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Molten Salt Steam Generator Subsystem Research Experiment Phase 1—Specification and Preliminary Design Final Report Volume II—Appendices

Babcock & Wilcox Company
Barberton, Ohio

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MOLTEN SALT STEAM GENERATOR

SUBSYSTEM RESEARCH EXPERIMENT

Phase I: Specification and Preliminary Design

Vol. 2 - Appendices

FINAL REPORT

Prepared for: Sandia National Laboratories
Livermore, California

Prepared by: The Babcock & Wilcox Company

Nuclear Equipment Division
Barberton, Ohio

and

Contract Research Division
Alliance, Ohio

Sandia Contract No. 20-9909A

TABLE OF CONTENTS

APPENDICES:

Appendix A

Steam Generator Subsystem Requirements Specification

STEAM GENERATOR SUBSYSTEM
REQUIREMENTS SPECIFICATION

FOR

MOLTEN SALT STEAM GENERATOR SYSTEM
SUBSYSTEM RESEARCH EXPERIMENT
(PHASE I)

Prepared For: Sandia National Laboratories
Livermore, California

Prepared By: The Babcock & Wilcox Company
Martin Marietta Corporation
Black & Veatch Consulting Engineers
Arizona Public Service Company

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TABLE OF CONTENTS

1.0 GENERAL

1.1 Scope - This specification defines the necessary requirements to design the molten salt steam generator subsystem (SGS) for:

- a 100 MWe solar stand-alone power plant
- a 50 MWe solar component of a 100 MWe fossil-fueled plant 50% repowered by solar energy.

The specification establishes the basis for the detailed design of the SGS.

1.2 Subsystem Description - The SGS consists of the following major components:

a. Preheater;
b. Evaporator;
c. Steam drum;
d. Boiler water recirculating pumps, piping, and valves;
e. Superheater;
f. Reheater;
g. Main steam and startup attemperators;
h. Salt, feedwater, and steam piping and valves;
i. Salt drain sump;
j. Salt drain sump pumps;
k. Thermal insulation and trace heating;
l. Foundations, component structural supports, and berm;
m. Controls and instrumentation.

The Steam Generator Subsystem (SGS) uses molten salt (60% $NaNO_3$, 40% KNO_3 by weight) as a heat transfer fluid and storage medium. The SGS is a forced recirculation system employing a separate preheater, evaporator, superheater, reheater and steam drum. Separate superheater, reheater, and evaporator components are mandated by the recirculating system and by the specification of a reheat turbine. A separate preheater results in a more economic utilization of the total heat transfer surface. The heat exchangers are horizontally oriented with both salt and water nozzles arranged to facilitate venting and draining.

The SGS flow schematic is shown in Figure 1. On the salt side, hot salt at 566°C (1050°F) is pumped from the hot salt tank and through the superheater and reheater in parallel. After delivering energy to these units the two flows are mixed to give 448°C (838°F) salt which is passed through the evaporator where it is cooled to 336°C (637°F). The salt then flows through the preheater where it reaches its minimum temperature of 288°C (550°F) before being pumped back to the cold salt tank.

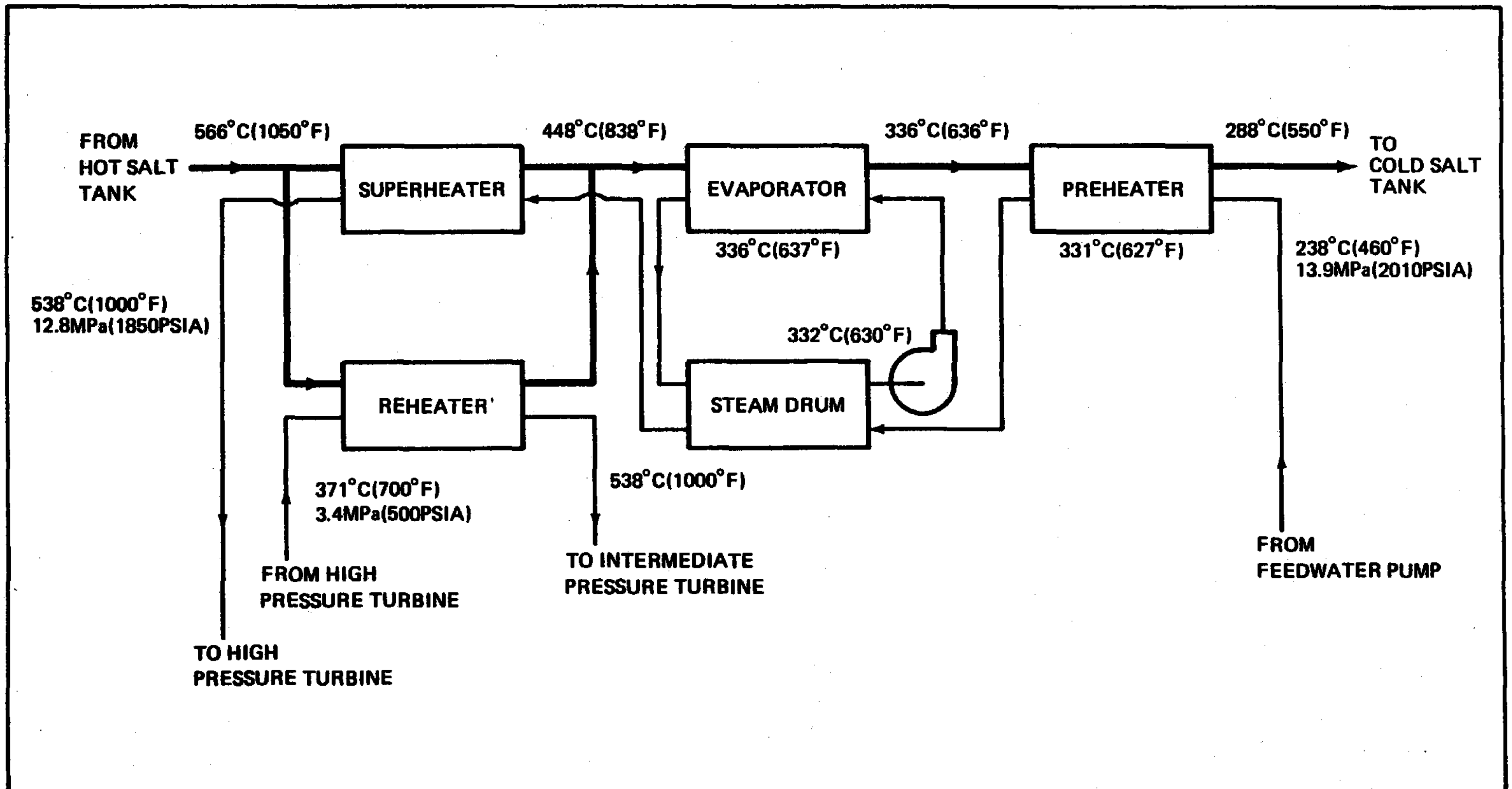


FIG. 1 STEAM GENERATOR SYBSYSTEM FLOW SCHEMATIC (100 MWe RECIRCULATING CYCLE)

On the steam/water side, boiler quality steam at 538°C (1000°F) and 12.8 MPa (1850 psia) leaves the superheater and is expanded through the high pressure turbine to 3.4 MPa (500 psia) and 371°C (700°F). The steam then flows through the reheater where it is reheated to 538°C (1000°F) before passing through the intermediate pressure turbine, low pressure turbine, condenser, and feedwater pump of the Electrical Power Generation Subsystem (EPGS).

The water is then returned to the preheater to be heated from 238°C (460°F) to 331°C (627°F) before entering the steam drum. Water from the steam drum is forced through the evaporator by the recirculation pump. The evaporator produces a high-quality water/steam mixture at 336°C (636°F) that is fed back to the steam drum. Saturated steam is separated from the steam/water mixture in the drum. It then flows to the superheater completing the cycle.

1.3 Definition of Terms and Abbreviations

1.3.1 Definitions

Attemperator - Apparatus for reducing and controlling the temperature of a superheated vapor.

Code - ASME Code.

Cold Shutdown - State when the steam generator subsystem is at ambient temperature with the salt side drained.

Fouling - The process of forming an encrusting layer which may be permeable or imperemable on the tube walls due to precipation of dissolved and suspended solids from the fluids or due to the insitu chemical reaction of the tube wall material with that of the fluids.

Hot Standby - The SGS will be maintained in hot standby for diurnal shutdown for both stand-alone and repowering applications:

a. Repowered - The SGS maintained at or very near the throttle pressure at which the Electric Power Generation System is operating;

b. Standalone - A term to imply that the SGS is at any condition of pressure and temperature between those existing when the turbine is tripped to a minimum condition described by warm standby. It is determined only by time since trip and SGS heat losses until warm standby is reached.

Steam Reheat - Steam leaving the high pressure stage of a turbine is reheated in a separate reheat superheater and returned at higher temperature and enthalpy to the low pressure stage.

Turndown Ratio - The ratio of the total thermal power transmitted from the salt system to the steam water system at specified full load power to that transmitted at the lowest load at which the system operates under fully automatic control.

Warm Standby - Describes the minimum temperature and associated saturation pressure condition in which the SGS will be maintained in the event of an extended turbine outage. It will be essentially isothermal at a few degrees below cold salt temperature.

1.3.2 Abbreviations

CR - Circulation Ratio;

DNB - Departure from Nucleate Boiling;

NDE - Non-Destructive Examination;

SGS - Steam Generator Subsystem;

TBD - To Be Determined;

TES - Thermal Energy Storage.

2.0 APPLICABLE DOCUMENTS

2.1 General - In addition to this specification, the equipment, materials, design, and construction of the steam generator subsystem shall comply with all federal, state, local and user standards, regulations, codes, laws, and ordinances currently applicable at the power plant site. These shall include, but not be limited to, the government and non-government documents listed below. If there is an overlap in, or conflict between, the requirements of these documents and the applicable federal, state, county, or municipal codes, laws, or ordinances, the applicable requirement which is the most stringent shall take precedence.

2.2 Government Documents

a. Specifications
- Regulations of the Occupational Safety and Health Administration (OSHA)
- International System of Units, NASA SP-7012, 2nd Revision.

b. Standards
- Applicable Human Engineering Design Criteria

2.3 Non-Government Documents

a. Standards and Codes
- Uniform Building Codes - 1979 Edition by International Conference of Building Officials
- ASME Boiler and Pressure Vessel Code
- Institute of Electrical and Electronic Engineers (IEEE) Standards as applicable
- National Fire Protection Association (NFPA) National Fire Design, Construction and Fabrication Standards
- Standards of ACI (American Concrete Institute)
- Standards of TEMA (Tubular Exchanger Association)
- Standards of ASTM (American Society of Testing Materials)
- Standards of NEMA (National Electrical Manufacturers Associaton)
- Standards of ICEA (Insulated Cable Engineers Association)
- Standards of AISC (American Institute of Steel Construction)
- ANSI B31.1 - Power Piping
- ANSI A58.1 - Building Code Requirements for Minimum Design Loads in Buildings and Other Structures
- ANSI B16.34 - Steel Valves, Flanged and Buttwelding Ends.

3.0 REQUIREMENTS

3.1 System Performance Requirements

3.1.1 Thermal Rating - The steam generator subsystem shall be designed for the following two (separate) applications:

a. 100 MWe - Recirculating Cycle, at 264.2 MWt overall thermal rating (Stand-alone);

b. 50 MWe - Recirculating Cycle, at 132.1 MWt overall thermal rating (Fossil-Fueled 50% repowered).

3.1.2 Operating Life - The SGS components shall be designed for a 30 year operating life and 95 percent availability.

3.1.3 Steam Conditions - The steam generator subsystem shall be capable of producing superheated steam at 538°C (1000°F) and 12,517 kPa (1,815 psia) and reheat steam at 538°C (1000°F) and 3,448 kPa (500 psia), with a feedwater preheat inlet temperature of 238°C (460°F).

3.1.4 Heat Transfer Fluid - The heat transfer fluid (heat source) shall be molten salt consisting of 60% $NaNO_3$ and 40% KNO_3 by weight. The thermophysical properties shown in Table 1a were used for the Phase I analysis. Sandia has very recently revised this data in accordance with the results of new tests. This revised data is shown in Table 1b and, for future analyses, should supersede that shown in Table 1a.

Table 1a Thermophysical Properties of Molten Salt (60% $NaNO_3$ - 40% KNO_3)
(used for Phase I analyses)

TEMP. °C(°F)	DENSITY $\frac{kg}{m^3}$ ($\frac{lb}{ft^3}$)	SPECIFIC HEAT $\frac{J}{kg\text{-}°C}$ ($\frac{BTU}{lb\text{-}°F}$)	VISCOSITY MPa-sec ($\frac{lb}{ft\text{-}hr}$)	THERMAL CONDUCTIVITY $\frac{W}{m}$-°C ($\frac{BTU}{hr\text{-}ft\text{-}°F}$)	COEFFICIENT OF THERMAL EXPANSION X10^4 $\frac{1}{°K}$
Solid					
38(100)	1922(119.8)	1553.3(0.371)		.363(.210)	
93(199)	1922(119.9)	1553.3(0.371)		.363(.210)	
	(Ref. 1)	(Ref. 1)		(Ref. 1)	
Liquid					
300(572)	1879(117.2)	1660.7(0.397)	3.22(7.79)	.500(.289)	3.4
350(662)	1848(115.4)	1628.2(0.389)	2.29(5.54)	.510(.295)	3.5
400(752)	1818(113.5)	1595.6(0.381)	1.80(4.35)	.519(.300)	3.5
450(842)	1787(111.5)	1563.0(0.374)	1.43(3.46)	.529(.306)	3.6
500(932)	1756(109.6)	1530.5(0.366)	1.21(2.93)	.539(.312)	3.6
550(1022)	1726(107.8)	1497.9(0.358)	1.05(2.54)	.548(.317)	3.7
600(1112)	1695(105.8)	1465 (0.350)	.93(2.25)	.558(.323)	3.7
	(Ref. 2)	(Ref. 2)	(Ref. 2)	(Ref. 2)	(Ref. 3)

Table 1b Thermophysical Properties of Molten Salt (60% NaNo$_3$ - 40% KNO_3)
(revised)

TEMP. °C(°F)	DENSITY	SPECIFIC HEAT	VISCOSITY
Liquid			
300(572)	1903(118.8)	1495(0.357)	3.26(7.89)
350(662)	1870(116.8)	1503(0.359)	2.34(5.66)
400(752)	1838(114.8)	1511(0.361)	1.78(4.31)
450(842)	1805(112.7)	1520(0.363)	1.47(3.56)
500(932)	1772(110.7)	1532(0.366)	1.31(3.17)
550(1022)	1739(108.6)	1541(0.368)	1.19(2.88)
600(1112)	1706(106.5)	1549(0.370)	0.99(2.40)

Ref. 1 "Molten Nitrate Salt Technology Development Status Report" SAND 80-8052, March 1981.

Ref. 2 "Background for Preparation of Quotes Dealing With Molten Salt Steam Generator SRE".

Ref. 3 "Alternate Central Receiver Power System, Phase II", Final Report, Contract Sandia-18-6879C, May 1981.

3.1.5 Molten Salt Temperatures - The salt-side temperatures associated with the steam conditions specified under 3.1.3 are as follows:

a. Salt inlet to SGS: 565 ± 11°C (1050 ± 20°F);
b. Salt leaving SGS: 288 ± 11°C (550 ± 20°F).

3.1.6 Water Quality - Preliminary water quality standards are identified in table 2:

Table 2 Water Quality Standards

Item	Feedwater Recommended Values*	Item	Boiler Water Without Condensate Polishing
Oxygen	.007 ppm max.	Total Solids	15 ppm max.
Iron	.010 ppm max.	PO_4	3-10 ppm
		Na/PO_4 (mole ratio)	2.6
Copper	.005 ppm max.	OH	1.0 ppm max.
Hardness	0 ppm**	pH @ 25°C(77°F)	9.2-9.7
CO_2	0 ppm**	Silica	As determined by drum pressure
Organic	0 ppm**		
pH @ 25°C (77°F)	8.8-9.2 (Copper Alloy Preboiler System) 9.2-9.5 (Copper Free Preboiler System)		

*Measurement made at preheater inlet.
** Below Detectable Limits

3.1.7 Component Heat Exchanger Performance - The performance characteristics of the four heat exchangers comprising the SGS shall be consistent with the overall SGS requirements specified above, with thermal ratings, and temperature allocations approximately as shown in Table 3:

Table 3 Subsystem Performance Characteristics

100 MWe Recirculating Cycle

	Preheater	Evaporator	Superheater	Reheater
Thermal Rating MWt	48.1	107.8	76.3	32.0
Molten Salt				
Inlet Temp. °C (°F)	336 (637)	448 (838)	566 (1050)	566 (1050)
Outlet Temp. °C (°F)	288 (550)	336 (637)	448 (838)	448 (838)
Flow Rate $\frac{kg}{sec}$ $\frac{lb \times 10^{-6}}{hr}$	603 (4.78)	603 (4.78)	425 (3.37)	178 (1.41)
Steam/Water				
Inlet Temp. °C (°F)	238 (460)	332 (630)	336 (636)	371 (700)
Outlet Temp. °C (°F)	331 (627)	336 (636)	538 (1000)	538 (1000)
Outlet Press. MPa (Psia)	13.9 (2010)	13.9 (2010)	12.8 (1850)	3.4 (500)
Flow Rate $\frac{kg}{sec}$ $\frac{lb \times 10^{-6}}{hr}$	96.3 (0.764)	145 (1.146)	96.3 (0.764)	83.4 (0.662)

50 MWe Recirculating Cycle

	Preheater	Evaporator	Superheater	Reheater
Thermal Rating MWt	24.1	53.9	38.2	16.0
Molten Salt				
Inlet Temp. °C (°F)	336 (637)	448 (838)	566 (1050)	566 (1050)
Outlet Temp. °C (°F)	288 (550)	336 (637)	448 (838)	448 (838)
Flow Rate $\frac{kg}{sec}$ $\frac{lb \times 10^{-6}}{hr}$	301 (2.39)	301 (2.39)	212 (1.68)	90 (0.71)
Steam/Water				
Inlet Temp. °C (°F)	238 (460)	332 (630)	336 (636)	371 (700)
Outlet Temp. °C (°F)	331 (627)	336 (636)	538 (1000)	538 (1000)
Outlet Press, MPa(Psia)	13.9 (2010)	13.9 (2010)	12.8 (1850)	3.4 (500)
Flow Rate $\frac{kg}{sec}$ $\frac{lb \times 10^{-6}}{hr}$	48.2 (0.383)	72.3(0.574)	48.2 (0.383)	41.6(0.330)

3.1.8 Turndown Ratio - The steam generator subsystem shall be capable of operating in fully automatic control at part load conditions ranging from 30 to 110% of the rating specified under 3.1.1 during automatic control, and between 10 and 30% with manual control.

3.1.9 Operating Modes - The steam generator subsystem shall be capable of functioning in the following operating modes, within the constraints specified herein:

a. Cold Startup - This operation entails filling of the salt and water sides of the heat exchangers with the respective heat transfer fluids, and establishing flow through the salt side from and to the cold salt tank (Figure 1). Constraints:

- Freezing of salt, including the formation of dispersed solid particles shall be prevented by insuring that the salt side surfaces of the heat exchangers are at least 20°C (36°F) above the freezing point (238°C or 460°F) from start of salt fill throughout the operation;

- Entrapment of air pockets on the salt and water sides of the heat exchangers shall be prevented.

b. Warm Standby - The SGS temperature is maintained above the freezing point of the salt by recirculating salt from and to the cold salt tank, in combination with heat tracing and insulation, as required. Constraints:

- Heat loss from the salt to the environment and to the water/steam side of the SGS by the combined mechanisms of conduction, convection, and radiation shall be reduced to minimum practical limits.

c. Hot Standby - The SGS will be maintained in hot standby during diurnal shutdown for both stand-alone and repowering applications. For standalone operation, the SGS is at any condition of pressure and temperature between those existing when the turbine is tripped to a minimum condition described by warm standby. For repowering applications, the SGS is maintained at, or very near, the throttle pressure at which the Electric Power Generation System is operating.

d. Transient: Hot Standby to Normal Operation (# of events - 10,000) - This transient entails: (1) raising the water/steam side temperature and pressure of the evaporator to saturation levels; (2) raising the salt side temperatures of the evaporator, superheater, and reheater to water side saturation levels or above; (3) establishing water/steam flow; (4) establishing hot salt flow (from the hot tank); (5) establishing controlled operation at design setpoint conditions (with automatic control). Constraints:

- Salt temperatures in the evaporator and preheater shall not exceed the limits established to prevent material corrosion;
- Startup attemperators shall be included in the system to cool the superheated steam leaving the SGS to saturated steam during this transient, before it is routed to the condenser;
- It shall be a design objective to minimize the quantity of hot salt required to accomplish this transient.

e. Normal Operation - This mode includes all steady state operation at the conditions specified under 3.1.3 , 3.1.5, and 3.1.8. Normal operation shall be accomplished with either manual or automatic control.

f. Load Changes (# of events - 10,000) - The SGS shall be compatible with load changes of 10% of rated capacity per minute, between 30 and 110% of rating during automatic control and between 10 and 30% with manual control.

g. Transient: Normal Operation to Hot Standby - This operation requires the capability of controlled reduction of steam and salt flow from normal operating levels to zero, while maintaining steam drum temperatures and pressures at saturation levels. Constraints:

- Salt temperatures in the evaporator and preheater shall not exceed safe limits established to prevent material corrosion.

h. Long Term Shutdown - This operation requires the capability of isolation of the SGS flow paths from the other subsystems of the power plant, and complete drainability of both water/steam and salt sides.

3.1.10 Shutdown from Emergency or Upset Conditions - The steam generator subsystem shall be capable of safe, controlled shutdown resulting from upset and emergency conditions due to any of the following:

a. Turbine trip;
b. Loss of feedwater flow;
c. Loss of salt flow;
d. Break of any water/steam/salt pipe;
e. Indication of water-to-salt leak;
f. Loss of pneumatics;
g. Control system failure;
h. Loss of all station power (some emergency power required).

3.2 Compatibility with Molten Salt Operation

3.2.1 Drainability - The salt side of the SGS, including heat exchangers, interconnecting piping, valves and fittings, shall be completely drainable.

a. The heat exchangers (including interconnecting piping and valves) shall be designed such that the system will drain to the sump by gravity alone. The salt will be pumped from the sump to the cold or hot storage tanks as appropriate. If the salt is contaminated the system will be capable of gravity draining to a holding pond (earthen dikes);

b. The drain path shall be carefully layed out with due consideration to the boundary layer flow phase; drain lines shall have a minimum slope of 1 cm/m;

c. All salt valves shall be drainable valves;

d. The drain path shall be insulated, and provided with trace heating that is not adversely affected by a subsystem or station power failure;

e. Drain valves shall be equipped with manual override capability, so that they can be opened in case of power or control system failure;

f. Provisions shall be made for the detection and/or elimination of accumulation of frozen salt due to valve leakage downstream of the drain valves, so that the drain path may be kept free throughout the operation of the SGS.

3.2.2 Freeze and Thaw Considerations (refer to Phase Diagram on Figure 2)

a. The SGS shall be designed to handle salt in the liquid phase only.

b. The design and operation of the SGS shall be such as to prevent incipient or bulk freezing of the salt in any and all parts of the subsystem.

c. Local thawing shall not be relied on as a pratical means of correcting a freeze-up situation in the SGS components. The melting of the salt mixture results in a significant increase in salt specific volume, thus creating the potential for failure of closed containers.

d. Should salt freeze-up occur, heat tracing shall be provided to thaw the salt, with isolation valves open to permit thermal expansion.

3.2.3 Heat Tracing - Heat tracing shall be provided to meet the requirements of Paragraphs 3.1 and 3.2.

a. The heat tracing subsystem may use steam, electric power, or a combination of the two, as an energy source.

b. The minimum pre-heat temperature for all trace heated surfaces of the SGS system which contact the molten salt is 277°C (530°F). The trace heating subsystem shall be designed to provide this minimum temperature prior to SGS system start-up.

c. Provisions shall be made to disconnect the power to electrical trace heaters when 1) this heating is no longer needed due to established molten salt flow or 2) the trace heating subsystem would experience temperatures above its maximum operating limit if left on.

d. Provisions shall be made to monitor the SGS component and piping metal temperatures adjacent to the trace heating subsystem heating elements.

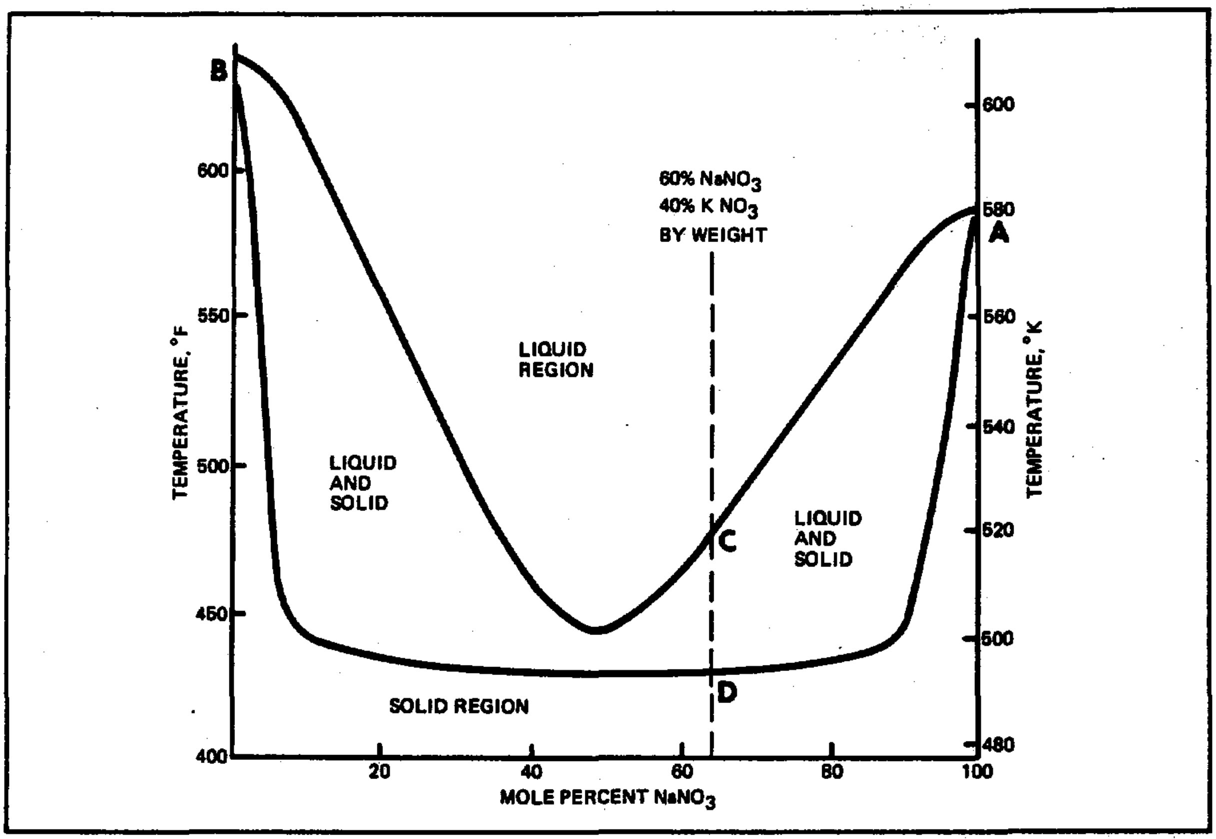


FIG. 2 TEMPERATURE-COMPOSITION PHASE DIAGRAM FOR $NaNO_3$-KNO_3

I. Initial Melting - Initial melting of the original mixture begins at A where $NaNO_3$ is isothermally melted. Then the temperature of the mixture is raised to B where the KNO_3 is melted isothermally to form a completely liquid mixture.

II. Solidification - Solidification first occurs when the temperature of the mixture is lowered to C at the 60/40 by weight composition point. Solidification takes place while the temperature is lowered from C to D where the mixture is completely solid.

III. Subsequent Operational Melting - Melting first occurs at D and continues until the temperature is raised to C where the mixture is completely liquid.

3.2.4 Molten Salt Component Design/Selection

a. Valves shall be of the drainable type, with laminated graphite packing or bellows-type seals to prevent leakage.

b. Pumps shall be of the open impeller, cantilever type.

c. Flanges shall be of the ring joint type where possible.

d. Electrical trace heaters shall use cabling with one-conductor Nichrome elements, 22 gage or larger (mineral insulated for high temperatures, Chemelex for low temperatures).

3.3 Steam Generator Components Design - This section of the specification identifies those requirements for the detailed design of the steam generator components.

3.3.1 Design Quality Assurance - The supplier shall establish and implement procedures required to assure that design, fabrication, inspection, and testing activities are planned and conducted in accordance with the requirements of applicable codes and this specification. Records shall be maintained in accordance with code requirements.

3.3.2 ASME Code Classification and Stamping - The steam generator subsystem components shall be designed and fabricated to Section VIII Division 1 of the ASME Code. Supplemental requirements for creep fatigue analysis will be developed as necessary.

3.3.3 General Requirements - The following requirements shall be met in designing the steam generator components:

- Heating surfaces must be oriented to promote efficient heat transfer and hydraulic stability of the heating fluid and steam/water mixture;

- Materials must be selected to provide adequate strength and corrosion/erosion resistance in the operating environment;

- Uniform distribution of flow to all heating surfaces must be assured;

- Sufficient flexibility must be provided for the U-tubes to preclude high stresses resulting from differential thermal expansion;

- Tube supports must be arranged to prevent potential damage resulting from flow-induced and machinery-induced vibration;

- Quality weld configurations and weld inspection standards must be provided to assure pressure boundary integrity;

- Access must be provided for inspection and corrective maintenance;

- The vessel must be capable of being fully drained and vented.

3.3.4 Design Conditions

Design Temperatures and Pressures

Table 4 lists the design temperatures and pressures for each SGS component for both water/steam and molten salt sides of each unit.

Table 4 Design Pressures and Temperatures

WATER/STEAM SIDE CONDITIONS	PRESSURE		TEMPERATURE	
	MPa	PSIA	°C	°F
Steam Drum	14.7	2125	343	650
Preheater	15.2	2200	371	700
Evaporator	15.2	2200	482	900
Superheater	14.7	2125	579	1075
Reheater	4.6	660	579	1075
MOLTEN SALT SIDE CONDITIONS				
Preheater	1.3	190	371	700
Evaporator	1.3	190	482	900
Superheater	1.3	190	579	1075
Reheater	1.3	190	579	1075

Seismic Loads - 0.1g in lateral direction (based on UBC zone 2).

Piping Loads - Maximum loads to be based on geometry at nozzle terminal.

3.3.5 Materials - Materials shall be selected for manufacture of the SGS components that meet the strength requirements of ASME Section VIII Division 1 as well as offering the corrosion resistance necessary in the operating environment. Materials selected for each component are identified in Table 5.

The materials identified in Table 5 were chosen after a review and evaluation of the available literature. However, data pertaining to the corrosion resistance of the selected alloys, particularly the low chromium alloys, in molten nitrate salt is very limited and often exhibits wide scatter. Thus, it will be necessary to reassess these choices based on the results of on-going and future test programs.

Table 5 Steam Generator Component Materials

COMPONENT	ENVIRONMENT	MAXIMUM OPERATING TEMPERATURE		MATERIALS
Preheater	Salt/Water	336°C	637°F	Carbon Steel
Evaporator	Salt/Water-Steam	448	838	2 1/4 Cr-1 Mo
Superheater	Salt/Steam	566	1050	304 Stainless Steel
Reheater	Salt/Steam	566	1050	304 Stainless Steel
Steam Drum	Water-Steam	336	636	Carbon Steel

Based on these material selections, the following allowances shall be made for corrosion (Table 6).

Table 6 Corrosion Allowances

	Carbon Steel		2 1/4 Cr - 1Mo		304 Stainless Steel	
Corrosion	mm	in	mm	in	mm	in
Salt Side	0.23	0.009	0.91	0.036	0.15	0.006
Water/Steam Side	0.28	0.011	0.41	0.016	0.10	0.004

3.3.6 Thermal/Hydraulic Design - The components in the SGS shall be designed to satisfy the following thermal/hydraulic requirments:

Fluid Velocities - The mass velocities of the water, water/steam, or steam shall be maximized, within pressure drop constraints, to develop efficient heat transfer and minimize surface requirements. Salt side velocities shall also be maximized within limits necessary to preclude tube vibration.

DNB - The evaporator circulation ratio shall be established sufficiently high to preclude departure from nucleate boiling (DNB).

Mixing - The heat exchanger components shall be designed to promote mixing of the molten salt and inhibit any tendency of the salt to stratify.

Subcooling in the Evaporator Downcomer - Sufficient subcooling will be provided in the downcomer to prevent flashing during transient operation.

Fouling - Component design shall consider the fouling on the salt side to be negligible. Water side fouling resistances are:

a. Preheater - 0.00002m-°C/watt (.0001hr-°F-ft²/BTU);

b. Evaporator- 0.00002m-°C/watt (.0001hr-°F-ft²/BTU);

c. Superheater- 0.000m-°C/watt (.000hr-°F-ft²/BTU);

d. Reheater - 0.000m-°C/watt (.000hr-°F-ft²/BTU).

Flow Induced Vibration - Flow induced vibration frequencies shall be safely below resonant frequencies at flow rates up to 110% of rated capacity.

3.3.7 Structural Design - The following structural design requirements shall apply.

Pressure Boundaries - Pressure boundaries will be designed to meet applicable codes.

Supports - Component supports and restraints shall be designed to account for deadweight and seismic loads.

Differential Expansion - Sufficient flexibility for differential thermal expansion shall be provided between tubes in the tube bundle so that the nominal stress in the tube bends will be in the elastic range.

Pressure Relief - Provisions shall be made for salt side pressure relief in the event of a heat exchanger tube leak.

Test Conditions - The SGS components shall be pressure tested as defined by the ASME Code on both salt and water/steam sides.

3.4 Control and Instrumentation Subsystem - The control and instrumentation subsystem shall provide the capability for manual or automatic control of the SGS and shall interface with the plant Master Control System (MCS) and Data Acquisition System (DAS), accepting commands from the MCS and providing data to the MCS and DAS. The control system shall provide the capability for manual or automatic start-up, normal operation, and shutdown of the steam generator subsystem. The control system will also issue emergency shutdown commands whenever critical process parameters exceed allowable operating limits.

3.4.1 Functional Requirements - The following capabilities shall be provided:

a. The control system shall automatically control the parameters listed below to the nominal conditions indicated during normal operation.

Superheater outlet steam temperature	538°C	(1000°F)
Reheater outlet steam temperature	538°C	(1000°F)
Steam supply pressure	12.5MPa	(1815 psi)
Drum fluid level	66.7cm	(26.25 in)
Evaporator salt supply temperature	Less than 482°C (900°F)	
Preheater water supply temperature	238°C - 204°C (460°F - 400°F)	

Figure 3 is a flow diagram showing the control valves that are used to control the SGS. The function of and the method of controlling each control valve is described below:

1) The reheater salt-line valve is used to control the salt-flow through the heat exchanger. The control consists of a load-following, feedforward term plus a feedback term correcting any deviation in steam exit temperature;

2) The superheater salt-line valve controls 70% of the salt-flow to the evaporator and is therfore used to control the pressure of the supply steam with minimal interference to the reheater. As with the reheater, the control consists of a load-following, feedforward term plus a feedback term which here corrects any deviation in a supply pressure;

3) The steam attemperator valve controls the flow of saturated steam from the drum for mixing with the steam from the superheater. The purpose of this control is to maintain the temperature of the superheated steam using temperature feedback only;

4) The evaporator salt attemperator valve controls the flow of cold salt for mixing with the salt from the reheater and superheater. The temperature of the salt entering the evaporator is used as the feedback term to drive the valve such that the salt into the evaporator does not exceed 482°C (900°F);

5) The feedwater supply valve controls the flow of the water supply. A load-following feedforward term is used along with a feedback term correcting the fluid level in the drum;

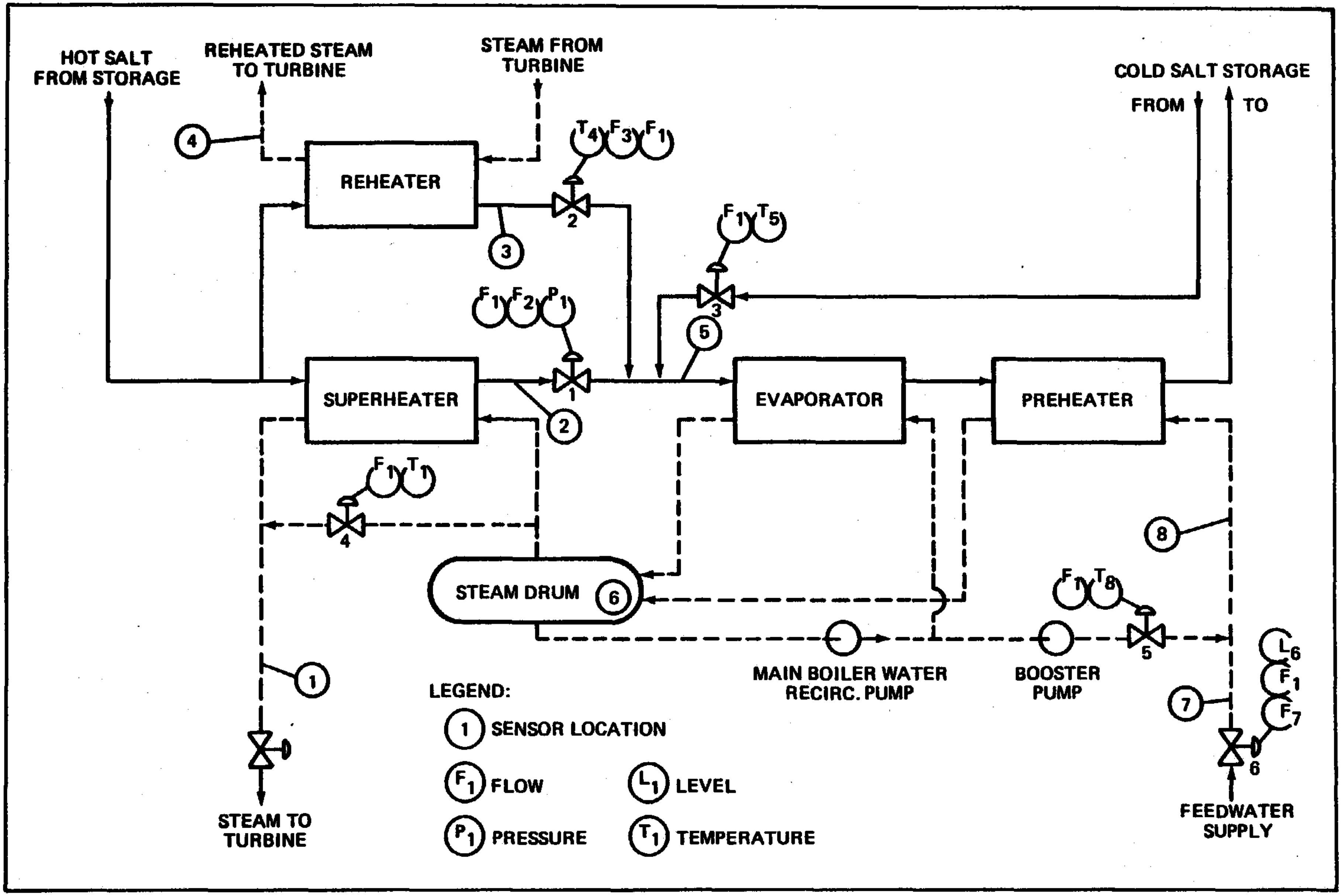


FIG. 3 STEAM GENERATOR CONTROL SCHEMATIC

6) The boiler water recirculation valve is used to ensure that the temperature of the preheater water supply does not fall below a specified value (TBD) high enough to limit local salt temperatures within the tube bundle to a safe minimum above the salt freezing point. As with the evaporator salt attemperator, temperature feedback of the water entering the preheater is used to generate the error signal.

b. The control system shall control the salt and steam systems in a safe and reliable condition under all modes of operation. Components/circuits shall have high reliability with redundancy incorporated where necessary to provide safe and reliable operation.

c. Manual control of the SGS will be possible during all operational modes. All control panel parameter displays and alarms will be easily read with all manual controls arranged for ease of operation. The following capabilities shall be available to the operator:

1. Capacity to change set points;
2. Display of system parameters and alarms;
3. Capability to accomplish start-stop and on-off functions.

d. Automatic control shall be possible during all operational modes except start-up and shut-down. The control system shall provide overall subsystem control and integration in the automatic mode.

e. During start-up, the SGS will be capable of a load increase of 2 to 3% of rated capacity per minute. When a preprogrammed sequence is followed, the control system will keep the operator apprised of the status of the start-up. The operator can interrupt the automated sequence at any point and complete the start-up manually. The system shall be capable of load changes between 30 to 110% of rated capacity automatically, and down to 10% with manual operation.

f. The control system shall monitor critical equipment parameters and operating conditions of the SGS. Upon detection of an abnormal condition which would compromise the safety of personnel or integrity of equipment, the control system will trigger an emergency shutdown of the system.

3.4.2 Major Components - The control and instrumentation subsystem consists of transducers, control valves and digital control equipment. The control system may be either a distributed or a centralized system.

A control console shall be provided for installation in the control room. Electronic control hardware shall be provided for installation in close proximity to the SGS to provide, as a minimium, the capability for transmitting data to and receiving commands from the control console in the control room. Communications between the control console in the control room and the equipment at the SGS shall be by high speed data highway.

The control system shall provide for ease of setting and changing control system gains, logic functions, set points, etc.

The control and instrumentation subsystem shall include transducers for the following measurements as a minimum.

Valve Being Controlled	Transducers
Superheater Salt-line	1) Turbine Steam Flow 2) Steam Throttle Pressure 3) Salt flow thru valve
Reheater Salt-line	1) Turbine Steam Flow 2) Steam exit Temperature 3) Salt flow thru valve
Feedwater Inlet Temperature Control	1) Preheater inlet temperature
Steam Attemperator	1) Steam temperature
Feedwater	1) Turbine Steam Flow 2) Feedwater Supply 3) Three independant drum levels 4) Optic transmission of water gauge to operator

3.5 Auxiliaries

3.5.1 Main Boiler Water Recirculation Pumps - The main boiler water recirculation pumps shall be vertical wet motor pumps designed specifically for boiler circulating water service. The pumps circulate water from the steam drum through the evaporator and back to the drum. Two half capacity pumps shall be provided each with a total developed head sized to overcome the piping and evaporator friction and static losses plus a suitable design margin. The pumps shall have a capacity of 409 m^3/hr (1800 gpm) for the 100 MW design and 204.5 m^3/hr (900 gpm) for the 50 MW design. Pump head shall be 18.3 m (60ft) for both designs.

3.5.2 Salt Piping, Valves, Trace Heaters and Insulation - Salt piping with design temperatures of 538 °C (1000 °F) and above shall be type 304 stainless steel. Salt piping with design temperatures between 427 °C (800 °F) and 538 °C (1000 °F) shall be ASTM A335 Grade P22 alloy steel.

Salt piping with design temperatures below 427 °C (800 °F) shall be ASTM A106 Gr B carbon steel. Pipe wall thickness shall be selected based on design pressure plus a suitable margin. Pipe size shall be selected based on providing reasonable fluid velocities and pressure loss.

Valves shall meet the code requirements of ANSI B16.34. Salt valves in piping with design temperatures of 538 °C (1000 °F) and above shall be stainless steel. Salt valves in piping with design temperatures between 427 °C (800 °F) and 538 °C (1000 °F) shall be alloy steel. Salt valves in piping with design temperatures below 427 °C (800 °F) shall be carbon steel.

Trace heaters shall be flexible type as manufactured by Chemelex or mineral insulated (MI) type depending on process temperature. Pipe insulation shall be calcium silicate with aluminum jacketing. Thickness of the pipe insulation shall be as indicated in Table 7.

3.5.3 Steam and Feedwater Piping, Valves and Insulation - High temperature steam piping above 371°C (700°F) shall be ASTM A335 Grade P22. Lower temperature steam piping and feedwater piping shall be ASTM A106 Grade B. Pipe wall thickness shall be selected based on design pressure plus a suitable margin. Pipe size shall be selected based on providing reasonable fluid velocities and pressure loss.

Valves shall meet the code requirements of ANSI B16.34. Steam valves in pipe with design temperatures above 371 °C (700 °F) shall be constructed of alloy steel. Valves in pipe with lower design temperatures shall be constructed of carbon steel.

Pipe insulation shall be calcium silicate with aluminim jacketing. Thickness of the pipe insulation shall be as indicated in Table 7:

TABLE 7 - Insulation Thickness

Operating Temperature	Pipe Size	Insulation Thickness
427°C (801°F) to 566°C (1050°F)	38 mm (1.5") and smaller	102 mm (4")
	51 mm (2") - 102 mm (4")	102 mm (4")
	127 mm (5") -203 mm (8")	127 mm (5")
	254 mm (10") and larger	152 mm (6")
261°C (501°F) to 427°C (800°F)	38 mm (1.5") and smaller	76 mm (3")
	51 mm (2") - 102 mm (4")	89 mm (3.5")
	127 mm (5") - 254 mm (10")	102 mm (4")
	305 mm (12") and larger	140 mm (5.5")
149°C (301°F) to 261°C (500°F)	51 mm (2") and smaller	76 mm (3")
	64 mm (2.5") and larger	89 mm (3.5")
66°C (150°F) to 148°C (300°F)	254 mm (10") and smaller	38 mm (1.5")
	305 mm (12") and larger	64 mm (2.5")

3.5.4 Structural Components - The structure in which the system components are located shall be designed in accordance with the AISC Manual of Steel Construction (Eighth Edition) and ACI Standard 318-77 (Building Code Requirements for Reinforced Concrete); this structure will be designed to make cost effective use of space, considering component size and weight, as well as potential seismic and wind loads. The berm for the salt drain sump shall be designed giving particular consideration to personnel safety during operation and maintenance.

4.0 INTERFACE DEFINITIONS

4.1 Turbine Generator

a.	Power	110 MWe (100 MWe net) or 55 MWe (50 MWe net)
b.	Throttle Temperature	538°C (1000°F)
c.	Throttle Pressure	12.5 MPa (1815 psia)
d.	Design Inlet Steam Flow Rate	96.3 kg/sec (764,000 lbs/hr) or 48.2 kg/sec (382,000 lbs/hr)
e.	Maximum Inlet Steam Flow Rate	105.9 kg/sec (840,000 lbs/hr) or 52.95 kg/sec (420,000 lbs/hr)
f.	Minimum Inlet Steam Flow Rate (30%)	28.9 kg/sec (229,000 lbs/hr) or 14.5 kg/sec (115,000 lbs/hr)
g.	Design Reheat Steam Flow Rate	83.3 kg/sec (661,000 lbs/hr) or 41.7 kg/sec (330,500 lbs/hr)
h.	Maximum Reheat Steam Flow Rate (110%)	91.6 kg/sec (727,000 lbs/hr) or 45.8 kg/sec (363,500 lbs/hr)
i.	Minimum Reheat Steam Flow Rate (30%)	25.0 kg/sec (198,000 lbs/hr) or 12.5 kg/sec (99,000 lbs/hr)
j.	Cold Reheat Steam Temperature	371°C (700°F)

k. Hot Reheat Steam Pressure — 3.5 MPa (500 psia)

l. Hot Reheat Steam Temperature — 538°C (1000°F)

m. Last Feedwater Heater Discharge Temperature — 238°C (460°F)

4.2 Hot Salt Supply

a. Flow vs. Head - Main Recirculation Pump:

100 MWe Size

Flow	Pressure
603 kg/sec (4.78 lb X 10^6/hr)	1.2 MPa (175 psi)

50 MWe Size

Flow	Pressure
301 k/sec (2.39 lb X 10^6/hr)	1.2 MPa (175 psi)

b. Salt Temperature: 565 ± 11°C (1050 ± 20°F)

4.3 Cold Salt Tank

a. Flow vs. Head - Recirculation Pump: (TBD)

b. Salt Temperature - 288 ± 11°C (550 ± 20°F)

4.4 Data Acquisition System - The SGS shall include transducers to provide signals to the plant Data Acquisition System (DAS). The DAS will provide the capability for data collection, storage, display, logging etc. for the whole plant. The required transducers are listed in Section 3.4. All of these signals shall be made available to the DAS. The signal interface between the SGS and the DAS is TBD.

4.5 Master Control System - The SGS control sytem shall provide the capability to accept commands from and transmit data to the plant Master Control System (MCS). The MCS will provide the capability for control of the total plant including emergency control. The commands and data to be transmitted between the MCS and the SGS and the signal interface are TBD.

5.0 ENVIRONMENTAL

5.1 General - The SGS shall be integrated into the design of a solar thermal central receiver power plant, and will be located near the turbine.

5.2 <u>Operating Requirements</u> - The system shall be capable of operating in and surviving appropriate combinations of the following environments:

a. Temperature - The plant shall be able to operate in the ambient air temperature range from -8 to 46^oC (17.6 to 114.8^oF). Performance requirements shall be met throughout and ambient air temperature range selected to be consistent with efficient plant operation.

b. Earthquake - Peak ground accelerations shall be as presented below per applicable UBC zone. Seismic design loads shall be calculated in accordance with the UBC 1979 conditions. The applicable UBC zone is 2.

Maximum Operational Ground Accelerations

UBC Zone	Peak Ground Acceleration(Average for Firm Soil Conditions)
2	0.07 g

5.3 <u>Survival</u> - The system shall be capable of surviving appropriate combinations of the environments specified below:

a. Wind - The plant shall survive winds with a maximum speed, including gusts of 40 m/s (90 mph), without damage.

b. Dust Devils - Dust devils with wind speeds up to 17 m/s (38 mph) shall be survived without damage to the plant.

c. Snow - The plant shall survive a static snow load of 250 Pa (5 lb/ft^2) and a snow deposition rate of 0.3 m (1 ft) in 24 hours.

d. Rain - The plant shall survive the following rainfall conditions:

Average Annual	-	340 mm (13.4 in.)
Maximum 24-hr rate	-	150 mm (6 in.)

e. Ice - The plant shall survive freezing rain and ice deposits in a layer 25 mm (1 in.) thick.

f. Earthquake - Peak ground accelerations shall be as presented below per applicable UBC zone. Seismic design loads shall be calculated in accordance with the UBC 1979 conditions. The applicable UBC zone is 2.

Maximum Survival Ground Accelerations

UBC Zone	Peak Ground Acceleration(Average for Firm Soil Conditions)
2	0.10 g

g. Sandstorm Environment - The plant shall survive after being exposed to flowing dust comparable to the conditions described by Method 510 of MIL-STD-810C.

5.4 Lightning Considerations - All electrical equipment enclosures, the energy storage tanks, horizontal piping and various points of the salt/steam heat exchanger subsystem shall be bonded to earth using ground straps and earth driven ground rods.

5.5 Water Quality Standards - The plant shall comply with the National Pollution Discharge Elimination Standards. The addition of the solar system should not affect that compliance.

6.0 PHYSICAL INTERFACES - Drawings to be provided.

7.0 FABRICATION REQUIREMENTS

7.1 Fabrication Quality Assurance - Quality Assurance for fabrication of the steam generator components shall be based on the requirements of the ASME Code.

7.2 Fabrication Process - The components of the steam generator subsystem shall be completely shop welded, assembled, stress relieved, pressure tested, and ASME Code stamped. Pressure testing may be performed as either a shop or field procedure but must precede Code stamping.

Heat Treatment - The need for heat treating after forming operations shall be evaluated and if necessary, temperatures, hold times, and heat up and cooldown rates in heat treatment procedures specified.

Surface Finish - The finish of surfaces subject to non-destructive examination shall be in accordance with Code requirements. Unless otherwise determined by the Supplier, all other surfaces shall be acceptable in the "as-formed" condition. Gross surface irregularities in pressure boundary material, such as dents or gouges, shall be ground to a smooth contour and shall not violate minimum wall thickness requirements.

Welding - Welding materials used for fabricating shall comply with the requirements of the ASME Code Section VIII, Section IX and applicable welding procedures.

7.3 Cleanliness - Care shall be taken to prevent unnecessary contamination of surfaces by dirt producing operations such as machining and grinding. Surfaces to be welded shall be clean and free of scale, rust, oil, grease, and other foreign material. Equipment shall be suitable for installation at the user's site without additional cleaning.

7.4 Spare Parts/Tooling - A list of spare parts for operation shall be developed. The list of spare parts to be stocked at the site shall include those parts and tools likely to be damaged or expended during delivery and/or operation.

7.5 Post-Fabrication Testing - Pressure vessels shall be hydrostatically tested in accordance with Code requirements.

7.6 Shipping and Handling - Shipping rigs and/or containers shall be provided to secure and protect components during shipment to the user's site. Open nozzles shall be sealed with temporary plugs or caps. Procedures for off-loading and lifting components shall be defined in the Operation and Maintenance Manual (see 9.2).

8.0 MAINTENANCE - Provisions shall be made for dry layup, cleaning, inservice inspection, and tube plugging for the components of the steam generator subsystem.

8.1 Layup - When steam generator components are shut down for short periods, adequate corrosion protection can usually be provided by blanketing the heat transfer surfaces with inert gas. For longer down periods, the components should be filled with treated water in addition to the inert cover gas. Procedures for wet and dry layup shall be defined in the Operation and Maintenance Manual (see 9.2).

8.2 Chemical Cleaning - Deposition on the water/steam side of steam generator components is generally produced by transport of corrosion products from the condensate and preboiler system. Depending on the quality of the user's water treatment practice, significant amounts of deposits may accumulate after several years of normal operation. This deposit build-up may contribute to corrosion of heat transfer surfaces and may eventually degrade the thermal-hydraulic performance of the equipment. Recommendations addressing cleaning solvents and procedures shall be provided in the Operation and Maintenance Manual (see 9.2).

8.3 Tube Plugging - Manway or handhole penetrations shall provide access to the water/steam side of tubesheets for plugging defective heat exchanger tubes. Plugged tubes shall be pierced to allow for draining salt, and the design and installation of plugs shall meet all Code pressure boundary requirements.

8.4 In-Service Inspection - Manways or handholes for visual inspection of components shall be provided in accordance with code requirements. Access shall be provided for in-service inspection of tubing (for example, by eddy current or ultrasonic examination techniques) if desired by the user. Procedures for tube inspection shall be defined in the Operation and Maintenance Manual (see 9.2).

9.0 SPECIAL REQUIREMENTS

9.1 Certification - Marking and certification of pressure vessels shall conform with Code requirements.

9.2 Operation and Maintenance Manual - An operation and maintenance manual shall be provided. This manual shall include instructions for:

a) Unloading and receipt inspecton;
b) Installation and post-installation inspection and check-out;
c) Testing, startup, and operation;
d) In-service inspection;
e) Preventive maintenance and trouble shooting;
f) Corrective maintenance and post-correction check-out;
g) Limits and precautions to be taken during filling, testing, startup, shutdown, and layup operations.

9.3 Safety - The steam generator subsystem shall be designed to minimize safety hazards to operating and service personnel, the public, and equipment. Electrical components shall be insulated and grounded. All components with elevated temperatures shall be insulated against contact with or exposure to personnel. Any moving elements shall be shielded to avoid entanglements, and safety override controls/interlocks shall be provided for servicing.

Appendix B

Pressure Boundary Code Calculations
Per
ASME Section VIII - Division 1

APPENDIX B

PRESSURE BOUNDARY CODE CALCULATION

PER ASME SECTION VIII, DIV. 1

INTRODUCTION AND PURPOSE

The basic design criteria for the SGS components is Section VIII, Division 1, of the ASME Code. Pressure boundary code calculations were made for all components, and wall thicknesses were established to meet minimum code requirements. Tubesheet thicknesses were calculated per the methods of reference 8 (TEMA), as a supplement to the code, since the code does not stipulate a specific calculation.

Table B-1 summarizes the results of the code calculations and lists the actual wall thicknesses for comparison. Table B-2 presents the SGS material list, including code specification and design allowable, and Table B-3 presents the corrosion allowances for salt and water-sides of the heat exchangers.

References to the applicable code paragraphs are made for each calculation, and remarks are included to identify the radiography requirements, type of weld, and joint efficiencies.

TABLE B-1

SUMMARY
100MWe SGS PRESSURE BOUNDARY
CODE CALCULATIONS

COMPONENT	CODE CALC. MIN. THICKNESS INCLUDING CORROSION ALLOWANCE (IN)	ACTUAL THICKNESS (IN)
SUPERHEATER		
Secondary Hemi-Head	1.423	2.250
Primary Inlet/Outlet	.359	.500
Primary Shell	.289	.375
180° Long Radius Return	.382	.500
Tubes	.060	.065
Tubesheet	5.777	6.125
REHEATER		
Secondary Hemi-Head	.600	1.500
Primary Inlet/Outlet	.430	.500
Primary Shell	.359	.500
180° Short Radius Return	.440	.500
Tubes	.031	.035
Tubesheet	4.606	4.875
EVAPORATOR		
Secondary Hemi-Head	2.205	4.500
Primary Inlet/Outlet	.416	.750
Conical Shell Section	.426	.750
Primary Shell	.378	.750
Primary Ellipsoidal Head	.374	.750
Tubes	.106	.148
Tubesheet	11.619	15.500
PREHEATER		
Secondary Hemi-Head	1.866	3.750
Primary Inlet/Outlet	.469	.750
Conical Shell Section	.481	.750
Primary Shell	.428	.750
Primary Hemi-Head	.189	.750
Tubes	.048	.058
Tubesheet	10.077	14.000

TABLE B-2

100MWe SGS MATERIAL LIST

COMPONENT	MAT'L	SPEC.	P-No.	SPECIFIED MIN. YIELD (KSI)	SPECIFIED MIN. TENS. (KSI)	DESIGN TEMP. (°F)	DESIGN ALLOW-ABLE (KSI)
Superheater	304 S.S.						
Tubes		SA-213,TP304	8	30.0	75.0	1075	9.2
Plate		SA-240,304	8	30.0	75.0	1075	9.2
Forging		SA-182,F304	8	30.0	70.0	1075	9.2
Seamless Pipe		SA-312,TP304	8	30.0	75.0	1075	9.2
Reheater	304 S.S.						
Tubes		SA-213,TP304	8	30.0	75.0	1075	9.2
Plate		SA-240,304	8	30.0	75.0	1075	9.2
Forging		SA-182,F304	8	30.0	70.0	1075	9.2
Seamless Pipe		SA-312,TP304	8	30.0	75.0	1075	9.2
Evaporator	2 1/4 CR-1 Mo						
Tubes		SA-213,T22	5	30.0	60.0	900	13.1
Plate		SA-387, 22Cl.2	5	45.0	75.0	900	15.8
Forging		SA-336,F22	5	45.0	75.0	900	15.8
Preheater	Carbon Steel						
Tubes		SA-210,C	1	40.0	70.0	700	16.6
Plate		SA-516,70	1	38.0	70.0	700	16.6
Forging		SA-266,4	1	36.0	70.0	700	16.6

TABLE B-3

100MWe SGS CORROSION ALLOWANCES

COMPONENT	SALT-SIDE (IN)	WATER-SIDE (IN)
SUPERHEATER	.006	.004
REHEATER	.006	.004
EVAPORATOR	.036	.016
PREHEATER	.009	.011

Secondary Hemi-Head (UG-27(d))

Remarks:
Seamless Head
Full radiography of circumferential butt weld required per UW-11 (a)(3)
Category C, type 1 joint
Joint efficiency (E) per UW-12(a)

$$t = \frac{PR}{2SE-.2P} = \frac{2125\ (12.0)}{2(9200)(1.0) - .2(2125)} = 1.419"$$

t_r = t + corrosion allowance = 1.419 + .004 = 1.423"

Primary Inlet/Outlet : 30" XS Pipe (UG -27(c)(1))

Remarks:
Seamless Shell
No radiography of circumferential butt weld required per UW- 11(a)(2), and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Category C, type 2 joint
Joint efficiency (E) = 1.0 with application of UW-12(c)

$$t = \frac{PR}{SE-.6P} = \frac{175\ (14.5)}{.8\ (9200)\ (1.0)-.6\ (175)} = .350"$$

t_r = t + corrosion allowance = .350 + .006 = .356"

Per Note 12,pg.20

$$t = \frac{PRo}{SE+.4P} = \frac{175\ (15.0)}{.8\ (9200)\ (1.0) + .4\ (175)} = .353"$$

t_r = t + corrosion allowance = .353 + .006 = .359"

Primary Shell: 24" STD Pipe (UG-27(c)(1))

Remarks:
Seamless Shell
No radiography of circumferential butt weld required per UW-11(a)(2), and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Category B, type 1 joint
Joint efficiency (E) = 1.0 with application of UW-12(c)

$$t = \frac{PR}{SE-.6P} = \frac{175\ (11.625)}{.8\ (9200)\ (1.0) -.6\ (175)} = .280"$$

t_r = t + corrosion allowance = .280 + .006 = .286"

SUPERHEATER (CONTINUED)

Primary Shell (continued)

Per Note 12, pg.20

$$t = \frac{PRo}{SE + .4P} = \frac{175\ (12.0)}{.8\ (9200)\ (1.0) + .4\ (175)} = .283"$$

t_r = t + corrosion allowance = .283 + .006 = .289"

Primary -180° Long Radius Return: 26" XS (UG-27(c)(1))

Remarks: Longitudinal seam; Category A, type 2 joint
Circumferential weld; Category B, type 2 joint
No radiography required of butt welds per UW-11 (a) (2), and it is not an unfired steam boiler portion of multichamber vessel (UW-11)
Joint efficiency (E) = .65 portable UW-12

$$t = \frac{PR}{SE - .6P} = \frac{175\ (12.5)}{9200(.65) - .6(175)} = .372"$$

t_r = t + corrosion allowance = .372 + .006 = .378"

Per Note 12,pg. 20:

$$t = \frac{PRo}{SE + .4P} = \frac{175\ (13.0)}{9200\ (.65) + .4\ (175)} = .376"$$

t_r = t + corrosion allowance = .376" + .006 = .382"

Tubes (UG-27(c)(1))

Remarks: Seamless tube : .500" O.D. x .065" wall

$$t = \frac{PR}{SE - .6P} = \frac{2125\ (.185)}{9200(1.0) - .6(2125)} = .050"$$

t_r = t + corrosion allowance = .050 + .006 + .004 = .060"

Tubesheet (TEMA 1968) - R - 7.122

Remarks: Class R Heat Exchanger
Integral tubesheet

$$t = \frac{FG}{2}\sqrt{\frac{P}{S}} = \frac{1.0\ (24.0)}{2}\sqrt{\frac{2125}{9200}} = 5.767"$$

Per Fig. R-7.141: curve U $F = f\left(\frac{\text{actual wall thickness}}{\text{I.D.}}\right) = f\left(\frac{2.25}{24.0}\right) > .05, F=1.0$

t_r = t + corrosion allowance = 5.767 + .006 + .004 = 5.777"

Secondary Hemi-Head(UG-27(d))

Remarks:
Seamless head
Full radiography of circumferential butt weld required per UW-11(a)(3)
Category c, type 1 joint
Joint efficiency (E) per UW-12 (a)

$$t \quad \frac{PR}{2SE-.2P} = \frac{660\ (16.5)}{2\ (9200)\ (1.0)\ .2(660)} = .596"$$

t_r = t + corrosion allowance = .596 + .004 = .600"

Primary Inlet/Outlet: 36" XS Pipe (UG -27(c)(1)

Remarks:
Seamless shell
No radiography of circumferential butt weld required per UW-11(a)(2), and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Category c, type 2 joint
Joint efficiency (E) = 1.0 with application of UW -12(c)

$$t = \frac{PR}{SE-.6P} = \frac{175(17.5)}{.8\ (9200)\ (1.0)\ -.6\ (175)} = .422"$$

t_r=t + corrosion allowance = .422 + .006 = .428"

Per Note 12, pg. 20

$$t = \frac{PRo}{SE\ +.4P} = \frac{175\ (18.0)}{.8\ (9200)\ (1.0)\ +.4\ (175)} = .424"$$

t_r = t + corrosion allowance = .424 + .006 = .430"

Primary Shell: 30" XS Pipe (UG-27(c)(1))

Remarks:
Seamless shell
No radiography of circumferential butt weld required per UW-11 (a) (2), and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Category B, type 1 joint
Joint efficiency (E) = 1.0 with application of UW-12(c)

$$t = \frac{PR}{SE-.6P} = \frac{175\ (14.5)}{.8\ (9200)\ (1.0)\ -\ .6\ (175)} = .350"$$

t_r=t + corrosion allowance = .350 + .006 = .356"

REHEATER (CONTINUED)

Primary Shell (continued)

Per Note, pg. 20:

$$t = \frac{PRo}{SE + .4P} = \frac{175\ (15.0)}{.8\ (9200)\ (1.0) + .4\ (175)} = .353''$$

t_r = t + corrosion allowance = .353 + .006 = .359"

Primary -180o Short Radius Return: 30" XS (UG-27(c)(1))

Remarks: Longitudinal seam; Category A, type 2 joint
Circumferential weld; Category B, type 2 joint
No radiography required of butt welds per UW-11(a)(2), and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Joint efficiency (E) = .65 per Table UW-12

$$t = \frac{PR}{SE - .6P} = \frac{175\ (14.5)}{9200\ (.65) - .6\ (175)} = .432''$$

t_r = t + corrosion allowance = .432 + .006 = .438"

Per Note 12, pg. 20:

$$t = \frac{PRo}{SE + .4P} = \frac{175\ (15.0)}{9200\ (.65) + .4\ (175)} = .434''$$

t_r = t + corrosion allowance = .434 + .006 = .440"

Tubes (UG-27(c)(1))

Remarks: Seamless tube: .625" O.D. x .035" wall

$$t = \frac{PR}{SE - .6P} = \frac{660\ (.2775)}{9200\ (1) - .6\ (660)} = .021''$$

t_r = t + corrosion allowance = .021 + .006 + .004 = .031"

Tubesheet (TEMA 1968) - R 7.122

Remarks: Class R Heat Exchanger
Integral tubesheet

$$t = \frac{FG}{2}\sqrt{\frac{P}{S}} = \frac{1.04\ (33.0)}{2}\sqrt{\frac{660}{9200}} = 4.596''$$

Per Fig. R-7.141: $F = f\left(\frac{\text{actual wall thickness}}{\text{I.D.}}\right) = f\left(\frac{1.5}{33.0}\right) = .045, F = 1.04$
Curve U

t_r = t + corrosion allowance = 4.596 + .004 + .006 = 4.606"

Secondary Hemi-Head (UG-27(d))

Remarks: Seamless Head
Full radiography of circumferential butt weld required per UW-11 (a) (3)
Category C, type 1 joint
Joint efficiency (E) per UW-12(a)

$$t = \frac{PR}{2SE-.2P} = \frac{2200\ (31.0)}{2\ (15800)(1.0) - .2(2200)} = 2.189"$$

t_r = t = corrosion allowance = 2.189 + .016 = 2.205"

Primary Inlet/Outlet (UG-27(c)(1),(2))

I. Circumferential weld at tubesheet per Fig. UW-13.2(d) and Para. UW-13(e)

Remarks: UT per UW-11 (a) (7)
Equivalent to type 2, full radiography
Joint efficiency (E) = .9 per Table UW-12

$$t = \frac{PR}{2SE + .4P} = \frac{175\ (33.75)}{2\ (15800)\ (.9) + .4\ (175)} = .207"$$

t_r = t + corrosion allowance = .207 + .036 = .243"

II. Longitudinal Weld

Remarks: Longitudinal seam; category A, type 1 joint
Full radiography of longitudinal butt weld required per UW-11(a)(2)
Joint efficiency (E) = 1.0 per Table UW-12

$$t = \frac{PR}{SE-.6P} = \frac{175\ (33.75)}{15800\ (1.0) - .6\ (175)} = .376"$$

t_r = t = corrosion allowance = .376 + .036 = .412"

Per Note 12, pg. 20:

$$t = \frac{PRo}{SE +.4P} = \frac{175\ (34.5)}{15800\ (1.0) + .4\ (175)} = .380"$$

t_r = t + corrosion allowance = .380 + .036 = .416"

Primary, Conical Shell Section (UG - 32(g))

Remarks: Longitudinal seam, category A, type 1 joint
Full radiography of longitudinal butt weld required per UW-11(a)(2)
Joint efficiency (E) = 1.0 per Table UW-12

$$t = \frac{PD}{2 \cos\ (SE-.6P} = \frac{175\ (67.5)}{2 \cos 15^{\circ}\ (15800\ (1.0) -.6\ (175))} = .390"$$

t_r = t + corrosion allowance = .390 + .036 = .426"

EVAPORATOR (CONTINUED

Primary Shell (UG-27(c))

I. Longitudinal Weld

Remarks: Longitudinal seam; category A, type 1 joint
Full radiography of longitudinal butt weld required per UW-11(a)(2)
Joint efficiency (E) = 1.0 per Table UW-12

$$t = \frac{PR}{SE - .6P} = \frac{175\ (30.5)}{15800\ (1.0) - .6\ (175)} = .342''$$

t_r = t + corrosion allowance = .342 + .036 = .378"

II. Circumferential Weld At Ellipsoidal Head Juncture

Remarks: Circumferential weld, category B, type 2 joint
Full radiography required per UW-11(a)(2)
Joint efficiency (E) = .9 per Table UW-12

$$t = \frac{PR}{2SE + .4P} = \frac{175\ (30.5)}{2\ (15800)\ (.9) + .4\ (175)} = .187''$$

t_r = t + corrosion allowance = .187 + .036 = .223

Primary Ellipsoidal Head (UG -32(d))

Remarks: Seamless Head
Full radiography required per UW-11(a)(2) of category B, type 2 joint
Joint efficiency (E) = 1.0

$$t = \frac{PR}{2SE - .2P} = \frac{175\ (61.0)}{2\ (15800)\ (1.0) - .2\ (175)} = .338''$$

t_r = t + corrosion allowance = .338 + .036 = .374"

Tubes (UG-27(c)(1))

Remarks: Butt welded tubes are not categorized by Sect. VIII, Div. 1. Per U-1(g) which references Sect. I, PW-41, circumferential welds in tubes and pipes do not require RT at nominal diameters equal to or less than 10", and wall thickness equal to or less than 1 1/8".

$$t = \frac{PR}{SE - .6P} = \frac{2200(.2895)}{13100\ (1.0) - .6\ (2200)} = .054''$$

t_r = t + corrosion allowance = .054 + .036 + .016 = .106"

Tubesheet (TEMA 1968) - R - 7.122

Remarks: Class R Heat Exchanger
Integral tubesheet

$$t = \frac{FG}{2}\sqrt{\frac{P}{S}} = \frac{1.0\ (62.0)}{2}\sqrt{\frac{2200}{15800}} = 11.567"$$

Per Fig. R-7.141 Curve U $F = f\left(\frac{\text{actual wall thickness}}{\text{I.D.}}\right) = f\left(\frac{4.5}{62.0}\right) = .07,\ F = 1.0$

t_r = t + corrosion allowance = 11.567 + .036 + .016 = 11.619"

Secondary Hemi-Head (UG-27(d))

Remarks: Seamless Head
Full radiography of circumferential butt weld required per UW-11(a)(3)
Category C, type 1 joint
Joint efficiency (E) per UW-12(a)

$$t = \frac{PR}{2SE - .2P} = \frac{2200\ (27.625)}{2\ (16600)\ (1.0) - .2\ (2200)} = 1.855''$$

t_r = t + corrosion allowance = 1.855 + .011 = 1.866"

Primary Inlet/Outlet (UG -27(c)(1),(2))

Remarks: Longitudinal seam; category A, type 1 joint
No radiography required per UW-11(a)(2) and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Joint efficiency (E) = .7 per Table UW-12.

$$t = \frac{PR}{SE - .6P} = \frac{175\ (30.0)}{16600\ (.7) - .6\ (175)} = .456''$$

t_r = t + corrosion allowance = .456 + .009 = .465"

Per Note 12, pg.20:

$$t = \frac{PRo}{SE + .4P} = \frac{75\ (30.75)}{16600\ (.7) + .4\ (175)} = .460''$$

t_r = t + corrosion allowance = .460 + .009 = .469"

Primary, Conical Shell Section (UG-32(g))

Remarks: Longitudinal seam; category A, type 1 joint
No radiography required per UW-11(a)(2), and it is not an unfired steam boiler portion of multichamber vessel (UW-11)
Joint efficiency (E) = .7 per Table UW-12

$$t = \frac{PD}{2 \cos\ (SE - .6P)} = \frac{175\ (60.0)}{2 \cos 15^{\circ} [(16600)\ (.7) - .6(175)]} = .472''$$

t_r = t + corrosion allowance = .472 + .009 = .481"

Primary Shell (UG -27(c))

Remarks: Longitudinal seam; category A, type 1 joint
No radiography required per UW-11(a)(2), and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Joint efficiency (E) = .7 per Table UW-12.

PREHEATER (CONTINUED)

Primary Shell-(continued)

$$t = \frac{PR}{SE-.6P} = \frac{175\ (27.25)}{16600\ (.7)\ -.6\ (175)} = .414"$$

t_r = t + corrosion allowance = .414 + .009 = .423"

Per Note 12, pg. 20:

$$t = \frac{PRo}{SE + .4P} = \frac{175\ (28.0)}{16600\ (.7) + .4\ (175)} = .419"$$

t_r = t + corrosion allowance = .419 + .009 = .428"

Primary Hemi-Head (UG-27(d))

Remarks: Seamless Head
No radiography required per UW-11(a)(2), and it is not an unfired steam boiler portion of a multichamber vessel (UW-11)
Joint efficincy (E) = 1.0 with application of UW-12 (c)

$$t = \frac{PR}{2SE-.2p} = \frac{175\ (27.25)}{2(.8)(16600)(1.0)-.2(175)} = .180"$$

t_r = t + corrosion allowance = .180 + .009 = .189"

Tubes (UG-27(c)(1))

Remarks: Seamless tube: .500" O.D. x .058" wall

$$t = \frac{PR}{SE-.6P} = \frac{2200\ (.192)}{16600\ (1.0)\ -\ .6\ (2200)} = .028"$$

t_r = t + corrosion allowance = .028 + .011 + .009 = .048"

Tubesheet (TEMA 1968) R-7-122

Remarks: Class R Heat Exchanger
Integral tubesheet

$$t = \frac{FG}{2}\sqrt{\frac{P}{S}} = \frac{1.0\ (55.25)}{2}\sqrt{\frac{2200}{16600}} = 10.057"$$

Per Fig. R-7.141 Curve U $F = f\left(\frac{\text{actual wall thickness}}{\text{I.D.}}\right) = f\left(\frac{3.75}{55.25}\right) = .06$, F=1.0

t_r = t + corrosion allowance = 10.057 + .011 + .009 = 10.077"

Appendix C

Structural Analysis Compliance Check List

APPENDIX C

Structural Analysis Compliance Check Lists

The results of mechanical stress analyses, thermal stress analyses, and elevated temperature analyses are summarized in the following tables.

STRUCTURAL ANALYSIS COMPLIANCE CHECK LIST (SACCL)

Component (Region)	Loading Condition	PRIMARY STRESS LIMITS: General Primary Membrane Stress Intensity	Local Primary Membrane Stress	Primary Membrane + Primary Bending Stress	Primary + Secondary Stress Difference Range	FATIGUE: Peak Alt. Stress Diff.	Usage Factor
Preheater	Allowable Limit	S_y	S_y	1.35 S_y (Design) S_y (Operating)	2 S_y		$\Sigma u_i < 1.0$
Tubesheet (Design Cond.)	Calc. Value	15.8		26.7			
	Allow. Value	23.8		32.1			
Tubesheet (Operating Cond.)	Calc. Value	14.0		24.0	37.8	37.2	0.83
	Allow. Value	24.2		24.2	52.8	40.0	1.00
Shell/Tubesheet Juncture (Design Cond.)	Calc. Value		8.2		21.6		
	Allow. Value		27.4		54.8		
Shell/Tubesheet Juncture (Operating Cond.)	Calc. Value		7.8		22.8		
	Allow. Value		27.9		59.0		
Head/Tubesheet Juncture (Design Cond.)	Calc. Value		9.2		35.5		
	Allow. Value		23.8		47.6		
Head/Tubesheet Juncture (Operating Cond.)	Calc. Value		8.4		31.5		
	Allow. Value		31.7		48.4		

*All units are in ksi unless otherwise specified

STRUCTURAL ANALYSIS COMPLIANCE CHECK LIST (SACCL)

Component (Region)	Loading Condition	PRIMARY STRESS LIMITS: General Primary Membrane Stress Intensity	PRIMARY STRESS LIMITS: Local Primary Membrane Stress	PRIMARY STRESS LIMITS: Primary Membrane + Primary Bending Stress	Primary + Secondary Stress Difference Range	FATIGUE: Peak Alt. Stress Diff.	FATIGUE: Usage Factor
Evaporator	Allowable Limit	S_y	S_y	1.35 S_y (Design) S_y (Operating)	2 S_y		$\Sigma u_i < 1.0$
Tubesheet (Design Cond.)	Calc. Value	24.7		38.5			
	Allow. Value	32.5		43.9			
Tubesheet (Operating Cond.)	Calc. Value	21.7		35.7	37.7		
	Allow. Value	36.1		36.1	72.4		
Shell/Tubesheet Juncture (Design Cond.)	Calc. Value		10.5		27.6		
	Allow. Value		32.5		65.0		
Shell/Tubesheet Juncture (Operating Cond.)	Calc. Value		10.0		18.4	38.5	.90
	Allow. Value		36.1		72.4	40.0	1.00
Head/Tubesheet Juncture (Design Cond.)	Calc. Value		9.2		39.3		
	Allow. Value		32.5		65.0		
Head/Tubesheet Juncture (Operating Cond.)	Calc. Value		8.4		34.6		
	Allow. Value		36.1		72.4		

*All units are in ksi unless otherwise specified

STRUCTURAL ANALYSIS COMPLIANCE CHECK LIST (SACCL)

Component (Region)	Loading Condition	PRIMARY STRESS LIMITS: General Primary Membrane Stress Intensity	PRIMARY STRESS LIMITS: Local Primary Membrane Stress	PRIMARY STRESS LIMITS: Primary Membrane + Primary Bending Stress	Primary + Secondary Stress Difference Range	FATIGUE: Peak Alt. Stress Diff.	FATIGUE: Usage Factor
Superheater	Allowable Limit	S_y	S_y	1.35 S_y (Design) S_y (Operating)	2 S_y		$\Sigma u_i < 1.0$
Tubesheet (Design Cond.)	Calc. Value	12.0		17.6			
	Allow. Value	15.0		20.2			
Tubesheet (Operating Cond.)	Calc. Value	9.8		14.5	16.2		
	Allow. Value	15.5		15.2	31.0		
Shell/Tubesheet Juncture (Design Cond.)	Calc. Value		4.7		12.9		
	Allow. Value		15.0		30.0		
Shell/Tubesheet Juncture (Operating Cond.)	Calc. Value		4.9		25.2		
	Allow. Value		18.1		36.2		
Head/Tubesheet Juncture (Design Cond.)	Calc. Value		5.2		20.5		
	Allow. Value		15.0		30.0		
Head/Tubesheet Juncture (Operating Cond.)	Calc. Value		4.6		16.8		
	Allow. Value		15.5		31.0		

*All units are in ksi unless otherwise specified

STRUCTURAL ANALYSIS COMPLIANCE CHECK LIST (SACCL)

Component (Region)	Loading Condition	PRIMARY STRESS LIMITS: General Primary Membrane Stress Intensity	PRIMARY STRESS LIMITS: Local Primary Membrane Stress	PRIMARY STRESS LIMITS: Primary Membrane + Primary Bending Stress	Primary + Secondary Stress Difference Range	FATIGUE: Peak Alt. Stress Diff.	FATIGUE: Usage Factor
Reheater	Allowable Limit	S_y	S_y	1.35 S_y (Design) S_y (Operating)	2 S_y		$\Sigma u_i < 1.0$
Tubesheet	Calc. Value	6.6		17.8			
(Design Cond.)	Allow. Value	15.0		20.2			
Tubesheet	Calc. Value	3.6		9.5	12.5		
(Operating Cond.)	Allow. Value	15.5		15.2	35.2		
Shell/Tubesheet	Calc. Value		5.0		15.6		
Juncture			15.0		30.0		
(Design Cond.)	Allow. Value						
Shell/Tubesheet	Calc. Value		4.2		16.9		
Juncture			17.6		35.2		
(Operating Cond.)	Allow. Value						
Head/Tubesheet	Calc. Value		3.5		22.7		
Juncture			15.0		30.0		
(Design Cond.)	Allow. Value						
Head/Tubesheet	Calc. Value		2.9		15.3		
Juncture			17.6		35.2		
(Operating Cond.)	Allow. Value						

*All units are in ksi unless otherwise specified

STRUCTURAL ANALYSIS COMPLIANCE CHECK LIST (SACCL)

Component (Region)	Loading Condition	SPECIAL STRESS LIMITS: DEAD LOAD**: Longitudinal Bending + Pressure Stress	SPECIAL STRESS LIMITS: DEAD LOAD**: Circum-ferential Bending Stress	SPECIAL STRESS LIMITS: DEAD LOAD**: Tangential Shear Stress	SECONDARY THERMAL GRADIENTS: Longitudinal Bending + Pressure Stress	SECONDARY THERMAL GRADIENTS: Circum. Bending + Pressure Stress	SECONDARY THERMAL GRADIENTS: Shear Stress	Displace-ments	Rotations
	Allowable Limit	S	1.25S	.8S	S_y	S_y	T_y	(in)	(Deg.)
SH Shell at Saddle Support	Calc. Value	8.5	2.9	1.3					
	Allow. Value	9.2	11.5	7.4					
Evap Shell at Center Saddle Support	Calc. Value	14.1	14.1	4.0					
	Allow. Value	15.8	19.7	12.6					
Evap Shell at Ring Stiffeners	Calc. Value				32.2	$<S_y$	9.7		
	Allow. Value				33.7	33.7	16.8		
Evap Cyl Shell to Cone Shell (at Large Dia)	Calc. Value				7.7	2.7			
	Allow. Value				33.7	33.7			
Evap Cyl Shell to Cone Shell (at Small Dia)	Calc. Value				6.9	13.6			
	Allow. Value				33.7	33.7			
Evap U-Tube Small Bend Rad	Calc. Value				17.1	6.7			0.5
	Allow. Value				26.5	26.5			0.6

* All Units are in ksi unless otherwise specified

** The dead load condition governs design since the increase in load and stresses for 0.1g seismic is less than the increase of 1 1/3 in allowable stress

STRUCTURAL ANALYSIS COMPLIANCE CHECK LIST (SACCL)

Component (Region)	Loading Condition	SPECIAL STRESS LIMITS (Con't) ELEVATED TEMPERATURE EFFECTS: Creep Ratcheting	Creep Fatigue Interaction	Creep Buckling
Superheater	Allowable Limit	$\varepsilon \leq 1.5\%$	$\Sigma u_f + \Sigma u_c \leq D^*$	Load Factor <20
Tubing @ Salt Inlet	Calc. Value	Regime E		
	Allow. Value	1.5%		
Tubing @ Hot Leg Midspan	Calc. Value	Regime E		
	Allow. Value	1.5%		
Tubing @ Hot Leg U-Bend Tangent	Calc. Value	Regime E		
	Allow. Value	1.5%		
Steam-Side Hemi-Head	Calc. Value	0.4%		
	Allow. Value	1.5%		
Tubesheet	Calc. Value		0.50	
	Allow. Value		1.00	
Head/Tubesheet Juncture	Calc. Value		0.45	
	Allow. Value		1.00	
Shell/Tubesheet Juncture	Calc. Value		0.34	
	Allow. Value		1.00	
Salt-Side Shell @ Rear Support	Calc. Value			4.5
	Allow. Value			20.0

* Total Damage Factor D, Determined From Fig. T-1420-2 of Reference 20

Appendix D

Supplemental Elevated Temperature Rules For ASME Section VIII - Division 1

SUPPLEMENTAL ELEVATED TEMPERATURE RULES
FOR SECTION VIII DIVISION 1

Introduction and Purpose

The basic design code for the SGS components is Section VIII Division 1 of the ASME Code. For elevated temperature service this code does address a primary creep failure mode due to pressure and dead loading conditions. There are however other creep related effects which should be addressed, therefore supplemental rules have been developed for guidance.

References 20, 22 and 14 are the principal references used in the development of the rules. Some of the material in paragraphs 3252 and 3260 are contained in reference 14, "An Interim Structural Design Standard, Jan. 1979." In the following paragraphs, the supplementary rules are presented, followed by a brief commentary on the development of the rules.

REVISION NO.	REVISION DATE	DESCRIPTION	PREPARED BY
0	Oct. 30,1981	Original Issue	EML
1	March 19,1982	Redefined stress parameter under 3251.1 Revised criteria for total creep damage in 3252.3 Revised the procedure for creep damage calculation in 3252.3 (d) Added section 3262.3 for time dependent buckling Added values for yield strength in Table 3251.1 Added Figure 3252.3.5 for creep-fatigue damage	EML

Supplementary Elevated Temperature Design Rules

For Section VIII-Division 1

-3000 DESIGN

-3100 GENERAL REQUIREMENTS FOR DESIGN

-3111 ACCEPTABILITY - An acceptable design is one which meets the requirements given below.

(a) the design satisfies the general design requirements of -3100 and the appropriate component rules in -3200.

-3200 DESIGN RULES (VESSEL)

-3210 GENERAL - The design of the pressure vessels and the vessel parts shall conform to the design requirements of -3200.

-3220 BASE DESIGN RULES

The design shall conform to the requirements of Section VIII-Division 1 of the ASME Boiler and Pressure Vessel Code. Additional requirements stated in -3250 shall also be met.

-3250 ADDITIONAL REQUIREMENTS - The additional requirements of -3251 and -3252 shall be satisfied if -3220 is used.

The buckling limits of -3260 may be used for those configurations and loading conditions for which buckling rules or charts are not provided in Section VIII-Division 1.

3251 CREEP RATCHETING EVALUATION - Ratcheting requirements for shells can be considered met for normal operating cycles if the limits of 3251.2 is satisfied. Each cycle may be evaluated independently in determining the final accumulated strain.

3251.1 Parameters

(a) The following definitions apply to 3251.2 for stresses across a shell thickness.

$$x = \frac{\sigma_p}{S_y}$$

where σ_p is the primary pressure membrane stress and S_y is the average of the S_y values at the maximum and minimum wall-averaged temperatures during the operating cycle being evaluated. Table 3251.1 lists values for S_y.

$$y = \frac{Q_r}{S_y}$$

where Q_r is the maximum range of secondary stress occuring with X during the operating cycle being evaluated.

(b) The following definitons apply to 3251.2 for stresses across the shell cross section.

$$x = \left(\sigma_p + \frac{\sigma_b}{1.27}\right) / S_y$$

where $\sigma_p + \frac{\sigma_b}{1.27}$ is the primary membrane and primary bending adjusted for bending distribution

$$y = \frac{Q_r}{S_y}$$

where Q_R is maximum range of secondary stress occurring with X during the operating cycle being evaluated.

(c) The secondary thermal stress from radial gradients shall be based on the linearized radial gradient.

3251.2 Ratcheting Limits

(a) The procedure in this paragraph may be used for shells remote from geometric and material discontinuities to show that the limits for creep ratcheting are satisfied for the stress parameter of X and Y (3251.1) occurring at temperatures in the creep regime. These temperatures are defined as those for which S_m equals S_t for 10^5 hours and where S_m and S_t are as defined in the ASME Code Case N-47. Figures 3251.2.1 and 3251.2.2 give these temperatures for Type 304 and Alloy 800H. Non-axisymmetric loads such as the bending of a pipe or vessel may be included as axisymmetric loads and the rules applied.

The elastically calculated primary and secondary stresses are used to determine an "effective creep stress" σ_c, which in turn is used to determine a total ratcheting strain. The effective creep stress σ_c, for any combination of loading is given in Figure 3252.2.2 in dimensionless form.

