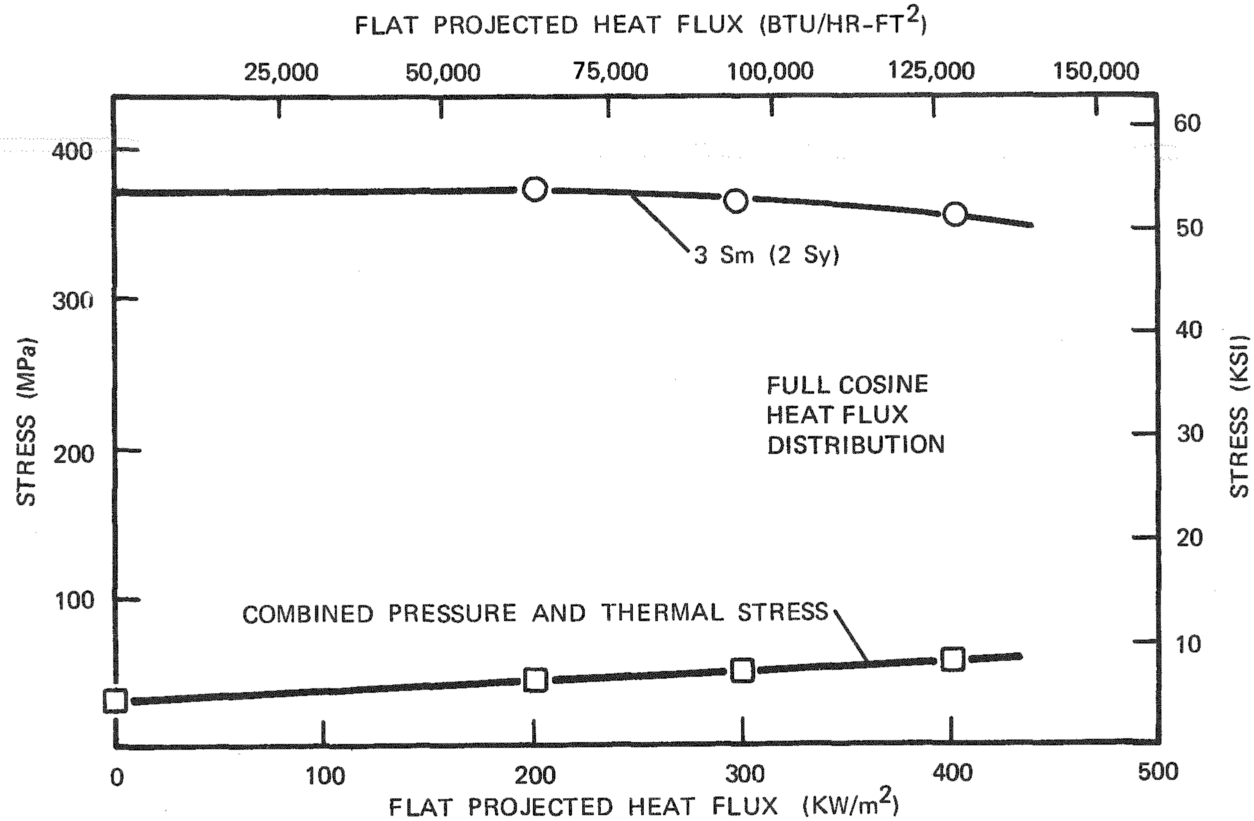

Figure D-12. Comparison of the Combined Pressure and Thermal Stress in the SRE Superheater Tubing to the Allowable Stress

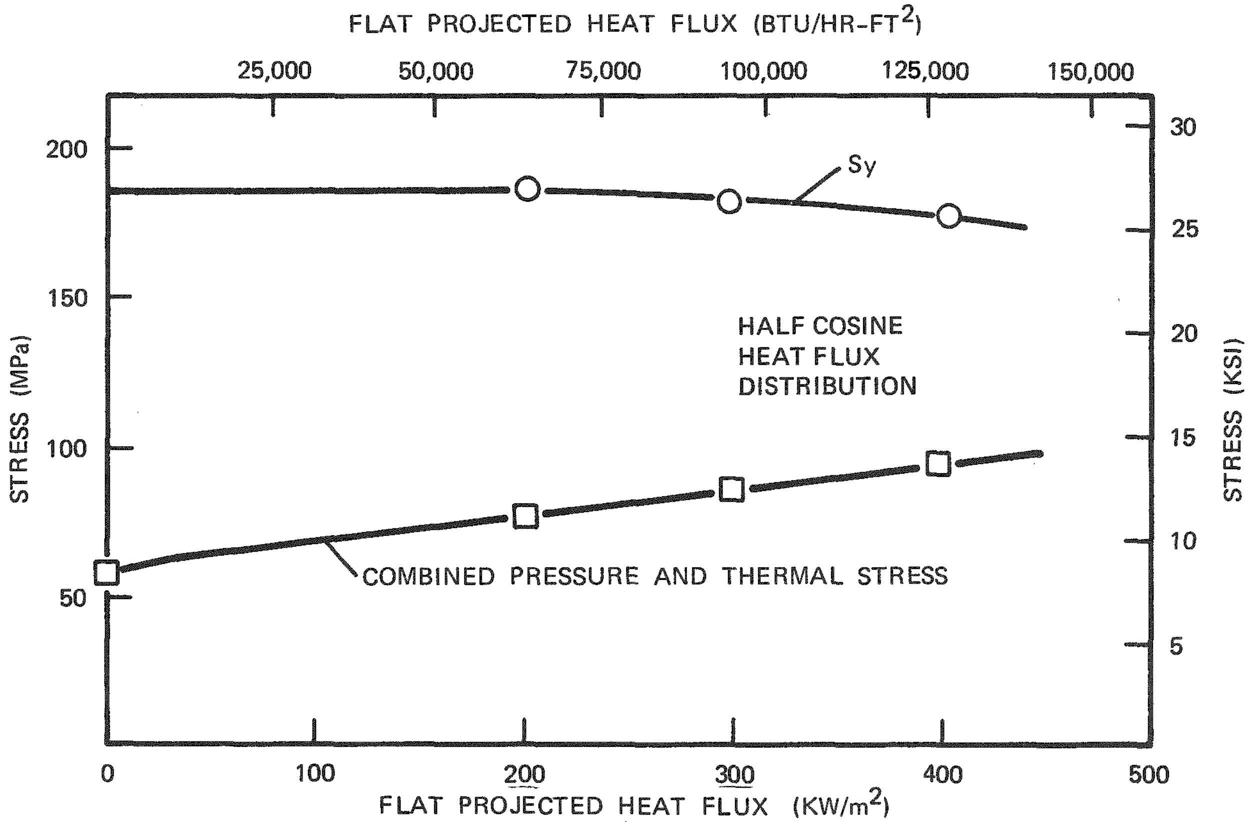

Figure D-13. Comparison of the Combined Pressure and Thermal Stress in the Pilot Plant Superheater Tubing to the Allowable Stress

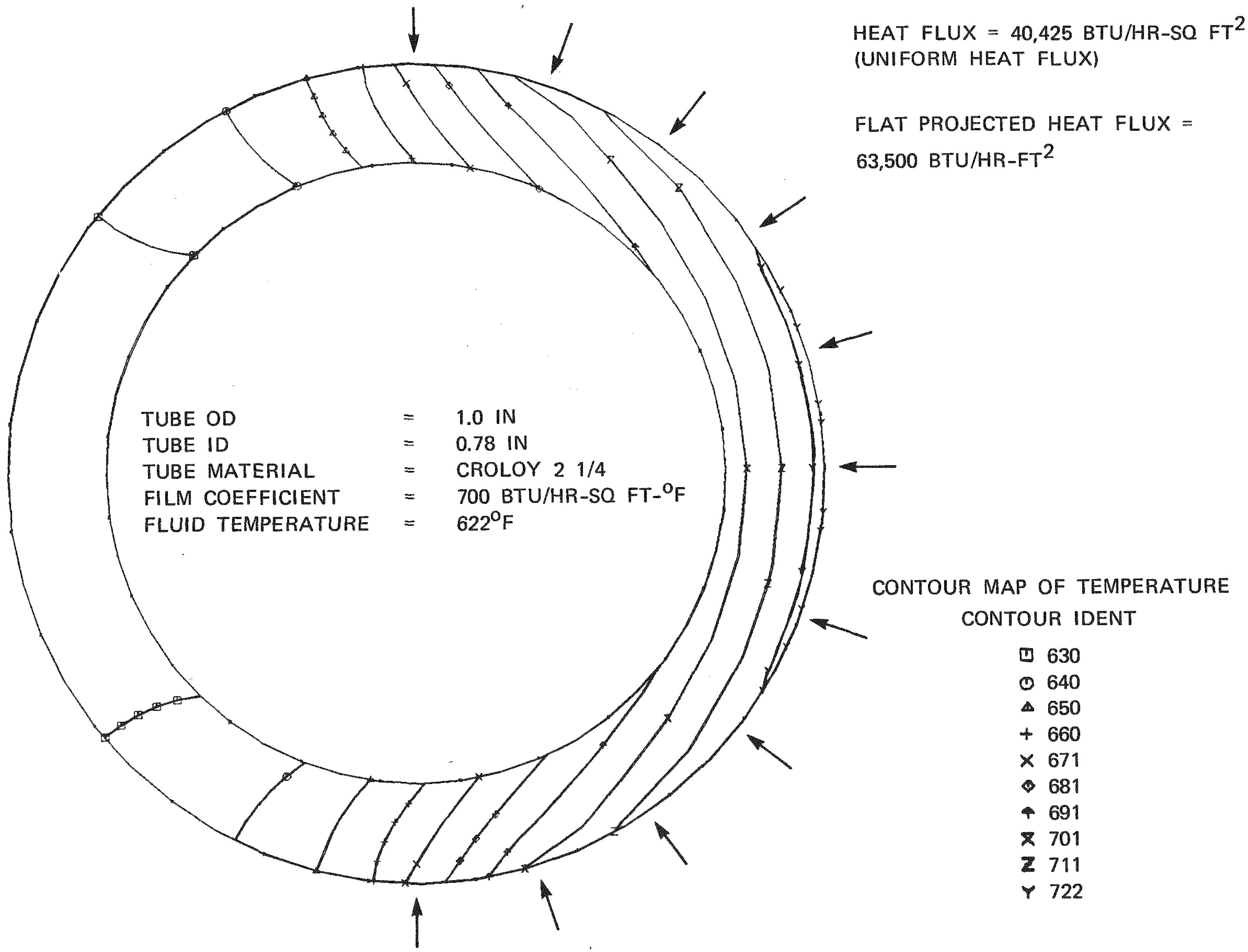

Figure D-14. Temperature Contour Lines in Pilot Plant Superheater Tube Due to Uniform Heat Flux

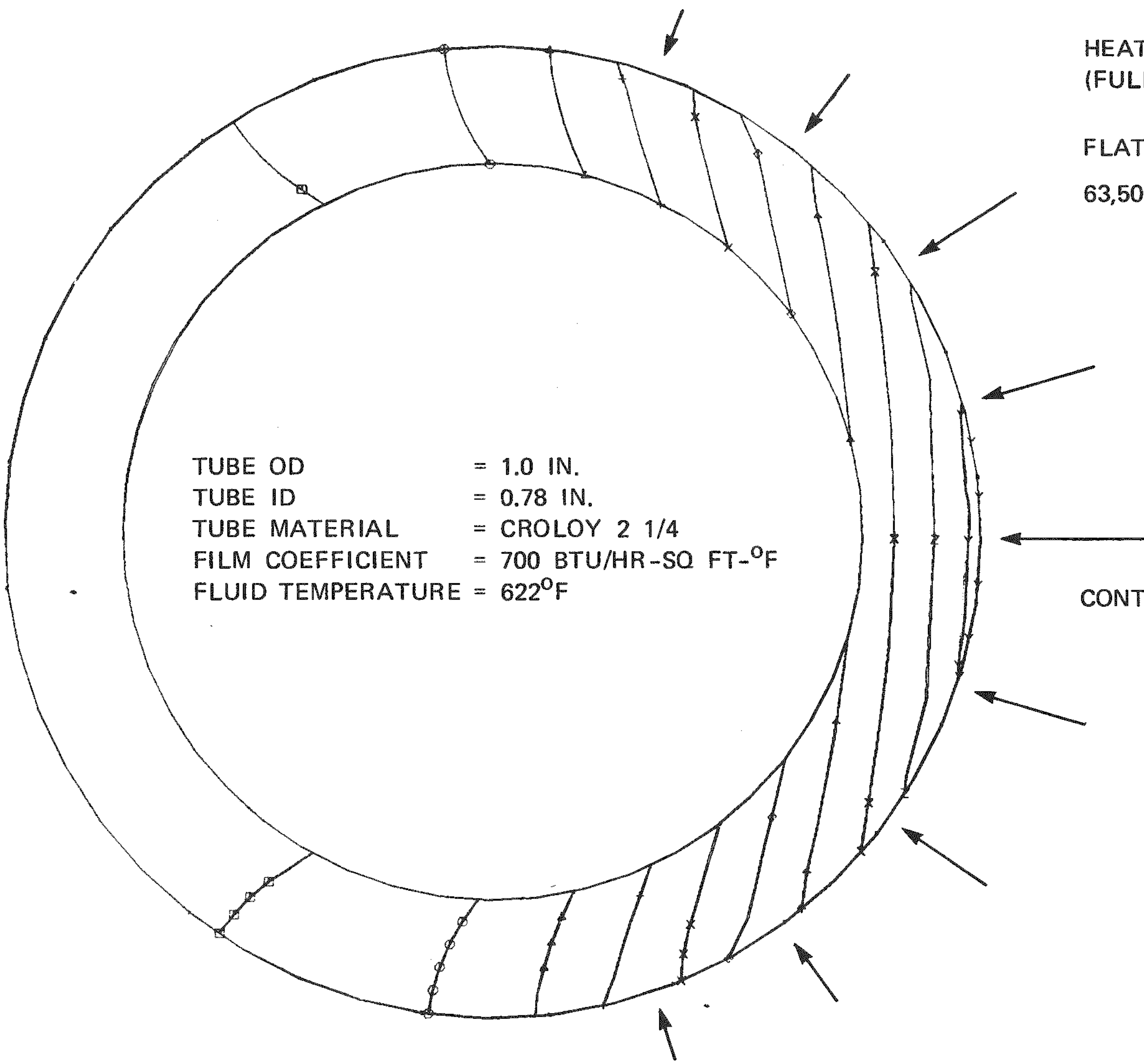

Figure D-15. Temperature Contour Lines in Pilot Plant Superheater Tubes Due to Full Cosine OD Peak Heat Flux

