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SUNFLOWER POWER SYSTEM TEST REPORT

TOPICAL REPORT

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SUNFLOWER POWER SYSTEM

TEST REPORT

THOMPSON RAMO WOOLDRIDGE INC.

Abstract

The Sunflower PCS I-1 system which was composed of the preprototype hardware of each major component was assembled and tested to determine component compatibility and system performance. The component integration was consistent with the flight specification of operating the condenser in a condensing direction opposing the gravitational field. Testing was augmented by auxiliary facilities for startup and steady state operation as required.

The program consisted of three separate tests which included twelve (12) individual system startups and a total accumulated operational time of 47 hours. Testing confirmed the integration of the preprototype components and their ability to operate in a system fashion. However, operation was characterized by sensitivity of the condenser to the operating conditions. The condenser performance was aggravated by a condition of tube wetting and the influence of liquid leakage into the condenser inlet through the turbomachinery seals. Hardware modifications have been recommended for the condenser and turboalternator components as well as review of the -1 g operational specification.

Power conversion system conclusions and recommendations are presented. Detailed results of individual component investigations and overall program recommendations can be obtained through the suggested list of references.

SUNFLOWER POWER SYSTEM TOPICAL

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1.0 INTRODUCTION

The purpose of this report is to present the initial test results of the Sunflower system development test program. The report is submitted in fulfillment of the requirement of a Sunflower System Topical Report as defined in NASA contract NAS 5-462.

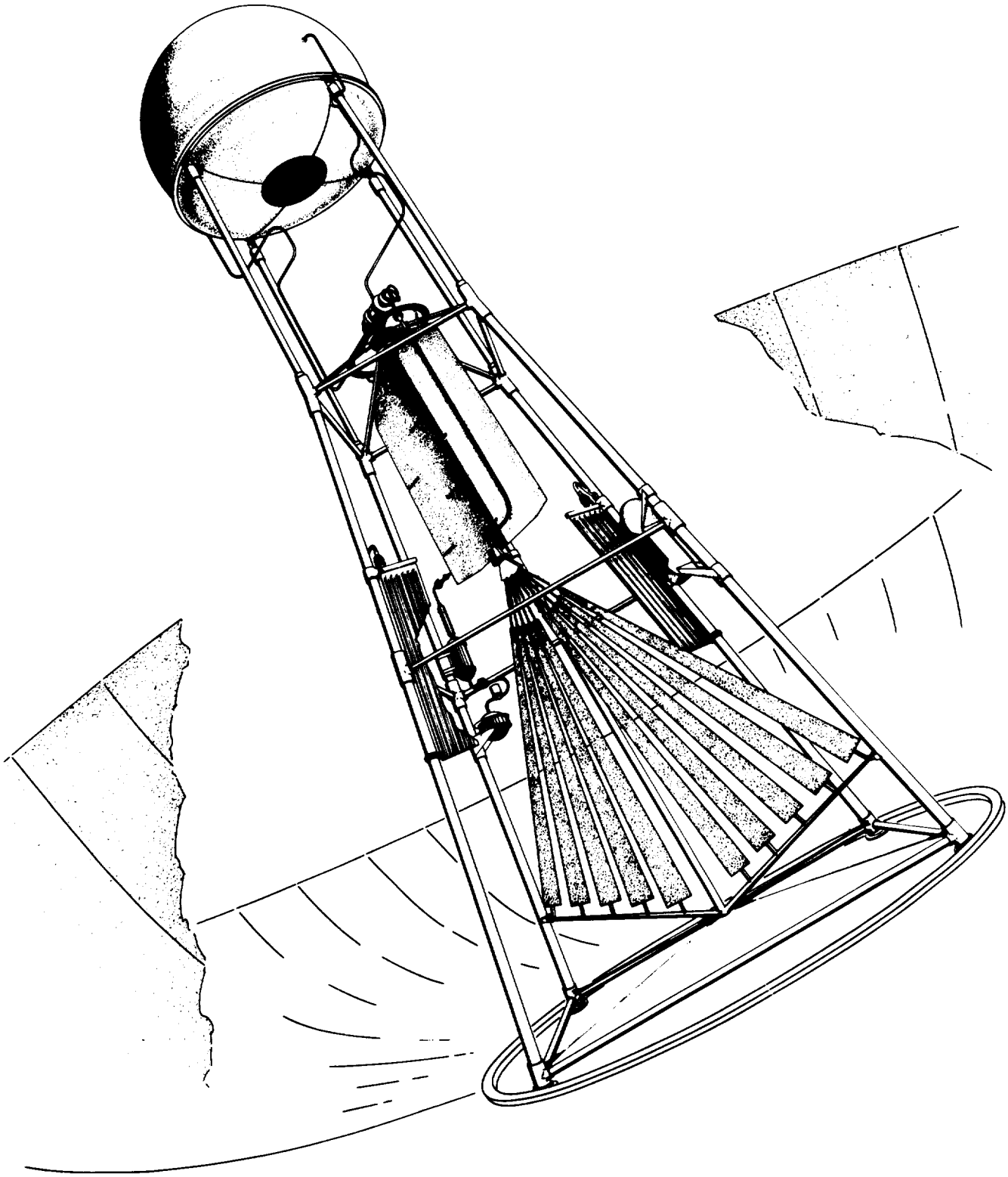
The Sunflower development was initiated on 1 June 1960 The program objectives were oriented at the demonstration of long term endurance capability of the Power Conversion System (PCS) concept for future space flight applications The Sunflower system test reported represents the first milestone in meeting this objective. The test reported was initiated in November 1962 and completed on 19 December 1962. The results obtained are both gratifying and informative and demonstrate the basic feasibility of the system concept employed.

2.0 THE SUNFLOWER POWER CONVERSION SYSTEM

2.1 General Description and Background

Sunflower is a 3KW solar power system. The system employs a mercury Rankine cycle to convert solar energy to useful electrical power. The principle components of the system are the solar concentrator, the boiler heat storage unit, the combined shaft unit and condenser-subcooler unit. In addition, auxiliary components are required for frequency control of the generated electrical power and system startup. The Sunflower system provides for the integration of these components on a suitable structure. Figure 2.1 shows an artist conception of the system in space application.

The early history of Sunflower was closely related to the SNAP 2 space power system. This association resulted from the identity of



SUNFLOWER FLIGHT SYSTEM

FIGURE 2.1

useful power requirements of the two system and the general objective that the SNAP 2 combined shaft unit (CSU) design be used in Sunflower with minimum of modification as required to account for the differences in energy source between the two systems. The major change was the elimination of the SNAP 2 CSU shaft mounted, Nak reactor coolant pump in the Sunflower CSU design. A second modification required changing the turbine design from a two stage to three stage axial impulse turbine. This was provided without basic change to the bearing design or bearing span in the SNAP 2 package. The design modification allowed the use of a higher cycle turbine inlet pressure in the Sunflower system without compromise or overall loss in turbine efficiency. In addition to these changes, minor changes to the basic SNAP 2 package were made to incorporate advanced design modifications planned for the next series of SNAP 2 rotating packages.

A secondary reason for maintaining the systems as similar in nature as possible was to draw on the available technology in order to keep parallel type development efforts to a minimum and likewise programs costs.

2.2 Mercury Rankine Cycle - Selection of Operating Points

The selection of the Sunflower Mercury Rankine Cycle operating points is based upon system weight minimization, consistent with maintaining conservative design requirements necessary to insure a reliable system. The major system weight is associated with the solar collector and boiler-heat storage components. To reduce the weight of these components, it is desirable to increase the operating cycle pressure

and temperature differential for higher thermodynamic cycle efficiency and thus reduce the source energy requirements of the system. The bounds of improvement of cycle efficiency in this manner are determined primarily by component limitations.

The upper cycle operating temperature is limited by the physical characteristic of the boiler heat storage material. The material, lithium hydride, melts and stores energy as the latent heat of fusion at a temperature of 1255°F. The melting temperature of the boiler-heat storage material thus establishes the upper cycle design temperature.