(b) The isochronous stress strain curves of T-1800 in Appendix T of Code Case N-47 may be used to obtain the creep ratcheting strain. The total service life may be subdivided into temperature-time blocks and the strain increment for each block may be evaluated separately. The strain increments for each time temperature block shall be added to obtain the total ratcheting strain. The resulting value shall be limited to 1.5%.

-3252 CREEP-FATIGUE EVALUATION - The following requirements on creep-fatigue evaluation apply to elevated temperature service.

-3252.2 RULES TO DETERMINE NEED FOR CREEP-FATIGUE ANALYSIS - A creep-fatigue evaluation need not be made provided the total number of significant load cycles is less than 25. If this condition is not met, a detailed creep-fatigue analysis shall be made in accordance with -3252.3. The load cycle is significant if any of the following is true:

(a) The range of the elastically calculated primary stress intensity is greater than 1.25 times the maximum allowable stress in Section VIII-Division 1.

(b) The range of the elastically calculated, secondary stress intensity range is greater than 1.5 times the maximum allowable stress in Section VIII-Division 1.

(c) The range of elastically calculated peak stress intensity range using a stress concentration factor of 2.5 at local structural discontinuities, unless otherwise specified, is greater than twice the allowable stress amplitude at 10^6 cycles from the design fatigue curves in Figures -3252.2.2.3.

-3252.3 CREEP-FATIGUE ANALYSIS

(a) All significant load conditions shall be evaluated for accumulated creep and fatigue damage including hold time and strain rate effects. For a design to be acceptable, the creep and fatigue damage shall satisfy the following relation:

$$\sum_{j=1}^{p}\left[\frac{n}{N_d}\right]_j + \sum_{k=1}^{q}\left[\frac{t}{T_d}\right]_k \leq D \qquad (1)$$

where

D = total creep-fatigue damage from Figure 3252.3.4

n = number of applied cycles of loading condition, j.

N_d = number of design allowable cycles of loading condition, j. N_d is determined from one of the design fatigue curves in Figures -3252.3.1 or 3252.3.2 corresponding to the maximum metal temperature during the cycle. The design fatigue curves were determined from completely reversed loading conditions at strain rates greater than, or equal to those noted on the curves.

t = time duration of the load condition, k.

T_d = allowable creep rupture time at a given stress or an effective stress from load, k. T_d values are obtained by the procedure outlined in -3252.3 (d).

(b) Equivalent Strain Range Calculation - An equivalent strain range is used to determine N_d. When the Design Specification contains a histogram delineating a specific loading sequence, the strain range shall be calculated for the cycles described by the histogram. If the sequence of loading is not defined by the Design Specification, then an appropriate method of combining cycles shall be applied. The equivalent strain range is computed according to one of the following procedures:

<u>Procedure 1 -General Case</u>

<u>Step 1</u> - Calculate all strain components for the strain history ($\varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{yz}, \gamma_{zx}$ versus time) for the complete cycle.

<u>Step 2</u> - Select a time when conditions are at an extreme for the cycle, either maximum or minimum. Refer to this time point by a subscript i. In some cases it may be necessary to try different points in time to find the one which results in the largest value of equivalent strain range.

Step 3 - Calculate the history of the change in strain components by subtracting the values at the time, t, from the corresponding components at each point in time during the cycle. For example:

$$\Delta\varepsilon_x = \varepsilon_x - \varepsilon_{xi}$$

$$\Delta\varepsilon_y = \varepsilon_y - \varepsilon_{yi}$$

Step 4 -Calculate the equivalent strain range for each point in time.

$$\Delta\varepsilon_{equiv} = \frac{\sqrt{2}}{3}\left[\left(\Delta\varepsilon_x - \Delta\varepsilon_y\right)^2 + \left(\Delta\varepsilon_y - \Delta\varepsilon_z\right)^2 + \left(\Delta\varepsilon_z - \Delta\varepsilon_x\right)^2 + \frac{3}{2}\left(\Delta\gamma_{xy}^2 + \Delta\gamma_{yz}^2 + \Delta\gamma_{zx}^2\right)\right]^{1/2} \quad (2)$$

Procedure 2- Applicable Only When the Principal Strains do not Rotate

Step 1. No change from Step 1 of Procedure 1.

Step 2. Determine the principal strains versus time for the cycle.

Step 3. At each time interval of Step 2, determine the strain differences $\varepsilon_1 - \varepsilon_2$, $\varepsilon_2 - \varepsilon_3$, $\varepsilon_3 - \varepsilon_1$.

Step 4. Determine the history of the change in strain differences by subtracting the values at the time, t, from the corresponding values at each point in time during the cycle. Designate these strain difference changes as:

$$\Delta\left(\varepsilon_1 - \varepsilon_2\right) = \varepsilon_{12} - \varepsilon_{12i}$$

$$\Delta\left(\varepsilon_2 - \varepsilon_3\right) = \varepsilon_{23} - \varepsilon_{23i}$$

$$\Delta\left(\varepsilon_3 - \varepsilon_1\right) = \varepsilon_{31} - \varepsilon_{31i}$$

Step 5. Compute the equivalent strain range as:

$$\Delta\varepsilon_{equiv} = \frac{\sqrt{2}}{3}\left[\Delta\left(\varepsilon_1 - \varepsilon_2\right)^2 + \Delta\left(\varepsilon_2 - \varepsilon_3\right)^2 + \Delta\left(\varepsilon_3 - \varepsilon_1\right)^2\right]^{1/2} \qquad (3)$$

(c) Fatigue Damage Evaluation

1) For the fatigue damage term the strain range ε_T is used with the design fatigue curve Figures 3252.3.1 and 3252.3.2 to determine N_d.

2) The maximum total equivalent strain is obtained from the following:

$$\varepsilon_T = K_\varepsilon \varepsilon_\varepsilon + K_\varepsilon^2 \varepsilon_p + \varepsilon_F \qquad (4)$$

where

ε_T = the derived maximum strain for the loading condition

ε_ε = the elastic strain in the region under consideration, exclusive of strain concentration

K_ε = the theoretical elastic strain-concentration factor

ε_p = the inelastic strain in the region under consideration, exclusive of strain concentration and peak thermal strains

ε_F = peak thermal strain associated with the peak thermal stress intensity

The value, ε_p, is determine by subtracting the elastic strain component; ε_ε from the calculated total nominal strain, $\varepsilon_{equiv.}$ $\varepsilon_{equiv.}$ can also be expressed as the total nominal strain, ε_n, and is the sum of the load-controlled strain and deformation-controlled strain, exclusive of strain concentration and peak thermal strain. The load-controlled strain is determined by entering the appropriate isochronous stress-strain curve at a stress intensity equivalent to the load -controlled stress intensity in the region under consideration. The deformation-controlled strain is determined from the elastically calculated stress intensity due to the applied deformation.

$$\varepsilon_n = \varepsilon_{load\text{-}controlled} + (S_{strain\text{-}controlled}/E)$$

3) Equation (4) results in a conservative value of the maximum srain ε_t, relative to the nominal strain level $\varepsilon_{equiv.}$ or ε_n when compared to the values obtained by the use of the Neuber equation. A more accurate and less conservative value may be obtained by following the procedure in Paragraph T-1432 (d) of Appendix T of ASME code case N-47.

(d) Creep-Damage Calculation -Creep damage calculations may be done by the following procedure for elastic analysis. The quantities are defined as:

P_m = Primary stress intensity

S_1 = Primary + secondary stress intensity for sustained operating conditions in the load cycle k

S_y = Minimum yield strength

S_k = Stress quantity used to determined the allowable creep rupture time Td

σ_{eff} = Effective stress for the sustained operating conditions in the load cycle k

σ_i = Principal stresses

k = Subscript of load condition

Step 1 - Calculate and determine the following stress quantities:

1) $(P_m + 0.5\ S_1)_k$

2) Sy_k is the minimum yield strength at the average wall temperature for the sustained operating condition being analyzed in the load cycle condition k.

Select the lesser of 1) and 2) as S_{K1}

Step 2 - Calculate the following stress quantities:

1) Effective stress:

$$\sigma_{eff} = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}$$

2) The largest principal tensile stress component of the primary-plus-secondary stresses during the sustained portion of the load cycle k being analyzed.

Select the larger of 1) and 2) above and designate as S_{K2}. If this value is less than S_{K1} from step 1, use this quantity as S_k in Step 3. If this value is greater than S_{K1}, use $S_{k1} = S_k$ in Step 3.

Step 3 - Enter the stress-to-rupture curves in Figure 3252.3.3 and Table 3252.3.3 or Figure 3252.3.4 and Table 3252.3.4, with S_k from Step 2 to determine the value of allowable time T_d.

-3260 BUCKLING INSTABILITY LOADS

-3261 GENERAL REQUIREMENTS

(a) Scope of Rules - The stability limits in Section VIII-Division 1 and 2 pertain only to specific geometrical configurations under specific loading conditions. These limits include the effects of initial geometrical imperfections permitted by fabrication tolerances. The rules in Paragraphs -3131, and -3132 of Code Case N-253 provide additional limits which are applicable to general configurations and loading conditions that may cause buckling or instability.

(b) Load-Controlled and Strain-Controlled Buckling - For the limits specified in -3262.2, distinction is made between load-controlled buckling and strain-controlled buckling. Load-controlled buckling is characterized by continued application of an applied load in the post-buckling regime leading to failure, as exemplified by collapse of tube under external pressure. Strain-controlled buckling is characterized by the immediate reduction of load due to strain-induced deformations. Even though it is self-limiting, strain-controlled buckling should be avoided to guard against failure by fatigue, excessive strain, loss of function due to excessive deformation, and interaction with load-controlled buckling.

(c) Interaction of Load-Controlled and Strain-Controlled Buckling - For conditions under which strain-controlled and load-controlled buckling may interact, as exemplified by elastic follow-up, the higher load factors applicable to load-controlled buckling shall be used for the combination of load-controlled and strain-controlled loadings.

(d) Effect of Initial Geometry Imperfections - For load-controlled buckling, the effects of initial geometrical imperfections and tolerances shall be considered in the time-independent calculations according to the requirements of Paragraph -3262.2. In calculating the instability strain under pure strain-controlled buckling, the effects of geometrical imperfections and tolerances, whether initially present or induced by service, need not be considered.

(e) Strain-Controlled Buckling - The evaluation of strain-controlled buckling is not mandatory. However, the strain-controlled buckling limits provided in -3262.2 may be used if such evaluation is deemed necessary.

(f) Creep Buckling - The evaluation of time-dependent buckling is not mandatory.

-3262 BUCKLING LIMITS (Time-Independent)

-3262.1 Buckling limits of Section VIII-Division 1 or Division 2 shall apply. These rules provide buckling charts which are applicable to limited geometrical configurations under specific loading conditions. For general configurations and loading conditions, and for materials and temperatures for which limits of Section VIII-Divisions 1 or 2 do not apply, the limits of -3132 of Code Case N-253 may be used.

-3262.2 For load-controlled buckling, the load factor, and for strain-controlled buckling, the strain factor, shall equal or exceed the values given in Table -3262-2.

Table -3262-2 Buckling Limits

Loads	Load Factor[1]	Strain Factor [1,3]
Design	3.0[2]	1.67
Testing[4]	2.25	1.67
Normal Operating Steady State	3.0	1.67

[1]Load (Strain) = Load (strain) which would cause instant instability at the design or actual service temperature / Design or expected load (strain).

[2] Changes in configuration induced by service need not be considered in calculating the buckling load.

[3] For thermally-induced strain-controlled buckling, the strain factor is applied to loads induced by thermal strain. To determine the buckling strain, it may be necessary to artificially induce high strains concurrent with the use of realistic stiffness properties. The use of an "adjusted" thermal expansion coefficient is one technique for enhancing the applied strains without affecting the associated stiffness characteristics.

[4] These factors apply to hydrostatic, pneumatic, and leak tests.

-3262.3 Time-Dependent Buckling - To protect against load-controlled time-dependent creep buckling, it shall be demonstrated that instability will not occur during the specified lifetime for a load history obtained by multiplying the specified Service Loading by the factor given in Table 3262.3. A design factor is not required for purely strain-controlled buckling because strain-controlled loads are reduced concurrently with resistance of the structure to buckling when creep is significant.

Table 3262.3

Time-Dependent Load-Controlled Buckling Factors

Service Loadings	
Normal Operating	
Steady State	1.5

Table 3251.1

Yield Strength Values, [1] S_y, vs. Temperature

Temp., F	304 SS	316 SS	Ni-Fe-Cr Alloy 800H
		(Stresses in ksi Units)	
RT	30.0	30.0	25.0
100	28.8	29.2	24.3
200	25.0	25.8	22.5
300	22.5	23.3	21.1
400	20.7	21.4	20.0
500	19.4	19.9	19.0
600	18.2	18.8	18.3
700	17.7	18.1	17.5
750	17.3	17.8	17.2
800	16.8	17.6	17.0
850	16.5	17.4	16.6
900	16.2	17.3	16.5
950	15.9	17.1	16.2
1000	15.6	17.0	16.0
1050	15.2	16.7	15.8
1100	14.7	16.5	15.6
1150	14.4	16.4	15.5
1200	14.1	16.2	15.3
1250	13.7	15.8	15.1
1300	13.2	15.3	14.7
1350	12.5	14.9	14.5
1400	11.6	14.4	14.0
1450	10.6	13.8	13.5
1500	9.5	13.1	13.0
1550			12.0
1600			11.2

Table 3251.2.1
S_{mt} - Allowable Stress Intensity Values, Ksi
Type 304 SS - 30-YS, 75-UTS (30-YS, 70-UTS)

Temp. °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
850	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8
900	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6
950	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.2	12.2
1000	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.1	11.1	9.3
1050	13.6	13.6	13.6	13.6	13.6	13.6	13.6	12.2	10.3	8.7	7.3
1100	13.2	13.2	13.2	13.2	13.2	13.2	11.5	9.7	8.2	6.8	5.7
1150	12.9	12.9	12.9	12.9	12.9	11.0	9.3	7.7	6.4	5.3	4.4
1200	12.7	12.7	12.7	12.2	10.6	8.9	7.4	6.1	5.1	4.1	3.4
1250	12.3	12.3	11.9	10.3	8.7	7.2	5.9	4.9	4.0	3.2	2.7
1300	11.9 (11.8)	11.4	10.0	8.5	7.0	5.9	4.8	3.9	3.2	2.5	2.1
1350	10.9 (10.5)	9.7	8.4	7.1	5.9	4.8	3.9	3.1	2.5	2.0	1.6
1400	9.5 (9.0)	8.1	6.9	5.9	4.8	3.9	3.1	2.5	2.0	1.6	1.2
1450	8.2 (7.5)	6.8	5.8	4.6	3.8	3.0	2.4	1.9	1.5	1.2	0.9
1500	7.0 (6.4)	5.3	4.4	3.5	2.8	2.2	1.7	1.3	1.0	0.8	0.6

Figure 3251.2.1 S_{mt} - Type 304 SS

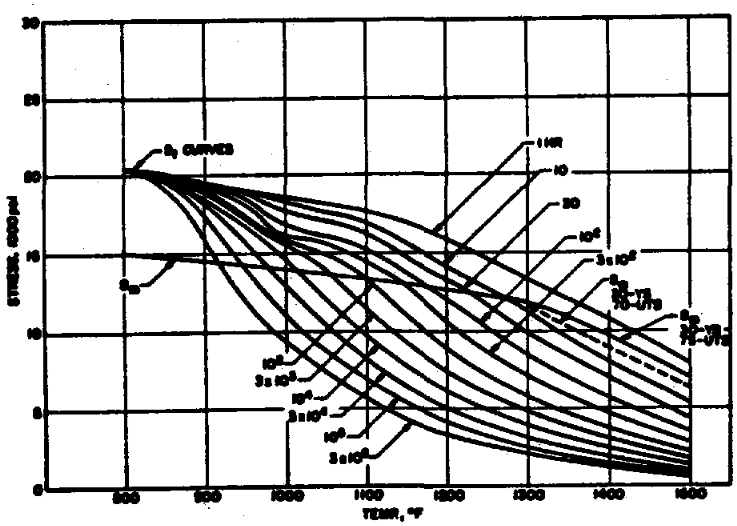


Table 3251.2.2
Ni-Fe-Cr (Alloy 800H), S_{mt} Allowable Stress Intensity Values, Ksi

Temp. °F	1 hr	10 hr	30 hr	100 hr	300 hr	1000 hr	3000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
800	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
850	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1
900	14.8	14.8	15.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8
950	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6	14.6
1000	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4	14.4
1050	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	13.4
1100	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1	13.6	11.7	10.3
1150	13.9	13.9	13.9	13.9	13.9	13.9	13.9	12.8	10.5	9.1	8.0
1200	13.8	13.8	13.8	13.8	12.8	12.5	10.9	9.4	8.2	7.2	6.4
1250	13.5	13.5	13.5	13.3	11.5	9.8	8.6	7.5	6.6	5.8	5.1
1300	13.2	13.2	12.4	10.5	9.1	7.9	6.9	6.0	5.3	4.6	4.1
1350	12.8	11.4	9.9	8.4	7.4	6.4	5.6	4.9	4.3	3.7	3.3
1400	11.8	9.2	8.0	6.8	6.0	5.2	4.6	4.0	3.5	3.0	2.6

Figure 3251.2.2 S_{mt} - Ni-Fe-Cr (Alloy 800H)

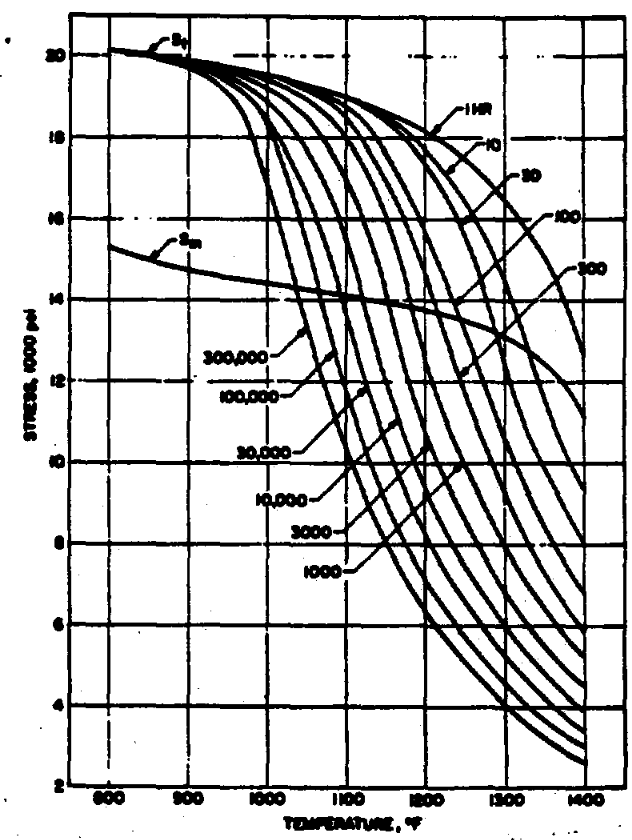


Figure 3252.2.2 Strain Limits Using Elastic Analysis

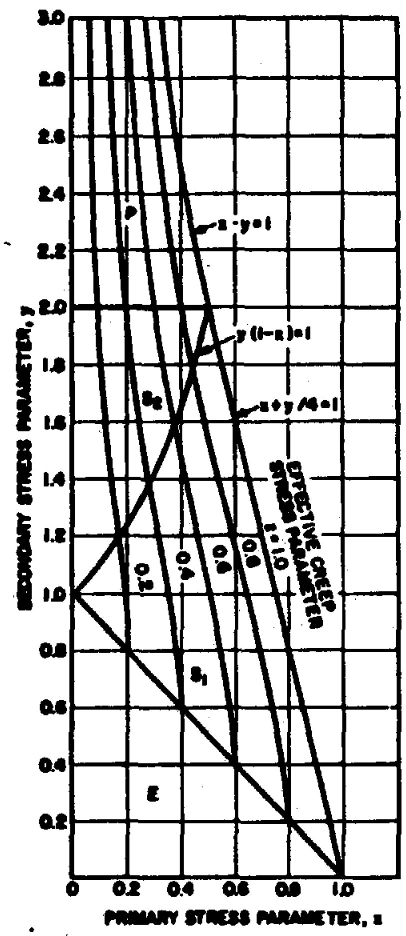


Figure 3252.2.3 Design Fatigue Strength, Sa, For High-Alloy Steels and Ni-Cr-Fe Alloys up to 1200°F

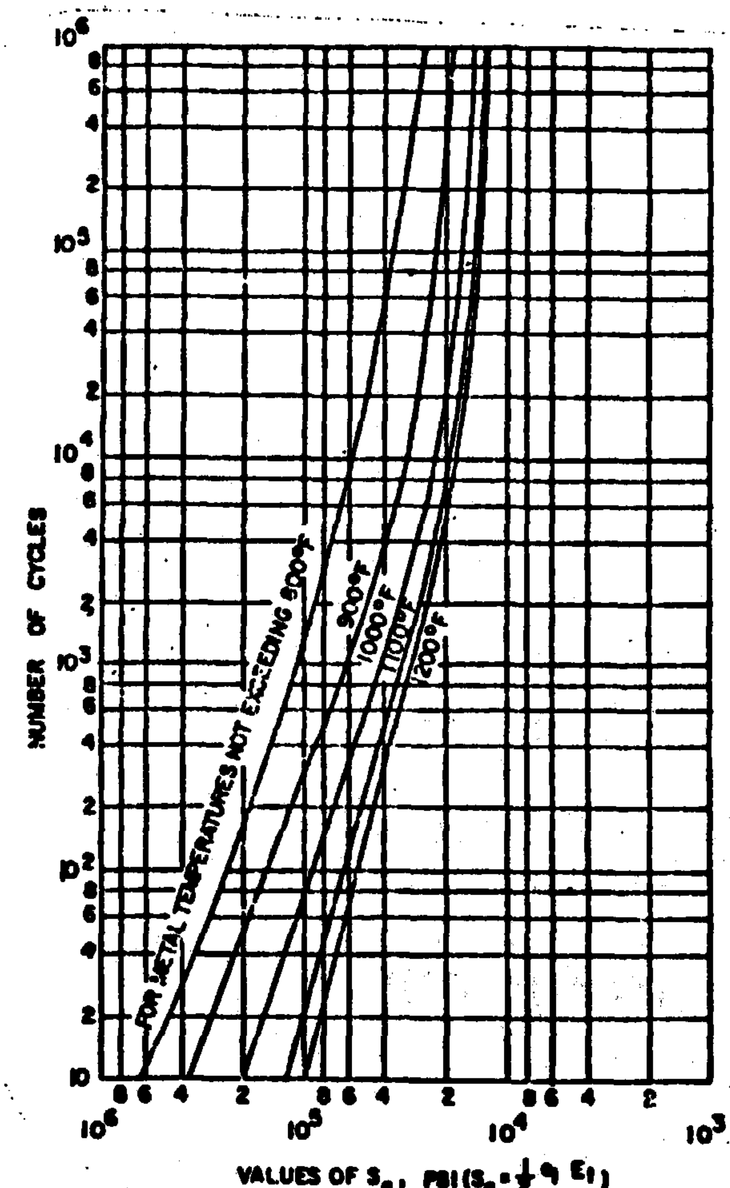


Table 3252.3.1

Design Fatigue Strain Range, ϵ_t, for 304 SS

N_d Number of Cycles*	ϵ_t, Strain Range (in./in.) at Temperature						
	100 F	800 F	900 F	1000 F	1100 F	1200 F	1300 F
10	0.051	0.050	0.0465	0.0425	0.0382	0.0335	0.0297
20	0.036	0.0345	0.0315	0.0284	0.025	0.0217	0.0186
40	0.0263	0.0246	0.0222	0.0197	0.017	0.0146	0.0123
10^2	0.018	0.0164	0.0146	0.0128	0.011	0.0093	0.0077
2×10^2	0.0142	0.0125	0.011	0.0096	0.0082	0.0069	0.0057
4×10^2	0.0113	0.00965	0.00845	0.00735	0.0063	0.00525	0.00443
10^3	0.00845	0.00725	0.0063	0.0055	0.0047	0.00385	0.00333
2×10^3	0.0067	0.0059	0.0051	0.0045	0.0038	0.00315	0.00276
4×10^3	0.00545	0.00485	0.0042	0.00373	0.0032	0.00263	0.0023
10^4	0.0043	0.00385	0.00335	0.00298	0.0026	0.00215	0.00185
2×10^4	0.0037	0.0033	0.0029	0.00256	0.00226	0.00187	0.00158
4×10^4	0.0032	0.00287	0.00254	0.00224	0.00197	0.00162	0.00138
10^5	0.00272	0.00242	0.00213	0.00188	0.00164	0.00140	0.00117
2×10^5	0.0024	0.00215	0.0019	0.00167	0.00145	0.00123	0.00105
4×10^5	0.00215	0.00192	0.0017	0.0015	0.0013	0.0011	0.00094
10^6	0.0019	0.00169	0.00149	0.0013	0.00112	0.00098	0.00084

*Cyclic strain rate: 1×10^{-3} in./in./sec.

Figure 3252.3.1 Design Fatigue Strain Range, ϵ_t, For 304 SS

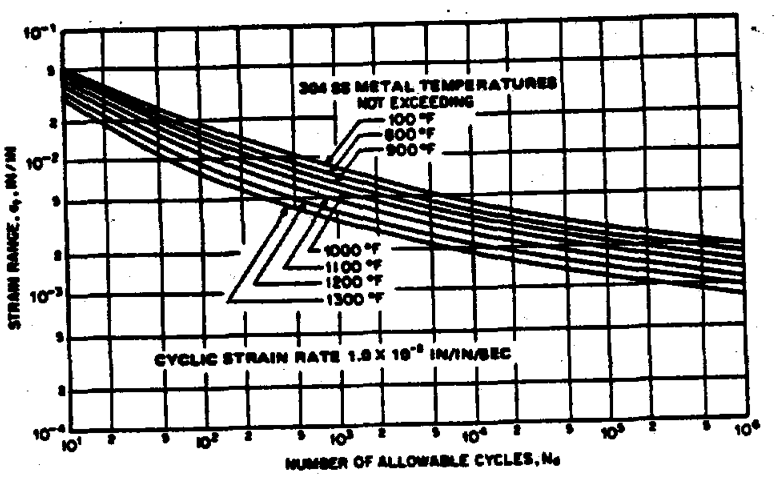


Table 3252.3.2
Design Fatigue Strain Range, ϵ_t, For Ni-Fe-Cr, Alloy 800H

N_d Number of Cycles*	ϵ_t, Strain Range (in./in.) at Temperature						
	800 F	900 F	1000 F	1100 F	1200F	1300 F	1400 F
10^1	.0513	.0498	.0468	.0378	.0308	.0263	.0231
2×10^1	.0328	.0313	.0296	.0243	.0198	.0168	.0129
4×10^1	.0218	.0208	.0190	.0163	.0130	.0113	.00966
10^2	.0139	.0129	.0119	.01	.00823	.00725	.00566
2×10^2	.0103	.00939	.00861	.00722	.00608	.00535	.00426
4×10^2	.00777	.00699	.00641	.00542	.00463	.00405	.00331
10^3	.00537	.00489	.00441	.00392	.00328	.00285	.00254
2×10^3	.00427	.00379	.00351	.00312	.00261	.0023	.00209
4×10^3	.00347	.00314	.00291	.00259	.00213	.00196	.00176
10^4	.00277	.00249	.00233	.0021	.00174	.00159	.00143
2×10^4	.00242	.00219	.00201	.00182	.00155	.00142	.00125
4×10^4	.00215	.00198	.0018	.00162	.0014	.00127	.00109
10^5	.00187	.00164	.00151	.00139	.00122	.00115	.000959
2×10^5	.00169	.00149	.00141	.00128	.00113	.00105	.000919
4×10^5	.00157	.00139	.00129	.00121	.00108	.000987	.000889
10^6	.00139	.00129	.00119	.00112	.00108	.000937	.000869

*Cyclic strain rate: 1×10^{-3} in./in./sec.

Figure 3252.3.2 Design Fatigue Strain Range, ϵ_t, For Ni-Fe-Cr Alloy 800H

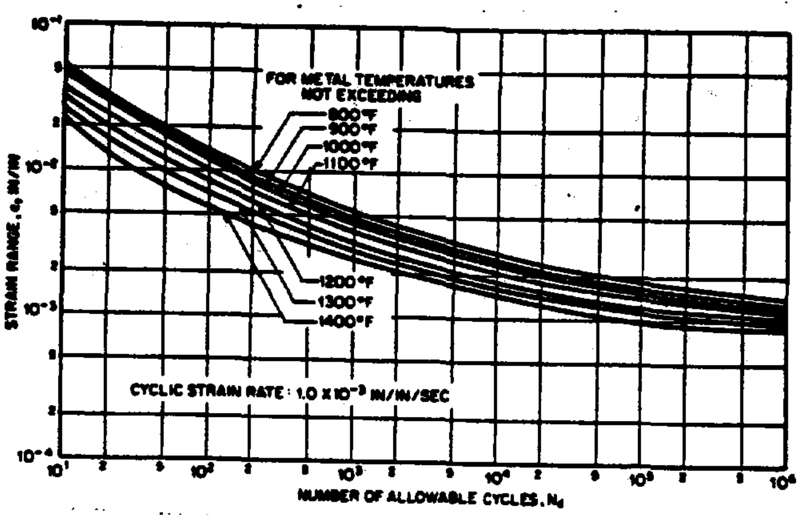


Table 3252.3.3
Expected Minimum Stress-To-Rupture Values For Type 304 SS, Ksi

Temp., °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	57	57	57	57	57	57	57	57	51	44.3	39
850	56.5	56.5	56.5	56.5	56.5	56.5	50.2	45.4	40	34.7	30.5
900	55.5	55.5	55.5	55.5	51.5	46.9	41.2	36.1	31.5	27.2	24
950	54.2	54.2	51	48.1	43	38.0	33.5	28.8	24.9	21.2	18.3
1000	52.5	50	44.5	39.8	35	30.9	26.5	22.9	19.7	16.6	14.0
1050	50	41.9	37	32.9	28.9	25.0	21.6	18.2	15.5	13.0	11.0
1100	45	36.2	31	27.2	23.9	20.3	17.3	14.5	12.3	10.2	8.6
1150	38	29.5	26	22.5	19.3	16.5	13.9	11.6	9.6	8.0	6.6
1200	32	24.7	21.5	18.6	15.9	13.4	11.1	9.2	7.6	6.2	5.0
1250	27	20.7	17.9	15.4	13	10.8	8.9	7.3	6.0	4.9	4.0
1300	23	17.4	15	12.7	10.5	8.8	7.2	5.8	4.8	3.8	3.1
1350	19.5	14.6	12.6	10.6	8.8	7.2	5.8	4.6	3.8	3.0	2.6
1400	16.5	12.1	10.3	8.8	7.2	5.8	4.7	3.7	3.0	2.3	1.9
1450	14.0	10.2	8.8	7.3	5.8	4.6	3.8	2.9	2.3	1.8	1.4
1500	12.0	8.6	7.2	6.0	4.9	3.8	3.0	2.4	1.8	1.4	1.1

Figure 3252.3.4 Minimum Stress-To-Rupture Values For Type 304 SS, Ksi

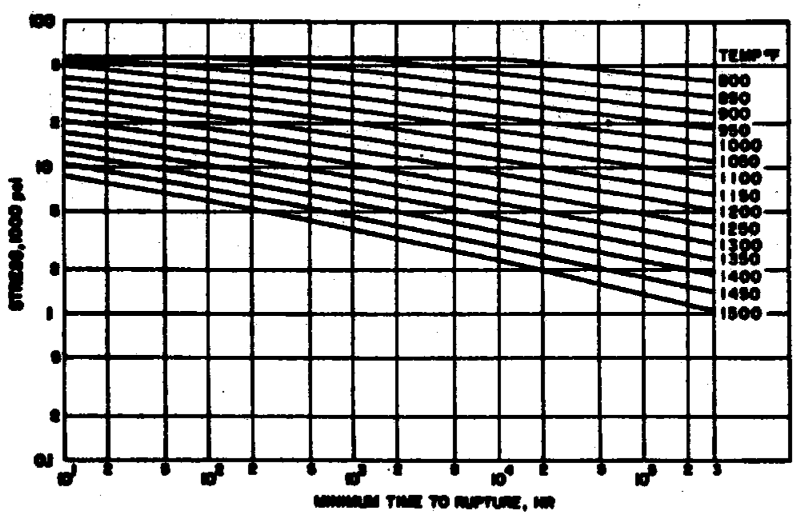


Table 3252.3.4
Expected Minimum Stress-To-Rupture Values For Ni-Fe-Cr Alloy 800H, Ksi

Temp., °F	1 hr	3 hr	10 hr	30 hr	100 hr	300 hr	1000 hr	3000 hr	10000 hr	30000 hr	100000 hr	300000 hr
800	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.0	55.0
850	60.7	60.7	60.7	60.7	60.7	60.7	60.7	60.7	57.5	53.5	49.3	45.6
900	60.7	60.7	60.7	60.7	60.7	60.7	57.9	53.8	49.4	45.5	41.5	38.0
950	60.7	60.7	60.7	60.7	59.0	54.7	50.1	46.1	41.9	38.2	34.4	31.2
1000	60.7	60.7	60.7	56.3	51.5	47.2	42.8	39.0	35.0	31.6	28.2	25.4
1050	60.7	58.5	53.5	49.0	44.3	40.3	36.1	32.6	29.0	25.9	22.9	20.4
1100	56.1	51.4	46.5	42.2	37.8	34.0	30.1	26.9	23.7	21.1	18.4	16.3
1150	49.3	44.7	40.0	36.0	31.8	28.4	24.9	22.1	19.3	17.0	14.7	12.9
1200	42.9	38.5	34.1	30.3	26.6	23.5	20.5	18.0	15.5	13.6	11.7	10.2
1250	37.0	32.9	28.8	25.4	22.1	19.3	16.7	14.5	12.5	10.9	9.3	8.1
1300	31.6	27.8	24.1	21.0	18.2	15.8	13.5	11.7	10.0	8.6	7.4	6.4
1350	26.8	23.4	20.1	17.5	14.9	12.9	10.9	9.4	8.0	6.9	5.8	5.0
1400	22.6	19.6	16.7	14.4	12.2	10.4	8.8	7.5	6.4	5.5	4.6	4.0

Figure 3252.3.4 Minimum Stress-To-Rupture Values For Ni-Fe-Cr Alloy 800H, Ksi

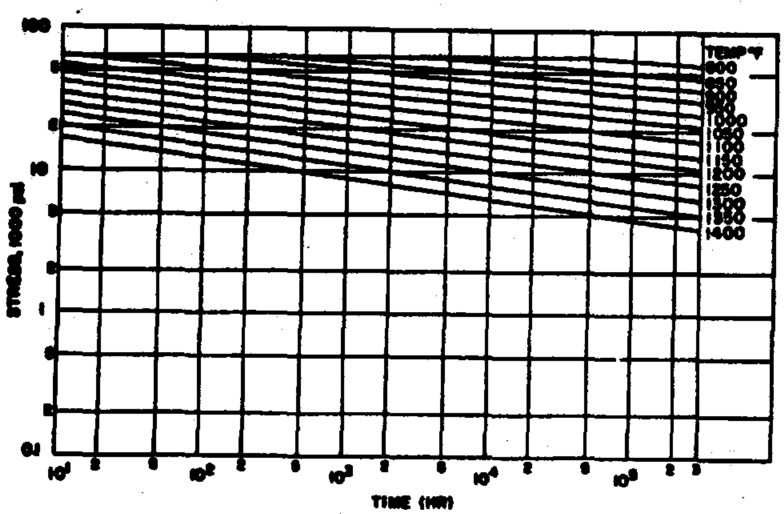
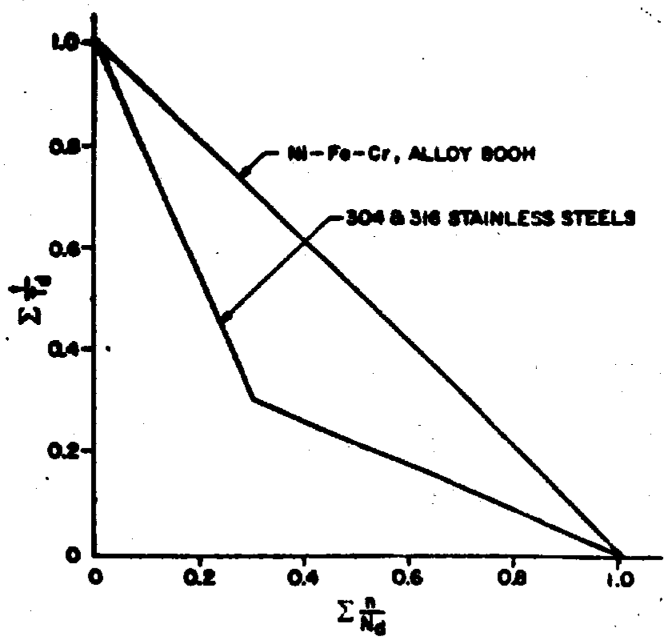


Table 3252.3.5

Creep-fatigue damage envelope



Commentary to the Supplemental Elevated Temperature Rules for Section VIII Division 1

Introduction and Purpose

The basic design code for the SGS and receiver components is Section VIII Division 1 of the ASME Code. For elevated temperature service this code does address a primary creep failure mode due to pressure and dead loading conditions. There are however other creep related effects which should be addressed, therefore supplemental rules have been developed for guidance.

References 20, 22, and 14 are the principal references used in the development of the rules. Some of the material in paragraphs 3252 and 3260 are contained in reference 14, "An Interim Structural Design Standard, Jan. 1979".

-3251 Evaluation for the potential ratcheting of the main shell pressure boundaries is necessary for several reasons:

1) There is very little creep-fatigue data existing for conditions where the mean strain may be continually rising. When ratcheting occurs the mean strain continually rises leading to unknown effects on creep-fatigue damage.

2) In low temperature design by Section III, the limit of 3 S_m assures shakedown and therefore the determination of peak fatigue stress ranges by elastic analysis will be valid. Although for elevated temperature the 3 S_m limit need not apply, there should be some assurance that shakedown limits are not excessively exceeded in order again that elastically calculated peak stresses can validly be used for fatigue evaluations.

3) The ratcheting evaluation results of accumulated strain are needed for comparison to safe limits for progressive distortion.

O'Donnell in Reference 21 points out that the procedure in his report (and incorporated in N-47) does not account for strain hardening and could be approximated by using a higher effective yield strength. In these supplementary rules strain hardening could be accounted for by using a value of yield exhibiting strain hardening. However, until strain hardening values are available, the yield strength values given in reference 20 will be used.

-3251.2 The requirements of paragraph T-1324 of Appendix T (Reference 20) limits the ratcheting rules to locations away from structural discontinuities. This is consistent with the development work done in Reference 21. O'Donnell in Reference 21 has developed the upper bound accumulated strain due to creep-ratcheting using the concept of interacting circumferential principal stresses for the thermal stresses and membrane pressure stress. Since there will not in general be primary bending across the vessel walls, the procedure will apply to cylindrical or spherical shells having primary membrane stress and secondary thermal bending stresses through the vessel wall. Therefore, the creep-ratcheting procedure in the supplementary rules will apply only to cylindrical and spherical shells at locations removed at least an attenuation length of $2.5\sqrt{RT}$ away from geometric or material structural discontinuities.

O'Donnell in Reference 21 uses the maximum surface stress as the linearized stress and states that this is conservative. In the supplementary procedure the actual linearized value will be used.

Reference 20 limits the elastic stress ratcheting procedure to loading cases where at least one stress extreme is below the creep regime. In the supplementary rules this requirement is deleted, and the procedure will be used without this restriction. The reason being that an elastic analysis alternative is not available, therefore it can be used without restriction and consider the effect in setting the limits.

The procedure can also be used for circular cross-sectional bending and longitudinal pressure membrane, e.g., piping or shells. In this case, there could be primary bending in addition to primary membrane. The expression for the stress parameter X in this case is based on using a bending distribution factor of K_t = 1.27 for thin tubes as discussed in Section 5.4 of Reference 22.

3251.2 (b) (1) CC N-47 requires that the effective creep stress σ_c be increased by 1.25. This is a result of basing the evaluation on minimum isochronous curves and making the assumption that they will be 25% lower than the "average" curves given in T-1800 of N-47. This is discussed in Reference 22 Section 6.4.2. In this procedure the evaluation will be based on the average curves, therefore the 1.25 will be replaced by 1.

(2) O'Donnell in Reference 21 concludes the residual stresses relax, therefore do not influence long term effects. However, because of the uncertainties of weld material properties and degree of residuals, strain limits for weld was recommended to be reduced by an arbitrary amount of one-half. The resulting limits were set to e 1% for base metal and 1/2% for weld metal. However, Section 6.2 of Reference 20 sets a limit 1% for membrane strain and 2% for bending. The stress parameters for the ratcheting rules are both membrane and bending.

Therefore, this procedure will allow for this by setting the limit at an averge value of 1.5%. The concern for welds has not been conclusively proven and since there is conservatism in the rules, the limit of 1.5% will also apply to welds.

(3) CC N-47 in paragraph T-132(d) requires consideraton of stress "elastic follow-up". As discussed in Section 9.3 of Reference 22, this concern is addressed mainly to piping where the system can have significant unbalanced stiffness. This section cites that a "built-in" cylinder is another example, however, admits that requiring it to be included as a primary bending source is conservative and not fully justified. Therefore in this procedure, this conservative follow-up requirement will not be applied.

3252.3 (c) (1) The effect of fatigue life due to slow strain rates or cycling with hold times has not been well defined or quantified. One of the factors known to be involved is the relaxation of peak residual thermal stresses. In this supplementary prodedure fatigue will be evaluated using the continuous cycling fatigue design curves in lieu of the conservative hold time fatigue curves,and the effect of the peak residual thermal stresses will be include in determining the creep life-fraction ratio. This will avoid double counting creep that may be done by using hold time curves.

(2) The equation for determining the maximum strain is from Reference 21 Section 7.72. This equation is considered to be the most appropriate for these simplified rules and is judged to provide adequate conservatism in accounting for plastic strain concentration.

3252.3(d) In section 7.7.3 of reference 22 the philosophy and assumptions are given for the rules developed for determining the time fraction of creep damage. Because of residual stress relaxation it was assumed that an upper bound of primary plus secondary stress during a sustained condition would be the yield strength. The rules as written in N-47 Appendix T-1433 required a factor of 1.25 to be applied. A surmise is that this factor is to adjust the minimum values of yield strength to an average value. In the Supplementary rules the factor is reduced to 1. The reason for this is that the stress to rupture curves used in finding the allowable time are based on minimum times to rupture, therefore the additional conservatism of applying the 1.25 factor is not required in order to have a safe analysis. In other words, it is consistant to use minimum yield strength for correlation with minimum stress rupture data.

There are test data results cited in Section 4 of reference 14 that show for types 304 and 316 stainless steels, only the tensile stress contributes to creep damage. However, insufficient data are available to verify this for Incoloy 800 material, therefore the "effective stress" should be used. The Supplementary rules provide steps for analyzing either case to assure that the most valid quantity is considered.

Appendix T-1431 of reference 20 limits the total creep-fatigue damage to unity for an elastic analysis. In the Supplementary rules the total creep-fatigue damage is limited to the more conservative creep-damage envelope based on Figure T-1420-2 of reference 20. The reason for this change is that the Supplementary rules allow the use of the less conservative inelastic fatigue curves, therefore any unaccounted for cyclic hold time creep will be covered by the additional conservatism in the damage envelope.

Appendix E
System Simulation Analysis

APPENDIX E

System Simulation Analysis

of

Molten Salt Steam Generator Subsystem

March, 1982

SYSTEM SIMULATION OF THE

MOLTEN SALT STEAM GENERATOR SUBSYSTEM

Objective

The objective of the study is to develop a system simulation model capable of predicting the response of the steam generator subsystem to normal and upset transients. Results obtained via the simulator are used to assess plant performance, control concepts, and thermal loads on the steam generators.

Defining the Extent and Composition of the System

The first step in simulation is to define the extent and composition of the system. There are three questions to be answered in this definition: (1) What is of interest? (2) What is the degree of accuracy or depth required in the study? (3) Are there practical limitations involved?

In answering the first question, the modeler decides focal points of interest in the system. The main focus of this simulation is to show the dynamic response of the components within the Molten Salt Steam Generator Subsystem, in particular the heat exchangers. Figure 1 shows the components that are included in the simulation model.

Secondly, the degree of accuracy required must be determined in view of the overall objectives. Since thermal performance is of prime interest, macroscopic modeling (one dimensional heat transfer, fluid flow, lumped parameters, etc.) is adequate.

Finally, the modeler must decide the practical limitations involved. The limitations are usually dependent on the method of computation chosen. For a steam generator simulation, the hybrid computer has three distinct advantages over a digital computer. The first advantage deals with the accuracy of the model representation. The analog computer can be used to solve problems continuously in space and/or time, thus, avoiding the discrete nodes (with averaged properties) normally associated with digital computation. Secondly, the hybrid computer is faster due to parallel processing. Most stable digital computational schemes require that fluid particles do not transverse more than the distance between node centers in a time step. This requirement results in time steps in the millisecond range going hand-in-hand with high resolution spatial solutions. This problem is accentuated further when dealing with superheated steam where velocities are in the 100 to 250 ft/sec range. Integrating continuously in space on the hybrid computer eliminates this problem. Finally, the hybrid computer provides hands-on capability to the analysist. Manual override or operation actions of the control system, trip initiation and operational sequences can all be accomplished while a simulation is executing. It is for these reasons that the hybrid computer was chosen for the steam generator subsystems simulation.

Computer Models

All the component models of the subsystem were derived from the conservation laws of mass, energy, and momentum. For simplicity, the conservation of mass and momentum are decoupled from the conservation of energy equations. This is allowable for the group of transients under investigation since they do not involve rapid depressurization of the working fluids.

The evaporator and preheater were modeled using the Continuous-Space-Discrete-Time (CSDT) models previously developed by Babcock & Wilcox for use in pressurized water reactor nuclear systems. This model was modified to allow for salt flow on the shell side and horizontal tube bundle orientation. The model is capable of calculating heat transfer along the water-side tube surface in the subcooled, boiling, and superheated regimes. Salt-side heat transfer was determined from a longitudinal heat transfer correlation using an average salt temperature and time-varying flow rate. Figure 2 depicts the modeling assumptions for the preheater and evaporator.

The superheater and reheater were also CSDT models; but, since single-phase fluids exist on both sides of the tube, average parameters were utilized. The modeling assumptions for the superheater and reheater are shown in Figure 3.

The steam drum model conserves mass and energy to determine the drum pressure and level. Three relief valves are on the drum, each with 100,000 lbm/hr relieving capacity. Free surface boiling and condensation are also modeled (Figure 4).

The steam drum is also an integral part of the piping and valve network of the steam generator subsystem. Figure 5 is a schematic of the hydraulic system as it appears to the mathematic model. Incompressible flow was assumed throughout the network. Friction, form loss, and the gravity heads were included in the model, along with pumps which operate on predetermined head-capacity curves (see Figure 6 for an example). Each numbered circle represents a junction point where the pressure will be determined. Twenty-five pipe segments connect these junctions in which the fluid velocity is calculated via the conservation laws of mass and momentum. The valves in this network are modeled using performance curves (see Figure 7 for an example) which relates the sizing coefficient to valve position.

Temperature boundary conditions are required to complete the mathematical model. The hot and cold salt storage tanks are assumed to contain molten salt at constant temperatures (1,050^{o}F and 550^{o}F respectively). The feed-water temperature varies as a function of load. Figure 8 shows this relationship. Being influenced by the high pressure stage of the turbine, the cold reheat temperature varies as a function of load (Figure 9).

The control system was programmed to take advantage of the hands-on capability of the analog computer. Gains of individual controllers were patched to potentiometers to allow on-line adjustments. Trip initiation for the valves and pumps were patched to push buttons on the analog console to allow manual control at any time during a simulation run. The automatic control system is shown pictorially in Figures 10-15. The transfer functions which are shown in the figures are transformed from the Laplace domain to the time domain and solved by the digital computer.

<u>Computer Hardware</u>

Six pieces of hardware are used to solve the mathematical model of the steam generator subsystem. Figure 16 depicts the hardware used and the relationship between the components. At the heart of this system is a CDC 1700 digital computer. The CDC 1700 is in control of the overall simulation and also contains the software which solves the mathematical models for the control, valve, and piping systems. The CDC 1700 is assisted by the AP-120B array processor which calculates all the floating point operations due to its accuracy and speed relative to the CDC 1700. Due to the architecture of the AP-120B, it is capable of high speed vector mathematics and, therefore, is used to obtain the pressure and velocity field of the subsystems hydraulic network. Initial conditions, which are required for the CSDT heat exchanger models, are sent by the CDC 1700 to a DAC (Digital-to-Analog Converter), where they are converted to corresponding analog signals (voltages). These signals are then sent to the EAI 680 consoles which are patched to solve the CSDT heat exchanger models. The resulting spatial solutions are sampled every millisecond and converted from an analog signal to a digital value by an ADC (Analog-Digital-Converter). This information is now available to the CDC 1700, and the cycle is complete. The sequence of events, mentioned above, is required to progress through each time step of the model.

Steady State Benchmark Analysis

The hybrid simulation model was benchmarked against two sources. The first source was VAGEN design information at 100 percent power. The spatial profile concerning enthalpy, temperature, heat transfer coefficients, and quality were compared. It was also recognized that if digital heat exchanger models were used in the present hybrid model that a completely digital simulation code would result. It was decided that this work should be done to provide another source for benchmarking and a vehicle for software checkout. Results from the all digital simulation model can be seen in Figures 17-20.

Spatial profiles from the hybrid model were recorded on the strip chart recorder for comparison with the VAGEN and digital model benchmarks (Figures 21-22). A word of explanation is required to understand this output. A timing signal is shown on the bottom of Figure 21. This signal starts the integration of the spatial quantities for the various heat exchangers each time this signal goes from a high to low state. On the first change in state, the salt side integrations are performed for the evaporator and the superheater while the water side integrations are performed for the preheater and the reheater. On the second change in state (small blip) the situation is reversed, thus, completing the calculation at the current time step. Each set of profiles represents "snapshots" taken at one-half second intervals. Figure 21 contains the profiles for the evaporator and preheater. Figure 22 contains the profiles for the superheater and reheater. These solutions agree well with the VAGEN information and the digital models presented earlier.

Accident Analysis

The following accident analyses were performed:

- Turbine Trip (Figures 23-37)
- One Recirculating Pump Tripped (Figures 38-52)
- Both recirculating Pumps Tripped (Figures 53-67)
- Feedwater Valve Failed Open (Figures 68-82)
- Feedwater Valve Failed Closed (Figures 83-97)
- Two Relief Valves Failed Open (Figures 98-112)
- One Relief Valve Failed Open (Figures 113-127)
- Superheater Salt Valve Closure (Figures 128-142)
- Hot Salt Pump Trip (Figures 143-157)
- Feedwater Pump Trip (Figures 158-178)
- Reheater Salt Valve Closure (Figures 179-193)
- Preheater Salt Valve Closure (Figures 194-208)

It should be pointed out that these results are preliminary. For example, a flow induced transient will be a function of pump inertia, pipe geometry, valve characteristics, control system set points, and gain settings. For the most part, almost all of these parameters were estimated due to the lack of detailed design data. For this reason,the results of this simulation should be used in a qualitative manner, and quantitative assessments should be derived from the behavior shown by the model coupled with some engineering judgment. For example, the gains which act upon the control valve actuators were set to provide reasonable plant responses to load-maneuvering type transients. This does not ensure that the actuator will be quick enough to provide for a quick isolation. If fast isolation is required, a backup valve may be required. Most of the controllers were set at a low gain for stability criterion, and this results in fairly slow valve closures (~20-30 seconds). Also, in this analysis the reheater salt control valve does not load follow; it responds only to temperature.

Figures 23 through 208 represent the transient analysis completed. In some instances, scaling problems on the analog computer resulted in amplifier saturation. When this occurs, the results past that time are not valid. The oscillatory behavior of the steam drum and the evaporator is believed to be due to the non-equilibrium model of the steam drum in which the drum's potential to flash has been underestimated producing a larger pressure swing than expected, and the large digital time step used in the hybrid program resulting in high gain integrators being used to evaluate the thermal inertia of the evaporator. This results in the evaporator becoming artificially over-sensitive to changes in pressure.

Conclusions

For each heat exchanger, the following conclusions have been made:

Preheater: After reviewing the feedwater valve failed open (Figures 68-82), feedwater valve failed closed (Figures 83-97), and loss of feedwater transients, (feedwater pump trip, Figures 158-178), the following can be concluded:

1. The preheater is protected by the evaporator that yields a nearly constant inlet salt temperature. Thus, boiling can occur during a reduction in flow at normal operating pressures, but the thermodynmaic potential does not exist to produce superheated steam.

2. The current preheater design has a large thermal inertia capacity on the salt side yielding nearly constant salt outlet temperatures due to spatial profiles which do not travel fast in the heat exchanger.

Evaporator: After reviewing the one and two recirculating pump trip transients (Figures 38-67), the following can be concluded:

1. Natural circulation provided ~75 percent of rated flow to the evaporator.

2. Due to the size of the evaporator and its long boiling length, it removes all the energy the salt has up to the limits set by heat transfer considerations, yielding nearly constant outlet temperature.

3. Pressure transients can cause a potential for superheating and seems to be more severe than flow transients since boiling heat transfer dominates through the change in sink temperature.

4. The turbine trip (Figures 23-37) shows that high temperature salt will enter the evaporator when the heat sink provided by the superheater and reheater are lost. Since the salt flow control valves will be tied to a load following signal, this increase in temperature is accompanied by reduced salt flow; and, hence, the available energy to the evaporator does not increase. This results in the water side remaining at TSAT while the salt temperature is increasing.

Superheater: Comparison of the results of the turbine trip (Figures 23-37) and the superheater salt valve closure transients (Figures 128-142) have lead to these conclusions:

1. The thermal inertia of the salt is an order or magnitude greater when compared to the steam. This results in the steam seeing a constant salt temperature in the short run. This also means that the salt if not affected by the steam in any rapid sense at normal flow rates.

2. Due to poor heat transfer and the thermal inertia of the salt, temperature changes at the salt outlet are inversely proportional to salt flow.

3. The inlet conditions are fairly fixed in time, i.e., inlet salt temperature is 1,050 as a given, and the inlet steam temperature is based upon the drum pressure. Variations in TSAT are not large for the rage of transients explored.

Reheater: The reheater is very similar to the superheater. Two basic exceptions are noted.

1. Since the salt system has considerable flow inertia, large salt flow rate increases can occur when a superheater salt valve occurs.

2. A large swing in inlet steam temperature is shown being dependent.

FIGURE 1: MOLTEN SALT STEAM GENERATOR SUBSYSTEM

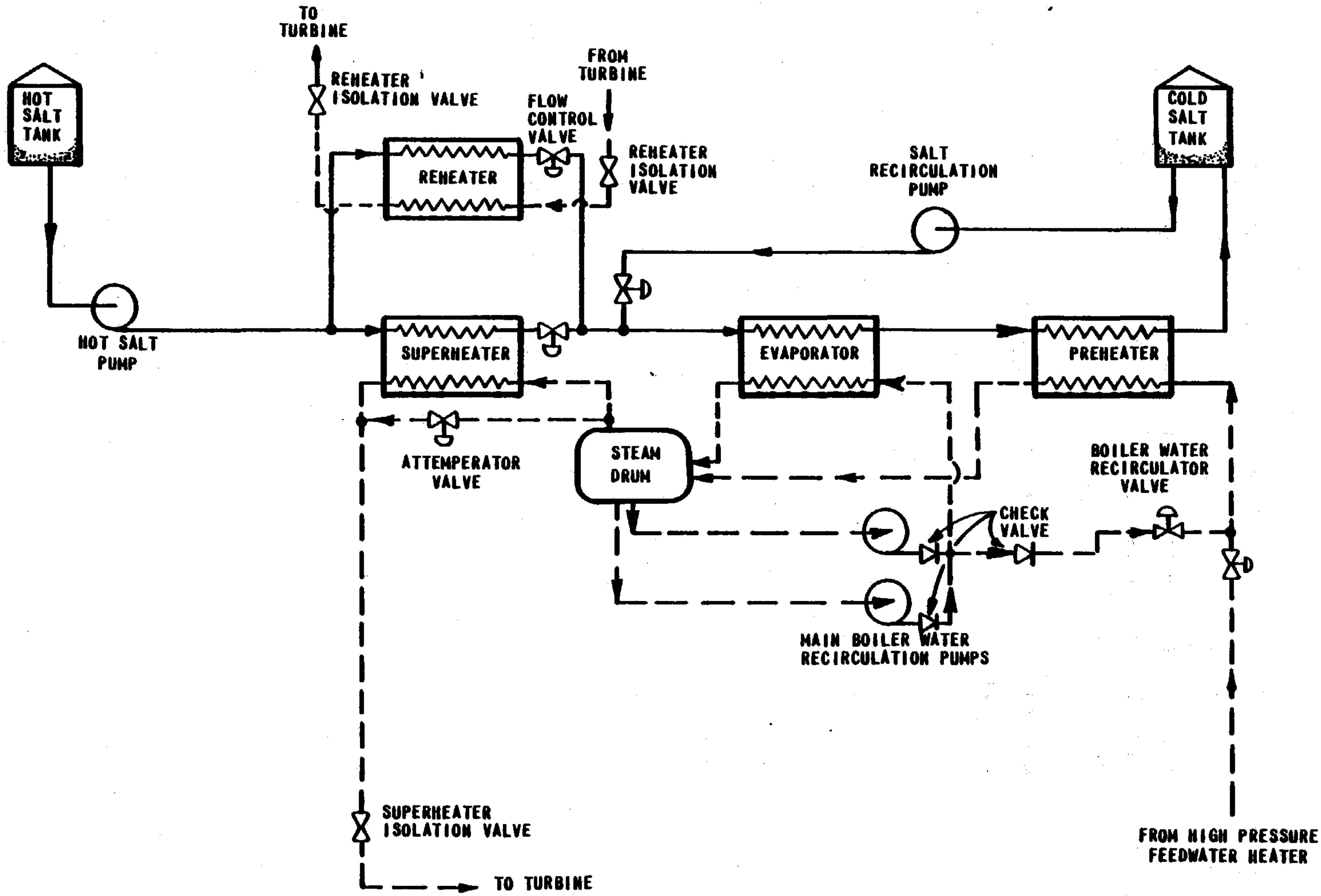


FIGURE 2: MODELING ASSUMPTIONS FOR THE PREHEATER AND EVAPORATOR

1. Single phase/incompressible fluid on salt side.
2. Salt longitudinal heat transfer correlation.
3. One dimension heat conduction through tube wall.
4. Gravity head loss is small in comparison to friction and form losses.
5. Overall dynamic behavior can be represented by an average channel.
6. Momentum integral model used on water side (i.e., enthalpy transport occurs at average pressure allowing evaluation of spatial thermal properties).
7. Three region water heat transfer model:
   a. subcooled force convection $x \leq 0$
   b. nucleate boiling $0 < x < x_{DNB}$
   c. superheat force convection $x \geq x_{DNB}$
8. Counterflow heat exchange arrangement.

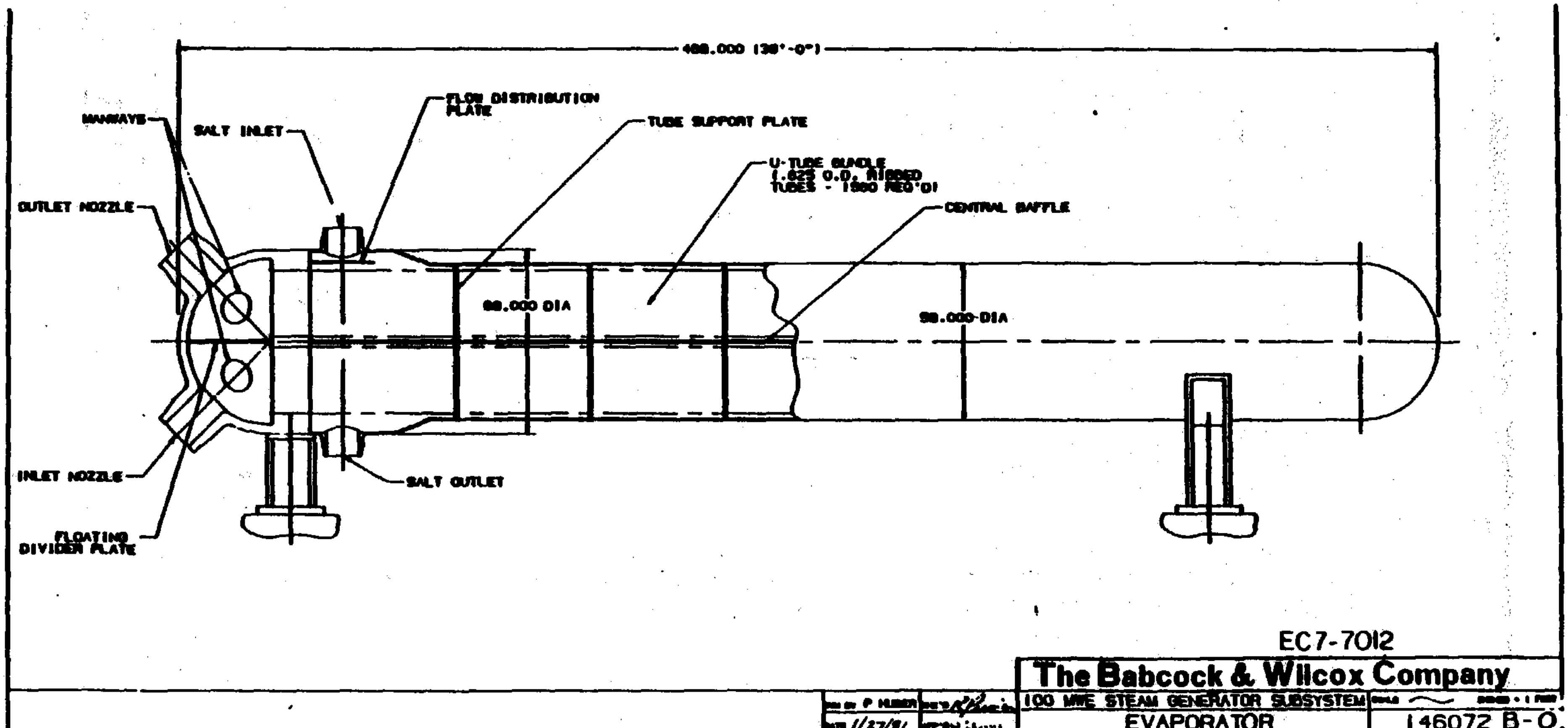


FIGURE 3: MODELING ASSUMPTIONS FOR THE SUPERHEATER AND REHEATER

1. Single phase/incomrpessible fluid on both sides of heat exchanger.
2. Salt longitudinal heat transfer correlation.
3. One dimensional heat conduction through tube wall.
4. Gravity head loss is small in comparison to friction and form losses.
5. Overall dynamic behavior can be represented by an average channel.
6. Superheat force convection heat transfer assumed at average steam velocity.
7. Counterflow heat exchange arrangement.

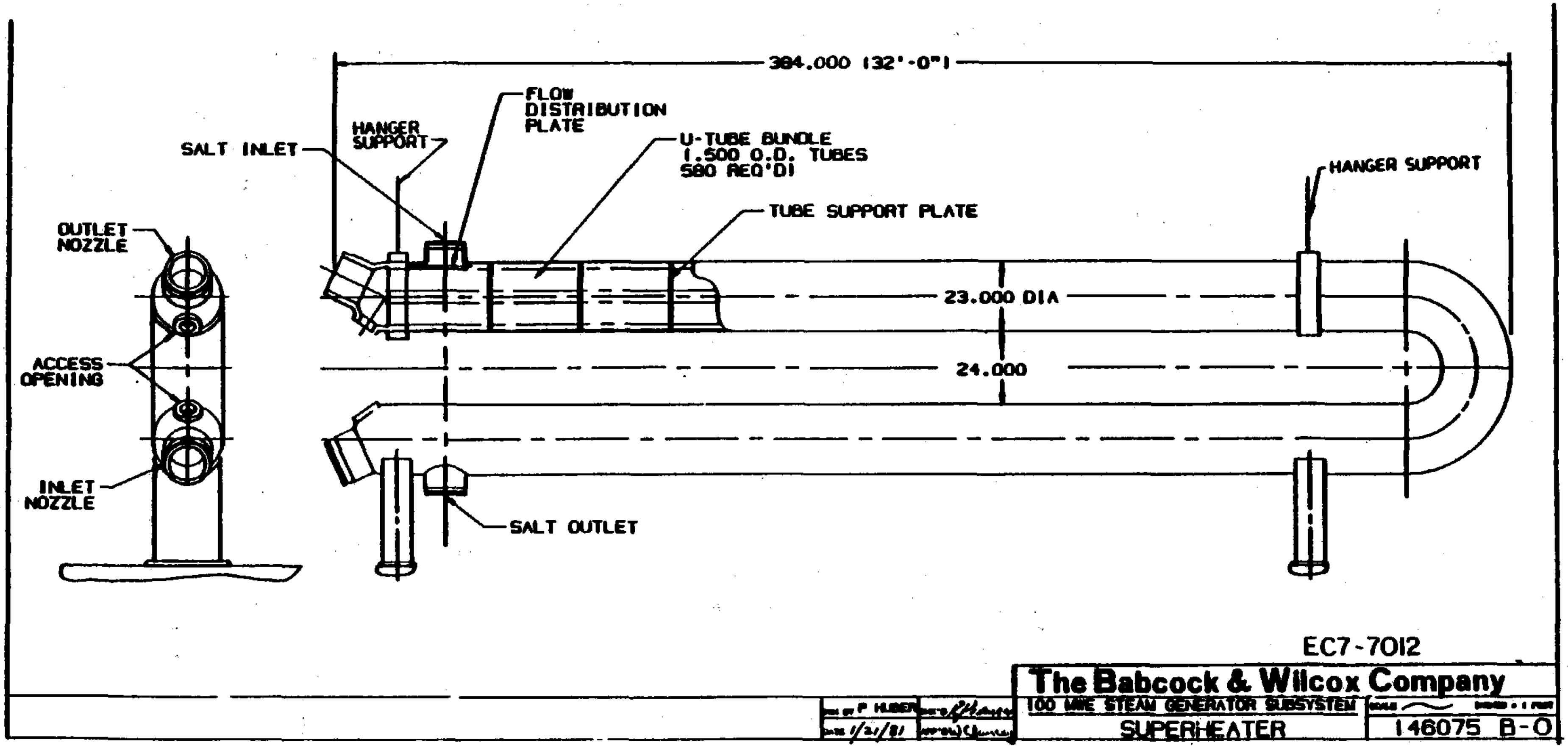


FIGURE 4: MODELING ASSUMPTIONS FOR THE STEAM DRUM

1. Cyclone separators are 100 percent efficient.
2. Neglectable pressure drop within drum.
3. Perfect mixing of water from cyclones and preheater.
4. Nonequilibrium model between the water and steam regions (energy and mass transport being determined by sufrace boiling and condensation rates).

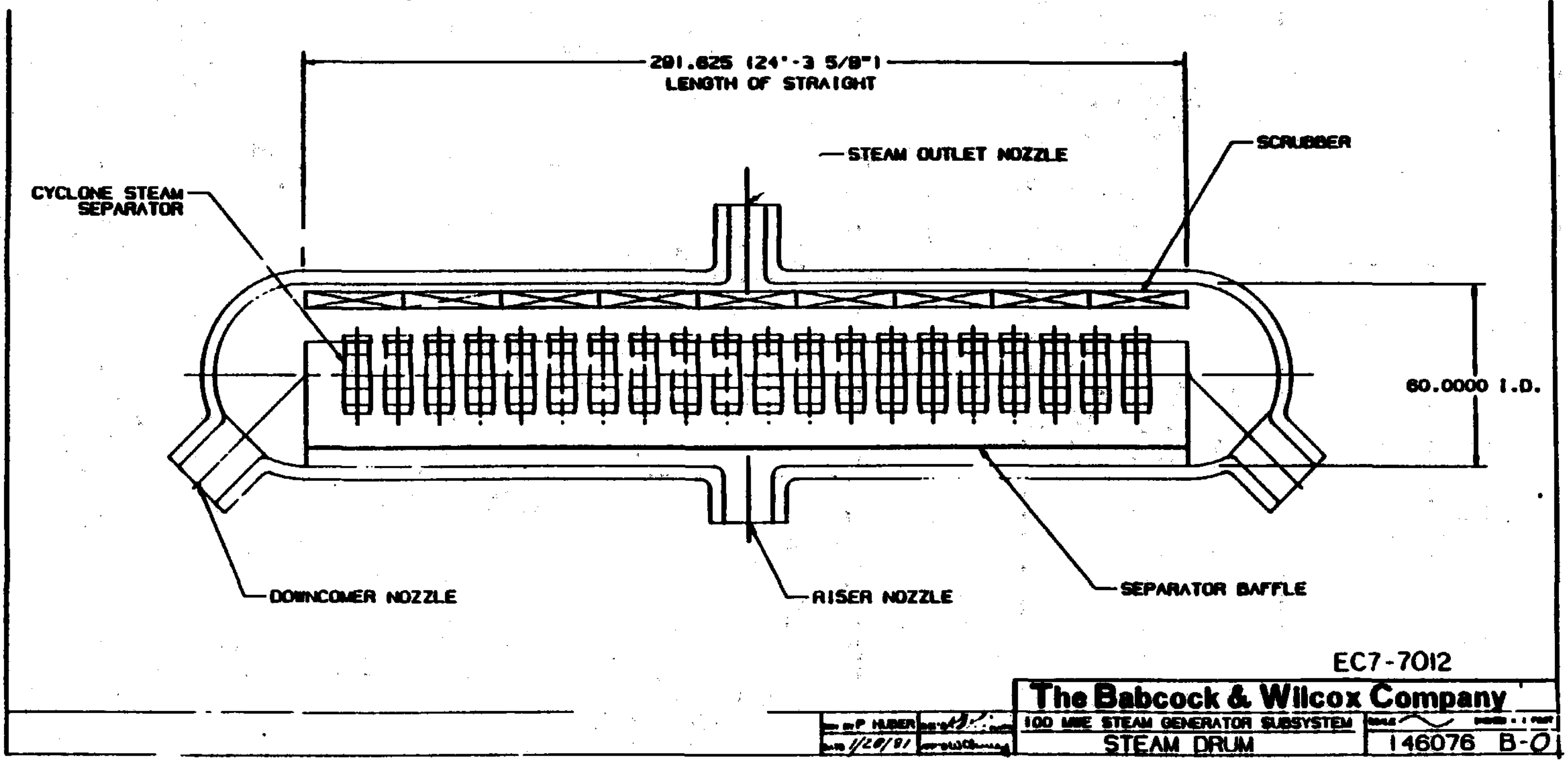


FIGURE 5

HYDRAULIC NETWORK

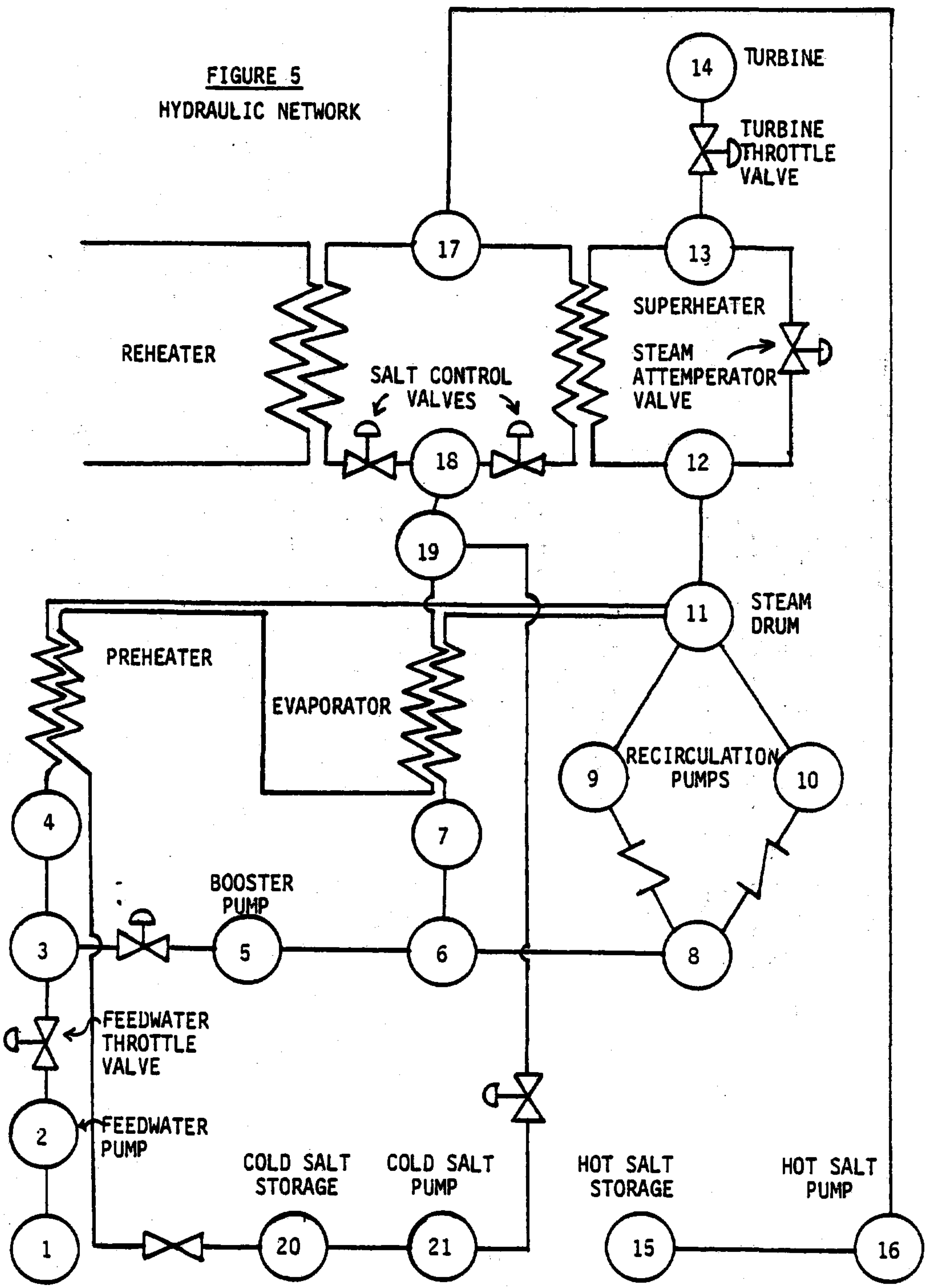


FIGURE 6

PUMP HEAD VS. CAPACITY

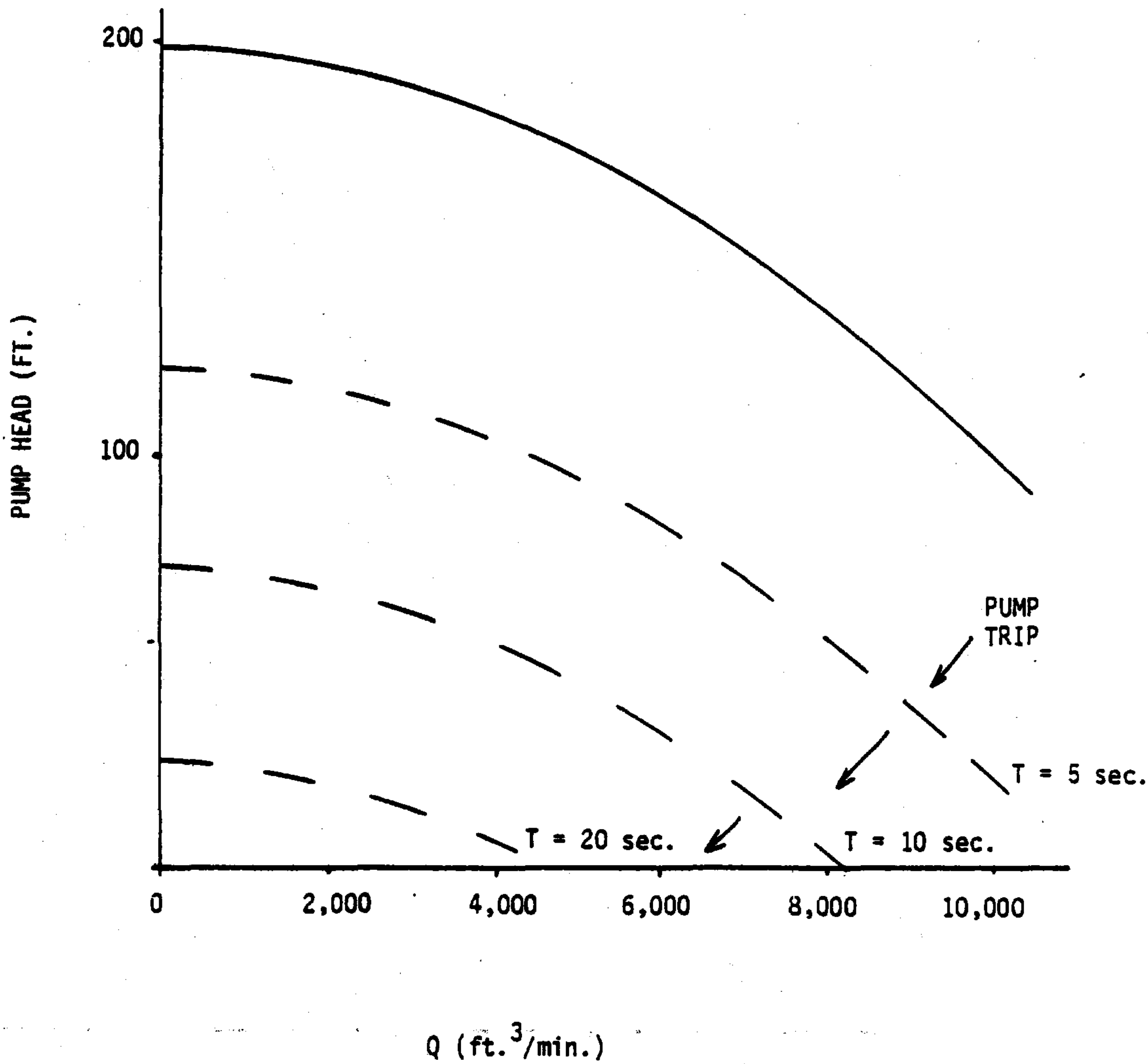


FIGURE 7

SIZING COEFFICIENT VS. PERCENT TRAVEL

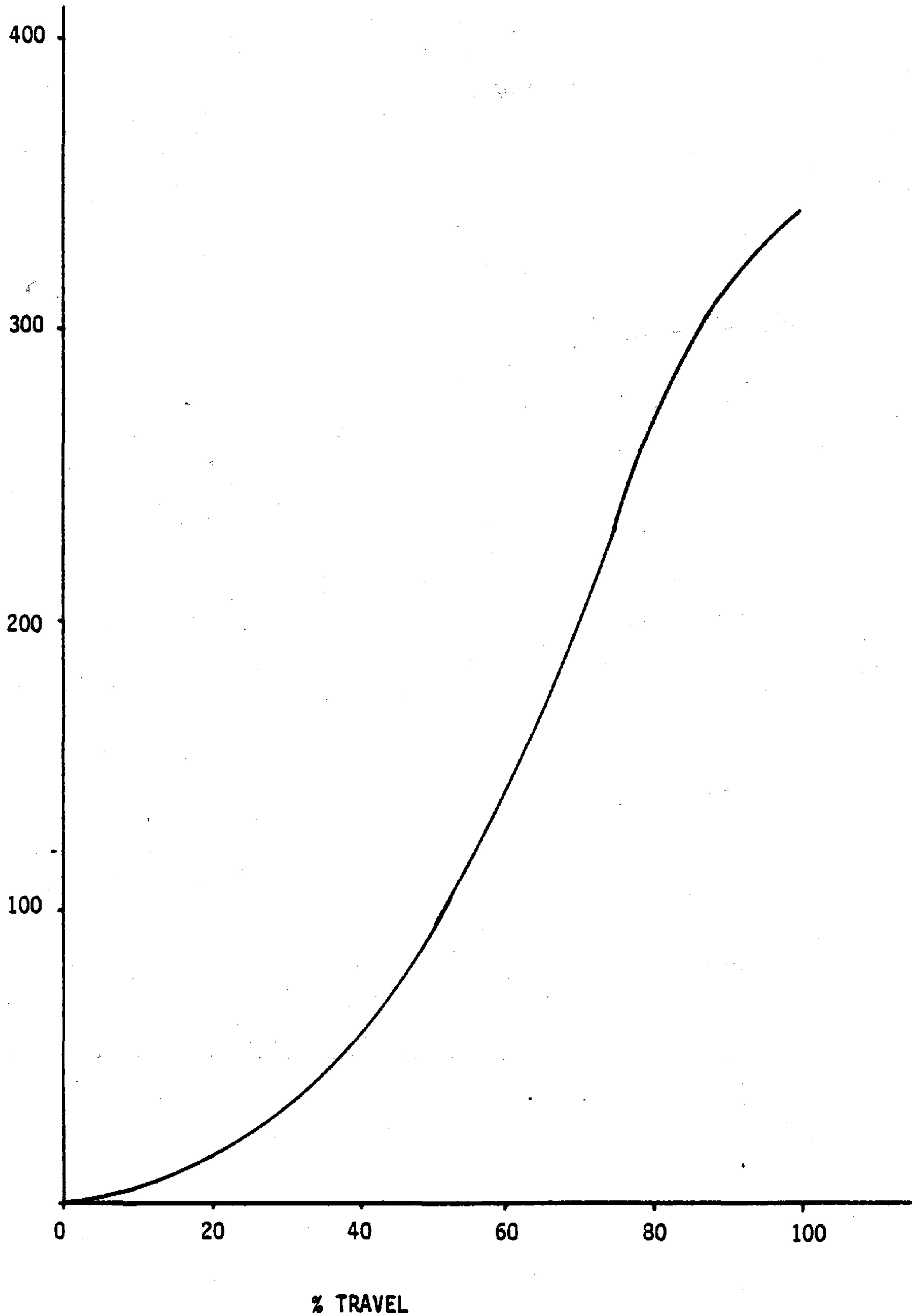


FIGURE 8

FEEDWATER TEMPERATURE VS. LOAD

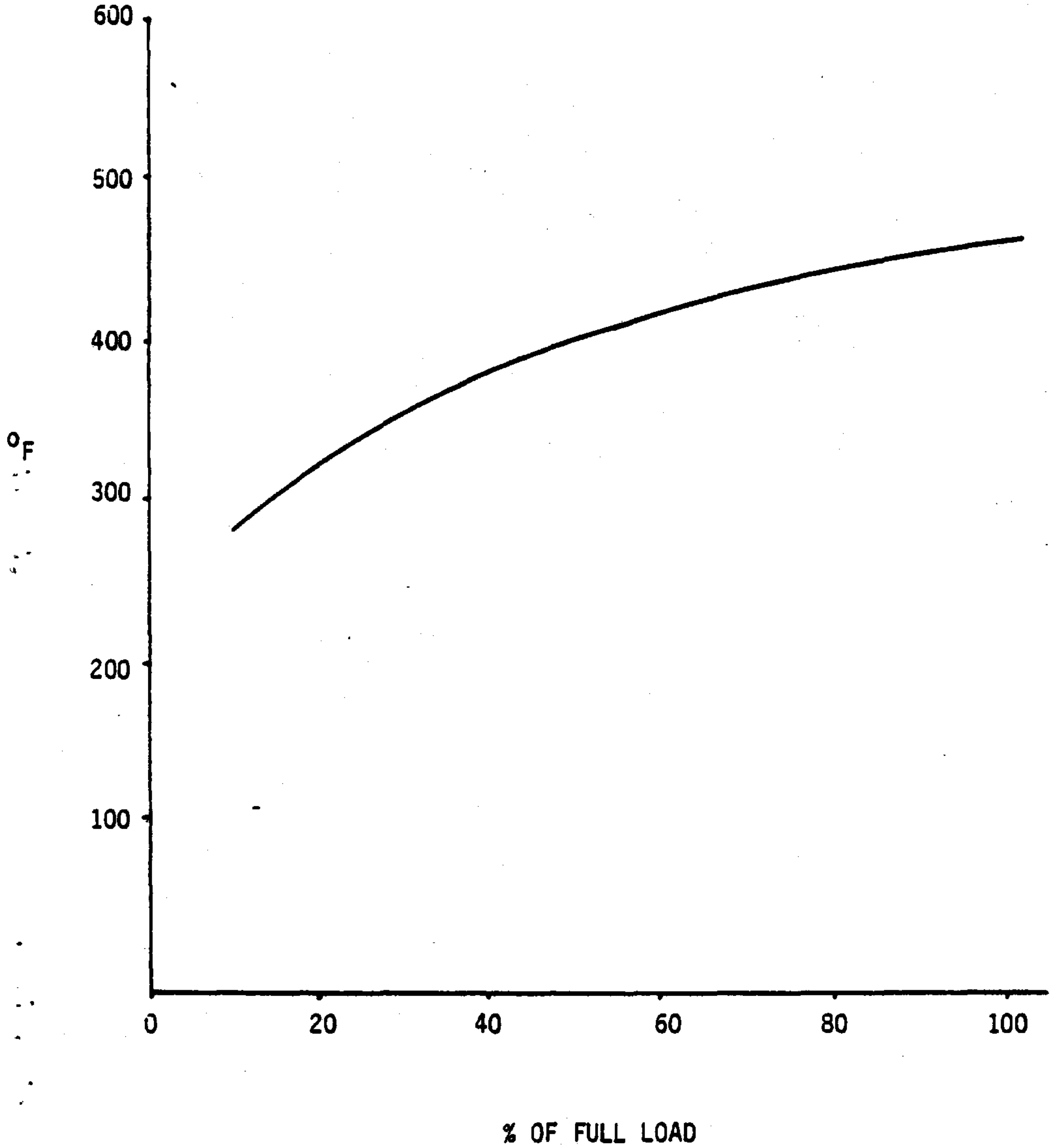
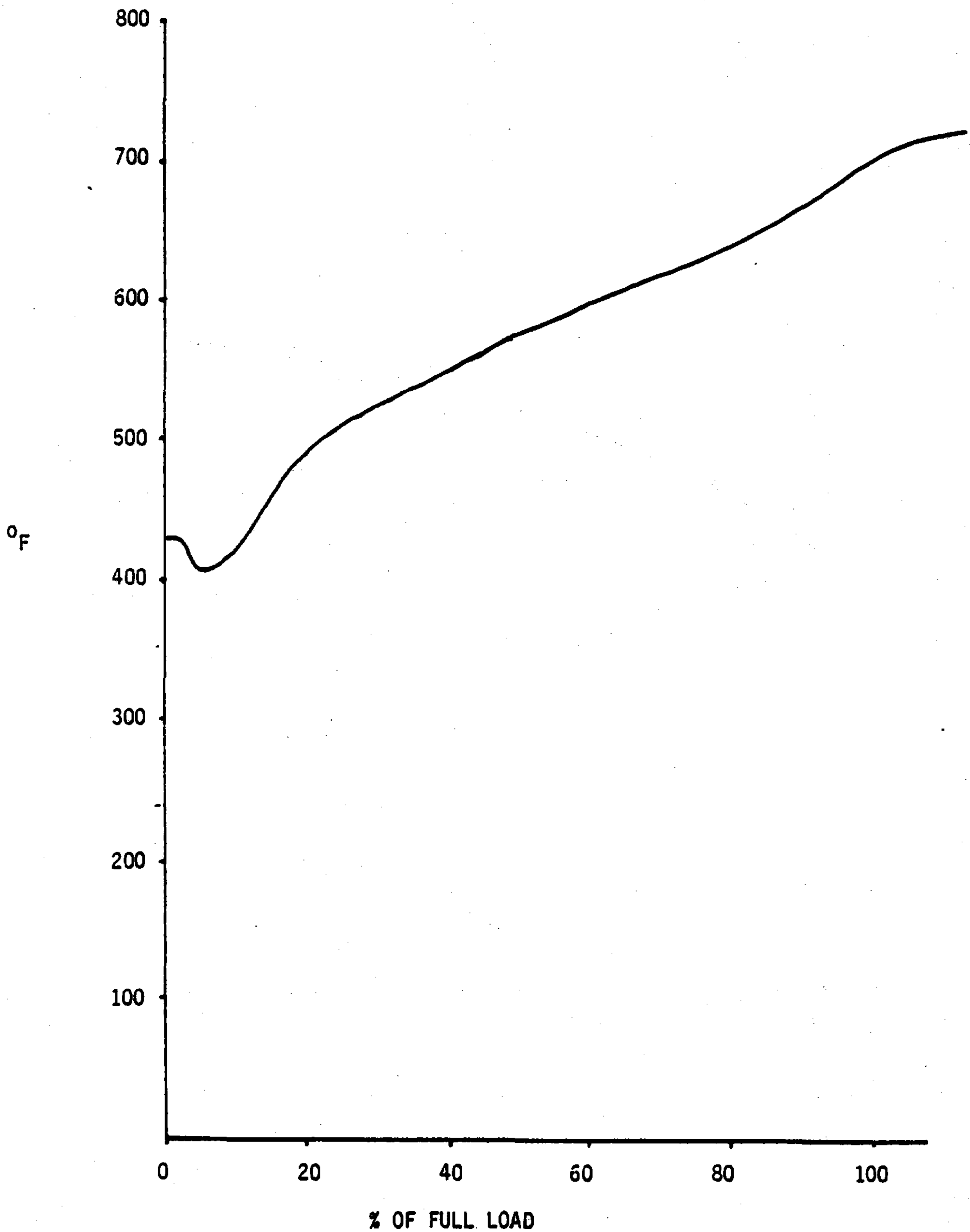