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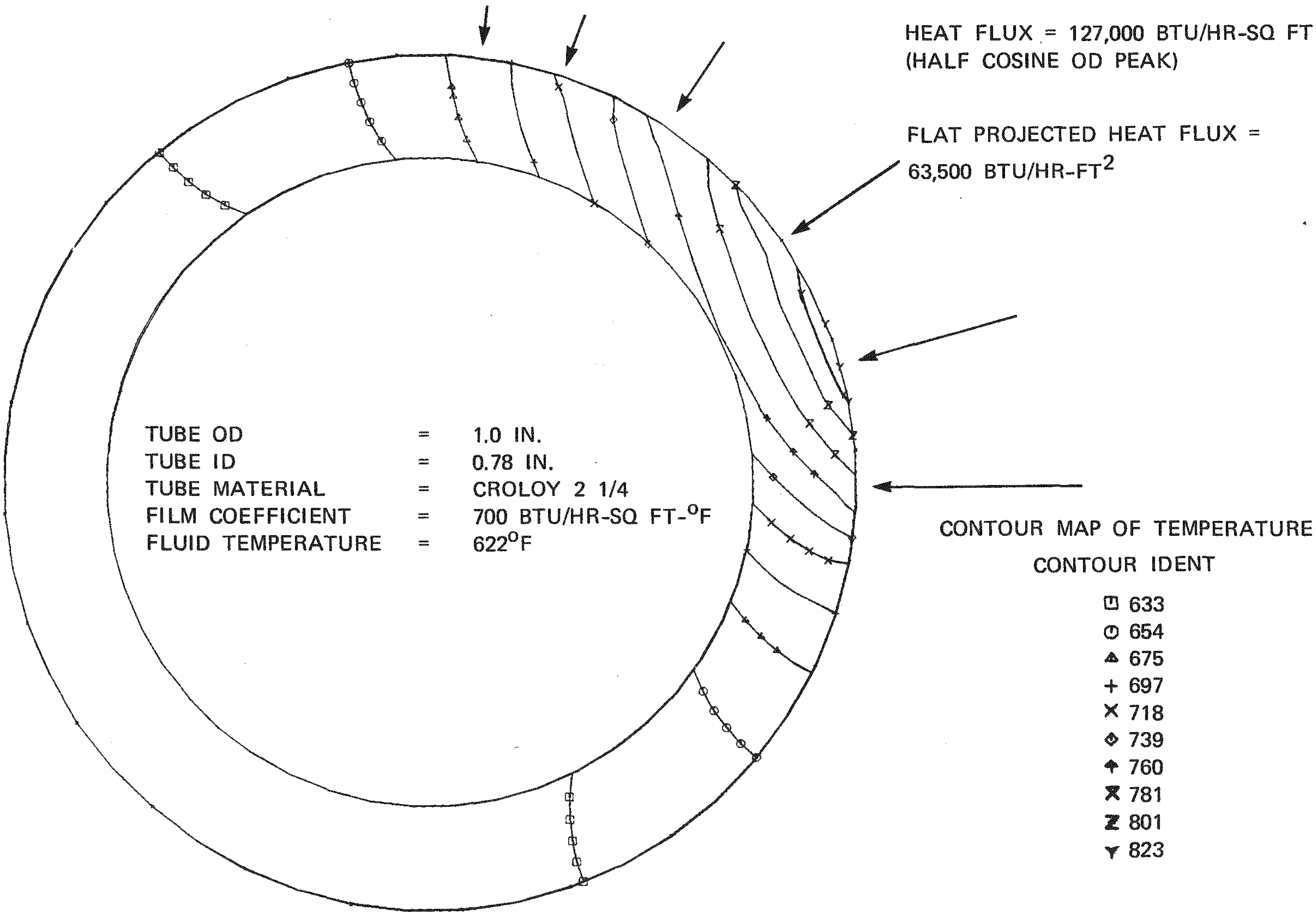

Figure D-16. Temperature Contour Lines in Pilot Plant Superheater Tube Due to Half Cosine OD Peak Heat Flux in Figure D-14, the heat flux was applied uniformly about two quadrants of the tube with an amplitude of 63,500*2/π. Figure D.15 illustrates the temperature distribution due to the application of a heat flux over two quadrants of the tube with a full cosine distribution having a 63,500 Btu/hr-sq ft OD peak amplitude. The last of the three cases is illustrated by Figure D-16which shows the thermal distribution due to a heat flux applied over one quadrant of the tube with a half cosine distribution having a 127,000 Btu/hr-sq ft OD peak amplitude. The results of the three analyses demonstrate that different heat flux distributions cause a significant difference in the maximum temperature experienced by the superheater tubes. However, as can be seen in Table D-1, the in-plane stresses resulting from the three distributions are not affected significantly by the different distributions. The primary detrimental effect of the higher metal temperatures is that the allowable stress intensity decreases with the increasing metal temperature. Thus, even though the plane stresses due to the different heat flux distributions are approximately the same, the allowable stress decreases as the heat flux tends from a uniform to half cosine distribution and this gives less margin for safety.

To verify the assumption that the superheater tubes do indeed approximate a plane stress situation, a three-dimensional model similar to that shown in Figure D-17 will be generated. The finite element model will consist of 20 node solid isoparametric elements and will represent an entire superheater tube sweeping through an arc of 360 degrees. The model will accommodate a variable temperature distribution through the tube thickness, around the tube circumference and along the tube length. The model will be used to evaluate the support concept to insure freedom of expansion of the tubes while keeping the tubes "stacked" in approximately a vertical coil and to insure that bending stresses are not introduced into the tubes by the intermediate supports. Once the total stress

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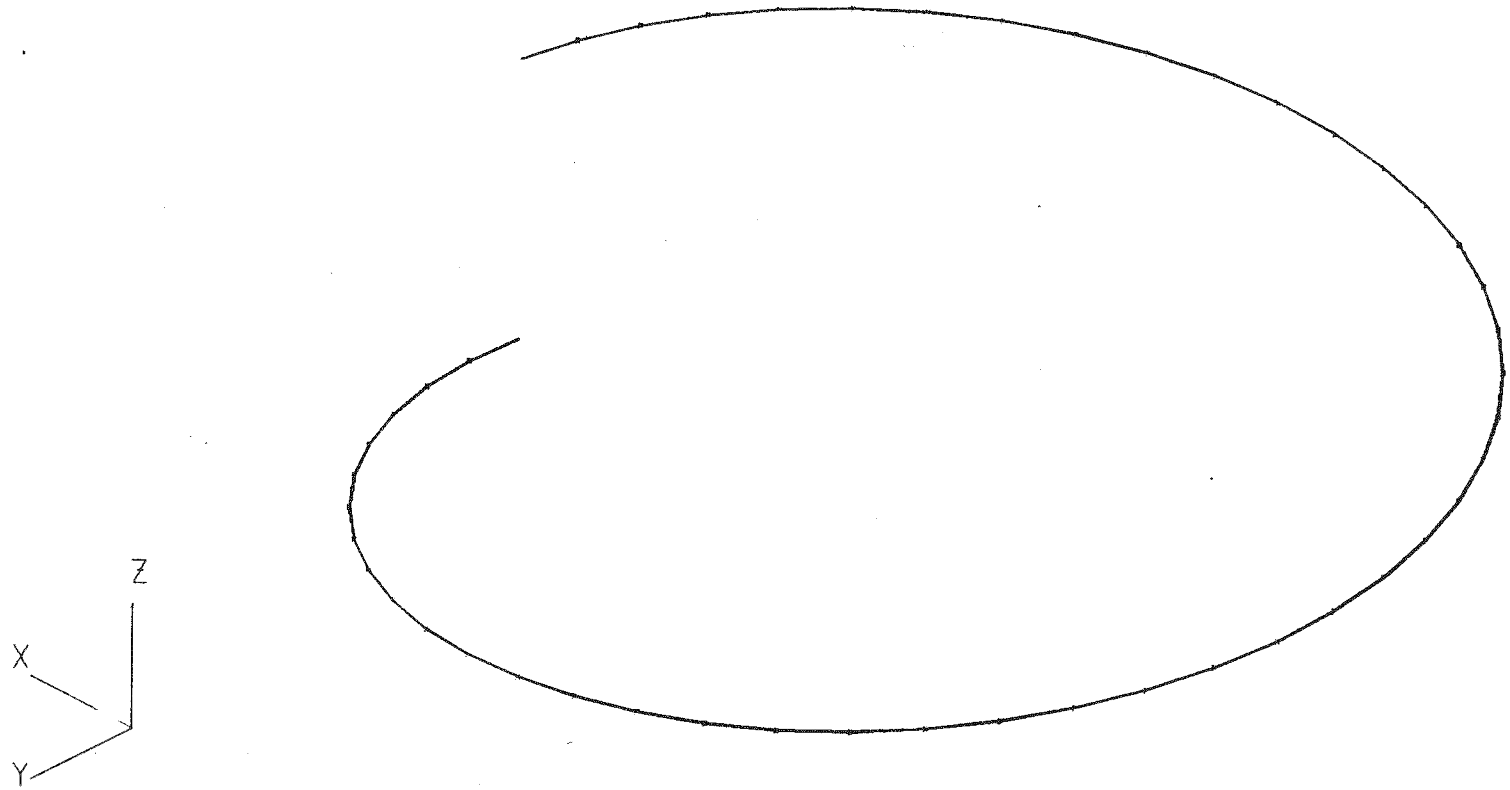

Figure D-17. Three Dimension Finite Element Model of Superheater Tube state has been obtained from the three-dimensional model, the philosophy of ASME Code Case 1592 will be used to evaluate thermal fatigue and creep-fatigue failure of the superheater cavity.

APPENDIX E

PILOT PLANT HEAT FLUX DISTRIBUTION ON THE SUPERHEATER TUBES

E.1.0 ANALYSIS

The following analysis was derived in order to find the worst case heat flux distribution on the superheater tubes. The heat flux distribution is used for the thermal stress analysis. The following assumptions are made:

1. The sun rays from the heliostats pass through the aim point at the aperture and form a given angle on the superheater tubes.
2. The rays as seen by a superheater tube are parallel.
3. There is no reradiation.
4. The heat flux results from the Ray Trace Analysis are the flat projected heat fluxes.
5. The total heat input to the superheater tube is equal to the flat projected heat flux distributed over the flat projected area of the tube regardless of the heat flux distribution.
6. The heat flux distribution is a cosine function.

The following parameters are defined in Figure E-1.