With the objective of increasing the energy available for turbine useful work, it is desirable to increase mercury boiling pressure and thus boiling temperature. The limit of increase, however, is determined by the affect of higher inlet pressure upon turbine performance for the relatively fixed turbine configuration of the Sunflower system. For the three stage Sunflower turbine configuration, an inlet selection of 240 psi is near optimum in terms of maximizing the product of available energy and turbine efficiency. Other factors which tend to influence the selection of pressure are both considerations of increased corrosion with boiling temperature and higher quality vapor in the later stages of expansion through the turbine.

At the low temperature extreme, condensing pressure is selected with considerations to cycle efficiency, and radiator area, and thus radiator weight, in conjunction with the requirements of net positive suction

head at the mercury pump inlet. In view of the weight predominance of the solar collector and boiler-heat storage system, the selection of condensing pressure and temperature was made to maximize thermodynamic cycle efficiency. The selection of condensing pressure is thus primarily dependent upon meeting the mercury pump requirements under transient and steady state operation. For zero gravity, at the design inlet condensing pressure and temperature of 7 psia and 609°F, the NPSH will be 4.75 psia at a temperature of 400°F, meeting the minimum pump requirements of 3.4 psia. This allows a tolerance of 2.7 inches in location of the liquid-vapor interface under negative 1-g acceleration.

The selected Sunflower I mercury Rankine cycle is shown schematically in Figure 2.2 illustrating the system components. The cycle state conditions result from a thermodynamic heat balance for the specified component efficiencies and power requirements. Figure 2.3 illustrates the cycle conditions of the components during developmental tests.

A unique feature of the proposed system is the use of regenerative cycling of the mercury pump discharge to provide both condensing and subcooling of the mercury vapor and liquid, respectively. In terms of system performance the use of regeneration accomplishes the desirable objective of partially returning to the system normally lost heat or otherwise unavailable energy and thus reducing the input energy requirements. However, of greater significance has been the ability, through regeneration, to strategically locate the vapor-liquid interface and to provide the necessary subcooling, within the limitations imposed by 1-g operation in all directions, with liquid heat exchangers. The Sunflower I system operating between the design extremities of

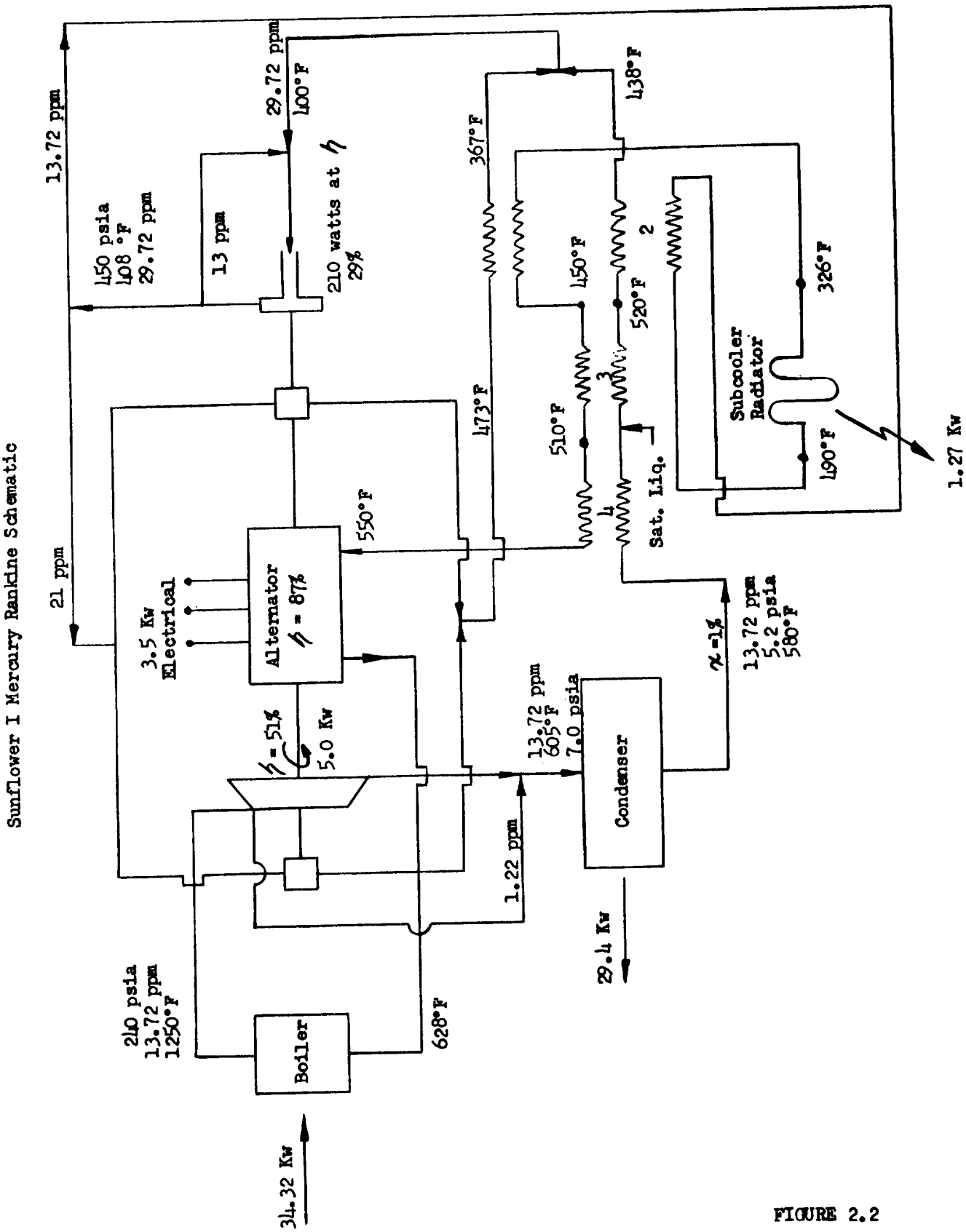

Sunflower I Mercury Rankine Schematic
13.72 ppm
29.72 ppm
100°F
450 psia
408 °F
29.72 ppm
13 ppm
210 watts at
29%
367°F
438°F
450°F
520°F
326°F
Subcooler
Radiator
473°F
510°F
490°F
1.27 Kw
550°F
Sat. Liq.
21 ppm
3.5 Kw
Electrical
Alternator
= 87%
13.72 ppm
5.2 psia
580°F
= 51%
5.0 Kw
13.72 ppm
605°F
7.0 psia
Condenser
1.22 ppm
29.4 Kw
240 psia
13.72 ppm
1250°F
Boiler
628°F
34.32 Kw