FIGURE 9

INLET REHEATER TEMPERATURE VS. LOAD



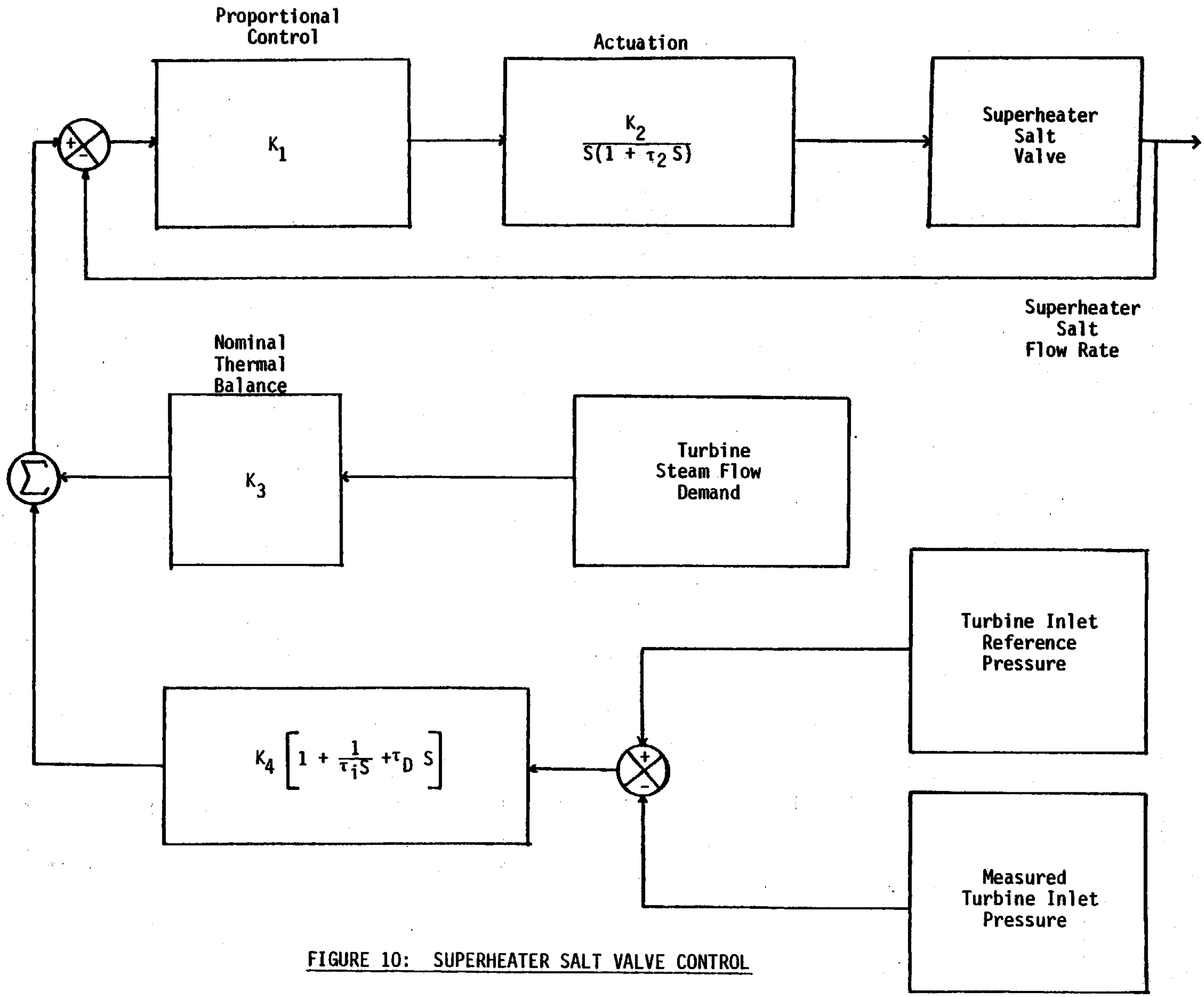


FIGURE 10: SUPERHEATER SALT VALVE CONTROL

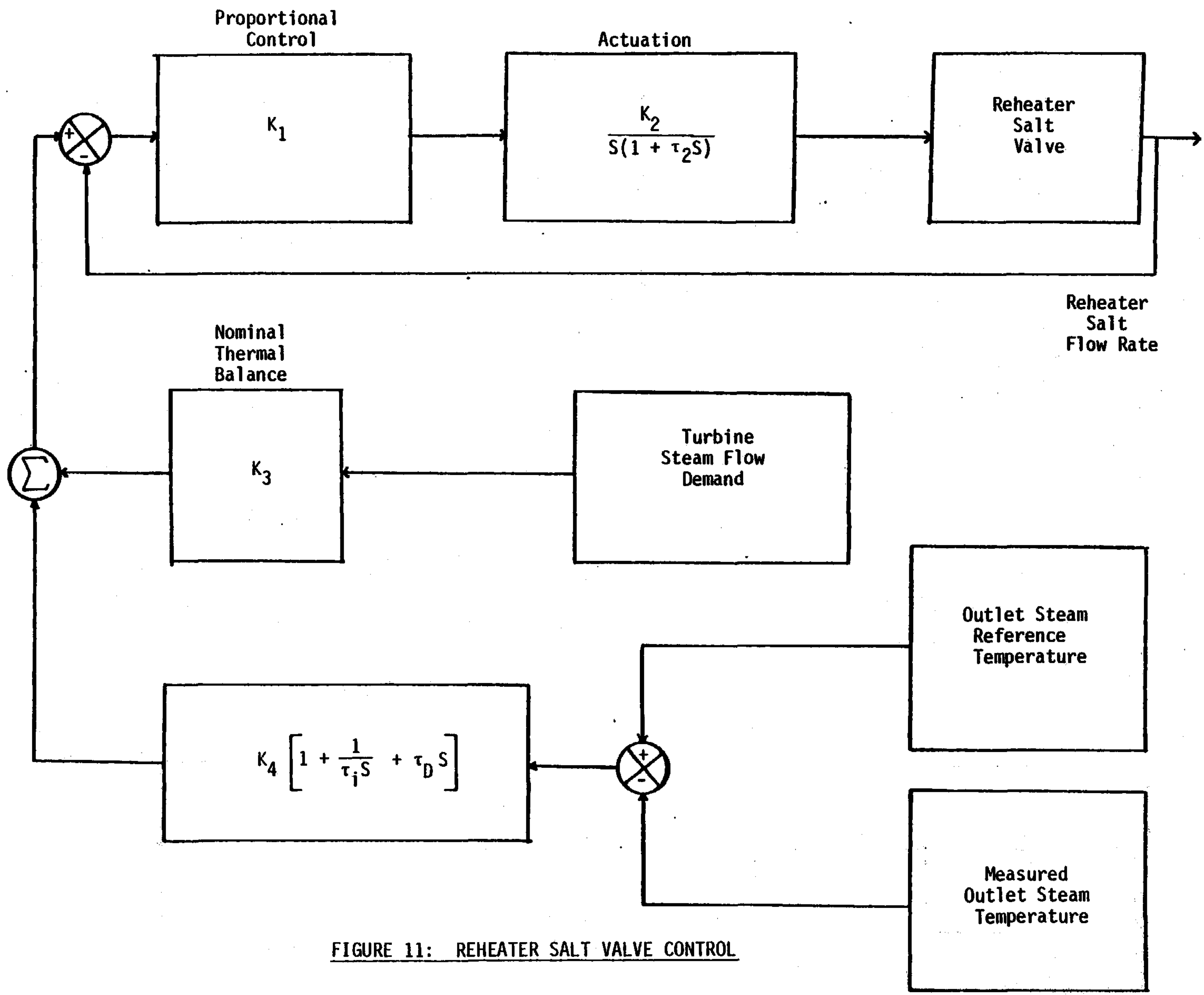


FIGURE 11: REHEATER SALT VALVE CONTROL

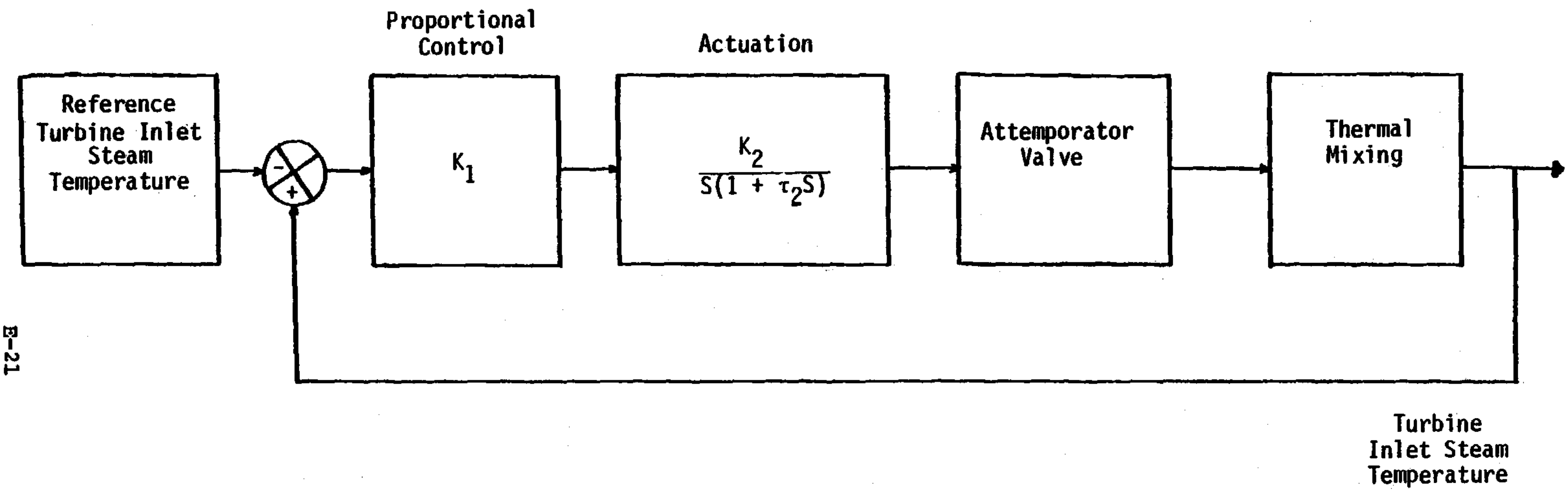


FIGURE 12: TURBINE STEAM ATTEMPERATOR VALVE

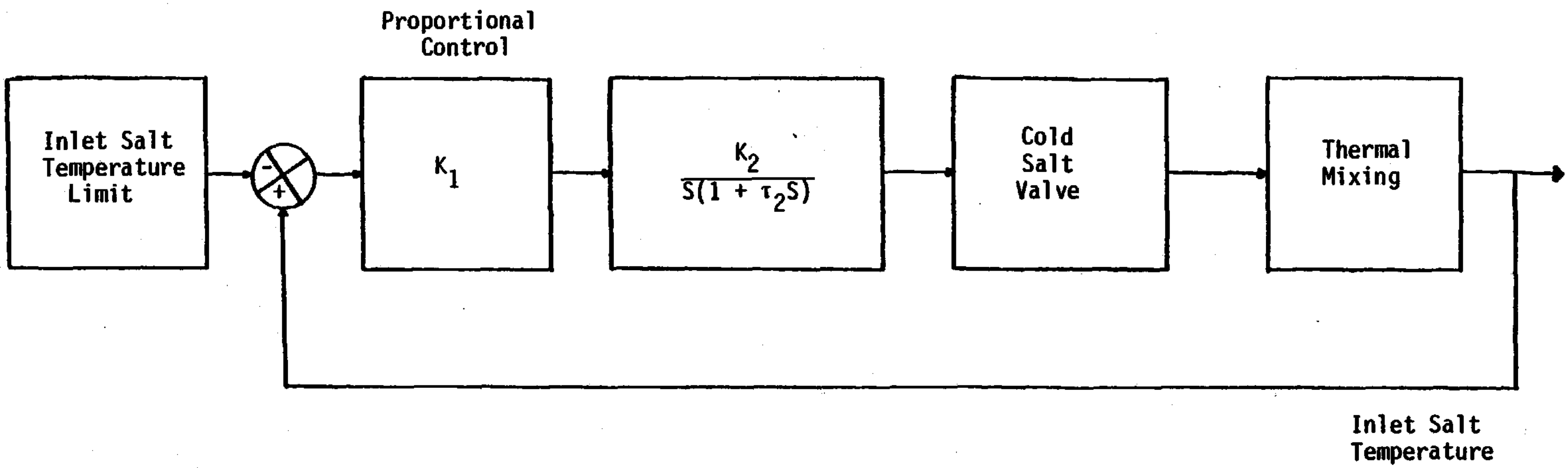


FIGURE 13: EVAPORATOR SALT TEMPERATURE LIMIT

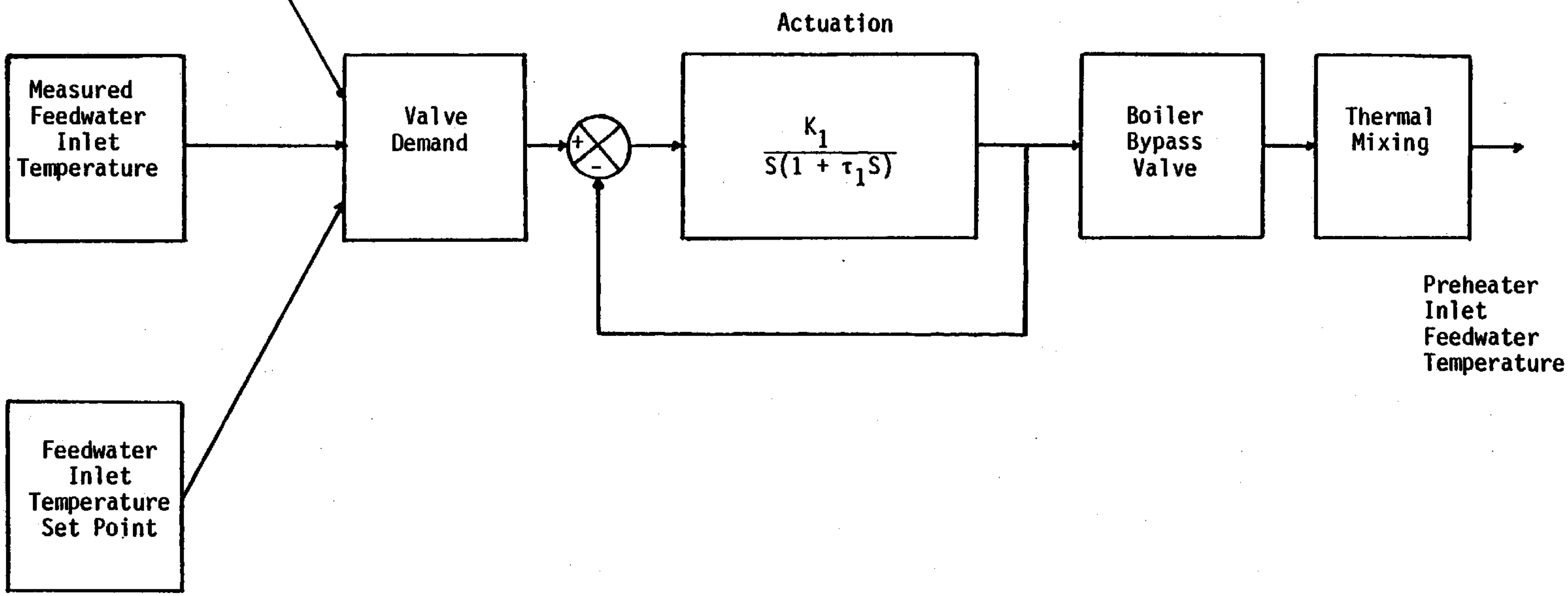


FIGURE 14: FEEDWATER TEMPERATURE CONTROL FOR PREHEATER

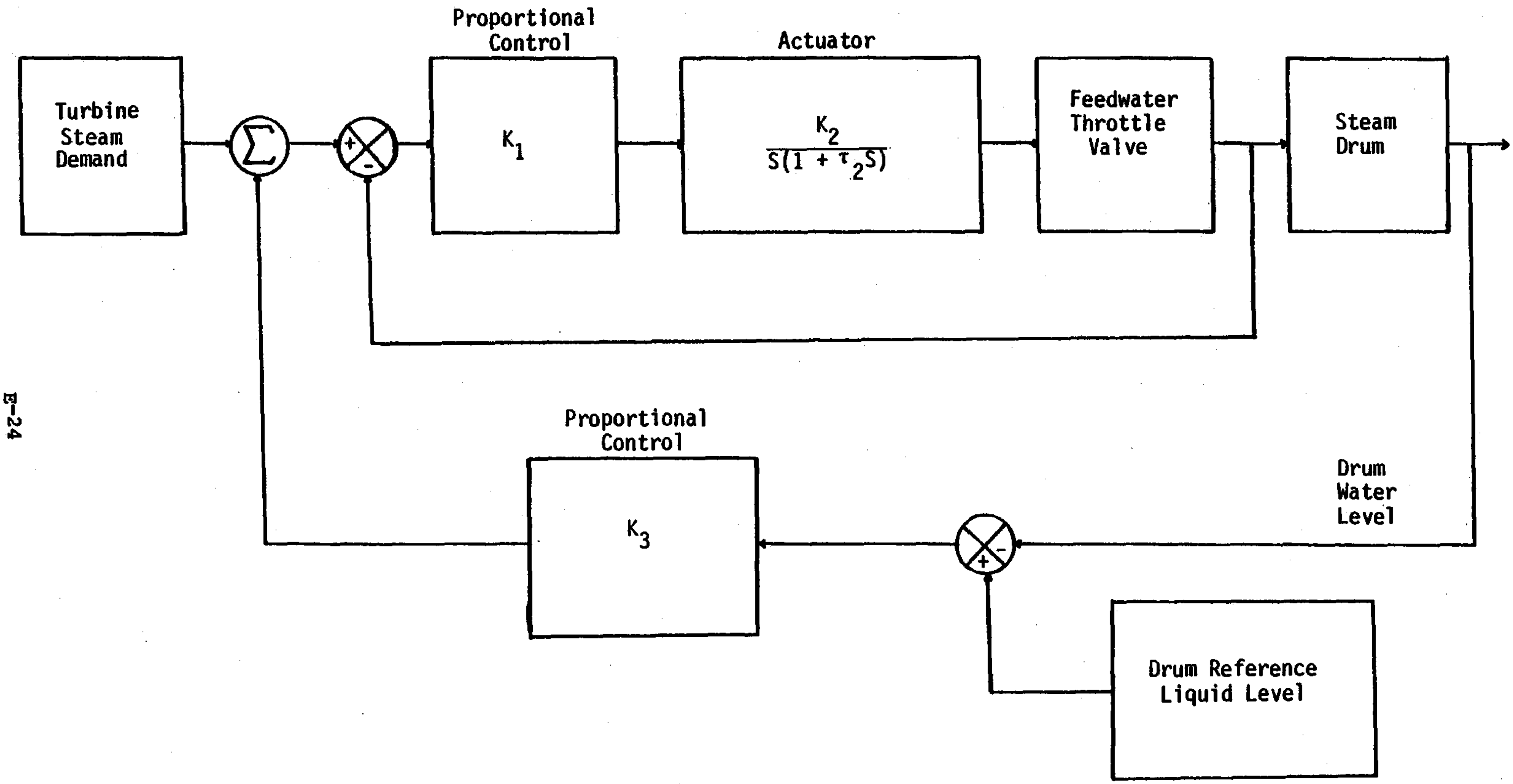


FIGURE 15: STEAM DRUM WATER LEVEL CONTROL

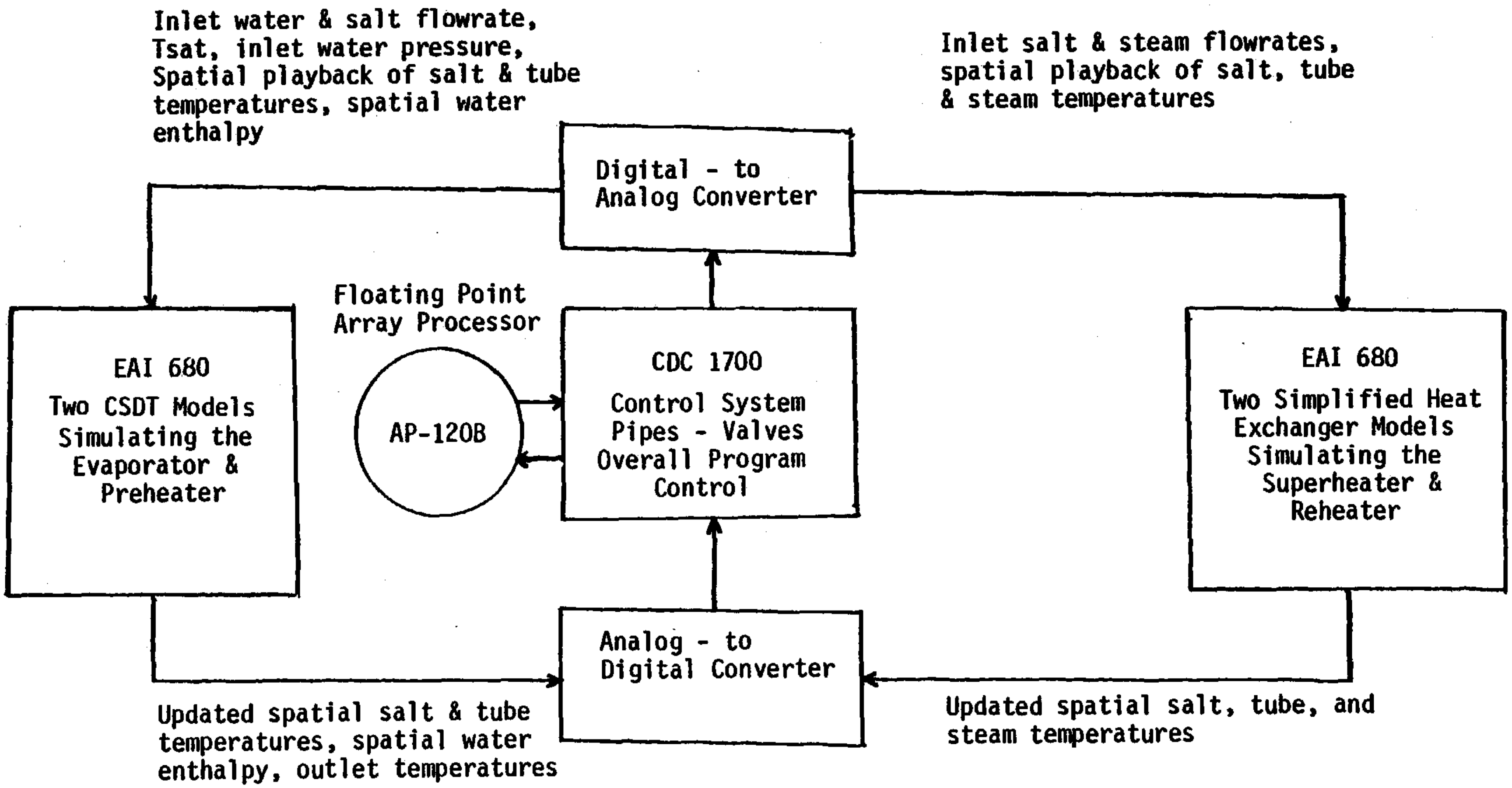
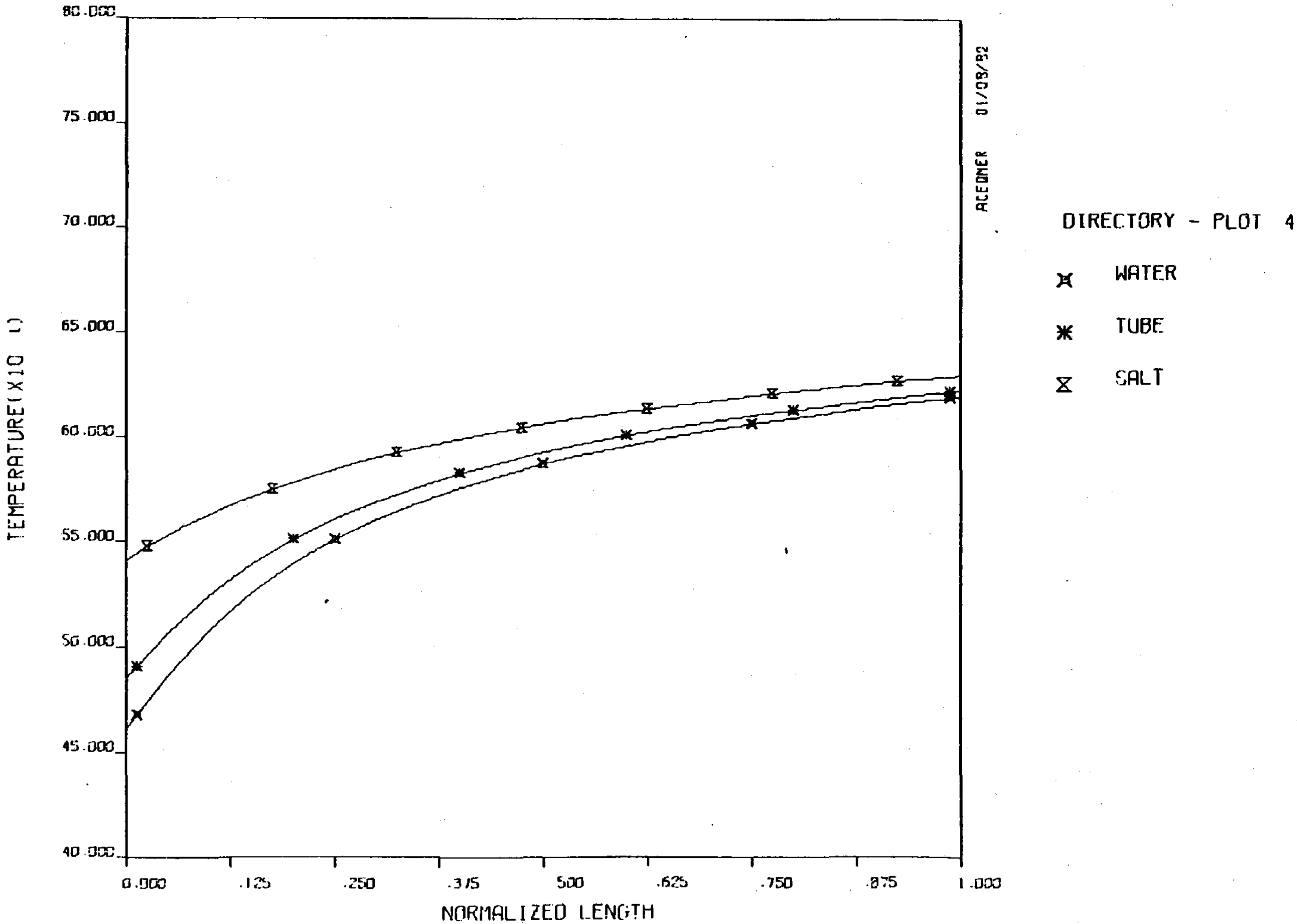


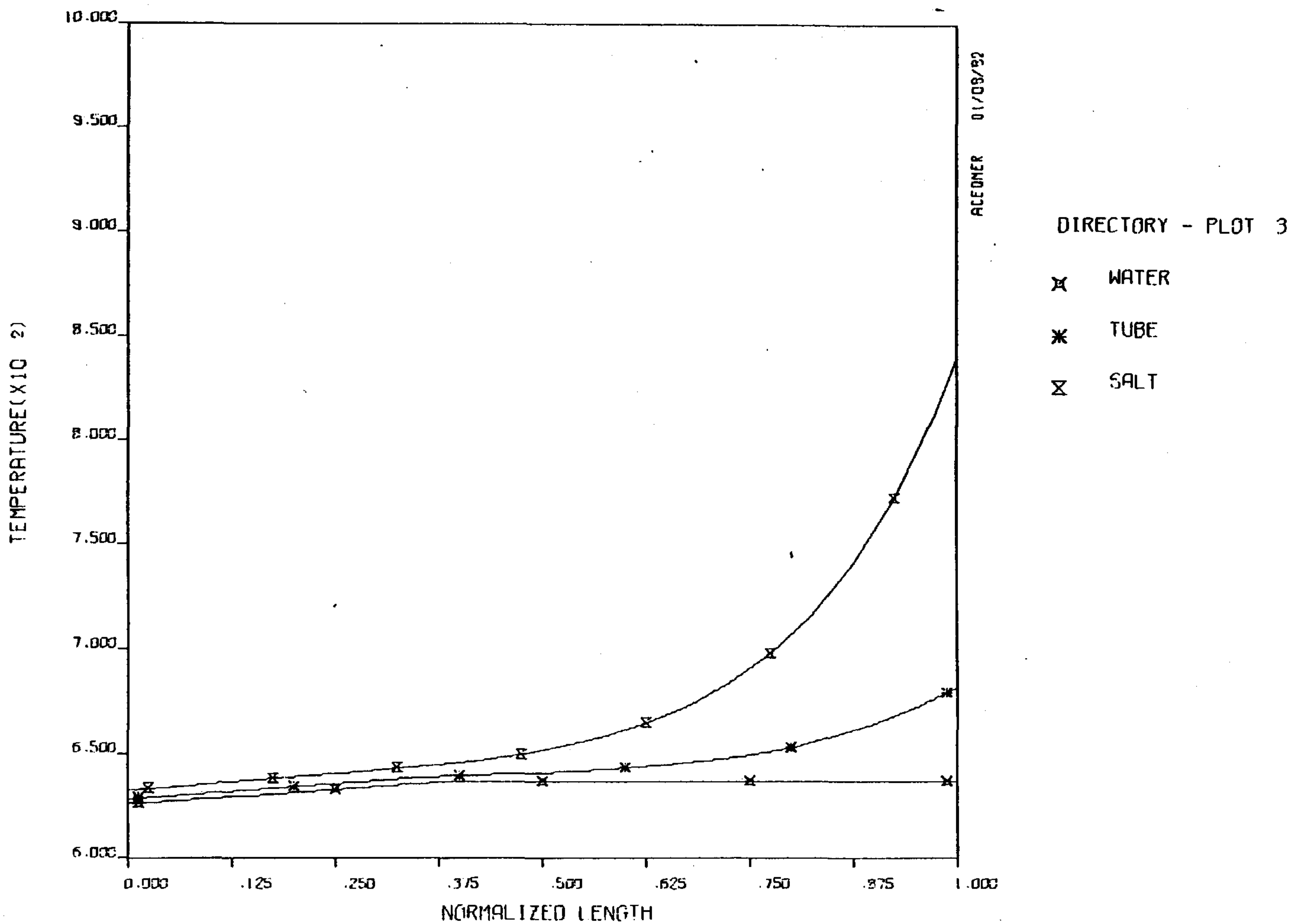
FIGURE 16: COMPUTING HARDWARE

FIGURE 17: PREHEATER



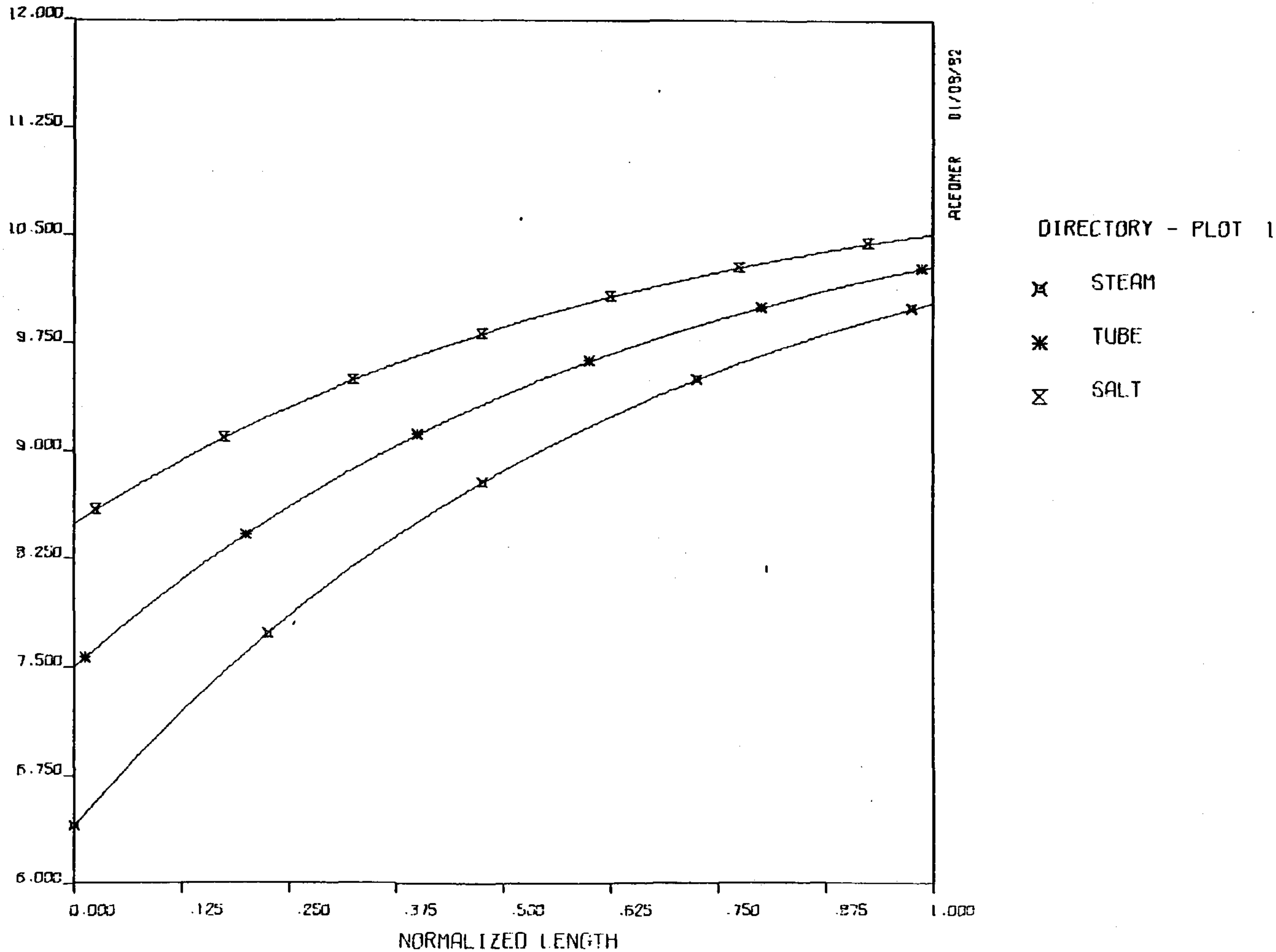
TEMPERATURE VS NORMALIZED LENGTH

FIGURE 18: EVAPORATOR



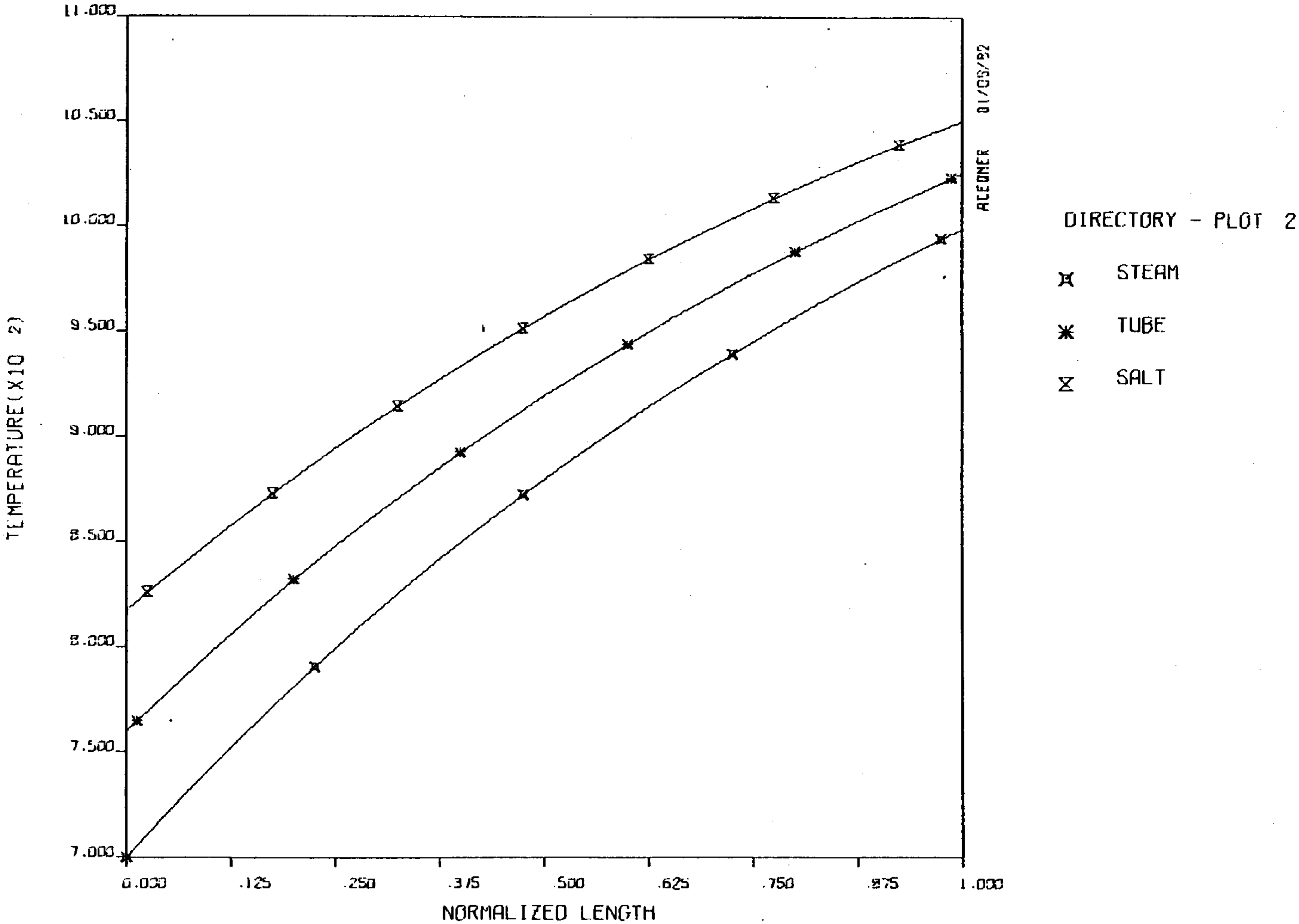
TEMPERATURE VS NORMALIZED LENGTH

FIGURE 19: SUPERHEATER



TEMPERATURE VS NORMALIZED LENGTH

FIGURE 20: REHEATER



TEMPERATURE VS NORMALIZED LENGTH

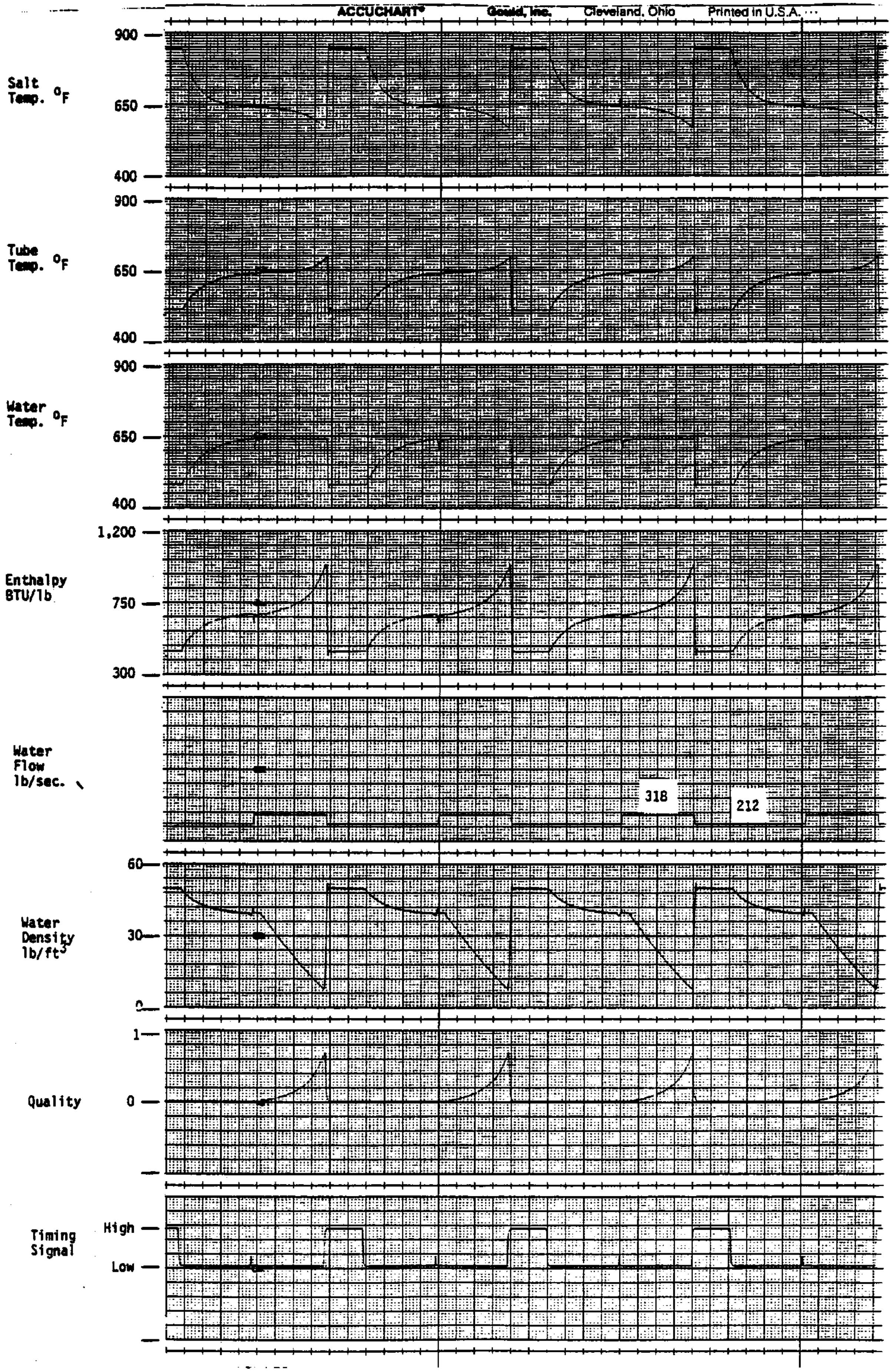


Figure 21: STEADY STATE EVAPORATOR AND PREHEATER BENCHMARK PROFILES

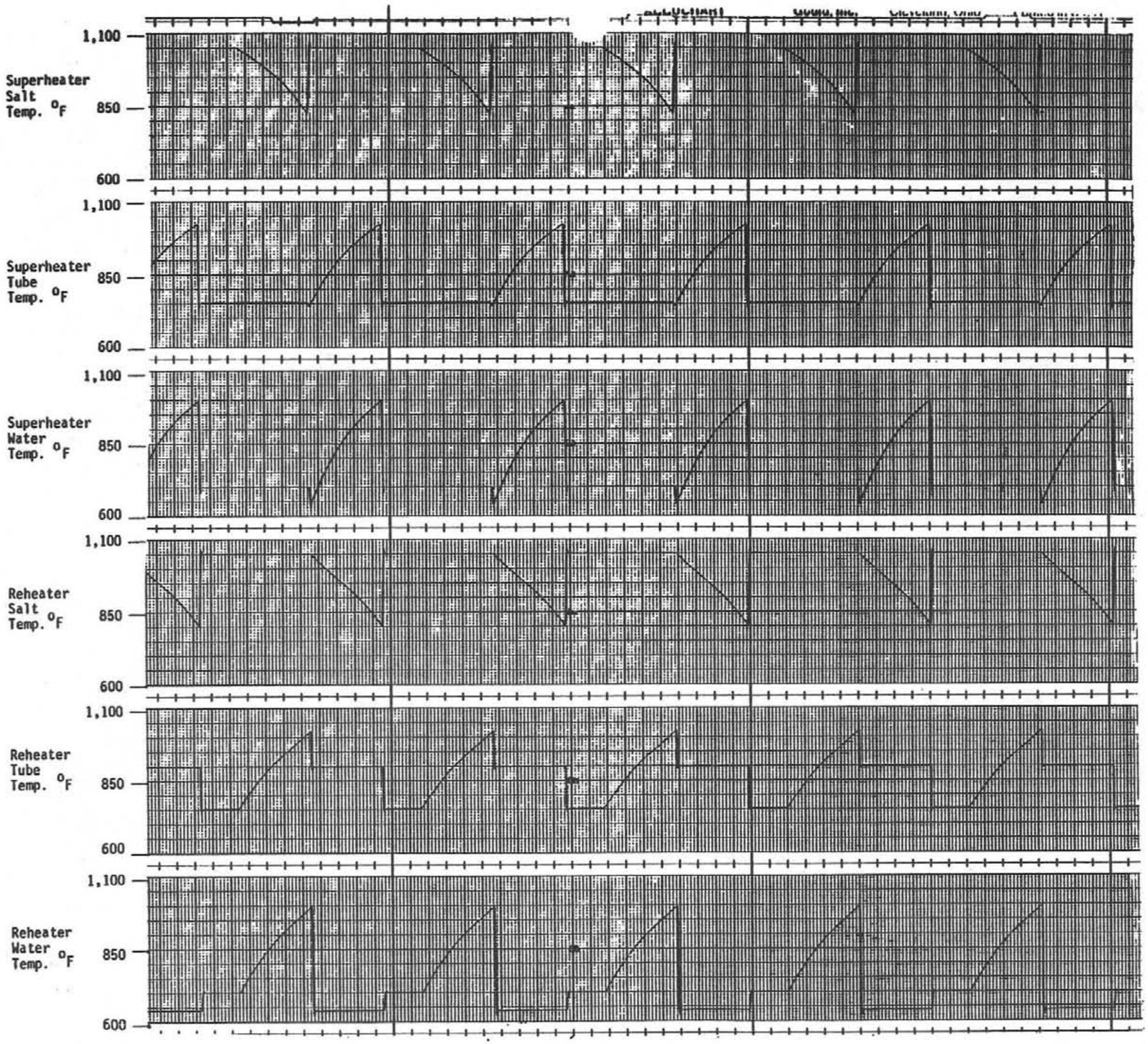
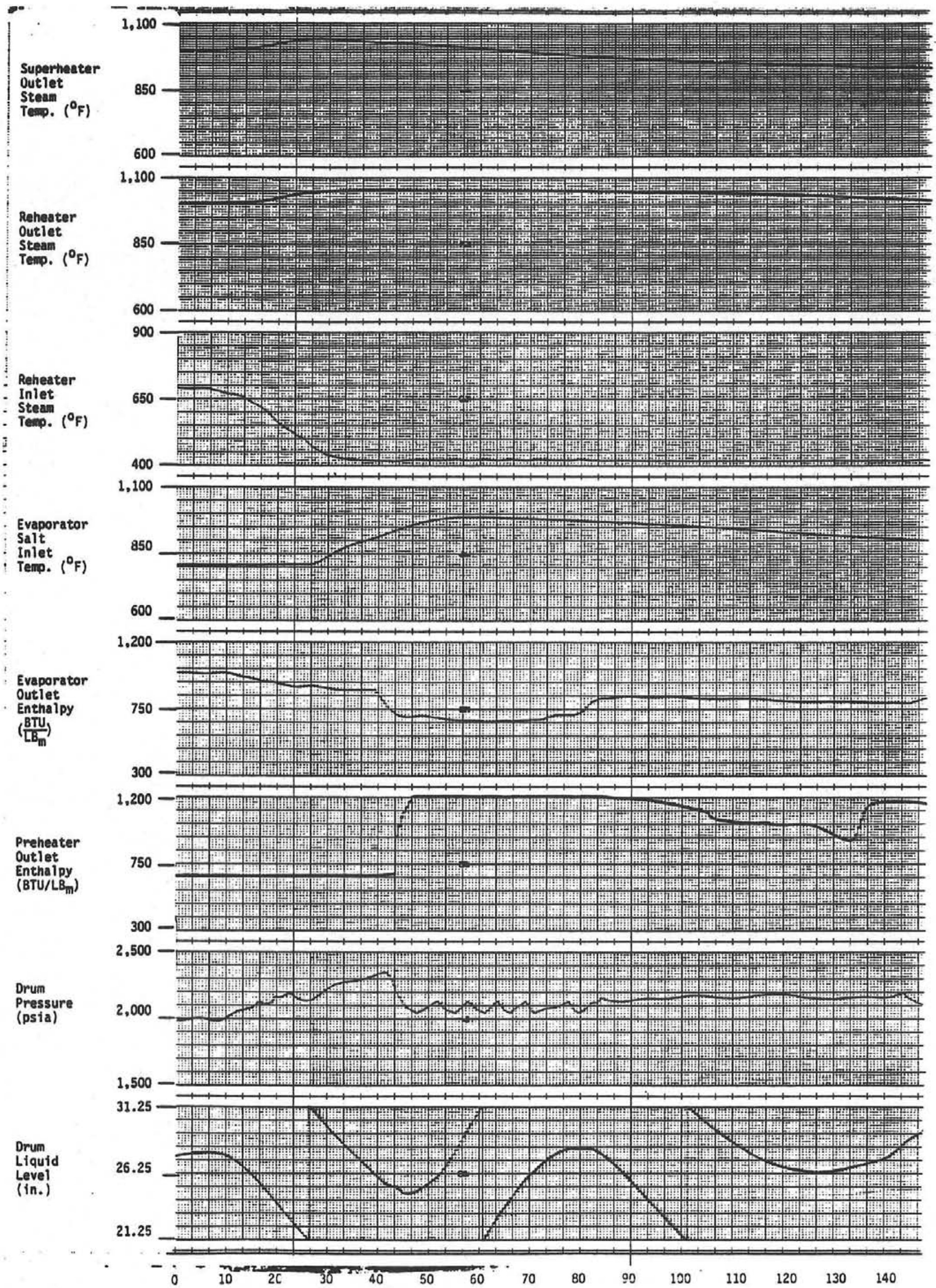
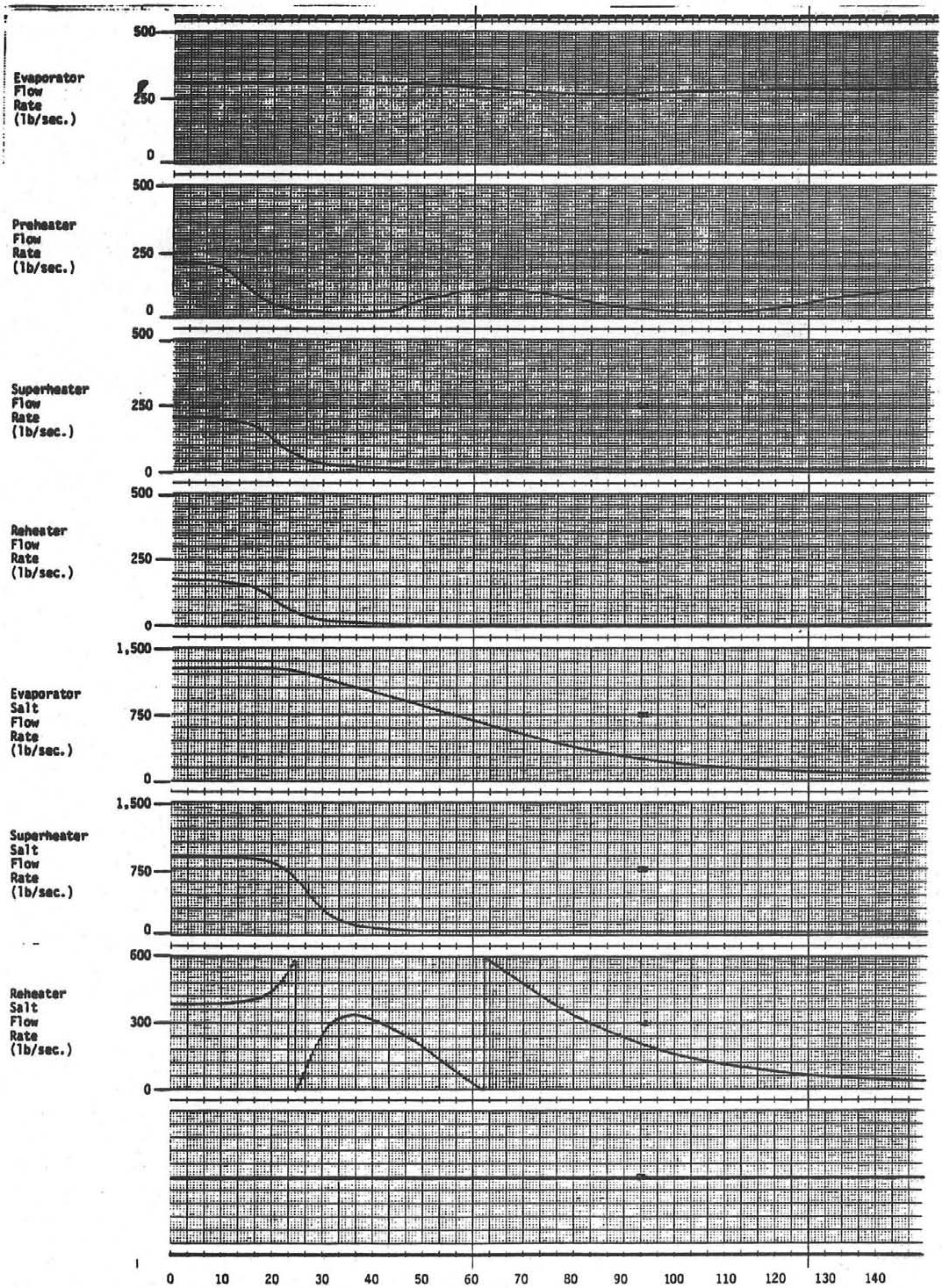


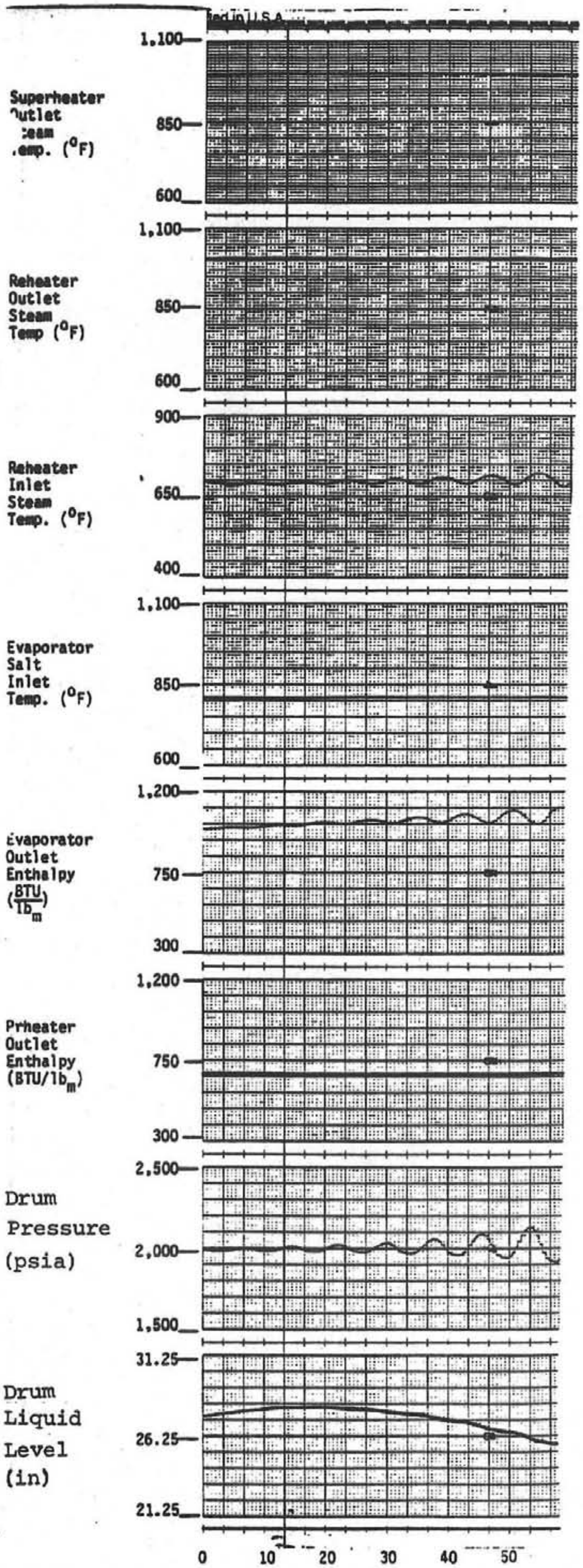
Figure 22: STEADY STATE SUPERHEATER AND REHEATER BENCHMARK PROFILES



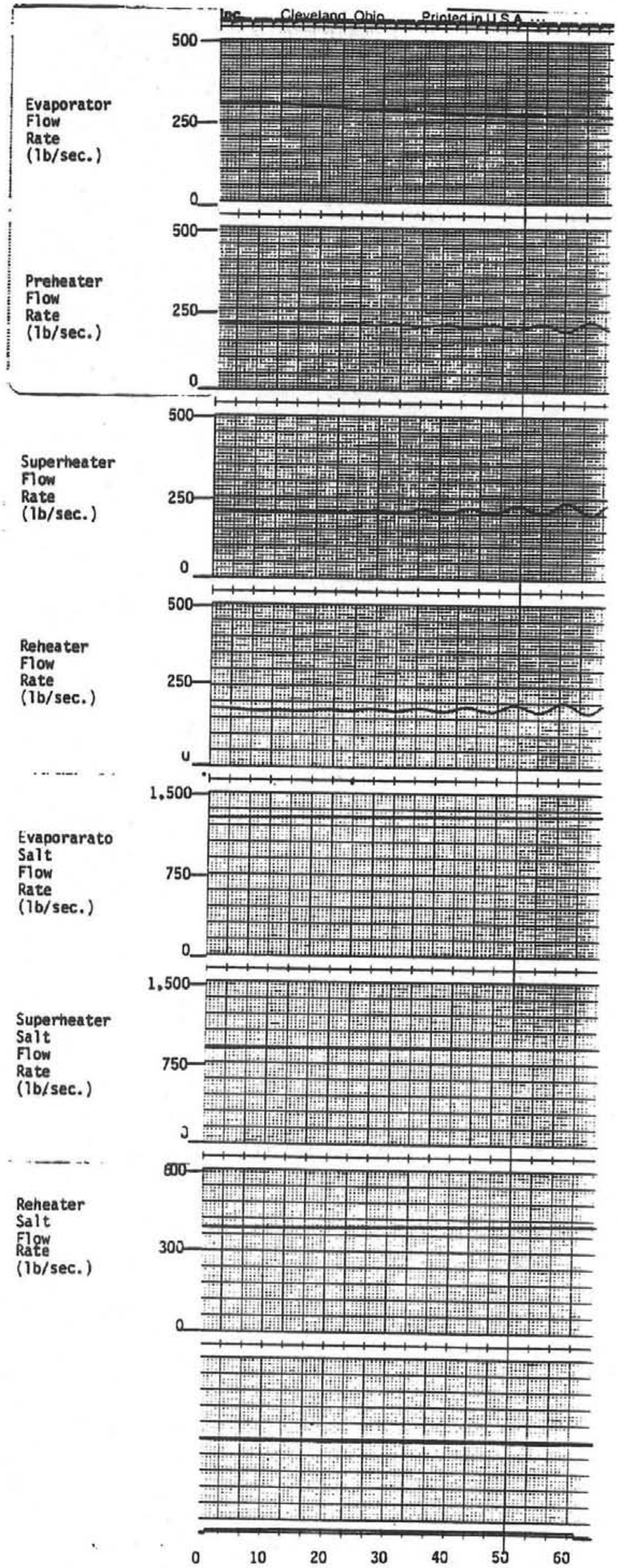
TURBINE TRIP (Figures 23-30)



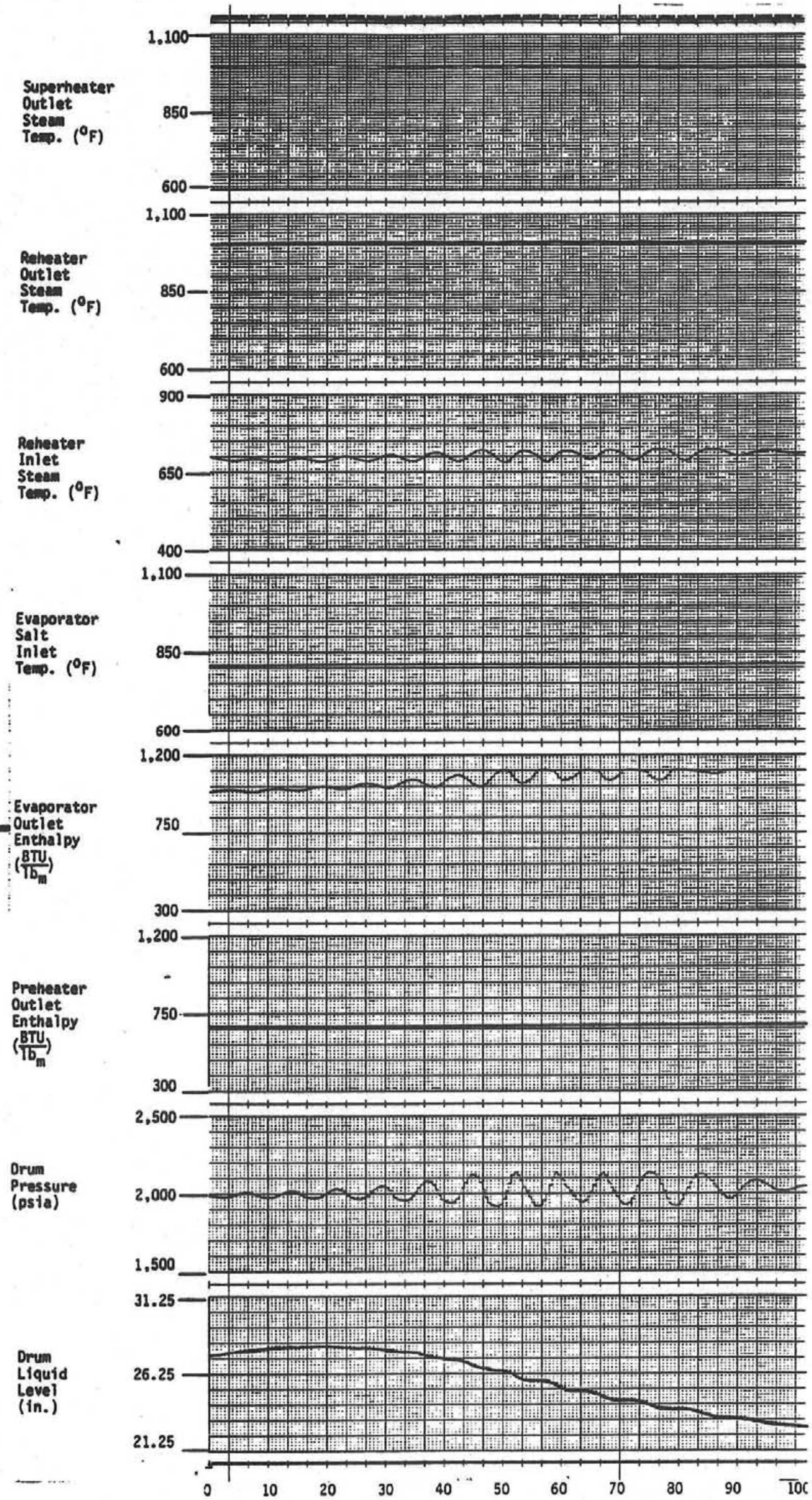
TURBINE TRIP (Figures 31-37)



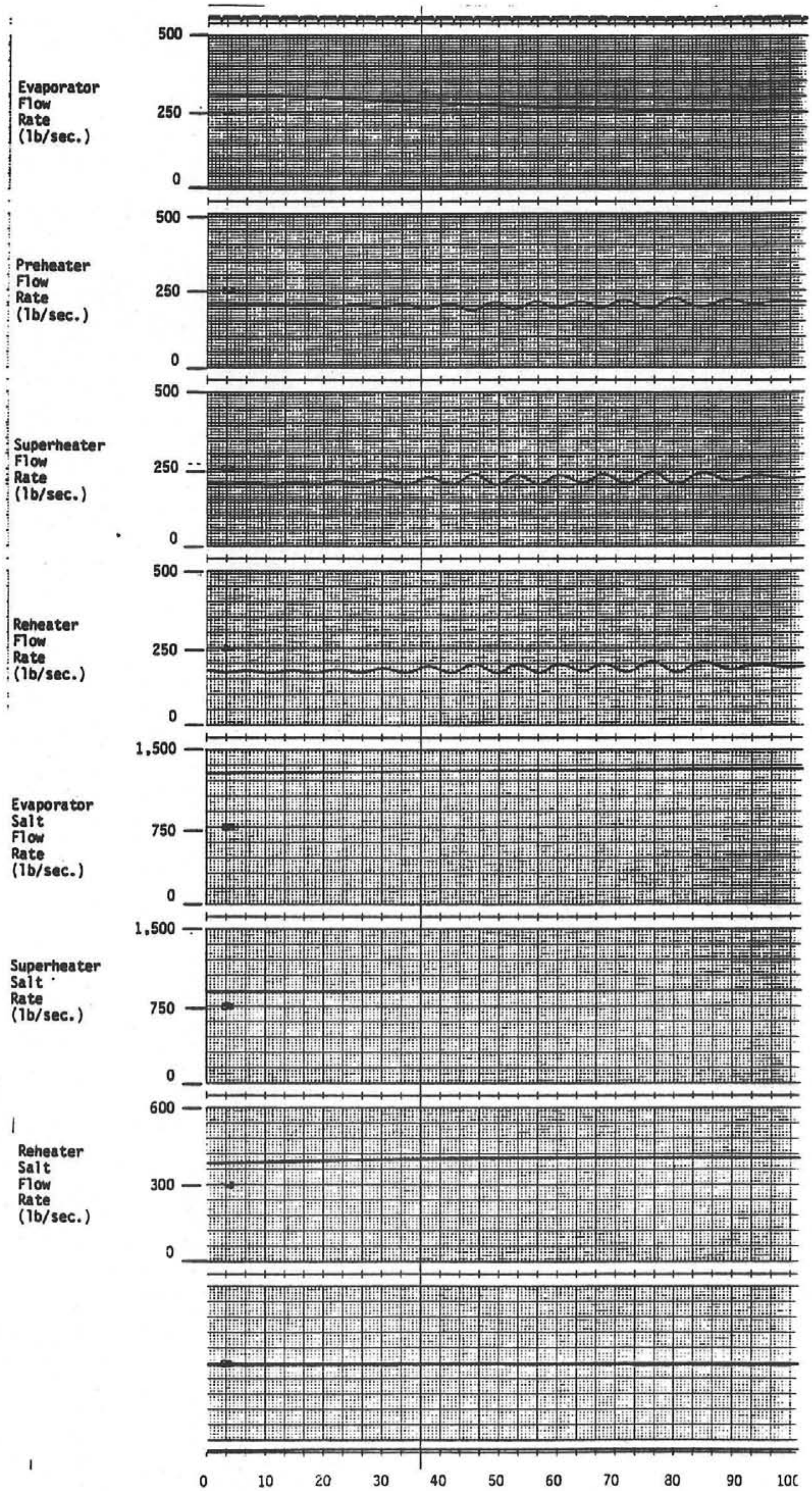
ONE RECIRCULATING PUMP TRIPPED
(Figures 38-45)



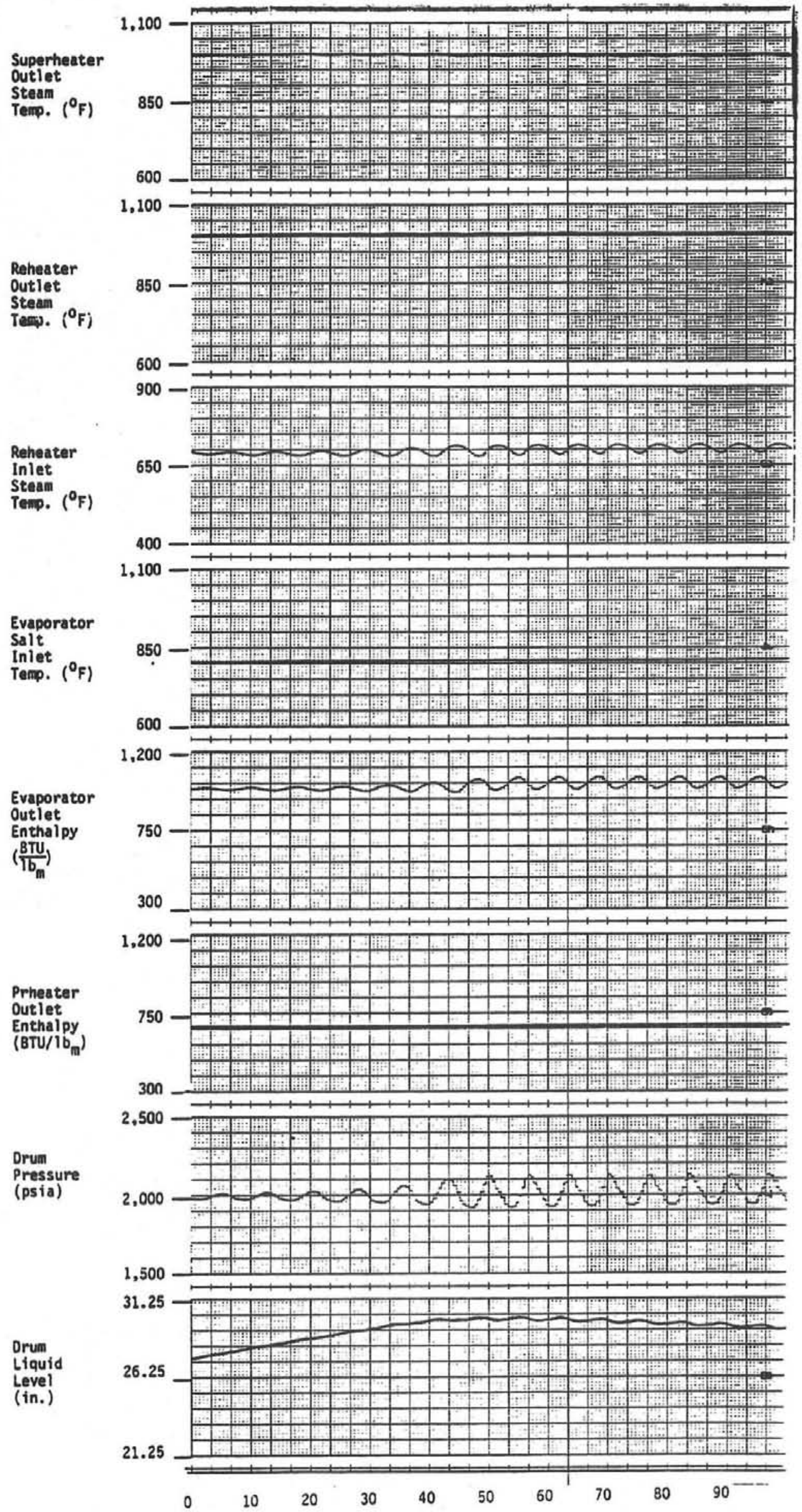
ONE RECIRCULATING PUMP TRIPPED (Figures 46-52)



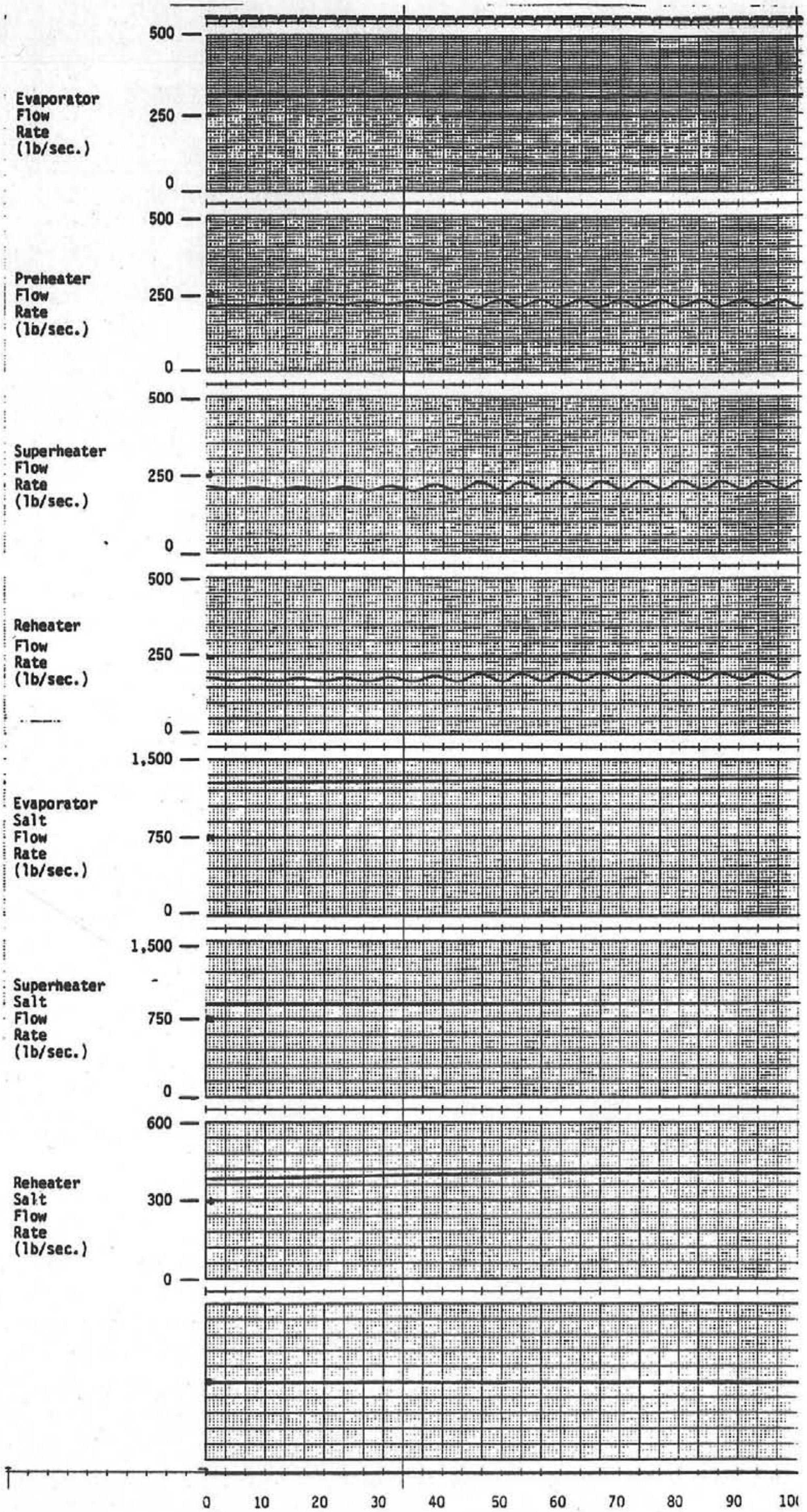
BOTH RECIRCULATING PUMPS TRIPPED (Figures 53-60)



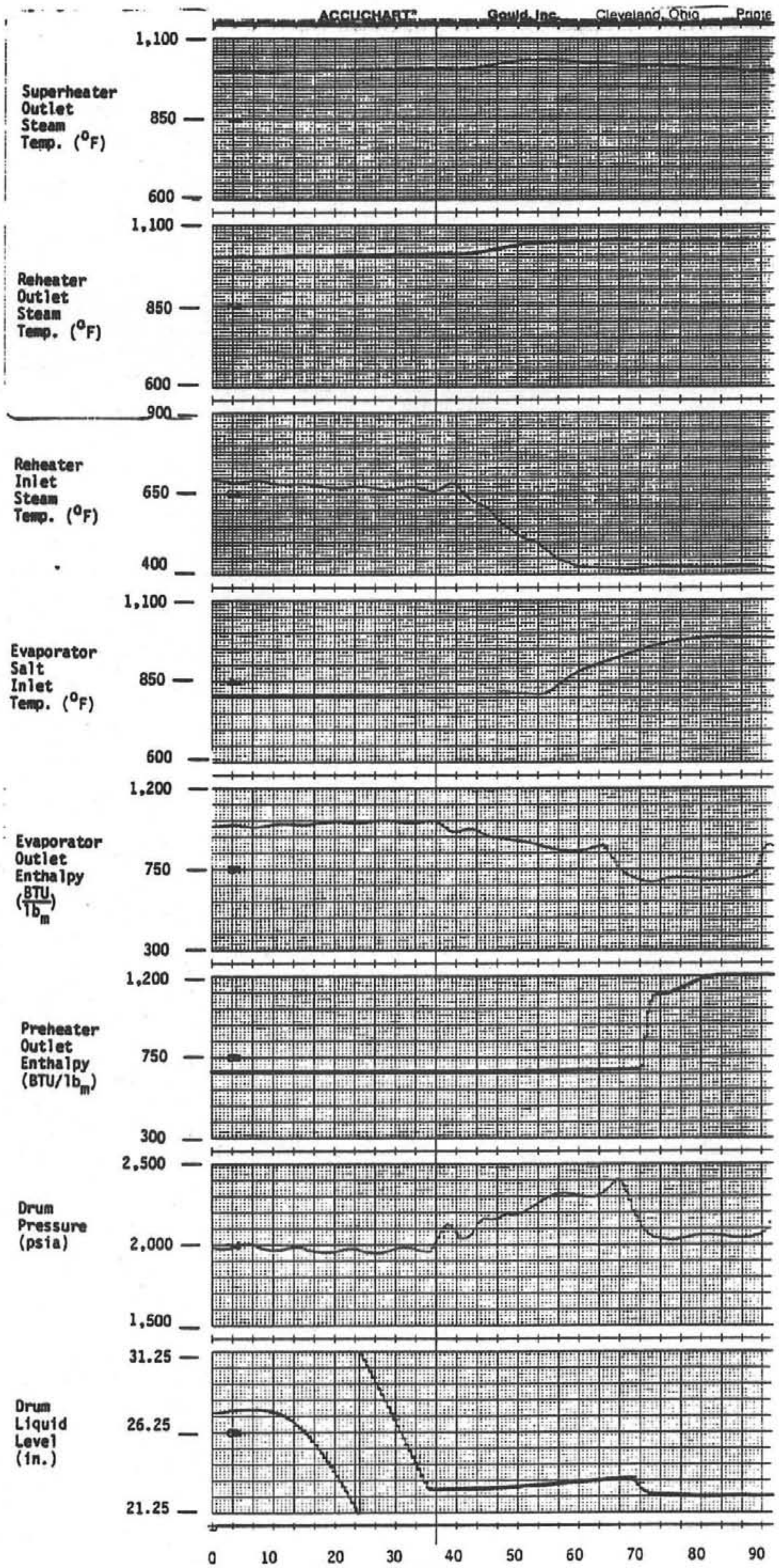
BOTH RECIRCULATING PUMPS TRIPPED (Figures 61-67)



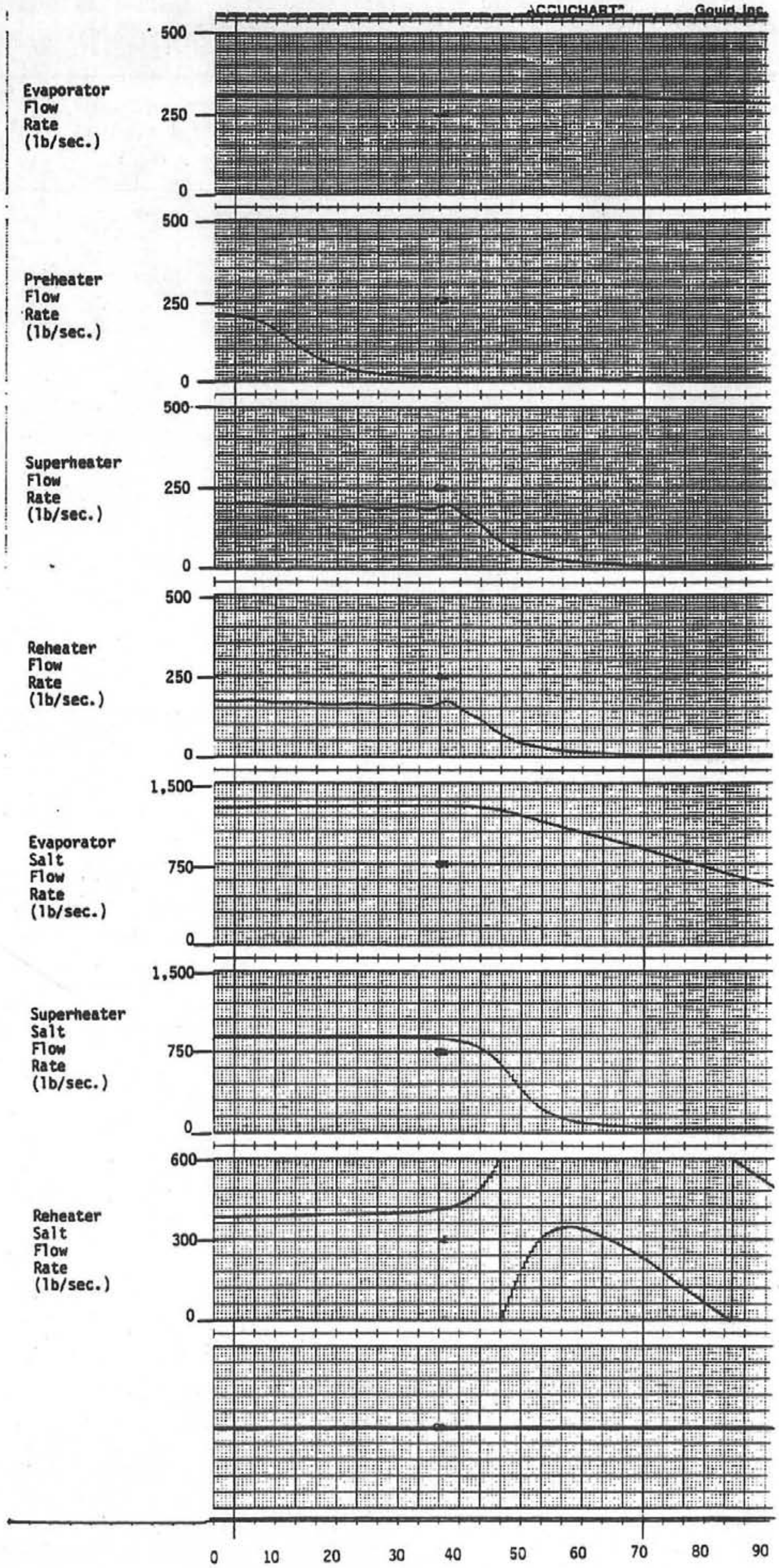
FEEDWATER VALVE FAILED OPEN (Figures 68-75)



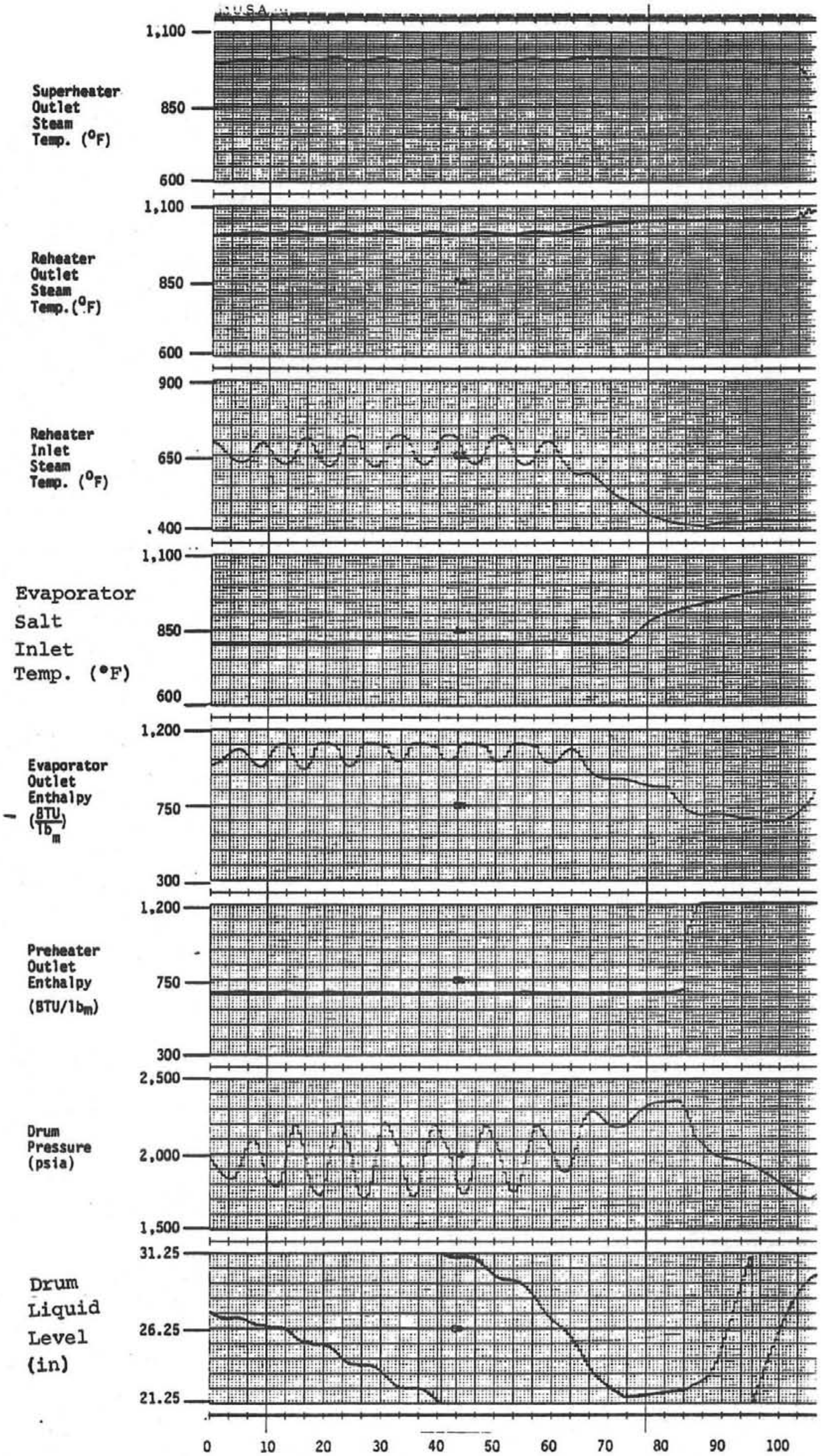
FEEDWATER VALVE FAILED OPEN (Figures 76-82)