H = cavity height

D_1 = cavity diameter

D_2 = tower diameter at top

L_B = boiler height

SEP = vertical height of aperture

α = angle at which rays are incident on superheater tubes

$$\alpha = \tan^{-1} \frac{Y}{X}$$

$$Y = D_1 - \frac{D_1 - D_2}{4}$$

$$L_B + \frac{SEP}{2} \leq X \leq H + \frac{SEP}{2}$$

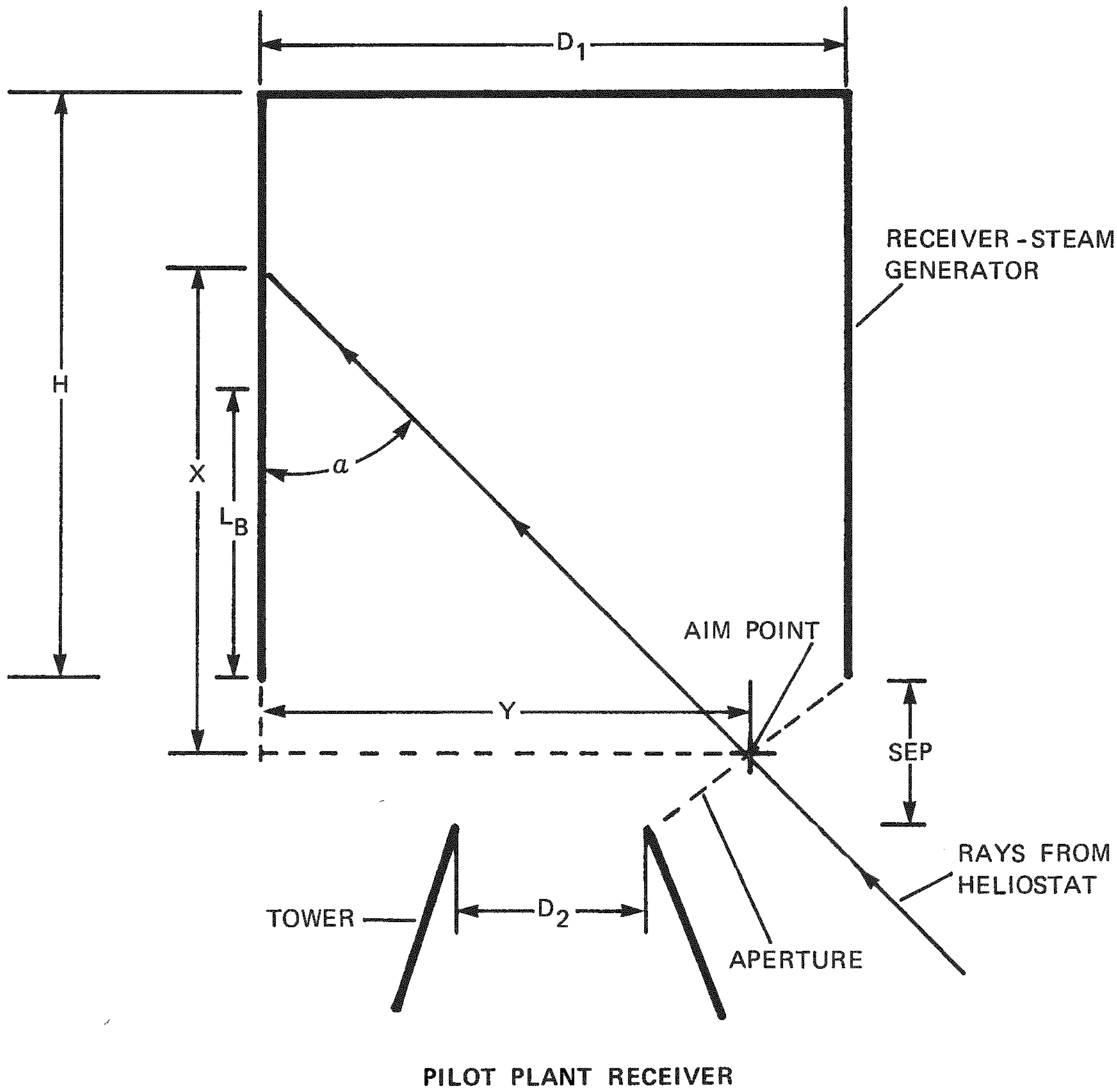

Figure E-1. Pilot Plant Receiver

The following parameters are defined in Figure E-2.

$$W = \frac{OD/2\ (1-\sin\alpha)}{\sin\alpha}$$

$$C = \sin^{-1}\left\{\frac{(OD/2 - W)\ [\sin\ (180 - \alpha)]}{OD/2}\right\}$$

$$\beta = 90 - \alpha + C$$

Heat Flux Distribution

Total heat input is equal regardless of the direction of the heat flux.

$$q = q_{max}\cos\sigma$$

$$q_{FP} \times OD \times L = L \times \frac{OD}{2} \times q_{max}\left[\int_0^{\frac{\pi}{2}} \cos\sigma\, d\sigma + \int_0^{\alpha+\beta-\frac{\pi}{2}} \cos\sigma\, d\sigma\right]$$

$$\alpha + \beta \geq 90$$

$$\therefore q_{max} = \frac{2q_{FP}}{1 + \sin\ (\alpha + \beta - 90)}$$

$$q = q_{max}\cos\sigma$$

$$0 \leq \sigma \leq \alpha + \beta$$

E.2.0 HEAT FLUX DISTRIBUTION FOR THE PDBR PILOT PLANT

The following calculations are summarized in Figure E-3.

Calculations

Cavity Height	- H	= 46.1'
Cavity Diameter	- D_1	= 39.4'
Tower Diameter at Top	- D_2	= 20'
Boiler Height	- L_B	= 24'
Vertical Height of Aperture	- SEP	= 8.2'
OD of Superheater Tube	- OD	= 1.0"

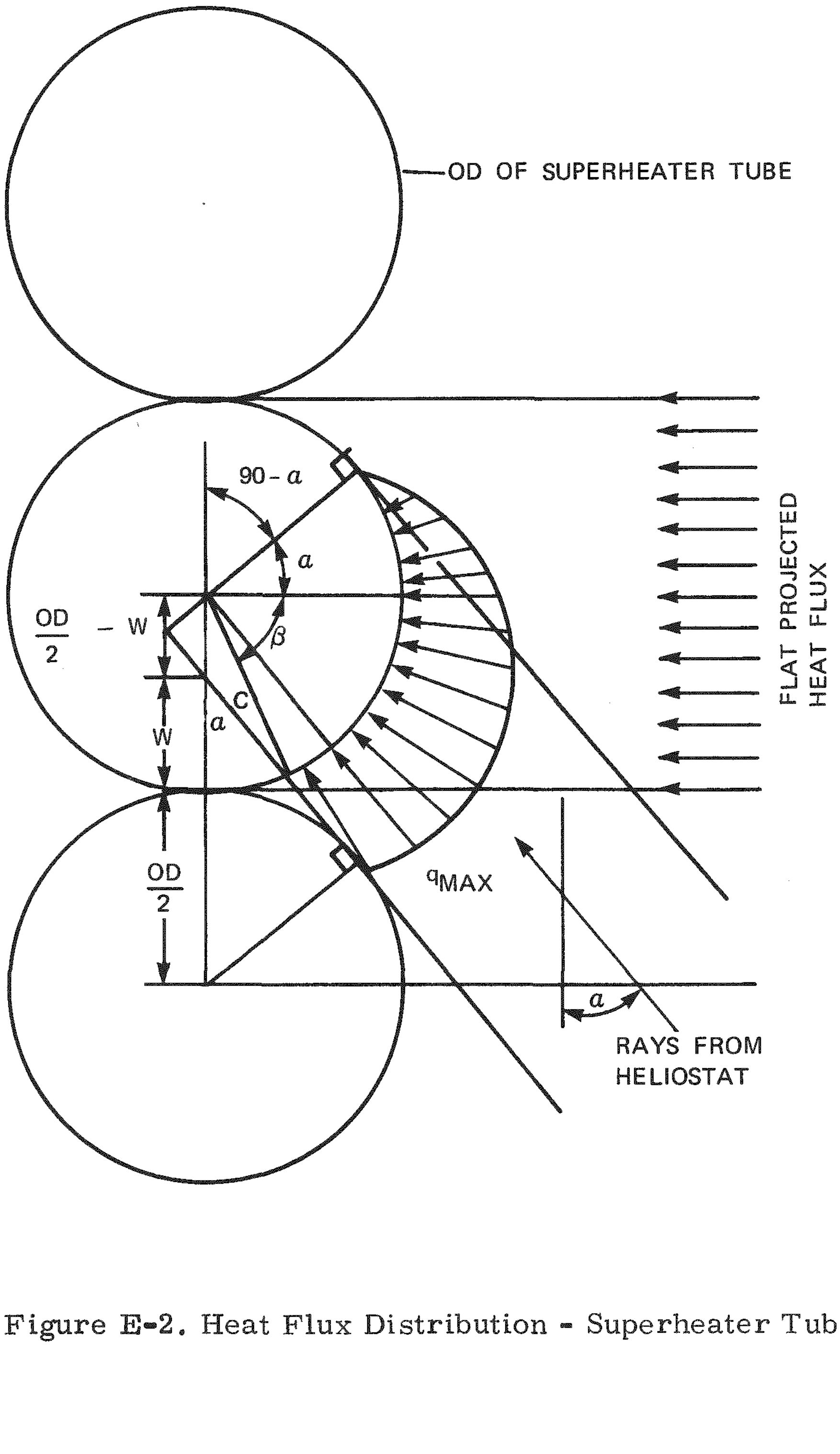

Figure E-2. Heat Flux Distribution - Superheater Tubes

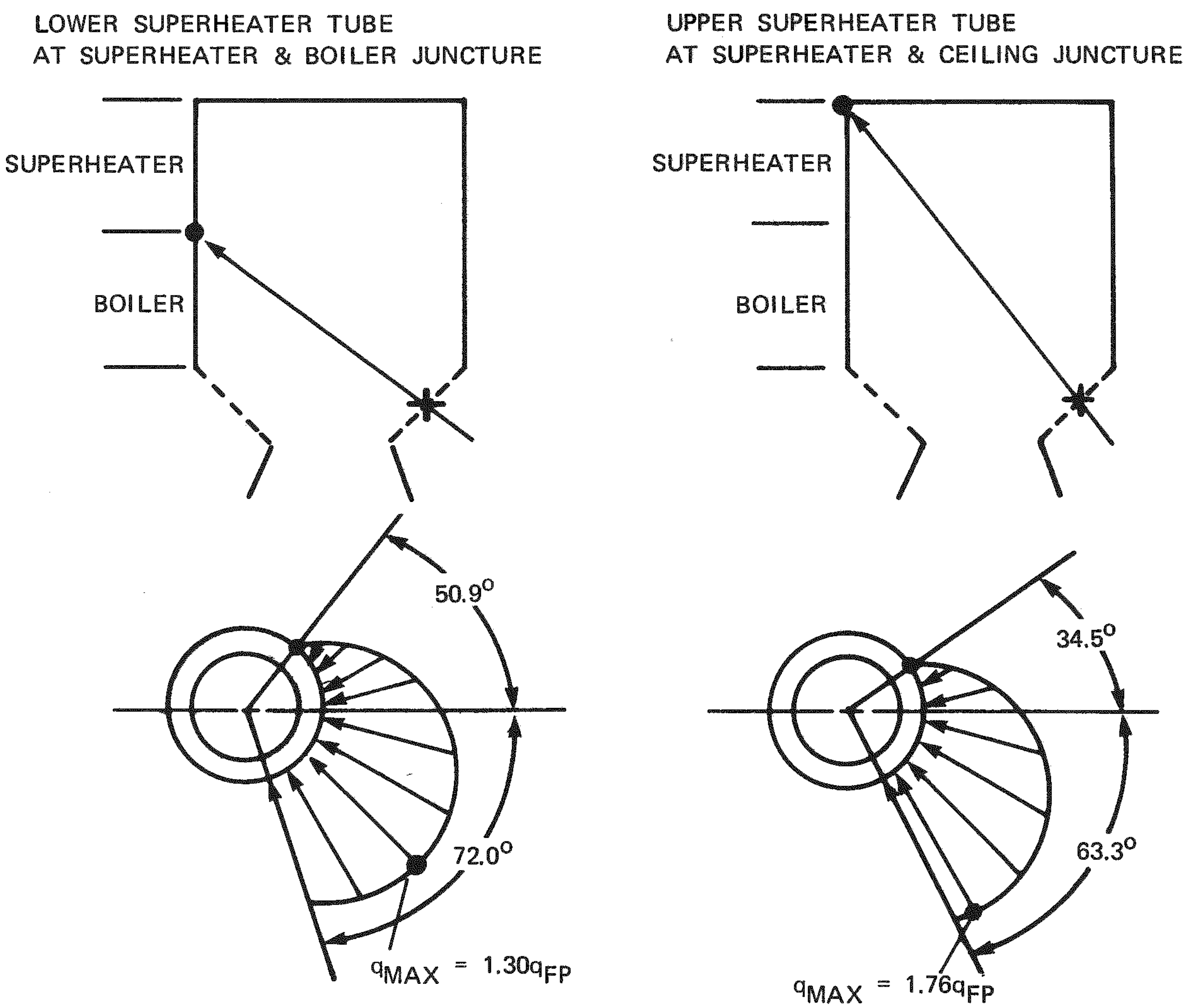

Figure E-3. Heat Flux Distribution on the Lower and Upper Superheater Tubes

Lower - Superheater Tube at Boiler Juncture

$$Y = D_1 - \frac{D_1 - D_2}{4} = 34.55 \text{ feet}$$

$$X = L_B + \frac{SEP}{2} = 28.1 \text{ feet}$$

$$\alpha = \tan^{-1}\left(\frac{34.55}{28.1}\right)$$

$\underline{\alpha = 50.88 \text{ degrees}}$

$$W = \frac{.5\,(1 - \sin 50.88°)}{\sin 50.88°}$$

W = 0.15 inch

$$C = \sin^{-1}\left[\frac{0.35 \sin (180-50.88)}{.5}\right]$$

C = 32.89 degrees

$\beta = 90 - 50.88 + 32.89$

$\underline{\beta = 72.0 \text{ degrees}}$

$\alpha + \beta = 122.88$ degrees

$$q_{max} = \frac{2q_{FP}}{1 + \sin(122.88 - 90)}$$

$q_{max} = 1.30\ q_{FP}$

$\underline{q = 1.30\ q_{FP} \cos \sigma}$

$\underline{0 \leq \sigma \leq 122.88}$

Upper - Superheater Tube at Ceiling Juncture

Y = 34.55 feet

$$X = H + \frac{SEP}{2} = 50.2 \text{ feet}$$

$$\alpha = \tan^{-1}\left(\frac{34.55}{50.2}\right)$$

$\underline{\alpha = 34.54 \text{ degrees}}$

$$W = \frac{.5\,(1 - \sin 34.54°)}{\sin 34.54}$$

W = 0.38 inch

$$C = \sin^{-1}\left[\frac{0.12 \sin (180 - 34.54)}{.5}\right]$$

C = 7.82 degrees

$\beta = 90 - 34.54 + 7.82$

$\underline{\beta = 63.3 \text{ degrees}}$

$\alpha + \beta = 97.82$ degrees

$$q_{max} = \frac{2q_{FP}}{1 + \sin(97.82 - 90)}$$

$q_{max} = 1.76\ q_{FP}$

$\underline{q = 1.76\ q_{FP} \cos \sigma}$

$\underline{0 \leq \sigma \leq 97.82}$

E.3 SUMMARY

The results presented in Figure E-3 for the PDBR cavity and tower dimensions show that the heat flux distribution on a superheater tube approaches a 1/2 cosine function as the superheater and ceiling juncture is approached. Therefore, the worst heat flux distribution will occur on the tubing at the upper part of the superheater. Here the maximum heat flux approaches twice the flat projected heat flux as a 1/2 cosine function is approached.