FIGURE 2.2

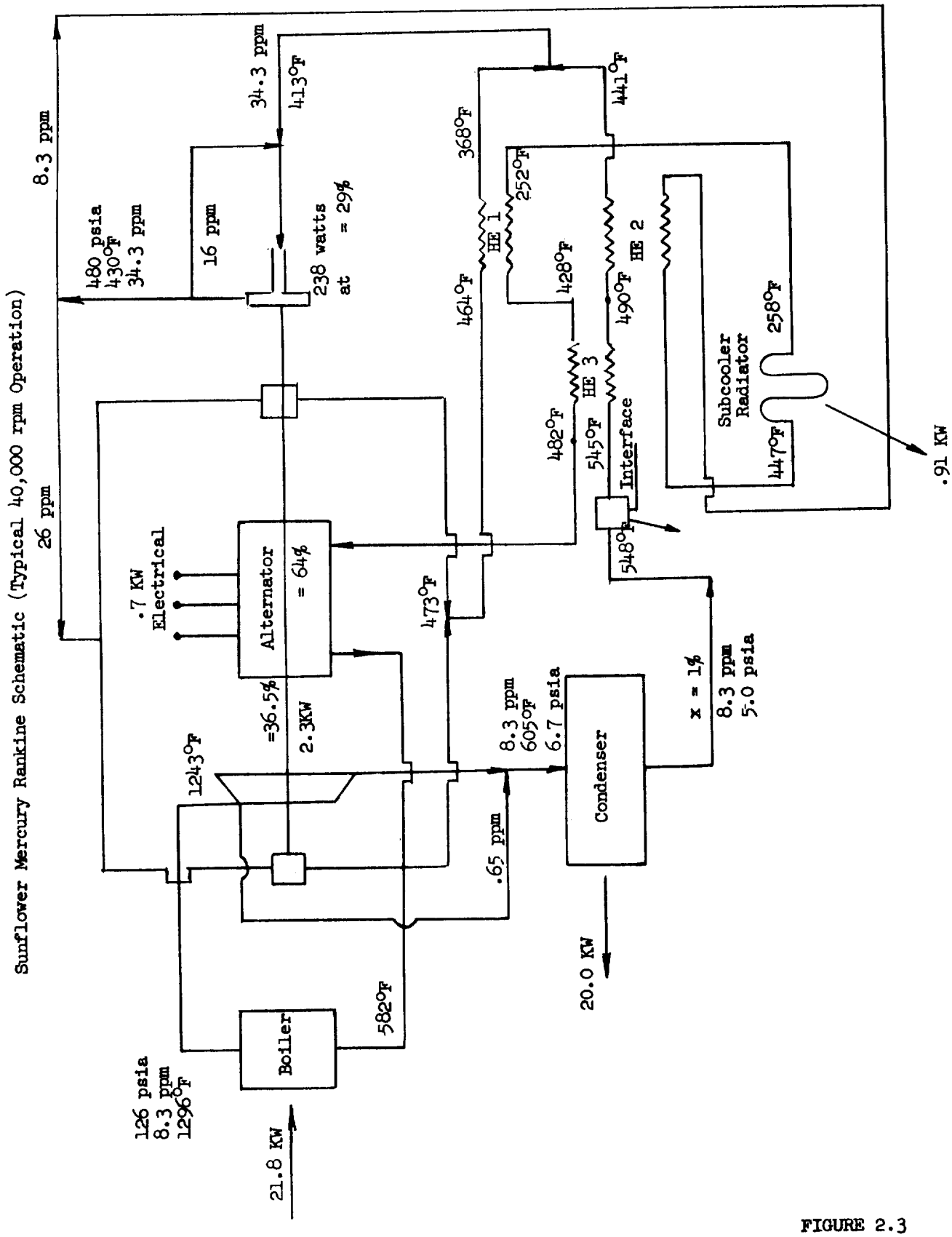

Sunflower Mercury Rankine Schematic (Typical 40,000 rpm Operation)
8.3 ppm
26 ppm
480 psia
430°F
34.3 ppm
16 ppm
34.3 ppm
413°F
238 watts
at = 29%
.7 KW
Electrical
Alternator
= 64%
=36.5%
2.3KW
1243°F
473°F
368°F
252°F
464°F
HE 1
428°F
482°F
HE 3
545°F
441°F
490°F
HE 2
Interface
548°F
Subcooler
Radiator
258°F
447°F
.91 KW
8.3 ppm
605°F
6.7 psia
Condenser
x = 1%
8.3 ppm
5.0 psia
.65 ppm
20.0 KW
582°F
Boiler
126 psia
8.3 ppm
1296°F
21.8 KW

FIGURE 2.3

upper and lower cycle temperature and pressure will have an ideal thermodynamic cycle efficiency of 28.6 percent. The overall conversion efficiency of useful work in the form of electrical energy to heat input is 10.2 percent.

2.3 System Specification

The system specifications represent the design requirements of the Sunflower system. From this specification detail component specifications result which form the basis of system component design and integration.

2.3.1 System Performance

2.3.1.1 Power Output

The system shall be capable of producing a useful electrical power output which may be varied continuously or in discrete steps in the range from 300 watts to 3000 watts when used in earth satellite or lunar vehicles. Performance limitations and any modifications of the basic system which are necessary for operation of the system in the vicinity of Venus or Mars shall be minimized. A continuous power output capability of 3 Kw shall be required.

2.3.1.2 Voltage and Frequency

The system shall deliver two-phase AC power at 110 volts, line-to-neutral and at a frequency of 2000 cps.

2.3.1.3 Regulation

The voltage shall be regulated at 110 volts ±5% and frequency shall be maintained within ±1% of 2000 cps from 10% to full load. An automatically adjustable

impedance load will be used in parallel with the useful load to insure constancy of total load on the power system.

2.3.1.4 Operating Life

The system shall be developed ultimately to attain a reliability of at least 95% for mission durations of one year. Two systems shall be delivered for experimental flight test within three years with maximum possible reliability for mission durations of 90 days. The contractor shall analyze and submit a prediction of the expected reliability of the experimental prototype prior to delivery.

2.3.1.5 Launch Power Requirements

No power shall be required during launch. After establishment of an operation orbit, the solar collector shall be deployed and oriented to the sun. System startup shall occur as soon as possible after orientation is accomplished.

2.3.1.6 Load Characteristics

The system shall meet the above power and regulations with variation of load power factor from 0.8 lagging to unity.

2.3.1.7 Voltage Distortion

The harmonic content of the alternator output shall not exceed 7% of the fundamental at design load conditions with a linear impedance load. No individual harmonic shall exceed 5% of the fundamental.

2.3.2 Environmental Conditions

2.3.2.1 Launch Conditions

The power system when packaged within a vehicle shall be capable of withstanding the following environmental conditions before and during launch:

2.3.2.1.1 Temperatures ranging from 0°F to 200°F.

2.3.2.1.2 Pressures ranging from 1 atmosphere to 0.

2.3.2.1.3 Relative humidity ranging from 0% to 100%.

2.3.2.1.4 Maximum acceleration of 10 "g's" along the longitudinal axis and 3 "g" along any laterial axis of the vehicle.

2.3.2.1.5 Vibration for a period of 10 minutes within the range of 20 to 2000 cps with 0.050 inch double amplitude or 10 "g", which ever corresponds to the lesser amplitude of vibration.

2.3.2.1.6 Aerodynamic loads and stagnation temperatures on the packaged power system after jettisoning of the vehicle nose fairing at an altitude as low as 400,000 ft and a velocity as high as 13,000 ft/sec at a flight angle of attack up to 6 degrees.

2.3.2.2 Space Conditions

After injection into any earth satellite orbit above 300 nautical miles or into any lunar, Mars or Venus trajectory, the power system shall be capable of unfolding, and upon being properly oriented toward the sun, operate for one year under the following conditions:

Adequate energy storage shall be provided for any circular

earth satellite orbit between the altitudes of 300 and 20,000 nautical miles having, respectively, orbital and shade periods of 96-36 minutes and 1500-70 minutes.

2.3.2.2.1 Zero-absolute pressure.

2.3.2.2.2 Linear accelerations up to 10^{-3}g continuously in any direction.

2.3.2.2.3 Linear accelerations of up to 1 "g" and vibrations as in 2.3.2.1.5 in any direction during three periods of 5 minutes each.

2.3.2.2.4 Angular accelerations of up to 1 degree/sec^2 and angular rotation rates up to 10 degree/sec about any axis during six periods of up to 5 minutes each. Three of these periods may be simultaneous with the acceleration periods of 2.3.2.2.3. The remaining three periods of angular orientation will be required to be performed without folding the solar collector.

2.3.2.2.5 Zero gravity during a large portion of the operating life.

2.3.2.2.6 Meteor bombardment, Van Allen radiation, and cosmic radiation consistent with the latest scientific data.

2.3.3 Vehicle Compatibility

The following disturbing effects of the power system upon a representative space vehicle weighing from 2000 to 30,000 lbs. shall be considered in the design of the system.

2.3.3.1 Vibration

The power system shall not impart to the vehicle support points any vibration disturbances with double amplitudes greater than 0.0001 inch when the vibration is unrestrained. In addition, instantaneous accelerations at the support points shall be less than 0.01 "g" at any frequency when the vibration is unrestrained.

2.3.3.2 Torque

Any torque resulting from moving parts within the power system shall be eliminated to the maximum extent practicable.

2.3.3.3 Electrical Interference

The electrical interference caused by the system shall be minimized.

2.3.3.4 Switching Transients

The power system shall be designed so that instantaneous values of surge current equal to twice the nominal maximum current can be tolerated without impairment of the system performance.

2.3.3.5 System Weight

The power system weight shall not exceed 722 lbs. This weight shall be maintained consistent with the critical requirements for reliability and performance.