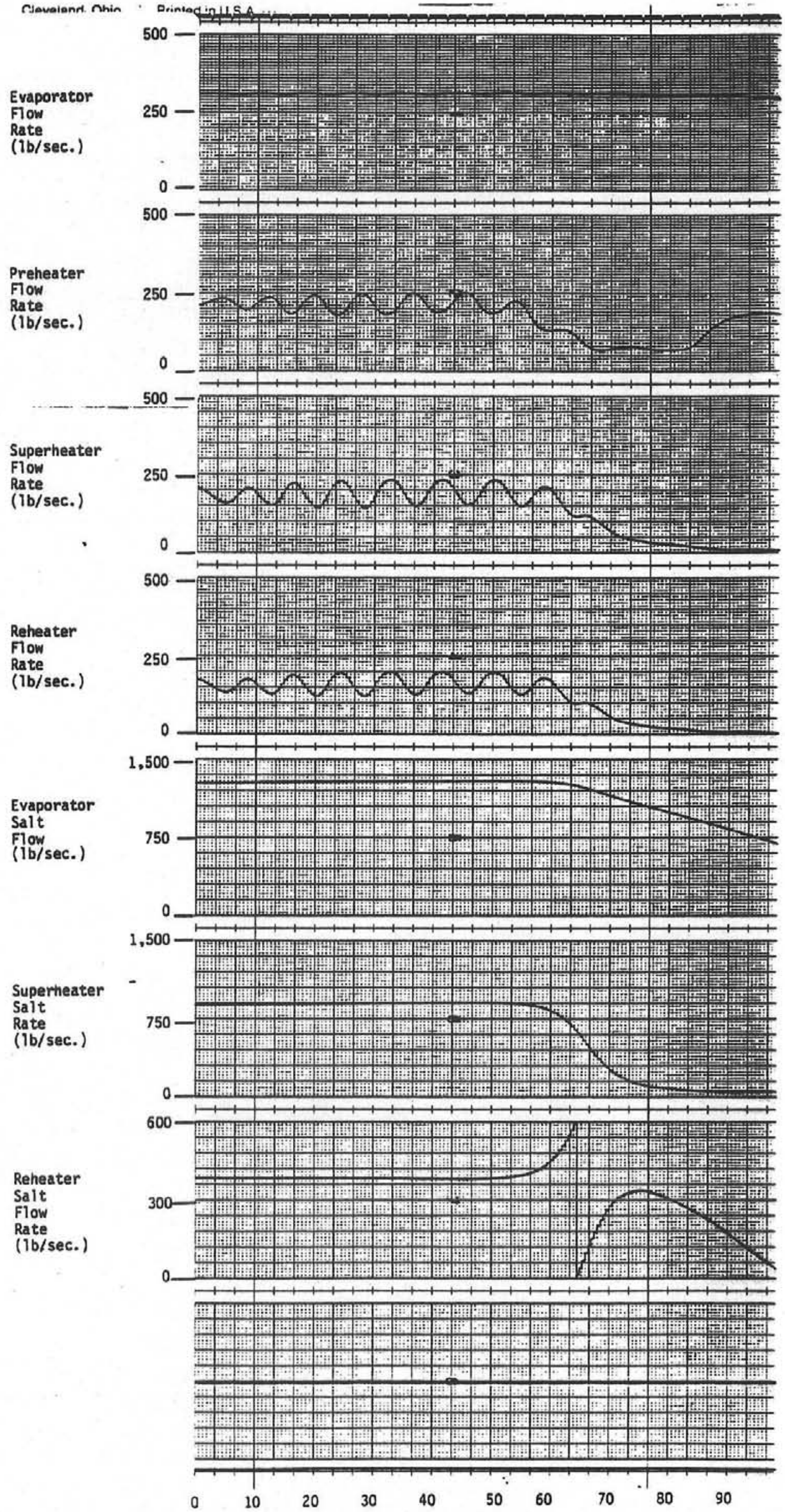
FEEDWATER VALVE FAILED CLOSED (Figures 83-90)



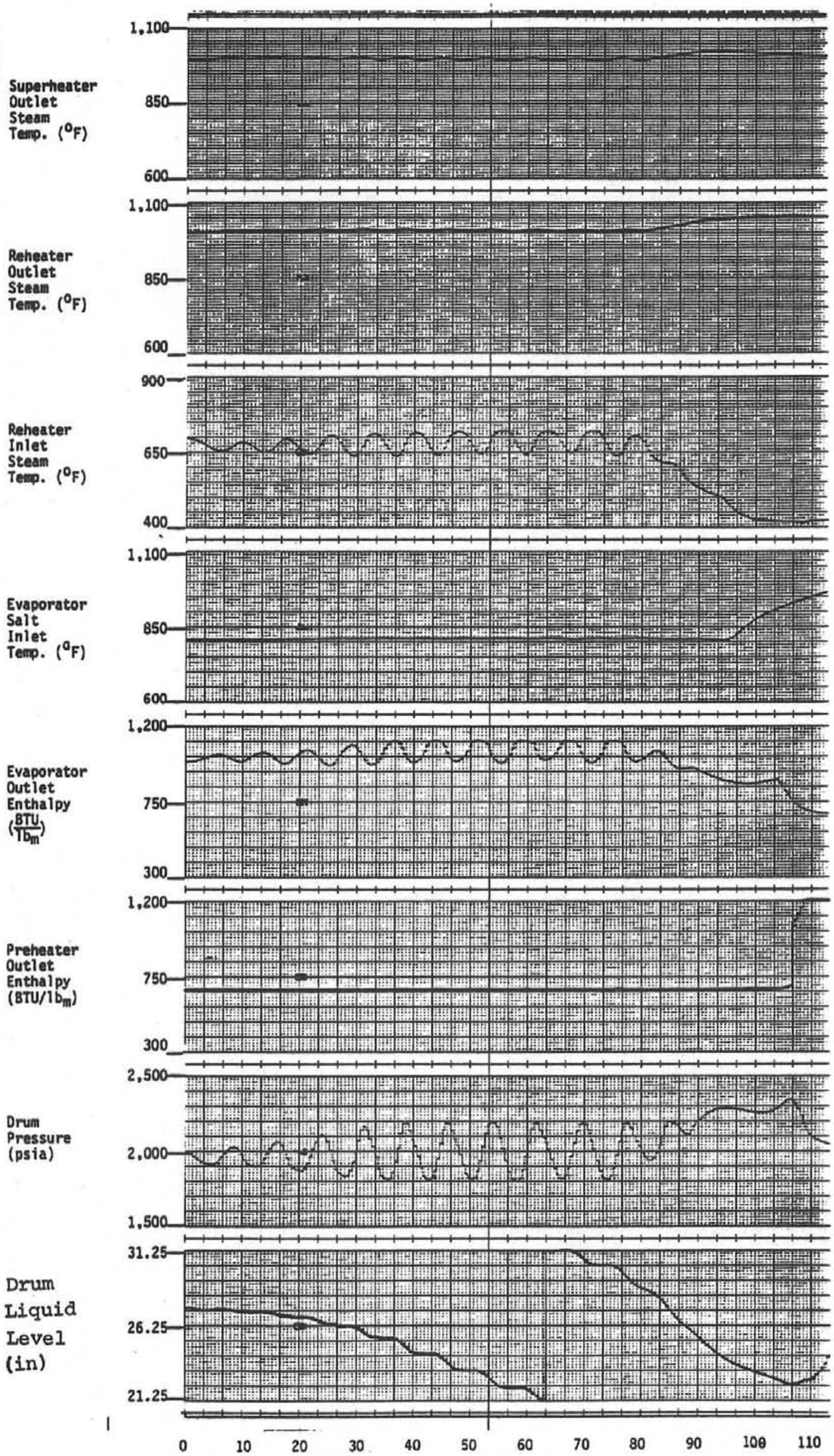
FEEDWATER VALVE FAILED CLOSED
(Figures 91-97)



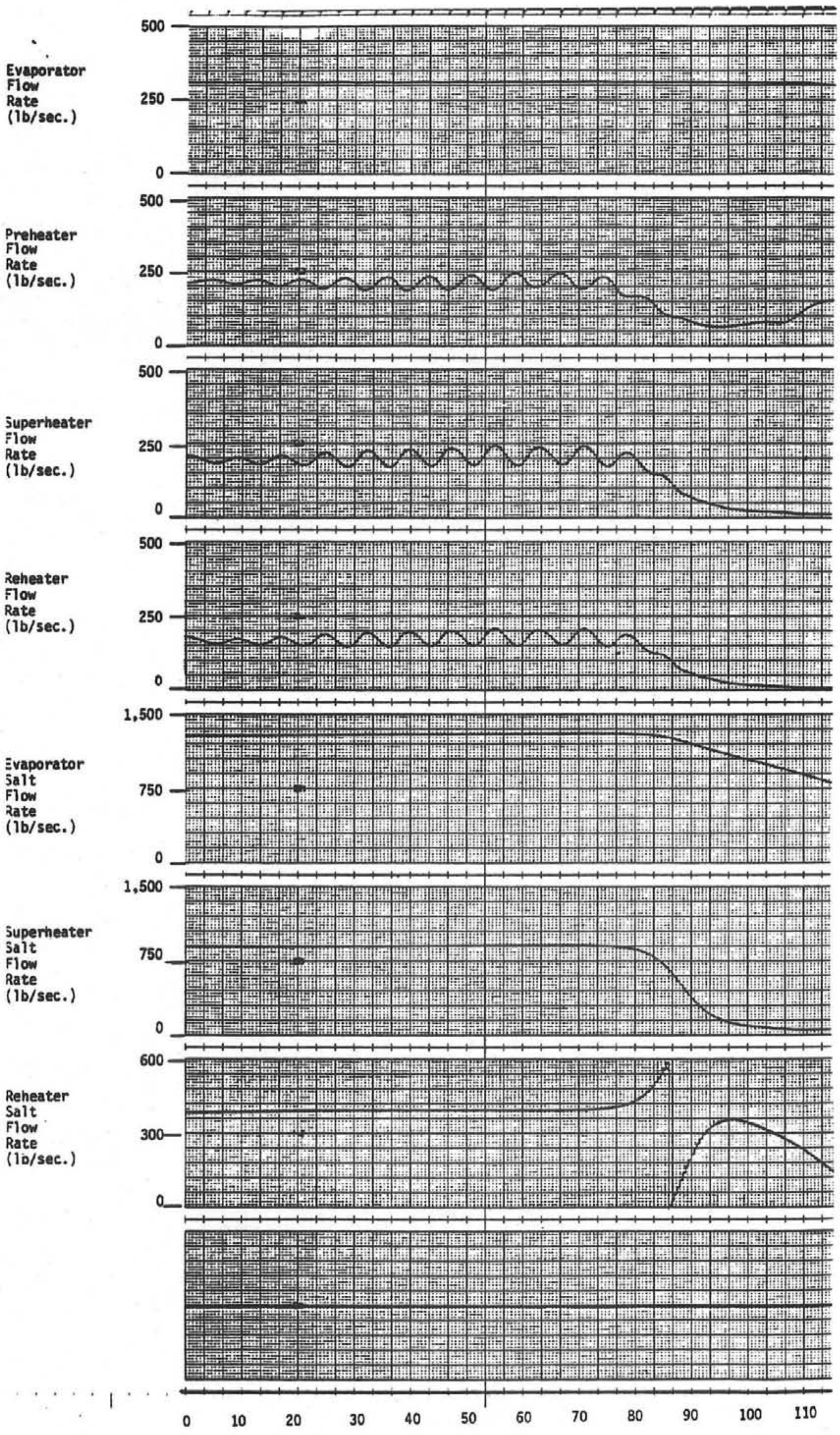
TWO RELIEF VALVES FAILED OPEN (Figures 98-105)



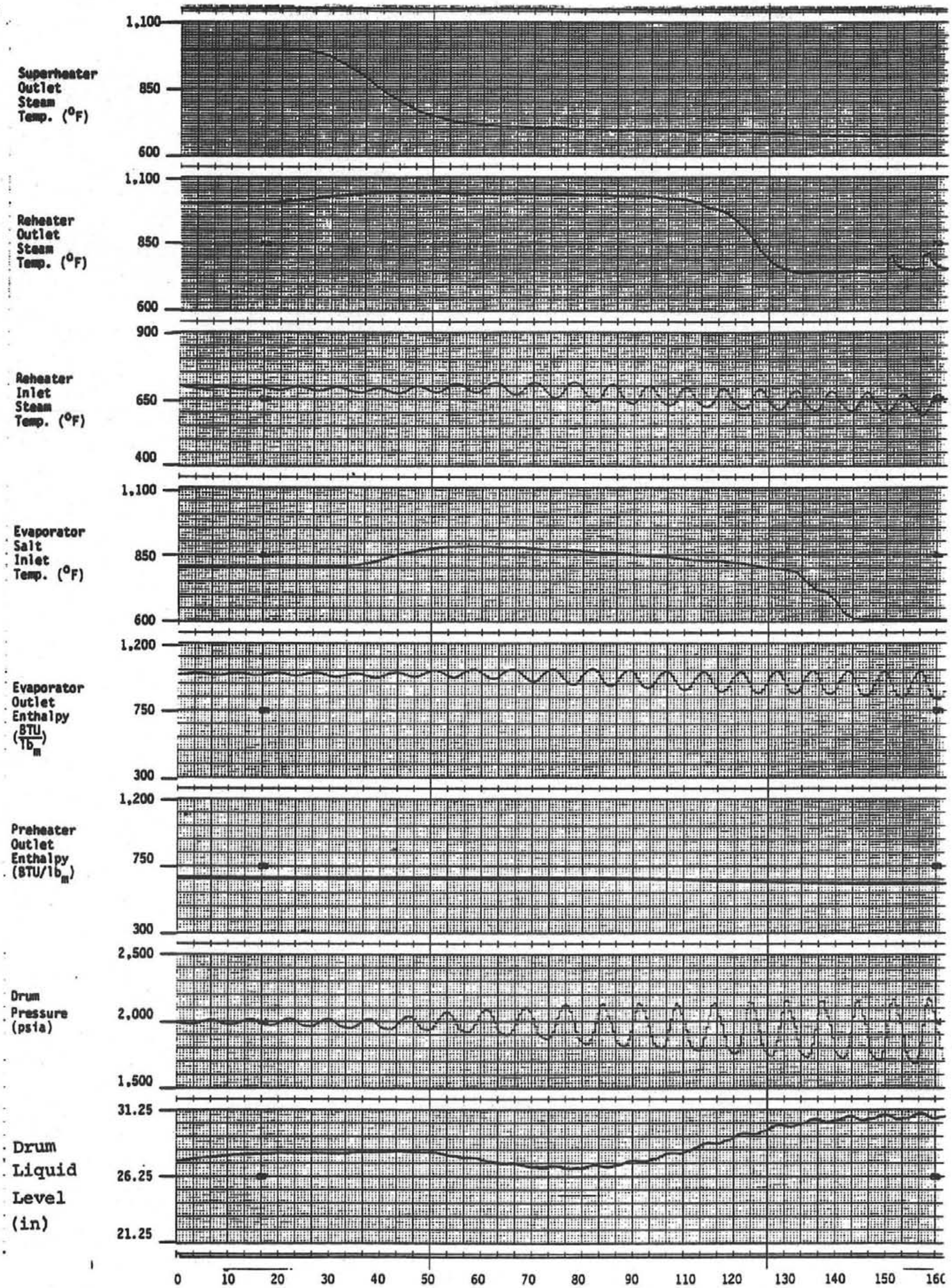
TWO RELIEF VALVES FAILED OPEN (Figures 106-112)



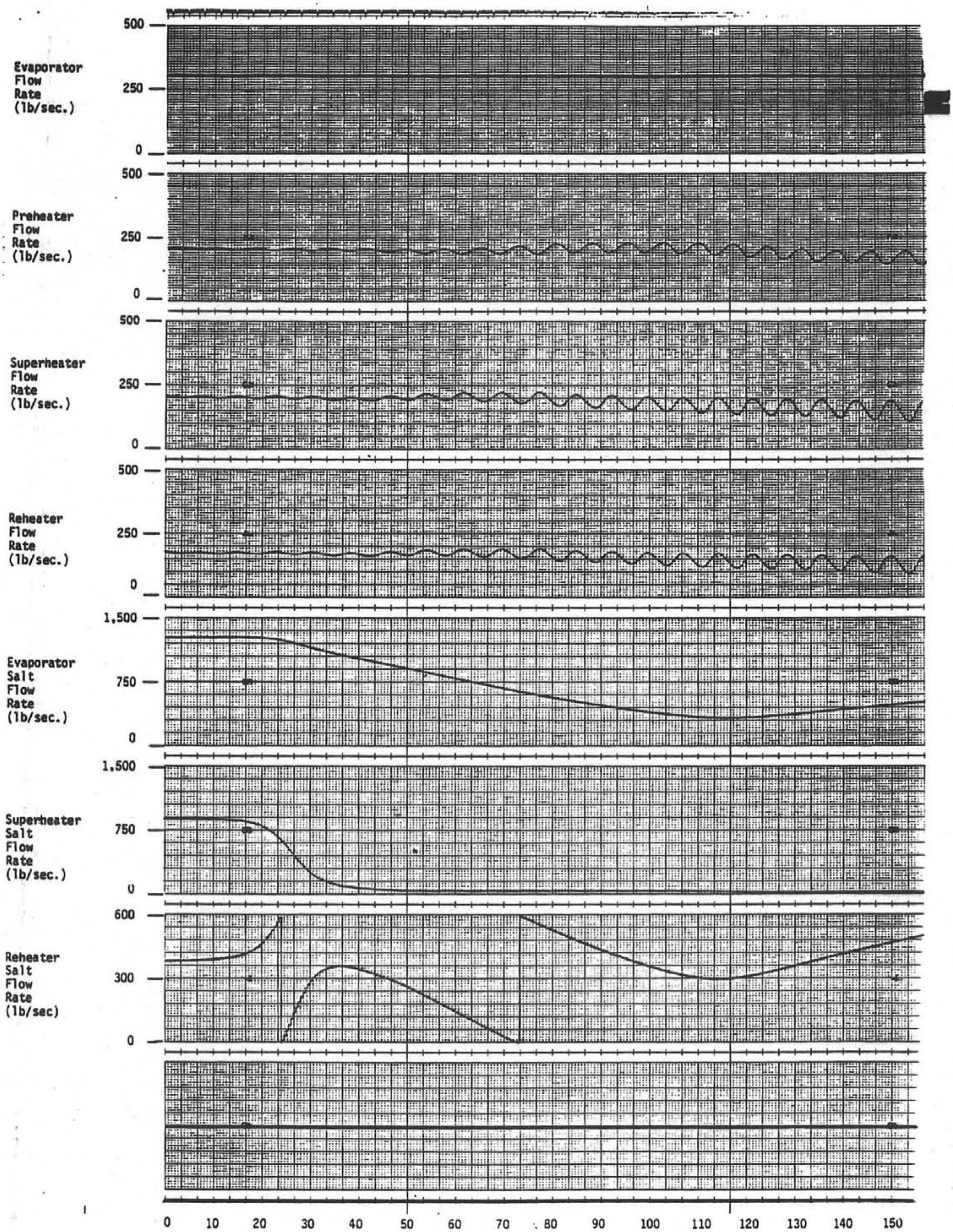
ONE RELIEF VALVE FAILED OPEN (Figures 113-120)



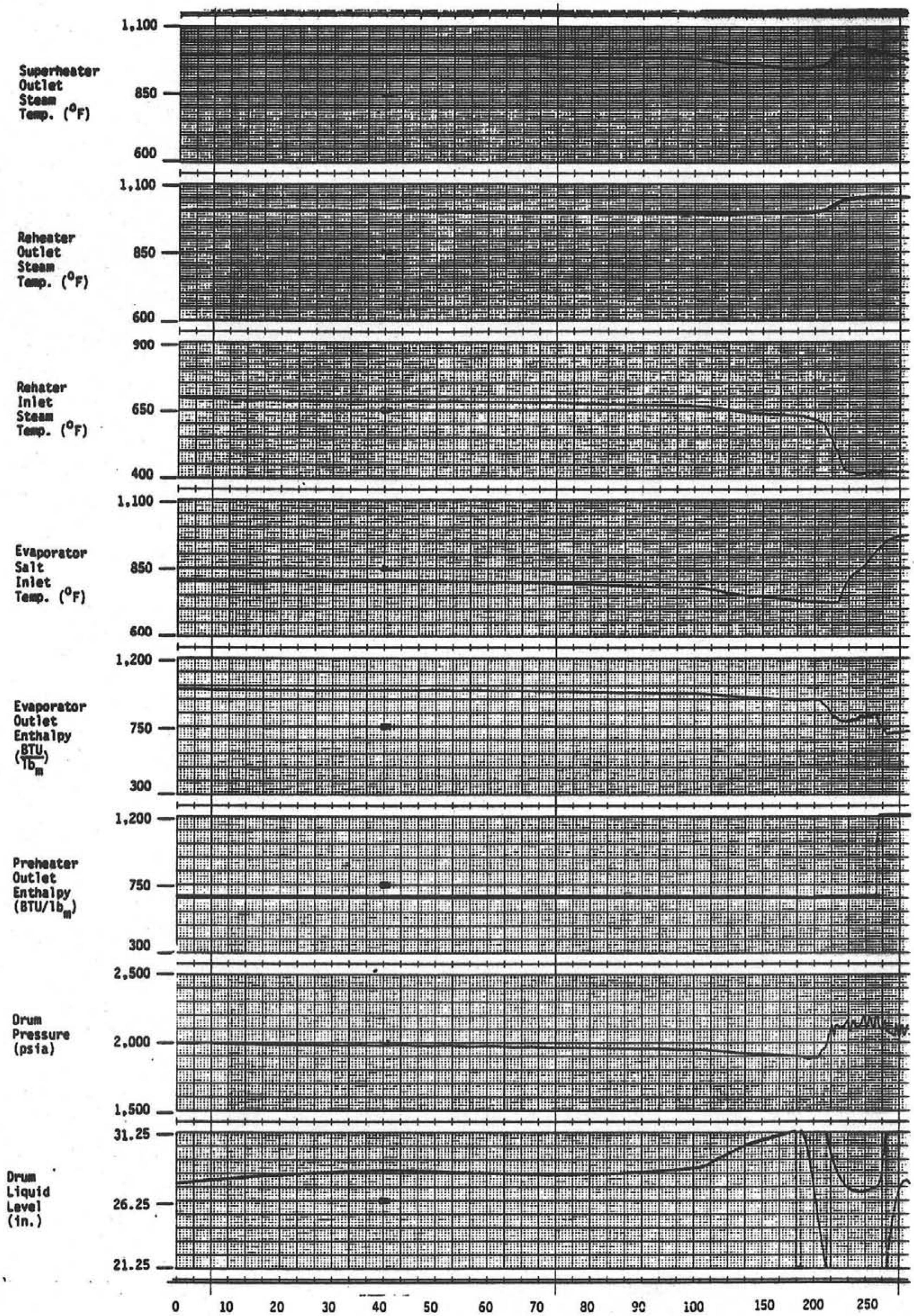
ONE RELIEF VALVE FAILED OPEN (Figures 121-127)



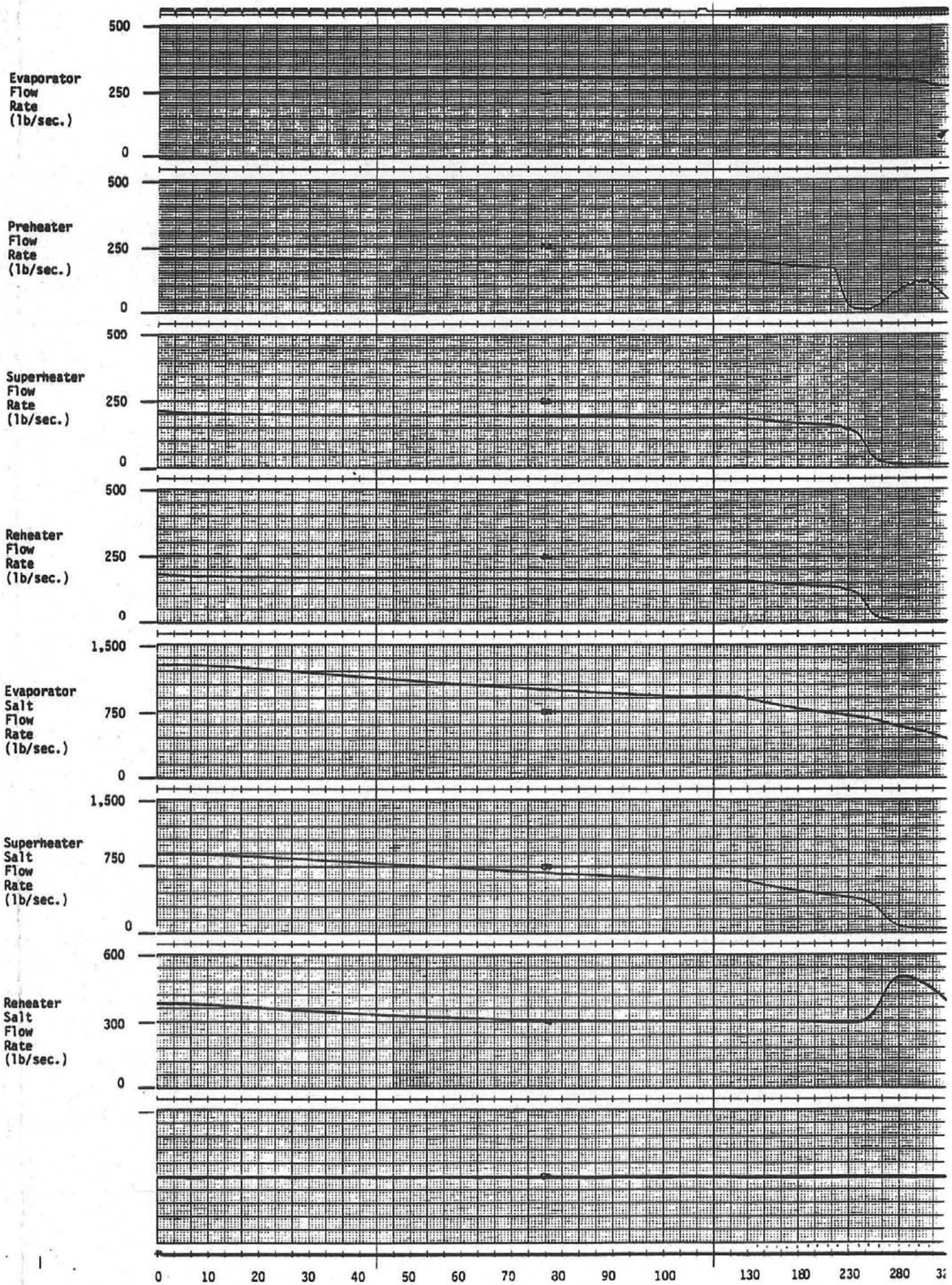
SUPERHEATER SALT VALVE CLOSURE (Figures128-135)



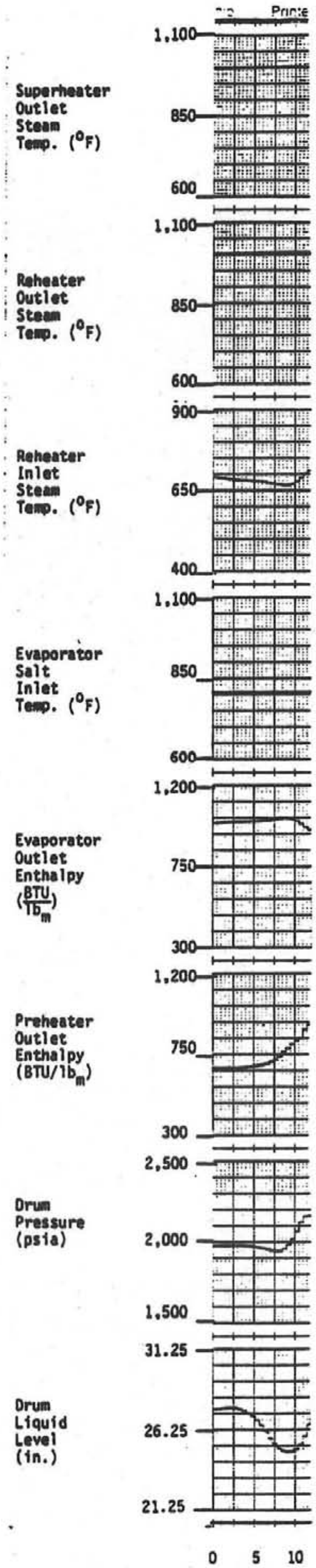
SUPERHEATER SALT VALVE CLOSURE (Figures 136-142)



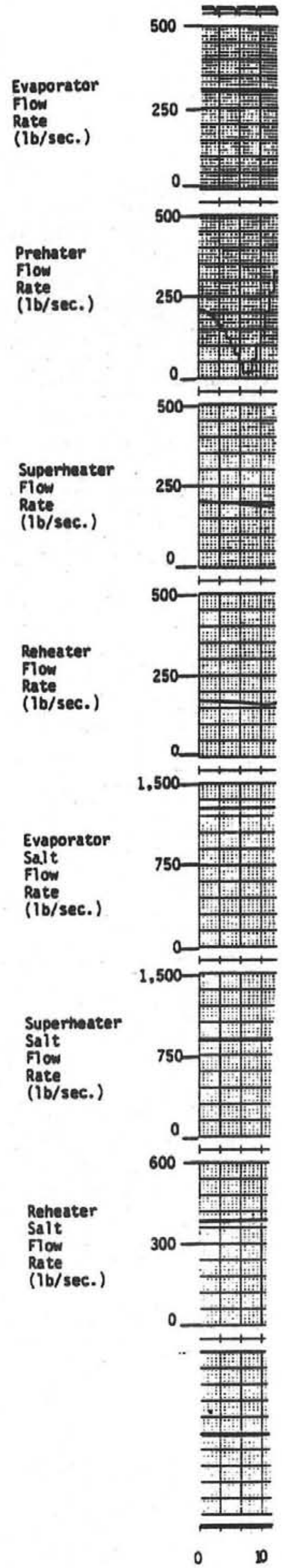
HOT SALT PUMP TRIP (Figures 143-150)



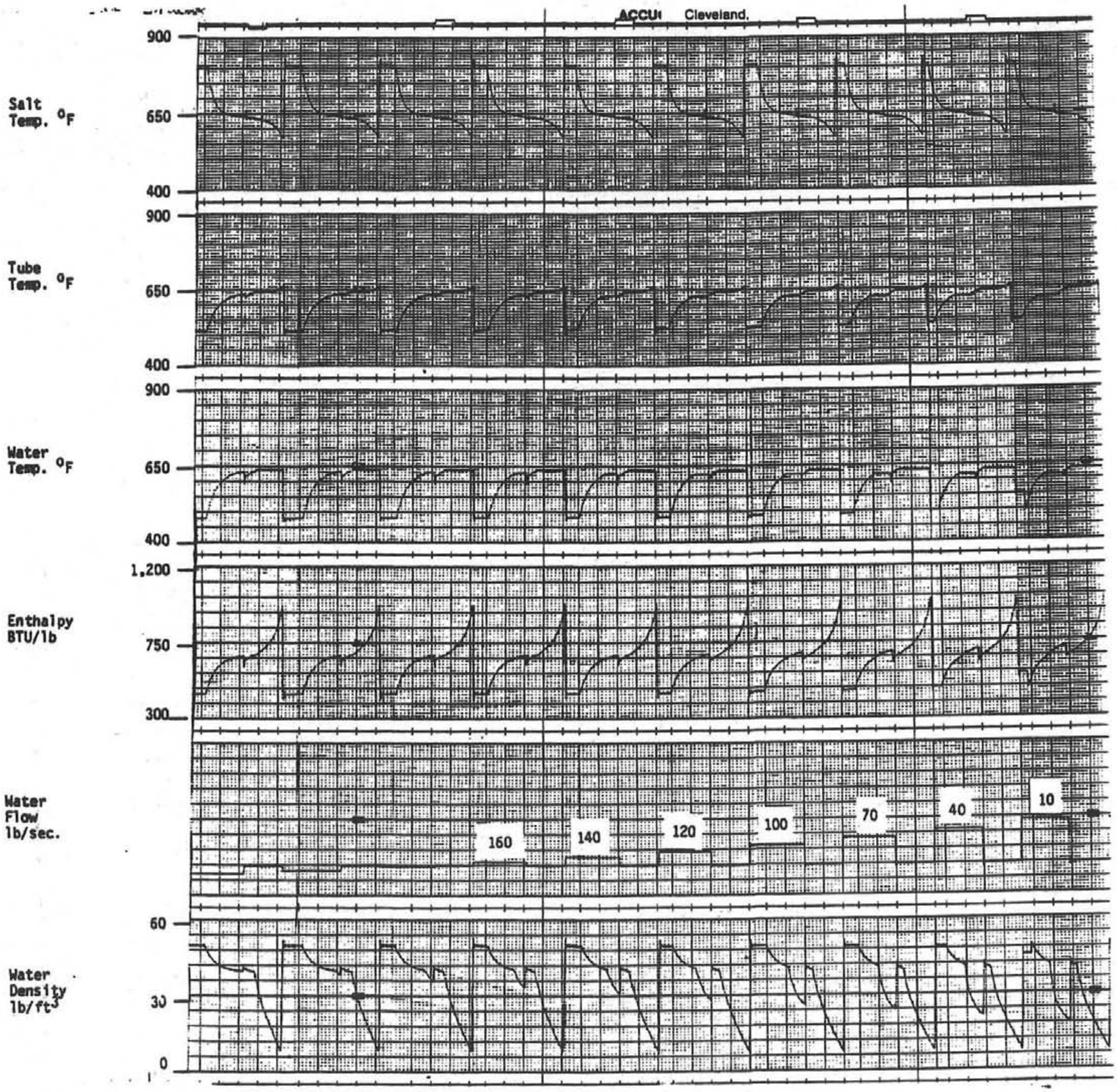
HOT SALT PUMP TRIP (Figures 151-157)



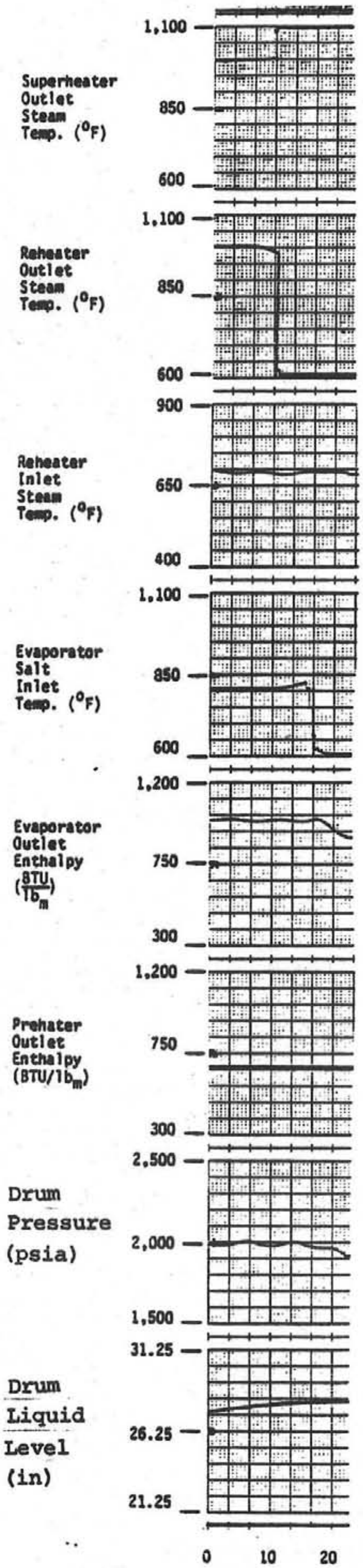
FEEDWATER PUMP TRIP
(Figures 158-165)



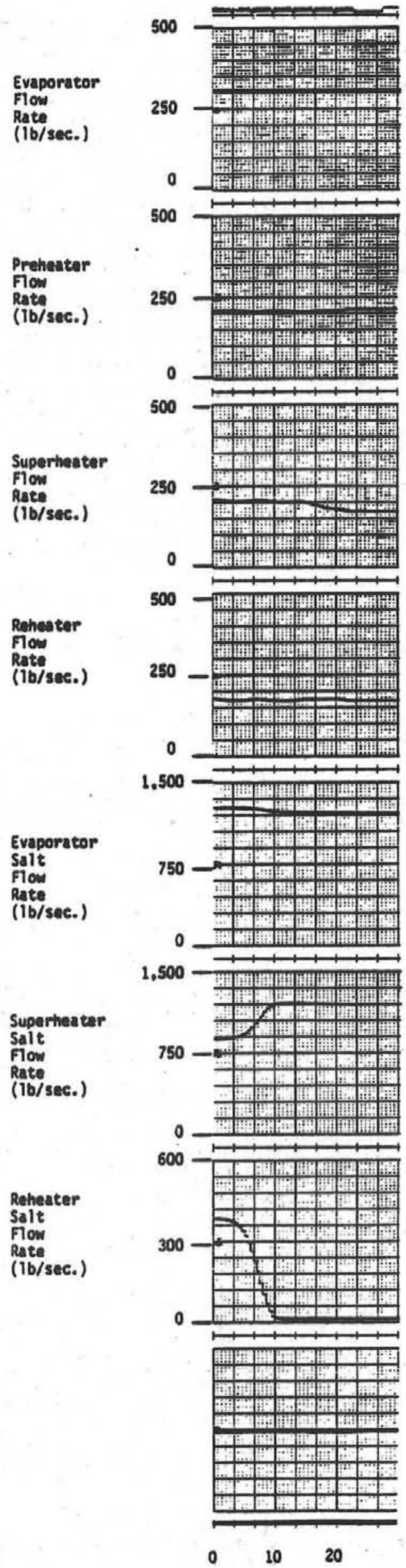
Feedwater Pump Trip
(Figures 166-172)



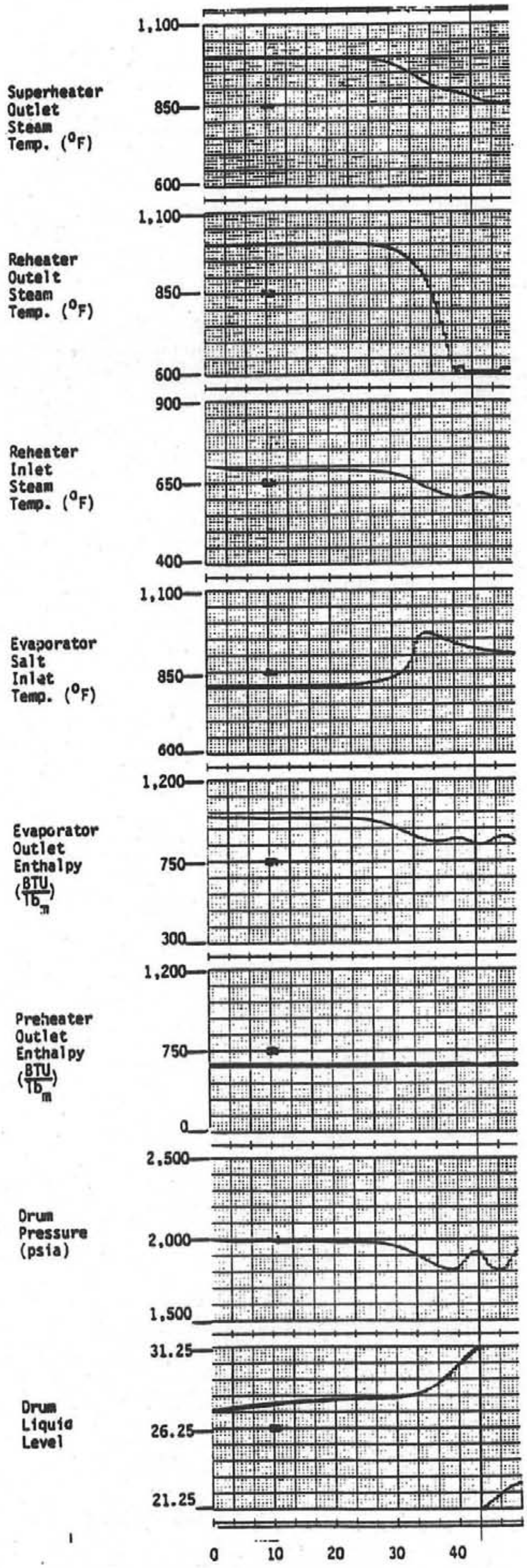
FEEDWATER PUMP TRIP (Figures 173-178)



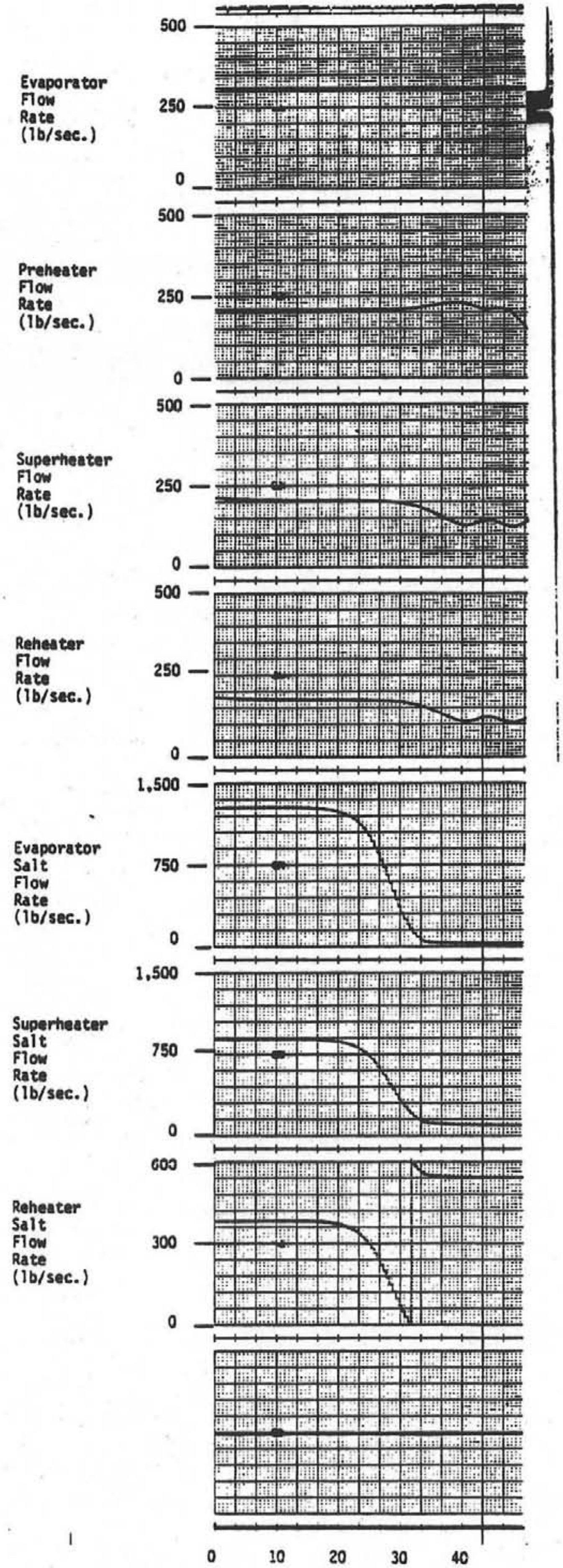
REHEATER SALT VALVE CLOSURE
(Figures 179-186)



REHEATER SALT VALVE CLOSURE
(Figures 187-193)



PREHEATER SALT VALVE CLOSURE (Figures 194-201)



PREHEATER SALT VALVE CLOSURE (FIGURES 202-208)

Appendix F
Control System Design

APPENDIX F

CONTROL SYSTEM DESIGN

FOR

MOLTEN SALT STEAM GENERATOR SUBSYSTEM

Prepared for: The Babcock & Wilcox Company
Barberton, Ohio

Prepared by: Martin Marietta Corporation
Denver, Colorado

February,1982

TABLE OF CONTENTS

TABLES

APPENDIX

GLOSSARY

1. **LOAD FOLLOWING, FEEDFORWARD:** this is an open loop control such as the superheater salt-line valve. Here the steam flow to the turbine constitutes the load and the salt flow through the valve is set proportionally to it (hence feedforward).

2. **FEEDBACK:** this is usd in addition to feedforward to correct any errors that exist such as steady state errors and errors in computing the feedforward term. (Feedback for the steam generator takes the form of either temperature, pressure of drum level).

3. **INTEGRATOR/LAG TRANSFER FUNCTION:** this is a differential equ ation describing the relationship between the input and output of a block ie.

$$\frac{dx_o}{dt} + \tau \frac{d^2x_o}{dt^2} = k.x_i \quad , \quad o = \text{output}, \; i = \text{input}$$

Ignoring initial conditions and applying the Laplace transform we have,

$$x_o = \frac{k}{S(1+\tau S)} x_i \quad , \quad S = \text{integrator}, \; 1+\tau S = \text{lag}$$

which is the general, elementary representation of a servo mechanism.

4. **PID CONTROL:** is a general control algorithm of the form

$$\text{DEMAND} = k \left\{ 1 + \frac{1}{\tau_i S} + \tau_d S \right\} \text{ERROR}$$

or expressed digitally:

$$\text{DEMAND} = k \left\{ \text{ERROR} + \Delta t . \sum_n \frac{\text{ERROR}(n)}{\tau_i} + \tau_d \left(\frac{\text{ERROR}(n+1) - \text{ERROR}(n)}{\Delta t} \right) \right\}$$

where Δt is the sample interval and n the sample.

5. **PI CONTROL:** this is identical to the PID Control but with τ_d set to zero.

6. **POLES, ZEROES:** these refer to the roots of the denominator, numerator polynomials of a transfer function, ie.

$$G(S) = \frac{(1+\tau_{z1} S)\ (1+\tau_{z2} S)}{S\ (1+\tau_{P1} S)}$$

In the complex frequency plane (S), this function has two zeroes at Z1 and Z2 with a pole at the origin (integrator) and a pole at P1.

1. INTRODUCTION

This report describes the control system design for the steam generating subsystem of a solar power plant. The work was performed under Tasks 4 and 5 of Phase 1 in the Molten Salt Steam Generator Subsystem Program (Sandia Contract: 20-9909A). The major objective was to design a control system to be used in the generation of steam from molten salt. This included defining the locations for valves, their control algorithms, the necessary instrumentation and the control hardware.

The location of the valves and components of the Steam Generator Subsystem is illustrated in Figure 1. These valves are used to control the process variables in the following manner:

i) The reheater salt-line valve (#2) is used to control the salt-flow through the reheat exchanger. The control consists of a load-following, feedforward term plus a feedback term correcting any deviation in steam exit temperature.

ii) The superheater salt-line valve (#1) controls 70% of the salt-flow to the evaporator and is therefore used to control the pressure of the supply steam with minimal interference to the reheater. As with the reheater, the control consists of a load-following, feedforward term plus a feedback term which here corrects any deviation in steam throttle pressure.

iii) The steam attemperator valve (#4) controls the flow of lower quality steam from the drum for mixing with the steam from the superheater. The purpose of this control is to maintain the temperature of the superheated steam using temperature feedback only.

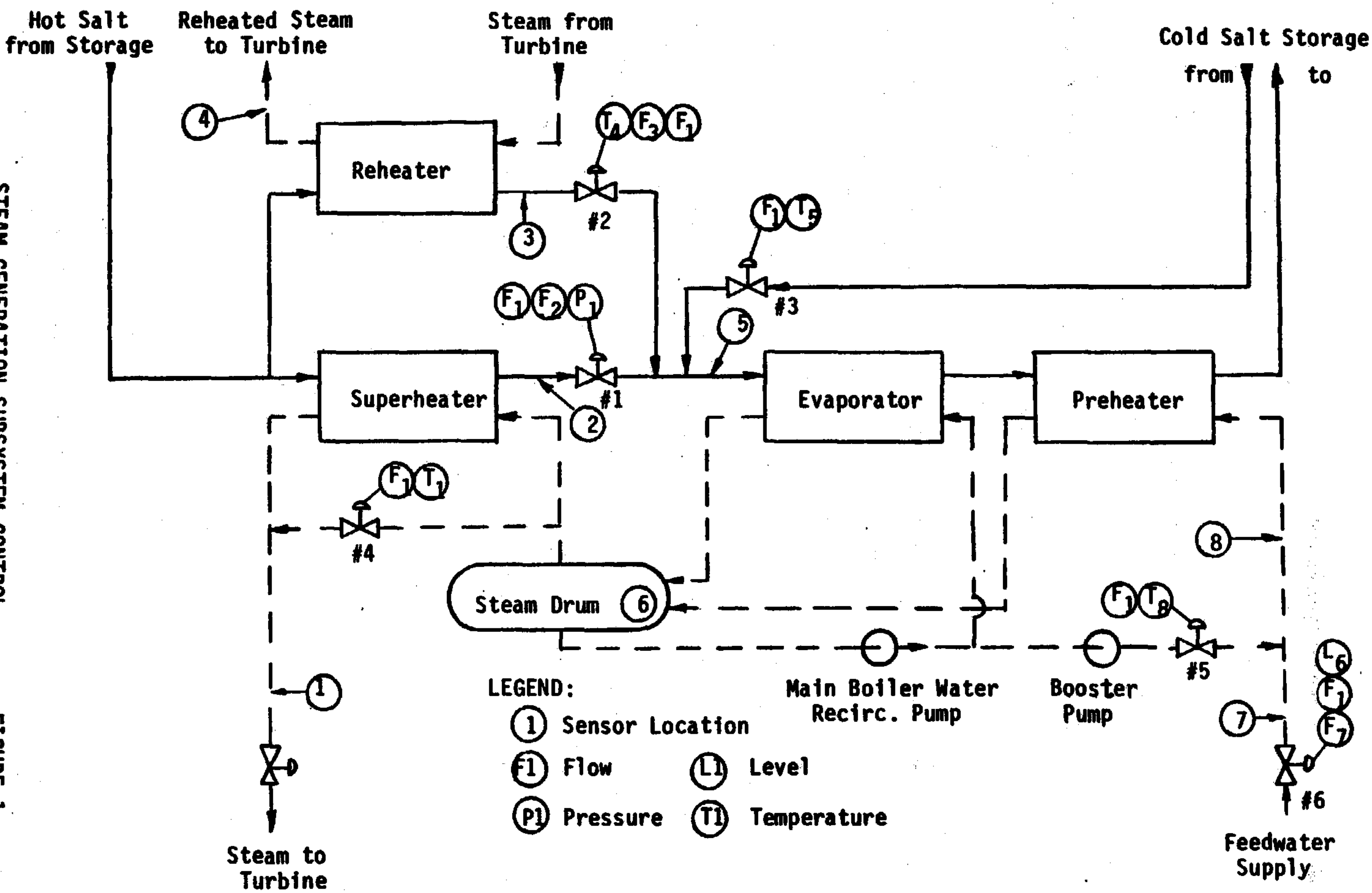


FIGURE 1

STEAM GENERATION SUBSYSTEM CONTROL

iv) The evaporator salt attemperator valve (#3) controls the flow of cold salt for mixing with the salt from the reheater and superheater. The temperature of the salt entering the evaporator is used as the feedback term to drive the valve such that the salt into the evaporator does not exceed 496°C (925°F).

v) The feedwater supply valve (#6) controls the flow of the water supply. A load-following feedforward term is used along with a feedback term correcting the fluid level in the drum.

vi) The boiler water recirculation valve (#5) is used to ensure that the temperature of the preheater water supply does not fall below 238°C (460°F). As with the evaporator salt attemperator, temperature feedback of the water entering the preheater is used to generate the error signal.

In order to identify the significant control parameters, control theory was used to predict transient response and steady state errors. This technique also enabled the calculation of the control gains to be used by the Babcock and Wilcox Hybrid Simulation. To achieve this, first order lags were assumed representative of the plant with the following time constants at 100% load:

i) Superheater, 8 secs.

ii) Reheater, 32 secs.

iii) Preheater, 50 secs.

iv) Evaporator, 80 secs.

v) Steam Drum, 200 secs.

It was further assumed that the time constants relating to the heat exchangers were linearly related to the residence times. To complete the mathematical models for each control loop, the valve actuation was represented by an integrator/lag transfer function. By assuming critical damping and specifying the valve time-to-open, the time constant and velocity constant for each actuation can be calculated.

The control system was analyzed using the following requirements:

i) maintain steam temperatures out of the reheater and superheater of 538°C (1000°F),

ii) maintain steam throttle pressure at 12.51 MPa (1815 psi),

iii) maintain a drum fluid level of 67cm (26.25"),

iv) keep the evaporator salt supply temperature below 496°C (925°F),

v) keep the preheater water supply temperature above 238°C (460°F).

These requirements were assessed against transients induced by a load maneuver swing from 100% to 30% at a rate of 10%/minute.

The final assessment of the control system was made using the same set of requirements and predicting the transient performance from the Babcock and Wilcox digital code of the plant.

This simulation model was used to tune the reheater and superheater feedback controllers using the Ziegler-Nichols recommended settings. First the pressure feedback loop for the superheater salt-line valve was tuned with the reheater temperature feedback path broken. The recommended gain settings were made and then the reheater temperature feedback loop was tuned. With the recommended gains for both the reheater and superheater determined, no further tuning was necessary and load swings could be performed. In each case, the results illustrate the ability to smoothly control the subsystem.

To finalize the design, alternatives are given for the control hardware. These take the form of digitally based analogue controllers with comparisons made between distributed microprocessor control and central processor control.

2. CONTROL ALGORITHMS

This section of the report describes the control algorithms considered for the control of each of the valves in the steam generation subsystem.

2.1 Reheater Salt Line Valve

Two schemes for reheater control were proposed during the study and comparison between them led to one being discarded from further analysis. The reasoning behind this decision and a description of both techniques is given below.

2.1.1 Active Thermal Balance

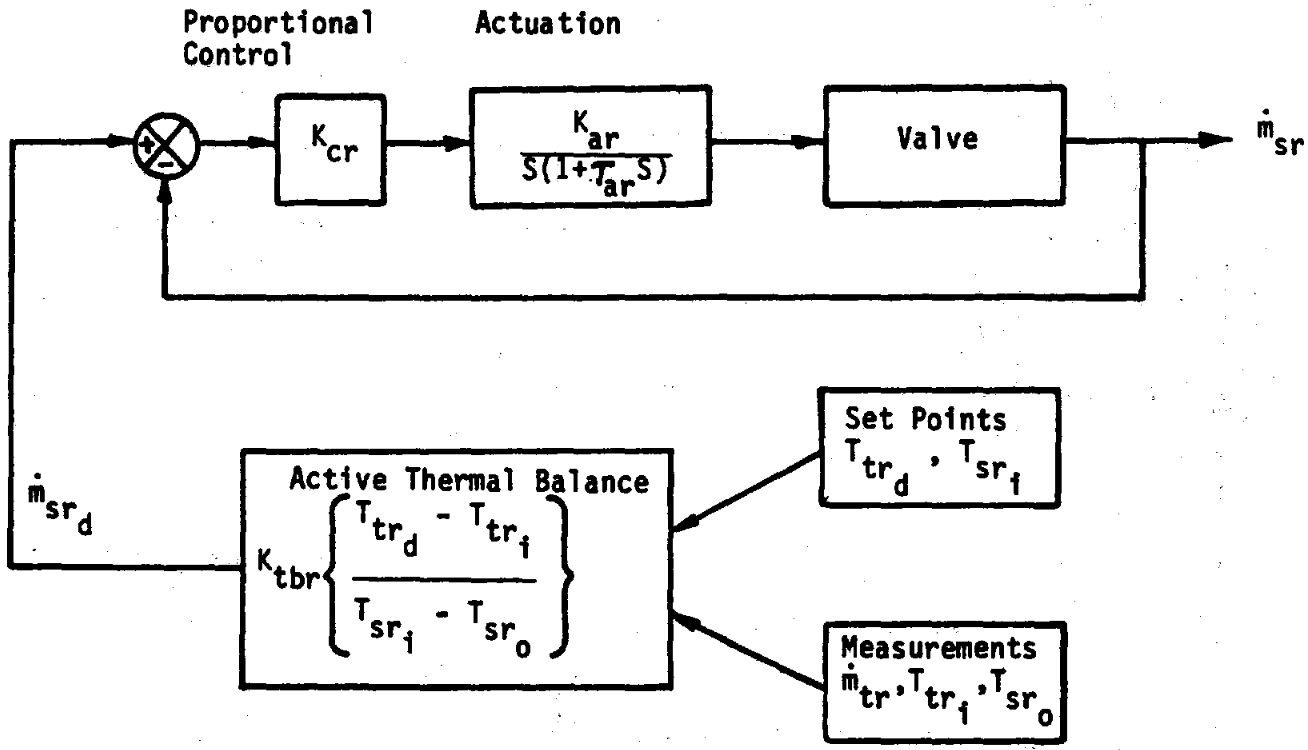
This form of control utilizes the temperature difference across the tubeside and shellside fluids to equate heat flow from one to another. The thermal balance for the reheater is described by:

$$\dot{m}_{sr}\, C_{ps}\, (T_{sr_i} - T_{sr_o}) = \dot{m}_{tr}\, C_{pt}\, (T_{tr_o} - T_{tr_i}) \qquad \text{1)}$$

The symbols are defined in figure 2, which illustrates this control concept with Equation 1 configured as a quasi-feedforward control. This particular technique is sensitive to transport delay effects on temperature measurements and errors in set point assignments. Consequently, the following technique was pursued.

2.1.2 Nominal Thermal Balance with Temperature Feedback

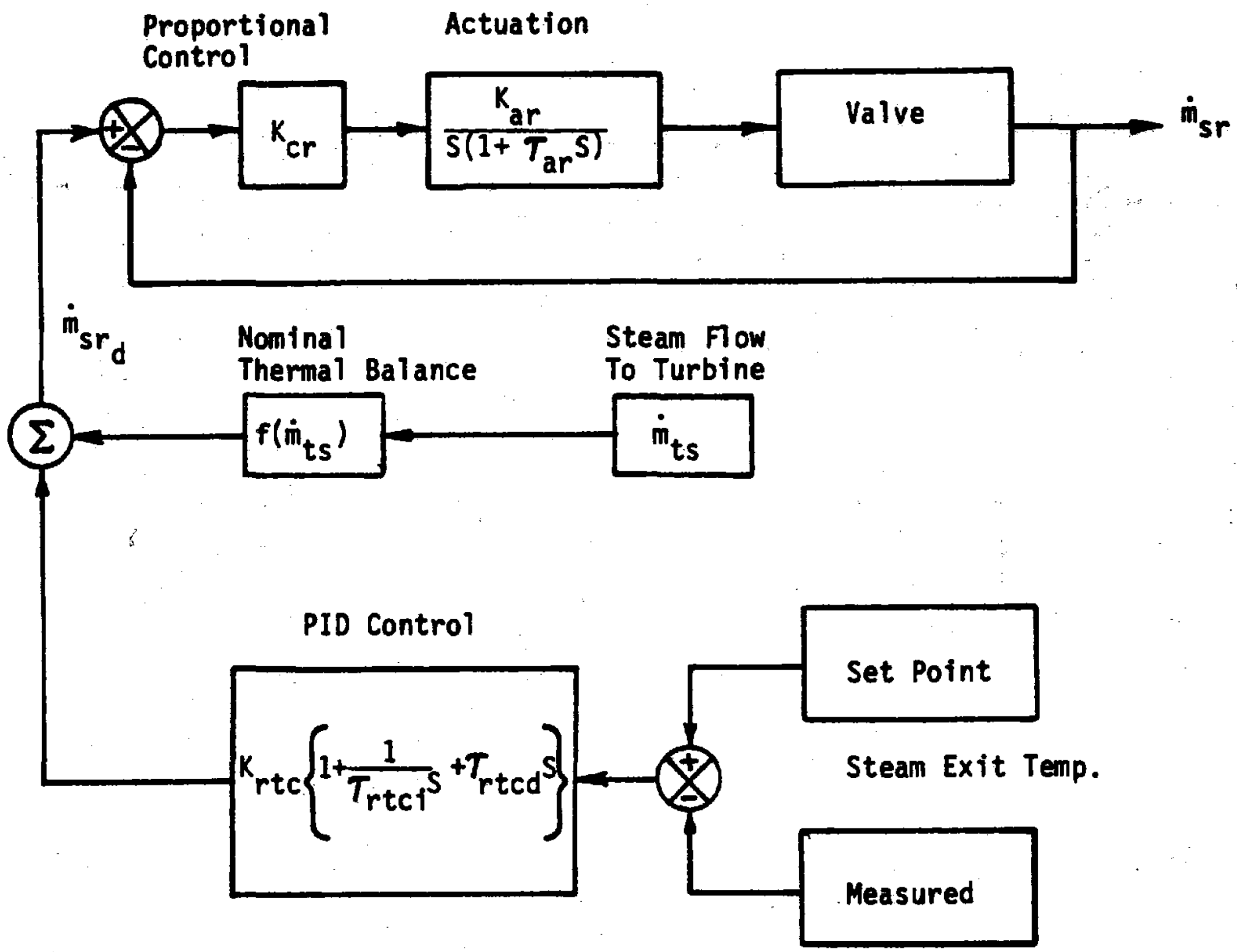
In this scheme, the demanded salt-flow rate through the reheater is calculated by summing two independent terms. A nominal thermal balance is used to approximately equate salt-flow and steam flow, this constitutes the load following term. In addition, the steam exit temperature is compared with the set point and the error signal is used to modify the salt-flow rate. This is illustrated in Figure 3. As can be seen, a PID control is used to provide both good damping and integrate out any steady state error.



Legend:

- K : Constant of Proportionality
- S : Laplace Transform
- T : Temperature
- $\mathcal{T}$: Time Constant
- $\dot{m}$: Flow Rate
- tr: Tubeside Reheater
- sr: Shellside Reheater
- cr: Control Reheater
- ar: Actuation Reheater
- i : Input
- o : Output
- d : Demand

Reheater-Salt Valve Control (Active Thermal Balance) Figure 2



Legend:

- k : Constant of Proportionality
- s : Laplace Transform
- T : Temperature
- τ : Time Constant
- $\dot{m}$: Flow Rate
- ts : Turbine Steam
- tr : Tubeside Reheater
- sr : Shellside Reheater
- cr : Control Reheater
- ar : Actuation Reheater
- d : Demand
- rtci: Reheater Tubeside Control Integrator
- rtcd: Reheater Tubeside Control Differentiator

<u>Reheater-Salt Valve Control (Load Following)</u> <u>Figure 3</u>

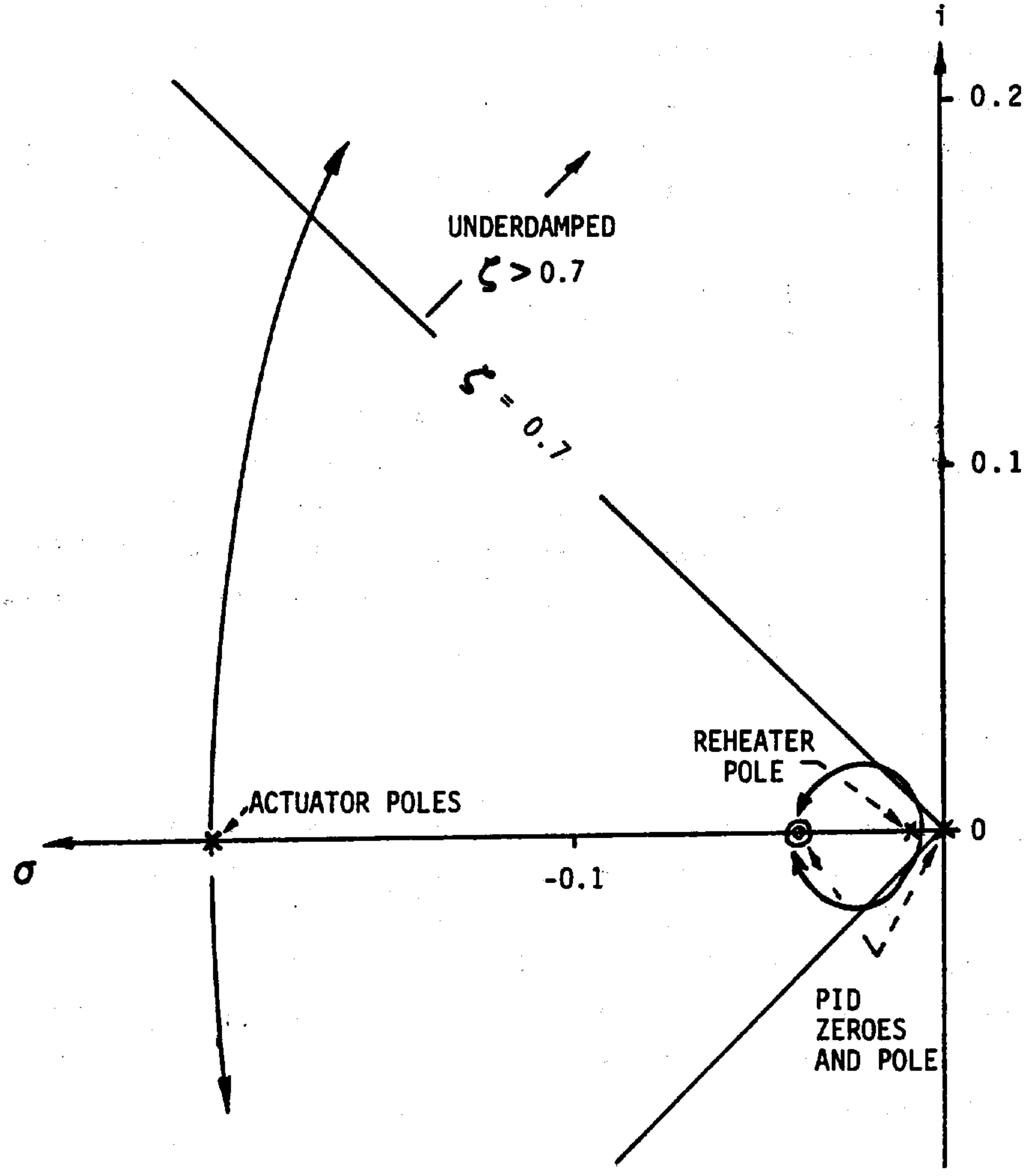
The effect of the load following term (nominal thermal balance) is to minimize the temperature transients induced by load manuevering. The temperature feedback term is used to zero any steady state errors and dampen small disturbances. It's ability to perform this task can be assessed from the root locus plot shown in Figure 4. The 30% load condition was considered to be the worst design case as this involved the largest reheater time constant, (τ_{rh}),

$$\tau_{rh} = \frac{32}{0.3} \text{ sec} \qquad\text{—————————} \qquad 2)$$

The lower the load, the higher the time constant becomes. As can be seen in Figure 4, the PID zeroes catch the migrating reheater/integrator poles and the system response is essentially dependant on the migrating actuator poles. The design criterion was to limit the temperature overshoot to 5%, therefore the loop gain was set with damping $\zeta = 0.7$.

2.2 Superheater Salt Line Valve

It was stated in the introduction that the main purpose of this valve is to control the steam supply pressure and that the position chosen for it minimized interference with the reheater salt-line valve. This argument is summarized in the first part of Table 1, where the relative advantages and disadvantages are noted by comparison with those relating to a position downstream of the evaporator. Although it is feasible to place the valve in either position, the present configuration, reference figure 1, was considered preferable for control as its only disadvantage is the thermal cross-coupling effect of the evaporator on steam supply pressure. By using load-following feedforward terms for both the reheater and superheater salt-line valves, this effect becomes insignificant.



INCREASING LOOP GAIN

DESIGN CONDITION: 30% LOAD

(σ, i) COMPLEX PLANE

REHEATER ROOT LOCUS: TEMPERATURE FEEDBACK FIGURE 4

COMPARISON BETWEEN VALVE POSITIONS **TABLE 1**

SUPERHEATER SALT-LINE VALVE POSITION

ADVANTAGE: Minimal hydraulic cross-coupling with the reheater leads to a simple control algorithm.

DISADVANTAGE: Transient changes in salt-flow through the reheater effects the evaporator thermal performance which cross-couples the superheater/reheater salt-line valves through steam supply pressure.

MAIN SALT-LINE VALVE POSITION

ADVANTAGE: This valve can be placed in the coolest down stream salt-flow below the preheater.

DISADVANTAGE:

1) The control algorithm is cross-coupled with that of the reheater.

2) Hydraulic cross-coupling with the reheater valve degrades response.

The schematic for the control algorithm is shown in Figure 5. As for the reheater control, a nominal thermal balance is used as a load following term and measured steam supply pressure used for the feedback term. This feedback is required to compensate for errors induced by the nominal thermal balance. An error in the thermal balance could be due to any one of the following:

i) a reduction in load affecting a reduction in the feedwater temperature,

ii) thermal losses due to waste fluid venting from the drum,

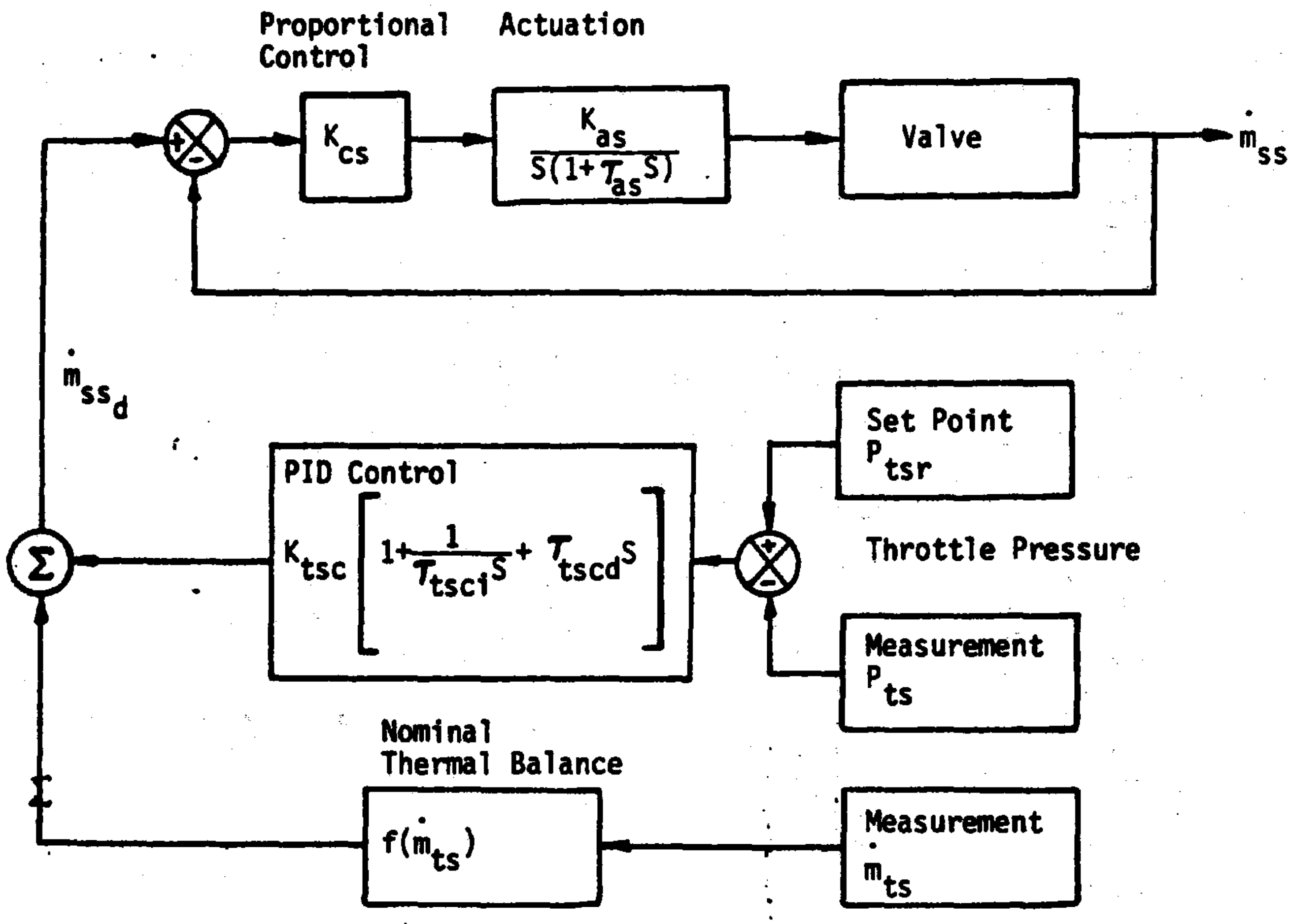
iii) any transient in either salt or water temperatures.

The effect of an error in salt-flow rate can be seen in Figure 6. The predominant terms in the pressure control loop are shown, with linearized hydraulics and simple lags representing the heat exchangers, actuation and drum. Due to the position of the error, $\epsilon \dot{m}$, in the loop, the pressure control must contain an integrator in order to zero any deviation in pressure from the set-point.

A PID control was again used for this loop, and root locus used to study the transient behavior. Figures 7 and 8 show the loop gain locus for the worst case, 30% load. Too high a loop gain will drive the migrating superheater/evaporator/integrator poles into the unstable right hand plane, as shown in Figure 7. These poles will predominate over the migrating actuator poles, reference Figure 8, as their decay rate is at least an order slower. This shows the loop to be most sensitive to the evaporator speed of response.

2.3 Turbine Steam Attemperation

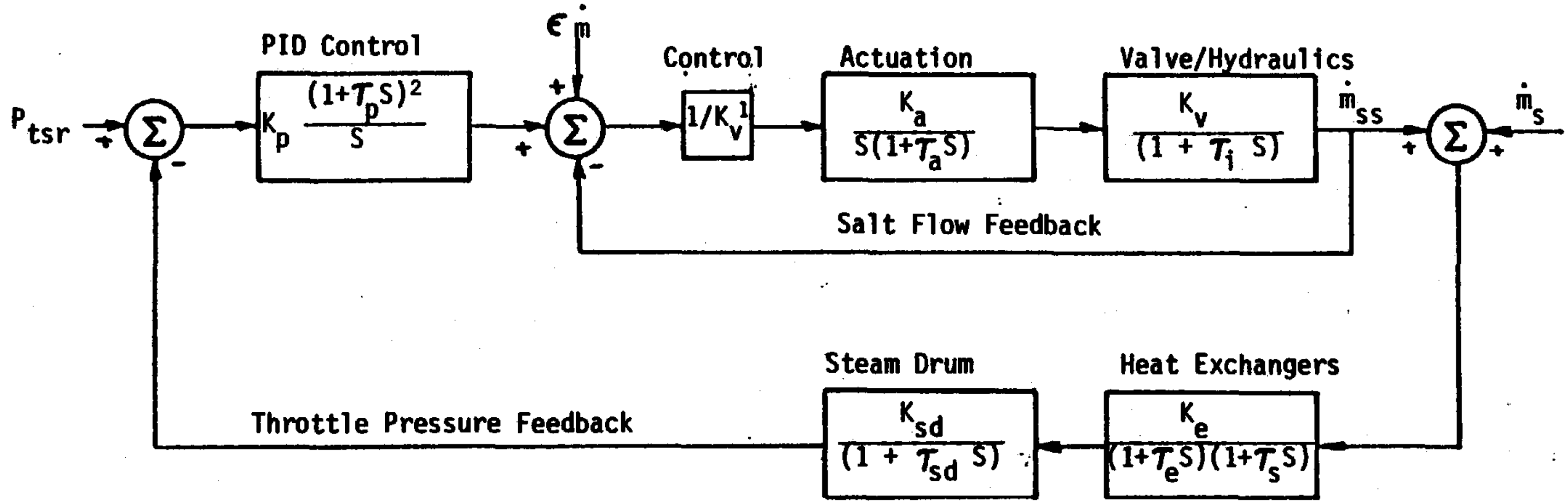
The superheater is designed such that the temperature of the steam leaving the heat exchanger is slightly higher than the required 538°C (1000°F). This allows a margin for variation as the salt-flow varies to control the steam supply pressure. The steam from the superheater is attemperated to 538°C by mixing with it lower quality steam from the drum. A thermal balance across the attemperator yields:



Legend:

- ts: Turbine Steam
- cs: Control Superheater
- as: Actuation Superheater
- tsci: Turbine Steam Control Integrator
- tscd: Turbine Steam Control Differentiator
- $f(\dot{m}_{ts})$: Function Generator

Superheater-Salt Valve Control — Figure 5



Legend:

K_p:	PID Gain	τ_a:	Actuation Time Constant
τ_p:	PID Zero Location	τ_i:	Linearized Hydraulic Time Constant
$\dot{m}$:	Error in Salt Flow Demand	τ_s:	Superheater Time Constant
K_v:	Valve Gain	τ_e:	Evaporator Time Constant
K_v^1:	Linearized Valve Gain ($K_v^1 \cdot K_v = 1$)	τ_{sd}:	Steam Drum Time Constant
K_e:	Heat Exchanger Gain	P_{str}:	Throttle Pressure Reference
K_{sd}:	Steam Drum Gain	$\dot{m}_{ss}$:	Salt Flow Through Superheater
		$\dot{m}_{sr}$:	Salt Flow Through Reheater

Figure 6

Throttle Pressure Control

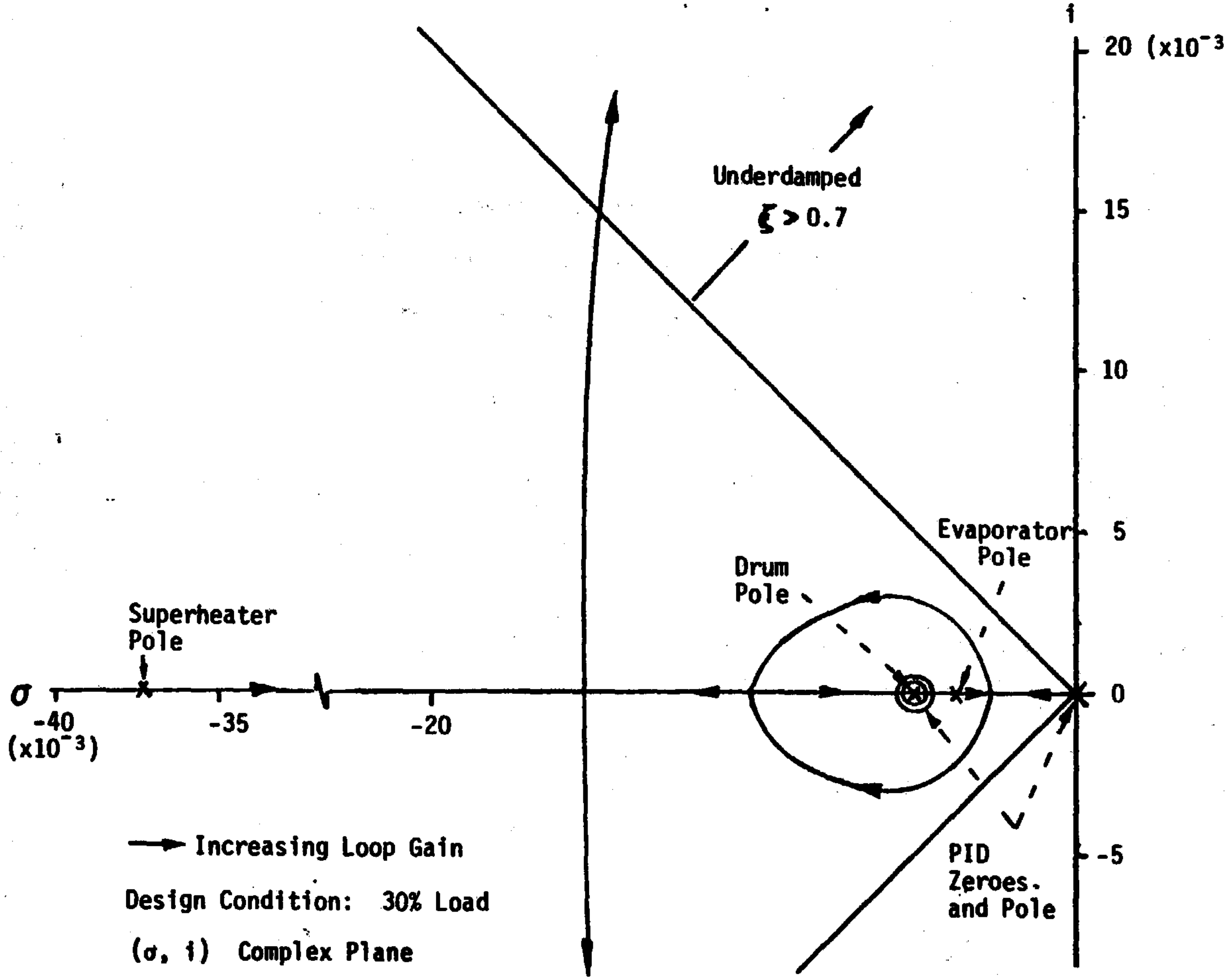
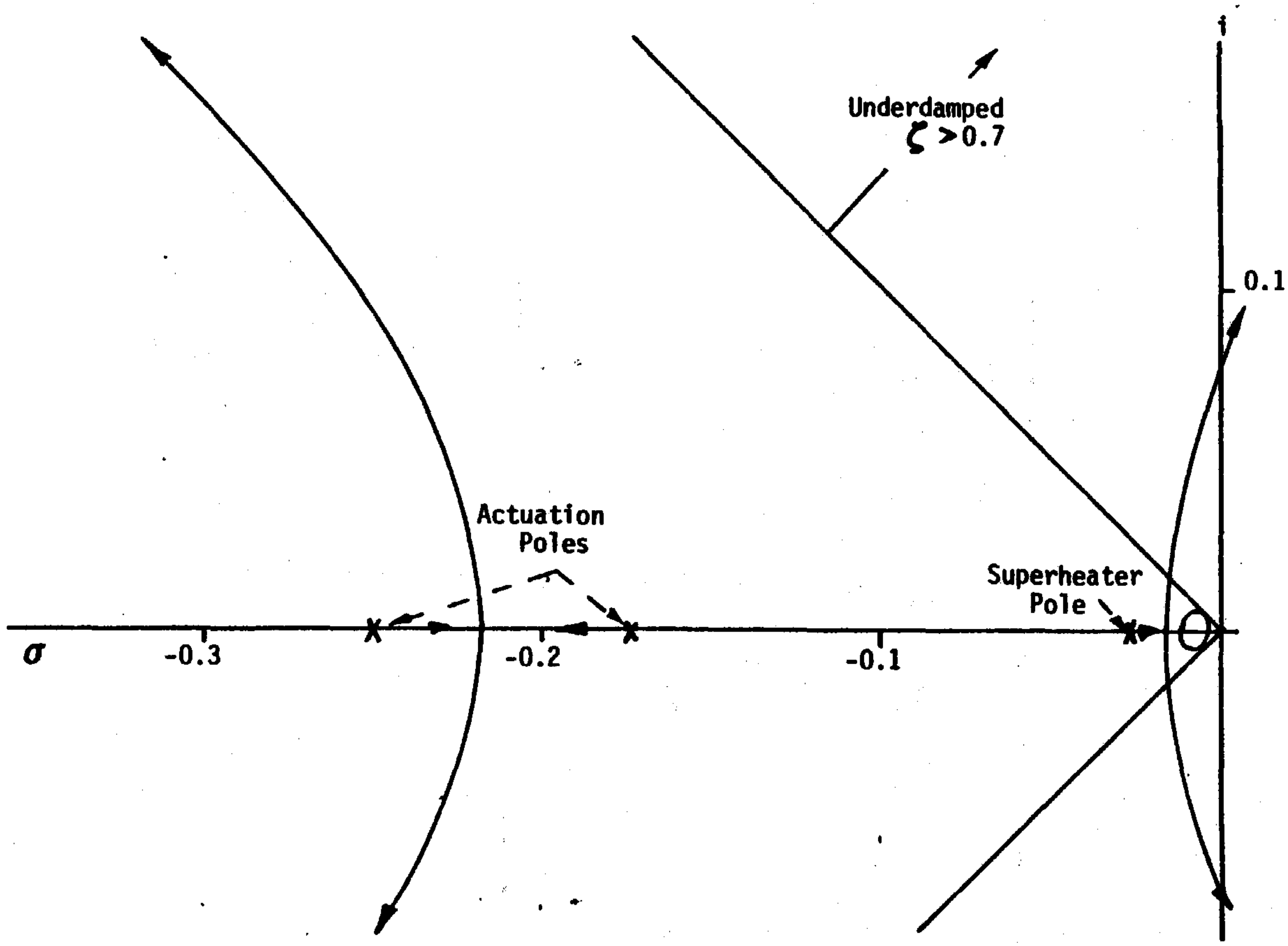


Figure 7

Superheater Root Locus: Pressure Feedback



Increasing Loop Gain

Design Condition: 30% Load

(σ, i) Complex Plane

Superheater Root Locus: Actuator Response

Figure 8

$$\dot{m}_s h_s + \dot{m}_b h_b = (\dot{m}_s + \dot{m}_b)\, h_r \qquad \text{3)}$$

$\dot{m}$ = mass flow rate

h = enthalpy

s = hot supply fluid

b = cold supply fluid

r = reference condition

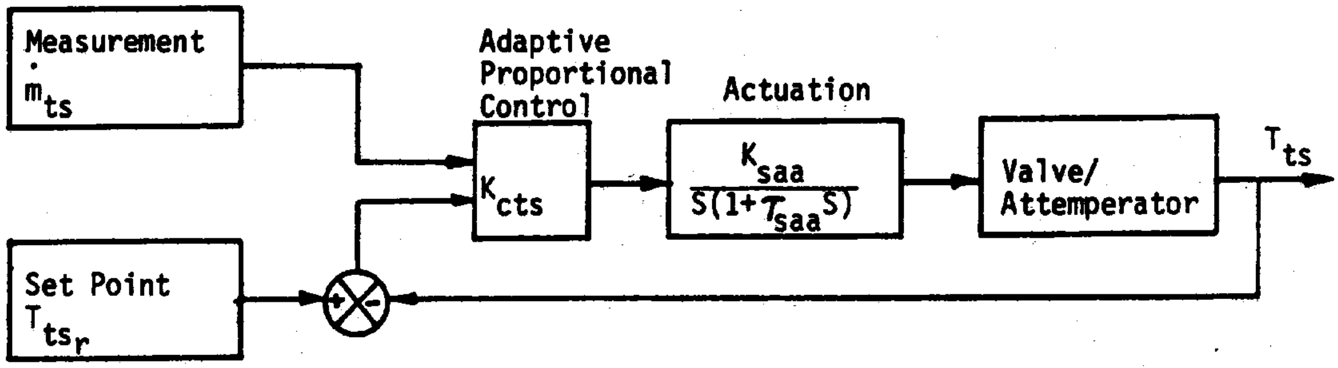
As the temperature deviation of the superheater steam is small, Equation 3 can be simplified to:

$$T_s - T_r = \left[\frac{h_r - h_b}{\dot{m}_s\, c_p}\right] \cdot \dot{m}_b \qquad \text{4)}$$

This relationship was used to define the attemperator shown in the control loop illustrated by Figure 9. This loop is a second order lag so that the proportional gain can be set simply by specifying critical damping (no overshoot). In practice, this gain will vary with the flow rate of steam from the superheater, $\dot{m}_s$ in Equation 4. Therefore, the proportional control gain is made to be adaptive, changing with load according to the relation.

$$\text{Proportional Gain X Steam Flow = Constant} \qquad \text{5)}$$

This ensures minimal variation in the response of the attemperator.



$$K_{cts} = 1.765 \ \frac{K_{tav}}{K_{1f}} \ (cm/^{o}C)$$

$$K_{tav} = \frac{\text{Valve position at 100\% rated flow}}{\text{Steam flow through valve at 100\% rating}} \left(\frac{cm}{Kg/s}\right)$$

$$K_{1f} = \frac{\text{Steam flow to turbine at 100\% load}}{\text{Measured steam flow to turbine}} \left(\frac{Kg/s}{Kg/s}\right)$$

Legend:

ts: Turbine steam

cts: Control on turbine steam

saa: Steam attemperator actuation

Turbine Steam Temperature Attemporation Figure 9

2.4 Steam Drum Fluid Level

The feedwater flow control is illustrated by Figure 10. The demanded flow rate is comprised of two terms:

i) a load-following term, namely the steam supply rate,

ii) a correction term to zero any errors in the drum level.