For a "worst case" analysis, the 1/2 cosine function of the heat flux distribution was used for the Pilot Plant superheater thermal stress analysis presented in Appendix D.

The 1/2 cosine peak assumption is probably much too severe because:

- At the lower part of the superheater where heat flux is highest the peak flux is 1.30 rather than 2 times the flat projected flux
- Reradiation in the cavity will more evenly distribute the heat flux around the circumference of the tube. This will be particularly true at the upper part of the cavity where the superheater tube will receive a large amount of reradiation from the insulated ceiling.

Additional study will be done during detailed design to define a more realistic heat flux distribution.

APPENDIX F

HEADER SUPPORT DETAILS

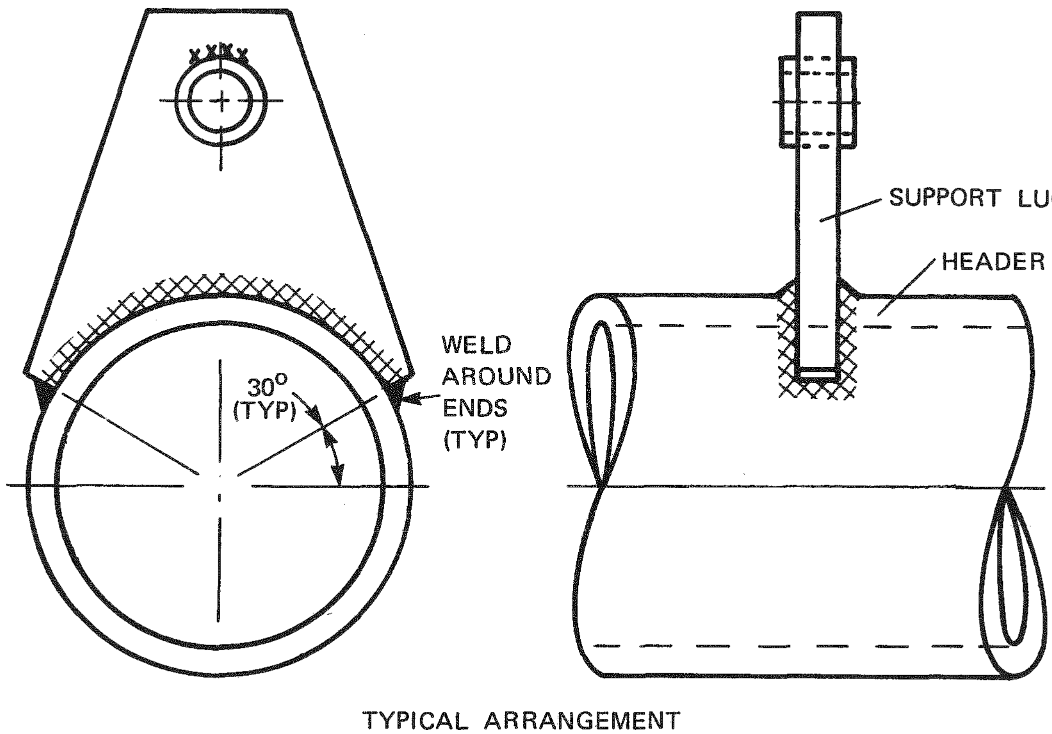

Figure F-1. Design for Header Support Lugs

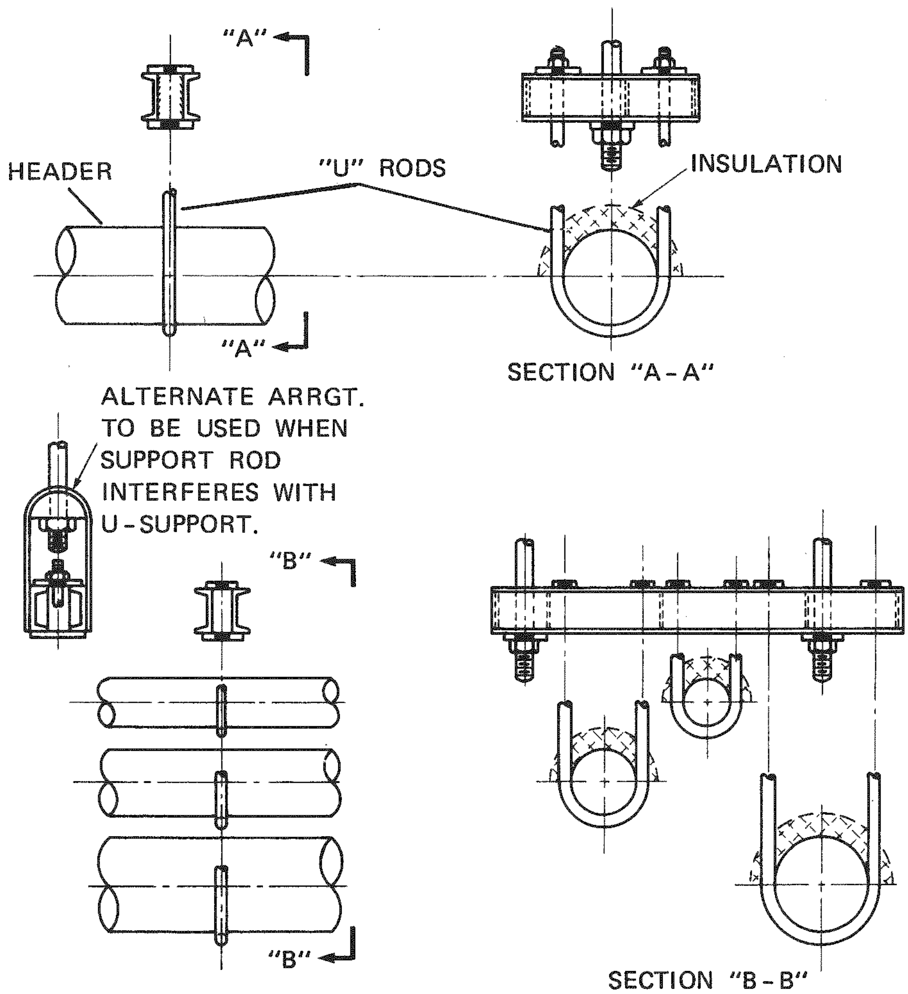

Figure F-2. Schematic

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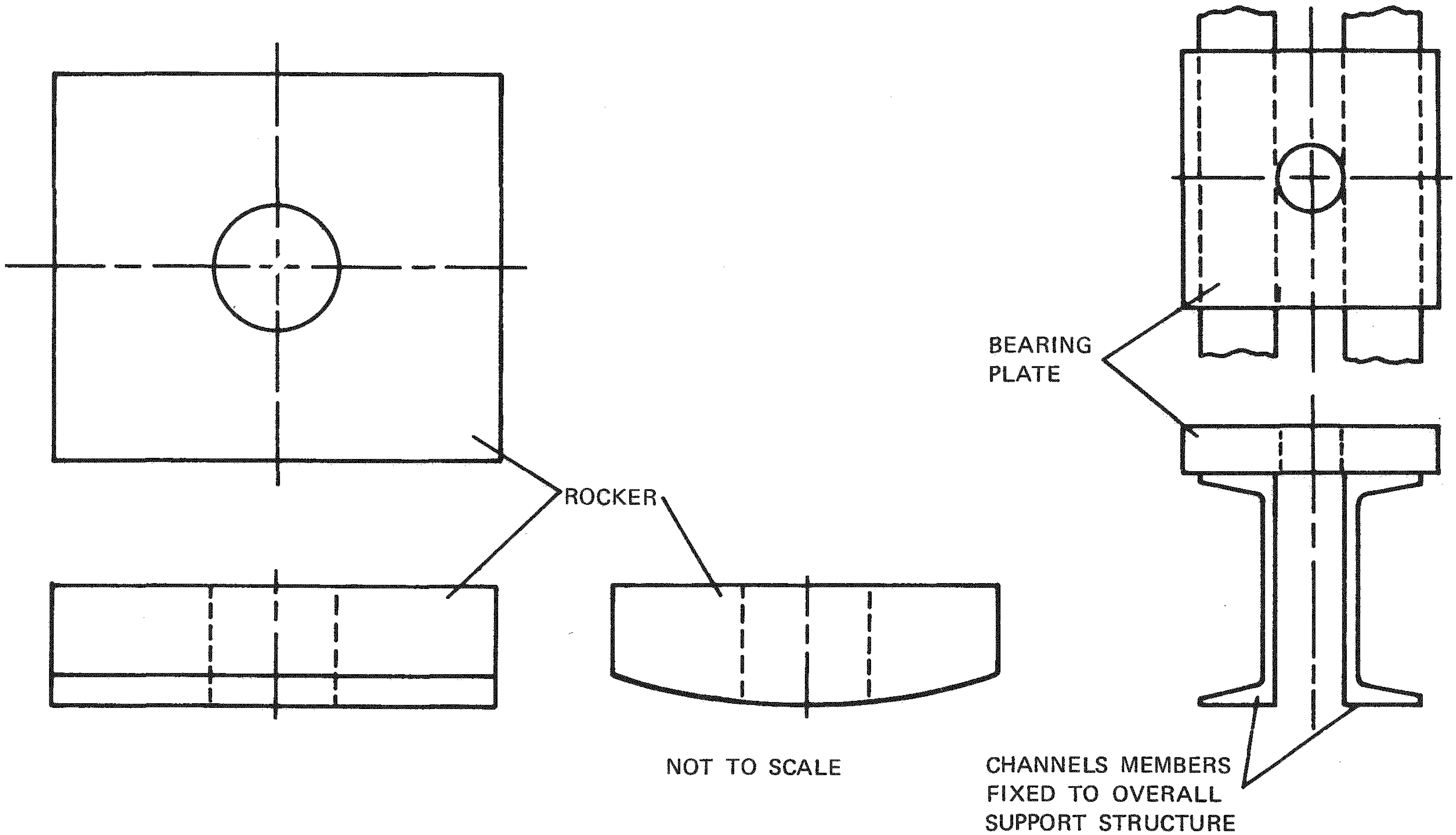

Figure F-3. Rocker and Bearing Plate Support

APPENDIX G

SOLAR SIMULATOR SYSTEM

Honeywell

SYSTEMS & RESEARCH CENTER Code Ident No. 27327

HONEYWELL REQUIREMENTS SPECIFICATION NO. HRS SK 133244

THIS HONEYWELL REQUIREMENTS SPECIFICATION IS FOR:

SOLAR SIMULATOR SYSTEM

SIGNATURES	DATE
PREPARED BY W. A. Harris	4 Dec. 1975
APPROVED BY PROJECT ENGR. R. E. Stiles	4 Dec. 1975
J. C. Powell	4 Dec. 1975
R. N. Schmidt	4 Dec. 1975

REVISIONS

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1.0 SCOPE

This specification establishes the performance, design and test requirements for a Solar Simulator to be used in Subsystem Research Experiment (SRE) Testing of the Solar Cavity Receiver.

2.0 APPLICABLE DOCUMENTS

a. Minnesota Uniform Building Code
b. ANSI Standards
c. OSHA
d. National Fire Protection Assn. Codes
e. National Electrical Code

3.0 REQUIREMENTS

3.1 Solar Simulator Definition

The solar simulator will be used to introduce up to 5 MW of radiant heat into the receiver cavity during SRE tests. The radiant heating system will simulate the redirected solar energy entering the receiver cavity from a heliostat field. The inside cavity of the solar receiver will be irradiated with an array of rapid responding tubular quartz tungsten filament infrared radiant heat lamps.

The heat lamp array will be mounted on a tower structure for insertion into the receiver cavity. The lamp tower will be

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elevated into the receiver cavity and mounted on the receiver support structure. A lower edge reflector (cover-plate) will be provided on the base of the lamp tower to prevent excessive reradiated heat leakage from the receiver. This cover plate or annulus cover, the lamp tower structure and the lamp controllers will be water cooled.

The heat lamp array will be divided into cylindrical zones, Power dissipation in each zone will be independently controlled by programmer or manual inputs. Flux distribution profiles will be realized by lamp density (number of lamps radiating to a unit area of receiver wall). The original cylindrical zone control configuration will be capable of field modification by changing the controller/array wiring. This field modification will change the cylindrical zones to vertical (a partial arc of the full array height) control zones.

3.1.1 Solar Simulator

Figure 1 is a schematic of the solar simulator with its controls and interfaces.

3.1.2 Interface Definition

The electrical, functional and physical interface between the solar simulator and the solar cavity receiver/SRE test configuration are as follows:

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3.1.2.1 Electrical Power

3.1.2.1.1 Control Cabinet Assembly

115 VRMS, 60 Hz single phase, 20 Amps.

3.1.2.1.2 Zone Power Controllers

a) (TBD)VRMS, 60 Hz, 3 phase Y connected (TBD) amps max/phase/controller (TBD)KVA, max input power.

b) A remote indicating power meter will be provided on each controller. The measurement terminals will be on control console.

c) Circuit breaker (overload) protection will be provided at the substation output and need not be included with the zone controllers. A 24 VDC trip switch (emergency stop) will be on the control console to open the substation circuit breaker.