2.3.3.6 Volume

The power system in launch configuration shall fit within a volume which is a cylinder 9 ft. 6 inches in diameter 8 ft. high topped by a right circular cone of 15° half angle. No

reliance shall be placed on an external noze fairing for mechanical support of the power system, since the nose fairing may be jettisoned at an altitude above 400,000 ft. at a flight velocity of 13,000 ft/sec during the boost trajectory. The power system shall be mechanically supported from points on the lower side, when in the launching attitude.

2.4 System Design Considerations

The selection of system component concepts and their integration into a useful system is influenced very strongly by performance objectives and the environment that the system is to operate in. In terms of performance, the objective is to define a system of minimum weight and volume. Unfortunately the two objectives are not always consistent with each other. The trade-off that exist between weight and volume is in most cases limited by eventual restraints either in total system weight or volume. In the case of the Sunflower system, for a given launch vehicle and storage volume availability the objective became that of minimizing total system weight consistent with system reliability objectives. Component operational concepts and designs were made to best meet the objective of high performance and minimum system weight.

The operational environment that the system must function in imposes certain restraints on design freedom in meeting the overall system objectives. The most imposing restriction in the Sunflower system is operation during short periods of ±1 "g" accelerations in any direction. This condition imposes a severe operational requirement on both the

solar concentrator and condenser-subcooler components. Gravitational forces acting on the solar concentrator can cause deflection and resulting deformation of the optical surfaces. For short periods, however, system operation can be sustained, using energy from the heat storage material without affecting overall system performance. The primary concern in the design of the concentrator is to prevent permanent deformation by the 1 "g" aceleration forces.

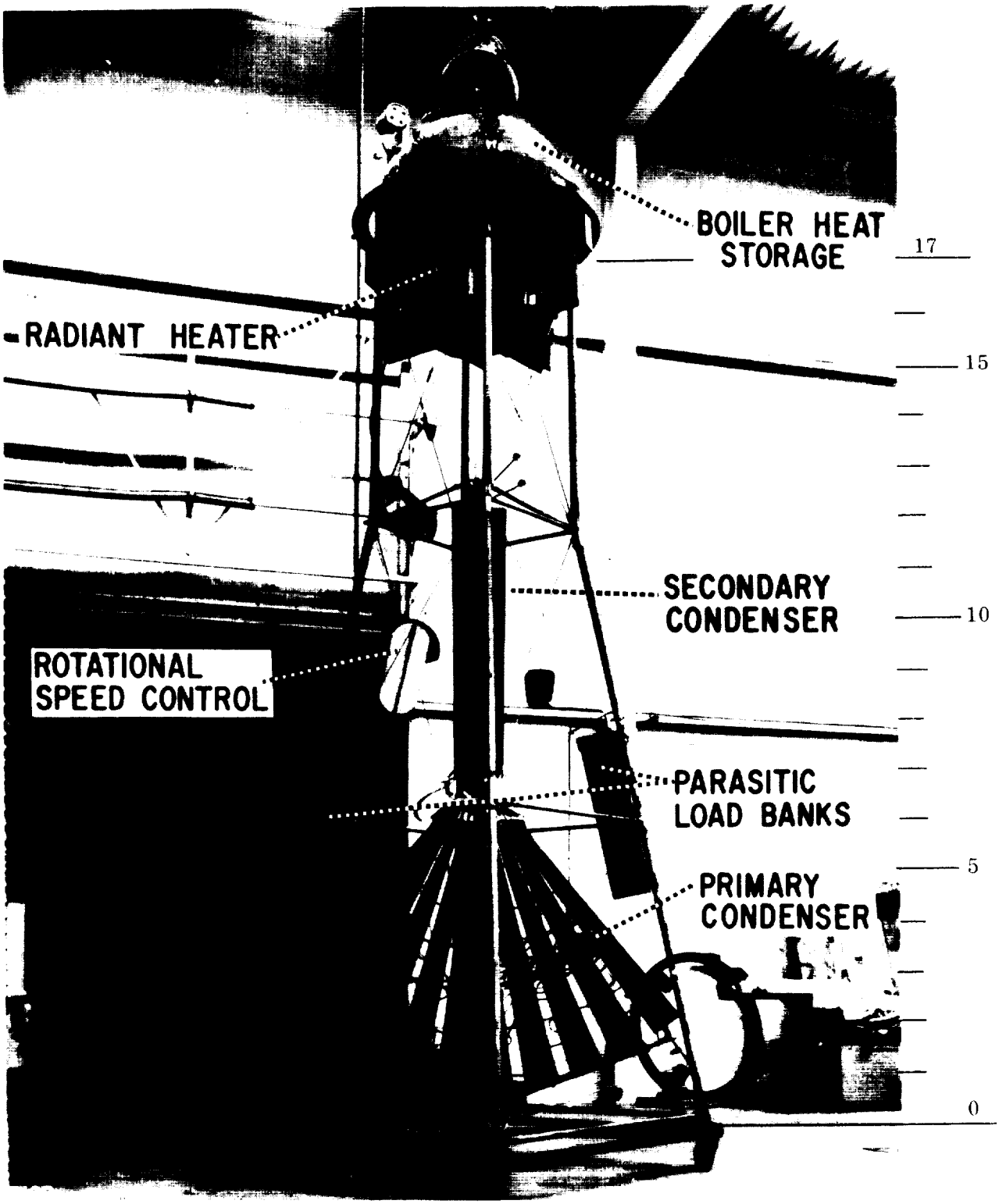
Liquid transportation in a negative gravity field however is a factor which has a pronounced affect in the design of the condenser-subcooler component. Vapor velocity must be selected high enough to transport the liquid condensate droplets against the artifical gravity force and the vapor-liquid interface must be located and maintained in close proximity to the condensate pump to prevent pump cavitation. To meet these design requirements and high performance objectives the Sunflower condenser is a direct condensing system, employing a planar, multiple tube fin design. Each of the condensing tubes are tapered to provide a constant vapor velocity along the condensing length. The terminal phase of condensing is provided in a single, tube fin secondary condenser which is fed by the multiple tube primary condenser through a common header. The condensate out of the secondary condenser provides the liquid-vapor interface between condensing and subcooling and is located close to the condensate pump inlet. Subcooling of the condensate is provided in compact heat exchangers which are located physically within the limits imposed by condensate pump cavitation in the ± 1 "g" environment.

In the absence of multiple direction accelerations, the design of the condenser-subcooler is simplified. Singular direction acceleration forces can be used to aid condensate transport and provide higher condensate pump inlet pressure. Secondly, greater freedom is available in location of the liquid-vapor interface and resulting subcooler design. Considerations such as this allow more compact packaging of the system and result in significant gains in terms of required stowage volume.

3.0 THE SUNFLOWER PCS I-1

3.1 General Description

The PCS I-1 is the prototype of the Sunflower system. The Sunflower PCS I-1 provides for the integration of prototype components to a flight configuration. These components are the Boiler/Heat Storage unit, BHS I-2, the Condenser/Subcooler unit, CSC I-1A, the Combined Shaft Unit, CSU I-1A, and the Rotational Speed Control, RSC III-1. For system ground testing, energy is supplied by a radiant, electrical heater to simulate the solar, concentrator energy source. Figure 3.1 shows the Sunflower PCS I-1 system. Installation of the CSU I-1A component and subcooler heat exchangers was performed after installation in the system test booth. The location of the CSU I-1A component is vertical above the secondary condenser, attaching at the turbine exhaust to the primary condenser inlet line. The inlet line simularly is vertically oriented which delivers the used vapor from the turbine exhaust to the primary condenser inlet header. The vapor flow passes vertically upward through the primary and secondary condensers, with heat rejection taking place to the vapor-liquid inter-



SUNFLOWER PSC I-1 SYSTEM (DURING ASSEMBLY

FIGURE 3-1

face. The interface forms part of the subcooler heat exchanger complex shown in Figure 3.2 and line schematic drawing Figure 3.2a. The interface liquid level is located 10-12 inches above the center line of the CSU condensate pump to insure the required net positive suction head to the condensate pump independent of condenser pressure drop. This modification to the flight configuration of the Sunflower system was made primarily to extend the range of system ground test capability.