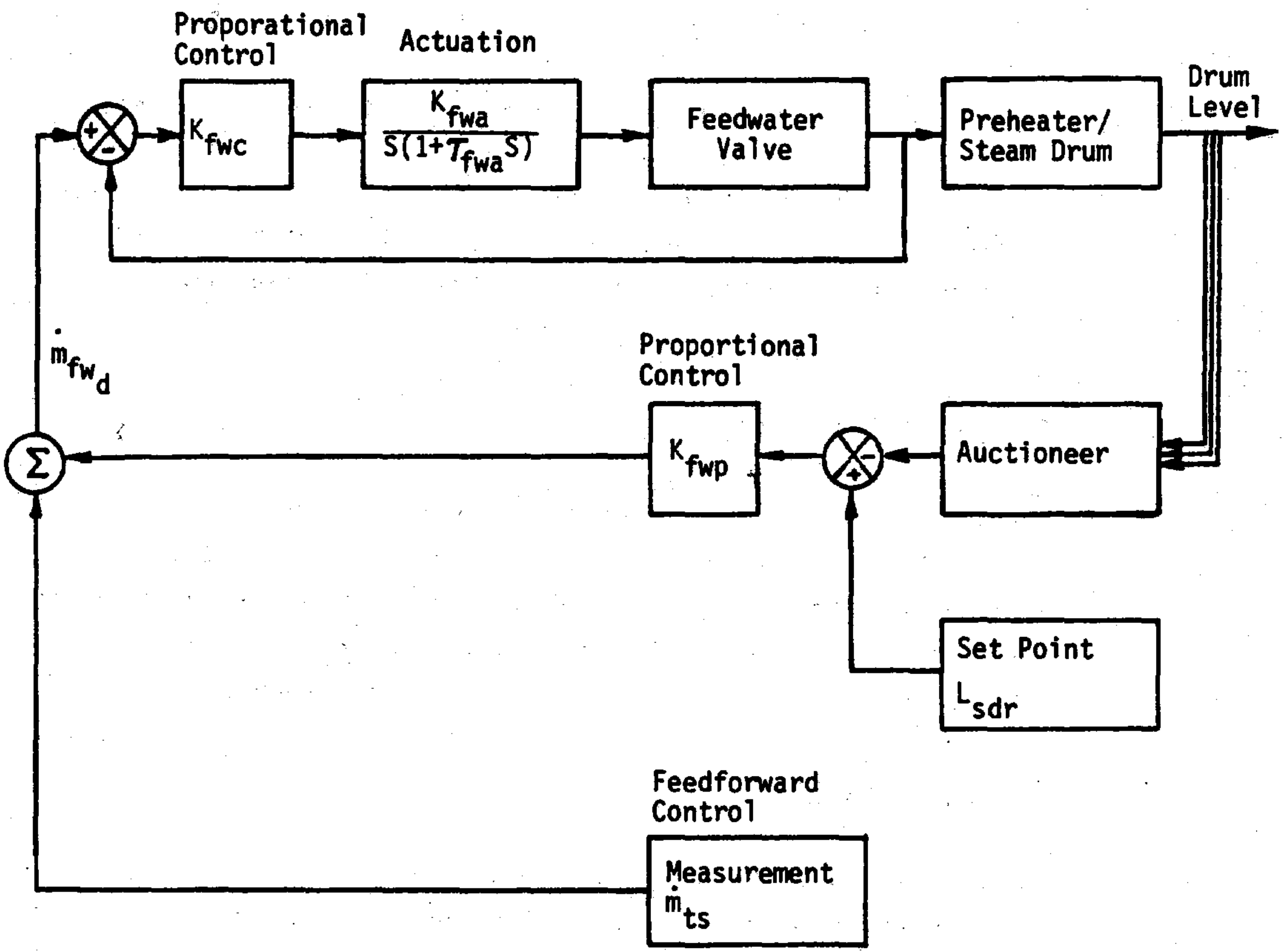
As flow rate is being used to control level, the loop contains an integrator which will cause instability if the loop gain is too high. The gain shown in Figure 10 was set using a 45^{o} phase margin to ensure stability.

2.5 Evaporator Salt Attemperation

Attemperation has already been described in Paragraph 2.2. In this case, cold salt is mixed with hot salt from the reheater and superheater. An adaptive gain is again employed so as to avoid large variations in response as the plant load maneuvers. As before, the damping was set such that there would be no overshoot.

2.6 Feedwater Temperature Control

The temperature of the water to the preheater is controlled by bleeding hot water from the steam drum into the feedwater supply. Figure 12 illustrates a schematic of the control loop. The principle is again identical to steam attemperation.

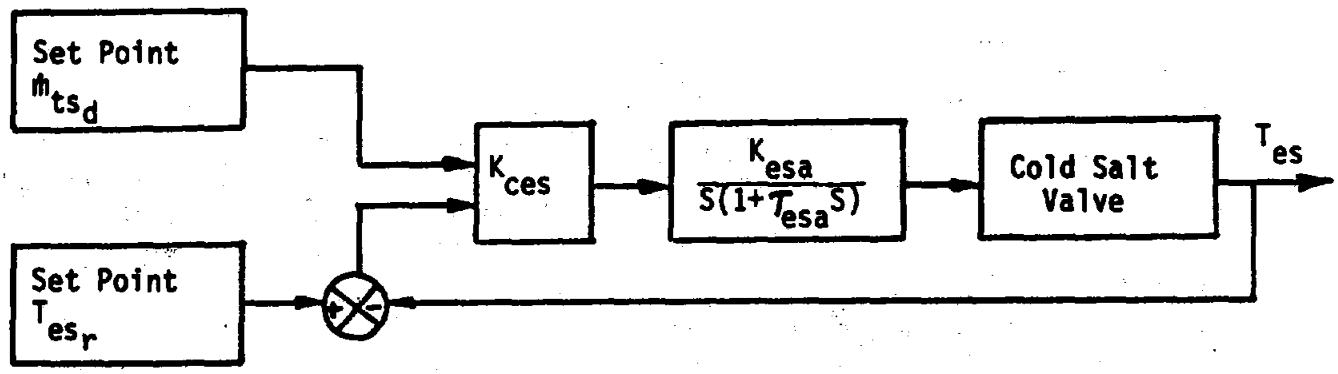


Legend:

- fw: Feedwater
- fwc: Feedwater control
- fwa: Feedwater Actuation
- fwp: Feedwater proportional constant
- sdr: Steam down reference
- ts: Turbine steam

Feedwater Flow Control — Figure 10

F24



$$K_{ces} = -16.5\,\frac{K_{eav}}{K_{1f}} \quad (cm/^{o}C)$$

$$K_{eav} = \frac{\text{Value Position at 100\% Rated Flow}}{\text{Salt Flow Through Valve at 100\% Rating}} \quad \left(\frac{cm}{Kg/s}\right)$$

$$K_{1f} = \frac{\text{Steam Flow to Turbine at 100\% Load}}{\text{Steam Flow Set Point}} \quad \left(\frac{Kg/s}{Kg/s}\right)$$

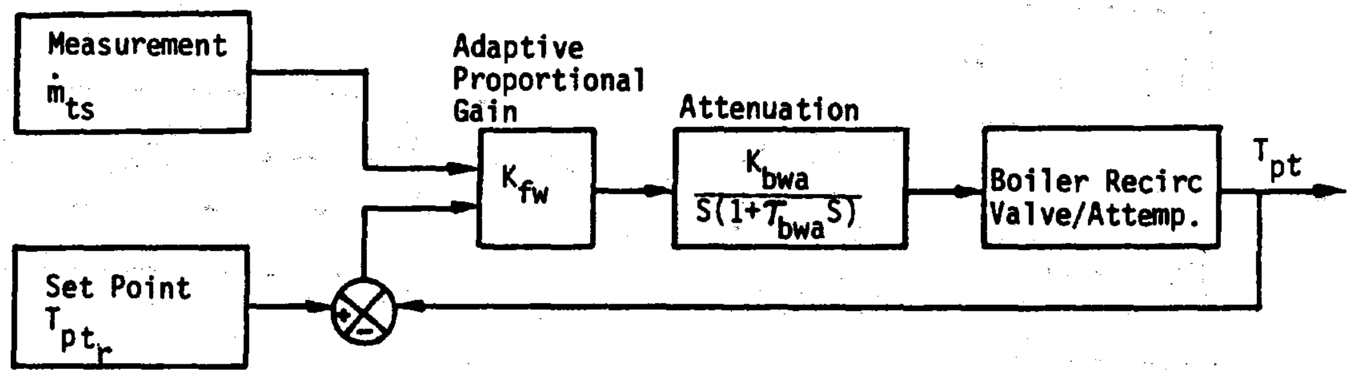
Legend:

ts_d: Turbine steam set point

ces: Control on evaporator attemperation salt

esa: Evaporator salt attemperator

Evaporator Salt Temperature Attemperator — Figure 11



$$K_{fw} = 2.5 \frac{K_{bwv}}{K_{1f}} \; (cm/^{o}C)$$

$$K_{bwv} = \frac{\text{Value Position at 100\% Rated Flow}}{\text{Feedwater Flow at 100\% Rating}} \; \left(\frac{cm}{Kg/s}\right)$$

$$K_{1f} = \frac{\text{Steam Flow to Turbine at 100\% Load}}{\text{Measured Steam Flow to Turbine}} \; \left(\frac{Kg/s}{Kg/s}\right)$$

Legend:

ts: Turbine steam

pt_r: Preheater temperature reference

fw: Feedwater

bwa: Bleed water actuation

Preheater - Water Temperature Control Figure 12

3. SYSTEM SIMULATION

This section of the report presents the results obtained using the Babcock and Wilcox digital code simulation of the plant. The aim of this work was to tune the control gains and verify the ability of the control system to manuever the steam generator subsystem. As will be seen, each of these objectives was satisfied.

3.1 Tuning the Throttle Pressure Loop

To tune this loop, the following techniques was used:

i) run the reheater temperature control loop using the load following term only (the temperature feedback path being broken),

ii) set all other loop gains according to the results obtained from the initial classical control analysis,

iii) close the pressure feedback path using a proportional control only,

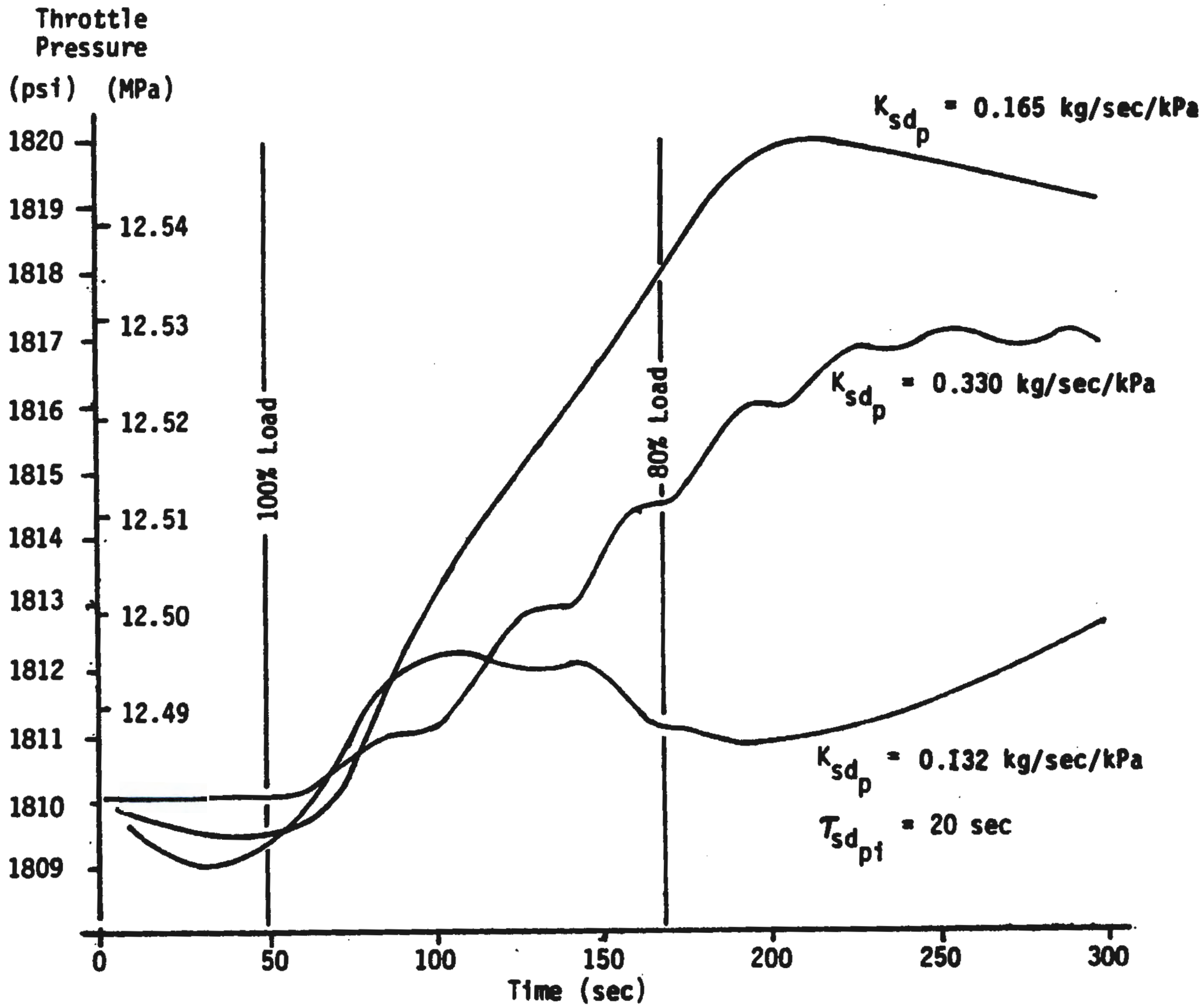
iv) increase this proportional gain until the loop begins to oscilate,

v) set Zeigler-Nichols recommended gains.

To assess stability, the plant was run at 100% load for 50 secs and then swung to 80% at 10%/minute, The reaction curve is shown in Figure 13 for proportional gains of 0.165 and 0.330 kg/sec/kPa, any gain above 0.33 kg/sec kPa was found to be unstable.

Figure 13 also shows the response using the Zeigler-Nichols recommended PI control:

$$G_c = 0.132\left(1 + \frac{1}{20s}\right)\text{kg/sec/kPa} \qquad 6)$$



<u>Tuning Pressure Loop</u> <u>Figure 13</u>

Figure 13 shows the response to be stable with the throttle pressure converging on 12.51 MPa.

It can be concluded from these results that the pressure loop responds faster than originally thought. Consequently the PI algorithm is quite acceptable, the additional derivative term (D) not being necessary.

3.2 Tuning the Reheater Temperature Loop

With the throttle pressure loop closed by the PI control, the reheater temperature loop was similarly treated. This loop was also closed using the PI control:

$$G_c = 4.1 \left(1 + \frac{1}{16s}\right) \text{kg/sec/}^{\circ}\text{C} \qquad \text{——— 7)}$$

The plant was then manuevered from 100% to 80%, 60% and 30% to test the controls. Figures 14 and 15 show the pressure and salt flow histories for the 100-30% case. The variation in pressure and temperature during this swing was:

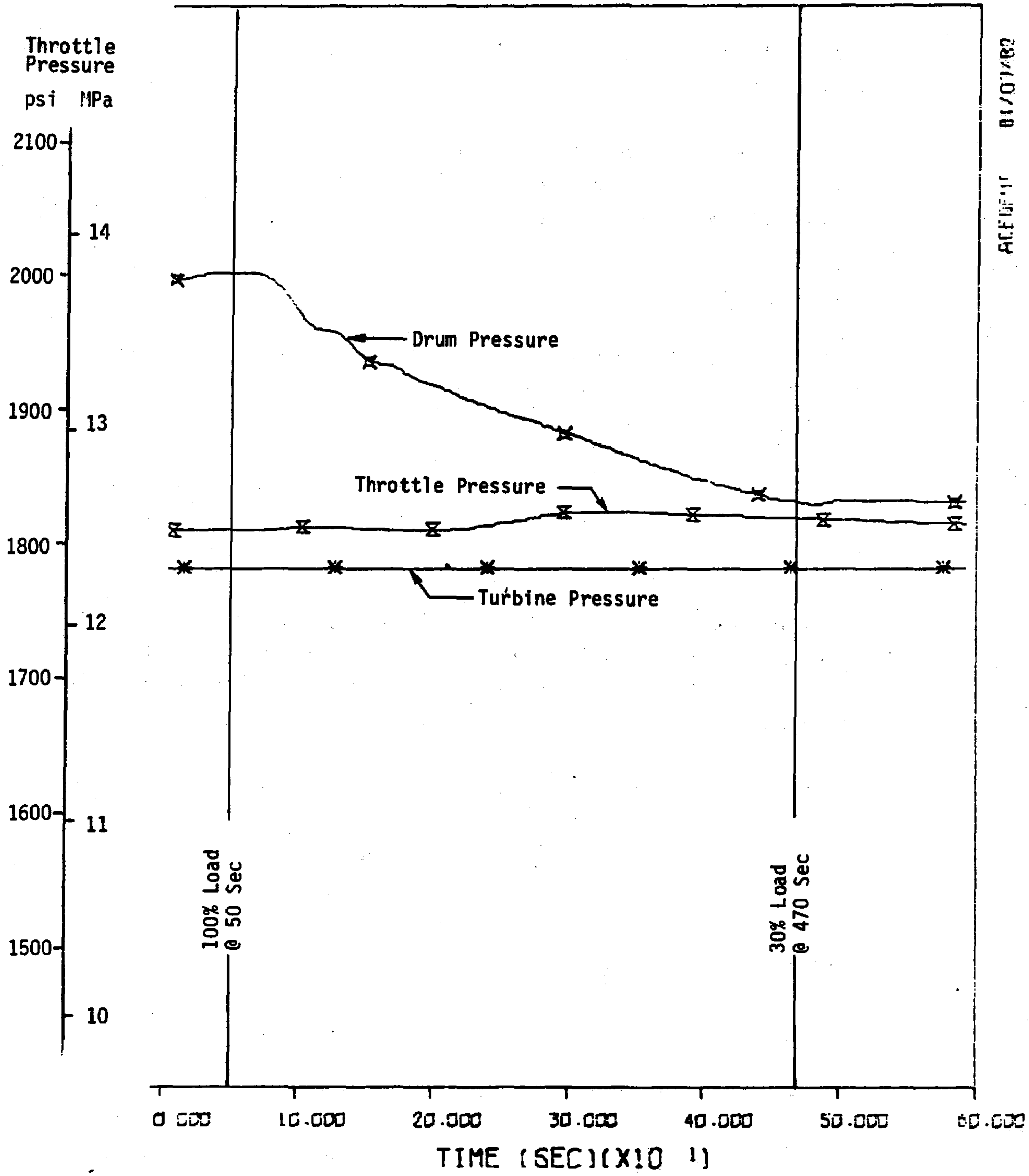
i) 12.45 - 12.58 MPa throttle pressure,

ii) 538 $\pm$ 0.5°C reheater steam exit temperature.

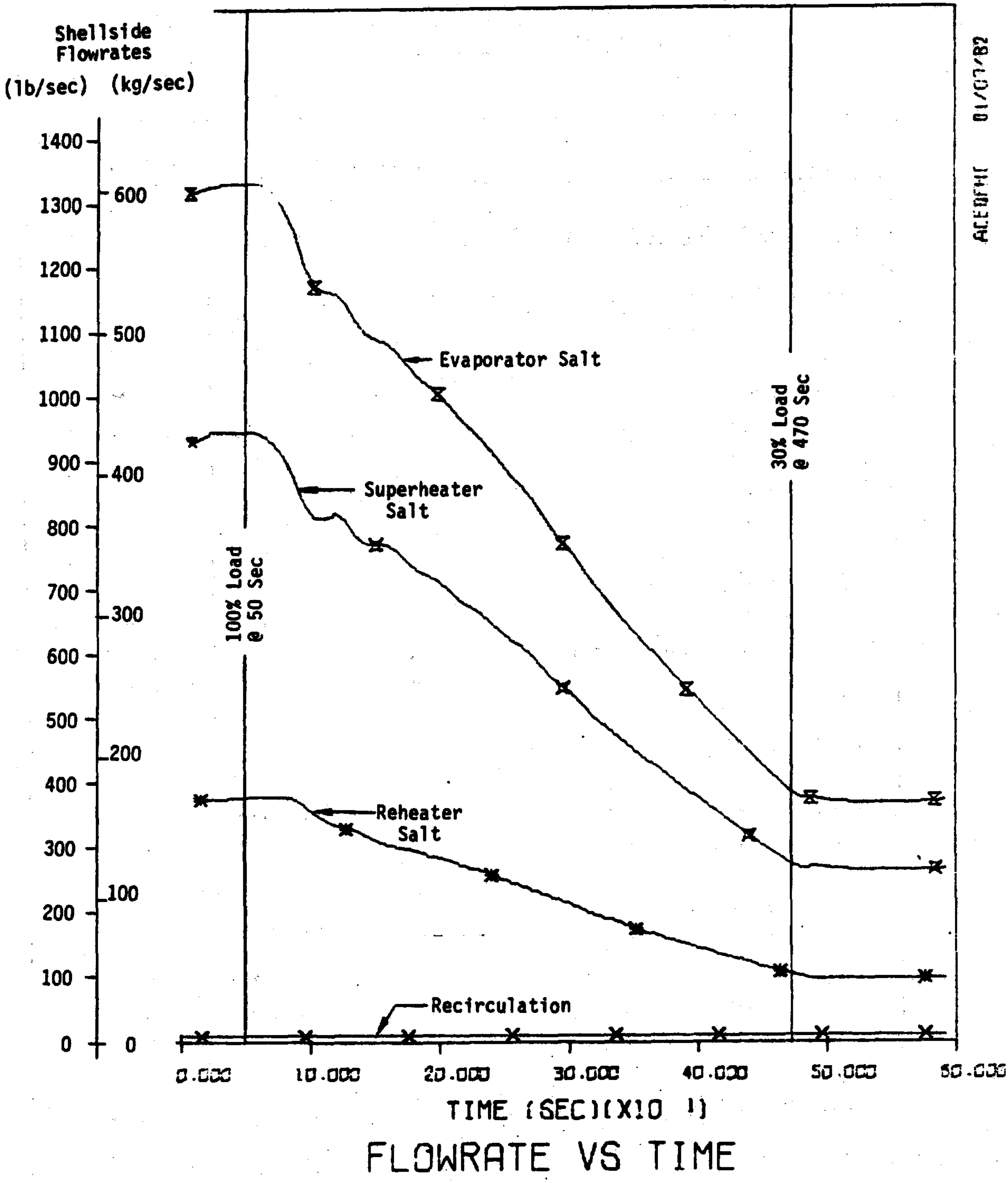
As can be seen, the steam generator subsystem is stable and controllable.

3.3 Performance Appraisal

Before appraising the steam generator subsystem performance, one further refinement was made to the control schemes. It was found from the load swings performed in Paragraph 3.2 that the superheater and reheater thermal balance relationships were non-linear. Hence, the salt-steam flow ratio was made a ratio of load. This function is listed in Table 2 along with all the gains and time constants used to represent the control system and actuation.



100 - 30% LOAD SWING TEST **FIGURE 14**



100 - 30% LOAD SWING TEST

FIGURE 15

CONTROL/ACTUATION GAINS AND SET POINTS TABLE 2

CONTROL LOOP	NOTATION	VALUE	UNITS
REHEATER SALT-LINE VALVE, Figure 3:			
Actuation: velocity constant	k_{ar}	0.10	sec^{-1}
time constant	τ_{ar}	2.50	sec
Thermal Balance:			
Load 100%	k_{tbr}	2.05	-
Load = 80%	k_{tbr}	2.00	-
Load = 60%	k_{tbr}	1.90	-
Load 30%	k_{tbr}	1.80	-
Temperature PI Control			
Set Point	T_{trr}	538	^{o}C
Proportional Gain	k_{rtc}	4.1	$kg/s/^{o}C$
Reset	τ_{rtci}	16.00	sec
SUPERHEATER SALT-LINE VALVE, Figure 5:			
Actuation: velocity constant	k_{as}	0.10	sec^{-1}
time constant	τ_{as}	2.50	sec
Thermal Balance:			
Load 100%	k_{tbs}	4.44	-
Load = 80%	k_{tbs}	4.40	-
Load = 60%	k_{tbs}	4.30	-
Load 30%	k_{tbs}	4.20	-

CONTROL LOOP	NOTATION	VALUE	UNITS
Throttle PI Control			
Set Point	P_{tsr}	12.51	MPa
Proportional Gain	k_{tse}	0.132	kg/sec/kPa
Reset	τ_{tsci}	20.00	sec
TURBINE STEAM ATTEMPERATOR, Figure 9:			
Actuation: velocity constant	k_{sas}	0.04	sec^{-1}
time constant	τ_{saa}	6.25	sec
Adaptive Gain:	k_{cts}	Figure 9	$cm/^{o}C$
Set Point:	T_{tsr}	538	^{o}C
FEEDWATER FLOW CONTROL, Figure 10:			
Actuation: velocity constant	k_{fwa}	0.04	sec^{-1}
time constant	τ_{fwa}	6.25	sec
Feedforward: turbine steam flow	$\dot{m}_{ts}$	Track	kg/sec
Feedback:			
drum level set point	L_{sdr}	0.67	m
proportion gain	K_{fwp}	1.11	kg/sec/cm

CONTROL/ACUTATION GAINS AND SET POINTS TABLE 2 (Cont.)

CONTROL LOOP	NOTATION	VALUE	UNITS
EVAPORATOR SALT ATTEMPERATOR, Figure 11			
Actuation: velocity constant	k_{esa}	0.04	sec^{-1}
time constant	τ_{esa}	6.25	sec
Adaptive Gain:	k_{ces}	Figure 11	cm/°C
Set Point:	T_{esr}	TBD	°C
PREHEATER FEEDWATER ATTEMPERATOR, Figure 12			
Actuation: velocity constant	k_{bwa}	0.04	sec^{-1}
time constant	τ_{bwa}	6.25	sec
Adaptive Gain:	k_{fw}	Figure 12	cm/°C
Set Point:	T_{pts}	238	°C

3.3.1 100-80-100% Load Swing

The results from this run can be found in Figures 16-21. The salient features of this run are:

i) Figure 16, the drum pressure changes due to the drop in steam pressure between the drum and the throttle valve.

ii) Figure 17, as the load swings, the temperature of the feedwater temporarily drops below 238°C. The resulting error then activates the boiler by-pass valve of the feedwater attemperator control.

iii) Figure 17, the load swing also causes a change in the temperature of the steam to the reheater. As can be seen, the reheater control maintains 538°C.

iv) Figure 18, the flow through the recirculation pumps increases to supply boiler water to the feedwater attemperator.

v) Figures 18 and 19, the feedwater supply does not follow the load during the 100-80% down swing due to the model not being exactly initialized.

vi) Figure 19 shows the drum level was controlled to within ± 5cm of the set point.

vii) Figure 20, during the 80-100% load swing the salt-flow through the superheater exceeds 100% nominal in order to pressurize the drum, ref. Figure 16.

viii) Figure 21, none of the valves hit limits.

3.3.2 100-60-100% Load Swing, Figures 22-27

These runs give results similar to those of the previous case.

3.3.3 100-30-100% Load Swing, Figures 28-33

This was the worst case considered and resulted in the largest transient errors:

i) Figure 28 shows the variation in steam pressure. The required 12.51 MPa throttle pressure was held to within $\pm$ 68.9 kPa, i.e., $\pm$ 1/2%.

ii) Figure 29, the feedwater attemperator worked such that the preheater water inlet temperature never fell below 453^{o}F.

iii) Figure 29, the reheater control was accurate to $\pm$ 0.5^{o}C ($\pm$ 0.1%), and the steam attemperator control $\pm$ 1^{o}C ($\pm$ 0.2%).

iv) Figure 32 shows the drum level to be held within $\pm$ 5cm.

v) Figure 33, the steam attemperator valve is approaching its limit. During the short period it was on limits, there was no appreciable degradation of turbine steam temperature.

A detailed comparison of these errors is made in Table 3, which shows the range predicted by the model and the allowable range during load swings. As can be seen, the predicted results fall well within the specifications.

3.4 Response to Trips

Although the computer code was unable to simulate plant trips, it can be appreciated that the control scheme will act to protect the steam generator subsystem during a trip. This action is due to the load following terms of the control algorithms.

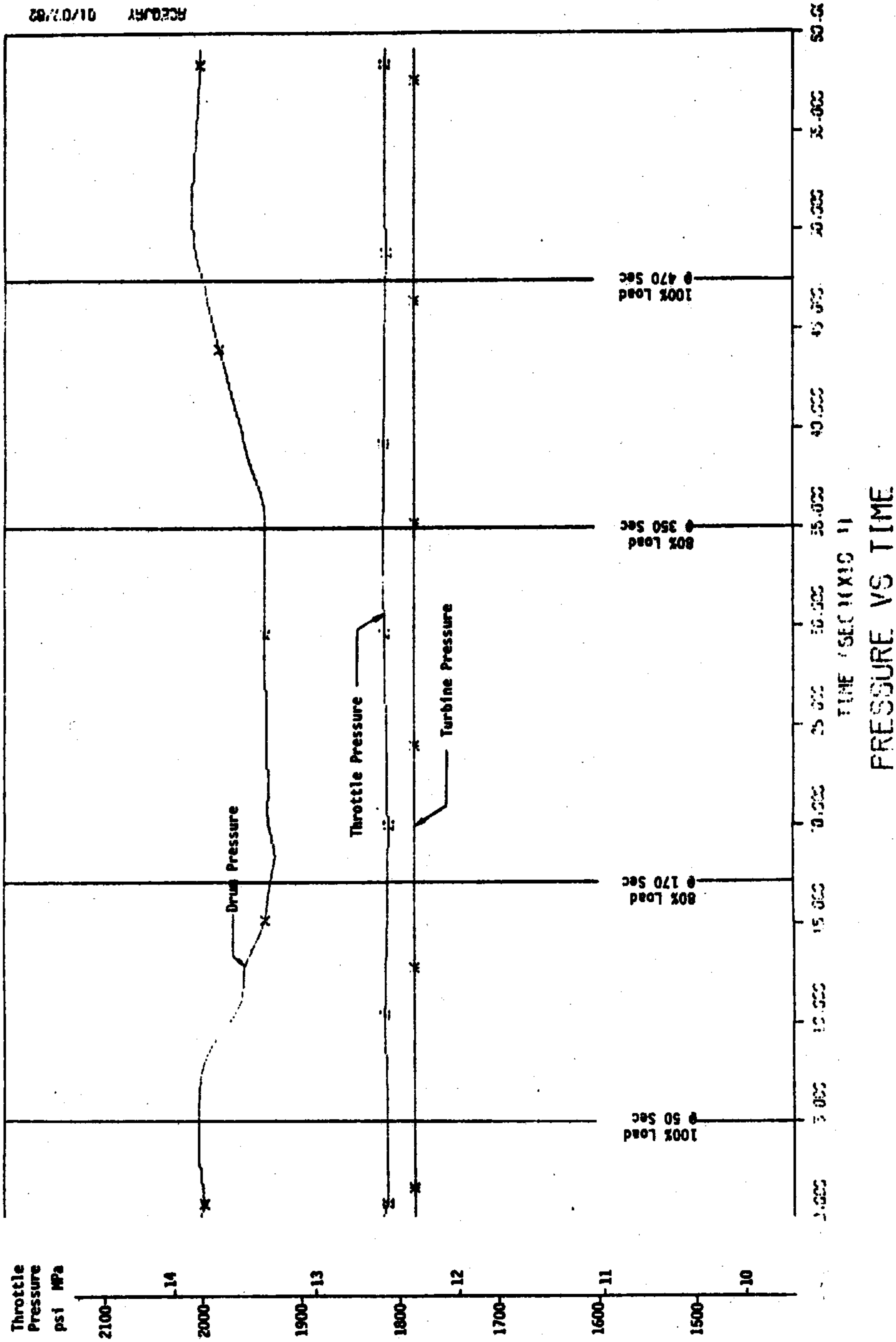
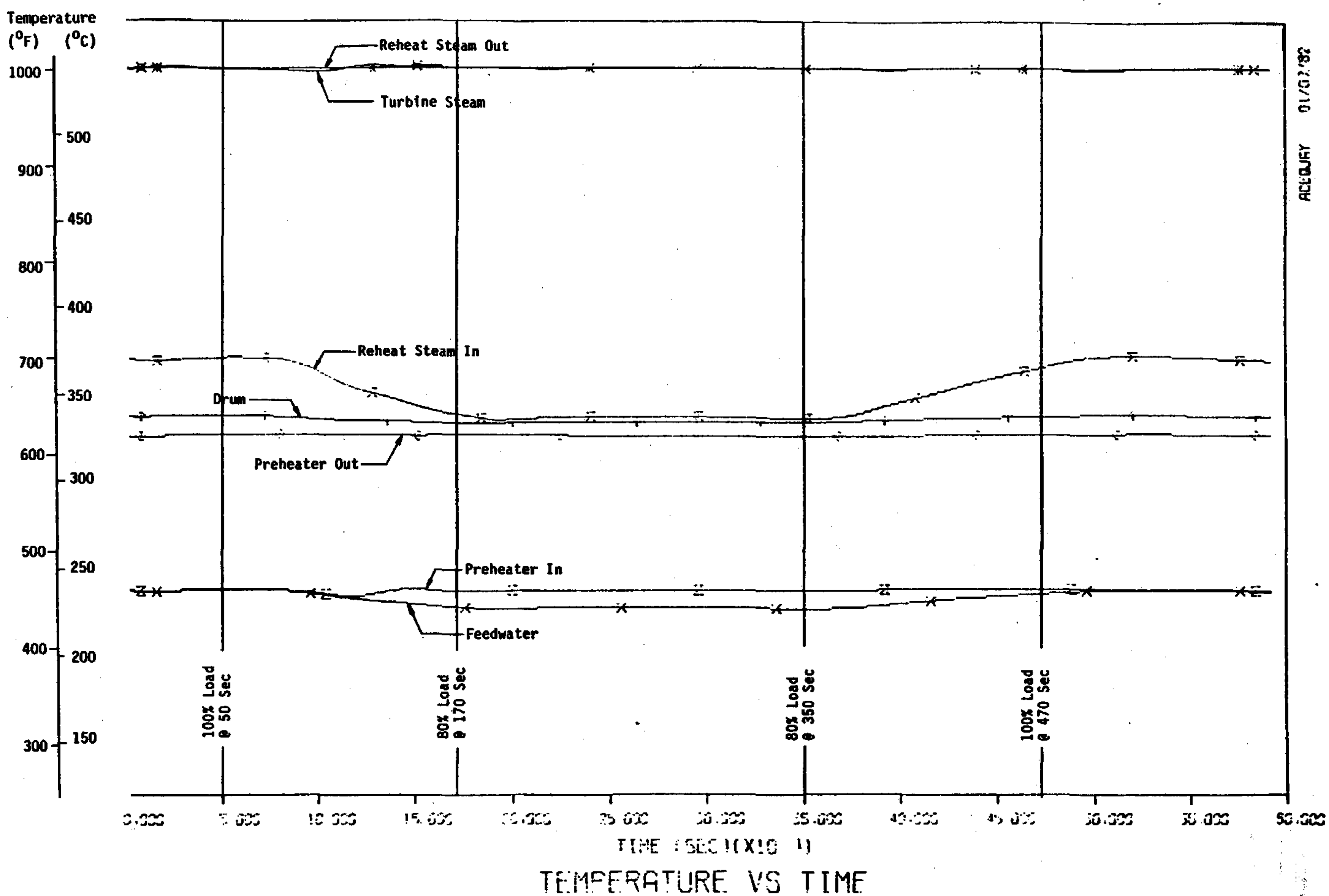
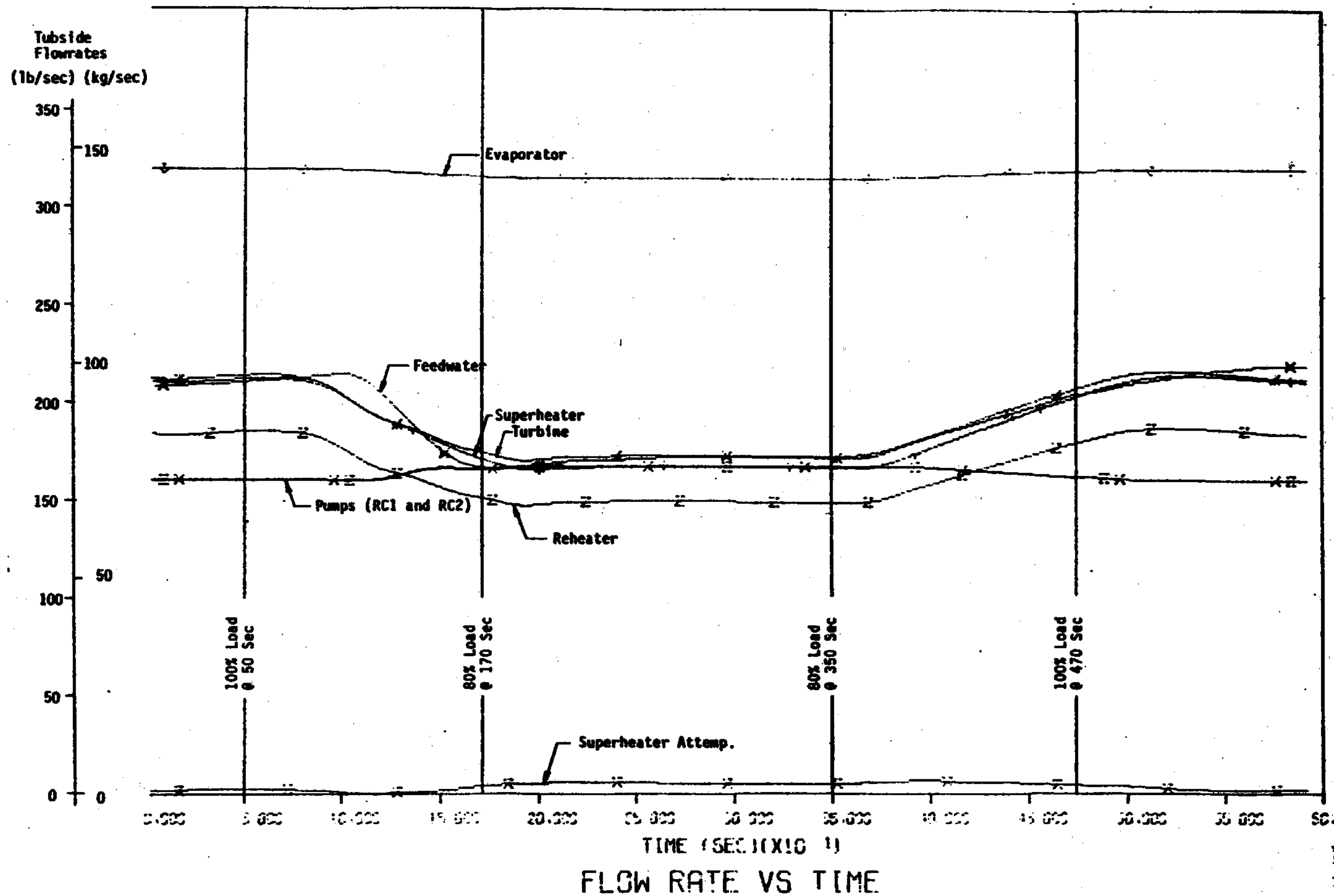


FIGURE 16

100 - 80 - 100% LOAD SWING

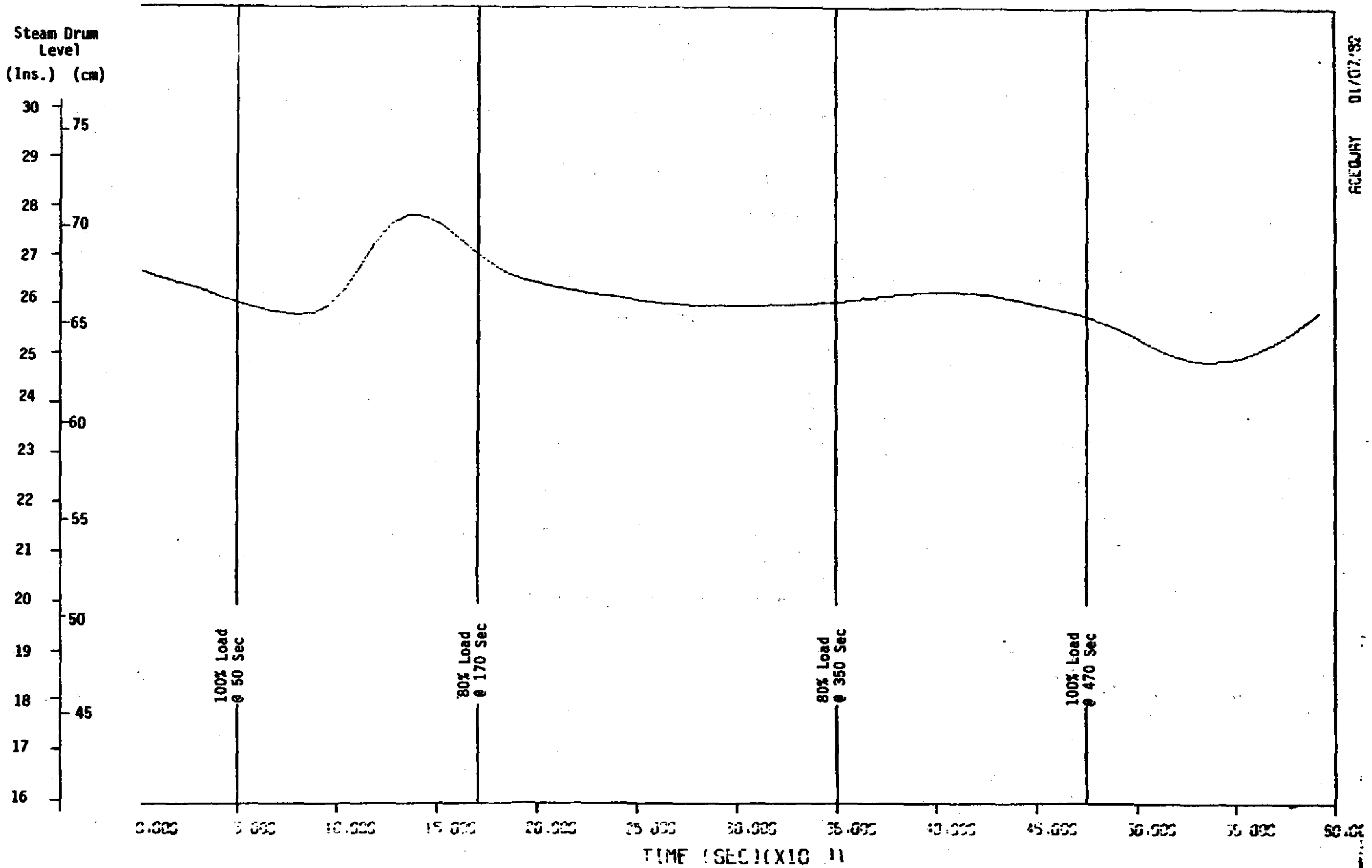


100 - 80 - 100% LOAD SWING **FIGURE 17**



100 - 80 - 100% LOAD SWING

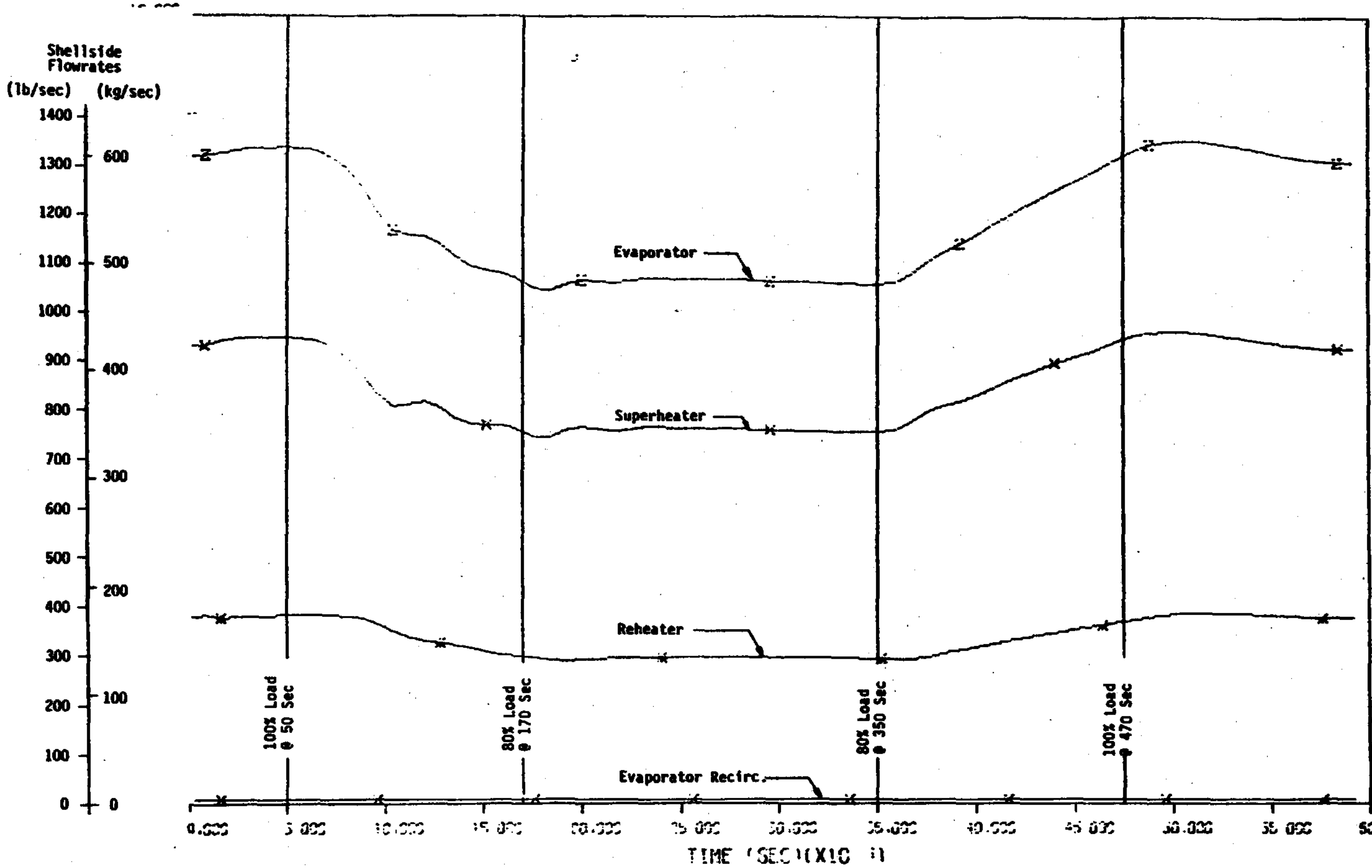
FIGURE 18



STEAM DRUM LEVEL VS TIME

100 - 80 - 100% LOAD SWING

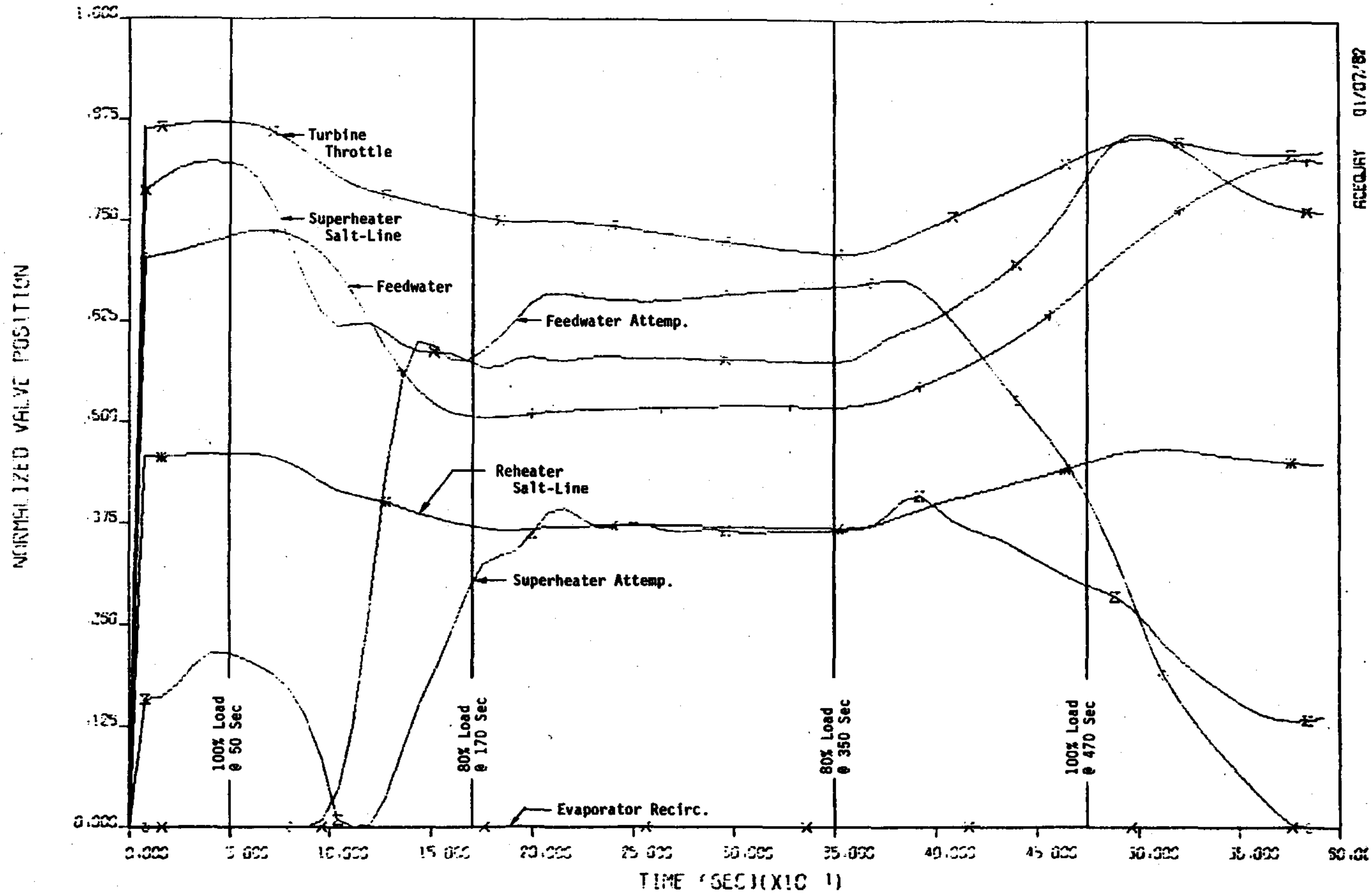
FIGURE 19



FLOWRATE VS TIME

100 - 80 - 100% LOAD SWING

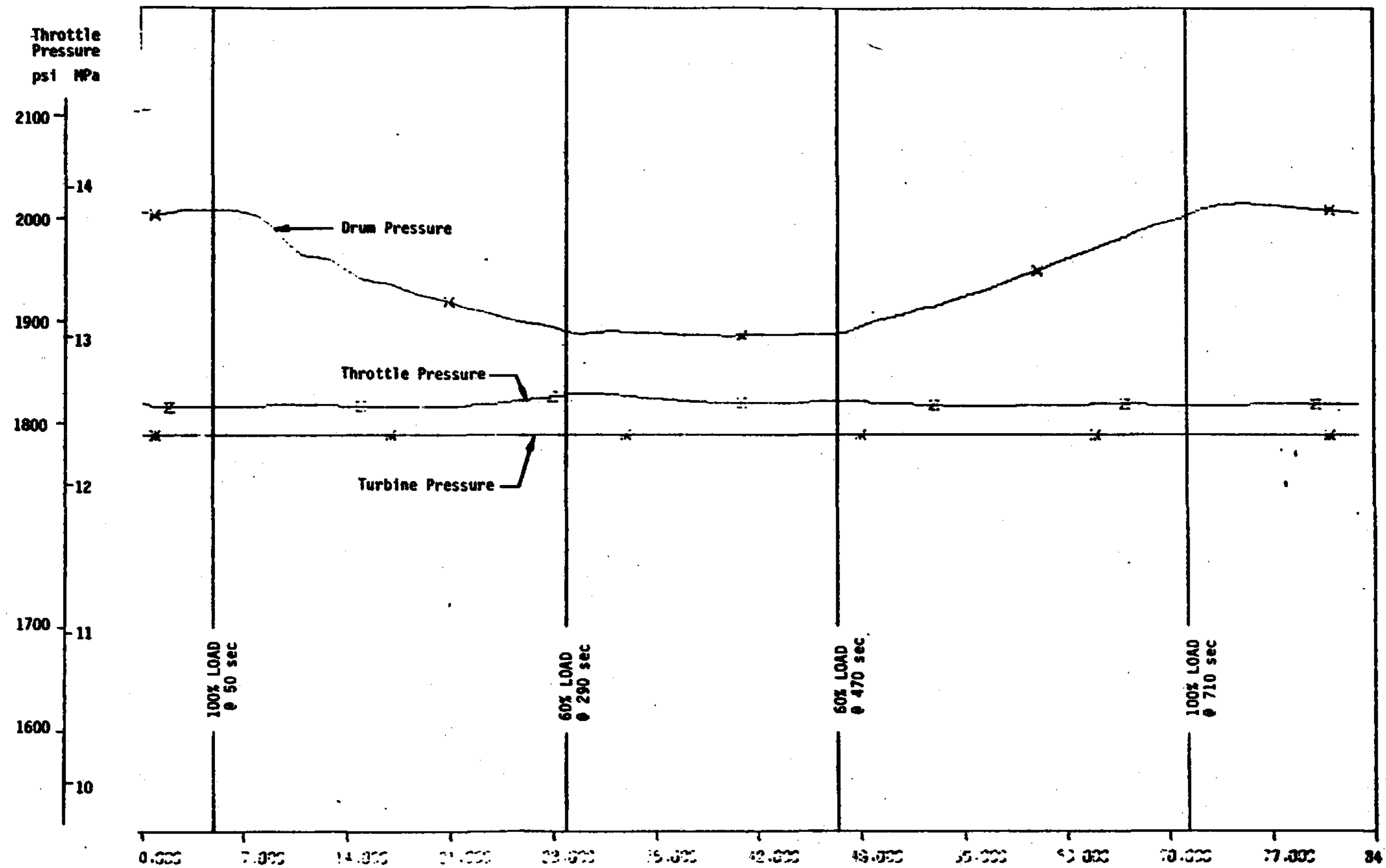
FIGURE 20



NORMALIZED VALVE POSITION VS TIME

100 - 80 - 100% LOAD SWING

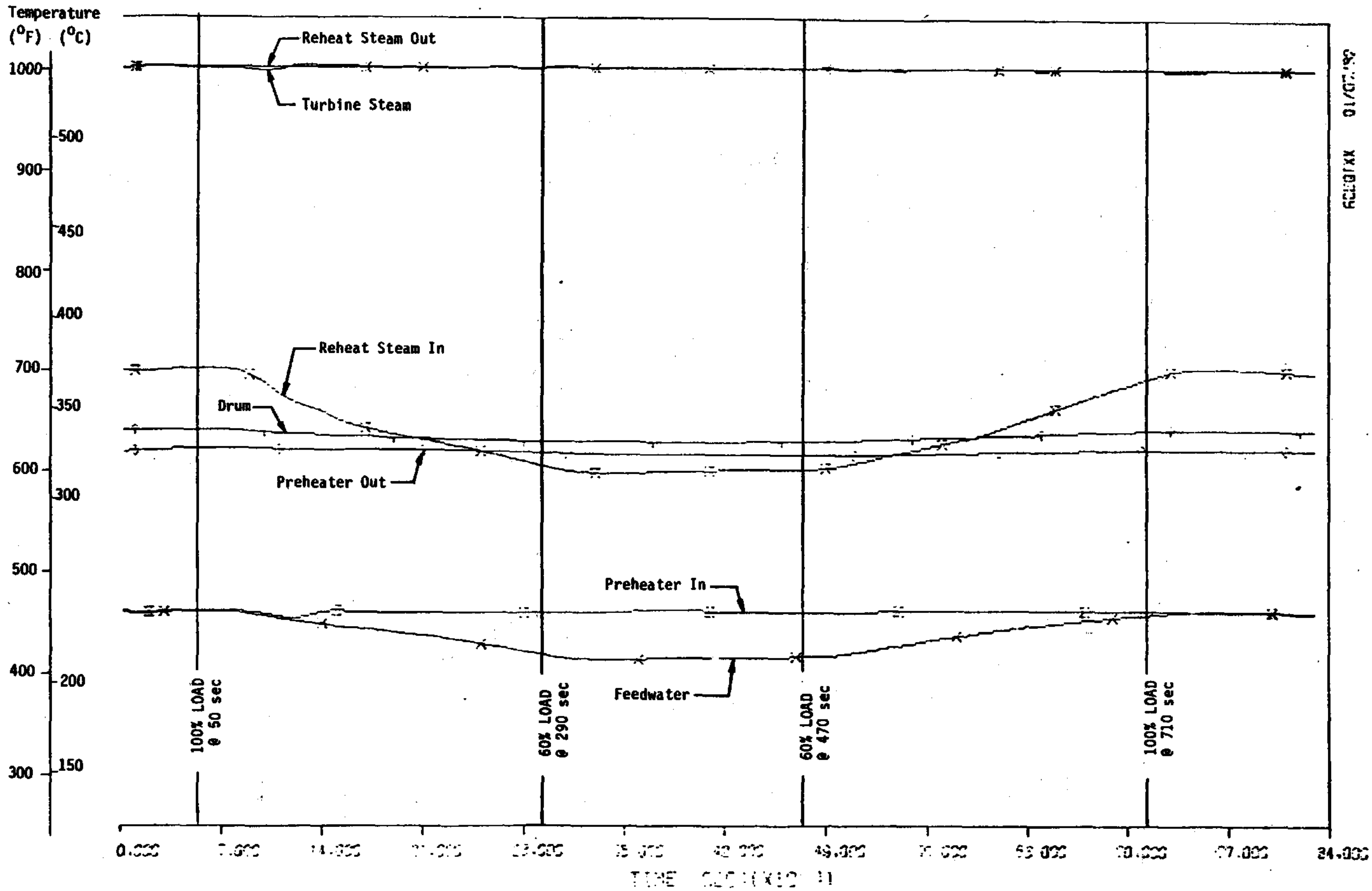
FIGURE 21



PRESSURE VS TIME

100-60-100% LOAD SWING

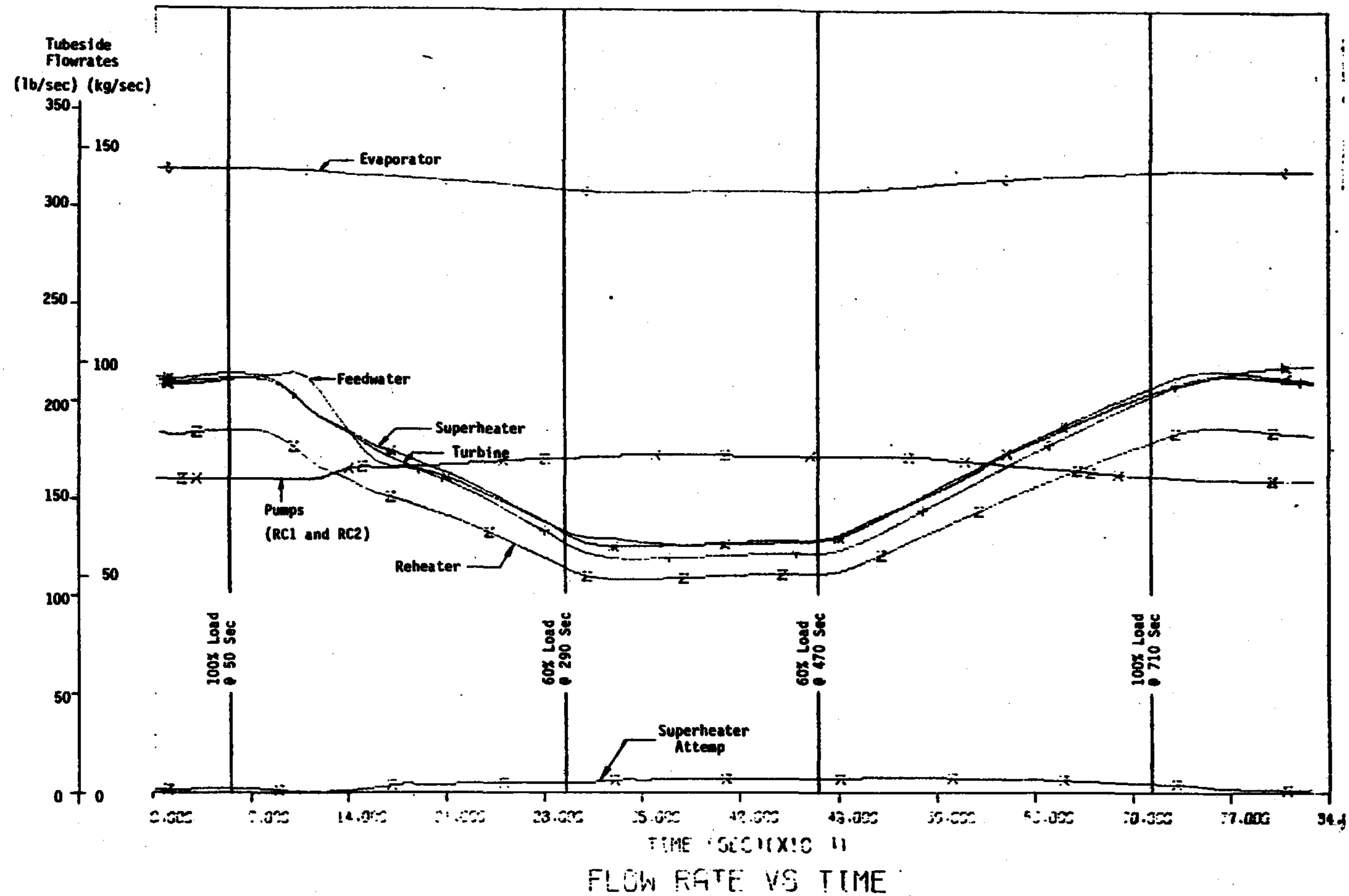
FIGURE 22



TEMPERATURE VS TIME

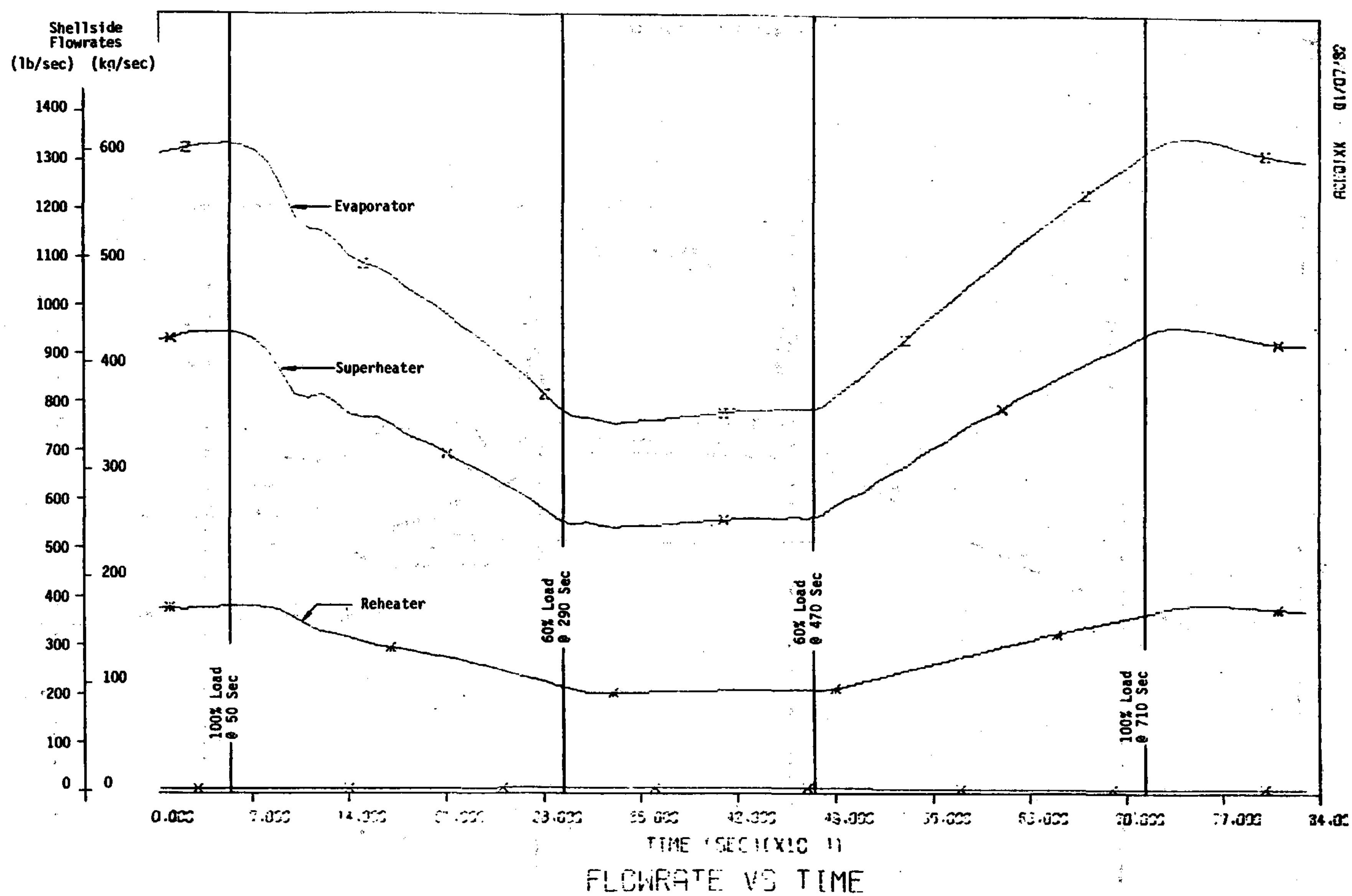
100-60-100% LOAD SWING

FIGURE 23



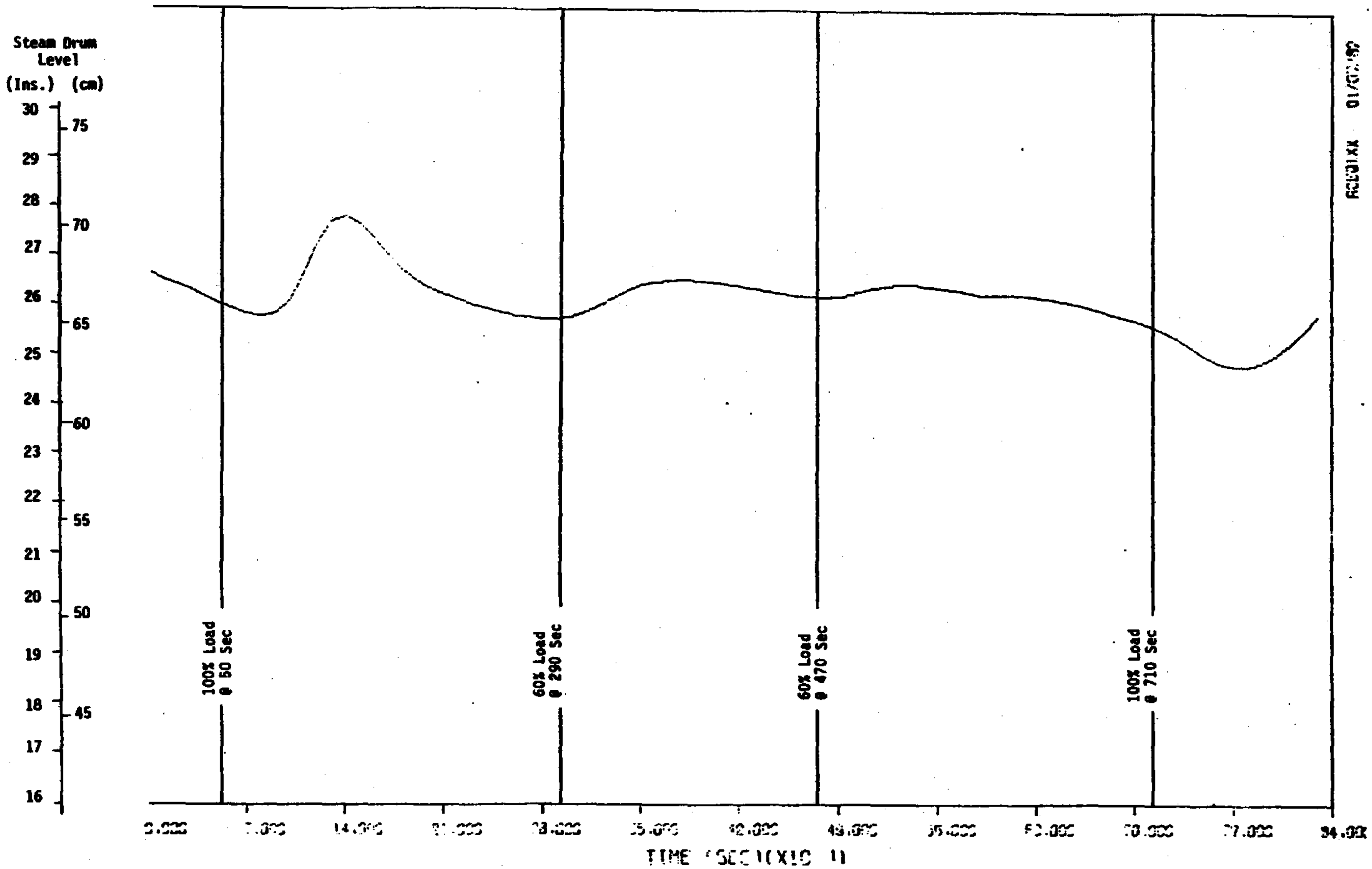
100 - 60 - 100% LOAD SWING

Figure 24



100 - 60 - 100% LOAD SWING

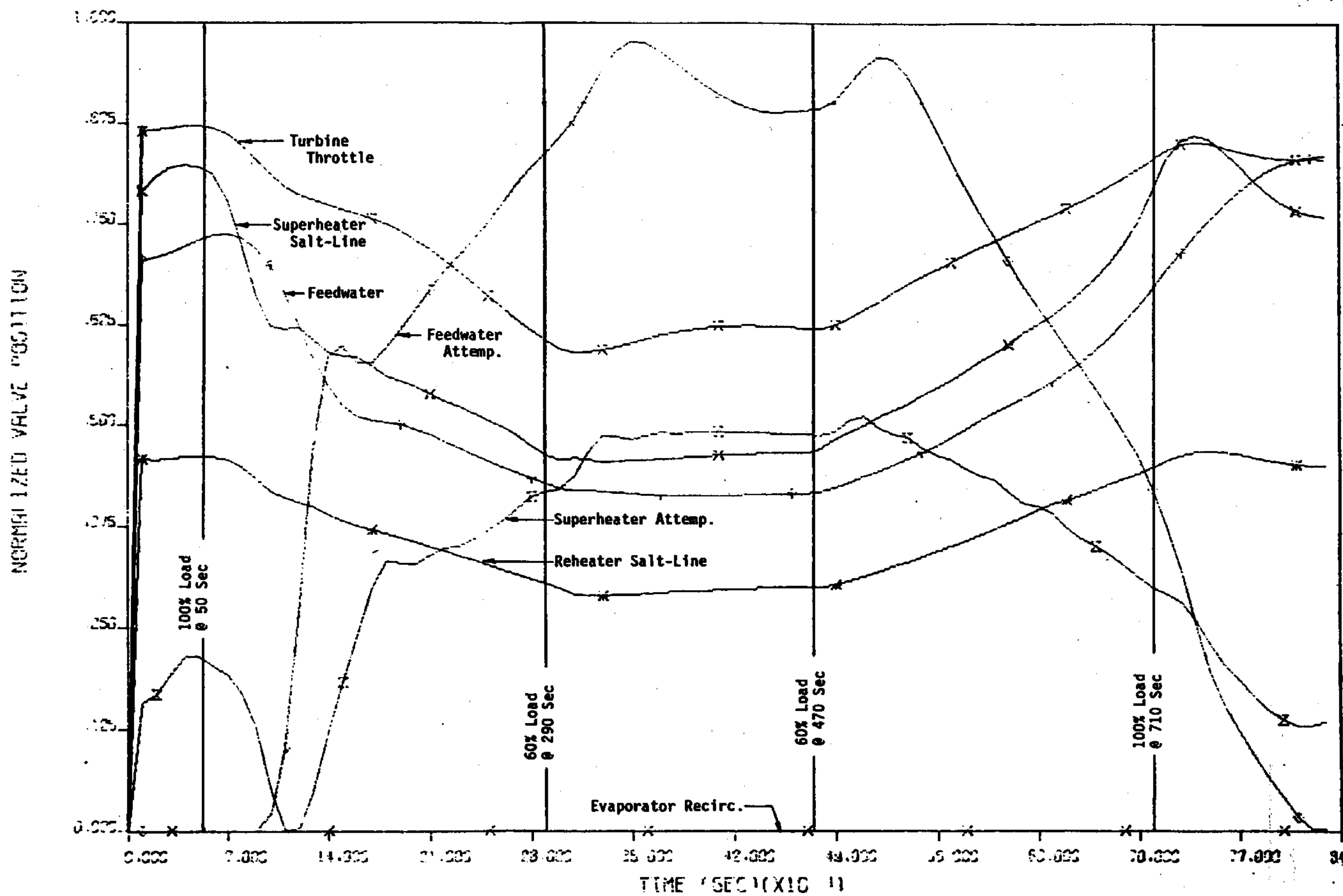
Figure 25



STEAM DRUM LEVEL VS TIME

100 - 60 - 100% LOAD SWING

Figure 26

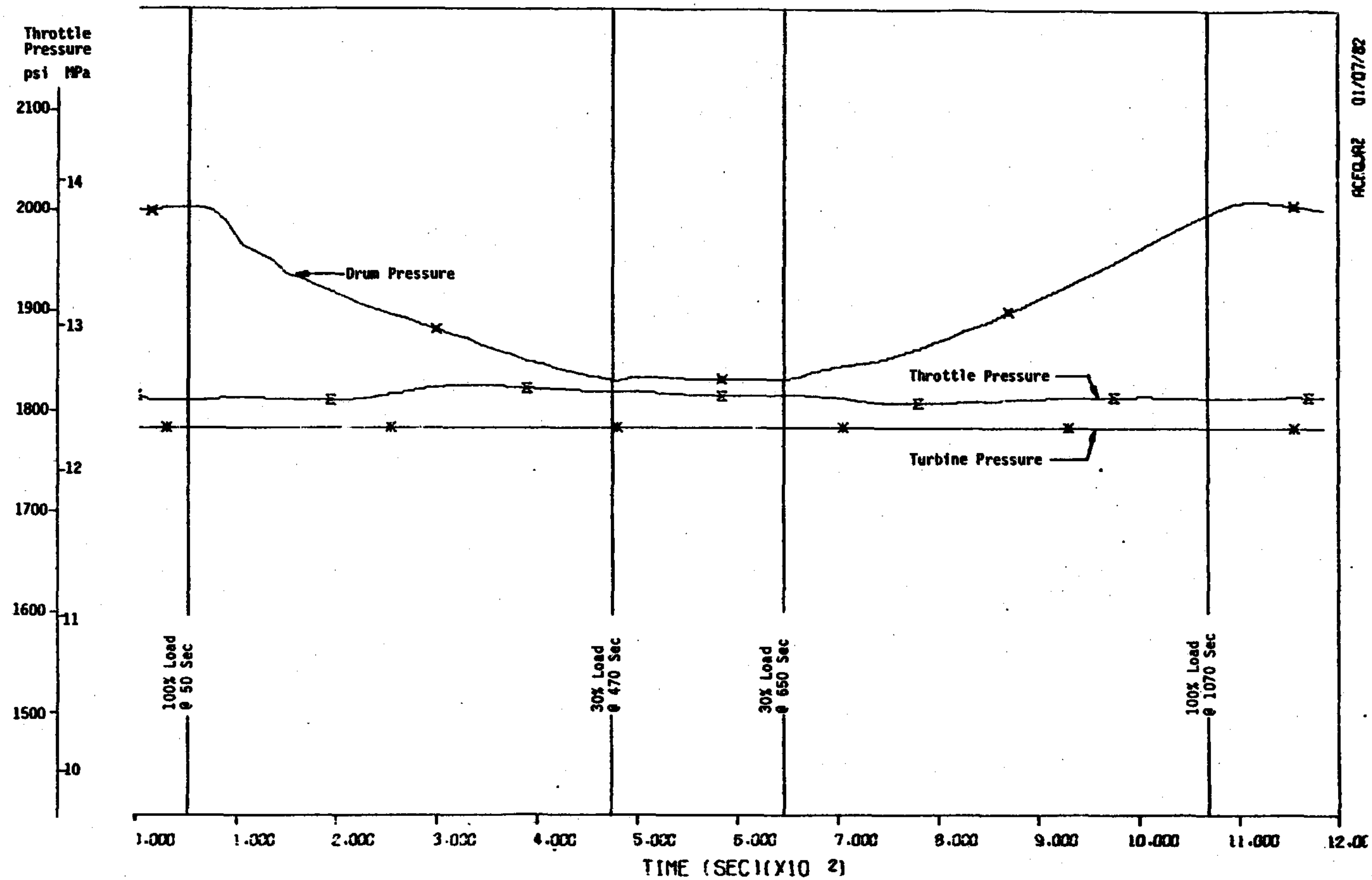


NORMALIZED VALVE POSITION VS TIME

<u>100 - 60 - 100% LOAD SWING</u>

Figure 27

7



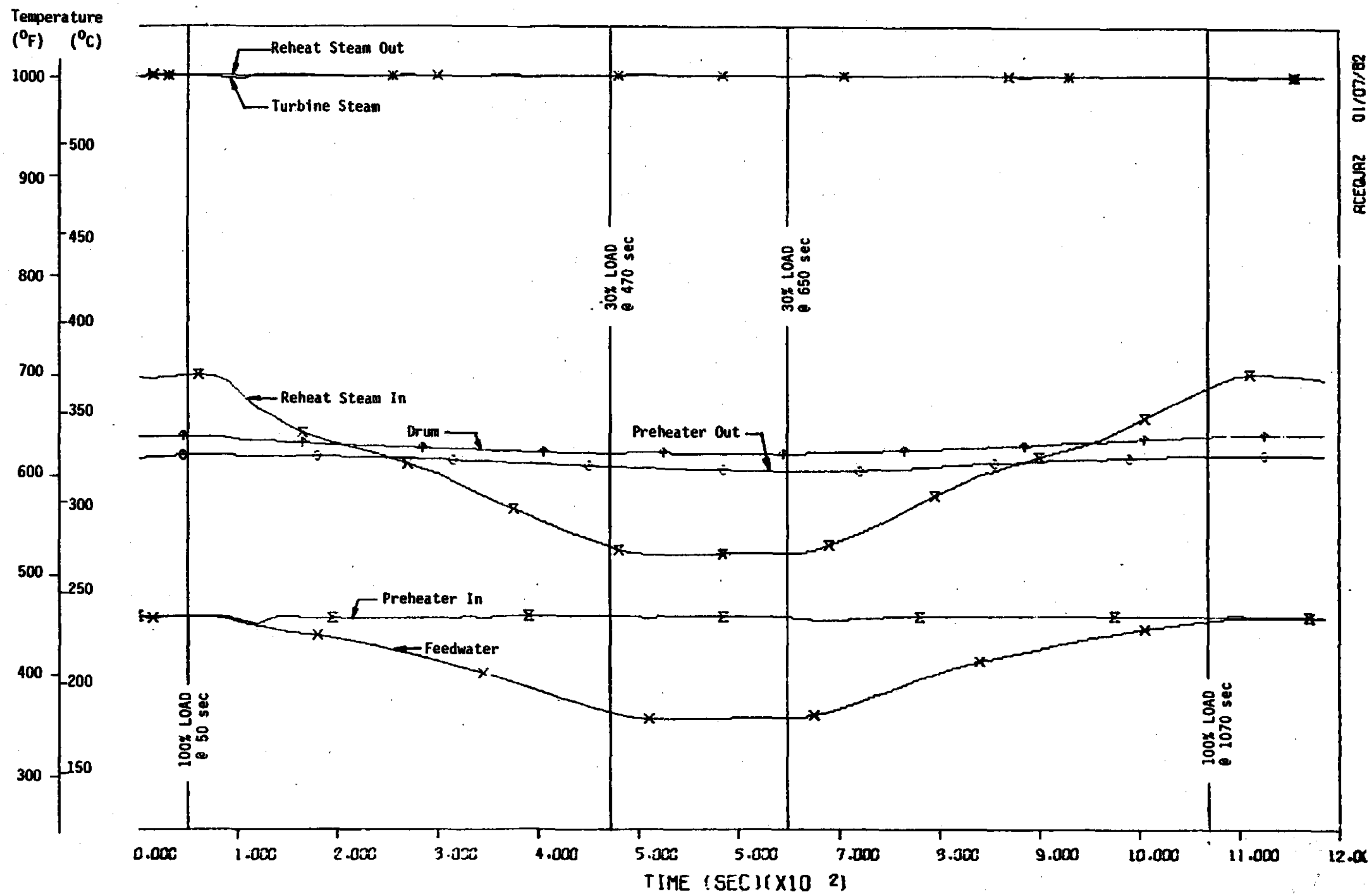
PRESSURE VS TIME

100-30-100% LOAD SWING

FIGURE 28

F-49

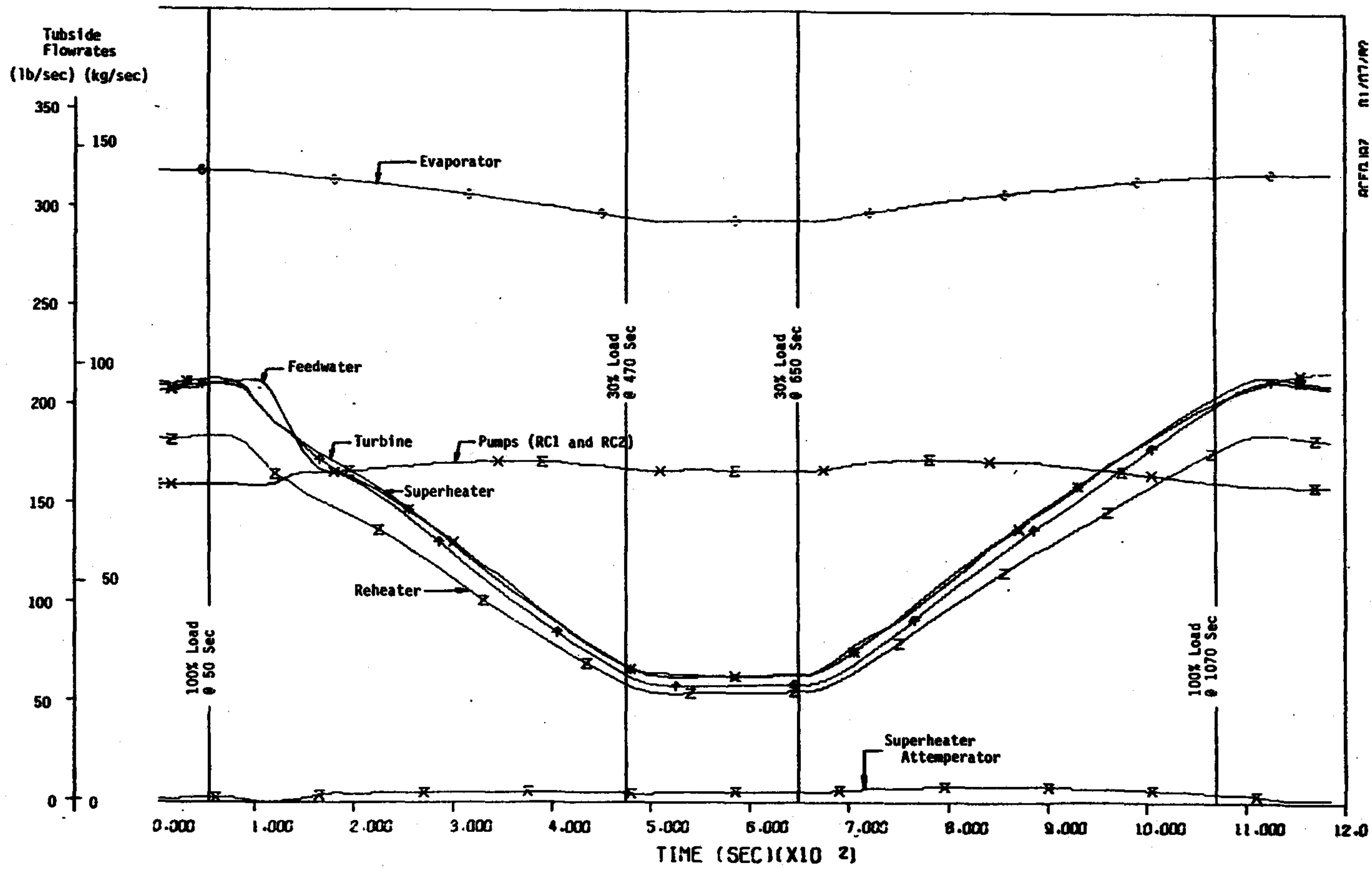
B-40



100-30-100% LOAD SWING

FIGURE 29

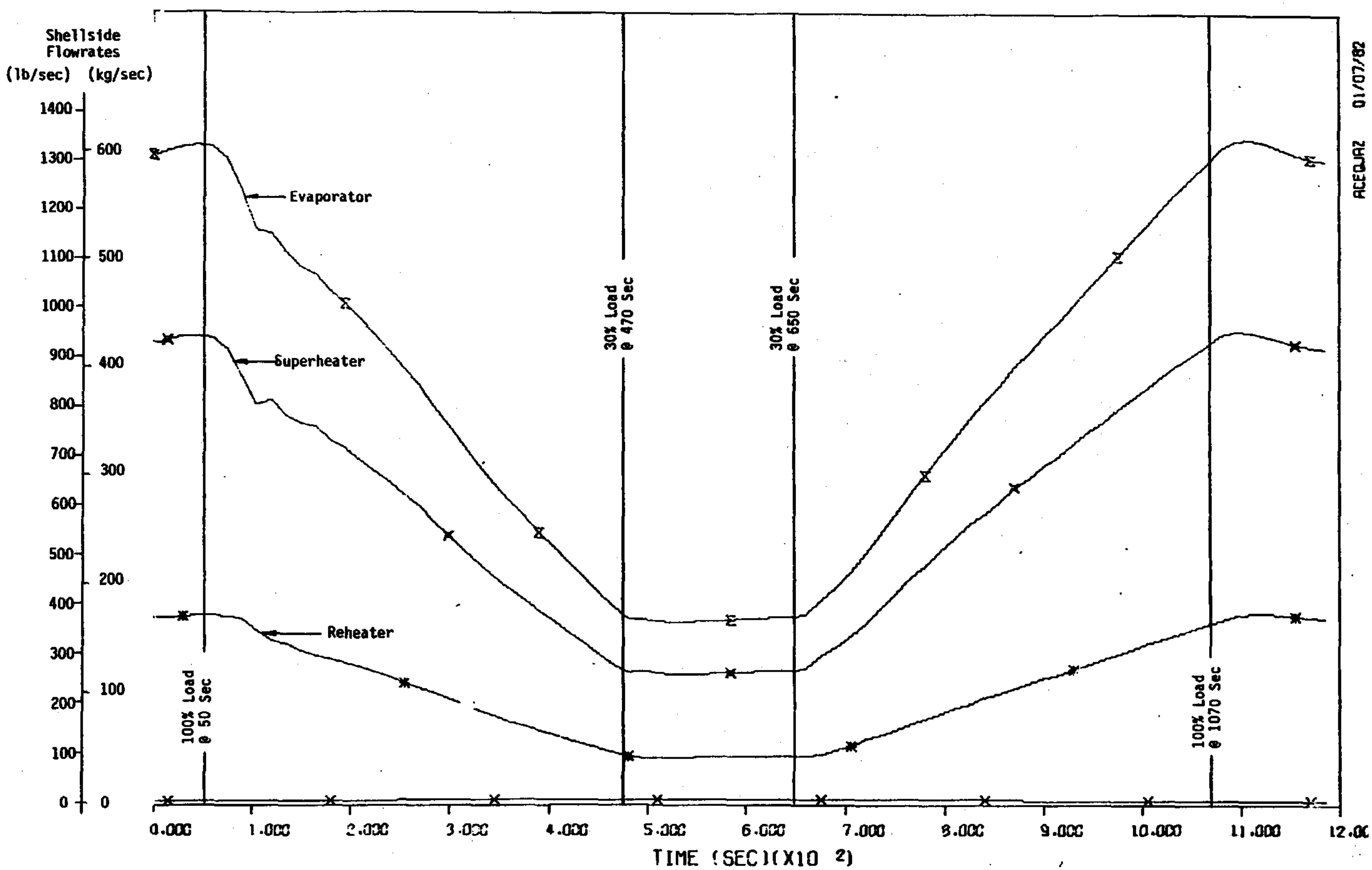
F-51



FLOW RATE VS TIME

100-30-100% LOAD SWING

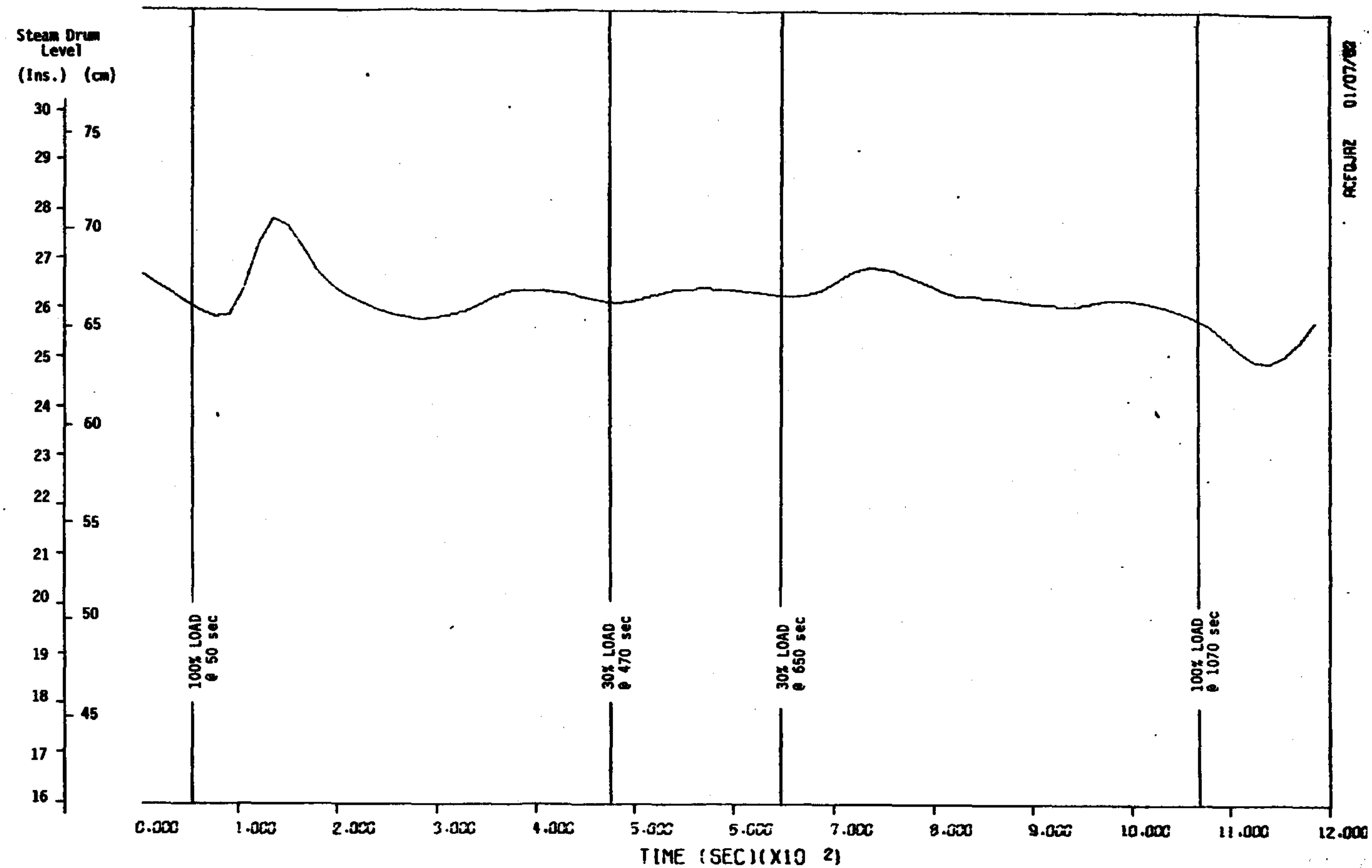
FIGURE 30



FLOWRATE VS TIME

100-30-100% LOAD SWING

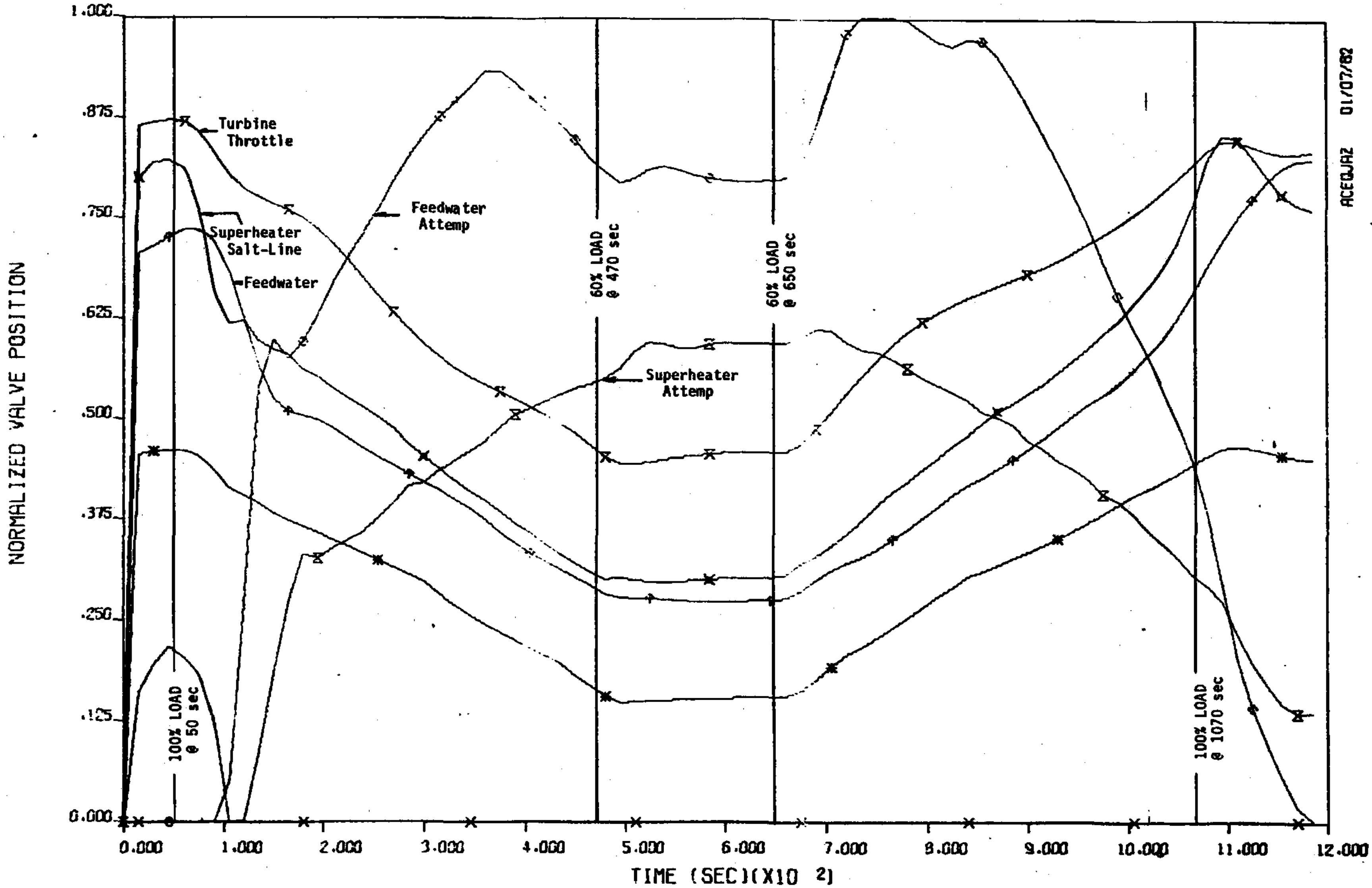
FIGURE 31



STEAM DRUM LEVEL VS TIME

100-30-100% LOAD SWING

FIGURE 32



NORMALIZED VALVE POSITION VS TIME

100-30-100% LOAD SWING

FIGURE 33

For example, the effect on both the reheater and superheater salt-line valves is largely determined by the steam flow to the turbine ie. the load following term. Any trip that causes this flow to cease would automatically cause the salt flow through both the reheater and the superheater to immediately drop to near zero. Any residual flow through these valves would be due to the temperature and pressure feedback error terms. These residual flows are contained by anti-windup limits on the integrators of the PI algorithms which eliminates the possibility of significant ammounts of hot salt reaching the evaporator during a trip.