3.1.2.2 Cooling Water

a) Lamp array/annulus cover 180 gpm flow 68°C temp. rise.

b) Zone power controllers 20 gpm flow/controller 68°C temp. rise.

c) Inlet temperature range 0°C to +30°C (+32°F to +86°F).

3.1.2.3 System Component Interconnections

a) Control Console/Power Controllers 40 foot (min.) signal cable with connector(s) to allow complete disconnect at one or both ends.

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3.1.2.3 System Component Interconnections (continued)

b) Power Controllers/Lamp Array
Power leads will be installed when the array is erected in the receiver. Lead length will be determined by exact placement of controllers relative to lamp array: estimated lead length 30 ft.

3.1.2.4 Physical Interface: Simulator Tower Structure to Receiver Cavity.

3.1.2.4.1 Installation

a) Suitable hard points will be built into the simulator tower structure to facilitate positioning and inserting into the receiver cavity.
b) Final assembly of the tower structure may be done during positioning and insertion into the receiver cavity.

3.1.2.4.2 Simulator Tower Dimensions and Mounting

a) The lamp array dimensions and position relative to the receiver cavity will be derived from the radiated heat profile requirements (Sec. 3.2.1.2).
b) The simulator tower must be insertable given the clearance distance shown on Figure 2. (Simulator Tower Installation Diagram).
c) Mounting dimensions for the solar simulator tower structure are shown on Figure 2.

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3.1.2.5 Instrumentation and Test Points

a) A load voltmeter and ammeter or a watt meter will be provided on each zone power controller for local display.

b) Terminals will be provided at the control console to measure the lamp array input power per zone.

3.1.2.6 Simulator Controls

3.1.2.6.1 Control Console

The simulator control console will contain the following operational control features:

a) Circuit breaker for console.

b) Master run control panel with emergency stop switch.

c) One kilowatt controller per zone power controller.

d) One power vs. time programmer per zone power controller.

3.1.2.6.2 Power Controllers

The power controller will consist of one zone power controller per lamp array zone. The number of lamp array zones will be determined by the flux profile requirements of Section 3.2.1.2.

3.1.2.7 Support Equipment

Special tools and test equipment which is necessary to install, maintain or disassemble the solar simulator system will be provided as part of the system.

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3.2 Characteristics

3.2.1 Performance

3.2.1.1 Total Radiated Power

The total radiated power to the receiver cavity will be 5000 KW minimum. This total power is the sum of the lamp zone power inputs. Each zone will have a 20:1 minimum controlled power turn down ratio.

3.2.1.2 Radiated Power (Flux) Profile

The radiated power incident on the receiver is shown on the cavity flux profiles (Figures 3a & 3b). The radiated power levels shown will be realized by lamp placement or lamp densities.

3.2.1.3 Array Zone Orientation

The array shall be configured in cylindrical zones. Provisions shall be included to change the zone orientation to vertical zones (full array length and partial arc) by rewiring the power controller/ array connections. Instructions to perform this zone reorientation shall be included in the operating manual.

3.2.2 Physical Characteristics

The Simulator size and dimensions will be derived from the installation diagram (Figure 2) and the required Flux Profiles of paragraph 3.2.1.2

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3.2.3 Reliability

Consideration will be given to achieving high reliability in the solar simulator system design by allowing operating margins, using conservative design practices and standard parts where available.

3.2.4 Maintainability

Consideration will be given in the solar simulator system design to assure that required service can be accomplished by personnel of normal skills, with a minimum of nonstandard tooling or special equipment.

3.2.5 Operating Environment

The solar simulator system will be operated in an indoor environment. The maximum ambient temperature environment for the system except the annulus cover and lamp array is 41°C (105°F). The top of the annulus cover and the lamp array structure will be exposed to maximum receiver cavity temperature of 1400°F.

3.2.6 Transportability

Transportation of all elements of the solar simulator system to the SRE test site will be subject to all pertinent federal and state transportation regulations. The solar simulator may be shipped partially assembled as required.

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3.3 Design and Construction

The solar simulator system will be designed and constructed in accordance with the applicable National Fire Protection Assn. codes including the National Electrical code. Piping (cooling waters) will meet applicable codes. Structures, facilities and enclosures will be designed and constructed in accordance with the best engineering practices and the Standards of the American Institute of Steel Construction, Uniform Building Code and special state codes will be employed as appropriate.

3.3.1 Materials

The solar simulator system will be fabricated from materials as dictated by good engineering practice.

3.3.2 Nameplates

All components, instruments and controls unless defined by System drawings will have identifying markings or nameplates which will be permanently attached to the respective items.

3.3.3 Workmanship

The solar simulator system and all associated items will be constructed, fabricated and assembled in accordance with the best modern engineering, shop and field practices, consistent with cost and performance requirements.

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3.3.4 Interchangeability

Components, with standard tolerances where available, will be used to permit interchangeability for servicing. Satisfactory replacement parts will be available for the period of the SRE tests.

3.3.5 Safety

The solar simulator system will be designed to minimize safety hazards to operating and service personnel and the public. Electrical components will be insulated and grounded. All parts or components with elevated temperatures will be insulated against contact with or exposure to personnel. Safety override controls will be provided for servicing. All pertinent OSHA rules and regulations will be observed.

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.

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3.4.2 Instructions

Instructions shall cover assembly, installation, alignment, adjustment, checking, lubrication and maintenance. Operating instructions shall be included for startup, routine and normal operation, regulation and control, shutdown and emergency conditions. 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 list shall be provided.

3.5 Precedence

The order of precedence of requirements of the Solar Simulator system characteristics is as follows:

a) Performance

b) Safety

c) Cost

4.0 QUALITY ASSURANCE PROVISIONS

Verification of conformance to designs and drawings as approved by ERDA at the DDR is required prior to initiation of the system tests.

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4.1 Test Program

All tests will be approved by Honeywell Inc. These tests may be witnessed by ERDA or its representatives or the witnessing may be waived. In either case, substantive evidence of hardware compliance with all test requirements is required.

4.1.1 Engineering Test and Evaluation

The performance of the instrumentation and control system shall be measured to verify compliance with power level control requirements, cooling requirements, emergency responses, and ability to maintain total system control under variable test conditions.

4.1.2 Acceptance Tests

Full power testing of the solar simulator system can not be done prior to insertion into the solar receiver cavity. Limited testing shall be performed prior to receiver insertion. Full power testing shall be conducted after installation.

4.1.2.1 Limited Power Tests

The tests will be limited to a power level which just produces a visible glow in the lamps. Tests to be performed separately on each zone-zone controller will include the following:

a) Verify that all lamps in the zone are lighted. (Replace any defective lamps).

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b) Verify manual control function from zero to the limited power level.

c) Verify program control from zero to the limited power level.

d) Verify that the emergency stop switch on the control console trips the substation circuit breaker with each controller output at the limited power level. (Three separate tests).

e) Check the cooling water flow paths for leaks as well as proper cooling function considering the power level limit.

4.1.2.2 Rated Power Tests

Rated power testing will be performed after the array tower is inserted into the receiver cavity. Test data will be taken to verify the following operating conditions.

a) Total power output of the array is 5 MW min. (Total array power output shall be calculated from total power to the lamps less the tower cooling water losses).

b) At the 5 MW output level the lamp power inputs to each zone are balanced within $\pm$ 25%.

c) A 20:1 controlled turn down ratio is possible with either manual or program control.

d) The cooling water steady state temperature at the controller and array exits are less than 95^{o}C (203^{o}F) at the 5 MW output level.

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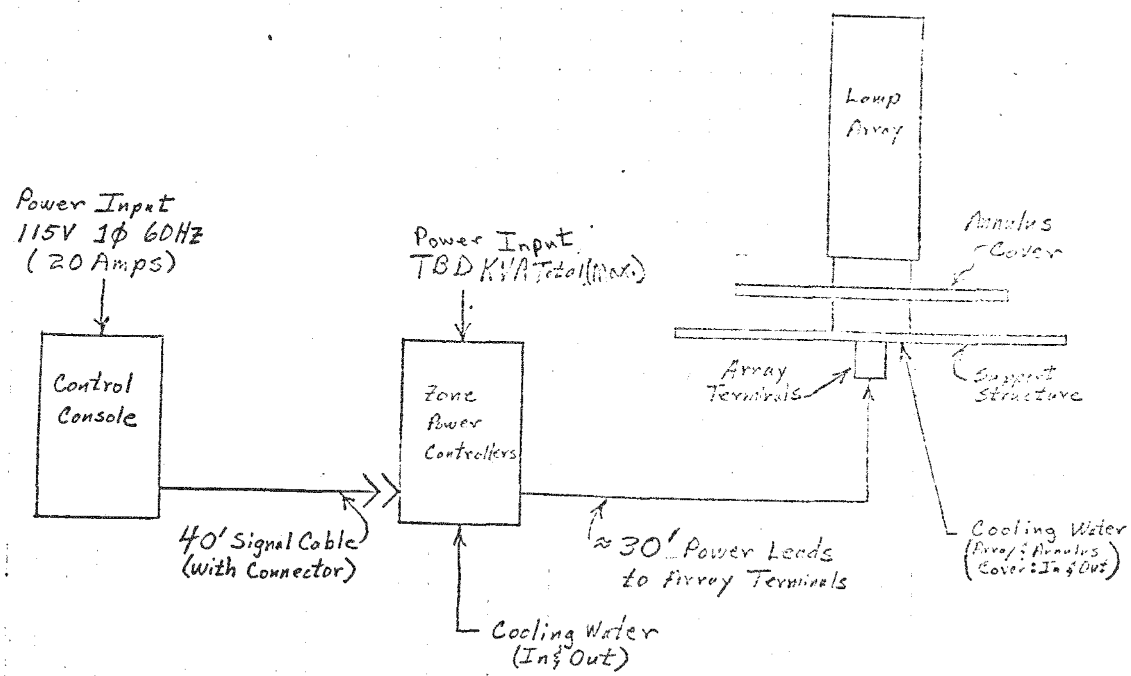

Figure 1 Solar Simulator System Schematic

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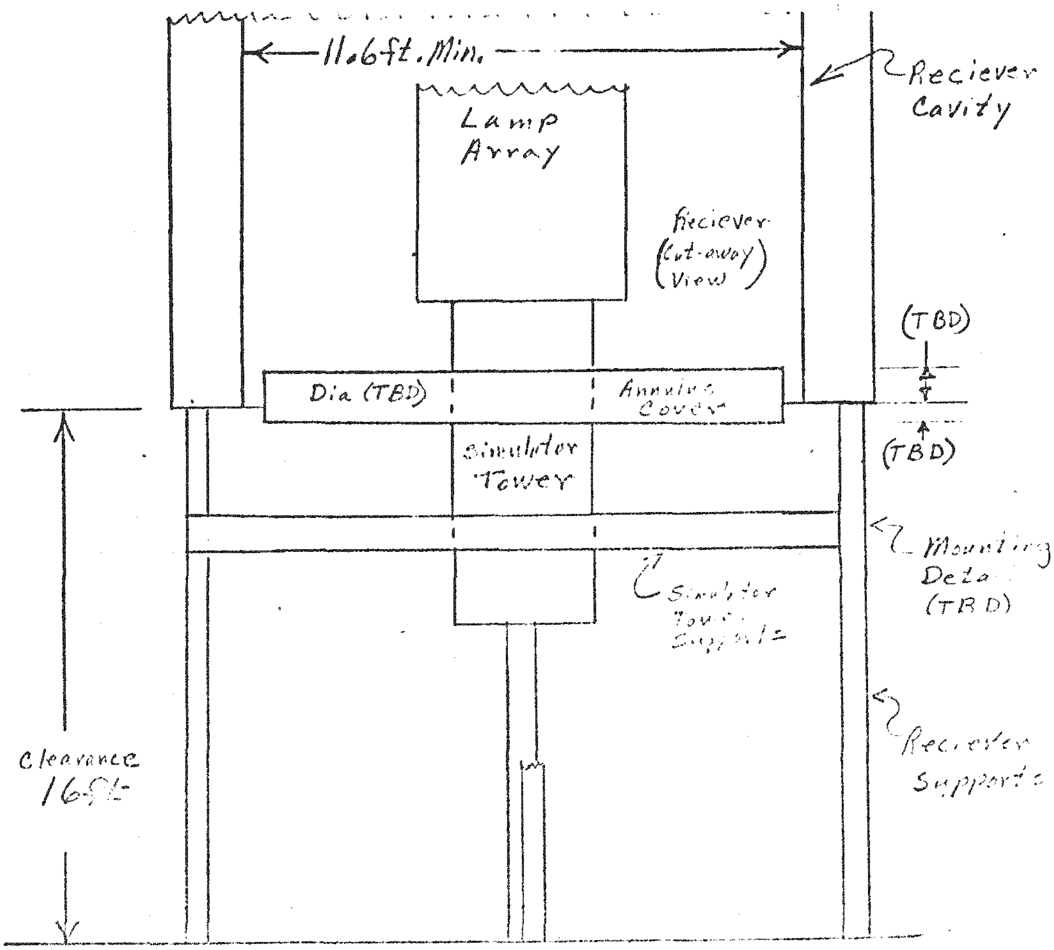

Figure 2 Simulator Tower Installation D

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Figure 3A CAVITY WALL [illegible] FLUX [illegible]
FOR 6/21 [illegible]