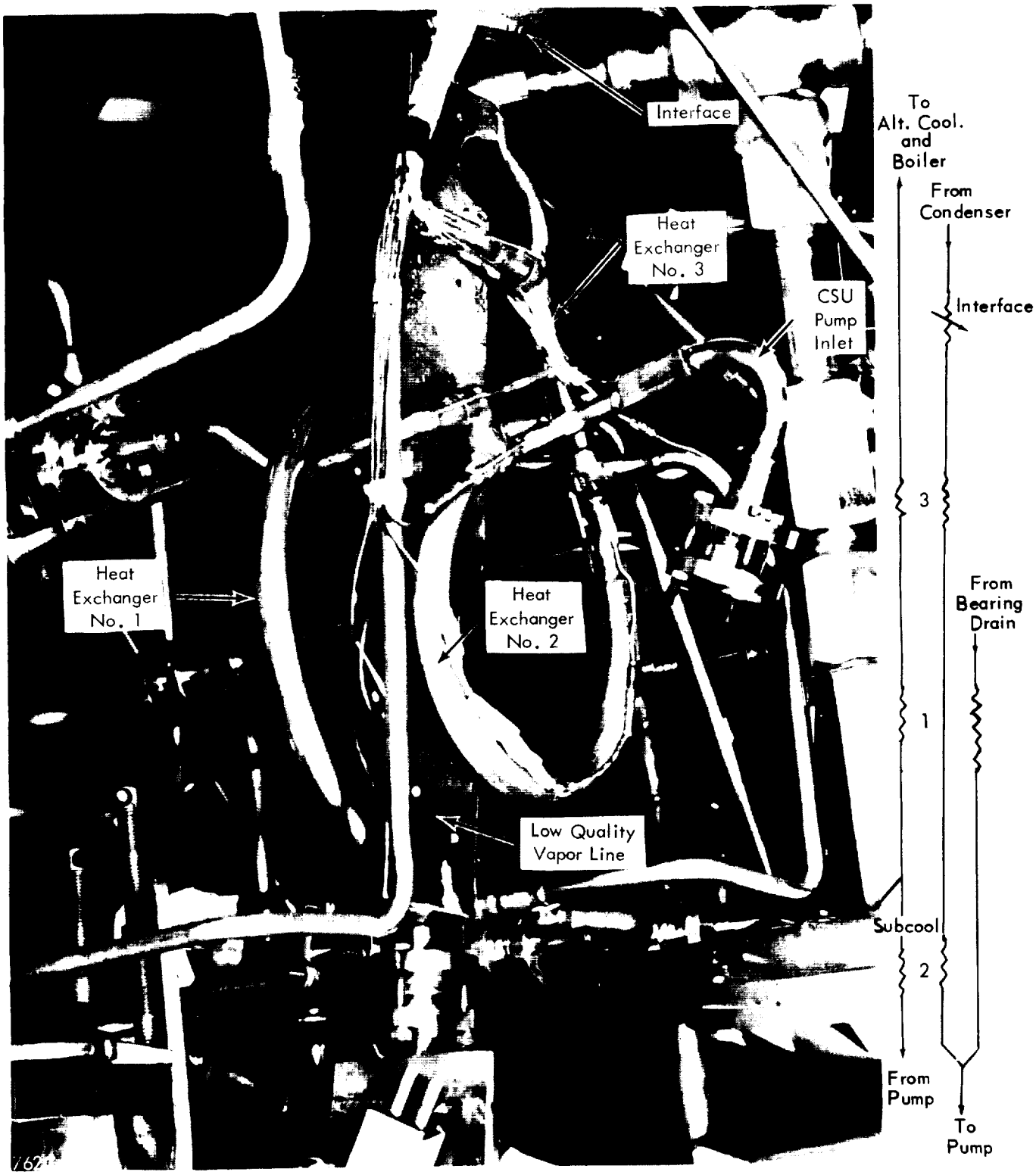
3.2 Components Description, Test and Status Summary

The objective on the preprototype component designs has been to provide components of specified performance consistent with weight objectives. In the initial component designs an emphasis has been placed upon design integrity and performance. As these factors are proven or demonstrated in test, the emphasis in component design would be shifted to component weight reduction to meet this part of the specifications. It is this state that is generally descriptive of the status of component development on the Sunflower system. In all cases, the feasibility of component designs has been shown and performance demonstrated.

With this general background in component design philosophy, a further description and developmental status report of each of the major components on the PCS I-1 system is presented.

Solar Collector

A full scale, flightweight, 32 foot diameter, epoxy bonded, aluminum, honeycomb solar collector has been fabricated and tested during the



SUNFLOWER SUBCOOLER HEAT EXCHANGERS

FIGURE 3.2

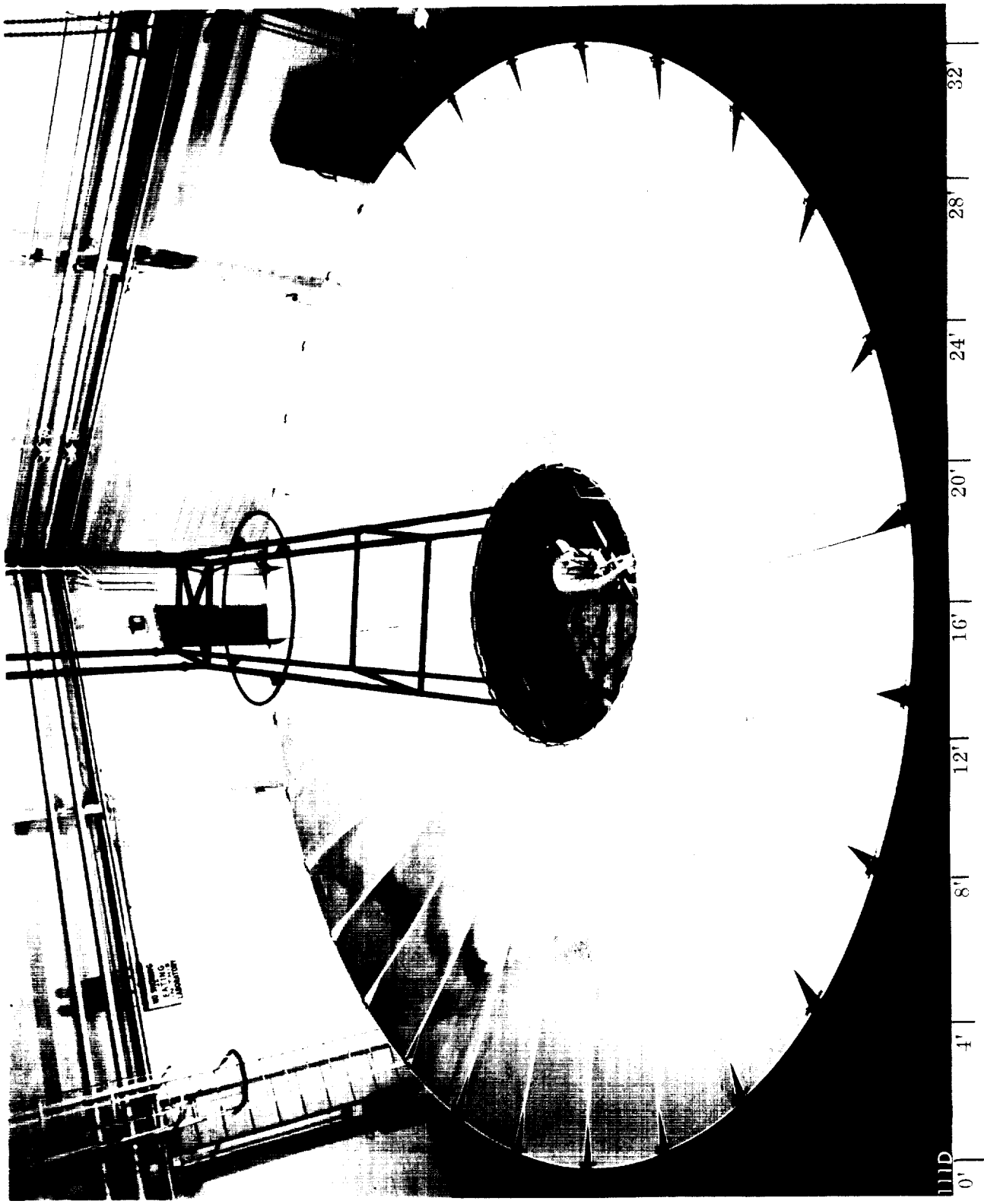
Sunflower development program. The collector is shown in Figure 3.3. In addition to the thirty petals which comprise the full scale solar collector, several additional panels have been fabricated, coated with reflectivity coatings and subjected to single panel solar testing.