Similarly, the turbine-steam load-following term in the drum level control also minimizes the risk of ever flooding the drum during a trip. The remaining term, drum level error, acts only to open the feedwater valve to bring the level up to that required.

PERFORMANCE SUMMARY: 100-30-100% LOAD SWING — TABLE 3

Component	Setpoint	Range	Allowable Range
Drum level	67 cm	63.25-70.60 cm	67cm $\pm$ 25 cm
Preheater Inlet Temp.	238°C	234-239°C	$\nless$ 231°C
Throttle Pressure	12.51 MPa	12.46-12.58 MPa	$\ngtr$ 13.1 MPa
Turb Steam Temp.	538°C	536-539°C	$\ngtr$ 546°C
Reheater Steam Temp.	538°C	537.0-538.3°C	$\ngtr$ 546°C

4. HARDWARE AND SOFTWARE REQUIREMENTS

There are various options open with respect to conrol hardware. This section outlines the technique used to study the options and compares two distinct contenders: distributed and centralized control. Both are described with reference to actual manufacturers and comparisons made with respect to relative abilities and cost. Specific application is made to the SGS experiment where distributed control provides the best solution.

4.1 Interface Specifications

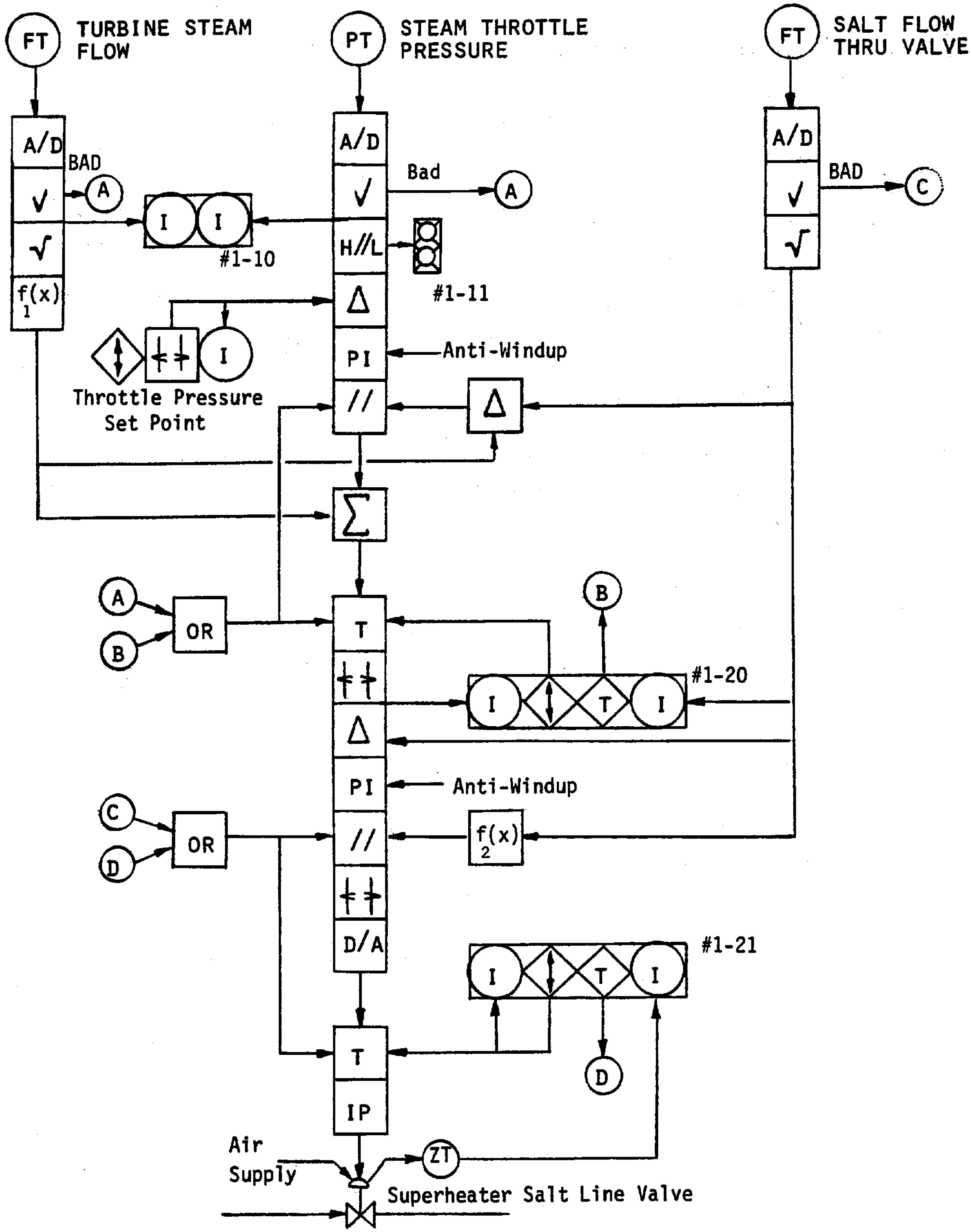
The control system interface is defined using control functional diagrams. These diagrams display the functional composition of each controller and define:

i) Transmitters required for each loop,
ii) Operator levels of intervention,
iii) Operator alarms and indicators,
iv) Software requirements.

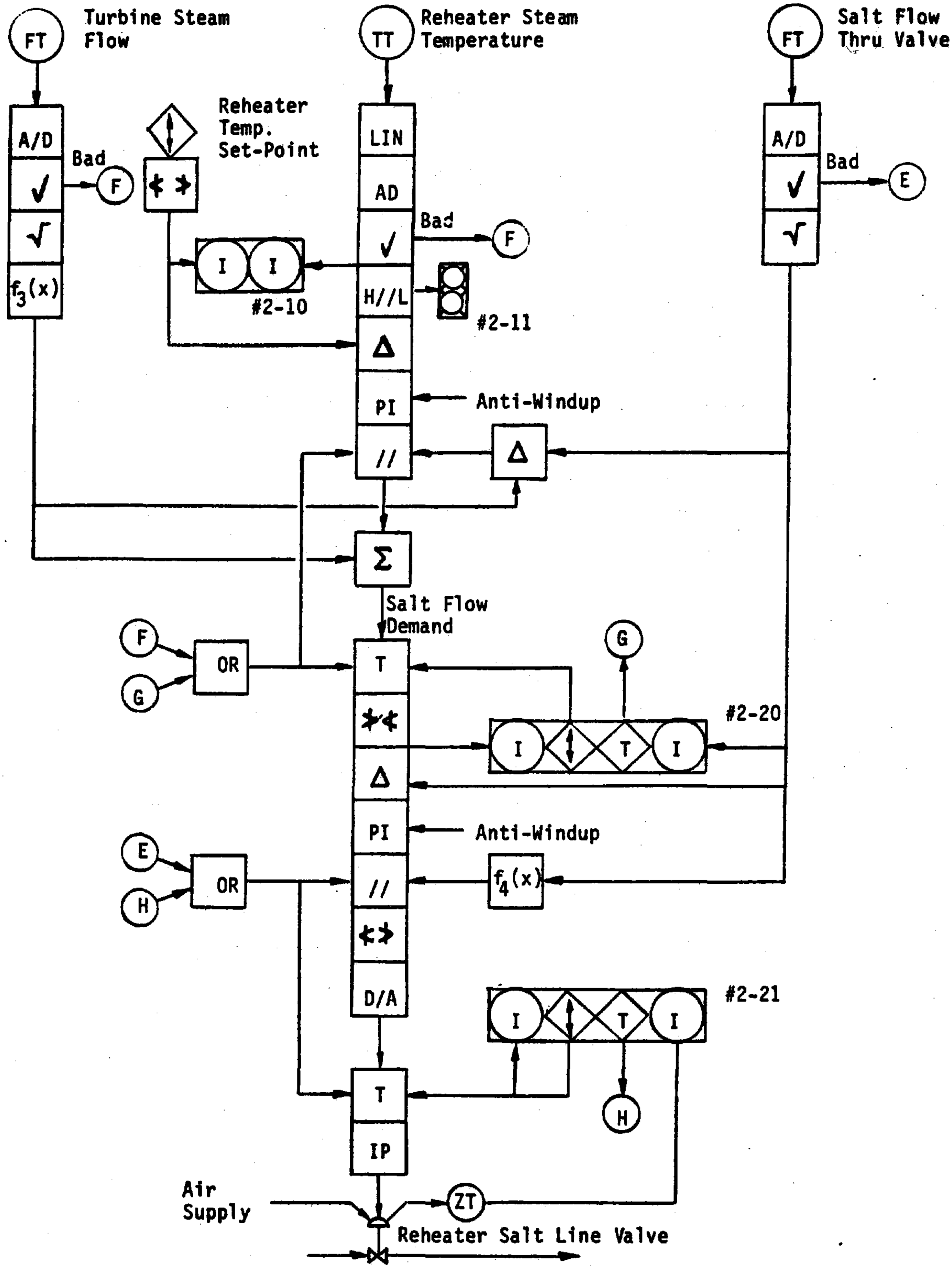
Figures 34-38 illustrate diagrams for the superheater salt-line valve, reheater salt-line valve, boiler recirculation valve, steam drum level auctioneering and steam drum level control. The symbol notation is shown in Figure 39.

The functional diagram for the superheater salt-line valve, Figure 34, is based on the control loop shown in Figure 3. The diagram shows a cascaded, three-term controller, with the operator able to intervene at either the valve position or salt-flow rate demand. The features of this control include:

i) Bumpless transfer of control from manual to automatic via the track term.
ii) Non-linear thermal balance using the function characterizer, $f_1(x)$.



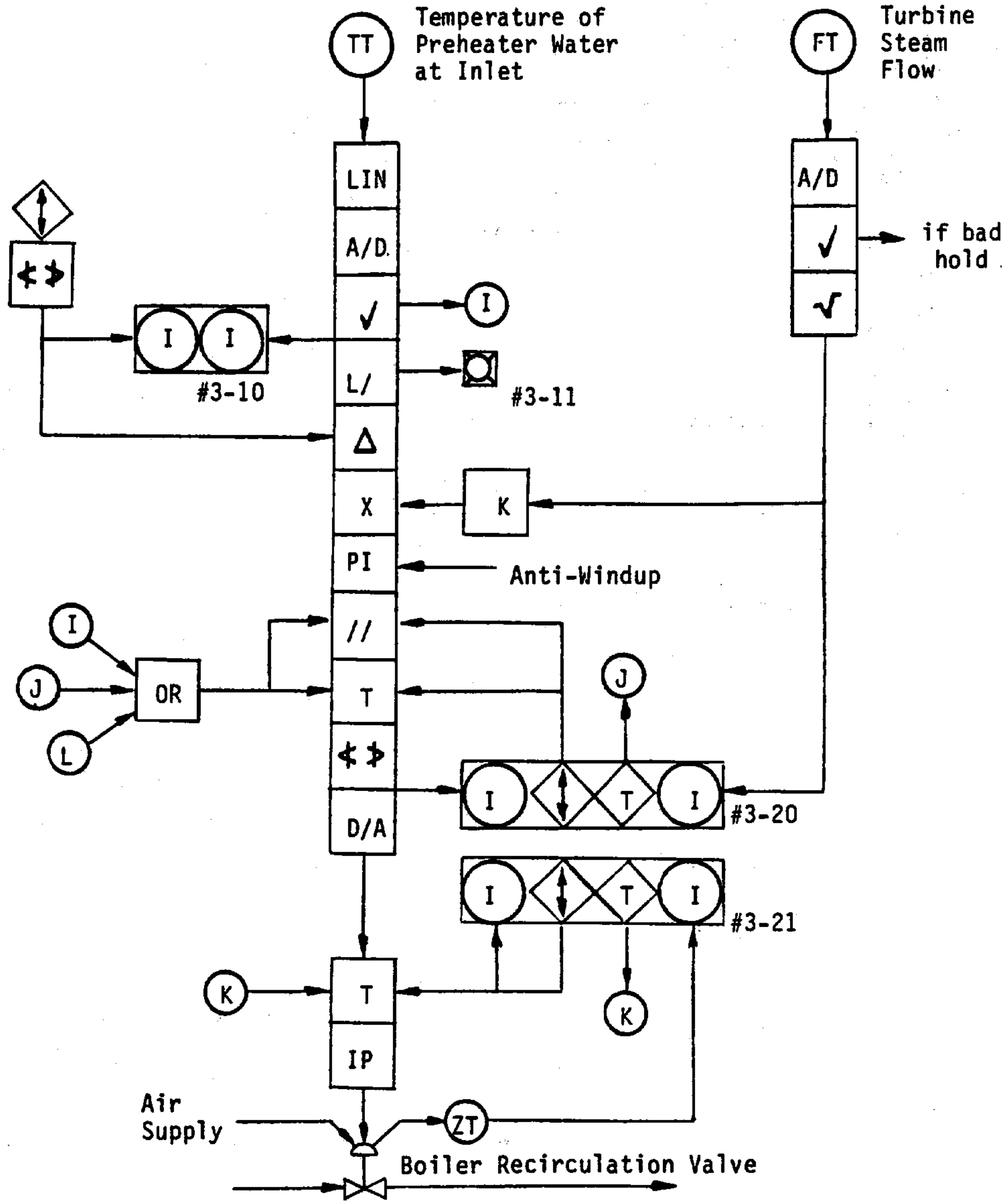
Control Functional Diagram - Superheater Salt Line Valve Figure 34



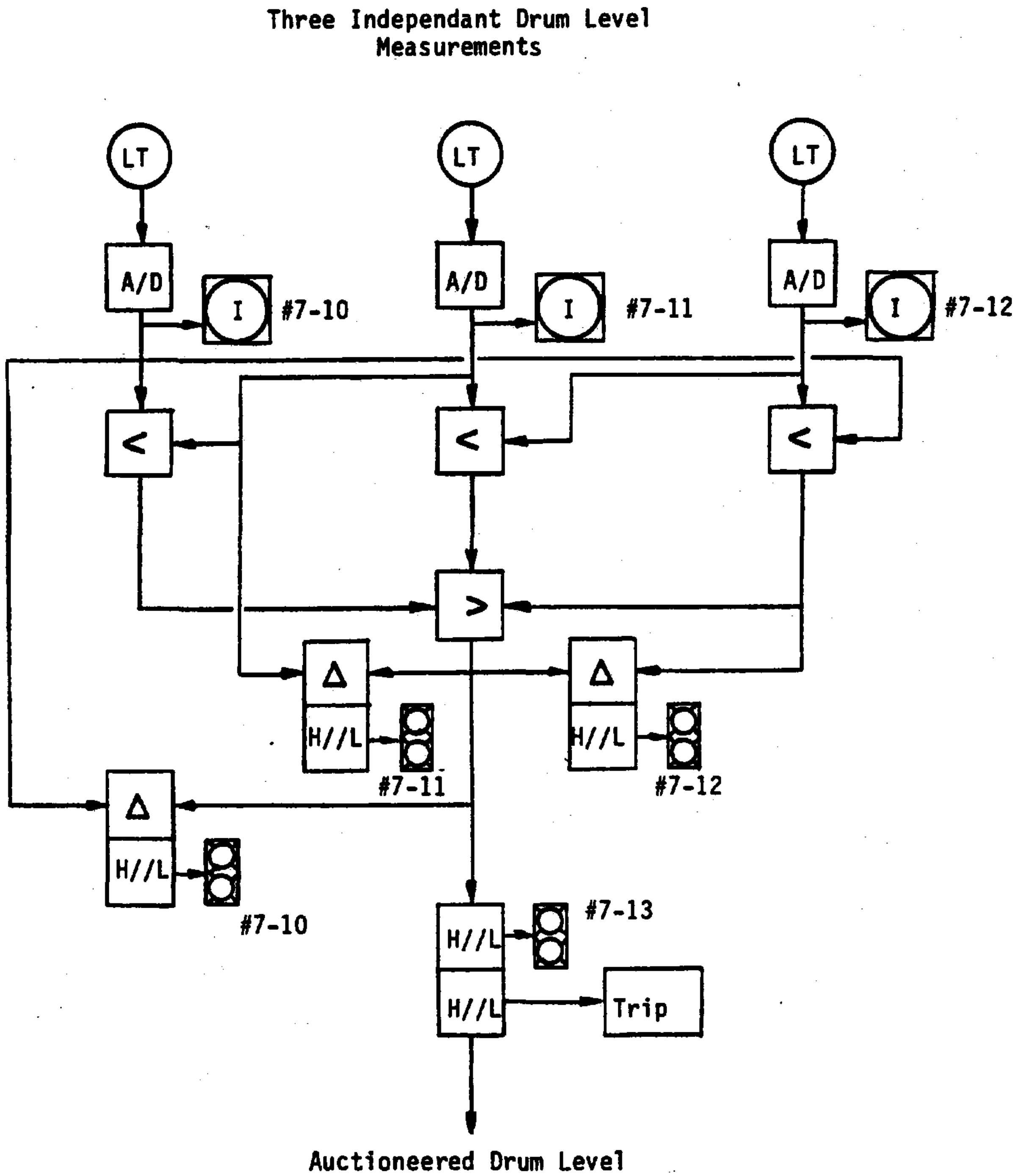
F-59

Control Functional Diagram - Reheater Salt Line Valve

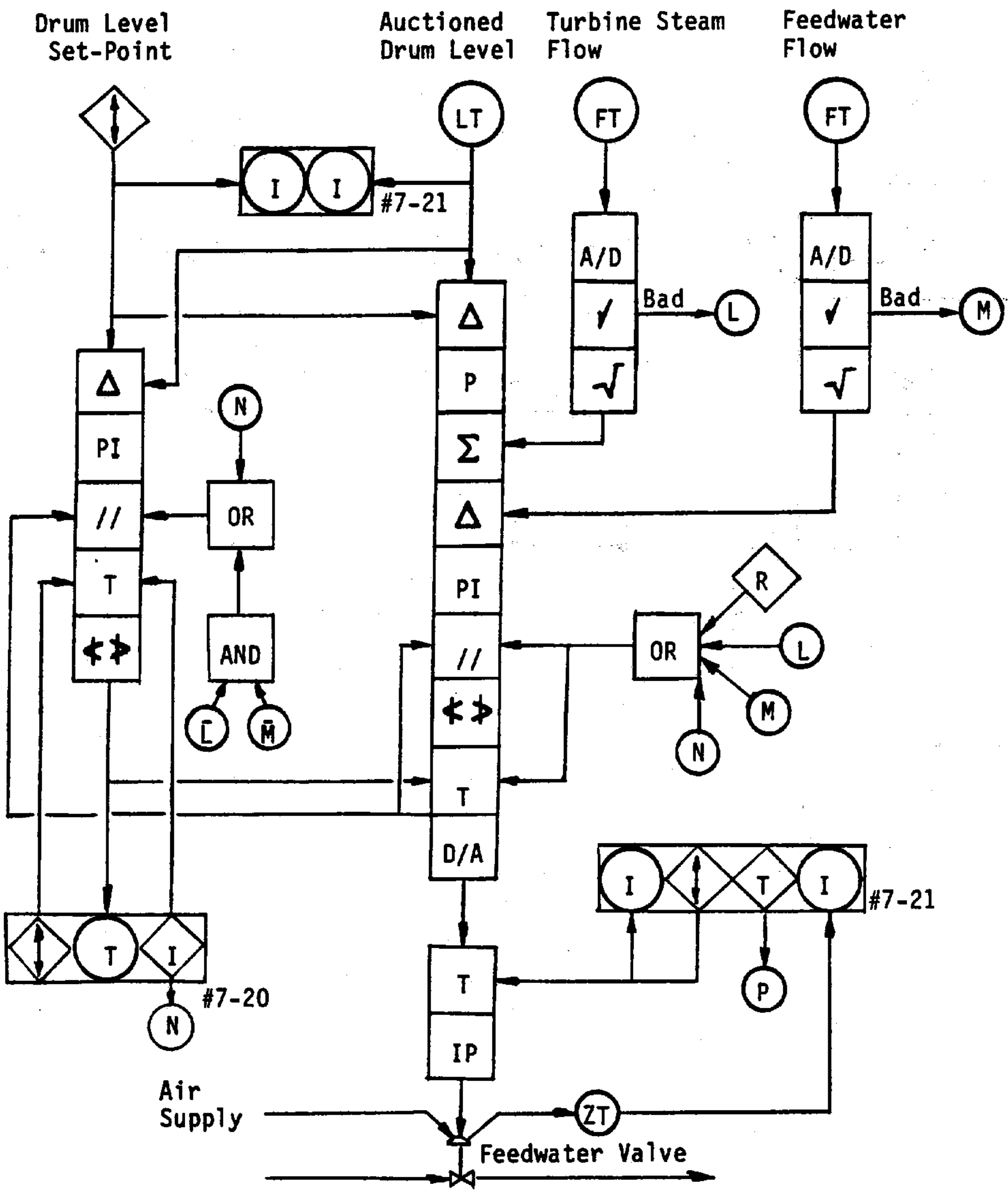
Figure 35



Control Functional Diagram-Boiler Recirculation Valve FIGURE 36



Control Functional Diagram - Steam Drum Level Auctioneer Figure 37



Control Functional Diagram-Feedwater Valve Control

Figure 38

(A)	Flag, A through Z
(PT)	Pressure Transmitter
(FT)	Flow Transmitter
(TT)	Temperature Transmitter
◇	Operator Set Point
A/D	Analogue to Digital Conversion
f(x)	Function Generator
D/A	Digital to Analogue Conversion
H/L	High, Low Signal Monitor
(I)	Indicator
◘	Alarm
T	Transfer
P	Proportional Control
I	Integral Control
D	Derivative Control
Δ	Difference
//	Track (Initializes Integrator)
Σ	Summer
√	Square Root Extractor
✓	Signal Check
IP	Current to Pneumatic Conversion
OR	OR Gate
≮ ≯	High, Low Limiter
<	Low Signal Selector

CONTROL FUNCTION DIAGRAM NOTATION Figure 39

iii) Transfer of control to operator setting of salt flow when either Flag A or B is set. Flag A is automatically set by the bad data check of steam flow or throttle pressure. Flag B is set by the operator transfer of control.

iv) Transfer of control to operator setting of valve position when either Flag C or D is set. Flag C is automatically set by the bad data check of the salt flow. Flag D is set by the operator transfer of control. The ability to contol the valve directly with a 4-20 ma signal maximizes system integrity as it allows the operator to control the plant in the case of processor failure.

v) A high/low alarm is included to warn the operator when the throttle pressure exceeds certain thresholds.

The reheater diagram, Figure 35, is essentially the same.

The boiler recirculation valve functional diagram is shown in Figure 36. This diagram is representative of the turbine steam and evaporator salt attemperator as all three are adaptive gain, single-loop controls.

The functional design of the steam drum control is directed at two goals of equal importance:

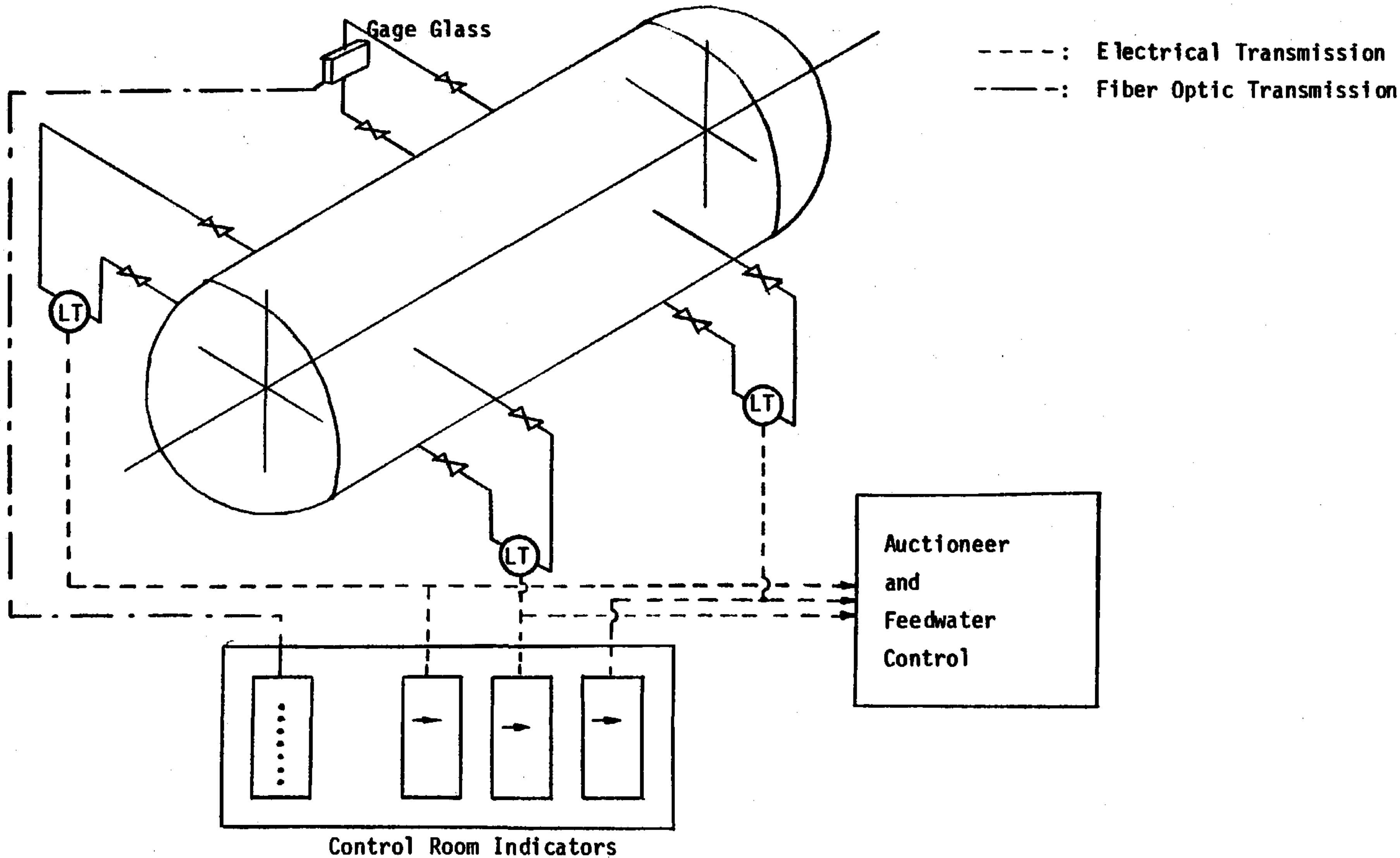
i) minimizing the occurance of nuisance trips by using redundancy,

ii) preventing the low water incident.

To this end the drum water level indication and control as illustrated in Figure 40 will be used. The three transmitter signals are processed, as shown in Figure 37, and the median used to control the level. The functional diagram of the level control, shown in Figure 38, is based on the control loop described by Figure 10. The features of this design can be summarized by the following:

Figure 40

Drum Level Transmission



i) The three element control uses steam flow as a feedforward term to provide fast response to load changes. The feedback loop trims the drum level.

ii) The operator can set Flag R to reduce the control to single element in drum level. This control is more responsive at low steam loads, and hence for low feedwater flows.

iii) The control will automatically revert to level-only control if either turbine steam or feedwater flow rates fail the check.

iv) The operator can control the valve through the controller, Flag N, or directly with a 4-20 ma signal, Flag P.

A summary of the instrumentation requirements is shown in Table 4. Shown are the transmitter requirement (total 13) and the loops (total 10, three cascaded as pairs) with the loop characteristics. The fiber-optic transmission of the drum water gauge is also included, as shown in Figure 40. Although a fiber optic path is shown, a TV monitor is also acceptable.

4.2 Network 90 - Bailey Controls

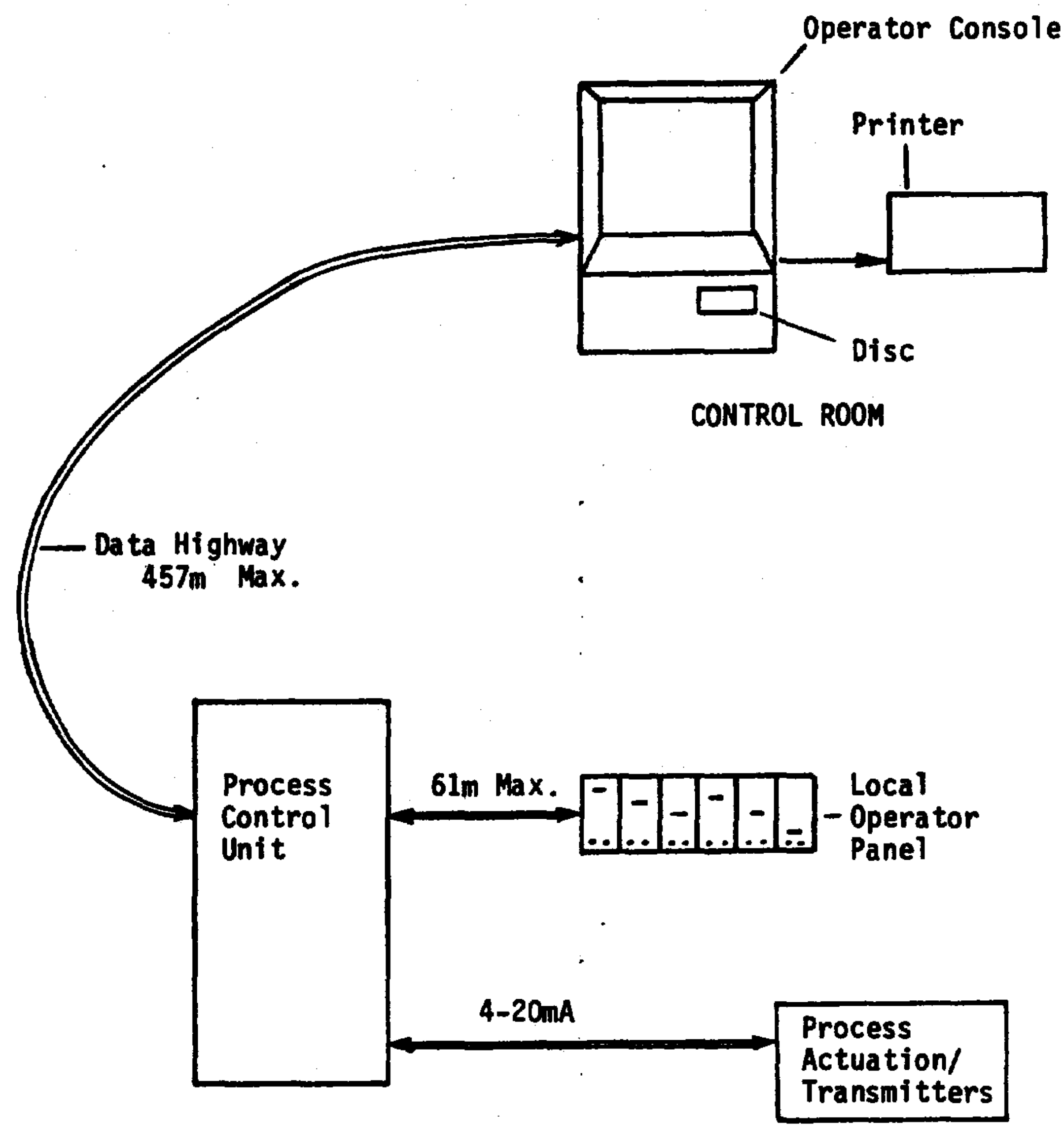
To meet the control requirements outlined in Table 4 along with those of the startup procedure, Network 90 has been considered as a possible solution. Network 90 is a micro-processor based system designed to provide both physical and functional distributed control and display. The following features of the system make it an attractive solution for solar powered steam generation.

i) Analog and sequential control integrated into one system.

ii) Conventional and CRT-based operator interfaces.

iii) Functional distributed control with single loop integrity.

iv) The control operator interface can be geographically distributed.



DISTRIBUTED CONTROL FIGURE 41

Figure 41 illustrates the contol layout of the modules.

The Process Control Unit is the major component and contains the power supply, cards housing controllers and I/O, and data bus/cabling. For this application, all the hardware and support packaging required for process control can be housed in one cabinet.

SUMMARY OF INSTRUMENTATION REQUIREMENTS TABLE 4

Valve	Transmitters	Control Loops	Characteristics
Superheater Salt-line	i) Turbine Steam Flow ii) Steam Throttle Pressure iii) Salt flow thru valve	Two cascaded loops	Both loops are PI
Reheater Salt-line	i) Turbine Steam Flow ii) Steam exit Temperature iii) Salt flow thru valve	Two cascaded loops	Both loops are PI
Boiler Recirculation	i) Turbine Steam Flow ii) Water inlet temperature	Single loop	Adaptive PI
Steam Attemperator	i) Turbine Steam Flow ii) Steam Supply Temperature	Single loop	Adaptive PI
Evap. Salt Attemperator	i) Turbine Steam Flow ii) Salt Temperature	Single loop	Adaptive PI
Feedwater	i) Turbine Steam Flwo ii) Feedwater Supply iii) Three independant drum levels iv) Fiber optic transmission of water gauge to operator	One single loop and two cascaded.	PI loops with level auctioneering

The Digital Control Station is a general purpose, panel-mounted, manual/automatic station used to locally interface an operator with a process control loop. For example, in Figure 34 the blocks notated as #1-10, #1-11, #1-20 and #1-21 relate to one auto-manual station. Each loop requires one such station to provide the following facilities to a local operator.

i) High/Low Alarm indication.
ii) Set Point and Process Variable display with Set Point adjustment.
iii) Auto/Manual transfer with manual output display and adjustment.

The Operator Console is situated remotely in the central control room and acts as the main interface between the operator and the Process Control Unit (PCU). It is connected to the PCU via a data highway and works in conjuction with a Console Driver and Floppy Disks to provide color graphics and dedicated pushbutton hardware. These are used for process overview, alarming, loop control, trend display, and configuration and tuning functions. A line printer can be included to make copies from the terminal display such as that shown in Figure 42. This illustrates the standard faceplate and trend display similar to the feedwater functional diagram described by Figure 38. Each loop would be represented by a display such as this. Another form of display would be the overview made up solely of faceplates from each of the loops and their alarms. The dedicated push buttons would be assigned to these displays providing ease of operation.

The Network 90 parts list is given in Appendix 1. This covers the system outlined by Figure 41 with the exception of the printer and is estimated to cost $145,000.00, the most expensive item being 27, the Operator Interface Unit at $59,000.00. A high speed printer would cost an additional $10,709.00. These prices do not include service and installation but do include system assembly and check out prior to shipment as well as system documentation, order administration, system configuration and engineering. The delivery time for this system has been quoted at 26 weeks.

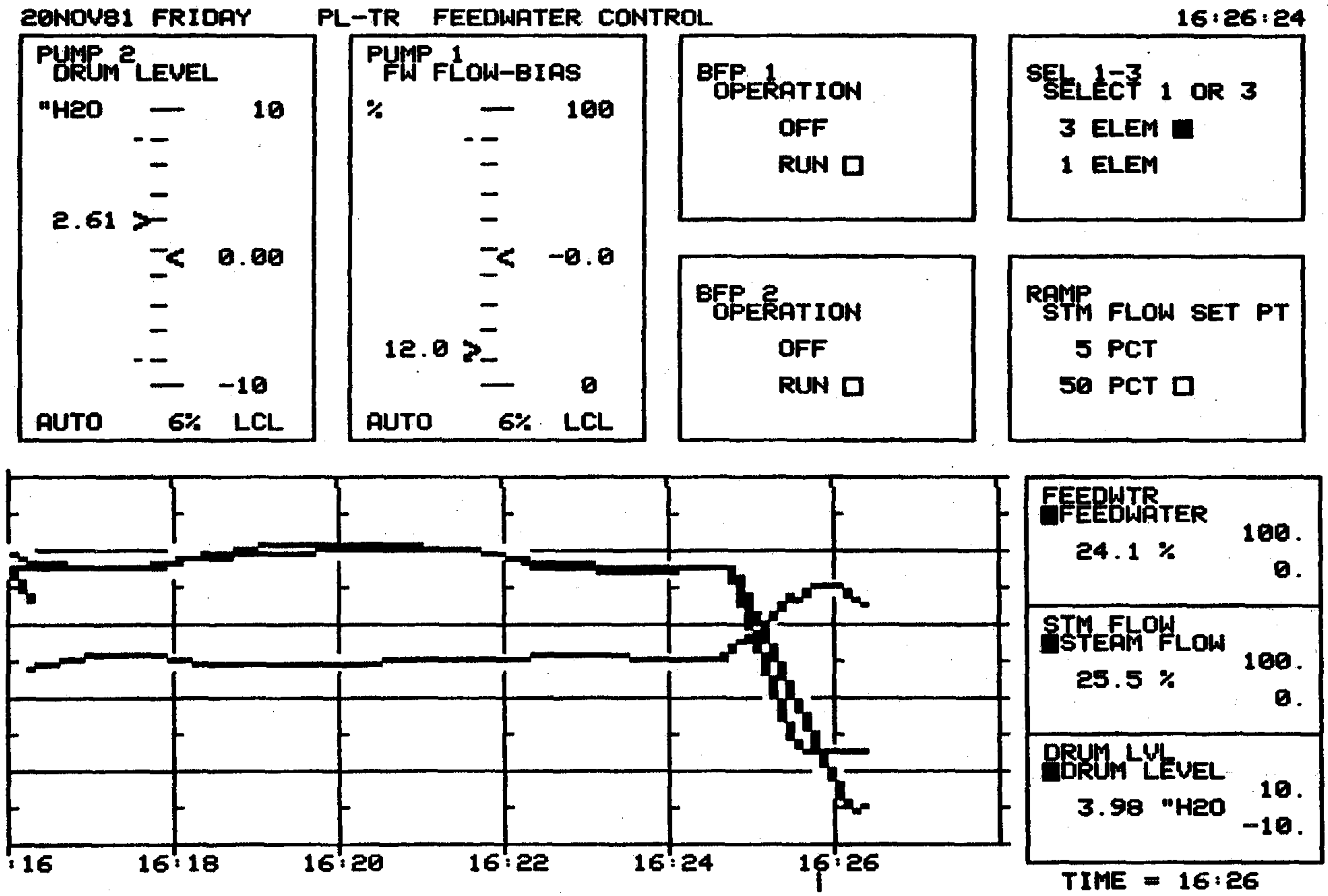


FIGURE 42 CONSOLE DISPLAY FOR DRUM LEVEL CONTROL

There are numerous alternative suppliers for this equipment. Fisher Controls market a system called PRoVOX which is designed to satisfy a near identical control philosophy as Network 90. Using the same control requirements, the PRoVOX system was estimated to cost approximately the same but require a longer lead time of 42 weeks. It should be remembered that the prices quoted in this document are estimates. It was found that detailed system analysis may well result in a relaxation of the number of cards required. This is due to the nature of microprocessor control; their capabilities are extensive and more efficient methods of solution are expected to be found during the writing of the programs.

4.3 Taylor 3103 Computer System

The previous paragraph described the use of a distributed type control system for steam generation. Although this type of control has its advantages, it can present a large degree of "over-kill" and result in an expensive solution. An alternative would be to use a mini-computer sytem for the following reasons.

i) It is better sized for handling the limited number of loops associated with this system.

ii) Close physical proximity of the steam generation hardware would not necessarily require geographically distributed control.

iii) The distributed control scheme proposed provides continuous and digital control. The 3103 system will provide continuous, digital and sequential control. Sequential control is resident software ideal for start up procedures, etc.

iv) The 3103 can be readily expanded to include additional control responsabilties associated with solar power generation. This is due to the upward compatability of the software to the 3106 (a larger machine) and also the facility of including MOD3, the Taylor distributed system, which is also software/hardware compatible. (Generally, suppliers of distributed control can only offer a hardware tie to a mini-computer. The software would still need to be written by the purchaser and this is a significant task).

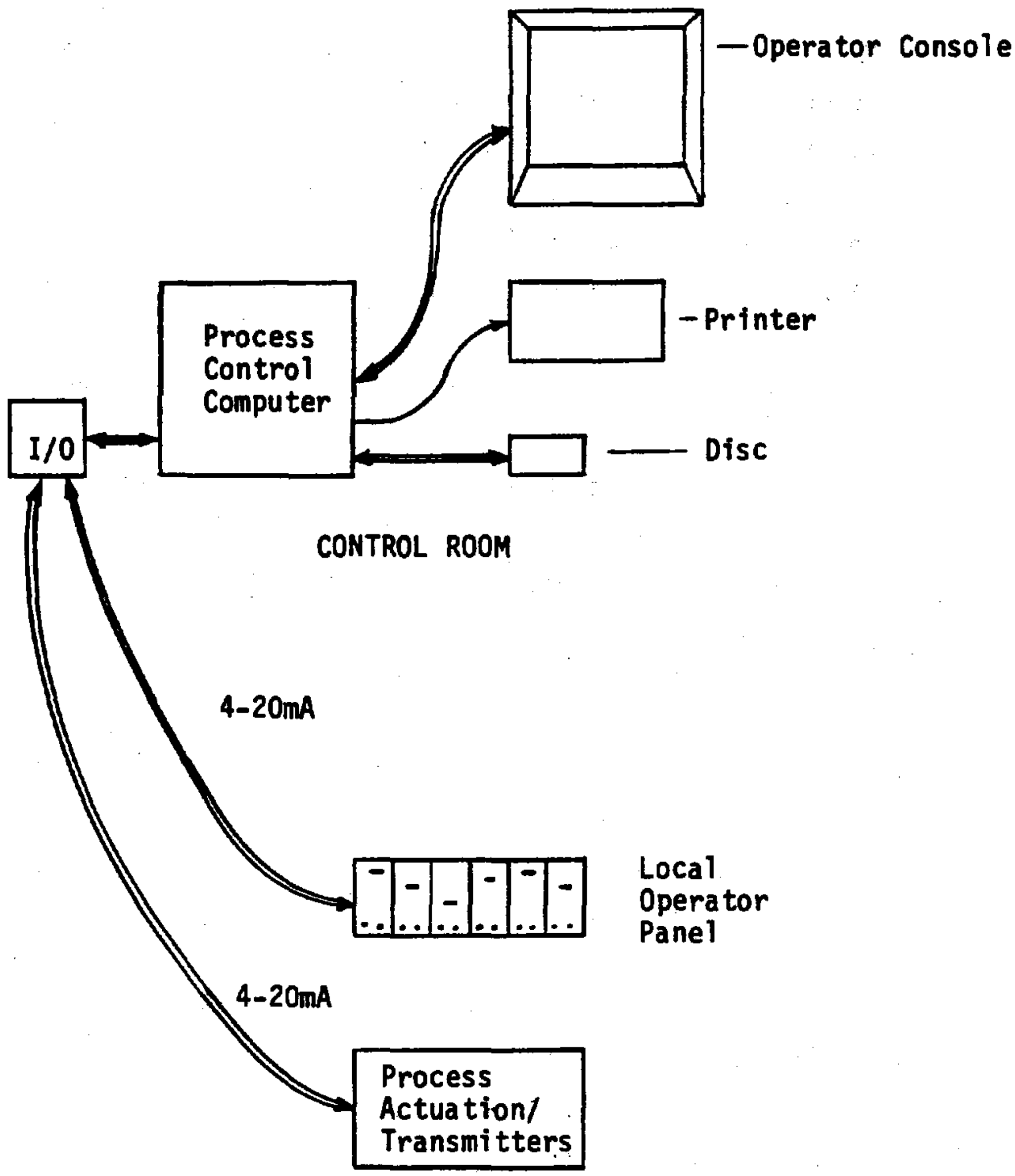
The hardware list shown in Appendix 2 is for the system illustrated in Figure 43, designed to fulfill the same requirements as that for which the Bailey and Fisher systems were designed. As such, their price tags are directly comparable. The cost of the Taylor 3103, with printer, is estimated to be $84,157.00. It should be noted that it is significantly cheaper than the distributed systems reviewed by 46%.

The drawbacks of using a centralized control system are:

i) If the Process Control Computer is situated a considerable distance from the plant, a data highway must be used as a communication link. The reliability of this highway then features in the overall reliability of the control system which is not the case for distributed control. Distributed control will continue to function even when the highway has malfunctioned, thus maximizing the operational safety of the plant.

ii) Distributed Control acts as a parallel processor of information. By having a seperate control card responsible for each loop, single loop integrity can be realized. The Central Computer system acts as a serial processor and cannot attain the same level of control integrity.

To conclude, although the Taylor 3103 computer System is cheaper and more powerful, its advantages are outweighed by the disadvantages of being less reliable, operationally, in comparison to the distributed schemes. Ideally, the best scheme would be to have the centralized control facilities of the 3101 combined with the distributed control reliability of the MOD 3 (as previously described). To justify such a scheme, however, the control of other subsystems within the solar power plant would need to be included.



CENTRALIZED CONTROL FIGURE 43

4.4 Steam Generation Subsystem Experiment

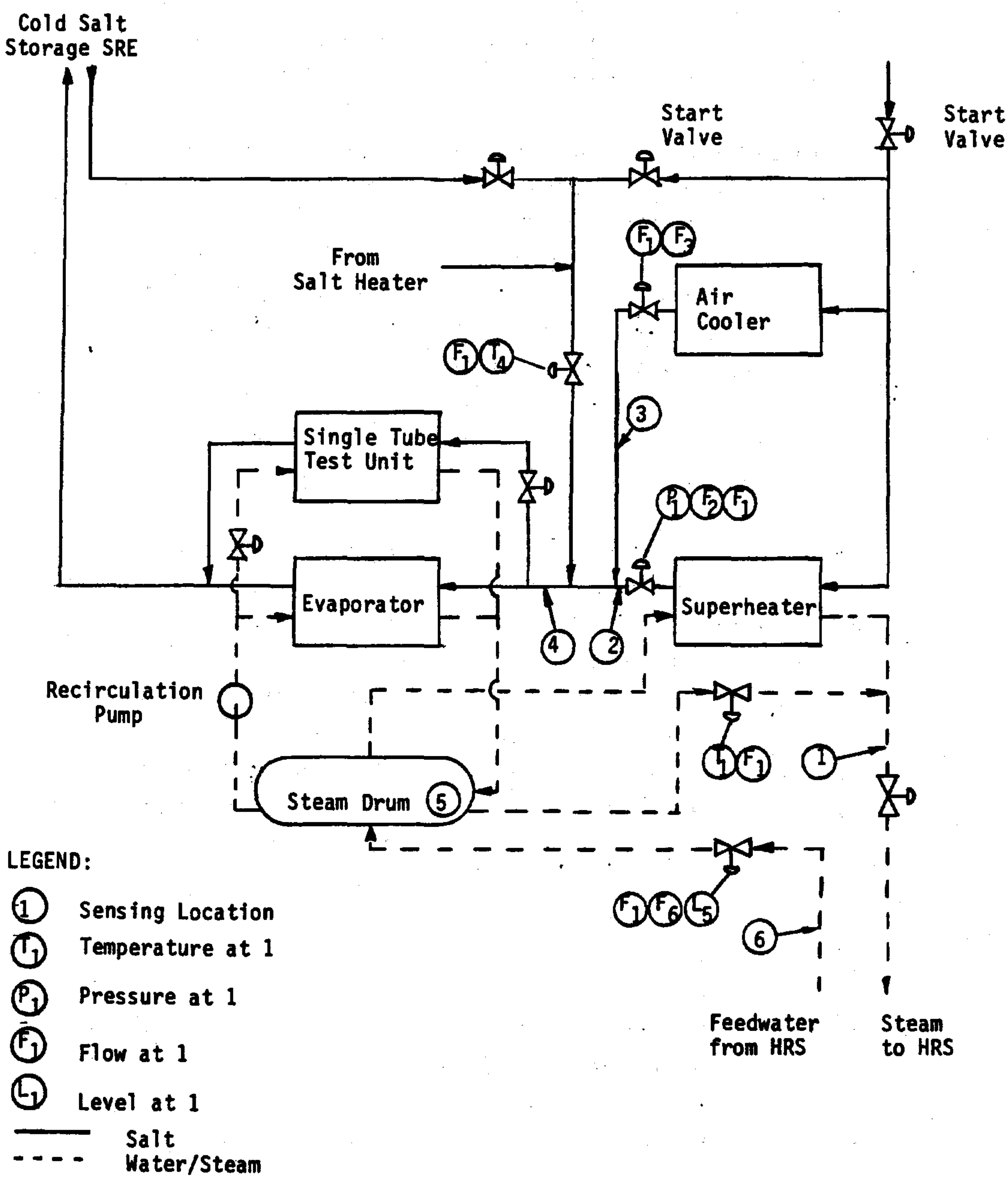
Figure 44 shows the layout for the Subsystem Research Experiment (SRE). The control of this plant is identical to that of the commercial steam generator subsystem with the following exceptions:

i) The replacement of the reheater by an air cooler results in the removal of the reheater salt-line valve control. It is replaced by a valve controlling the salt flow through the air cooler such that the flow rate is in direct relation to the steam flow through the throttle. This is a single control loop where the set point is tracking the steam flow and comparison with flow feedback generates the error signal to drive the valve actuation.

ii) The removal of the preheater precludes the need for a feedwater attemperation control.

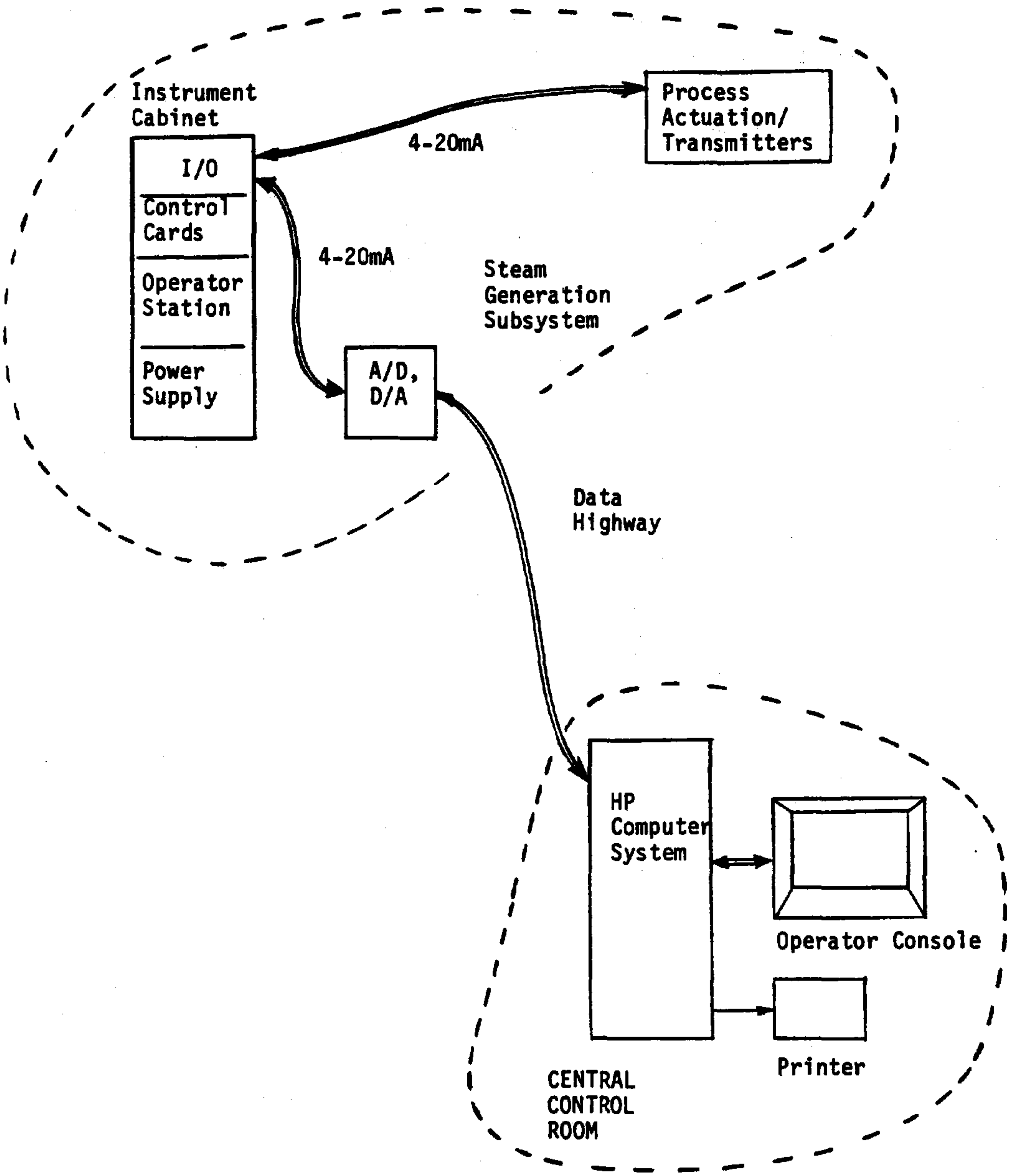
Appendix 3 lists the components required for this control scheme, using the Fisher PRoVOX system. The estimated cost is $30,000 with a 16 to 18 week delivery time. This delivery time is significantly less than that quoted for the commercial plant; this is due to the exclusion of the Operator Console which requires long lead times. The operator console is not required in this situation as the plant can be adequately controlled using operator stations mounted in the Instrument Cabinet. Any gain changes or reconfiguring of controllers can be made using a hand held device which plugs into the controller.

For the full scale experiment (FSE), the preheater is included and an additional controller is required for the feedwater attemperator. This requires an additional control card, listed in Appendix 3, at an estimated additional cost of $4000. The schematic for the full scale experiment control configuration is shown in Figure 45. The F.S.E. requires remote control of the steam generation. This is achieved using the data highway which already exists at Alberquerque, along with



SRE CONTROL SYSTEM FIGURE 44

A/D-D/A equipment which also exists. This unorthodox method of communication is expedient as it fully utilizes existing equipment giving the advantages of reliable distributed control and remote operation through the HP computers. The HP system will be used for data acquisition and logging, control overview with color graphics and remote set point and gain control.



SUBSYSTEM RESEARCH EXPERIMENT FIGURE 45

5. CONCLUSIONS

The results given in section 3 show the ability of the proposed control scheme to control the plant through the most severe load swing (100%-30%-100%). During this maneuver, the process variables being controlled showed minimal deviation from their setpoints as illustrated by Table 3.

Although it has not been possible to simulate the response of the control scheme to plant trips, it is considered that the control system will naturally protect the plant. However, it would be useful to further pursue this avenue in order to refine and perhaps simplify the present control scheme. For example, the evaporator salt attemperator is not used during normal operation. A simpler scheme using a bang-bang control may well be all that is needed for that valve. This would greatly simplify that control loop.

The control hardware for this plant can be readily purchased. It is recommended that the steam generation control system be developed as an integrated part of a total solar plant. This would allow the realization of digital control in a more cost effective manner.

If the control of the steam generation subsystem is to be a stand alone unit, then distributed control is recommended for its high reliability and integrity even though it has the highest price tag.

APPENDIX 1 NETWORK 90 - PARTS LIST FOR COMMERCIAL PLANT

Item No.	Quant.	Type and Description	Spec. No.
1	6	NDCE2 Digital control System and Bypass	E93-902
2	11	NCOM02 Controller Module w/Expander for up to 4 A/I 3 D/I and 2 A/O 4 D/O Field I/O Points	E93-906
		Additional controller modules and termination units, with capacity for accepting (4) four analog inputs, (3) three digital inputs, and providing (2) analog outputs, and (4) four digital outputs, may be added at a price of $2,284.00 each.	
3	4	B740*1 Modules Thermocouple Millivolt Conv.	E92-740
4	1	B76101 Modules T/C Card Rack Mtg. Unit 8) Eight additional thermocouple inputs can be added at $268.00 each point. If more than eight additional thermocouple imputs are required, an additional 12 card mounting rack unit must also be added at $228.00 per 12 card rack unit. These may be required for monitoring during start-up and shut down.	E98-761
5	1	NBIM01 Module Bus Interface Module	
6	1	NCAB01 Mounting Cabinet - Modules Only (no field wiring)	E93-910
7	1	MCAB03 Mounting Cabinet - Field Terminations	

Item No.	Quant.	Type and Description	Spec. No.
7	2	MCAPO* Top Cover for Cabinet	
8	1	NCGM01 Configuration and Tuning Module	E93-903
		Configuration and Tuning Initialization may be performd at the OIU or with a rack mounted module: The NCTM01 (Configuration and Tuning Module) may therefore be deleted from this proposal at $1,363.00 net, if this redundancy is not desired.	
9	1	NDSM01 Modules Digital Slave Modules for Digit I/O	E93-913
10	1	NLMM01 Logic Master Module for Digital Logic and I/O	E93-907
11	1	NFAN01 Fan Assembly 210v AC, 1 required per each Cabinet w/module	
12	10	NFTP01 Field Termination Panel - w/screw Type Terminals	E93-911
13	1	NIOP02 120v AC I/O Power Panel w/Auctioneer	E93-909
14	1	NKLM01*** 100' cable, Loop Interface Module	
15	4	MKPL01*** 100' cable, Plant Loop	
16	18	NKTU01*** 10' Cable, Terminations Units	
17	1	NLIM01 Loop Interface Module	E93-908

Item No.	Quant.	Type and Description	Spec. No.
18	3	NMMU01 Module Mounting Units, each can accept any of up to 12 Network 90 Modules	E93-909
19	1	NMPP02 Module Power Panel with auctioneer	E93-909
20	1	NPEP01 120v AC Power Entry Panel for modules and I/O Power Panel	E93-909
21	2	NPSI03 Modules I/O Power Supply 24v DC, 120v AC	
22	2	NPSM01 Modules 120v AC Module Power Supply 375 W	
23	17	NTCS01 Controller I/O Teminalion Units	E93-911
24	1	NTDI01 Digital I/O Termination Units	E93-911
25	1	NTPL01 Termination Unit, Plant Communication Loop	E93-911
26	0	NRYP01 Digital Relay Planes for up to 8 Digital Relay Contacts, Current Rated for 5A Inductive Load	May be added at $680,00/ Relay Panel with 8 Relays
27	1	NOIU Operator Interface Unit 19" Color Graphics CRT and Control Keyboard includes One Floppy Diskette System for Initial Program Loading and Memory Storage and Trending. (1) OIU can handle up to Tags of Data. Main Memory Storage on 4.2 K byte Winchester Sealed Hard Moving Head Disk Sytem. (1) Floppy and (1) Winchester per <u>each</u> OIU.	

Item No.	Quant.	Type and Description	Spec. No.
		If desired, one Okidata high speed printer may be added, or a second one added at an adder of $10,709.00 each.	

APPENDIX 2 **TAYLOR 3103 - PARTS LIST FOR COMMERCIAL PLANT**

Item No.	Quant.	Type and Description	Spec. No.
1	1	PROCESS CONTROL COMPUTER With 128K words of main memory composed of one 182K semiconductor boards error checking and correcting (ECC) Each word is 16 bits Including Automatic Bootstap Loader, Memory Protection, Multiply/Divide hardware, Real Time Clock and Power CPU power supply with the "Data Save" option of backup of semiconductor memory Memory Extender Board for enabling the CPU to address more than 64K words of memory	4001N
2	1	PERIPHERAL CONTROLLER CARD FILE Houses PIMs, Controllers, BICs, etc 19 I/O slots Includes power supply, E-Bus Buffer and ABL/Clock Board	125S1499
3	1	PRIORITY INTERRUPT MODULE (PIM) 16 interrupt channels per module Maximum of two modules/system (32 interrupts) Interrupts serviced on priority basis	4854N
4	1	COMPUTER CABINET Enameled steel cold rolled cabinet Engineered for maximum thermal cooling Easy access to internal equipment	4001N

Item No.	Quant.	Type and Description	Spec. No.
		A/C power distribution system	
		D/C isolated power supply system	
		Termination and wiring	
		Mounting rails and braces allow standard 19" equipment to be accomodated in each cabinet	
		Dimension: 49-1/2" high 36" wide, 32" deep (126 cm X 91 cm X 81 cm)	
5	1	5.0 KVA ISOLATION TRANSFORMER	
6	1	KEYBOARD/PRINTER TERMINAL - TI 825	
		Print speed 75 characters/second	
		Includes paper catcher, 25 ft. interface cable, box of paper, extra ribbon and controller	
7	1	FLEXIBLE DISK (DUAL DRIVE) (SYKES DISK 7000)	4251N
		W/STAND ALONE TABLE TOP ENCLOSURE	4252N
		242K words storage/2 diskettes	
		73 tracks/26 addressable sectors per diskette	
		250K bits/second data transfer rate	
		Includes controller, cable and 20 diskettes	
8	1	RELAY MULTIPLEXER CONTROLLER BOARD MASTER	4848R
		Controls eight (8) slave RTD/s and/or RMS and/or thermocouple boards	
		Speed - 150 pts/sec	
		A/D conversion	
		Resolution - 13 bit	

Item No.	Quant.	Type and Description	Spec. No.
9	2	RELAY ANALOG INPUT (RMS)	
		16 inputs	4832N
		Range - high level or thermocouple	4320F
		Resolution - 13 bit	
		Isolation - optical	
		With screw clamp terminal cable	
10	1	DEDICATED ANALOG OUTPUT	
		16 outputs	4830n
		Range - 4-20 mA through isolated output channels	4320F
		Resolution - 10 bit (15.63 microamps)	
11	1	CONTACT INPUT BOARD (CIB)	
		16 optical isolated versions for 12	4812N
		or 24 VCD external voltage sense	4325F
		or 24 or 5 VDC internal supply to complete dry contact inputs	
		Noise filtering - 20 msec analog and 2, 4, 8, and 16 msec digital filters switch selectable	
		Modes - periodic scan or interrupting on change of state	
		With screw clamp terminal cable	
12	1	SYSTEM INTEGRITY MODULE	125S140
		Provides I/O wrap around test capability, precision voltage source, and watch dog-timer for hardware self-test	

APPENDIX 2 TAYLOR 3103 - PARTS LIST FOR COMMERCIAL PLANT (cont)

Item No.	Quant.	Type and Description	Spec. No.
13	1	TYPE IV CARD FILE Type IV card file (Universal Analog & Digital) with power supply, Taylor Bus Control, Address decode board and Configurator Board	4028N
14	1	POL 300 OPERATING SYSTEM Including PIL *3 language compiler/ Interpreter/Executive, Utilities and Diagnostics	1 lot
15	1 lot	ICAP/CONTINUOUS POL *3 Allocation Software Package supporting the continuous control applications	
16	1 lot	ICAP/DIGITAL POL * 3 Application Software Package supporing the handling of discrete, multiple state process devices	
17	1	COLORGRAPHIC TERMINAL (ISC 8001) 8 foreground and 8 background colors 19 inch (483 mm) CRT screen 80 characters/line, 48 lines/screen 160 X 192 screen grid for complex graphics Keylock switch 16 dedicated function buttons - Hall effect for reliability	4140D

Item No.	Quant.	Type and Description	Spec. No.
		Standard ASCII Engineering Keyboard with optical encoding for reliability	
		Includes buffered controller and 50 ft. cable	
	1 lot	ICAP/Graphics	
		PIL *3 application software package Supporting generation of colorgraphic process displays.	
18	6	Computer Manual Station	1310CA12002-1
		Terminal Block Cable	1030FA12100
		Resistor 62.5 ohm	1002FK00001
		Electrical code: General Purpose	
		Power: 117V, 60 Hz	
		Computer Input: Incremental	
		Option Included: Transmitter Power Supply	
		Output monitor signal: 0.25 to 1.25 V dc	
19	1	Relay Rack Mtd Housing	
		Size: Mounting of up to 6 each 3 X 6" Taylor Panel Instruments	1000FB10006
20	3 cop.	DOCUMENTATION	
		System Configuration Manual	
		Interconnection Wiring	
		Addresses for peripheral & Major Components	
		Field Instrumentation Wiring	
		Terminations in End Bays	
		System Level Configuration Information	

Item No.	Quant.	Type and Description	Spec. No.
21	1 set	SYSTEM REFERENCE DOCUMENTATION Vendor Operating & Maintenance Manuals Diagnostic Software Listing Software Reference Manuals Engineering Information Taylor Peripheral Controller Manual Taylor I/O Module Descriptions	
22	3 cop.	SYSTEM EQUIPMENT OPERATION MANUAL System Operation Instructions System Startup Procedures System Initialization Procedures	

APPENDIX 3 PRoVOX - PARTS LIST FOR PILOT PLANT

Item No.	Quant.	Type and Description	Spec. No.
1	5	Computing Controller and Operator Station	CL6202X1-A1-B13-C1-D2
2	1	Card Files	CP6201X1-A1-B2-C4
3	1	Power Supply	CP6101X1-A1
4	1	Power Distribution Panel	CP7101X1-A2-B2-C2
5	1	Tuner	CS6002X1-A1-B1
6	5	On-Off Valve Switches With Indicators	
7	1	Instrumentation Cabinet With Cutouts and Above Equipment Mounted	
8	1	Computing Controller and Operator Station (for F.S.E. Preheater Water Attemperator Controp).	CL6202X1-A1-B13-C1-D2

Appendix G

Phase II Proposal

APPENDIX G

Phase II Proposal

for

Molten Salt Steam Generator Subsystem Research Experiment

Selected portions of the Phase II proposal are provided in the following pages - Three options were offered:

(a) A baseline 5 MWt subsystem design and test program supplemented by on-site DNB tests and laboratory corrosion tests. Total estimated cost = $2,165,310.

(b) On-site DNB tests and laboratory corrosion tests only. Total estimated cost = $842,929.

(c) The baseline 5 MWt subsystem design and test program, modified for a full system experiment (FSE), and supplemented by on-site DNB tests and laboratory corrosion tests. Total estimate cost = $2,254,930.

I. INTRODUCTION AND SUMMARY

We view the effort for Phase II of the Molten Salt Steam Generator Subsystem Research Experiment Program as extremely important since it represents the last subsystem experimental effort required for demonstration of a solar-thermal energy system using molten salt. Our proposal presents a thorough understanding of the effort to be undertaken and describes the capability of the Babcock and Wilcox team to achieve all program objectives.

The objective of the steam generator subsystem (SGS) program is to develop a cost effective system for solar-thermal plants to produce electricity or process heat. In Phase II of the program, the major objectives are to resolve the design, fabrication, operational, performance, and cost uncertianties associated with the full-scale (50- or 100-MWe) system. The subsystem research experiment (SRE) will utilize the design and analysis techniques proposed for the full-scale system to demonstrate the design adequacy of the full-scale molten salt SGS. The SGS components developed for the SRE will be usable in a molten salt full-system experiment (FSE) that may follow the SGS SRE.

Accomplishment of the program objectives requires not only the experience and knowledge to design and build steam generators but also knowledge of solar-thermal plant design, experience with molten salt systems, knowledge of plant design and construction, and operational experience with commercial steam generator systems. To satisfy these diverse requirements, we have assembled an outstanding group of companies--Babcock and Wilcox, Martin Marietta, Black and Veatch, and Arizona Public Service. With this team's experience in design, planning, research and development, manufacturing, and erection, the commercial steam generator susbsystem can be ready to meet the DOE repowering/retrofit schedule.

This proposal presents an SRE baseline option (Chapter II) along with an R&D option (Chapter III) and a FSE option (Chapter IV). These options are summarized:

1) Baseline option--This option meets the objectives of resolving the design, fabrication, operational, performance and cost uncertainties associated with the full-scale (50- or 100-MWe) system. It will demonstrate the design adequacy for the full-scale SGS. This option is described in depth in Chapter II;

2) R&D option--This alternative offers the Sandia National Labs a minimum-cost program that meets the objectives of optimizing component performance and cycle efficiency. The tasks associated with this option are a single-tube departure from nucleate boiling (DNB) test and a corrosion test. SRE components of the baseline option will not be fabricated. Chapter III describes this alternative;

3) FSE option--This alternative meets the objectives of the baseline option and in addition is also compatible with the FSE interface requirements. It is described in Chapter IV.

OVERVIEW OF PROPOSED PHASE II EFFORTS

The principal work to be accomplished in the subsystem research experiment is described:

1) Subscale steam generator models will be designed, fabricated, and tested to verify the thermal-hydraulic performance characteristics of the component designs developed during Phase I and demonstrate to potential users the operational capability of the steam generator subsystem as a whole;

2) A single-tube model will be designed, fabricated, and tested in parallel with the evaporator. These tests will be a well-controlled investigation to better define the thermal-hydraulic factors influencing DNB for the tube arrangment selected. The tests will verify the major thermal-hydraulic parameters chosen for the plant-size evaporator. Data that may allow further improvments in economics of the SGS will also be established.

The design of the SRE components was chosen to model the key design features of the plant-size units. Similar U-tube configurations were chosen with duplication of tube dimensions and spacing to ensure modeling of the important thermal-hydraulic parameters. Because of the similarity of design features and thrmal-hydraulics between the plant-size units and the SRE, the SRE tests will visibly demonstrate the expected performance of the plant components.

Figure I-4 shows the system arrangements for the 100-MWe subsystem design and the proposed SRE. To substantially reduce costs and provide better testing of the critical SGS components, only the evaporator and superheater components are included in the SRE because:

1) The total cost of the SRE can be reduced significantly. However, an amount of heat proportional to that normally consumed in the reheater will be dissipated in the existing air-cooled heat exchanger to maintain the proper thermal-balance throughout the system;

2) Elimination of the preheater allows better testing of the evaporator and superheater. The energy that would normally be transferred in the preheater is transferred through the other two components, increasing their size by 22% and significantly improving the scaling ratio.

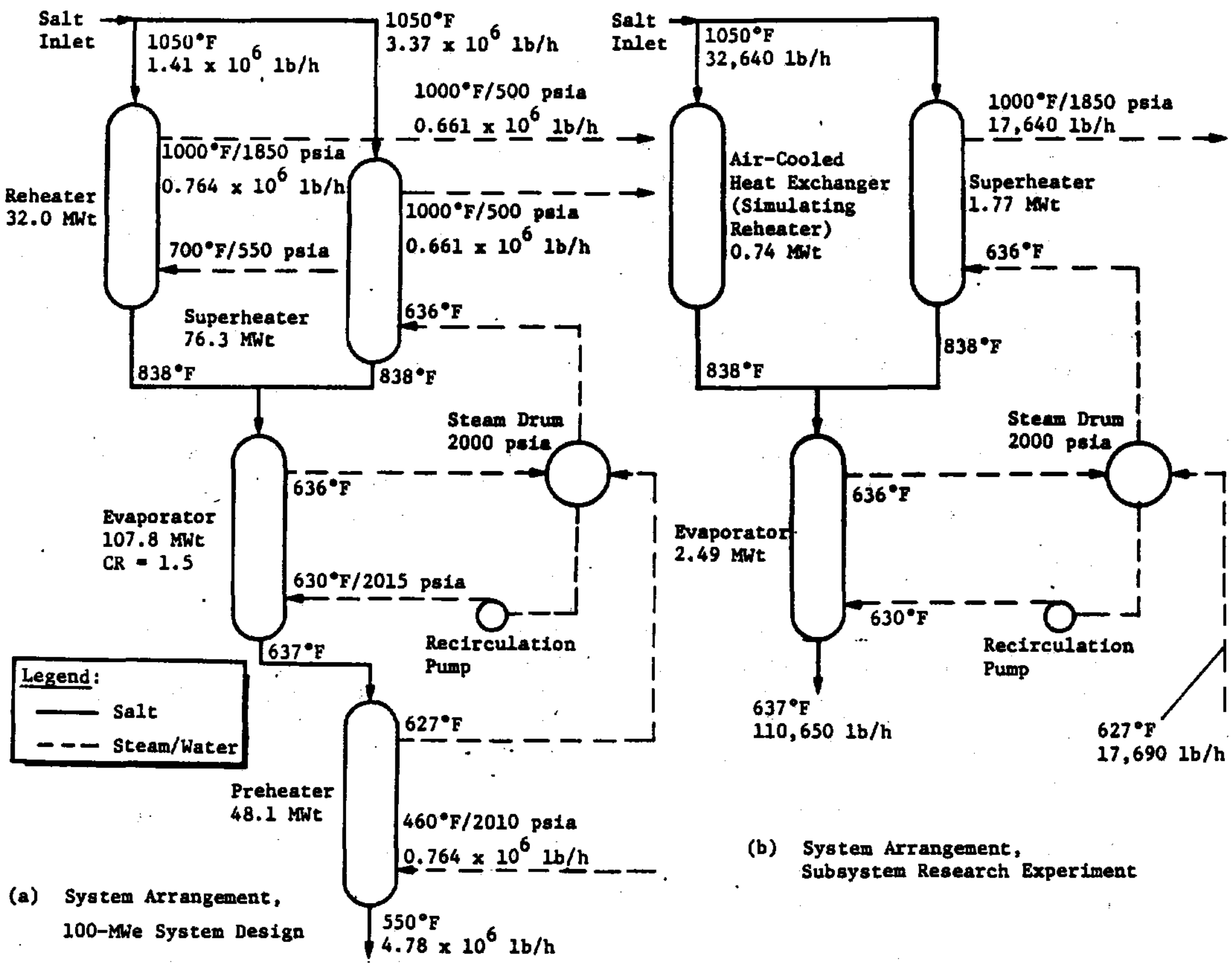


Figure I-4 System Arrangements

Deletion of the preheater and reheater reduces the complexity of the SRE without compromising the subsystem's performance. Eliminating two components reduces fabrication cost while properly maintaining the temperature and pressure profiles throughout the system and throughout the remaining heat exchanger components. The evaporator is a U-tube/straight shell arrangement and the superheater is a U-tube/U-shell arrangement. Thus one unit of each general configuration is included in the SRE, thereby demonstrating the key features of all the main SGS components.

To ensure satisfaction of the program's long-term goals, contractors were asked to submit two proposals:

1) A proposal optimized to meet the objectives of the Phase II contract (designated herein as the baseline option);

2) A proposal that meets the objectives of the Phase II contract and is compatible with the FSE interface requirements (designated herein as the SGS FSE option).

In view of some of the uncertainties surrounding the next steps of the solar program, an R&D option is proposed in addition to the two requested proposals. The R&D option is designed to allow Sandia National Labs to meet program goals by providing design information for a plant unit with lower cost than can be realized with the other proposals. The three options are summarized:

1) Baseline option - With this option we will,

    a) Supply and install a test loop with the major SRE components, namely superheater, evaporator, and drum,

    b) Perform corrosion testing and a single-tube heat transfer test to provide design data on boiling heat transfer,

    c) Perform a complete complement of performance tests for the SRE components,

    d) Evaluate the test data and modify the commercial subsystem design if necessary;

2) R&D option - We will perform corrosion testing and a single-tube heat transfer test to provide design data on boiling heat transfer and corrosion. The R&D work will verify the commercial plant design analyses and establish whether design margins can be safely and economically reduced;

3) Steam generator for full-system experiment (SGS FSE) - This is the same as the baseline option but adds a preheater to the SRE loop and ensures compatibility with the FSE.

We believe Item 1, the baseline option, offers the best approach to meeting the solar program goals. A successful test of the critical steam generator components will demonstrate to the utility industry viability of the design and the associated R&D tests will allow economic refinement of future plant designs.

PROJECT TEAM

The project team assembled for Phase I will continue to work together to complete Phase II of the steam generator program. This project team offers diverse experience in the critical areas necessary to the solar program, including solar thermal plant design, molten salt technology, design and fabrication of steam generators, plant design and construction, and operational experience with steam systems.

1. <u>Babcock and Wilcox</u>

Babcock and Wilcox will lead the project, coordinate the subcontractors, and report to Sandia National Labs. Babcock and Wilcox will design and fabricate the major SRE components, be responsible for conducting the test program, and evaluate the test data.

2. <u>Martin Marietta</u>

Martin Marietta will establish system requirements, prepare test procedures for the SRE, design and procure the control and instrumentation system, and conduct system-level data reduction and analysis for the SRE.

3. <u>Black and Veatch</u>

Black and Veatch will be responsible for site construction and interfaces with other centeral receiver test facility (CRTF) equipment. They will lay out the SRE components and design the piping system, foundations, wiring, pumps and valves.

4. <u>Arizona Public Service</u>

Arizona Public Service will assist in development of the SRE test plan and system design. APS will also identify user requirements, review the SGS SRE control system, and critique the work from a user's viewpoint.