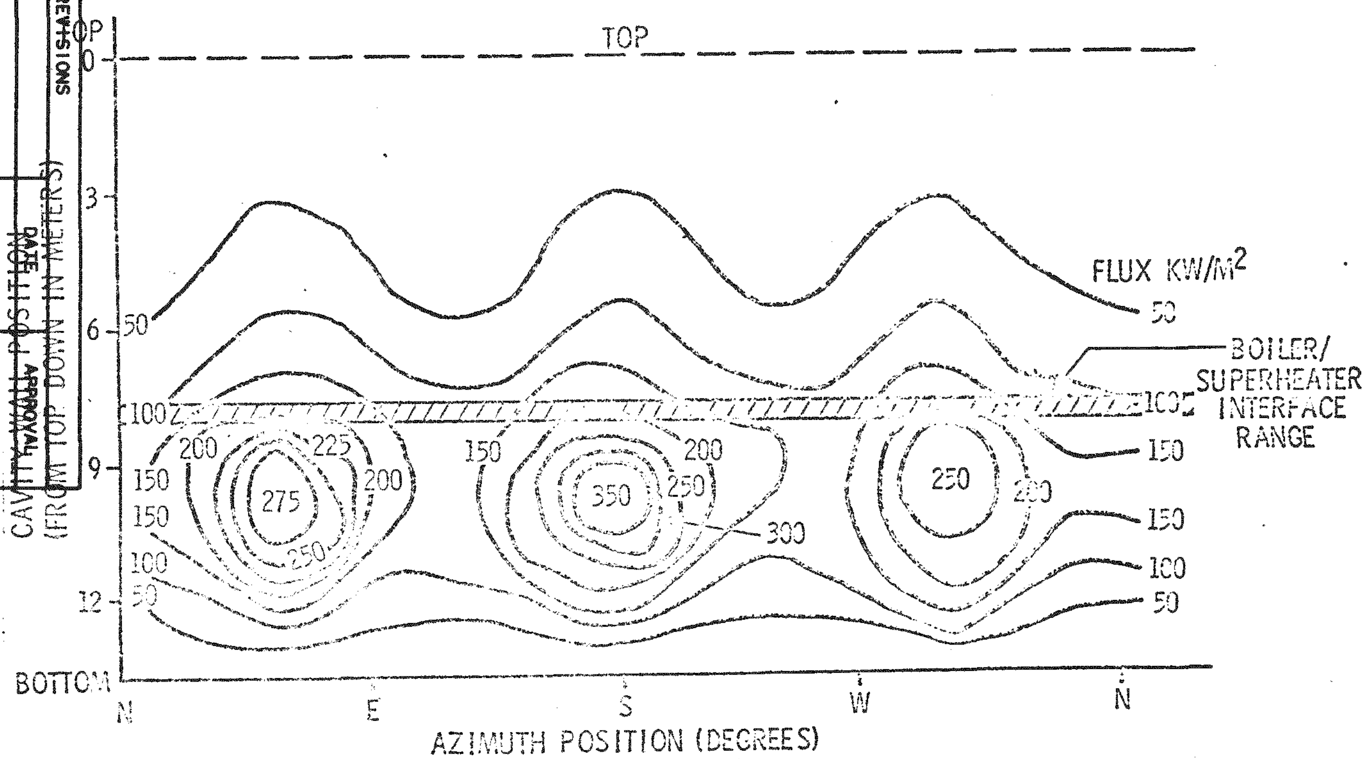

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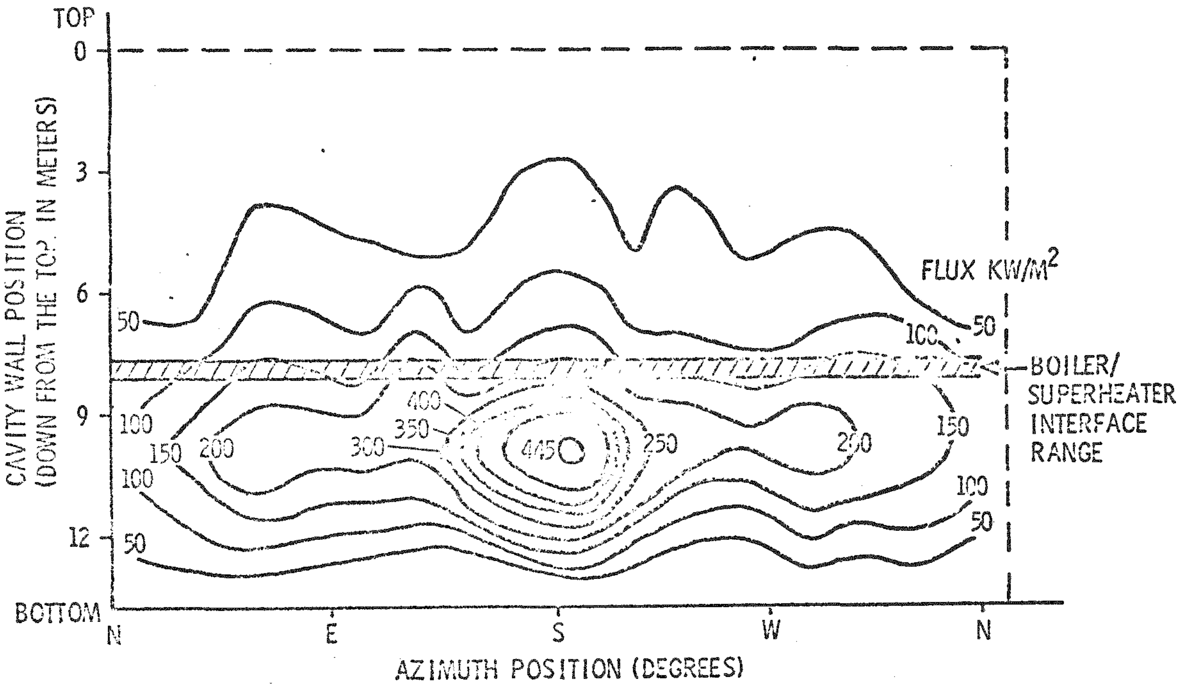
Figure 3 B CAVITY WALL INCIDENT FLUX MAP
FOR 12/21 NOON



APPENDIX H

SOFTWARE, DATA ACQUISITION SYSTEM (DAC), SOLAR POWER PLANT SYSTEM RESEARCH EXPERIMENT (SRE)

Honeywell

SYSTEMS & RESEARCH CENTER Code Ident No. 27327

HONEYWELL REQUIREMENTS SPECIFICATION NO. HRS SK 133245

THIS HONEYWELL REQUIREMENTS SPECIFICATION IS FOR:

SOFTWARE, DATA ACQUISITION SYSTEM
(DAC), SOLAR POWER PLANT
SYSTEM RESEARCH EXPERIMENT (SRE)

SIGNATURES	DATE
PREPARED BY W. A. Harris	
APPROVED BY PROJECT ENGR. R. E. Stiles	
J. C. Powell	

R. N. Schmidt

REVISIONS

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1.0 SCOPE

The software described in this specification will be designed to operate on a System 700 computer which will control a data acquisition system (DAC). The DAC will monitor two separate Subsystem Research Experiment (SRE) test sequences of a Solar Power Plant. The two test sequences, solar cavity receiver and thermal storage, will be interlaced but will not be performed simultaneously, The computer software will manage real-time measurement of up to 600 analog inputs. Real-time limit comparisons of each input point will be performed. Warning or alarm messages will be displayed based on the limit comparison results. Alarm conditions will initiate, through software control, emergency test actions such as power shut-off. All measured data will be sorted, converted to process dimensions, reduced and partially analyzed to provide real-time engineering data displays. At the conclusion of a test sequence all data will be available for tabulated and/or graphic print out. Final data analysis or formatting may also be done under computer software control at the test sequence conclusion.

1.1 Identification

Nomenclature and authorized abbreviations will be defined by cognizant personnel as the software program is developed.

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2.0 APPLICABLE DOCUMENTS

The following documents of exact issue shown, form a part of this specification to the extent specified herein.

- Applicable manuals describing the selected computer system.
- Applicable manuals or descriptions of software subroutines used which are not specifically written for this program.

3.0 REQUIREMENTS

The computer software shall be written such that the DAC system will provide real-time test status data for the Receiver and Thermal Storage SRE tests. Software generated limit comparisons will activate applicable emergency procedures. Hard copy data outputs will be provided after the test sequence is completed.

3.1 Program Definition

The major functions of the computer programs during the Solar Receiver or Thermal Storage SRE tests are the following:

3.1.1 Measure all analog test points.

3.1.2 Convert each measured voltage to process dimensions (temperature, pressure, etc.).

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3.1.3 Perform limit comparisons for each measurement's level and rate of change. Provide warning or alarm messages as determined by the results of the limit comparisons.

3.1.4 Initiate emergency actions for alarm limit conditions.

3.1.5 Sort and store all measured data.

3.1.6 Reduce and analyze data as required to provide real-time engineering data to describe the test status and trends.

3.1.7 Lineprinter operational priority will be: alarm messages, warning messages and engineering data respectively.

3.1.8 Any set of measured or calculated (stored) data may be commanded to output by instructions from the teleprinter keyboard or tape reader. The outputs will be available on either the CRT, teleprinter or the lineprinter/plotter (subject to priority limitation of 3.1.7).

3.2 Detailed Functional Requirements

3.2.1 Inputs

3.2.1.1 Analog inputs

The Solar Receiver SRE test will have about 600 test points.

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3.2.1.1 Analog Inputs (continued)

The Thermal Storage SRE test will have about 140 test points. A connector assembly will be used such that all Thermal Storage test points will be connected to similar input points vacated by removing the Solar Receiver test connector. The test points will be combinations of the following:

- K Type Thermocouples (0 to 30 MVDC)
- Pressure Transducers (1 to 5 VDC)
- Flow Transducers (1 to 5 VDC or 4 to 20 ma)
- Displacement Transducers (0 to 4 VDC)
- Liquid Level Transducers (1 to 5 VDC)
- Strain Gages (0 to 0.1 VDC)

3.2.1.2 Digital Inputs

Operational digital inputs will be from:

- Teleprinter keyboard (operator)
- Teleprinter tape reader

3.2.2 Processing

3.2.2.1 Memory Requirement: 64K 16-Bit words

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3.2.2.2 Bulk Storage Requirement:

Disk and/or magnetic tape
7.2M16-Bit words

3.2.2.3 Measurement cycle time design goal is 5 seconds.

3.2.3 Outputs

3.2.3.1 Engineering data to operator via CRT, lineprinter/plotter and/or teleprinter (real-time as well as post test records).

3.2.3.2 Alarm and warning messages to operator via lineprinter/plotter.

3.2.3.3 Relay contacts suitable to mechanize alarm condition emergency actions.

3.2.4 Special Requirements

3.2.4.1 A quick disconnect assembly (connector) will be required to enable convenient change over from Thermal Storage SRE measurements to Solar Receiver SRE measurements.

3.2.4.2 A minimum of six , DMA Channels capable of simultaneous independent operation.

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3.2.4.3 A multiplexed input analog-to-digital converter capable of handeling the quantities and levels of analog input signals listed in Section 3.2.1.1.

3.3 Adaptation

The software will be adapted for use on a system 700 computer with sufficient peripheral devices to meet the requirements listed in this specification.

4.0 QUALITY ASSURANCE PROVISIONS

4.1 General

The program software shall be subjected to the following controls, examinations and tests to assure compliance with the requirements specified in Section 3.0 herein. The testing will be conducted at SRC, Minneapolis.

4.2 Responsibility For Tests

Honeywell, SRC Engineering will be responsible for conducting the software tests.

4.3 Quality Conformance

The software shall be inspected and tested to verify compliance with the specification requirements.

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4.3.1 Inspection

Examination of the documentation will be conducted for compliance with the specification requirements.

4.3.2 Testing

Testing will be conducted to demonstrate that the software compiles with the requirements of this specification.

5.0 PREPARATION FOR DELIVERY

The completed software will be delivered on 9 track magnetic tape. The tape reel(s) will be suitably protected to prevent physical damage during normal handling.