Optical testing of the full scale solar collector has revealed geometric errors of 1.0° compared to the objective of 0.5°. Some of the error has been traced to a flaw in the original lay-up tool. Fabrication of a new tool will correct this in future collectors. Full scale structural environment tests have been conducted. These have included a full scale deployment test in a simulated zero "g" condition as well as stowed vibration testing and open vibration testing over a spectrum from .25 "g" at 5 cps to 7.5 "g" at 2000 cps. These tests simulated the launch environments during boost and demonstrated the capability of the collector to withstand both deployment and severe vibration associated with launch and orbital transfer maneuver type operations.

A comparison of the solar collector test achievements with design objectives is shown in Table 3.1.

CSU I-1A Turboalternator

The combined shaft unit, CSU I-1A, is an integral assembly with the turbine, alternator and boiler feed pump mounted on the same shaft. The entire shaft assembly is supported by two journal bearings and a double acting thrust bearing in a common housing assembly which in turn is hermetically sealed to prevent leakage and/or loss of



SUNFLOWER 32-FOOT DIAMETER COLLECTOR

FIGURE 3.3

TABLE 3.1

SOLAR COLLECTOR STATUS SUMMARY

	WEIGHT		PERFORMANCE	
	TARGET	ACHIEVED	TARGET	ACHIEVED
ASSEMBLY	0.25#/Ft^2	0.26#/Ft^2		
SURFACE CONTOUR			0.5° over 95% of the area	Approx. ±1° Deployment Errors not Confirmed Non-isothermal correct ability indicated
SPECULAR REFLECTIVITY			91%	84% Full Panel 90.7% Small Scale
EFFICIENCY			91% at 0° 74% at 0.75° Misorientation	72% Not Evaluated
ENVIRONMENT		.25 "g" at 5 cps to 7.5 "g" at 2000 cps		Confirmed

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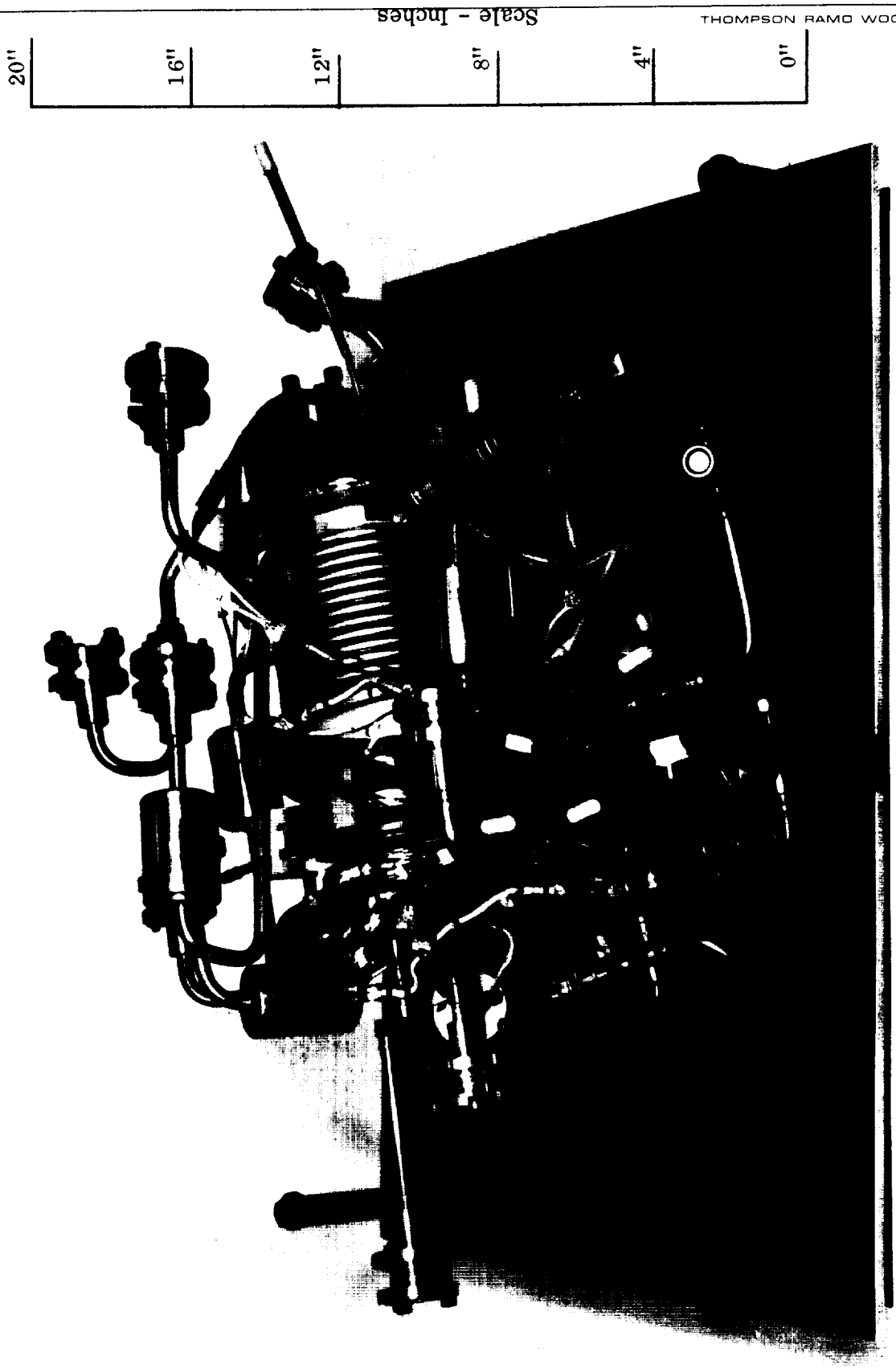
working fluid. Figure 3.4 shows a Sunflower turboalternator unit which for the purposes of illustration is identical to the CSU I-1A unit. Figure 3.5 shows the Sunflower rotational speed control, RSC III-1, used to monitor and control frequency of the CSU I-1A alternator output during test.

The CSU I-1A was tested prior to installation into the PCS I-1 system. The test was initiated on 3 October, 1962 and covered a total test duration of 62 hours. The general test objective was to investigate anticipated system parametric conditions upon operation and performance of the unit as well as define general performance criteria as follows:

1. CSU I-1A package pump performance at rated speed and NPSH of 3.5 psia.
2. Bearing flows versus inlet pressure requirements as a function of operational speed.
3. Influence of ±50°F variation in bearing flow inlet temperature.
4. Influence of ±100°F variation in alternator coolant temperature.
5. Operational limits imposed by flooded bearing drains up to 12" Hg head differential.