D. TASK FLOW SUMMARY

The work to be done is outlined in Figure I-5. No exceptions are taken to the statement of work, and the tasks defined for the project will be performed. The contract effort will be directed to obtain the following outputs:

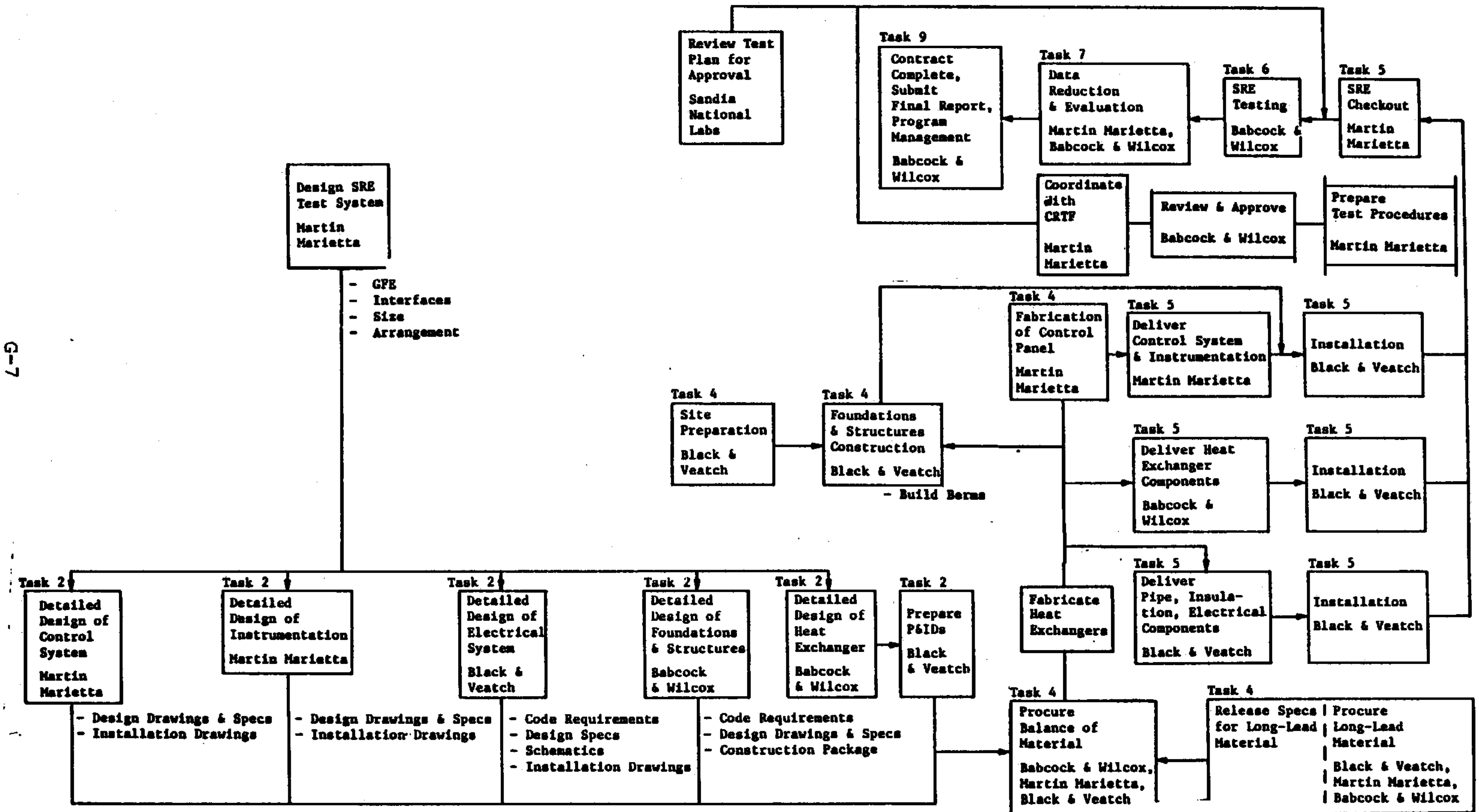


Figure I-5 Task Flow

1) Identification of the steam generator subsystem (SGS) requirements and subsystem research experiment (SRE) interface requirements needed for successful implementation of the experiment;

2) Detailed designs for the experimental hardware and interfaces required to perform the SRE;

3) A test plan consisting of a set of tests with integrated test procedures necessary to satisfy the objectives of the SRE;

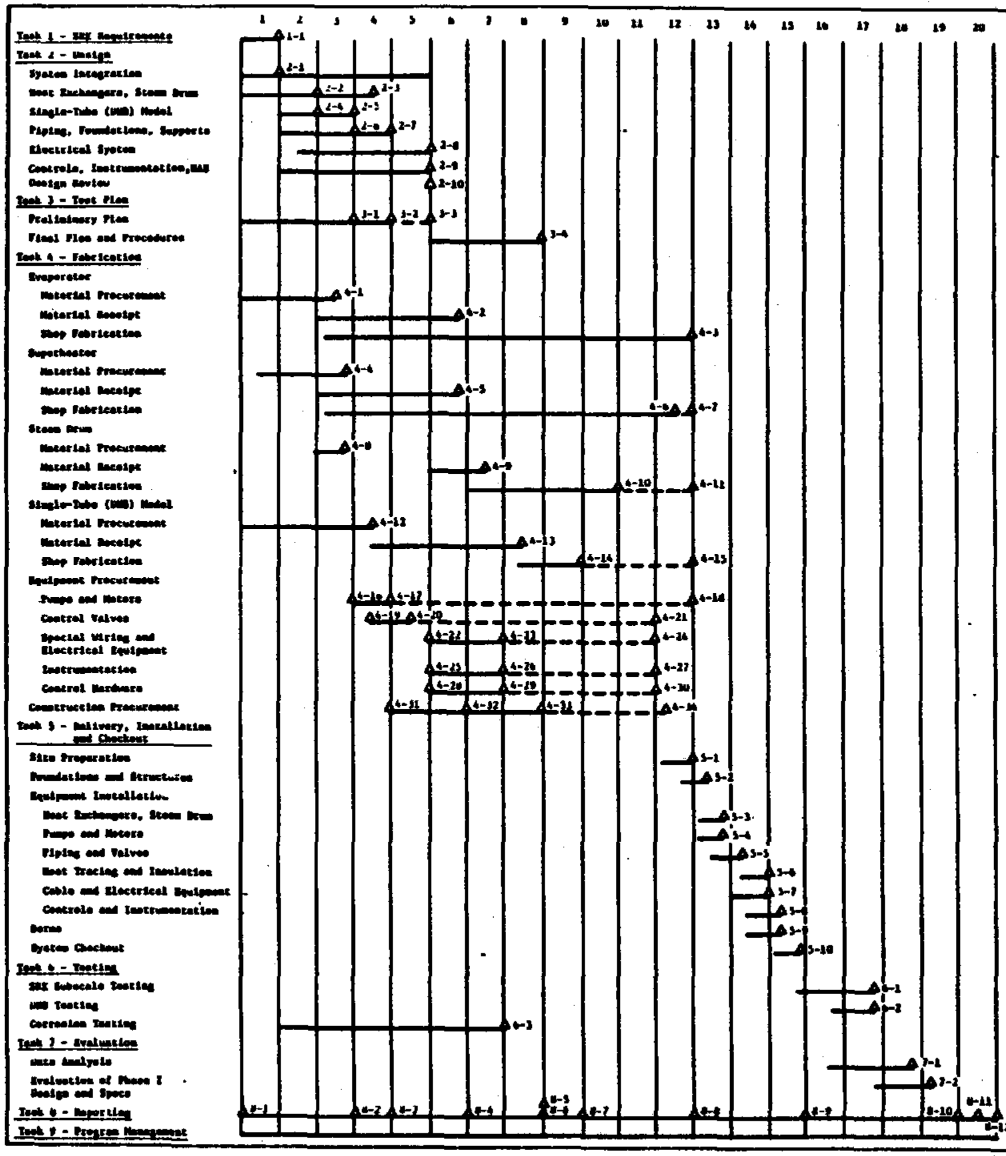
4) Fabrication of experimental hardware;

5) Delivery, installation, and checkout of the experimental hardware and interfaces in a field test environment at CRTF;

6) Testing of the SGS to the procedures defined in the test plan (including DNB and corrosion tests);

7) Evaluation of the data obtained by operation and testing of the SGS. The results will be used to finalize the commercial system design to reflect the updated information on performance estimates, surface area requirements, tubing requirements, operating procedures, control system design, and structural and maintenance requirements.

The Phase II program for the SGS SRE baseline experiment is planned for 20 months' duration (Fig. I-6). This plan provides 12 months for design and fabrication of the experimental hardware. Installation and readiness checkouts of the hardware will take three months and will be followed by a two-month test program. The schedules for the other options are shown in the chapters describing each option.



1-1 Review of SRE requirements and CRTF interface parameters completed.

2-1 P&I diagram completed.
2-2 Heat exchanger and steam drum designs completed.
2-3 Heat exchanger and steam drum fabrication drawings completed.
2-4 Single-Tube (MMB) model design completed.
2-5 Single-Tube (MMB) model fabrication drawings completed.
2-6 Piping design completed.
2-7 Design of component foundations and supports completed.
2-8 Design of electrical system completed.
2-9 Design of controls, instrumentation, and DAS completed.
2-10 Design review.

3-1 Preliminary MMB test plan completed.
3-2 Integrated test plan (preliminary) completed and submitted to Sandia.
3-3 Sandia comments received.
3-4 Final test plan and procedures completed.

4-1 All material for evaporator ordered.
4-2 All material for evaporator received.
4-3 Evaporator fabricated and shipped.
4-4 All material for superheater ordered.
4-5 All material for superheater received.
4-6 Superheater fabricated.
4-7 Superheater shipped.
4-8 All material for steam drum ordered.
4-9 All material for steam drum received.
4-10 Steam drum fabricated.
4-11 Steam drum shipped.
4-12 All material for single-tube model ordered.
4-13 All material for single-tube model received.
4-14 Single-Tube model fabricated.
4-15 Single-Tube model shipped.
4-16 Specifications for pumps and motors prepared.
4-17 Pumps and motors ordered.
4-18 Pumps and motors delivered.
4-19 Specifications for control valves prepared.
4-20 Control valves ordered.
4-21 Control valves delivered.
4-22 Specifications for Special Wire and electrical equipment prepared.
4-23 Special wiring and electrical equipment ordered.
4-24 Special wiring and electrical equipment delivered.
4-25 Specifications for instrumentation prepared.
4-26 Instrumentation ordered.
4-27 Instrumentation delivered.
4-28 Specifications for control hardware prepared.
4-29 Control hardware ordered.
4-30 Control hardware delivered.
4-31 Construction specifications prepared.
4-34 Construction bids received.
4-35 Construction contract award made.
4-36 Construction crew mobilized.

5-1 Site preparation completed.
5-2 Foundations and structures completed.
5-3 Heat exchangers and steam drum set.
5-4 Pumps and motors set.
5-5 Piping and valves installed.
5-6 Heat tracing and insulation installed.
5-7 Cable and electrical equipment installed.
5-8 Control hardware and instrumentation installed.
5-9 Berms built.
5-10 Preoperational system checkout completed.

6-1 Subscale SRE testing completed.
6-2 MMB testing completed.
6-3 Corrosion testing completed.

7-1 Data analysis completed.
7-2 Phase 1 designs and specifications revised, if necessary.

8-1 Kickoff meeting.
8-2 1st quarterly review.
8-3 Preliminary test plan submitted to Sandia National Labs.
8-4 2nd quarterly review.
8-5 Final test plan and procedures submitted to Sandia National Labs.
8-6 Corrosion test report submitted to Sandia National Labs.
8-7 3rd quarterly review.
8-8 4th quarterly review.
8-9 5th quarterly review.
8-10 Final report in draft form submitted to Sandia National Labs.
8-11 Final review.
8-12 Final report submitted to Sandia National Labs.

Figure I-6 Phase II Program Schedule

II. BASELINE SYSTEM OPTION

A. SRE SYSTEM DESCRIPTION

1. System Design

This baseline system is proposed to meet the primary objectives of the SGS SRE program, which are to demonstrate the design adequacy, fabrication techniques and operational capability of the full-scale system. The system will produce steam at the same outlet conditions as the full-scale system (1000°F and 1865 psia). The system produces the steam using molten salt at 1050°F from the storage SRE. The steam produced is cooled and condensed in the CRTF heat rejection system (HRS). The condensed steam is returned to the system as feedwater at the desired temperature. The system will be controlled locally using the storage SRE control building to house the SGS controls. In addition to the subscale steam generator testing, the SRE program includes a single-tube DNB test and a short-term corrosion test program.

In selecting the size of the SGS, the desire to have the system as large as possible was compared with the performance of the existing facilities at CRTF and the cost of improving that performance. To arrive at the proper total heat rate for the system, we have examined seven alternatives (Table II-1). Concept 1 is the least expensive since it uses the existing 3-MWt propane heater to supply energy continuously. However, the heat exchanger is extremely small and does not employ the capabilities of the other CRTF equipment, i.e., the HRS. The second concept would use the 3-MWt heater to fill the hot tank at the same time the tank is being discharged at a rate of 5 MWt. Thus the net discharge rate of the storage tank is 2 MWt. This rate can be maintained for a period of 3.5 hours. This system results in a good compromise between heat exchanger size and an adequate test time. This system is also consistent with the capability of the CRTF collector field and the current receiver designs. While remaining alternatives offer better scaling ratios or increased test times, the cost of adding the additional equipment was considered to be in excess of the SGS SRE budget. Further, the gain in size does not become significant until the heat rate reaches 12.5 MWt. Thus we have selected the 5-MWt system, concept 2, as the baseline system.

To ensure that the technical objectives of the Phase II program are satisfied, particular attention was given to the configuration of the individual heat exchangers and to the arrangement of the heat exchangers in the system. To accomplish the objectives of demonstrating design adequacy and operational capabilities and to resolve any performance uncertainties, we decided that each heat exchanger would simulate the thermal and hydraulic characteristics of the full-scale plant components. This means that the temperatures and pressures throughout each heat exchanger will be identical to the commercial units. Therefore the average tube length, tube diameter, wall thickness, tube spacing and shape will be the same as the full-scale design.

Table II-1 Comparison of SRE Size Options

Concept Number	Concept	Commercial 100-MWe Size-to-SRE Size Ratio	Test Time at Full Power	Additional Salt Equipment Required and Estimated Cost	Advantages	Disadvantages
1	3 MWt Continuous	88:1	Unlimited	None.	Minimum-cost system, unlimited test time.	Very small HX size.
2	5 MWt from Storage	53:1	3.5 h	Larger hot pump (17k).	Adequate HX size, adequate test time.	Cost.
3	5 MWt Continuous	53:1	Unlimited	2-MWt propane heater (92k), larger hot pump (17k).	Adequate HX size, unlimited test time.	Cost.
4	7 MWt from Storage	38:1	1.75 h	Larger hot pump (22k), hot sump (43k), 2-MWt propane heater (92k).	Good HX size.	Very short test time, cost.
5	7 MWt from Storage	38:1	3.5 h	2-MWt propane heater (92k), larger hot pump (22k), larger hot sump (43k), larger cold sump (43k).	Good HX size, adequate test time.	Cost.
6	7 MWt Continuous	38:1	Unlimited	4-MWt propane heater (160k), bigger hot pump (22k), larger hot sump (43k), larger cold sump (43k).	Good HX size, unlimited test time.	Cost.
7	12.5 MWt Continuous	21:1	Unlimited	9.5-MWt propane heater (320k), larger hot pump (34k), larger hot sump (56k), larger cold sump (56k), new water/steam heat rejection system (200k).	Very good HX size, unlimited test time.	Cost.

To maximize the size of each heat exchanger within the system, we decided to simulate the superheater and evaporator. The description of the commercial design given in Chapter I shows that the evaporator and preheater designs are similar. Because of this similarity and because the evaporator was the more critical component, we decided the preheater could be eliminated. The reheater was eliminated because of its similarity to the superheater and to allow a reduction in the total system cost.

Departure from nucleate boiling must be prevented in molten salt systems to eliminate any possibility of tube failure due to corrosion. This can be done by maintaining the proper circulation ratio. However, no empirical data exist for small-diameter ribbed tubes in a horizontal orientation. To obtain these data and thus improve the efficiency of the evaporator, a single-tube test has been included. The tube and shell are installed in parallel with the evaporator and can be run along with or independent of the rest of the SGS. The single tube is required because of the relative ease of instrumenting the unit compared to the problems of instrumenting a multitube unit.

A simplified flow schematic of the SGS SRE is shown in Figure II-1. On the water/steam side, boiler quality feedwater is supplied by the CRTF heat rejection system at 627°F and 2000 psia and enters the steam drum and mixes with recirculated water. Water from the steam drum is forced through the evaporator by the recirculation pump. The recirculation ratio, i.e., the ratio of the evaporator water flow rate to the feedwater flow rate, is 1.5:1, the same as the commercial system. The evaporator produces a high-quality water/steam mixture that is fed back to the steam drum.

Saturated steam is separated from the steam/water mixture in the drum. It then flows through the superheater where it is heated to 1000°F. The superheated steam is piped to the CRTF HRS.

On the salt side, hot salt at 1050°F is provided by the storage SRE and flows into the superheater. It exits the superheater at 838°F and flows into the evaporator. It leaves the evaporator at 637°F and flows into the cold salt tank in the storage SRE. An air-to-salt heat exchanger is shown in parallel with the superheater. This air cooler is the existing 5-MWt salt unit being used in the storage SRE. It will be used here to simulate the effects of a reheater on the salt-side flow. We decided not to use a reheater on the SGS SRE since the cost required to incorporate it would not add any new technology to the SRE. The salt side of the reheater, however, must be simulated to maintain the correct proportion of salt flow through each unit.

The maximum water/steam and salt mass flow rates and heat loads for the SRE are tabulated. These were determined on the basis of using the maximum discharge rate of the hot tank (5 MWt), the same operating temperatures as in the commercial SGS design, and the correct proportion of flow rates in each unit.

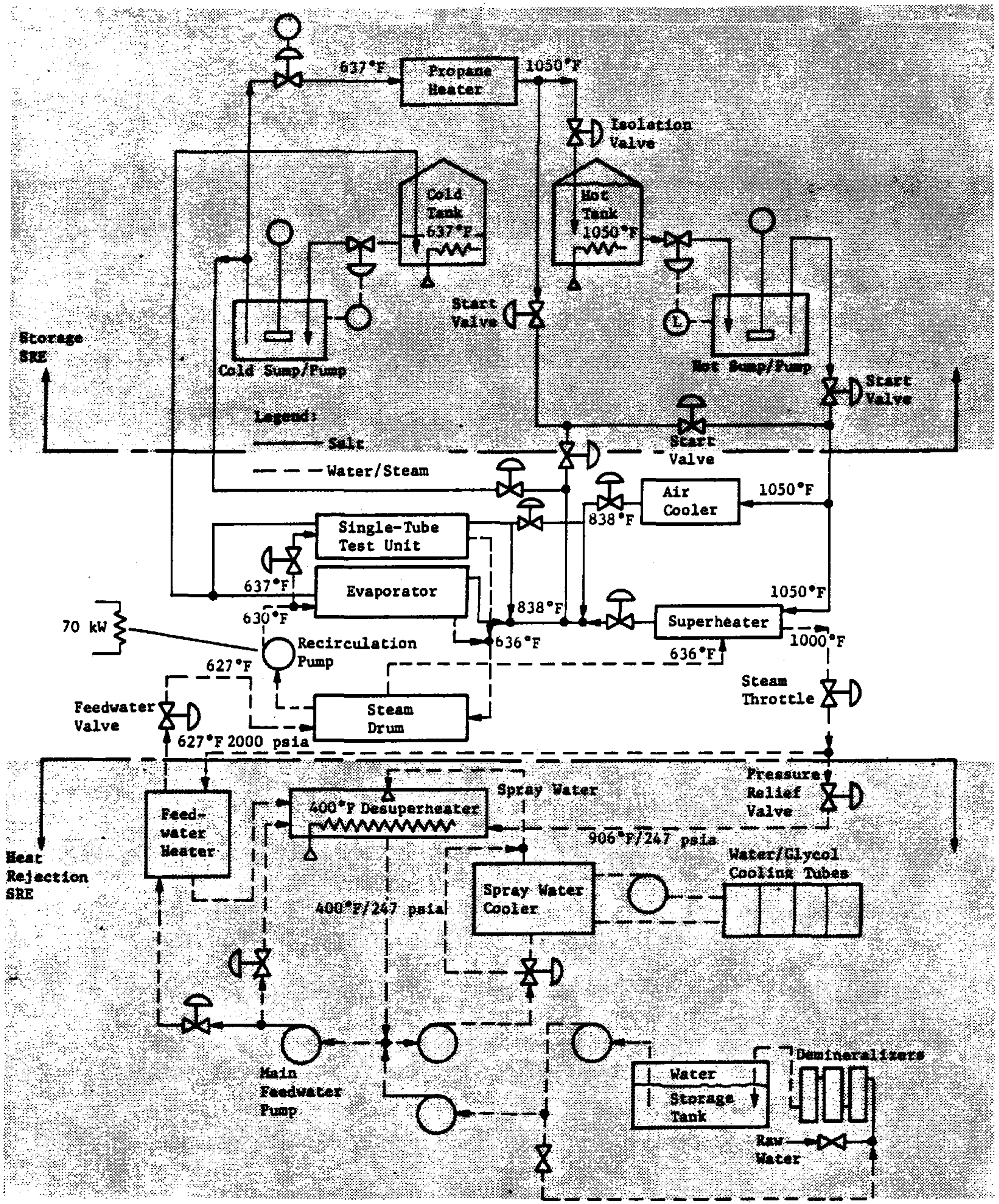


Figure II-1 CRTF Water/Steam Heat Rejection System Flow Schematic

Unit	Heat Load, MWt	Flow Rate, lb/h	
		Water/Steam	Salt
Evaporator	2.49	26,535	110,650
Superheater	1.77	17,690	78,010
Air Cooler	0.74	N/A	32,640
	5.00		

Figure II-1 includes a simplified flow schematic of the molten salt thermal energy storage SRE that is available at the CRTF. Basically the system consists of a hot tank, a cold tank, a propane heater and associated pumps, sumps, pipes and valves. Cold salt is pumped from the cold tank at 637°F through the propane heater where it exits at 1050°F. From there it flows into the hot tank where it is stored for subsequent use. When the SGS SRE needs hot salt, it is pumped from the hot tank.

The storage capacity of the hot salt tank is 5.7 MWht with the temperature difference used in this test. The maximum charge rate of the hot tank is 3 MWt and is limited by the ability of the propane heater. The maximum discharge rate of the hot tank is 5 MWt. The storage system is capable of simultaneous charge and discharge. The experiment can be run for 3.0 hours continuously at 5MWt before storage is exhausted.

Figure II-1 shows a simplified flow schematic of the CRTF water/steam heat rejection system. Steam is taken at 1000°F and 1865 psia, passed through a pressure-reducing valve where the pressure is reduced to 247 psia through a feedwater heater, and thence into a spray water desuperheater where it is condensed at 400°F. Water is taken from the desuperheater, pumped to 2000 psia, forced through a feedwater heater to be heated to 627°F, and then piped back to the SGS SRE. When there is no source of high-temperature high-pressure steam (as during startup), the feedwater outlet temperature is limited to a maximum value of 400°F. Part of the water exiting the desuperheater is extracted and sent through the spray water cooler and recirculated to the desuperheater as spray water. The spray water cooler is a heat exchanger, with the other fluid being a water/glycol mixture that rejects heat to the atmosphere via a cooling tower. The HRS also has a 20,000-gallon water storage tank and a system of demineralizers so it is capable of providing an adequate supply of boiler quality feedwater at all times.

Figure II-2 shows the general arrangement of all the components at the CRTF. Since the storage SRE and the HRS exist, their layout is fixed. The SGS SRE layout gives an idea of the space required and the run lengths for the piping. The most advantageous location for the SGS SRE will be determined. The operation of the SGS SRE, as well as the storage SRE and the HRS, will be directed from the existing storage control building.

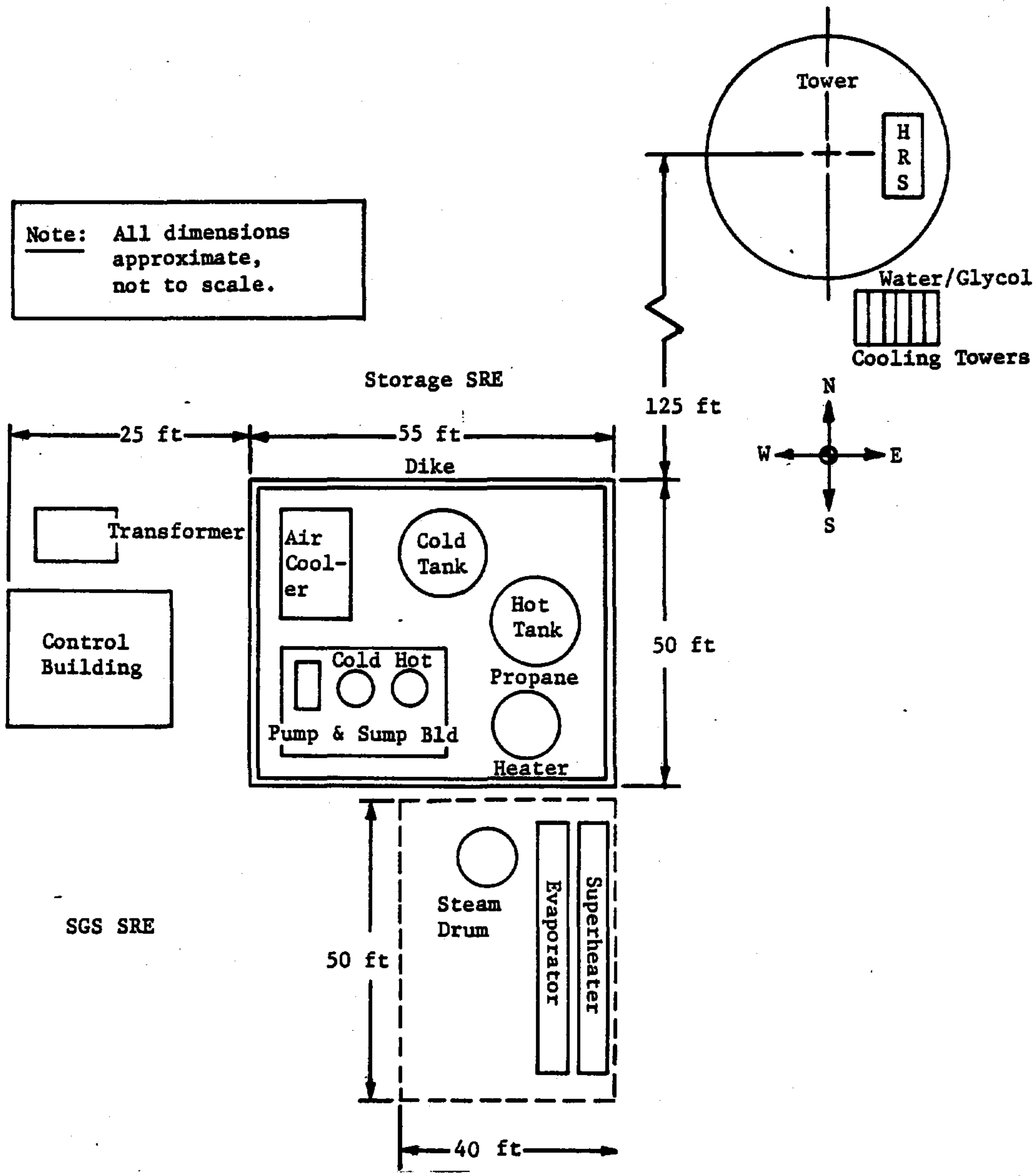


Figure II-2 General Arrangement

The SGS SRE is designed to make maximum use of the CRTF facilities and equipment. The SGS will interface with the storage system SRE to simulate operation of a commercial unit. The size of the SGS will be consistent with the size of the other major components of the molten salt central receiver system at the CRTF. The SGS SRE will require the use of a plot of land, all existing thermal storage SRE equipment, and the CRTF water/steam heat rejection system. The details of these interfaces are:

1) Land - The SGS SRE will need a plot of CRTF land adjacent to the storage SRE. A rectangular plot approximately 40x50 feet should suffice. This land will have to be cleared of any existing heliostat foundations and wiring;

2) Molten salt thermal storage SRE - The SGS SRE will need to use all of the existing storage SRE equipment on a fully dedicated basis during SGS testing. This includes the hot tank, cold tank, sumps, pumps, piping, controls, control building, etc. The SGS will require hot salt at 1050°F from the storage SRE at rates up to 5 MWt (mass flow rates up to 110,650 lb/h). The SGS SRE testing will also require lesser salt flow rates for startup, shutdown, and part-load operation. The SGS SRE will also return cold salt at 637°F to the storage SRE at rates up to 110,650 lb/h. The SGS SRE will need electricity from the storage SRE substation to run the recirculation pump, controls, and trace heating. Compressed air will be required to operate the control valves. The SGS SRE will require that the current hot pump be replaced by Sandia with a larger pump capable of a 110-psi head at 135 gpm;

3) Water/steam heat rejection system (HRS) - The steam generator SRE will generate 1000°F/1865 psia superheated steam at a maximum rate 17,690 lb/h. It will require up to 17,690 lb/hr of 627°F/2000 psia boiler quality feedwater. The HRS will be required to cool and condense the steam and to supply feedwater at the given conditions when the SGS SRE is in operation. Since the feedwater flow rate is critical, the SGS SRE will have to be able to control the HRS main feedwater pump;

4) Air molten salt cooler - The reheater will not be used on the SGS SRE because it would add additional cost without providing any new technology. But the salt side of the reheater must be simulated to maintain the correct proportion of salt flow through each heat exchanger. Therefore an air cooler that was previously used on the storage SRE will be used to simulate the reheater (Fig. II-1). The air cooler is a fan-type unit with a maximum capacity of 5 MWt of heat rejection. Molten salt will enter the air cooler at 1050°F and exit at 838°F. The SGS SRE control system will interface with the air cooler to control salt flow rate and temperature;

5) Instrumentation and controls - Operation of the SGS SRE will be controlled from the existing storage SRE control building. A mobile data logger available at the CRTF will be the mainframe of the data acquisition system. Two existing CRTs on the storage SRE operator's console will monitor selected parameters and an alarm CRT will display warning and alarm information. The raw data will be

recorded on a magnetic tape. Following the experiment, the data tape will be taken to the main control room and reduced by the MCS computer;

6) Steam generator blowdown - The steam generator blowdown will be discharged to a small blowdown tank on an intermittent basis and ultimately discharged to the ground;

7) Salt drain - The SGS SRE salt piping and heat exchangers will be designed so the molten salt can be drained into the existing cold salt sump.

2. Heat Exchanger and Steam Drum Preliminary Design

Table II-2 provides a material list for the principal components of the SRE--the evaporator, superheater, and steam drum. Preliminary designs for each of these components are shown in Figures II-3 thru II-5.

Table II-2 SRE Steam Generator Component Materials

Component	Material
Evaporator	
Tubes only	2 1/4 Cr-1Mo Steel
All other material	1 1/4 Cr-1/2Mo Steel
Superheater	304 Stainless Steel
Steam Drum	Carbon Steel

A major objective was to simulate the important thermal-hydraulic characteristics of the large plant components so performance test data would visibly demonstrate the expected performance of the plant units. Therefore the SRE components duplicate the average tube length, tube diameter, wall thickness, and tube spacing so the thermal profile along the tube (and thus the heat flux distribution) and the tube-side and shell-side mass flow rate and velocity are suitably modeled. The number of tubes in the bundle is then proportional to the thermal ratings of the components.

Efforts were made to maximize the size of the SRE components while maintaining compatibility with the CRTF test capability. By choosing only two components, i.e., the evaporator and superheater, the unit sizes were maximized to get the best test performance while minimizing component cost.

Since the structural design and anticipated fabrication techniques for the commercial plant component designs involve standard practice, simulation of mechanical design features in the SRE components has been considered a secondary objective. Where appropriate, facilitating the assembly process and reducing fabrication cost and schedule has been emphasized. Nonetheless, important mechanical design features such as the tube-to-tube sheet weld and broached tube support plate hole configurations are modeled. The SRE component designs comply with the requirements of Section VIII, Division 1 of the ASME code.

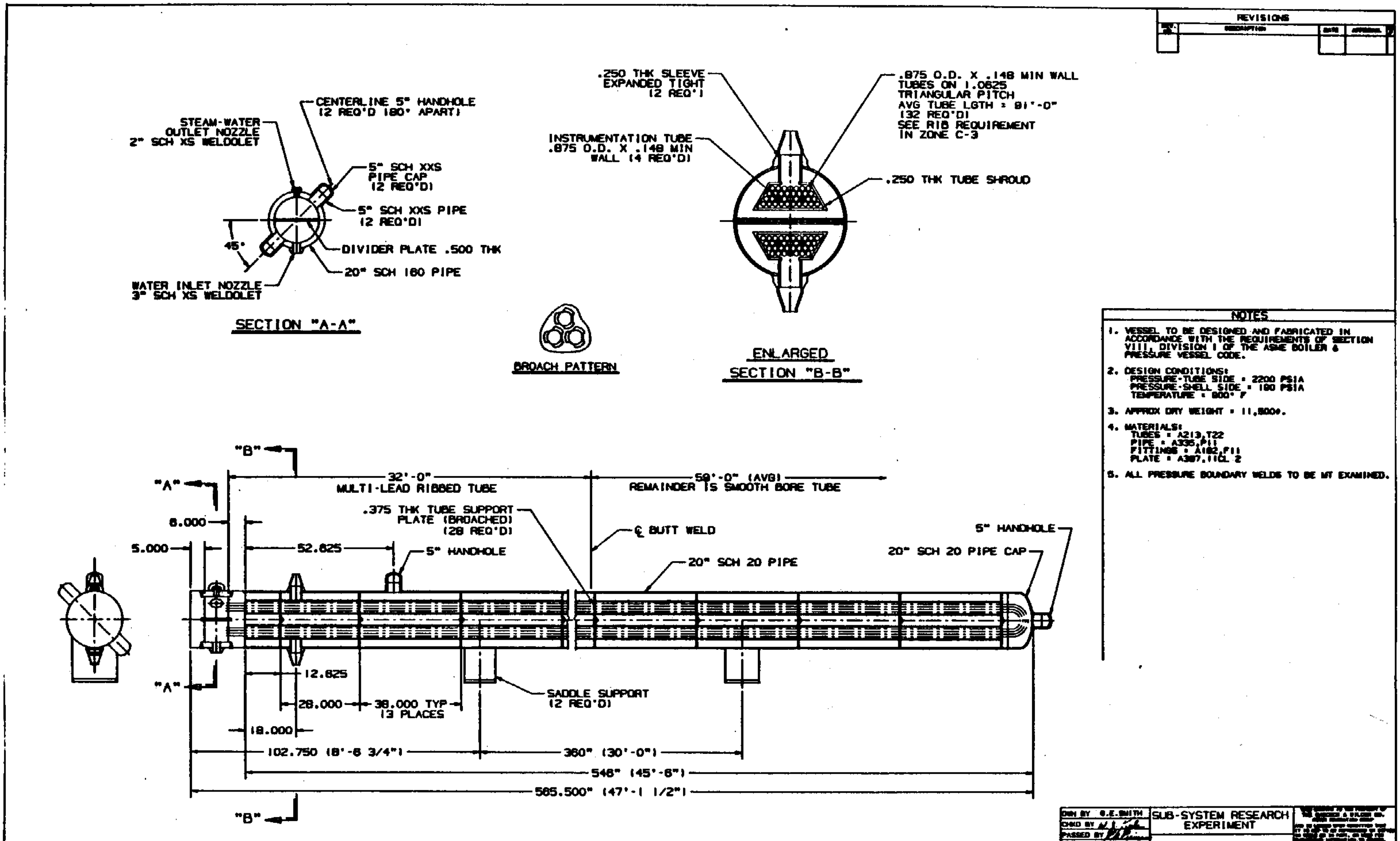


Figure II-3 SRE Evaporator Design

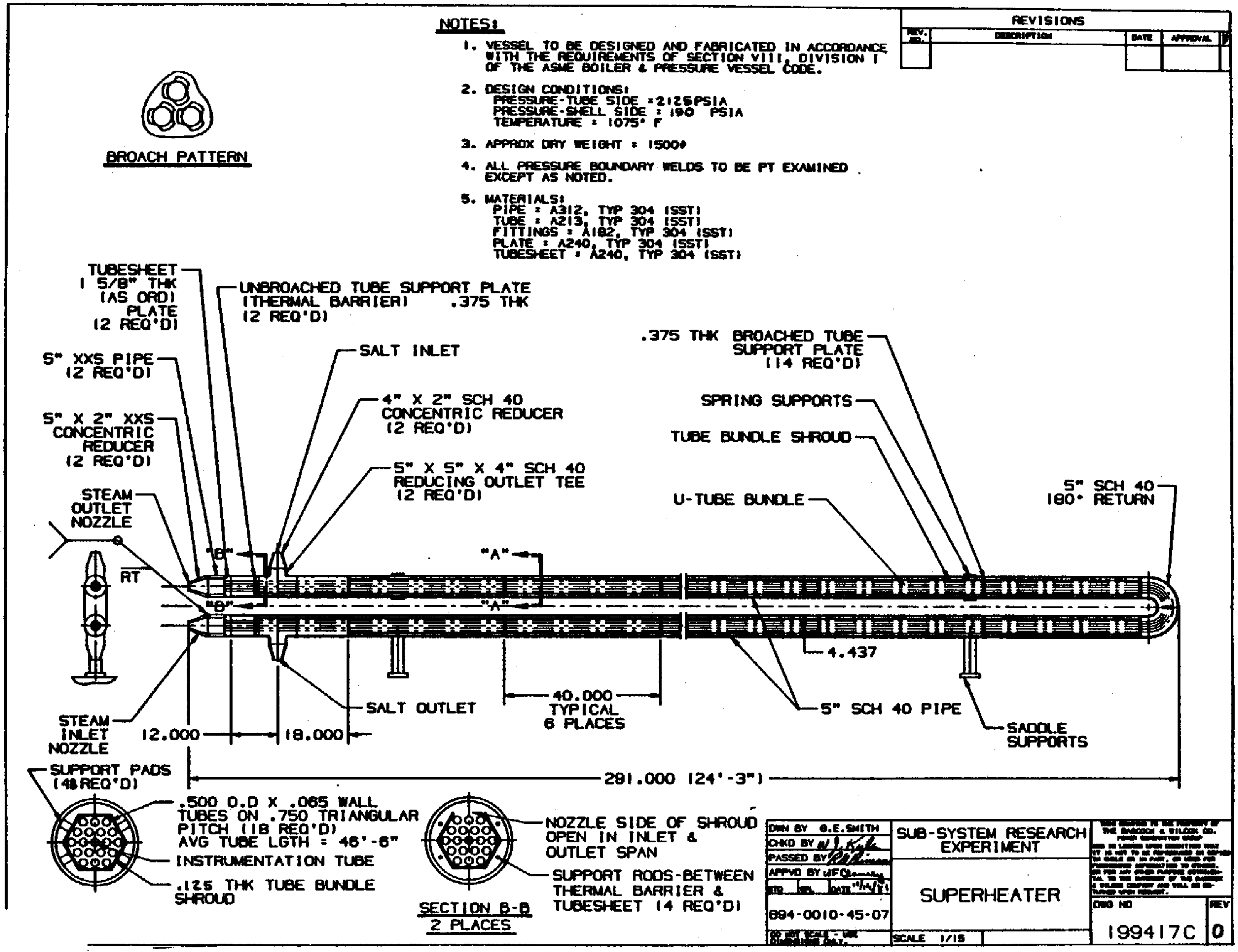


Figure II-4 SRE Superheater Design

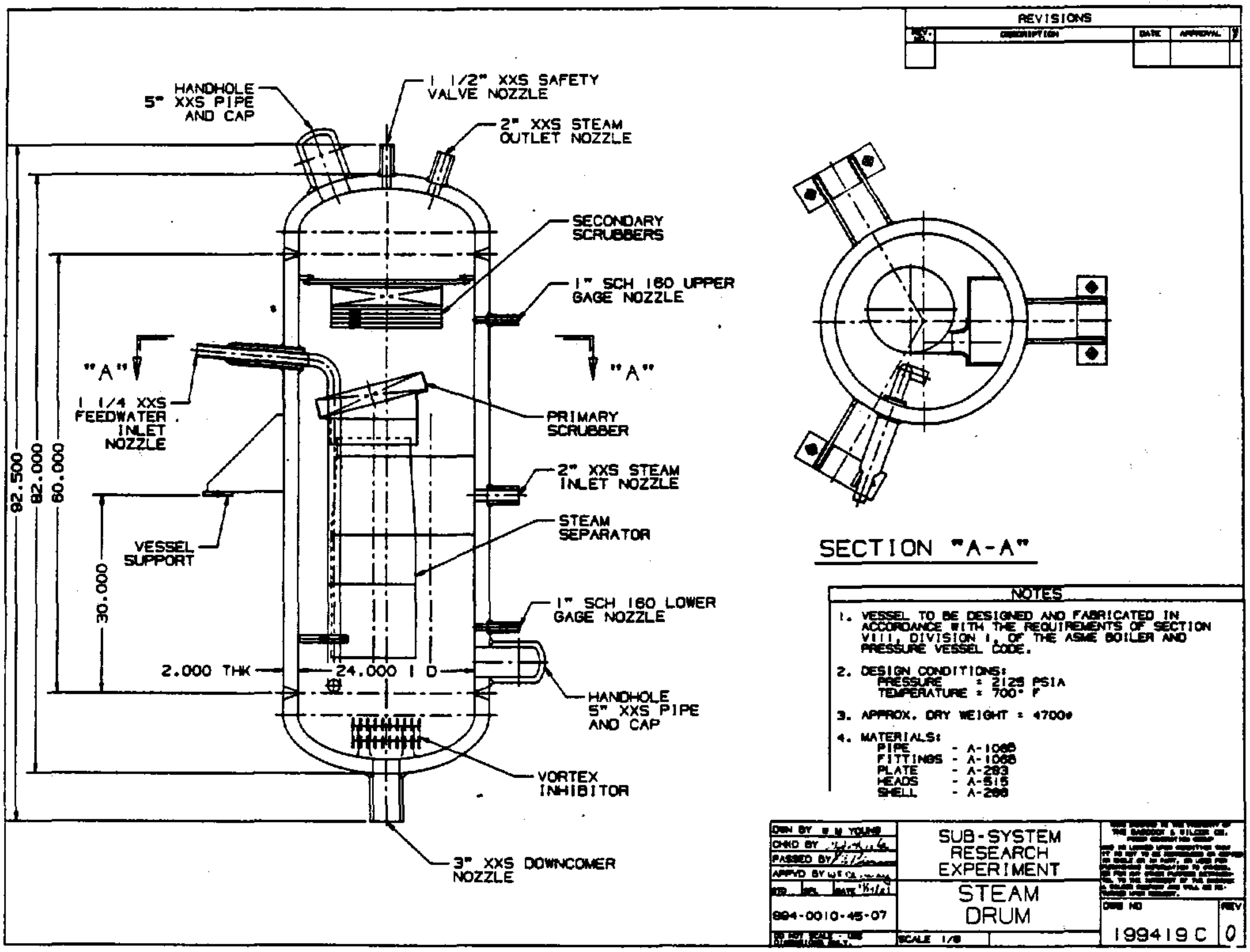


Figure II-5 Design Detail - Steam Drum

Performance and key features of the evaporator and superheater designs for the SRE and 100-MWe plant are compared in Tables II-3 thru II-5. Each of the SRE components is described in the following paragraphs. Where the SRE component designs deviate from those of the 100-MWe plant, the deviations are described and justified.

Table II-3 Evaporator Design Comparison (SRE and 100-MW Arrangements)

Characteristics	SRE Design	100-MW Design
Tube Length (avg)	91.0 ft	91.0 ft
Tube OD	0.875 in.	0.875 in.
Tube Wall Thickness	0.148 in.	0.148 in.
Tube Pitch	1.062 in.	1.062 in.
Number of Tubes	32	1230
Heat Transfer Area	667 ft^2	25500 ft^2
Tube Support Plate	Broached Hole	Differentially Broached Hole
Loop End Tube Support	None	"Wiggle Bars" for Vibration Restraint
Tube Bundle Shroud	Tight-Fitting Shroud	None
Inlet Flow Distributor	None	Perforated Inlet Distribution Plate

Some of the key features of the SRE design compared to the 100-MW are:

1) The average tube length in the SRE is equivalent to that in the 100-MW design. Thus the temperature profile along the tube is modeled in the 100-MW design and heat transfer is enhanced by crossflow induced through differential broaching of support plate holes. Crossflow cannot be accomplished in the SRE because of the small bundle diameter. Thus the number of tubes in the SRE is about 10% greater than expected from a simple ratio of the thermal ratings of the heat exchangers. The flow per tube is then slightly less in the SRE than the 100-MW design;

2) The tube support plate holes in the 100-MW design are differentially broached to induce crossflow and enhance heat transfer (see above);

3) The developed length of tube bends in the SRE is insufficient to require vibration restraint;

4) A shroud is used in the SRE to limit flow bypassing the heat transfer surface and enable the tube bundle to be housed in a standard-size pipe;

5) The diameter of the salt inlet nozzle in the SRE is increased to limit impingement velocity.

Table II-4 Superheater Design Comparison (SRE and 100-MW Arrangements)

Characteristics	SRE Design	100-MW Design
Tube Length (avg)	46.5 ft	46.5 ft
Tube OD	0.500 in.	0.500 in.
Tube Wall Thickness	0.065 in.	0.065 in.
Tube Pitch	0.750 in.	0.750 in.
Number of Tubes	18	772
Heat Transfer Area	107 ft^2	4600 ft^2
Tube Support Plate	Broached Hole	Broached Hole
Loop End Tube Support	None	"Wiggle Bars" for Vibration Restraint
Tube Bundle Shroud	Tight-Fitting Shroud	None

Table II-4 shows that the average tube length in the SRE is equivalent to that in the 100-MW design. The number of tubes in the SRE is reduced in proportion to the thermal ratings of the heat exchangers so the important thermal-hydraulic characteristics (temperature profile along the tube and flow per tube) are properly modeled.

The developed length of tube bends in the SRE is insufficient to require vibration restraint. A shroud is used in the SRE to limit flow bypassing the heat transfer surface and enable the tube bundle to be housed in a standard-size pipe. The diameter of the salt inlet nozzle in the SRE is increased to limit impingement velocity.

a. Evaporator - The evaporator is arranged horizontally and employs U-tubes housed in a straight shell. Slightly subcooled water returned from the steam drum is delivered to the lower leg of the tube bundle and flows through the tubes in counterflow with the molten salt stream. The tubes are 0.875-inch OD and are compactly arranged on a 1.0625-inch triangular pitch. The tube bundle is enclosed by a shroud that prevents any significant amount of salt bypassing the heat transfer surface. The inherent flexibility of the U-tube readily accommodates tube/shell and tube/tube differential thermal expansion during normal and transient operation.

The final 32 feet of each tube is of a multilead internal rib construction. These ribs promote boundary-layer turbulence and centrifugal forces that maintain nucleate boiling to a higher quality than possible with a smooth-bore tube of the same general dimensions. At full load, the steam water mixture is discharged from the evaporator at a quality of approximately 67%.

Table XI-5
Comparison of Performance Characteristics (SRE and 100-MW Arrangements)

Characteristics	SRE Design	100-MW Design
Evaporator		
Thermal Rating	2.49 MWt	107.9 MWt
Salt Inlet Temperature	838°F	838°F
Salt Outlet Temperature	637°F	637°F
Salt Flow Rate	110,650 lb/h	4.78×10^6 lb/h
Water Inlet Temperature	630°F	630°F
Steam Water Outlet Temperature	636°F	636°F
Steam Water Flow Rate	26,540 lb/h	1.15×10^6 lb/h
Circulation Ratio	1.5	1.5
Superheater		
Thermal Rating	1.77 MWt	76.3 MWt
Salt Inlet Temperature	1050°F	1050°F
Salt Outlet Temperature	838°F	838°F
Salt Flow Rate	78,010 lb/h	3.37×10^6 lb/h
Steam Inlet Temperature	6.36°F	636°F
Steam Outlet Temperature	1000°F	1000°F
Steam Flow Rate	17,690 lb/h	0.76×10^6 lb/h
Steam Drum		
Feedwater Temperature	627°F	627°F
Feedwater Flow Rate	17,690 lb/h	0.764×10^6 lb/h
Saturation Temperature	636°F	636°F
Saturation Pressure	2000 psia	2000 psia

The evaporator design for the SRE deviated from the 100-MWe commercial plant design as follows:

1) In the 100-MWe design, heat transfer is enhanced by crossflow induced through differential broaching of support plate holes. However, crossflow cannot be accomplished in the SRE because of the small bundle diameter. Thus the number of tubes in the SRE is about 10% greater than expected from a simple ratio of the thermal ratings of the heat exchangers. The flow per tube is then slightly less in the SRE than in the 100-MWe design. Because DNB (departure from nucleate boiling) is sensitive to mass flow rate, the SRE design may be considered slightly less conservative than the 100-MWe design;

2) A shroud is used in the SRE to limit flow bypassing the heat transfer surface. A shroud is not required in the 100-MWe design because the much greater number of tubes can be arranged in a pattern closely approximating a perfect circle and fitting snugly within the round heat exchanger shell;

3) In the 100-MWe design a perforated inlet distributor is used to disperse the molten salt evenly to the tube bundle. To simplify the SRE design, the salt inlet nozzle has simply been oversized to limit impingement velocity;

4) "Wiggle-bar" supports are provided for vibration restraint in the tube bend region of the 100-MWe design. The developed length of the bends in the SRE is short, eliminating the need for loop end supports;

5) All material in the 100-MWe design is 2 1/4 Cr-1Mo. In the SRE, this alloy is used only for the tubing. All other material is 1 1/4 Cr-1/2Mo steel. Use of the lower alloy permits radiography of certain pressure boundary welds to be waived while still satisfying all code requirements. This enables vessel assembly procedures to be simplified and fabrication cost and schedule to be reduced without compromising performance characteristics.

b. Superheater - The superheater is also arranged horizontally and employs U-tubes housed in a U-shell. Saturated steam from the steam drum is delivered to the lower leg of the tube bundle and flows through the tubes in counterflow with the molten salt stream. The tubes are 0.500-inch OD and are arranged on a standard 0.750-inch triangular pitch. The tube bundle is enclosed by a shroud that prevents any significant amount of salt bypassing the heat transfer surface.

The U-shell configuration is employed because the tube-side inlet-to-outlet terminal temperature difference is large and unacceptable thermal stresses may be developed unless the tube sheets are independent. The inherent flexibility of the U-tubes still readily accommodates tube/tube and tube/shell differential thermal expansion during normal and transient operation.

Deviations in regard to the tube bundle shroud, inlet flow distributor, and loop end supports described previously for the evaporator design also apply to the superheater design. There are no other deviations of significance.

c. Steam Drum - The steam drum is quite similar to a previous design developed by B&W and tested by Honeywell in an early DOE 5-MWe steam/water receiver experiment. The drum is oriented vertically and contains a single cyclone steam separator and scrubber assembly. The 100-MWe design is by nature a modular arrangement incorporating 40 separators. Thus the modeling process is straightforward because the steam flow rate in the SRE is approximately 1/40 of that in the 100-MWe design. One separator is required for the SRE.

Steam/Water - The steam/water mixture from the evaporator is delivered to the drum and the phases are separated. The saturated steam is delivered to the superheater, while the saturated water is mixed with incoming feedwater and returned via the downcomer to the evaporator.

d. Single-Tube DNB Test - In conventional steam generating equipment, experience has shown that departure from nucleate boiling must be prevented to avoid failure of tubes from overheating in an extremely short time, and corrosion of tubes in zones where overheating is not a consideration. In solar steam generators where heat input is limited by the temperature of the heating fluid, overheating of tubes is not of concern. However, under-deposit corrosion where DNB occurs in the presence of porous waterside deposits is a major design and operational consideration. This corrosion can occur either rapidly or over a long period depending on the level of heat flux and the boiler water purity.

In traditional steam generator design practice, the circulation ratio (or mass flow rate through the evaporator) is fixed high enough to maintain nucleate boiling in all circuits. However, high circulation rates lead to increased pumping power requirements and reduced cycle efficiency. Thus ribbed tubes are often used in the evaporator surfaces. This tube construction produces a swirling flow and centrifugal forces that keep the tube surface wetted and maintain nucleate boiling to a higher quality for a given pressure, heat flux, and mass flow rate than with a smooth-bore tube of the same general dimensions.

In the SRE as well as in the commercial subsystem designs ribbed tubes are used for the last 32 feet of the evaporator surface, which constitutes the steam/water outlet end of the evaporator surface. Smooth tubes are used in the remaining low heat flux sections of the component. To preclude DNB, a circulation ratio of 1.5 has been established.

Figure II-6 shows a sample of available DNB data. The limiting mass flow rate is described as a function of steam quality for various values of heat flux. Typically the limiting curves uniquely depend on steam pressure, tube diameter and angle of inclination, and rib helix angle. Because specific data applying to small-diameter ribbed tubes in horizontal orientations is not available, we have reviewed the most applicable published and B&W proprietary data, added prudent design margins, and selected a circulation ratio we believe to be conservative. We propose that well-controlled DNB tests be completed for the applicable design configuration to confirm our choice of circulation ratio and to determine if design margins can be safely reduced.

Special problems in detecting the location of DNB can occur. With vertical tubes, DNB normally occurs at high steam quality where the amount of liquid available for tube wetting is small. In horizontal tubes, the same phenomenon at high quality is encountered, but DNB may also occur at low qualities where the liquid fraction is high but where the steam velocity is low. This is shown in Figure II-6 where a peak in the limit curve shows possible DNB at the SRE design mass flow of

450,000 lbm/h-ft².* The mechanism of low-quality DNB is stratification of the liquid and vapor phases. In this case the DNB is usually detected at the top of the tube. The DNB test should therefore address both the high- and low-quality flow regimes.

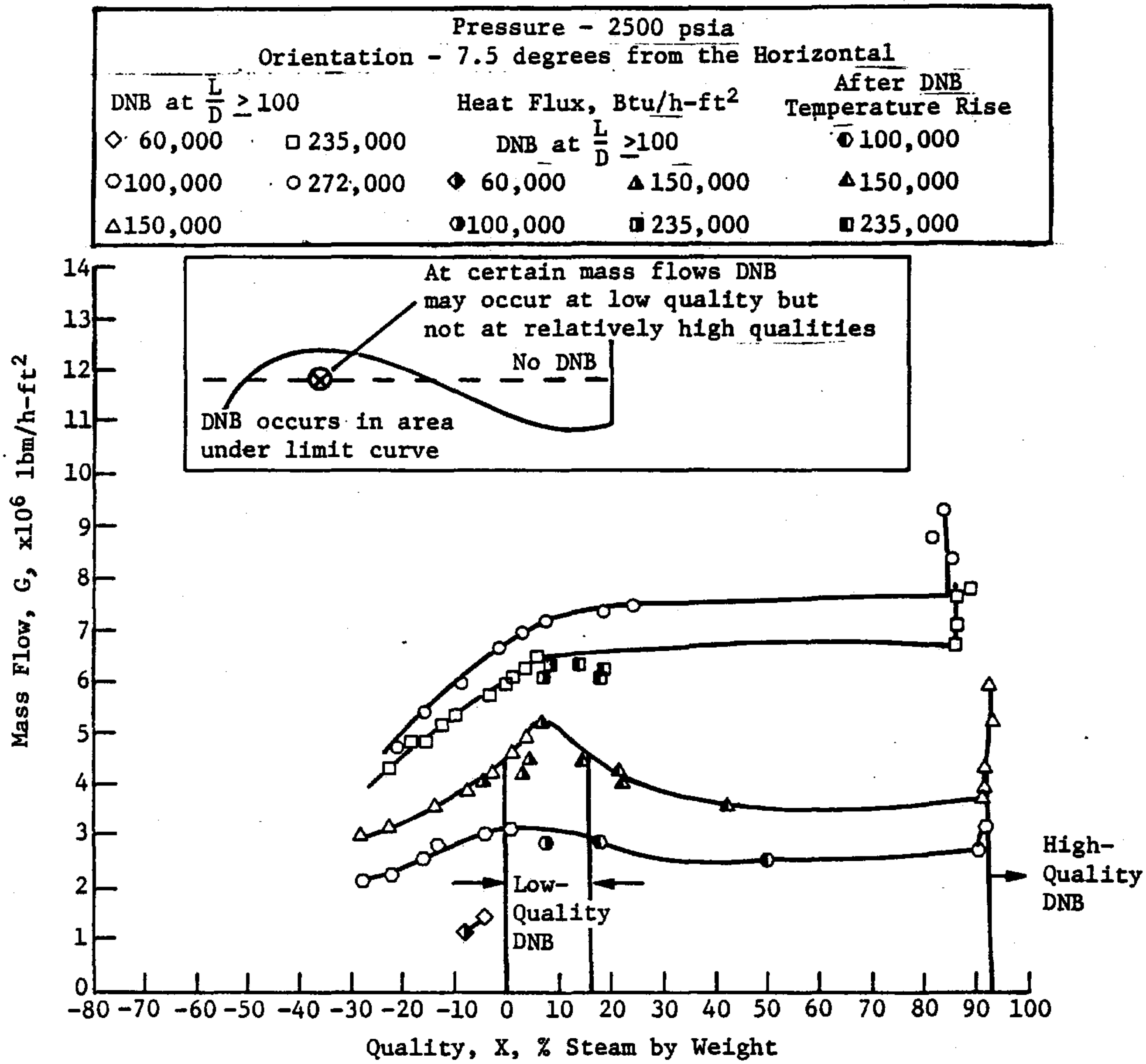


Figure II-6
Ribbed Tube DNB Limits at 2500 psia and 7.5-deg Inclination

To perform the DNB testing, we propose that a single-tube test section be installed along with the other components in the SRE steam system. The single tube will have counterflow of salt outside a ribbed tube as

*It should be noted that the heat flux in this example is higher than expected in the SRE at these low qualities. The limiting curve for lower heat flux would be much lower and DNB is not exptected to occur.

in the evaporator. Molten salt therefore will be the heat source rather than the electrically heated elements used in conventional DNB tests. The resulting heat flux profile will be more similar to the evaporator profile than a constant heat flux electrically heated test section. The single tube will be less costly to instrument for tube metal temperatures than the evaporator since it does not have the evaporator shroud between the tubes and shell.

Single-Tube Test Section - The single-tube test section will be placed in parallel with the evaporator as shown in Figure II-7. During DNB testing a portion of the molten salt from the air-cooled reheater outlet and the cold salt recirculation supply will be bypassed to the single tube. Salt inlet temperature will be manually controlled by varying the relative flow from the two streams with two remotely actuated control valves. Total salt flow will be manually controlled with a third remotely actuated control valve at the exit. Total heat input will be obtained calorimetrically from the change in salt temperature measured at the outlet leg. When other SRE system tests are being performed, the single-tube section will be isolated on the salt side with two isolation valves.

On the steam side, a portion of the recirculation water flow to the SRE evaporator is bypassed to the single tube. The flow will be manually controlled with a remotely actuated control valve. A flowmeter in the line will be used to set up the range of the single-tube mass velocities required for the test. The thermocouple in the main recirculation line will be used to obtain the single-tube inlet temperature.

The single-tube temperature measurements are shown in Figure II-8. The test section is composed of the ribbed tube enclosed by an outer pipe that forms the salt pressure boundary. A tee at one end of the pipe provides an inlet for the salt. Salt flows in the annulus formed by the outside surface of the ribbed tube and the inner surface of the pipe. The area of the annulus will be as close as possible to the flow area per tube in the evaporator. The salt exits the test section through a second tee at the opposite end of the pipe.

Tube metal temperatures will be measured to facilitate detection of DNB and pipe metal temperatures will be measured to establish the salt temperature profile. Since DNB may occur with stratification of liquid and vapor, tube metal temperature will be taken at both the top and bottom of the tube at many locations along the length of the tube. More thermocouples will be placed on the top than on the bottom since this is where DNB will most likely be initiated. By comparing differences in top and bottom tube metal temperatures, the local DNB due to stratification can be detected.

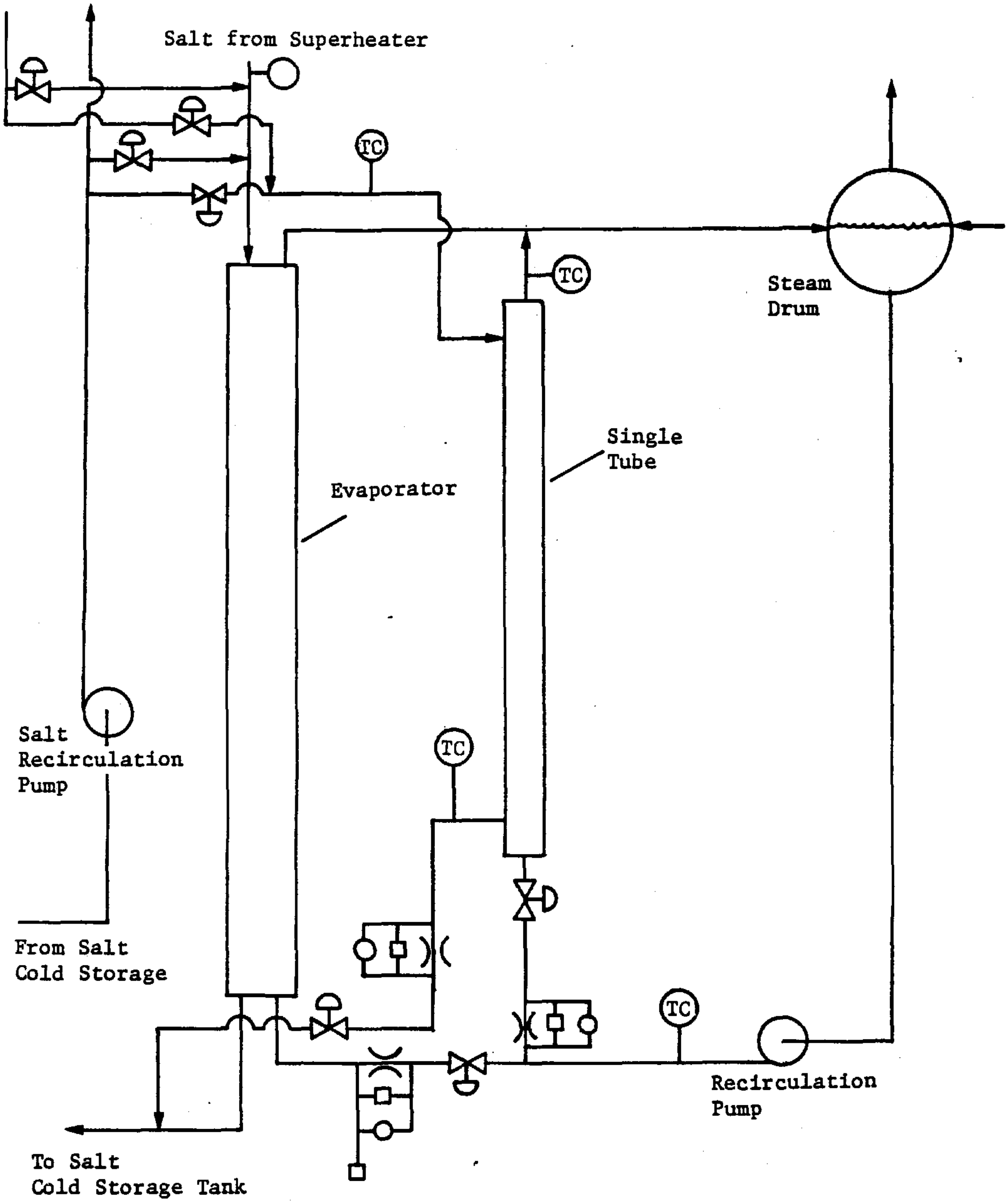


Figure II-7 Single-Tube Test Section

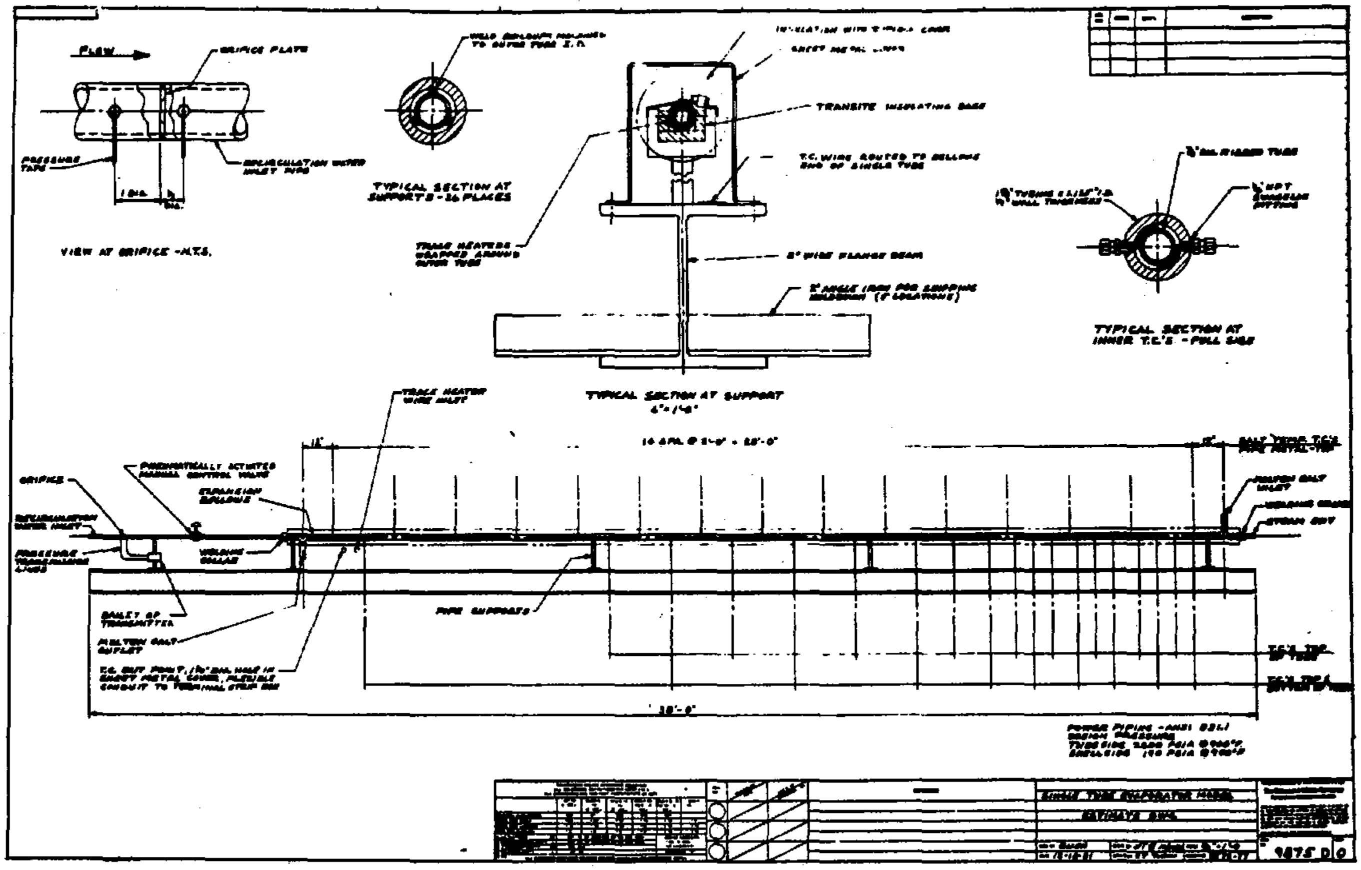


Figure II-8 Single-Tube Temperature Measurements

Single-Tube Heat Transfer Characteristics - The heated portion of the ribbed tube will be approximately 30 feet long. It will be manufactured from the maximum continuous length of ribbed tube available, which is 32 feet. The heated length has a significant influence on the heat flux profile that can be obtained for a given steam mass velocity, recirculation water temperature, steam exit quality, and salt inlet temperature. Predicted heat flux profiles (developed using B&W's VAGEN computer program) for the 30-foot single tube and the 90.5-foot SRE evaporator tube are shown in Figure II-9. Recirculation water flow, inlet salt temperature, and steam exit quality are identical in each case. In Case A the single-tube salt flow is 1.34 times the evaporator salt inlet temperature. In Case B the salt flow is 71 times the evaporator flow. The salt inlet temperature is 800°F rather than 838°F, but the exit heat flux is identical to the evaporator exit heat flux.

Since the total heat transfer for Cases A and B is the same as the evaporator, the average single-tube heat flux is approximately three times the average evaporator heat flux. Although average heat fluxes differ significantly, the single-tube exit heat flow exceeds the evaporator exit heat flux by only 14% in Case A. Case B shows that the exit heat fluxes can be matched by simply adjusting the salt flow and inlet temperature.

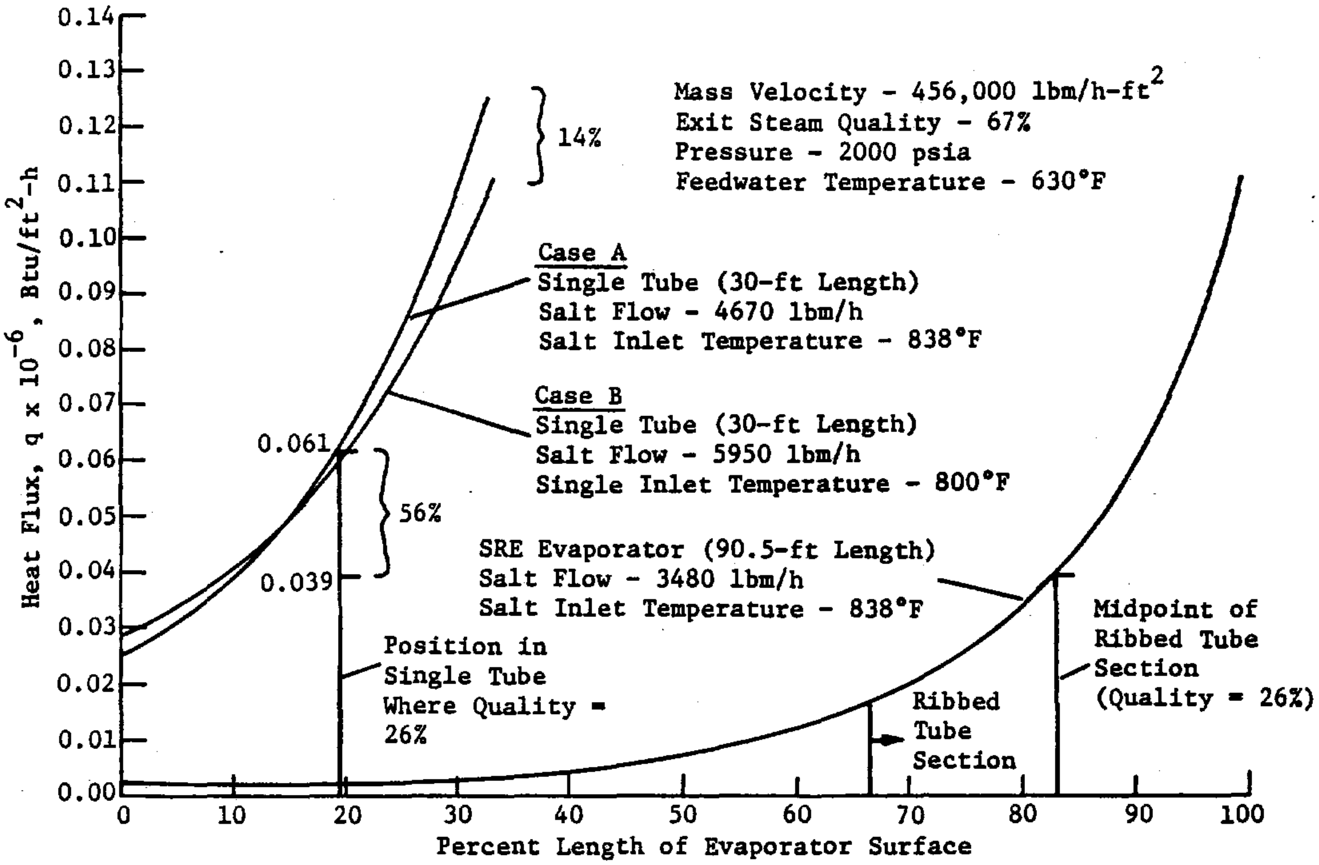


Figure II-9 Heat Flux Profiles

Figure II-9 also shows that for a fixed set of salt inlet conditions the difference in single-tube and evaporator heat flux increases for matching single tube and evaporator steam qualities. For example, at the midpoint of the ribbed tube section in the evaporator, the steam quality is 26% and the heat flux is 39,000 Btu/ft^2-h. In the single tube (Case A) at a quality of 26%, the heat flux is 61,000 Btu/ft^2-h. The difference in heat flux is 56% at a quality of 26% and the difference is only 14% at 67% quality.

For the heat transfer characteristics of the single tube, we recommend the following be done for the DNB test:

1) Tube metal temperature measurements should be concentrated near the steam exit (salt inlet) portion of the single tube. Temperature measurements should be made in the other areas, but at wider spacings along the length;

2) The heat flux at the exit can primarily be controlled by varying the salt inlet temperature. Salt flow rate has a secondary effect due to the change in the overall heat transfer coefficient;

3) The salt flow rate can be used to set up a nominal (design) steam exit quality. Once this is done, salt inlet temperature and flow rate should be held constant;

4) Other heat transfer analyses with the VAGEN code not presented here have shown that changes in steam flow rate have a small effect on the heat transfer and heat fluxes because the nucleate boiling coefficient is relatively large, implying a small contribution to the total thermal resistance. Similarly, this coefficient is also not strongly influenced by flow rate. Thus once the salt side conditions are set, the steam flow rate should be lowered until DNB is detected. This process will take place at a nearly constant exit heat flux until DNB occurs;

5) Due to the differences in single-tube and evaporator heat fluxes with quality, the DNB testing should be broken up into two phases. The first phase should be a high-quality DNB test and the second a low-quality DNB test. In the low-quality test, the difference in heat flux of 56% at 26% quality presented in the previous example would be reduced to the same level of uncertainty as at the higher qualities. The low-quality test would be accomplished by lowering the salt inlet temperature, total heat transfer, and steam exit quality. The low-quality steam would then occur at the exit where the tube metal temperature measurement instrumentation is concentrated.

Single-Tube Test Matrix - A 3x3 test matrix is planned for both the high-quality and low-quality test phases. A total of 18 combinations of salt flows and inlet temperatures will be tested as shown in Figure II-10. There will be nine combinations each for the high-quality and low-quality tests. At each of the 18 salt inlet conditions, a nominal steam flow rate corresponding to the evaporator recirculation water flow rate will be set. If no DNB is indicated, the single-tube water flow will be lowered until DNB is detected. This will indicate the DNB design margin.

For the high-quality tests, thermal loads of 70, 100, and 130% will be established for each of the three inlet temperatures. The salt flows for the design inlet temperature of 838°F have been calculated with the VAGEN code for each of the loads. The relative values are shown in Figure II-10. The salt flows for the other loads will be calculated during the detailed test preparations.

For the low-quality tests, a thermal load of approximately 39% will yield the same recirculation water flow and salt flow as in the high-quality test with an inlet salt temperature of 720°F. The 27 and 50% loads on either side of 39% have been selected to give a similar range of salt flows used in the high-quality test. The other salt flows at the 680 and 760°F inlet temperatures are yet to be determined.

High-Quality DNB Test Matrix

Salt Temperature, °F	Thermal Load 70%	100%	130%
800	*	*	*
838	0.64	1.0	1.38
890	*	*	*

Salt Flow (Relative Units)

Low-Quality DNB Test Matrix

Salt Temperature, °F	Thermal Load 27%	39%	50%
680	*	*	*
720	0.64	1.0	1.38
760	*	*	*

Salt Flows (Relative Units)

*Salt flow to be determined.

Figure II-10
Single-Tube DNB Test Matrix

3. Controls and Instrumentation

a. Controls - A complete steam-electric generating system deriving thermal energy from a solar system with significant thermal storage is inherently a base load plant. Load maneuvering requirements will essentially be limited to diurnal startup and shutdown. The control of such a steam generating system is relatively simple.

The control system for the SRE will be a straightforward scheme based on conventional boiler operating practice. It will provide the following functions required of any well-designed boiler control system:

1) Control of the superheater outlet pressure by adjustment of molten salt flow rate (analogous to fuel input in conventional practice);

2) Regulation of the supply of feedwater to maintain a predetermined water level;

3) Flexibility during operation by provision of "switch to manual" operation when occasion demands;

4) Protection against equipment damage by activation of functional operations that limit temperatures when an established criterion is reached.

Another normal requirement is to maintain final steam temperature within prescribed limits. This is usually accomplished through attemperation. For the SRE this requirement will be waived to simplify the system and reduce cost. The final steam temperature can then be expected to slightly exceed the 1000°F design point (depending on the amount of excess heat transfer surface in the superheater). This temperature will of course be limited by the maximum salt inlet temperature of 1050°F.

Control Philosophy Requirements - The control system will have two modes of operation. At its lowest level of control, it will allow the operator to manually control the position of each valve in the system. The highest level relates to the automatic tracking and control of specific process variables. These are described in Table II-6, complete with the control requirement (set points).

Table II-6 Singular Control System Requirements

Process Variable	Set Point
Steam Supply Pressure	1865 psia
Evaporator Salt Supply Temperature	845°F
Supply Steam Temperature	1000°F
Steam Drum Level	50% Full
Steam Throttle for Automatic Control	30-100% of Full Load
Air Cooler Salt Outlet Temperature	845°F

Figure II-11 shows the process schemetic complete with tagged valves indicating the measurements required for the control of that valve.

The control will be effected using microprosessor-based hardware. These will be mounted in an instrument cabinet located in the control room along with the power supply, I/O cards and all additional hardware required to support startup and shutdown. The operator interface will consist of remote auto-manual stations for the valves with automatic control, and a custom-built panel to house the manual valve controls. Motor switches, alarms and all the additional indicators necessary for controlling the plant will also be situated on this panel.

Control Methodology - The startup procedure involves sequential control of the salt-side and water-side valves so thermal stress is minimized along with the risk of freezing the salt.

The procedure will be to use salt heated by the propane burner along with feedwater at 400°F to warm up the heat exchangers. Each heat exchanger will be warmed up in turn, starting with the evaporator, the superheater, and the air cooler. The salt temperature can then be gradually increased to generate steam and pressurize the system. Finally the salt supply will switch over from the propane burner to the hot salt tank when the plant has reached its standby condition.

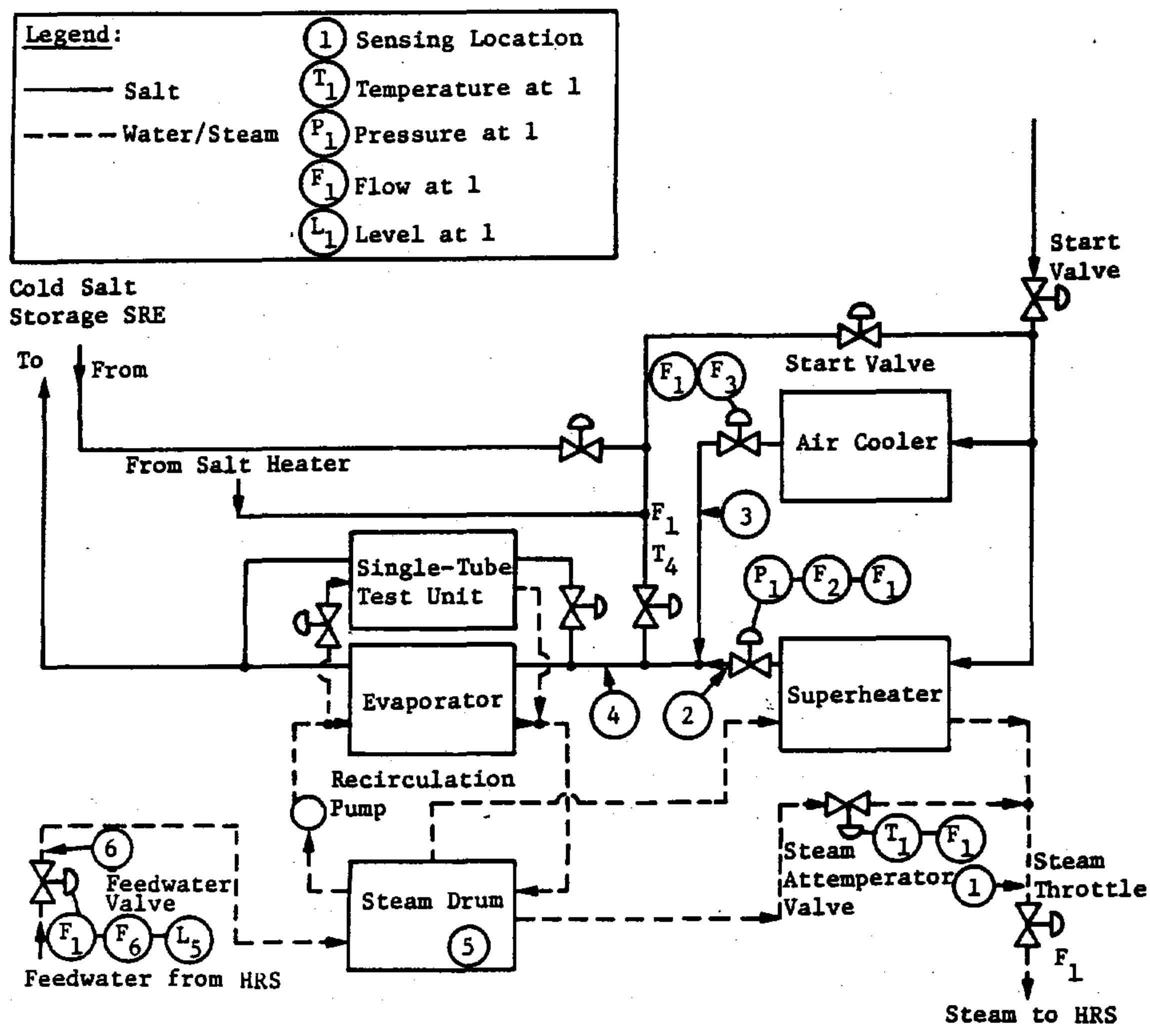


Figure II-11 Steam Generator Control Schematic

The air cooler is used in place of a reheater. Its function is to produce salt at varying rates (but at a constant temperature) for mixing with salt out of the superheater. To control the salt flow through the air cooler, feedback of flow through the valve will be used in conjunction with a PID control algorithm. To control the temperature of the salt leaving the air cooler, a PID algorithm, using exit salt temperature as the feedback term, is used to control the pitch of the fan.

The superheater salt-line valve is used to supply the mainstream salt to the plant and control the steam supply pressure. To this end it uses a three-term control—steam pressure, supply steam flow and salt flow through the valve. The form of the control is:

1) A nominal thermal balance based on steam supply rate set point;

2) Salt flow to correct pressure error using a PID control algorithm;

3) Salt flow through the valve as the cascade control's inner loop.

The evaporator salt attemperator uses temperature feedback to control the flow of salt from the cold tank to limit the temperature of the salt entering the evaporator.

The steam throttle utilizes flow feedback to set the valve position, using a PID control algorithm.

The steam drum level is maintained via the feedwater valve, which uses a three-element controller, drum level and steam supply rate for set point with feedwater flow as the feedback signal. In addition to steam drum level feedback, it is necessary to provide the operator with an independant measurement drum level. This is normally in the form of a closed-circuit TV monitor of a water gage mounted on the drum. Microprocessor-based controllers will be used for each of the controls outlined.

b. Instrumentation - Instrumentation for the SRE will be required to monitor and record information for both control/warning purposes and for the collection of engineering data. All SRE measurements will be transduced to an analog electrical signal and transferred to the data acquisition system. The data acquistion system has the facility to acquire plant data, analyze data, display performance data to the operator, and store data for future detailed analysis. Table II-7 summarizes the measurement locations.

Temperature - The temperature sensors selected for this experiment are all type K or type T thermocouples but vary in configuration to meet the requirements of respective installations. Type K (chromel-alumel) thermocouples are used to measure the temperature of the molten salt throughout the system.

Pressure and Flow - All pressures are obtained via pressure transducers that are strain gage nonindicating instruments. Molten salt pressure transducers use stainless steel diaphragms and produce 4 to 10-mA signals proportional to pressure. A differential pressure is taken across a segmented orifice for flow measurements.

Fluid Level - The fluid level in the steam drum is determined with a manometer. The fluid level manometer for the steam drum will be monitored visually by video equipment.

Valve Position - The control valves of this system are of the pilot-operated, air-actuated diaphragm-type and are equipped with open and closed limit switches. Valve position displacement is measured using a valve position potentiometer.

Table II-7 SGS SRE Measurement List

Temperatures	Pressures
Salt	Salt
Hot Salt Storage* Cold Salt Storage* Hot Salt Pump Inlet* Superheater Inlet* Superheater Exit Evaporator Inlet Evaporator Exit Salt Heater Inlet* Salt Heater Exit* Air Cooler Exit* Start Valve Exit	Hot Salt Pump Exit* Superheater Inlet Superheater Exit Evaporator Inlet Evaporator Exit Cold Salt Pump Exit* Salt Heater Exit Start Valve Inlet Start Valve Exit Salt Normal Flow Valve Salt Flow Control Valve Steam Temperature Valve Blowdown Valve Evaporator Isolation Valve Water Recirculation Valve HRS Valves
Water/Steam	Steam
Feedwater Evaporator Inlet Superheater Inlet Superheater Exit HRS Inlet Main Circulation Pump Inlet	Steam Drum Inlet (from HRS) Steam Drum Inlet (from Evaporator) Steam Drum Exit (liquid) Steam Drum Exit (vapor) Evaporator Inlet Evaporator Exit Superheater Inlet Superheater Exit Throttle Valve Inlet Throttle Valve Exit HRS Inlet
Metal	Valve Position
Evaporator Superheater Salt Lines Steam Lines	Main Steam Throttle Valve Salt Flow Block Valve Start Valve Water Recirculation Valve Warmup Steam Valve Isolation Valve Steam Drum Drain Valve
Flow Rates	Pump rpm
Salt	Water Recirculation Pump Feedwater Circulation Pump Hot Salt Pump Cold Salt Pump
Superheater Exit Air Cooler Exit	
Steam	Control System Voltages
Main Circulation Pump Inlet Water Recirculation Feedwater Blowdown Superheater Exit Temperature Regulator HRS Inlet HRS Makeup	
Fluid Level	
Steam Drum Hot Salt Tank* Cold Salt Tank*	
Impurity Analysis	20 Locations

*Already in place on storage SRE.

Data Acquisition - The SGS SRE control console and data recording equipment will be located in the existing storage SRE control room. The mainframe of the data acquisition system is a mobile data logger available at the CRTF and being used on the storage SRE. Its specifications are:

1) Acurex Auto Data 10;

2) 30-channel/s sample rate;

3) 60-channel mainframe capacity;

4) 4 to 100 channel remote scanners;

5) 460-channel total capacity.

The data logger will be programmed for a fast sample rate (such as 2 seconds) when recording critical parameters that change quickly during transients, and programmed for a slow sample rate when recording slowly changing parameters (such as molten salt measurements). During the experiment, raw data from the data logger will be transferred to a digital magnetic tape. Two CRTs on the SRE operator's console will monitor selected performance parameters. An alarm CRT will display information concerning warnings and alarms, as well as information pertaining to system control. In the evening following the experiment, the raw data tape from the data logger will be taken to the MCS-DAS computer located in the main control room and used to generate a "floating point tape" of reduced data. The next morning the reduced data can be routed to the printer or plotter as necessary. In addition to the discrete measurements taken, analog stripchart recorders will monitor such critical measurements as steam throttle temperature during the test for operator control.

4. Site Preparation, Component Installation and Piping

a. Physical Arrangement - The SRE equipment will be located just to the south of the energy storage SRE. The physical arrangement of the SRE components and primary piping is shown in Figure II-12. The location and arrangement of the SRE were designed to minimize the lengths of salt piping that interface with the energy storage SRE; this arrangement also provides for reasonably short wiring connections. The evaporator and superheater are arranged in a north-south orientation with piping connections at the north end; this provides short feedwater and steam piping lengths for SRE interfaces with the heat rejection equipment and feedwater pump that are located at the base of the CRTF tower. The steam drum and recirculation pump are located adjacent to the evaporator to minimize piping lengths and pressure drop in the recirculation loop. The location of the SGS SRE will be optimized during the design phase of the contract.

b. Field Erection - The construction contractor will survey the area to determine the exact locations of the SRE equipment foundations. Next, the contractor will remove sections of asphalt as necessary and dig the foundations. Following soil excavation and the application of a gravel or crushed rock base, the concrete foundations will be poured. Component installation will include setting the evaporator and superheater on their foundations, installing the steam drum on its steel support structure, and setting the pumps and motors on their foundations. The piping system will be installed and hydrostatically tested. Then the instrument detectors, heat tracing elements, insulation and lagging will be added to the piping system. Next all electrical distribution, control and instrumentation equipment will be installed. The installation of raceway and circuits will be followed by grounding of the electrical distribution system equipment. Finally, an earth berm will be built around the SRE.