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APPENDIX I

PIPING AND INSTRUMENT DIAGRAMS

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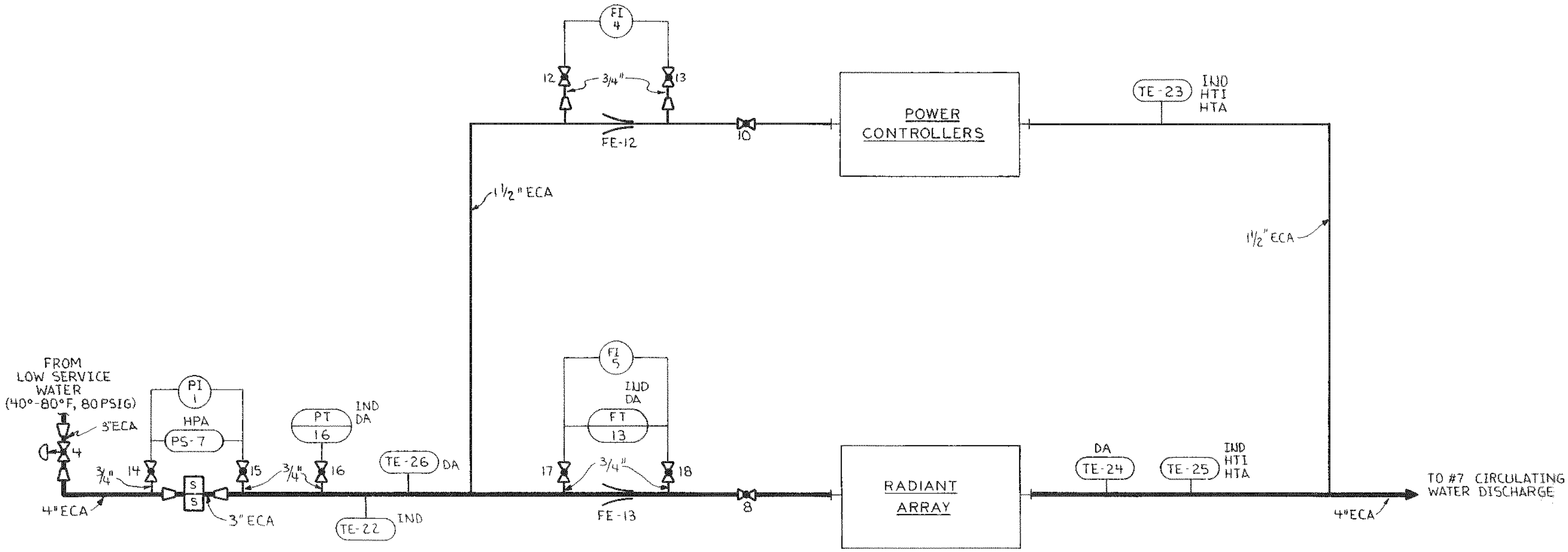

Figure I-1. Piping and Instrument Diagram Cooling Water System

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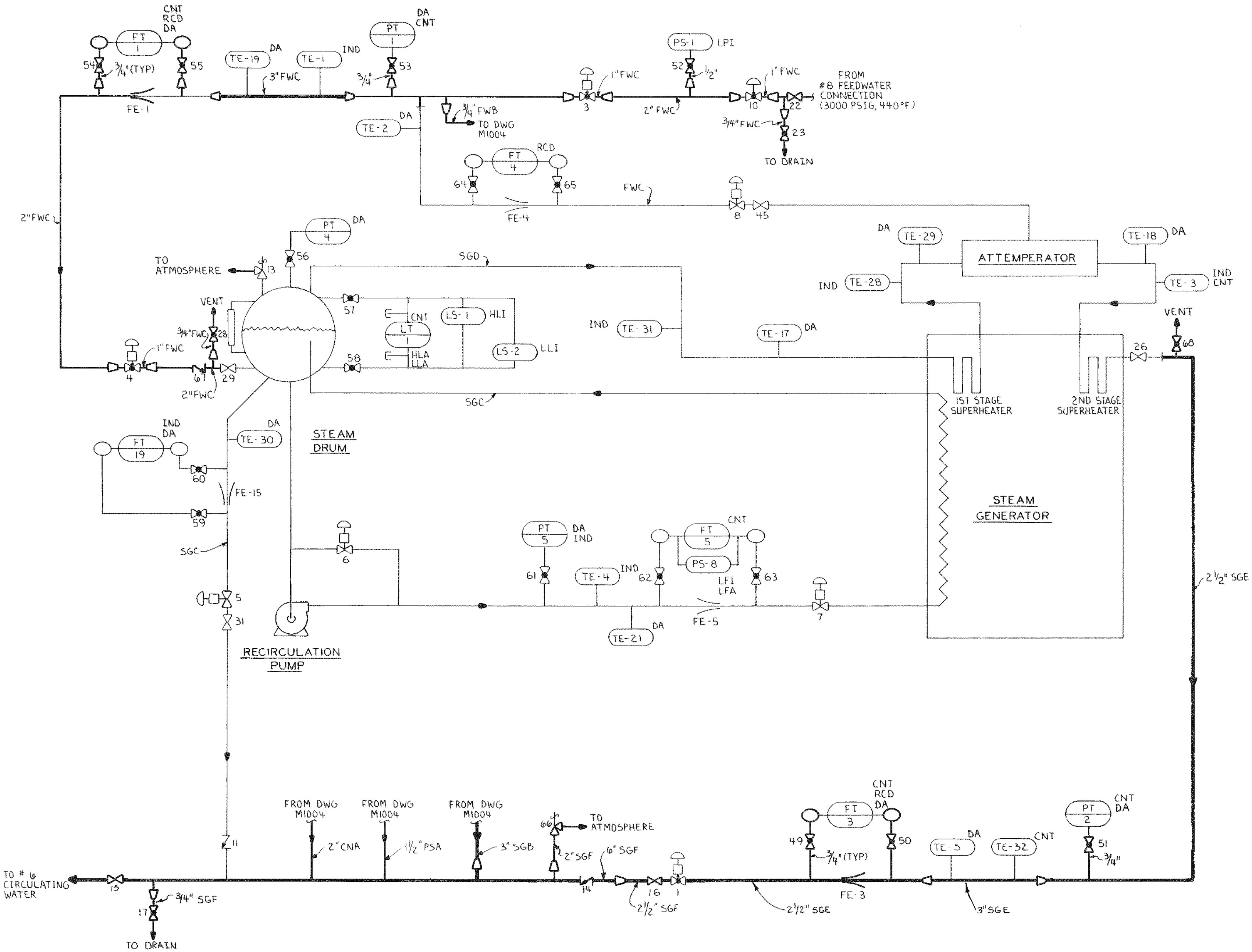

Figure I-2. Piping and Instrument Diagram Steam Generator SRE

APPENDIX J
STEAM GENERATOR SPECIFICATIONS

Honeywell

SYSTEMS & RESEARCH CENTER Code Ident No. 27327

HONEYWELL REQUIREMENTS SPECIFICATION NO. HRS

THIS HONEYWELL REQUIREMENTS SPECIFICATION IS FOR:

RECEIVER SUBSYSTEM STEAM GENERATOR REQUIREMENTS SPECIFICATION FOR SUBSYSTEM RESEARCH EXPERIMENT ON THE CENTRAL RECEIVER SOLAR THERMAL POWER SYSTEM

SIGNATURES	DATE
PREPARED BY	
APPROVED BY PROJECT ENGR.	

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1.0 SCOPE

This specification establishes the performance and design requirement for the steam generator for the research experiment, hereinafter referred to as the SRE steam generator.

2.0 APPLICABLE DOCUMENTS

The following documents of the latest issue 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.

- American Society of Mechanical Engineers, Boiler and Pressure Vessel Code:

SECTION I	Rules for Construction of Power Boilers
SECTION II	Material Specifications
SECTION V	Nondestructive Examination
SECTION IX	Welding and Brazing Qualifications

- American National Standards Institute
  B31.1 Power Piping
- Standards of the American Institute of Steel Construction, American Concrete Institute
- Interstate Commerce Commission
  Shipping Standards and Regulations

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- Uniform Building Code
- American Society of Testing (ASTM) Construction Codes
- Standards of the National Electrical Manufacturers Association

3.0 REQUIREMENTS

3.1 SRE Steam Generator Definition

The SRE steam generator for the research experiment is a small-scale configuration leading to the design of steam generator subsystems for pilot plant and commercial versions of the Central Receiver Solar-Thermal Power System. The SRE steam generator will be operated in the ground environment, but in later program phases may be operated in a tower environment at the Solar Thermal Test Facility (STTF). The steam generator will consist of:

- A 5 MWt maximum heat input to the cavity of the steam generator with boiler/superheater, drums, valves and actuators, instrumentation (e.g. low water indication, recirculating pump monitoring, temperature indication) insulation and thermal protection;

- Steam generator support structure, fluid and service interface connections.

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3.2 Steam/Water Operating Conditions

3.2.1 Pressure/Temperature/Flow

Steam/water operating conditions for the SRE steam generator at maximum load are to be as follows:

- Feedwater at drum inlet and at all spray attemperation points: 440°F
- Drum operating pressure: 1775 psig
- Boiler and superheater design pressure: 1875 psig
- Steam pressure at superheater outlet: 1575 psig
- Steam temperature at superheater outlet: 955°F
- Steam flow: 16,064 lb/hr.

3.2.2 Feedwater Chemistry

The SRE steam generator will operate with feedwater conditions as follows:

pH	9.0 - 9.5
Oxygen, O_2, ppm	0.007
Iron, Fe, ppm	0.01 max.
Copper, Cu, ppm	0.005 max
SiO_2, ppm	0.02 max
Total Hardness, ppm	Detection Limit
Organics, ppm	Detection Limit
Total Solids, ppm	0.05 max

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3.3 Physical Requirements and Features

3.3.1 Size/Form

3.3.1.1 Boiler/Superheater

The cavity dimensions of the SRE steam generator are to be as follows:

- Inner diameter (boiler & superheater): 11.42 ft.
- Height of boiler section: 5.71 ft.
- Height of first stage superheater section: 3.33 ft.
- Height of second stage superheater section: 3.33 ft.

3.3.1.2 Structural

The support structure of the SRE steam generator will consist of a nine-sided polygon frame supported by three vertical equiangularly placed, legs corresponding to corbel positions in the tower installation. The boiler and superheater sections of the steam generator will be hung from the support structure to allow for their un-restrained expansion. The circle diameter inscribing the support structure will be about 16 feet; the height of the support structure will be about 30 feet. The three vertical legs will be flanged, or jointed, to accomodate ground installation and solar simulator installation clearances, or tower mounting where the solar simulator and legs are not used. Installation clearance shall be provided to accomodate the 12-foot base diameter, 10-foot lamp array (top) diameter, and 16-foot clearance height of the solar simulator.

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3.3.2 Structural/Piping Features

3.3.2.1 Piping Support/Termination

The steam generator feedwater line, attemperator inlet line, and superheater outlet line as well as water sample lines, blow-down and vent lines, are to be terminated at, and supported by, the steam generator support structure. Connection configurations of these terminations are (TBD) and are to be compatible with either ground or tower installation.

3.3.2.2 Structural Support

The steam generator support structure is to be designed to be self-supporting and mounted on a suitable foundation. Foundation loading is (TBD).

3.3.3 Auxiliaries and Supporting Services

3.3.3.1 Recirculating Pump

The recirculating pump is to be located adjacent to the steam generator on a suitable foundation. The driving motor for the pump is to operate on 3-phase, 480 volt power. The recirculation pump will be mounted in the tower at the STTF.

3.3.3.2 Auxiliary Services

The following functions and services will be furnished to the subcontractor for the operation of the steam generator and are external to the steam generator.

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- A sink for the generated steam;
- A feedwater supply;
- 3-phase 480 volt electrical power for the recirculating pump. Pump power requirements to be specified by the sub-contractor.
- Readout instrumentation and control for the actuators provided by the sub-contractor.
- A radiant heater (solar simulator) for operation within the steam generator cavity.
- Electrical power and compressed air (delivery requirements to be specified by the sub-contractor) for operation of steam generator controls and instruments.
- Isothermal environment for thermocouple junctions for measurements throughout the steam generator.

3.3.4 Instrumentation

Control valves for operation of the SRE steam generator will be pneumatically operated using positioners responding to standard 4 to 20 milliampere control signals. Measurements of steam and water conditions will be done using electrical transmission with standard 4 - 20 milliampere signals. Measurement of metal temperatures may be made using thermocouples. Requirements for junction temperature referencing are to be specified by the sub-contractor.

Provision will be made for the following measurements:

- Metal temperatures throughout the boiler and superheater areas to determine operating values, heat fluxes, and heat losses.

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- Steam temperatures at drum, attemperator, and superheater outlets.
- Drum pressure, level, and alarm levels
- Mass flows: recirculation, steam delivery, blow-down.
- Boiler panel mass flow distribution
- Thermal expansion of steam generator structure and piping.

3.3.5 Thermal

3.3.5.1 Radiant Flux Input

The solar simulator will supply radiation within the SRE steam generator cavity as shown in Figures J-1 and J-2. The total radiated power to the cavity will be 5000 KW maximum. Three vertically situated, radiation zones will be provided by the solar simulator each having a maximum flux level of 1667 kilowatts and with approximate vertical dimensions as follows:

Lower:	3.6 feet
Intermediate:	1.9 feet
Upper:	6.6 feet

The radiation will be provided by arrays of tungsten filament lamps. Flux distribution according to Figures 1 and 2 will be provided by lamp spacing. Each of the three zones will have at least a 20:1 power turn-down capability.

3.3.5.2 Heat Losses

The heat losses through the insulation of the steam generator while operating at 5 MW thermal input are to be estimated by the subcontractor assuming an indoor installation (room conditions).