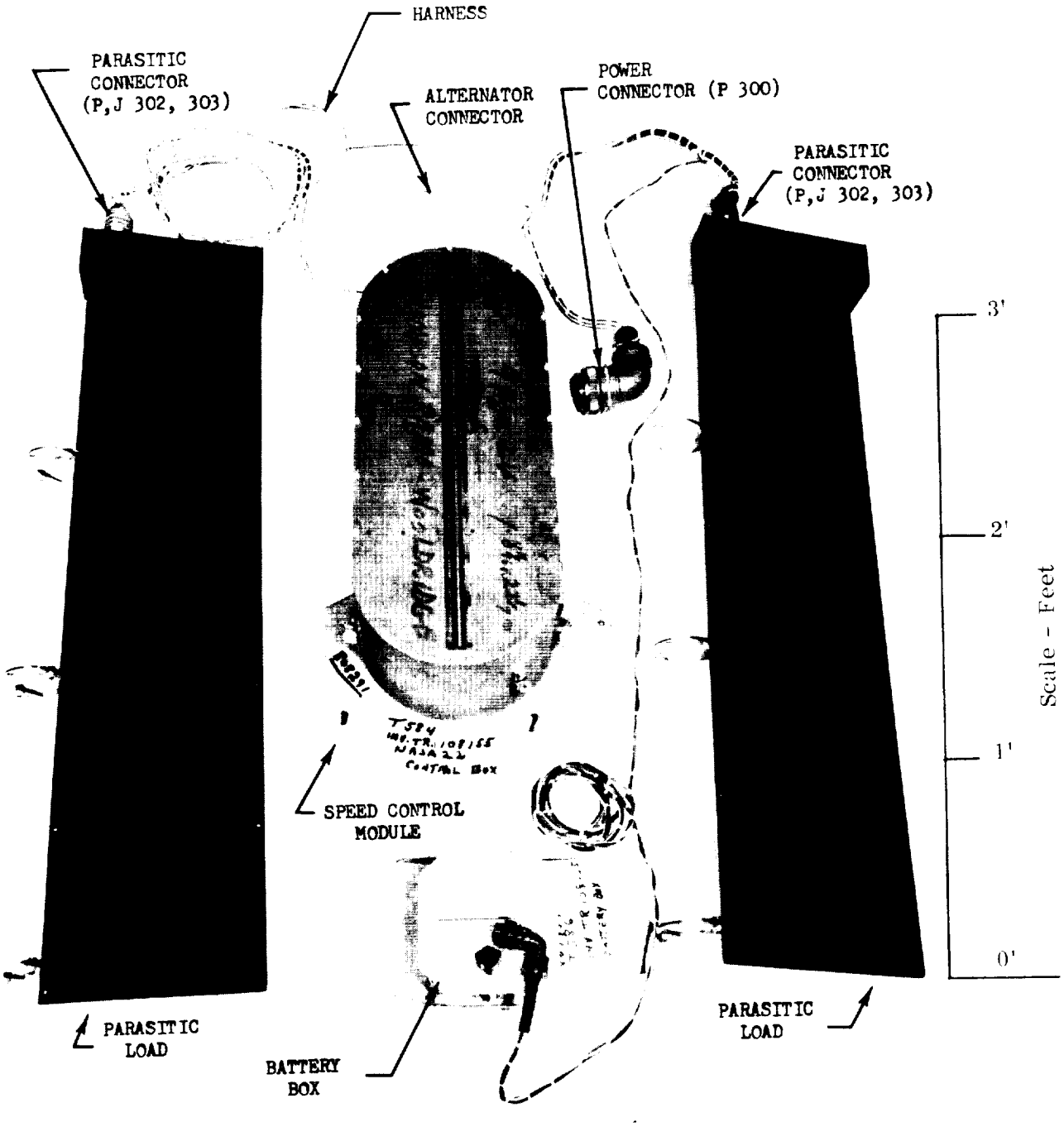
The general performance test results are compared to predicted performance of the CSU unit in Figure 3.6. Figure 3.6 illustrates the close agreement between predicted performance and the component test data.

Figure 3.7 illustrates the CSU I-1A package pump performance. The data is plotted with net positive suction head (NPSH) as a parameter.