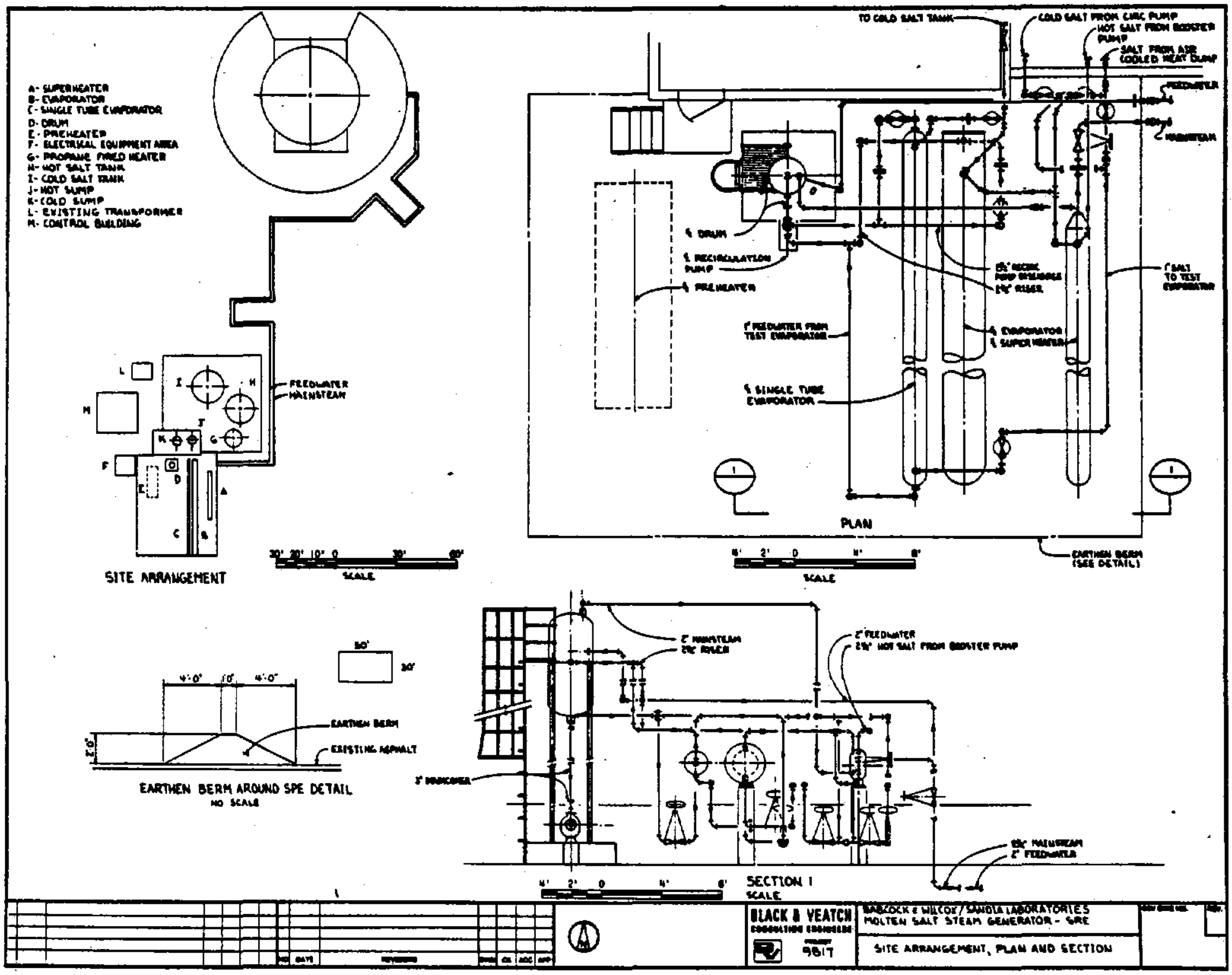


Figure II-12 Site Arrangement, Plan and Section

c. <u>Balance of Subsystem</u> - This section describes the baseline design of the components that comprise the balance of the steam generator subsystem. The components addressed in this section include the foundations and support structures, piping, wiring, insulation and lagging, trace heating, and pumps.

Foundations and Structures - The evaporator will be supported at three locations with saddles that will be mounted on reinforced concrete pads. One support will be fixed and the other two supports will be free to slide on pads to permit thermal expansion of the evaporator. The U-shell SRE superheater will be supported similarly to the commercial-scale superheater (Fig. II-13). The lower leg of the superheater will be supported by three saddles in a manner similar to the evaporator and the upper leg will be supported at required locations by U-bolts attached to a structural steel frame. The steam drum will be mounted on three structual steel legs spaced at 120°. These legs will be supported by a reinforced concrete pad.

Piping - The key characteristics of the piping system baseline design include the material selected and routing of the various sections of pipe. The cold salt piping from the evaporator outlet to the cold salt tank will be carbon steel; all other salt piping wil be type 304 stainless steel. High-temperature steam pipe from the superheater outlet will be ASTM A335 SR P22; all other steam piping and all feedwater piping will be carbon steel.

Salt piping will be routed from the discharge of the hot salt pump to the superheater, from the superheater to the evaporator, and from the evaporator to the cold salt tank. Feedwater piping will be routed from the heat rejection equipment at the base of the CRTF tower to the drum; high-temperature steam piping will be routed from the superheater outlet back to the heat rejection equipment. Saturated steam piping will lead from the drum to the superheater inlet. Saturated liquid will be piped through a downcomer from the drum to the recirculation pump suction. Finally, the pump piping discharge will connect to the evaporator and the evaporator outlet to the drum. All pipe will be routed to provide flexibility for thermal expansion. Vents and drains will also be provided in accordance with power industry standards.

Wiring - Electrical cable assemblies will be selected to provide economical performance. Cable insulation will be selected considering physical and mechanical properties. Cable conductor sizes will be conservatively selected using ICEA standards.

Insulation - Insulation for piping, heat exchangers and the steam drum will be calcium silicate. The insulation will be covered with aluminum jacketing for weather protection.

Trace Heating - Heat tracing, consisting of trace heaters and controls, will be provided for piping and equipment to meet the following requirements.

1) Heat tracing will be electrically powered;

2) Trace heaters will be a flexible, self-limiting, parallel-circuit type with a monitor conductor for surfaces of low maximum operating temperature (65°C, 149°F);

3) Trace heaters will be mineral-insulated (MI) with an Inconel sheath for surfaces of high operating temperatures (572°C, 1061°F);

4) Controls will be provided with the heat tracing system to prevent salt solidification by maintaining a minimum molten salt temperature of 277°C (530°F) during periods when the SRE is not operating. During process operating conditions, these controls will de-energize the heating cables at approximately 277°C (550°F);

5) Alarms will be provided to indicate system malfunctions;

<u>Pumps</u> - The evaporator recirculation pump will be a submerged motor pump specifically designed for high temperatures and high suction pressure.

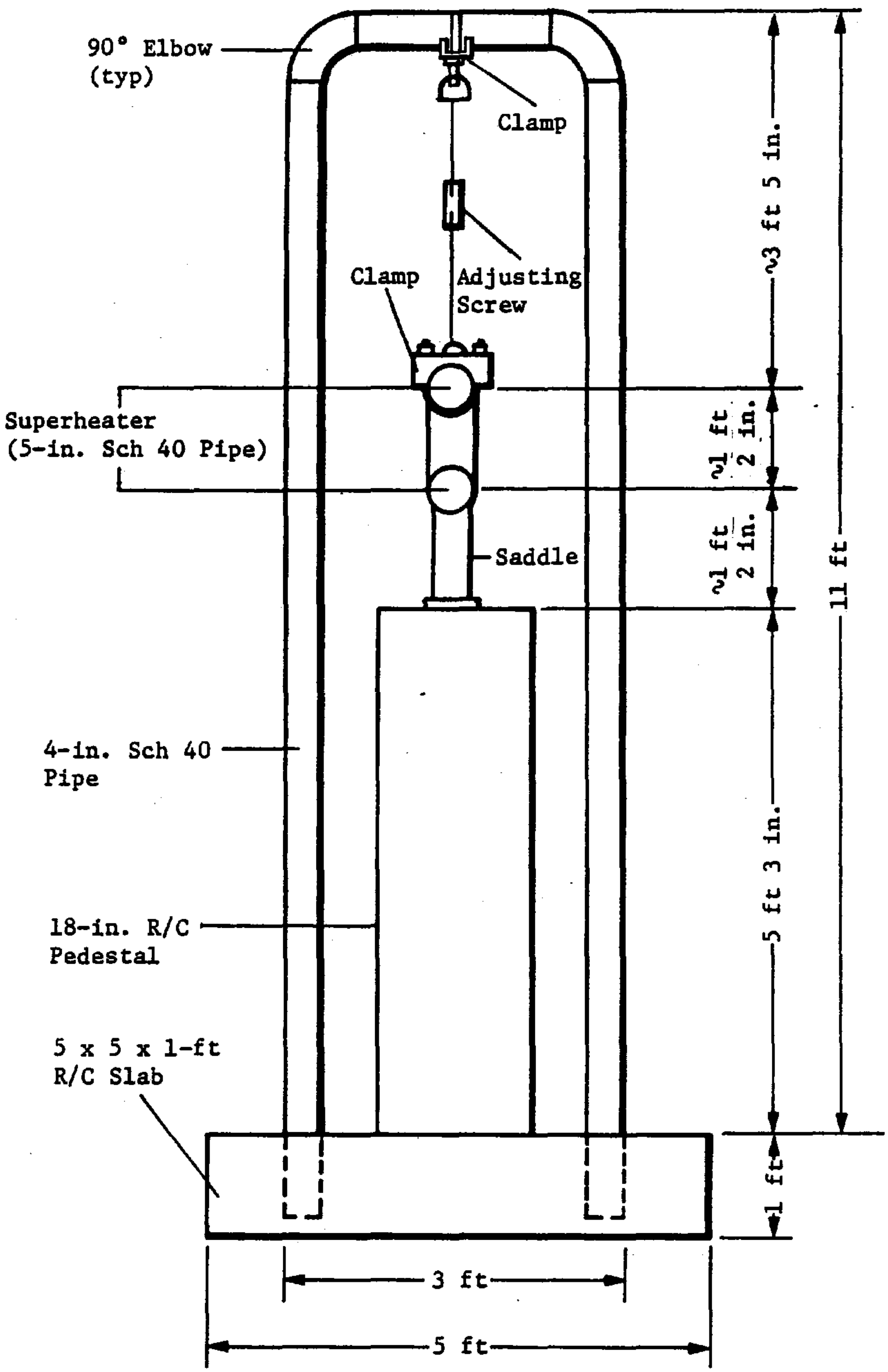


Figure II-13 Superheater Support Detail

B. TECHNICAL DISCUSSION OF APPROACH

1. Task 1 - SRE Requirements

The SGS requirements specification was initially developed during Phase I. During Phase II the most current document will be reviewed and revised if necessary. The SRE interface requirements will also be reviewed to determine the experimental requirements needed to satisfy program objectives.

2. Task 2 - Design

The primary objective of the Phase II design effort will be to demonstrate design and fabrication techniques that can be applied to commercial-scale molten salt steam generation components. The design effort will be directed toward obtaining detailed designs for the experimental hardware, and the component interfaces required to perform the SGS SRE. The experimental hardware and interfaces will be delivered, installed, and checked out in a field test environment at the CRTF.

The SRE will be designed to demonstrate:

1) Steam generator component compatibility with the heat transfer fluid (60% $NaNO_3$ 40% KNO_3) and heat transfer correlations for the shell-side salt flow;

2) The resistance of the component materials used against corrosion, wear, fretting, and mechanical damage;

3) The thermal-hydraulic factors influencing DNB by conducting a single-tube test;

4) Verification of thermal performance and simulation of all transients including charging and discharging of salt;

5) Verification of the fabrication and leak check techniques;

6) The control and instrumentation techniques required for solar-thermal molten salt steam generator systems.

A Steam Generator Subsystem SRE Design and Interface Control document will be prepared early in Phase II of the program. The requirements of all components of the system will be identified as to size, performance, utilities, instrumentation, fabrication, weight, and materials. All requirements necessary to design the SRE will be included.

a. Steam Generator Subsystem - The SGS and component designs for the SRE will be based on the commercial plant designs developed during Phase I. This effort will include thermal-hydraulic design of the components, mechanical design of the components, and selection of materials. Each of these design categories is briefly discussed in the following paragraphs.

Thermal-Hydraulic Design - In developing the component designs, the principal objective will be to simulate the important performance characterisitcs of the 100- and 50-MWe commercial plant designs. Such critical parameters as the average tube length and tube OD, wall thickness, and pitch will be modeled to assure appropriate representation of the time-variable thermal profile along the tube (and thus the heat flux distribution), and to assure data concerning the tube-side and shell-side mass flow rate and velocity.

The number of tubes (and thus the heat transfer surface) in each of the SRE heat exchangers will be approximately equal to the ratio of the thermal ratings of the SRE and commercial plant designs. The tube bundle will be precisely sized using the Babcock and Wilcox VAGEN computer code. This code provides determination of the required heat transfer surface as a function of specified fluid flow rates and temperatures, tube-side pressure drop limitations, and tube configuration and material.

Special features of the functional design are described:

1) The final 32 feet of each tube in the evaporator will be of a multilead internal rib construction. This arrangement is consistent with the 100- and 50-MWe commercial plant designs. These ribs promote the boundary layer turbulence and centrifugal forces that maintain nucleate boiling to a higher quality than possible with a smooth-bore tube of the same general dimensions;

2) In the SRE heat exchangers, tight-fitting shrouds will be used to limit flow bypassing the heat transfer surface and assure proper modeling of the shell-side flow distribution. These shrouds are not required in the larger bundles of the commercial plant designs.

Mechanical Design - The following work will be accomplished in the mechanical design of the evaporator, superheater, and steam drum:

1) Pressure boundaries will be sized to meet the applicable requirements of Section VIII, Division 1 of the ASME code;

2) Tube sheets will be sized to meet the applicable requirements of the TEMA standards;

3) Vessel supports and restraints will be provided for deadweight and seismic loads;

4) Sufficient flexibility for differential thermal expansion will be provided between individual tubes and between tubes and shell;

5) Tube supports will be arranged to prevent potential damage from flow-induced vibration. Baffles will be provided as thermal shields and for flow distribution control if necessary;

6) Valves for steam-side and salt-side pressure relief will be provided.

Selection of Materials - Where necessary, the alloys selected for the evaporator, superheater, and steam drum will be the same as those chosen for the commercial plant design to assure proper modeling of performance characteristics. For example, all tubing material in the SRE must be identical to that in the commercial plant designs to duplicate thermal conductivity. Alloys selected for the pressure boundaries and structural members that do not influence performance characteristics may deviate from the commercial plant design if such deviations produce significant advantages in reducing fabrication cost and/or schedule. However, as a minimum, all materials chosen will offer adequate strength and corrosion resistance in the operating environment.

b. Single-Tube Test Model Design - The single-tube DNB test model has been described in detail in Section A and its principal features are shown in Figure II-7. The tube-and-shell assembly and associated instrumentation will be designed and assembled by B&W's research and development division. The orifice for water-side flow measurement will be fabricated as an integral part of this assembly and will be calibrated in the laboratory prior to shipment. Other piping, fittings, valves and instrumentation associated with the facility will be assembled onsite.

The mechanical design of the tube-and-shell assembly will be in accordance with the requirements of Section VIII, Division 1 of the ASME code. Other piping and fittings will comply with the power piping code ANSI B31.1.

Since the tube-and-shell assembly has limited inherent flexibility, an expansion joint will be incorportaed in the shell to accommodate thermal growth between the shell and tube. Insulation and lagging will be applied in the shop to minimize potential damage to the thermocouple wires in the field. The test assembly will be enclosed in a lightweight weatherproof enclosure for protection during shipping, erection, and testing.

c. Control and Instrumentation - The methodology previously outlined was established during Phase 1 as a technique for control of a steam generation plant. This was achieved using the following approach:

1) Analyze the control loop using a first-order model to establish the control algorithm;

2) Investigate the ability of the algorithm on a high-order model.

Figure II-14 illustrates the model used to describe the control of steam supply pressure to the turbine. The blocks in the flow chart show the elements involved and the feedback used. In the case of the supply pressure, two loops form a cascade control. The inner loop controls salt flow through the superheater via a PI control that positions the valve for the required flow. The use of flow feedback overcomes the problem of varying pressure heads and valve nonlinearities. The set point for the flow is determined by the load and error in supply pressure. The nominal thermal balance tracks the load on the plant by monitoring steam flow through the superheater, setting the salt flow proportionally. This is effectively a feed-forward term and its use avoids large pressure transients during load changes. The second term, pressure feedback, uses salt flow to eradicate pressure errors. By increasing salt flow through the evaporator and superheater, higher quality steam is produced that, in turn, increases the steam pressure via the drum.

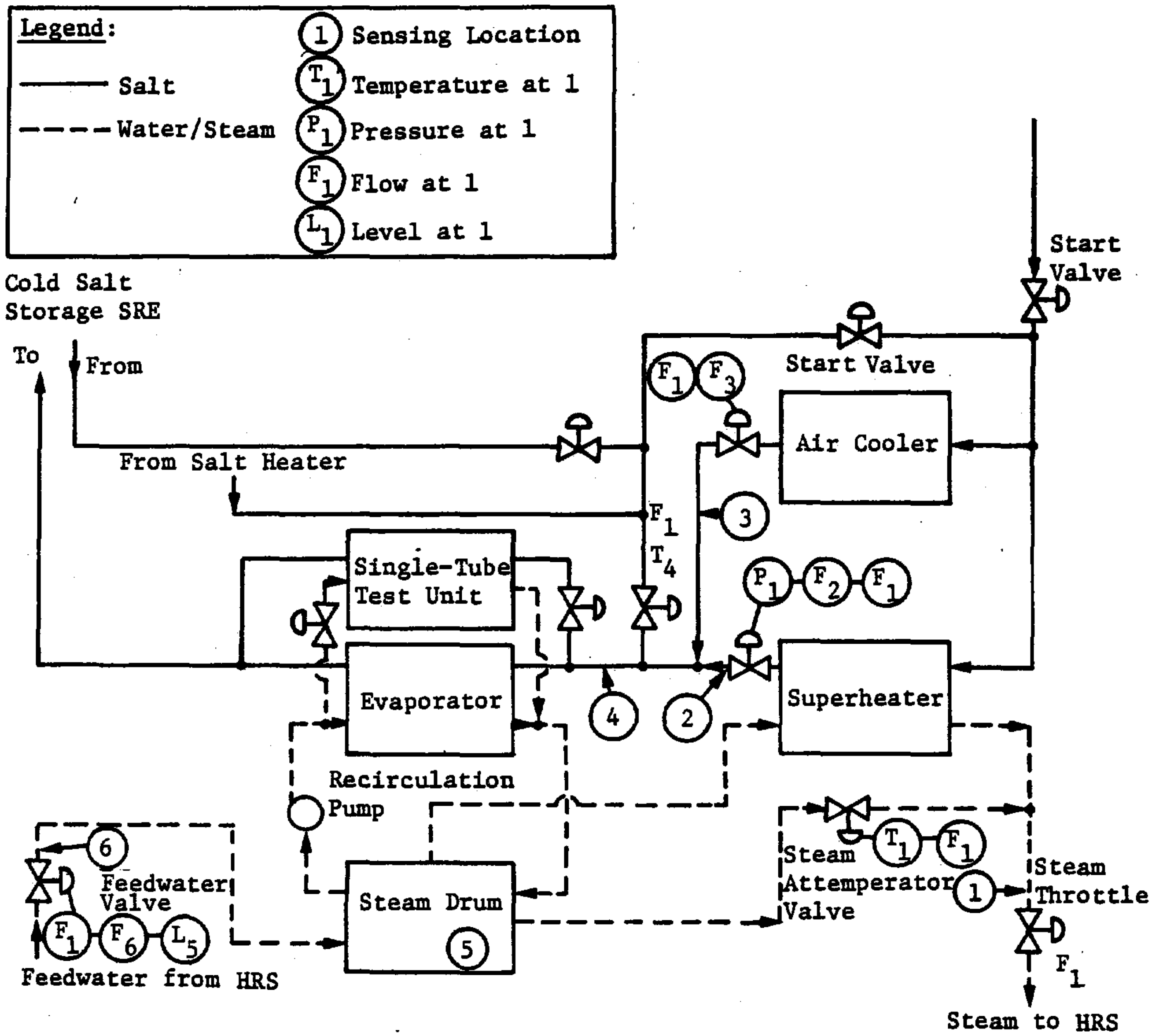


Figure II-14 Steam Generator Control Schematic

This type of flowchart is used to develop the simple mathematical model required for the preliminary control analysis. An all-linear time-invariant math model is used with the root locus technique of transient analysis (Fig. II-15). The root locus technique is used to derive information on steady-state errors, transient peaks, and dynamic performance. This method was used to validate the use of a PID control and to as initial gains. In conjunction with root locus, Nyquist plots can be made in cases where the plant is nonlinear. Although it does not offer the same amount of information, it provides a necessary check on stability. This is particularly important in cases where transport delays occur.

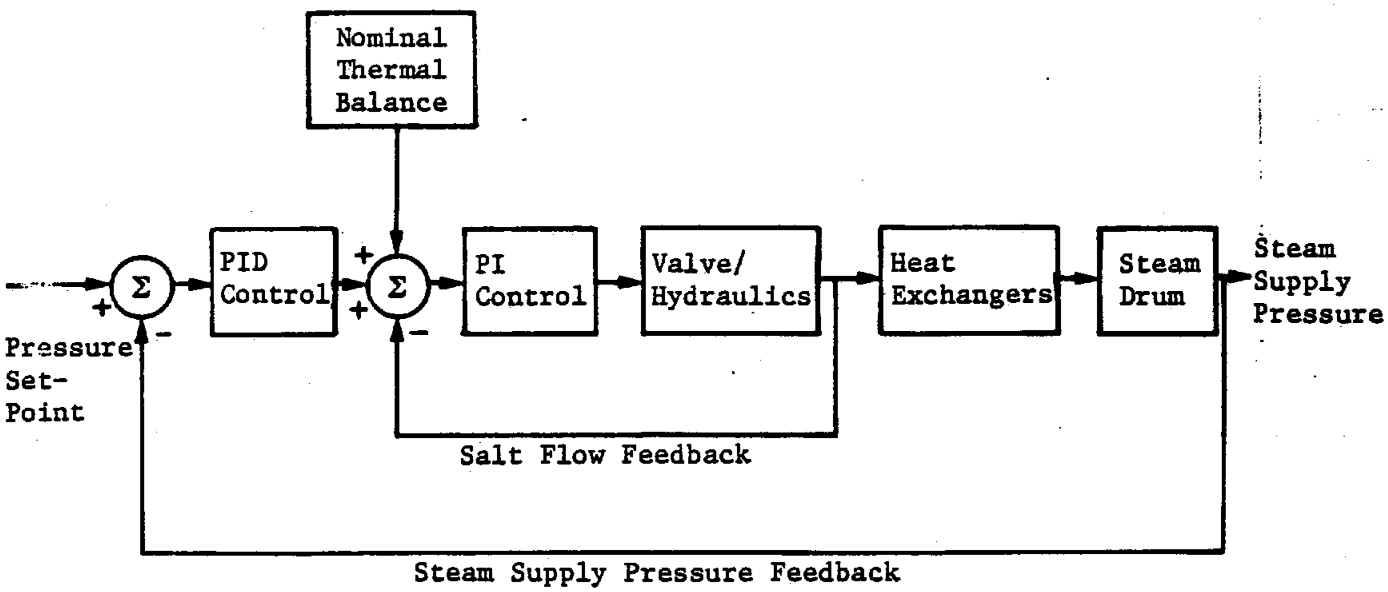


Figure II-15 Steam Supply Pressure Control Schematic

A preliminary analysis will be performed to validate the control algorithm and provide the insight necessary before using a higher order model. The output from the preliminary study will be "control functional diagrams." This diagram serves two purposes. First it is used as a control hardware requirement to define the input/output software functions and overall control program. Its second purpose is to define the control algorithm for inclusion in the system simulation. Each control loop, both manual and automatic, will have its functional diagram.

The final stage in design of the control algorithm is to prove it on a higher order model. A Martin Marietta digital simulation will be used. Having programmed the control functional diagrams, open-loop tests will be run to derive the Ziegler-Nichols recommended settings for P, PI and PID gains. Having closed all the loops, the process can be repeated to fine-tune the algorithm.

As well as proving and tuning the control algorithms, sensitivity tests can be run. Figure II-14 showns that the turbine steam is used in conjunction with two function generators--$f_1(x)$, the nominal thermal balance and $f_2(x)$, the supply pressure set point. The nominal thermal balance is not linearly proportional to load and a linear approximation can induce pressure transients. Similarly, at low load it may be advantageous to reduce the pressure set point. Questions of this nature are best addressed using the computer simulation.

To summarize, the plant will be extensively analyzed to first establish the method of control. The consequent control functional diagrams validated using a high-order model will be used to define both the hardware and software requirements.

d. Foundations, Piping and Wiring

Foundations and Structures - The foundations and support structures will be designed to meet the requirements of the evaporator, superheater, steam drum, and salt and water/steam piping.

Minimum loads for all SRE equipment will be per the SGS requirements specification. Structural steel will be ASTM Grade A36. Concrete will be designed in accordance with ACI-318-77 and structural steel will be designed in accordance with the Eighth Edition of AISC. Concrete will have a minimum design strength of 281 kg/cm^2 (4000 psi) and steel reinforcement will be Grade 40.

Piping - The piping arrangement will be designed by considering a number of constraints--piping strength and flexibility, supports, ease of installation, reactions at each major component connection, ability to gravity-drain, and proper installation of instrumentation required for data collection and operation.

All piping will be sized for reasonable fluid velocities and pressure losses considering the tradeoff between piping capital cost and pump operating cost. Wall thickness will be suitable for the design pressures and temperatures.

Wiring - Electrical cable assemblies will be selected to provide economical performance. Cable insulation will be selected considering physical and mechanical properties. Cable conductor sizes will be conservatively selected using ICEA standards.

Insulation - Insulation thickness will be determined based on two considerations--limiting the external temperature for personnel protection and a tradeoff between insulation capital cost and the energy cost of heat loss.

Pumps and Valves - The evaporator recirculation pumps will be selected to satisfy system requirements for flow and head with a margin for each. Valve types will be selected based on their control and operational functions. Valve class and material will be determined by the design conditions, considering the material of the piping in which they are installed.

e. Instrumentation - Appropriate instrumentation for the SGS SRE will be specified in Phase II of the program based on requirements derived from the operational mode analyses, equipment and component limitations, and customary utility practices. Adequate instrumentation is required to determine heat balance and heat loss characteristics for control purposes, and to assist in the development of an accurate analytical model of the system. Detailed control and instrumentation schematics and logic diagrams will be prepared in Phase II to be used in procuring and installing instrumentation. A complete list of instruments and control items will be provided to reflect the specified instrumentation scheme. Before installation of the instrumentation for the SRE, existing instrumentation on the storage SRE, heat rejection system, air cooler, and the storage SRE control room equipment will be defined.

The data acquisition system will serve as both an integral part of the control system and as a method to acquire engineering data. The following capabilities will be provided:

1) Display of selected system parameters and alarms;

2) Capacity to change the value or state of any parameter;

3) Adequate sample rate for critical system parameters;

4) Display calculated variables;

5) Monitor or change control logic.

The SGS SRE will be operated from the storage SRE control room being used for the storage SRE . A mobile data logger located at the CRTF will be the mainframe of the data acquisition system. The data logger and other equipment available at the CRTF such as flow control valves, recording equipment, and CRTs will be assessed and reserved for the SRE well in advance.

3. Task 3 - SRE Test Plan and Procedures

A preliminary test plan has been prepared as a part of the Phase I effort. This plan will be reviewed and revised in performing this task. The plan has the same format as the test plan prepared for the Martin Marietta storage system SRE program. This document will be a formally released drawing that will be used to control the test program. Sandia National Labs' approval will be required prior to initial release of the document and for all changes that significantly affect test program conduct or accomplishment of the test objectives. The plan will include an introduction that defines the test objectives and scope of the document and summarizes the test program. The introduction will be followed by a description of the test system and components. The test description will include the objective and a summary of how each test will be performed. All tests will be described, including startup and checkout tests. The test sequence and test schedule will be defined in the following section. Finally, a section describing the special safety condsiderations to be used in these tests will be prepared.

The detailed operating procedures by which each of the tests will be conducted will not be a part of the test plan but will be issued separately. A separate procedure will be written for each of the tests. These procedures will also be formally released documents. The test procedures will be submitted to Sandia National Labs for comment prior to release. They will include a definition of the test hardware, support requirements (including commodities and equipment), special safety

... the detailed sequence of steps required to perform ...

4. Task 4 - Fabrication

Manufacturing activites during Phase II will provide an evaporater, superheater and steam drum for testing purposes and will demonstrate the fabricability of commercial-size plant units. Critical operations such as tube fabrication, welding, bending and inspection will be proved in fabrication of the SRE units. Figures II-16 thru II-18 outline the fabrication sequence for the steam drum, evaporator and superheater. The part numbers and assembly numbers correspond to those to be provided on the SRE component drawings. Fabrication outlines that indentify the operations to be performed on major parts and assemblies of the SRE vessels have already been developed. No operations in fabrication of the SRE or commercial units are uncommon to the industry or considered risk techniques in a properly staffed and equipped manufacturing facility.

Manufacturing activities during Phase II of this project will consist of:

1) Preparation of detailed fabrication drawings. The drawings prepared by the Graphic Design Section will be reviewed by Design Engineering and Process Engineering personnel to assure that contract objectives are satisfied and that the design can be fabricated without undue hardship or excessive cost;

2) Preparation of material ordering information. The procurement material orders will also be prepared by the Graphic Design Section and will be reviewed by Materials Engineering and Process Engineering to assure proper selection of materials;

3) Preparation of detailed fabrication instructions. The detailed processing prepared by Process Enginering will provide the manufacturing shop with the instructions required for fabrication, inspection and testing of the components;

4) Scheduling of manufacturing operations. The detail processing will be reviewed by the Production Planning Control Section and operations will be spanned and scheduled for completion. Production Control will monitor, expedite and report progress of software items, material, and fabrication activites throughout the project;

5) Fabrication, inspection and testing in accordance with detail processing instructions, design drawings and approved procedures. All fabrication, inspection and testing operations will be documented through signoff of the detail processing as operations are completed;

6) Upgrade and shipment. All completed and signed off detail processing will be reviewed and upgraded by Quality Assurance to assure proper completion and documentation of all operations before code stamping and shipment of the SRE components.

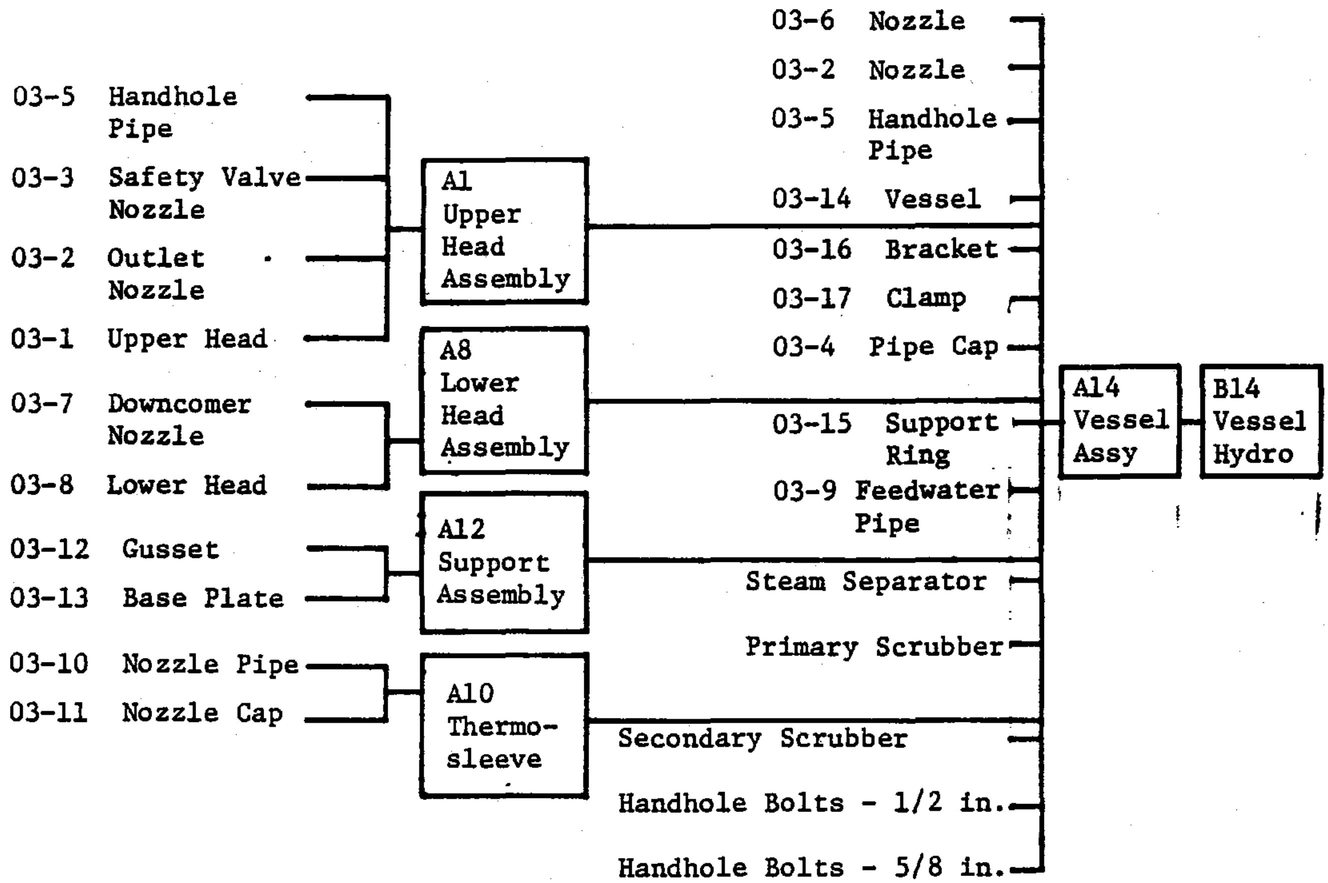


Figure II-16 Steam Drum Part/Assembly Diagram

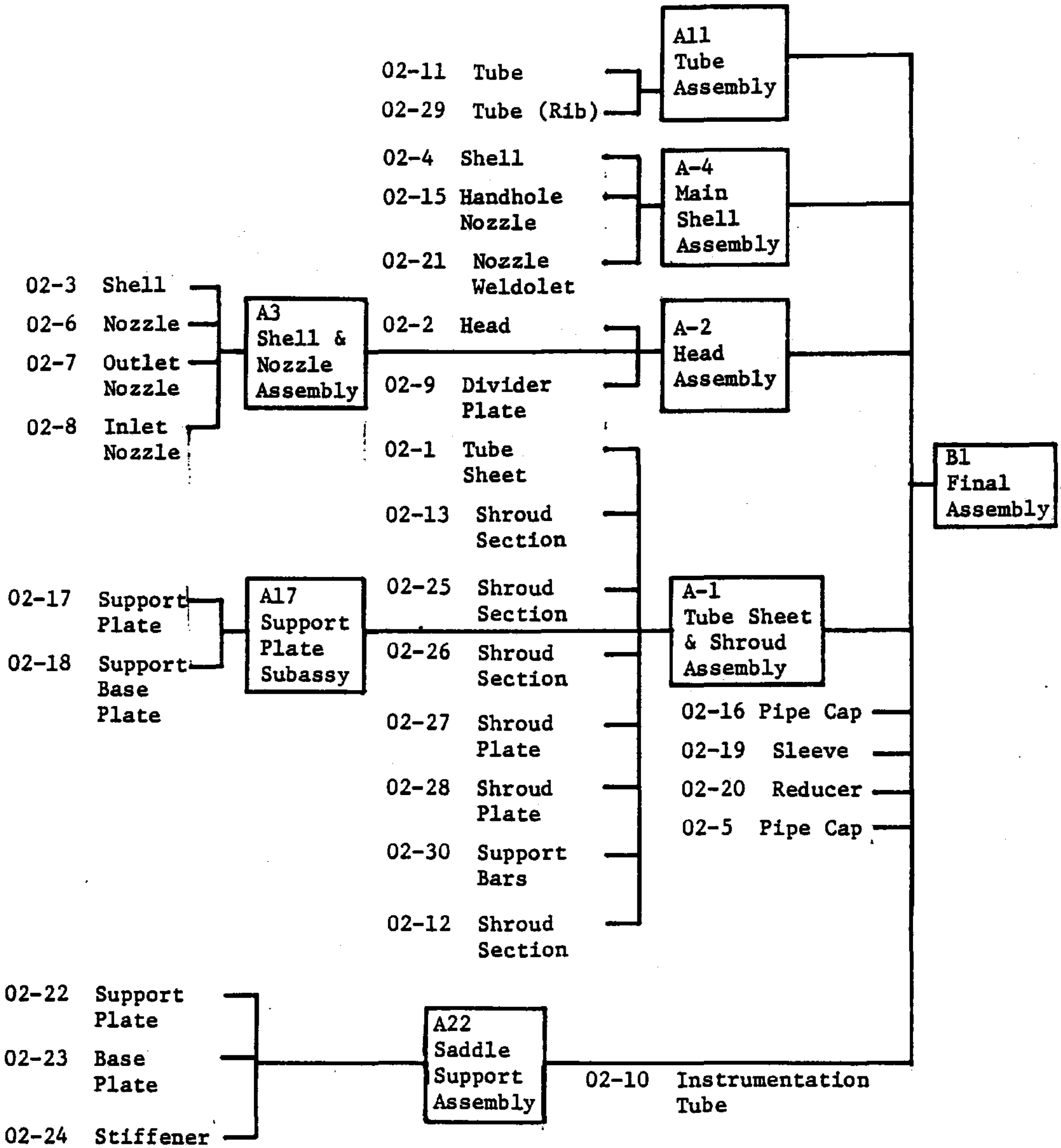


Figure II-17 Evaporator Part/Assembly Flow Diagram

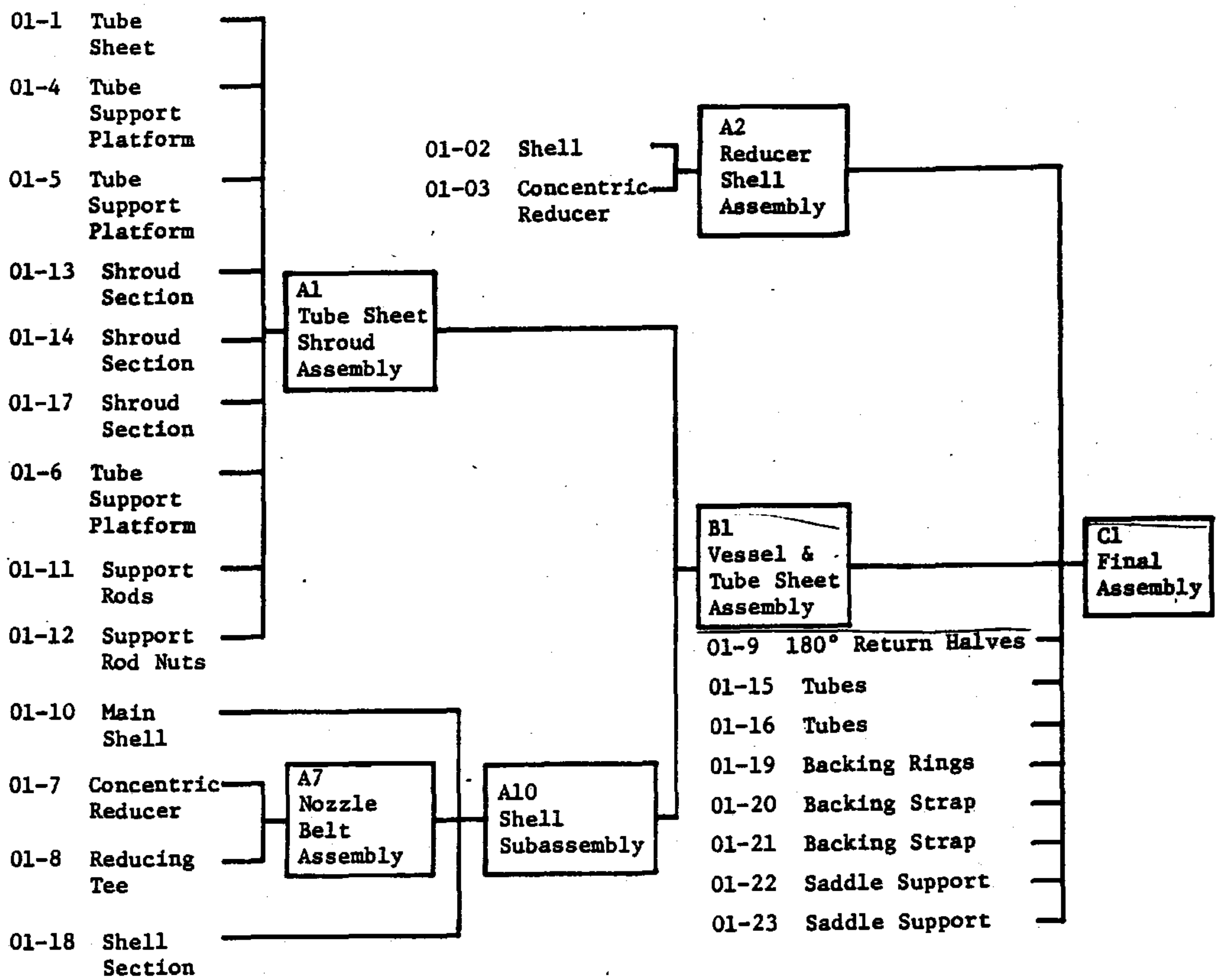


Figure II-18 Superheater Part/Assembly Flow Diagram

The fabrication schedule for the SRE steam generator components is shown in Figure II-19.

5. Task 5 - Delivery, Installation and Checkout

a. Field Erection - Field erection of the SRE will be performed by the construction contractor under the direct supervision of the construction manager. The construction contractor will survey the area to determine the exact locations of the SRE equipment foundations. The asphalt surface in the immediate vicinity of each foundation will be removed. Any heliostat foundations that would interfere with the SRE will also be removed. Soil will be excavated below the frost line and a 0.15-meter (6-in.) gravel or crushed rock base will be provided to support the SRE equipment foundations. Formwork and placing of reinforcing steel and embedments will precede the pouring of concrete foundations. After the foundations have been installed, soil will be backfilled or asphalt will be replaced around the foundations as appropriate.

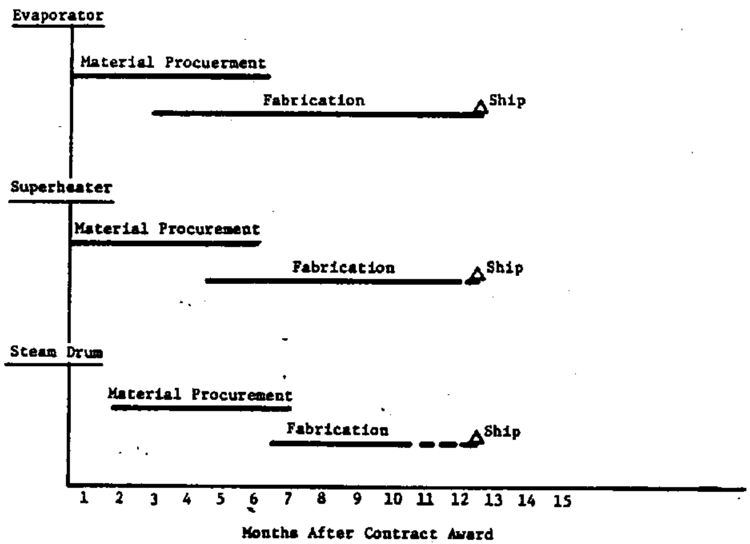


Figure II-19 Fabrication Schedule for SRE SG Components

b. Component Installation - Component installation will begin with the mounting of supports for the evaporator and superheater on the foundations. Then the evaporator and superheater will be set by bolting the saddles to their supports. The steel structure that will support the steam drum will be concurrently erected and the steam drum set on the structure. This will be followed by setting the pump on its foundation. Piping will be fabricated in the field. All piping and valves will be installed and welded in accordance with the piping drawings. Existing drain lines will be used where appropriate. After the piping system has been installed, it will be hydrostatically tested to ensure integrity of the weld connections. The final step in the piping system installation will be mounting of the instrument detectors, heat tracing elements, insulation and lagging.

c. Electrical and Control Installation - Before installation of the instrumenation for the SGS SRE, the interface requirements of the existing instrumentation on the storage SRE, heat rejection system, air cooler, and the stoarge SRE control room equipment should be defined. Installation of the electrical and control system will begin with installation of all electrical distribution, control and instrumentation equipment. All instrumentation will be calibrated and installed prior to the experiment. End-to-end checkouts of all thermocouples will be conducted to verify that the junctions and connections are completed. This checkout will also verify proper location of each thermocouple. The temperature of the salt piping must be heated to a temperature above the salt freezing point prior to salt introduction when filling the system. The poor thermal conduction of the tubing requires a thermocouple about every 4 feet to insure the system is above the salt freezing point. The piping and components should have sufficient instrumented points to characterize the heat loss and the salt temperature gradients. A heat gun will be used to apply heat to all accessible thermocouple junctions and the response will be verified using the data system. A functional molten salt test will be conducted to verify segmented orifice flow calibrations and to check control valve operation while operating from the control console. A weigh tank built for the molten salt receiver SRE will be used to calibrate the segmented orifice flowmeters prior to the experiment. Installation of a raceway from the control building in the energy storage SRE to components in the steam generator SRE will be followed by installation of the circuits.

d. Other - The final activities in field erection of the SRE will include building an earth berm around the perimeter of the SRE and cleaning the site area of construction debris.

6. Task 6 - Testing

a. Test Team Organization - The test team will be made up of personnel from Babcock and Wilcox and Sandia National Labs (CRTF). In general, the responsibilities will be as follows. B&W, the prime contractor, will have overall responsibility for successful accomplishment of the test and will direct the test conductor. Babcock and Wilcox will be responsible for conduct of the test and operation of the test system. Sandia/CRTF will be responsible for operating all of the necessary CRTF facility equipment.

b. Test Program - During all hot operations testing involving salt, the salt storge system SRE is presumed operational and capable of supplying hot or cold salt as required to the SGS SRE and accepting cooled salt discharged from it. Detailed instructions for operation and testing of the SGS will be coordinated with operations of the thermal energy storage (TES) SRE and the instructions ultimately integrated. The checkout and performance tests to be run on the SRE are described in the following paragraphs.

Checkout Tests - The objectives of these tests are to verify that the system is leaktight, verify the pressure capability of the system, verify the cleanliness of the system, verify the operation of each component, verify operation of the instrumentation and the data acquisition system, and verify functioning of the control system.

All components will have completed a proof and leak check at the manufacturer's facility before being shipped to the site. All joints of the system will be hydrostatically checked. The system will be subjected to a proof pressure test with pressures as specified in the ASME code. Finally the leak test will be repeated at operating pressure. This will be complete after the piping system is installed.

The operation of all components (valves, pumps, heaters, etc) will be demonstrated. Response times of control valves will be verified using the control system. End to end checks will be made of all instrumentation.

At the start of this test the system will be dry and at ambient temperature. The evaporator-drum system will be filled with deionized deaerated water to the minimum confirmable level in the drum and the recirculation pump started. Saturated steam at 400°F produced in the HRS desuperheater-condenser by the immersion heaters will be sparged into the drum water using the feedwater line. Trace heaters will be activated and regulated so shell temperature follows the water temperature. When conditions in the evaporator approach 400°F, the 70-kW immersion heater in the recirculating line will be energized and the system brought to 500°F. The temperature of the superheater will follow closely because the steam flowing through the superheater from the evaporator will condense. Salt at 550°F from the storage SRE will be introduced to the superheater and evaporator sequentially and trickled through until the pressure in the drum stabalizes at 1045 psia.

In parallel with heatup of the steam generating system, the air cooler will be brought up to TBD°F by electric heaters. After loading salt into the steam generator system, 550°F salt will be bled into the air cooler. A minimum salt flow will be established and the salt temperature ramped up. The steam throttle valve will be modulated to control the rate of increase of the superheater exit salt temperature to 100°F/h. When the pressure of the throttle valve reaches 1815 psia, the throttle valve will be modulated to hold the pressure until full salt temperature is reached.

The throttle flow will then be ramped to the minimum load required for implementation of full automatic control, with an accompanying salt flow rate increase to maintain constant throttle pressure.

To shut the system down, the salt flow will be stopped. Steam will be allowed to flow for a sufficient time to bring the system pressure to standby pressure. The system will then be secured with salt in all of the components, the steam side full and at pressure and the trace heaters operating. The system will be monitored at night and on weekends to take corrective action in the event of a power failure.

Control System Checkout - Once the system is brought up to operating conditions in the cold start test, several days will be spent in checking out the control system and its ability to effectively control the generation of steam under typical operating conditions. This will include diurnal startup, steady-state load, variable load and diurnal shutdown. Each element of the control system hardware and software will be exercised and carefully evaluated before full-scale testing begins. Any necessary control system changes will be made during these tests.

Single-Tube DNB Tests - The DNB testing will be performed in five stages:

1) Isothermal checkout;

2) Tube metal temperature checkout;

3) Salt-side calibration;

4) High-quality DNB testing;

5) Low-quality DNB testing.

The initial checkouts will indicate any erroneous temperature measurements prior to the DNB testing. The salt-side calibration will give the salt specific heat at several temperatures. Once this is determined, the steam exit qualities during the DNB testing can be obtained from the drop in salt temperature across the single tube and from the salt flow rate. The basis for the salt-side calibration will be the specific heat of subcooled water flowing on the tube side. In the last two steps, the testing will address both the high- and low-quality flow regimes.

The SRE steam system will be brought up to 60% thermal load (3 MWe). At this load the DNB testing can be performed continuously with heat input from the propane salt heater. This eliminates the 3.5-hour time limit on testing at full power.

In the first checkout test, salt will be introduced at the design flow rate at a temperature of 700°F. The recirculation water flow through the single tube will then be ramped to zero. Except for small heat losses through the insulation, the temperature will be constant. The thermocouples can then be checked for consistent readings within the expected accuracy range.

The tube metal temperature check will be made with subcooled water flowing through the single tube. The objective is to obtain predictable tube metal temperatures at each of the thermocouple locations. To accomplish this, only the forced convection-to-subcooled liquid heat transfer mode is needed. Subcooled nucleate boiling will be avoided by establishing a low salt inlet temperature that will be determined during the detailed test preparations. The salt-side temperature profile will be measured with the outer tube (shell) thermocouples. By using the measured salt temperature profile, inlet and outlet water temperatures, and a suitable heat transfer model, the expected tube metal surface temperatures can be calculated. The measured tube metal temperatures will be compared with the calculated values. Any thermocouples showing temperatures closer to the measured salt temperature than the calculated tube metal temperature will be recorded.

The salt specific heat calibration will also be performed with subcooled water flow. Salt-side and water-side inlet and outlet temperature measurements will be made. The specific heat at the average salt-side temperature will be obtained for several inlet salt temperatures.

The high- and low-quality DNB testing will then be performed. Salt-side inlet temperatures and flows will be established according to the test matrix shown in Figure II-10. At each of the 18 salt inlet conditions, a nominal steam flow rate corresponding to the evaporator recirculation water flow rate will be set. DNB will be detected by examining the wall temperature profiles obtained from the CRTF data plotting facilities. If no DNB is indicated, the single-tube water flow will be lowered in steps until DNB is detected. This will indicate the DNB design margin.

Corrosion Tests - In the central solar receiver concept molten nitrate salts will be used as the working fluid. In this system the steam generator will operate from 550 to 1050°F and is designed for a 30-year life. To account for corrosion allowances, it is necessary to have accurate corrosion rate data for the containment alloys under anticipated operating conditons.

In the final report by Martin Marietta, Badger and APS,* isothermal corrosion rates were measured using weight gain methods. These data are greatly affected by exfoliation of corrosion products and, as a result, some of the data are sporadic as evidenced by some of the weight gain/time curves. Consequently it is difficult to extract the necessary information regarding corrosion allowances of steam generator tubing mandated by good design practices. To cope with this difficulty, we propose to use electrochemical methods to continuously measure isothermal corrosion rates (actually one measurement/24 hours instead of one measurement/1000 hours as in the final report) for 50 days. Using the same electrochemical methods, we also propose to determine the corrosion rates under cyclic thermal conditons to simulate anticipated plant operation. Both tests will be conducted for a continuous 50 days. The data will then be extrapolated to 30 years to obtain the corrosion allowances for designing the steam generators.

Electrochemical techniques (semilogarithmic and linear resistance methods+ will be used to obtain the corrosion data. One high-temperature test system will be used for isothermal corrosion tests and one for cyclic corrosion tests. The heat cycle for the cyclic tests will be regulated by a Leeds & Northrup process programmer according to the cycle shown in Figure II-20. The test cell that will be used is shown in Figure II-21.

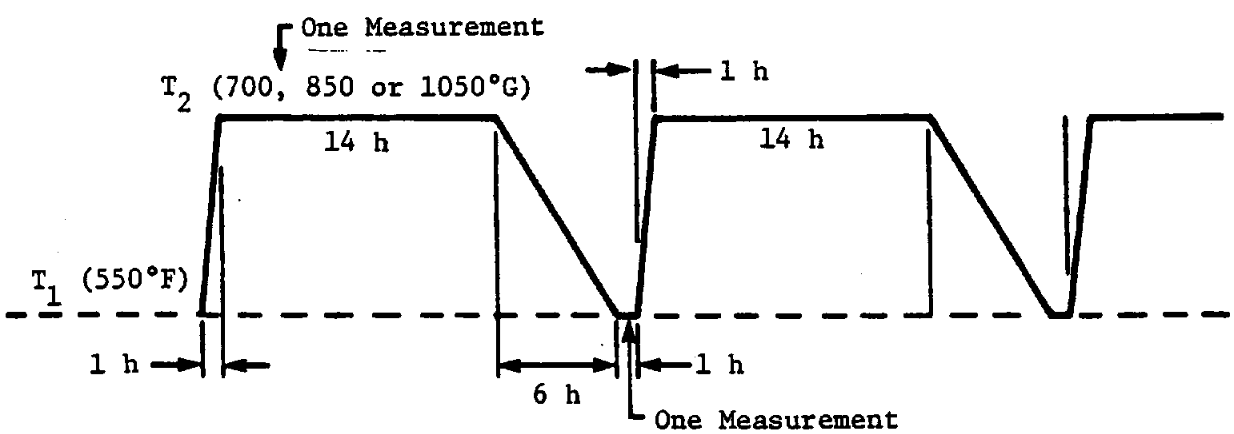
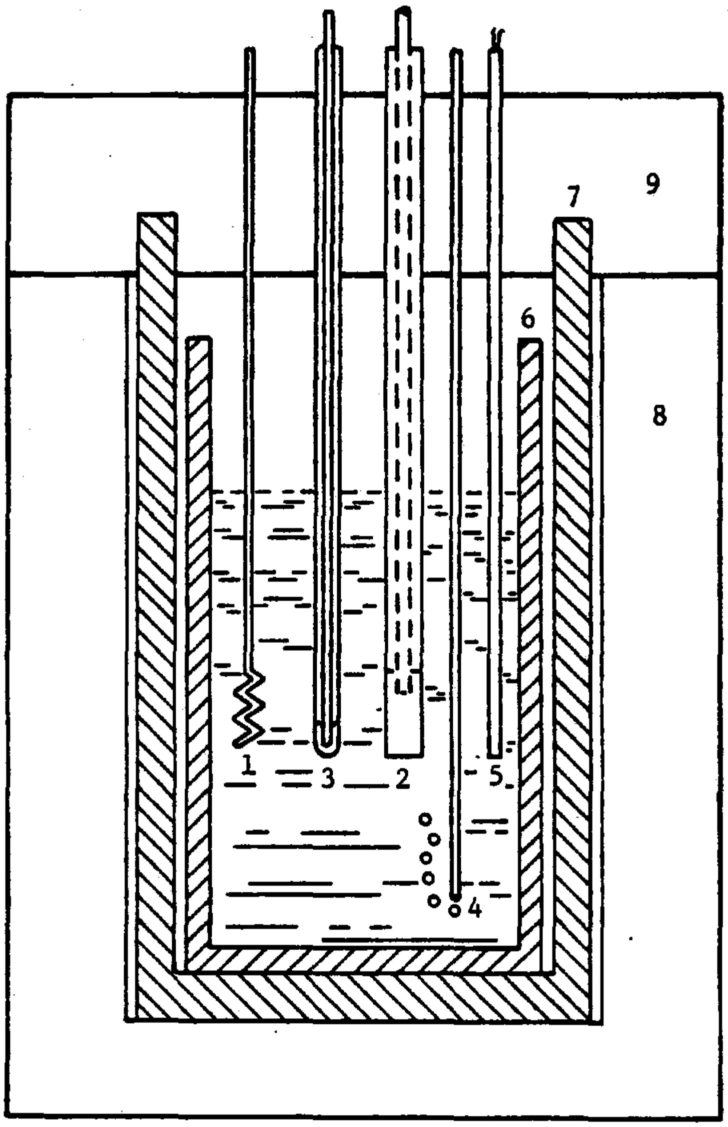


Figure II-20 Schematic Diagram for Thermal Heating Cycle

*Martin Marietta, Badger and PAS; Alternate Central Receiver Power System, Phase II, Final Report, Volume III (Molten Salt Materials Tests).

+C. M. Chen and G. J. Theus: Electrochemical Behavoir of Iron in Fused Salts. B&W RDTPA 79-13, 1979 or ASTM, STP 727, 1981, p 303.

Test materials will be carbon steel, 2-1/4 Croloy, and 304 stainless steel. The molten salt will be 60% $NaNO_3$/40% KNO_3 by weight without any special additions. The test temperatures for the isothermal corrosion tests will be as shown in Table II-8.



1. Platinum Electrode (Counter Electrode)
2. Specimen
3. Ag/Ag^+ Electrode (Reference Electrode)
4. Nitrogen Bubbler
5. Thermocouple
6. High-Purity Alumina Crucible
7. Stainless Steel Container
8. Furnace
9. Furnace Lid

Figure II-21 Test Cell

Table II-8
Temperatures (¼F) for Isothermal Corrosion Tests (Test Duration 50 Days)

Material		
C-Steel	2-1/4 Croloy	304 SS
550	550	550
700	850	850
		1050

The test conditons for the cyclic corrosion tests will be as shown in Table II-9. Table II-10 summarizes the proposed test plan and Table II-11 shows the test schedule.

Table II-9
Test Conditions for Thermal Cyclic Corrosion Tests (Test Duration 50 Days)

Cyclic Temperature	Material		
	C-Steel	2-1/4 Croloy	304 SS
T_1	550	550	550
T_2	700	850	1050

Performance Tests - The principal objective of these tests is to measure thermal performance of the SGS under steady-state operating conditions at several different steam rates to resolve any uncertainties in system performance. Corollary objectives are to demonstrate SGS operation under typical solar plant operating conditions and to demonstrate the effectiveness of the control system.

In the steady-state 100% design steam rate test, the SGS SRE will be operated at 100% of the design steam rate (17,690 lb/h) for several hours. The SGS SRE will be in a preheated condition as a result of leaving the electrical trace heaters on. Salt and water/steam flow rates will gradually be brought up to their maximum values and steady-state conditions at 100% of the design rates will be achieved.

The water/steam and salt flow rates, inlet temperature and pressure, and outlet temperature and pressure will be measured for each unit. These data will be used to calculate the heat transfer rate, log mean temperature difference, and heat transfer coefficients for each unit. These values will be compared with calculated values to assess the adequacy of the heat exchanger design. Pressure drops for both fluids in each unit will also be measured and compared with calculated values to assess hydraulic performance.

At least two tests will be run to assure repeatability and to provide some data redundancy. Since the storage SRE can only operate at 5 MWt for 3.0 hours, each test must be accomplished within this time frame.

Table II-10 Summary of Test Program Plan

Subtask	Procedure Employed	Expected Results
1. Isothermal Tests	- Set Up Test Assembly - System Modification - Selection of Reference Electrode - Tests - Electrochemical Method - C-Steel at 550 and 700°F - 2-1/4 Croloy at 550 and 850°F - 304 SS at 550, 850 and 1050°F	Modify test assembly in the footnote* for the present purpose. Pt or Ag/Ag electrode. Corrosion rate as function of time will be determined.
2. Cyclic Tests	- Set Up Test Assembly - Tests - Electrochemical Methods - C-Steel (550 700°F) - 2-1/4 Croloy (550 850°F) - 304 SS (550, 1050°F)	Similar to the test assembly in Task 1 except a process programmer for regulating the heat cycle shown in Figure II-21. Effect of exfoliate heat cycle will be determined.
3. Data Analysis	- Integration of Corrosion Rate/Time Curve and Extrapolation to 30-Year Weight Loss	Data will be used to obtain corrosion allowance for designing the steam generators.
4. Report	- Issue Final Report	

The objective of and procedure for the steady-state off-design steam rate tests is exactly the same as for the steady-state test described except that these tests will be run at 70% (Test 5), 50% (Test 6) and 30% (Test 7) of the maximum steam rates. These tests will provide SGS performance data at off-design conditions. These are important data for a solar plant application where the system may have to be operated at less than peak capacity due either to reduced insolation available or reduced and/or variable demand.

Table II-11 Isothermal Corrosion Tests

Material	Temperature, °F	Month 1	2	3	4	5	6	7
C-Steel	550	—	—					
	700			—	—			
2-1/4 Croloy	550	—	—					
	850			—	—			
304 SS	550	—	—					
	850			—	—			
	1050					—	—	
Report								—

Phase II Cyclic Corrosion Tests

Material	Month 1	2	3	4	5	6	7
C-Steel	—	—					
2-1/4 Croloy			—	—			
304 SS					—	—	
Report							—

The final test of this series (8) will be dedicated to finding the lowest steam rate at which the SGS SRE can be practically operated. The steam rate will be varied downwards from the 30% level until either automatic control or performance becomes impractical. This test will establish the margin on the minimum-load capability of the SGS with respect to its requirement of 30% maximum duty.

Several cyclic load tests will be performed. The steam flow will be cycled from 30% up to 100% of the maximum flow, and then back to 30% again to demonstrate the load-following capability of the SGS SRE. At first the cycling will be performed slowly, with one full cycle requiring up to several hours to execute. Eventually the rate will be increased with the goal of achieving the specification value of up to 10% load change per minute. Flow rate, temperature and pressure data will be analyzed for the cyclic operation to determine how well the SGS outlet conditons are controlled over the range of steam rates. Lags in output will be quantified to establish the capability of the system to follow a variable load.

Emergency shutdown tests will be run to simulate various emergency-type situations, to check out the emergency shutdown procedures, refine them where necessary, and demonstrate that the SGS SRE can be safely controlled under emergency conditions. These tests will probably be conducted early in the test program so the operators will be proficient in shutdown techniques before the bulk of the testing begins.

The following types of situations will be simulated:

1) Turbine trip;

2) Feedwater pump trip;

3) Salt pump trip.

In each case, it will be assumed that the particular emergency disturbance occurs at some point in time, t_o (e.g., the feedwater pump is manually shut off at t_o) and the situation is displayed to the operators at the console at that time. The operators will then implement the written procedures for that specific type of situation. In all cases, the objective is to shut the SGS SRE down with no hazard to personnel and no damage to equipment.

At the conclusion of testing, the SGS system will be shut down, drained of all fluids and allowed to cool down to ambient temperature. The heat exchangers will not be disassembled beyond that required for visual examination due to the possiblity of future tests.

7. Task 7 - Evaluation

Experimental data derived from the SRE test program will be examined and compared with the analytical results and assumptions used in the Phase I program (and on which the commercial subsystem and component designs are based). If the data signigicantly differ from those anticipated, the Phase I designs will be modified. Design documentation prepared during Phase I, such as the final design report and drawings, will be revised if necessary. The data analysis is briefly summarized in the following paragraphs.

a. Single-Tube DNB Testing - The principal objective of the DNB testing is to verify that the circulation ratio selected is sufficiently high to maintain nucleate boiling throughout the evaporator. Based on our review of available data we believe the circulation ratio has been chosen conservatively. Accepting that this will be confirmed, we will reassess the design margin and determine if the circulation rate can be reduced. Reduction of the circulation rate would result in some corresponding reduction in heat transfer surface and savings in pump costs.

b. Corrosion Testing - The corrosion tests are intended to better define the salt-side corrosion allowances to be applied to the heat exchanger tubing. If the test data compare favorably with our analytical assumptions, no design adjustments will be required. If the data deviate significantly from our analytical assumptions, the tube bundles of the affected heat exchangers must be resized. Assuming that our original assumptions were conservative, resizing will involve a reduction in heat transfer surface.

c. Performance Testing - The primary purpose of the 5-MWt steady-state performance tests is to verify the analytical predictions on which the heat exchanger designs are based. The salt-side specific heat will be derived from appropriate flow and temperature distribution measurements. The accuracy of the salt-side heat transfer correlations will be assessed from overall heat balances. The data will then be compared with the assumptions used in the design analyses accomplished with B&W's VAGEN computer code. If necessary, the performance analyses will be repeated and the effect on heat exchanger sizing determined.

8. Task 8 - Reporting

During the Phase II effort, the following reports and technical documents will be prepared and submitted to Sandia National Labs:

1) Monthly reports - Monthly reports will be submitted on or before the fifteenth day of the following month. These reports will describe technical accomplishments, problems, planned activity for the following month, and cost and schedule status. Management and financial reports will be provided on Sandia National Labs forms' 533 through 536. Technical reports will be in the form of a letter of at least one full page;

2) Final report - A final report describing the as-fabricated SRE components, the tests and the test assessments performed during Phase II and presenting results, conclusions and recommendations will be prepared. This report will be submitted to Sandia National Labs in draft form 30 days prior to the contract completion date. Sandia National Labs comments will be incorporated in the report and a final version issued;

3) Additional technical documents prepared and submitted to Sandia National Labs include a test plan, a revised SGS requirements specification, and a revised steam generator fabrication plan.

Both the International and English systems of units will be used to present data in written and oral reports.

9. Task 9 - Program Management

Program management, planning, direction, coordination, review and control will be provided to assure completion of work in accordance with the approved program plan. Babcock and Wilcox personnel will meet with subcontractors, as necessary, to coordinate the work effort. Oral presentations will be made to SNLL at the meetings tabulated.

Meeting Date (Months After Award)	Meeting	Location
1	Kickoff	Barberton
3	1st Quarterly Review	Livermore
6	2nd Quarterly Review	Barberton
9	3rd Quarterly Reveiw	Livermore
12	4th Quarterly Review	Barberton
15	5th Quarterly Review	Livermore
20	Final Review	Livermore

Babcock and Wilcox will also participate in annual contractor review meetings scheduled by the Department of Energy. Brief written and oral summaries of the program status will be prepared for these meetings.

C. PROGRAM PLAN

Figure I-6 presents the program schedule based on the tasks defined in the statement of work. Each task is further defined by milestones listed at the right of the schedule. The time required to prepare and submit reports has been included. The critical path is shown to emphasize key events in program performance.

D. GOVERNMENT-FURNISHED PROPERTY

To make maximum use of the facilities and equipment that exist at the CRTF and to perform this work in a cost effective and timely manner, Sandia National Laboratories must make the following hardware and/or services available for the duration of this project:

1) A rectangular plot of land approximately 40x50 feet. The best location for the SGS seems to be directly adjacent to the storage SRE because this will minimize piping and wiring;

2) All of the water/steam heat rejection system, including the desuperheater, spray water cooler, cooling towers, water storage tank, demineralizers, feedwater heater, pumps, piping, controls etc. Note that the CRTF will have to replace the current feedwater pump with a new pump;

3) All of the existing storage SRE equipment, including the hot tank, cold tank, salt heater, air cooler, salt, sumps, pumps, piping, controls, control building, etc. Note that the CRTF will have to replace the current hot pump with a larger one;

4) The SGS SRE control console and the data recording equipment will need to be located in the existing storage system control room and the existing CRTs will be needed to display system parameters;

5) The existing ACUREX AUTO DATA 10 mobile data logger data acquisition system;

6) The existing data measurement sensors (their display and alarm capabilities) for the measurement of salt temperatures, pressures, and storage tank fluid levels;

7) Propane to run the existing 3-MWt salt heater in the storage SRE;

8) Electricity to run the SGS SRE, the HRS, the storage SRE, the trace heaters and any other equipment that will require electricity;

9) Compressed air to operate the salt valves and other pneumatically operated controls;

10) Crane service to set all heavy equipment;

11) Operators for all Sandia equipment;

12) Telephone service.

III. SINGLE-TUBE TEST R&D OPTION

A. SYSTEM DESCRIPTION

This option is intended to satisfy the long-term technical objectives of the program with relatively low cost. This alternative includes only the DNB and the corrosion tests previously described in the baseline option. While the SGS SRE is intended as a visible demonstration of the principles of the basic steam generator subsystem, the tests in this option are designed to develop technical information to help optimize the large plant designs and to ensure successful operation of the plant units over the very long term.

The onset of DNB in an evaporator can, over the long-term, lead to corrosion of the evaporator tube walls. For the short-term testing proposed for the SGS SRE, the onset of DNB would, in all likelihood, go undetected. However for the large plant evaporator design, it is essential to demonstrate that DNB does not occur.

The plant unit evaporator has been designed using proprietory B&W data to ensure that DNB does not occur in the evaporator section. Because of the scarcity of data relative to the exact configuration desired, design margins were added resulting in a circulation ratio believed to be conservative. The DNB test program will confirm the choice of the circulation ratio and determine if design margins can be reduced. Reduction of the design margins on the recirculation ratio would allow optimization of the evaporator and an increase in cycle efficiency.

The corrosion tests are necessary to more accurately define the corrosion allowances for the life-of-the-plant units. Sufficient work has been done in the solar program to allow corrosion allowances to be conservatively estimated. While the corrosion tests are not necessary for short-term test of the SGS SRE, they will allow more accurate corrosion data to be obtained for the plant unit. Consequently a reduction in the thickness of the steam generator tube walls can be obtained with a corresponding reduction in steam generator unit size and cost.

The corrosion tests will be performed in B&W's research and development division laboratories. The work plan is unchanged from that described for the baseline option.

The basic test plan and instrumented single-tube and shell assembly for the DNB tests are also unchanged fom those described in the baseline option. However because the balance of the SRE system is not available, the CRTF facility must be modified as shown in Figure III-1.

Two 35-kW immersion resistance heaters and associated electrical controls will be provided. These are standard Cromolox heaters manufactured by the Weigand Company of Pittsburgh (or equivalent). The heaters function to bring the 400°F feedwater supplied by the HRS up to 628°F, the temperature supplied by the SGS SRE recirculating line in the baseline design.

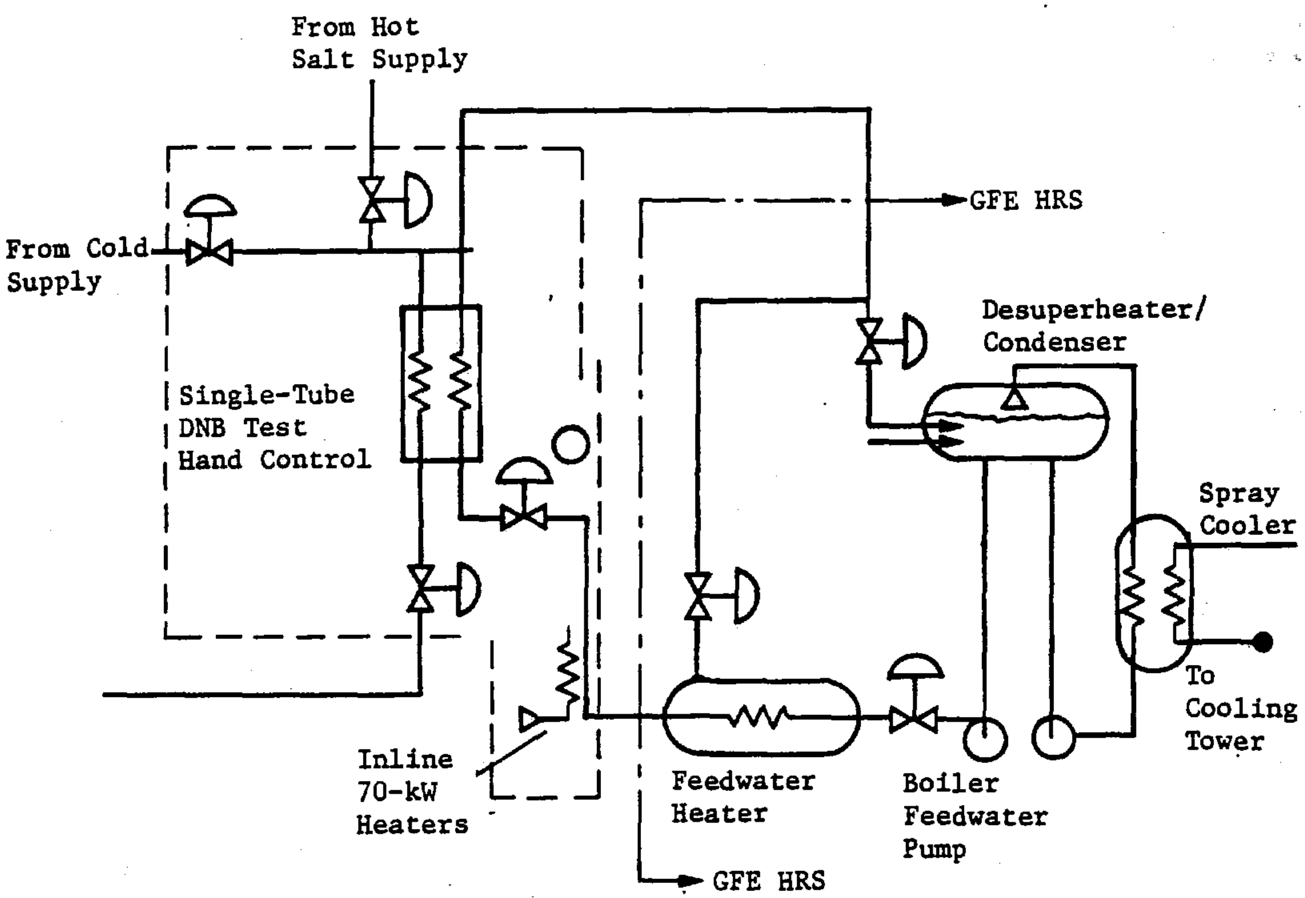


Figure III-1 Single-Tube Test R&D Test Option Schematic

B. SCHEDULE

Figure III-2 shows the schedule for this option. The total program span is 15 months with three months allowed for design and two months for the test plan and procedures followed by three months for fabrication of the test hardware. Installation and checkout starts in the ninth month and is completed in the tenth. DNB testing sill take six weeks followed by data analysis and the final report in the last two months of the program.

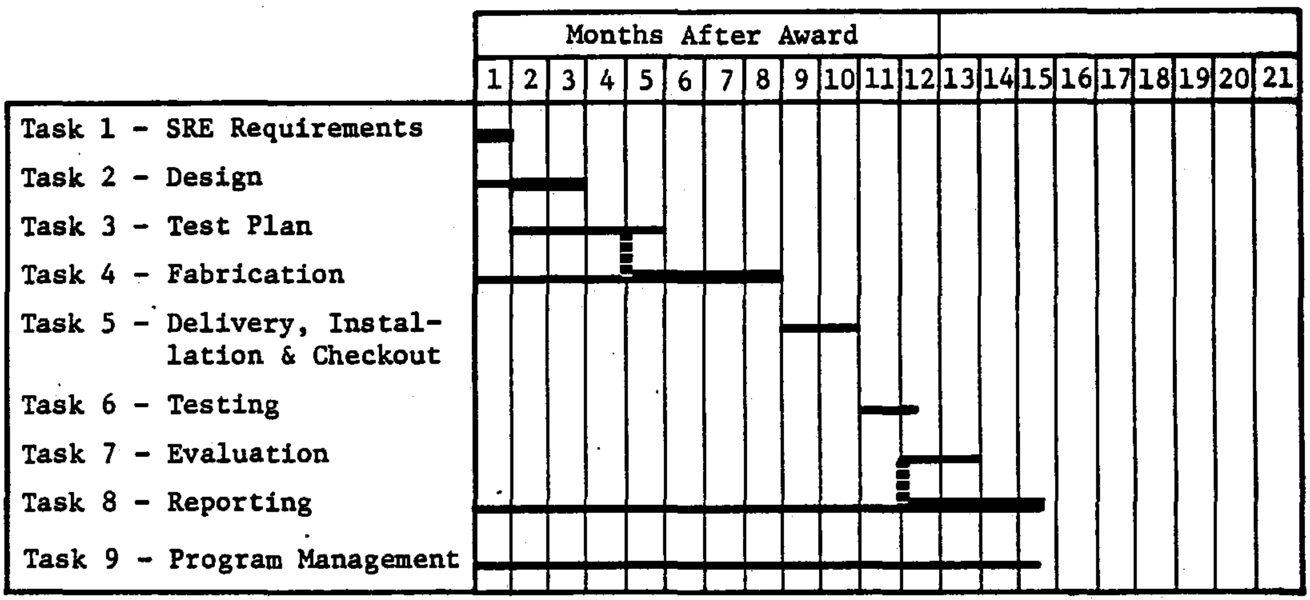


Figure III-2 Program Schedule for SRE R&D Option

C. GOVERNMENT-FURNISHED EQUIPMENT

The GFE is essentially the same as outlined in the baseline option except for the following changes:

1) A plot of land approximately 10x50 feet is required;

2) The air cooler would not be required;

3) The current hot pump will not need to be replaced.

IV. STEAM GENERATOR FOR FULL-SYSTEM EXPERIMENT OPTION

A. SRE SYSTEM DESCRIPTION

The purpose of this option is to satisfy both the primary objective of the SGS SRE program and the secondary objective of having an SGS that is compatible with an FSE test system. Several SGS design arrangements can meet these two overall requirements. The choice depends on the tradeoffs of operating conditions to be demonstrated during FSE operation. Figure IV-1 shows a concept that provides 10,000 lb/h of 1450-psi 950°F steam to the FSE turbine while continuing to maintain the SGS steam and salt terminal conditions required in the baseline SRE test program. This scheme provides all components required in the baseline system option SGS SRE plus the indicated preheaters. The SGS SRE test program, as described in the baseline option, will be run with these additional components either not installed or bypassed. When the FSE tests are run, the heat exchangers will be run at the heat loads shown in Figure IV-1. The superheater load is about 54% of its design capacity and the evaporator operates at 83% capacity. The evaporator operates at a higher capacity because it must supply the additional steam required to heat the feedwater in preheater 1. Note that the air cooler will be used in the steam generator testing but not in the FSE testing. Salt at 550°F from the cold tank will be used to limit the temperature of the salt entering the evaporator to 850°F. The instrumentation and control system will be modified to allow for additional measurements and to be compatible with the CRTF central data and control system. This will allow operation of the FSE from the main control room.

Preliminary analysis indicates an alternative scheme, which may not require any change to the baseline SGS, is also compatible with the FSE. In this scheme, after completion of the SGS SRE baseline test, the SGS system would be operated at the steam pressure and temperature terminal conditions required for the FSE (1450 psi, 950°F rather than 1800 psi, 1000°F).

Approximately 72,000 lb/h of 1050°F salt would flow through the superheater, exiting at 939°F. Cold salt is mixed with this and the mixture, amounting to 94,000 lb/h is passed through the evaporator. The salt exits the evaporator at 550°F. What makes this scheme viable is the reduction in recirculating water temperature to 460°F by introducing feedwater to the drum at about 240°F. This, in turn, reduces preheat requirements to the point where the GFE HRS appears to have sufficient capacity to raise the 125°F condensate to the required 240°F temperature. About 1000 lb/h of saturated steam would be bled to the HRS feedwater heater and the deaerator/desuperheater/condenser. Salt terminal conditions are thus maintained at prototype plant conditions, SGS steam conditions are slightly reduced to match the FSE requirements, and feedwater temperature is lower than plant conditions.

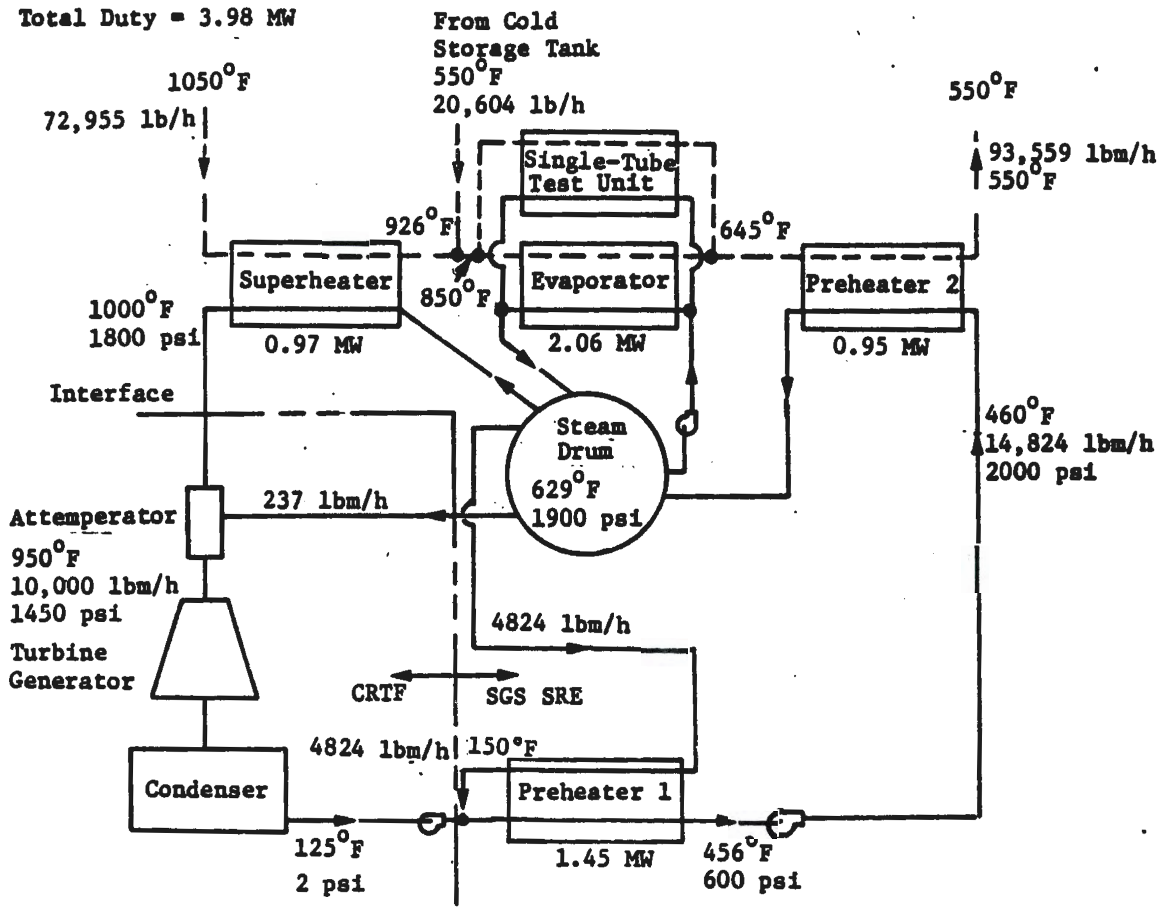


Figure IV-1 FSE/Heat Exchanger Heat Balance

In Phase II the various objectives of the FSE will be defined and evaluated and the most cost effective scheme for providing SGS SRE compatibility with the FSE will be selected.

1. Control and Instrumentation

The MCS-DAS computer located in the main control room will be required to control the FSE. This is because the controls and instrumentation requirements for the FSE will exceed the capacity of the mobile data logger used for the baseline case, and because the MCS-DAS computer has previously been used for receiver control and heliostat field control. To relay the control and instrumentation data from the SGS SRE to the MCS-DAS computer, a module will be required at the SGS site to digitize and multiplex all the data channels onto one line. A data bus will then be run to the main control room where the data will be demultiplexed and interfaced with the MCS-DAS computer.

Additional SGS instrumentation will be required to monitor and control the salt/water preheater and the water/steam preheater that are added to the subsystem. The flow rate of steam extracted from the steam drum will be regulated to control the feedwater outlet temperature of the water/steam preheater (preheater 1). This temperature must be controlled so feedwater entering the salt/water preheater (preheater 2) will be kept at 460°F to avoid salt freezing. The temperature of the salt leaving preheater 2 will also be monitored to ensure it is at 550°F.

The addition of a preheater to the system will have two effects on the control system:

1) The gains will require tuning;

2) An additional control loop is necessary.

The additional loop will be used to control the flow of steam from the drum for mixing with the feedwater supply. This is an attemperation loop using temperature feedback to position the valve controlling flow rate.

The effect of the second alternative on the control system has not been evaluated but is judged to be less significant than the first alternative discussed.

The additional control hardware for this loop is not a significant problem. However, a data link between the HP computer system situated in the main control room and the control rack situated by the steam generators will be required. This problem has already been discussed with Sandia Albuquerque and a feasible solution found using existing hardware. It will involve using the HP computer system to form the operator interface in supervising the distributed control and to provide graphics.

2. Testing

The test program described in the section on the baseline system will be run using the superheater and evaporator and bypassing the preheater. This will allow the use of the full 5 MW for the heat exchangers. These tests will be run from the storage SRE control building. On completion of the basic testing, the system will be configured to include the preheaters in the test loop. The instrumentation and controls will be connected to the equipment in the main control room. Checkout tests will then be conducted by first using local control and then by operating the system using the main control room. Operation of the collector field and the receiver will be simulated at the same time to ensure there are no interface problems in the control and data systems.

B. SCHEDULE

The schedule (Fig. IV-2) for the design and fabrication phase of the project is the same as the baseline system option. The installation and checkout task and the test task have each been lengthened by one month to allow installation of the additional hardware.

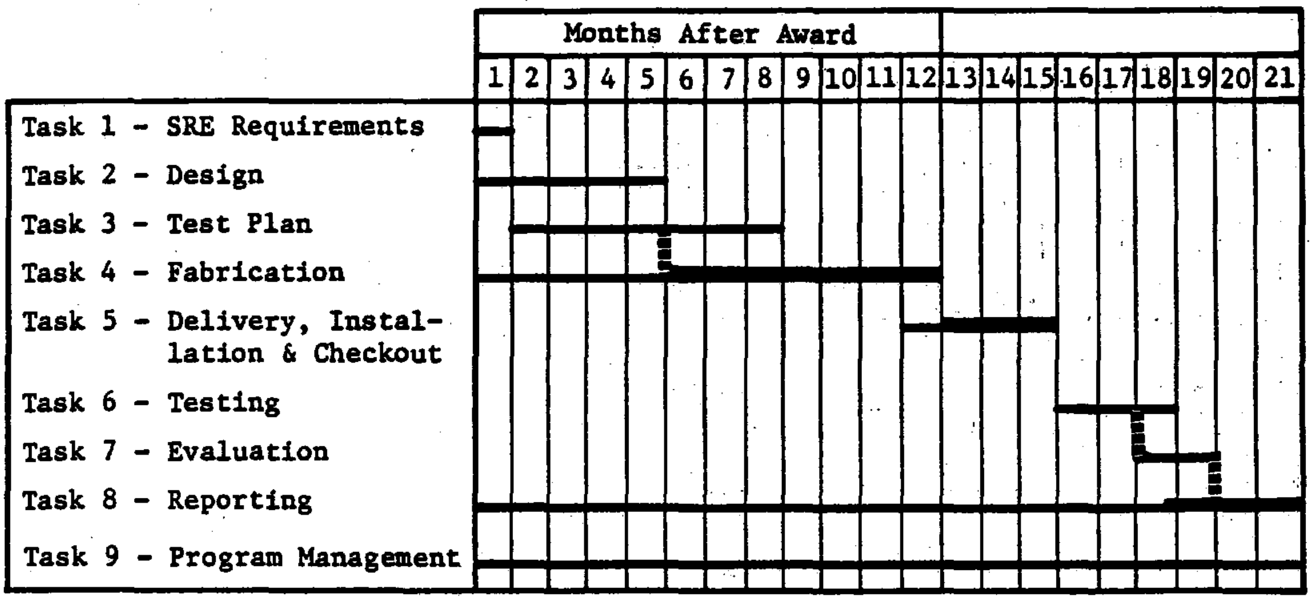


Figure IV-2 Program Schedule for FSE Option

C. GOVERNMENT-FURNISHED EQUIPMENT

The equipment to be supplied by Sandia National Labs will be the same as that used in the baseline system option. In addition, for the checkout tests of the FSE mode of operation, the MCS-DAS computer system, D-to-A and A-to-D converters and the data bus will be required.

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