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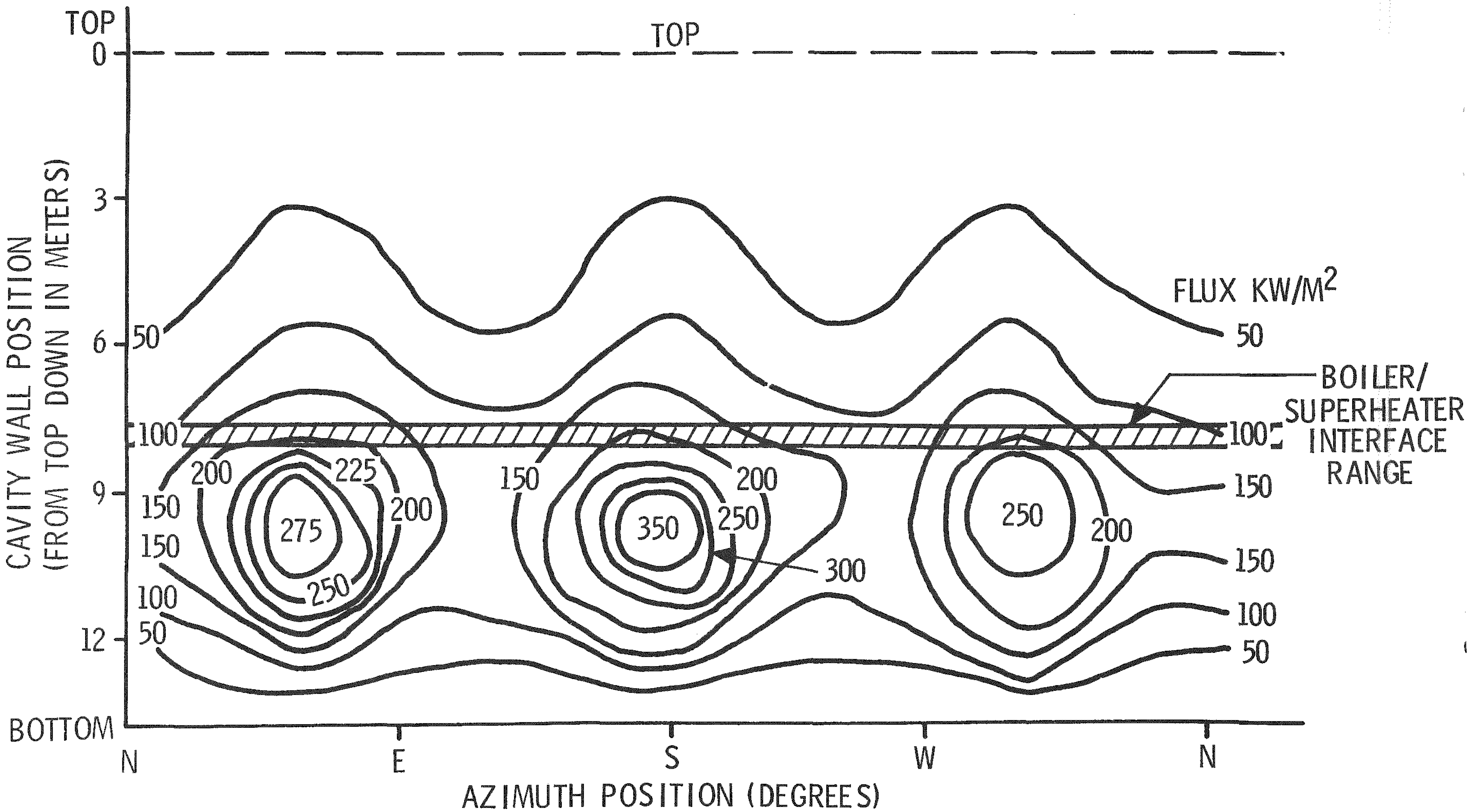

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Figure J-1. Cavity Wall Incident Flux Map for 6/21 Noon

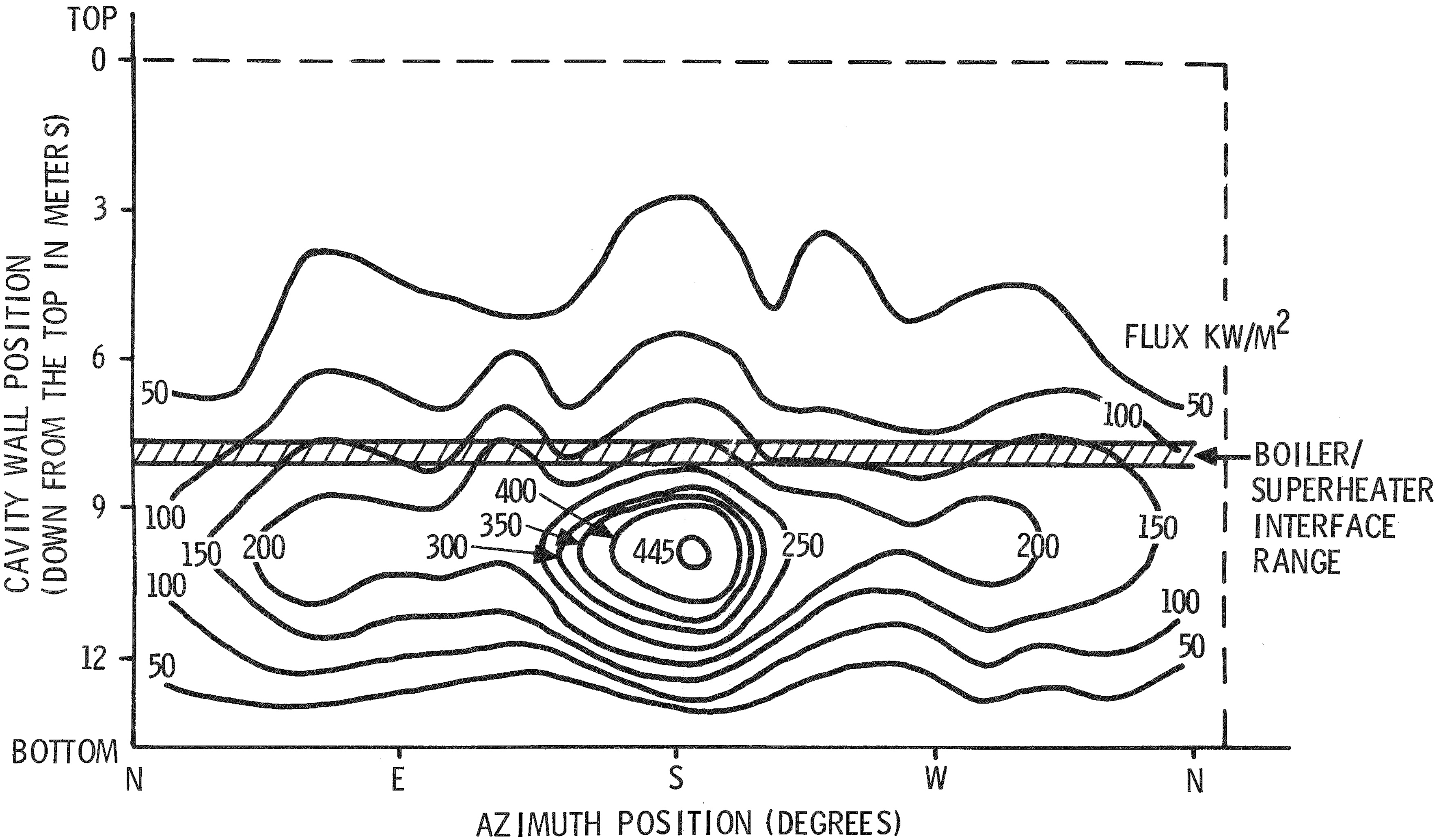

Figure J-2. Cavity Wall Incident Flux Map for 12/21 Noon

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3.3.6 Operating Constraints

The SRE steam generator will be designed to accomodate the following operating constraints:

Steam delivery range:	13 to 1
Variable pressure operation:	Startup and shutdown only
Variable superheat operation:	Startup and shutdown only
Variable feedwater-temperature:	None(FW temperature is constant)
Start-up Time:	
Cold	3 hours
From hot standby (overnight shutdown)	TBD
Number of hot & cold start-ups	TBD
Number of emergency shutdowns	TBD

3.3.7 SRE/Pilot Plant Steam Generator Scaling

Criteria that determine the scaling law for cavity dimensions will be that the magnitude and distribution of the absorbed heat flux be identical for the Pilot Plant and SRE steam generator. The linear cavity dimensions will be scaled by a factor of 3.32, (the square root of the power ratio 55:5). Local fluid and metal temperatures will be equal in the Pilot Plant and SRE steam generators requiring that the flow circuitry of the two generators be identical and that fluid flow be scaled directly with the power ratio; i.e. steam flow at noon summer solstice will be 176,700 lb/hr for the Pilot Plant and 16,064 lb/hr for the SRE steam generator.

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3.4 Reliability and Maintainability

High reliability will be achieved by selecting materials and components known to be reliable at the intended operating conditions and by using conservative design practices. Consideration will be given in the steam generator design to assure that required service can be accomplished by personnel of normal skills, with a minimum of non-standard tooling or special equipment.

3.5 Environmental Conditions

The SRE steam generator shall be designed to withstand ambient temperature exposure from -20°C to +60°C and earthquakes of Zone 3 intensity. It will be protected from damage to snow, ice, rain, hail, lightning and sand storms by a protective housing. The subcontractor should consider wind loading in the tower environment at the STTF. The stress in structural members under peak wind load will not exceed the yield strength of the material provided the ultimate strength of the material is at least 30% greater than the yield strength. The peak wind load is based on a 50-year expected maximum at the STTF (i.e. 1 in 25 million that winds will exceed 90 mph steady at 30 feet elevation with gusts to 105 mph or 118 mph steady at 200 feet with gusts to 138 mph).

The SRE steam generator instrument and control circuits will be shielded from electrical distrubances and currents including those caused by the solar simulator and those caused by the

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building grounding circuits during severe thunderstorms.

The SRE steam generator will be designed for a life time of 30 years.

3.6 Design Practice and Codes

3.6.1 Applicable Codes

The steam generator will be designed and constructed in accordance with the ASME Boiler and Pressure Vessel Code, Sections I, II, V and IX. Consideration will be given to incorporating the design principles of Section III, Code Case 1592, of the code, to assess the potential of creep-fatigue failure. The support structure will be designed and constructed in accordance with good engineering procedures and the standards of the American Institute of Steel Construction as appropriate. The recirculating pump will be specified and installed in accordance with the Hydraulics Institute Standards as appropriate.

3.6.2 Materials

The steam generator and piping shall be fabricated from materials as specified in the ASME Boiler and Pressure Vessel Code, Sections I, II and ANSI B31.1. Materials shall be suitable for service conditions. 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, Uniform Building Code as applicable.

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3.6.3 Nameplates

All components, instruments, and controls shall have identifying markings or nameplates which shall be permanently attached to the respective items.

3.6.4 Workmanship

The steam generator and associated equipment will be fabricated and assembled in accordance with the practices required by the applicable codes and standards.

3.6.5 Safety

Insulation will be provided for all parts or components with elevated temperatures exposed to personnel during access required for routine inspections, servicing, repair and maintenance procedures. All pertinent OSHA rules and regulations shall be observed.

3.7 Documentation

3.7.1 Performance Data

The steady-state operating characteristics of the steam generator at incident fluxes simulating summer solstice, winter solstice, and maximum azimuthal energy mal-distribution will be provided to the sub-contractor. The subcontractor will provide information as to steam generator functions, operating characteristics, limiting conditions, test data and performance curves as applicable.

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3.7.2 Operating Instructions

Instructions will be provided for operating the steam generator together with its auxiliaries. Alignment, adjustment, debugging, lubrication, and maintenance procedures for components will be provided. Recirculating pump operating instructions will be included for startup, normal operation, regulation and control, shutdown and emergency conditions. The manufacturer's operating information for the instruments and controls will be provided.

Performance Characteristics and limiting conditions for the steam generator shall be provided.

3.7.3 Design Records

Engineering and assembly drawings will be provided to show the construction of subcontractor designed equipment. Engineering data, wiring diagrams and parts lists will be provided.

4.0 QUALITY ASSURANCE PROVISION

4.1 Configuration and Performance Verification

Verification that the SRE steam generator conforms to the design as approved by Honeywell and ERDA at the Detail Design Review is required prior to performance testing. Quality assurance procedures required by the applicable codes in the design of the SRE steam generator will be documented. Substantive evidence of the design of components of the SRE steam generator will be

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furnished by the subcontractor. Testing by the subcontractor may be witnessed by Honeywell and ERDA representatives. Component performance prior to installation in the steam generator will be recorded, and a certification of performance will be supplied by the subcontractor. Test requirements will be specified by the subcontractor and a recommended test plan will be furnished.

4.2 Engineering Tests

Honeywell, assisted by the subcontractor, will conduct engineering tests on the steam generator. These tests will be conducted using a solar simulator as the radiant energy source to the steam generator cavity. The radiant flux levels will simulate those generated by an array of heliostats exposed to the sun during its annual and diurnal cycles. Performance acceptance of the SRE steam generator will be based upon these tests.

4.3 Hydrostatic and Mechanical Integrity

The steam generator will be subjected to a hydrostatic test prior to steaming in accordance with the ASME Boiler and Pressure Vessel Code. Mechanical integrity of the pressure-containing and structural parts of the steam generator will be demonstrated by design analysis, the results of subcontractor and supplier testing, and pre-operational check-out during and after erection at the engineering test site.

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4.4 Life Test and Analysis

4.4.1 Creep Rupture and Fatigue

Creep rupture and fatigue analysis will be carried out by the subcontractor in accordance with the ASME Boiler and Pressure Vessel Code for the design cycles specified by Honeywell.

4.4.2 Corrosion and Oxidation Rate

Corrosion and oxidation rates will be analyzed by the subcontractor for the design conditions specified by Honeywell using data available from standard references and the subcontractor's experience.

4.5 Instrument/Component Testing

The instruments furnished with the steam generator will be tested prior to use to verify correct performance and provide calibration data. Control valves will be stroked prior to use with the steam generator, and data will be provided as to stroke/flow response to a standard 4 - 20 milliampere input signal. Pumps will be checked out prior to engineering tests on the steam generator, and performance data (e.g. flow, head, rpm) will be supplied.

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4.6 Mean Time Before Failure

Mean time before failure/replacement (MTBF) analysis of steam generators shall be conducted to support Honeywell system effectiveness studies. The subcontractor shall document all failures both operating and non-operating prior to the engineering test program. The subcontractor shall assist Honeywell in determining the cause of failure of any subcontractor supplied pressure part or the steam generator support structure. Failure analysis data on commercially supplied hardware such as valves, pumps and instrumentation shall not be compiled unless the cause of failure warrants a review of such data.

4.7 Engineering Critical Component Qualification

Components for which reliability data are not available shall be subjected to sufficient qualification testing to estimate their impact on SRE steam generator MTBF.

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