SUNFLOWER TURBOALTERNATOR - CSU I-4

FIGURE 3.4



SUNFLOWER SPEED CONTROL MODULE III-1

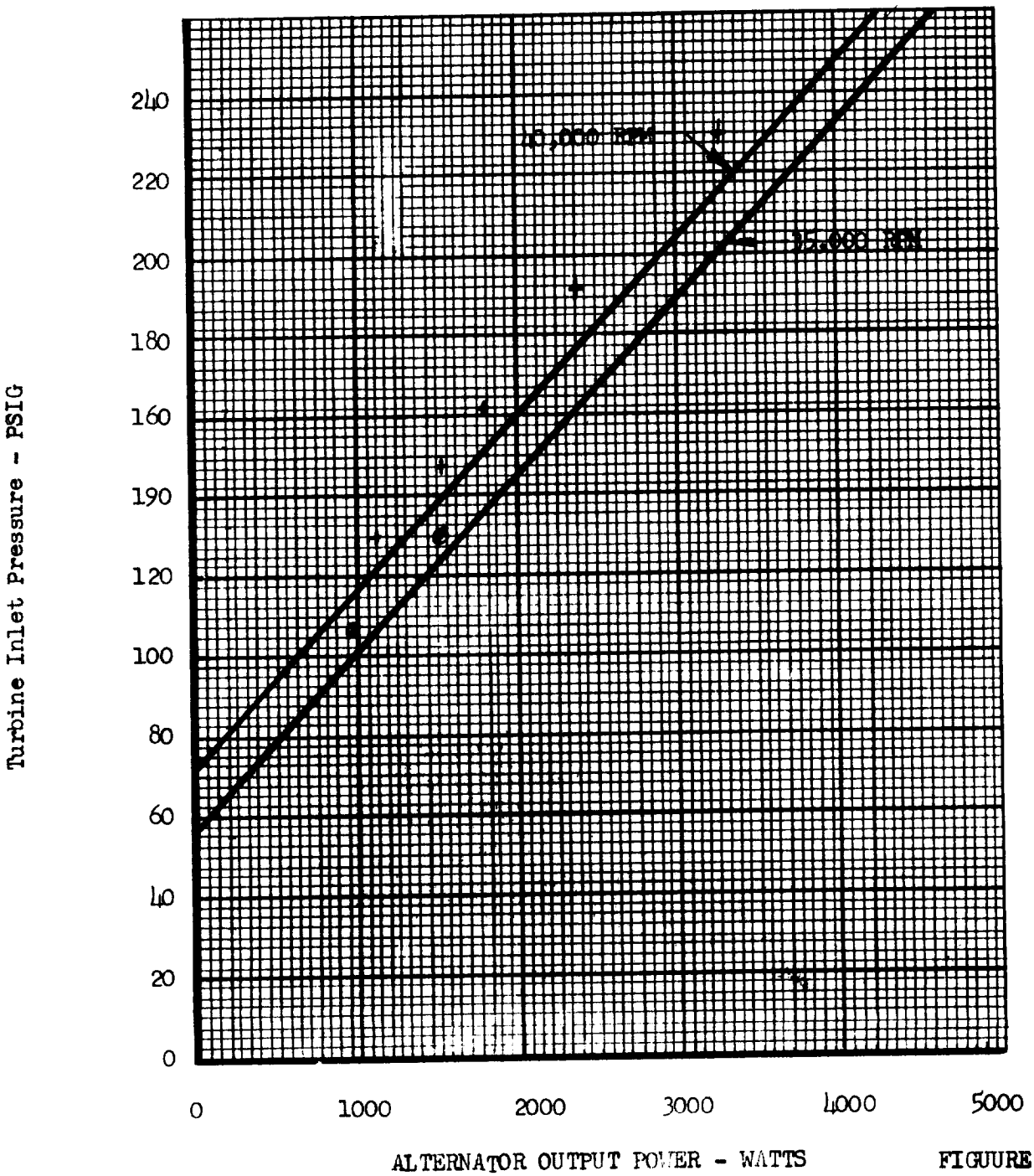
FIGURE 3.5

CSU I-1A Performance Test

—— CSU Predicted Performance

⊙ CSU I-1A Component Test - 35,000 RPM

✚ CSU I-1A Component Test - 40,000 RPM



FIGUURE 3.6

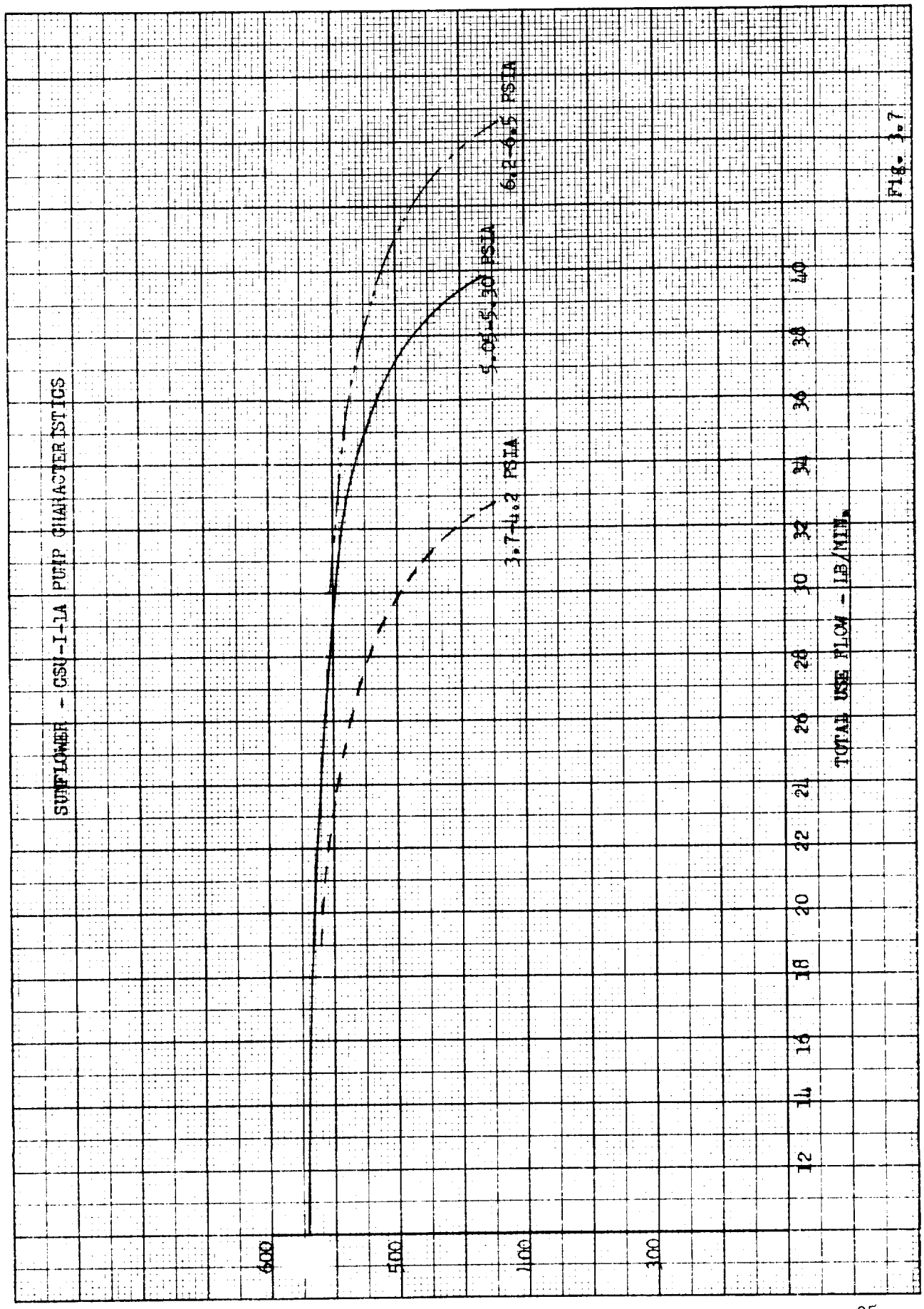

SUNFLOWER - GSU-I-1A PUMP CHARACTERISTICS
6.2-6.5 PSIA
5.0-5.30 PSIA
3.7-4.2 PSIA
TOTAL USE FLOW - LB/MIN.
PUMP DISCHARGE PRESSURE - PSIG
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
100
400
500
600

Fig. 3.7

The influence of NPSH is clearly indicated. The data illustrates the close conformance to design specification of 450 psia and 34 lb. per minute at 3.5 psia NPSH.

The influence of temperature on flow parameters was found to impose no operational limitations on the unit. The flooded bearing drain test, however, did result in a useful power loss of approximately 500 watts, from 3300 to 2800 watts at the extreme condition caused by increased drag losses associated with flooding and spillage of fluid into the alternator rotor cavity caused by the increased ΔP across the shaft labyrinth seal. This data is for design inlet pressure and temperature, and for a sink temperature of approximately 580°F.

A summary comparison of Sunflower CSU performance accomplishments to design specifications is given in Table 3.2. The demonstrated performance data is based upon the test of four (4) CSU units for combined performance and endurance capabilities. A summary of the Sunflower CSU test accomplishments is given in Table 3.3.

BSH I-2 Boiler Heat Storage

The BHS I-2 unit is the second of three units designed and fabricated on the program. The BHS I-1 unit was the initial preprototype unit designed and tested with the objective of confirming the the basic integrity of the design concept and comparison of performance with specifications. This was provided early in the program to supply information for the design of the BHS I-2 unit scheduled for the PCS I-1 system.

TABLE 3.2

COMBINED SHAFT UNIT STATUS SUMMARY

	WEIGHT		PERFORMANCE	
	TARGET	ACHIEVED	TARGET	ACHIEVED
ALTERNATOR Bore Seal			Hermetic Seal of Alternator Cavity at 650°F	Achieved Compatability at 700°F 8 Shocks of 250°F
TURBINE Efficiency			51%	50%
PUMP Output			450 psia at 34 lbs/min at 3.4 psi NPSH	450 psia at 32 lb/min at 3.7 psi NPSH
Power			220 watts	220 watts
Non-Condensables			Compatible with H_2 entering the system due to diffusion from BHS	Compatibility not confirmed requirement established at 0.18 lb/yr
SHAFT Critical Speed			52,000 rpm hot	60,000 rpm cold, extrapolated 56,000 rpm hot
ASSEMBLED Package	30 lbs	44 lbs	1 yr life at design conditions	CSU I-3A = 4329 hrs

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TABLE 3.2 (continued)
COMBINED SHAFT UNIT STATUS SUMMARY

	WEIGHT		PERFORMANCE	
	TARGET	ACHIEVED	TARGET	ACHIEVED
BEARINGS				
THRUST CAPACITY			15 lbs	25 lbs
RADIAL LOAD			25 lb/brg.	80 lb/brg.
POWER CONSUMPTION			600 Watts	600 Watts
ENDURANCE			8750 Hrs.	No wear after 6676 hrs.
ALTERNATOR				
EFFICIENCY			85%	87%
HARMONIC CONTENT			7%	5%
REGULATION			±5 V	±5 V
OVERLOAD			Momentary at 300% Rated	Continuous Short with Capacitors

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TABLE 3.3

TURBOALTERNATOR TEST SUMMARY

Unit	Test No.	Test Objectives	Duration Hrs.	Reason for Shutdown	Corrective Action & Disposition of Unit
CSU 1-1	1	Performance Checkout	1.5	Bearing Wear and Improper Package Drainage	Unit Redesigned and Rebuilt
CSU 1-3	1	Performance Checkout and Endurance	2348	Obstruction of First Stage Nozzle with Products of Corrosion From the Testing	Modification of Test Rig & Redesign of Turb. Inlet Line Unit Rebuilt. Alternator Thrust and Journal Brgs. Unchanged
CSU 1-1A	1	Performance Checkout	64	To integrate with System	Installed in System
	2	System Performance Checkout	50	Test Objective Completed	Cleaned and Stored
CSU 1-3A	1	Performance Testing and Endurance	769	Foreign Particles Dislodged from Test Rig Resulting in Partial First Stage Nozzle Blockage	First Stage Nozzle Cleaned and Unit Reassembled
CSU 1-3A	2	Endurance	3555	Municipal power failure. Unit was undamaged.	After minor rig repairs the unit was restarted
CSU 1-3A	3	Endurance	4	Test Rig Electrical Connector short which failed the alternator and allowed the unit to overspeed.	Completely disassembled for dimensional and metallurgical examination

Notes:

1. Alternator and thrust bearings total cumulative test time - 6676 hrs.
2. CSU 1-3A accumulated a total of 4328 hours.
3. During CSU I-3A-2 test there was no detectable change in output power as observed in CSU 1-3 indicating nozzle obstruction problem corrected.

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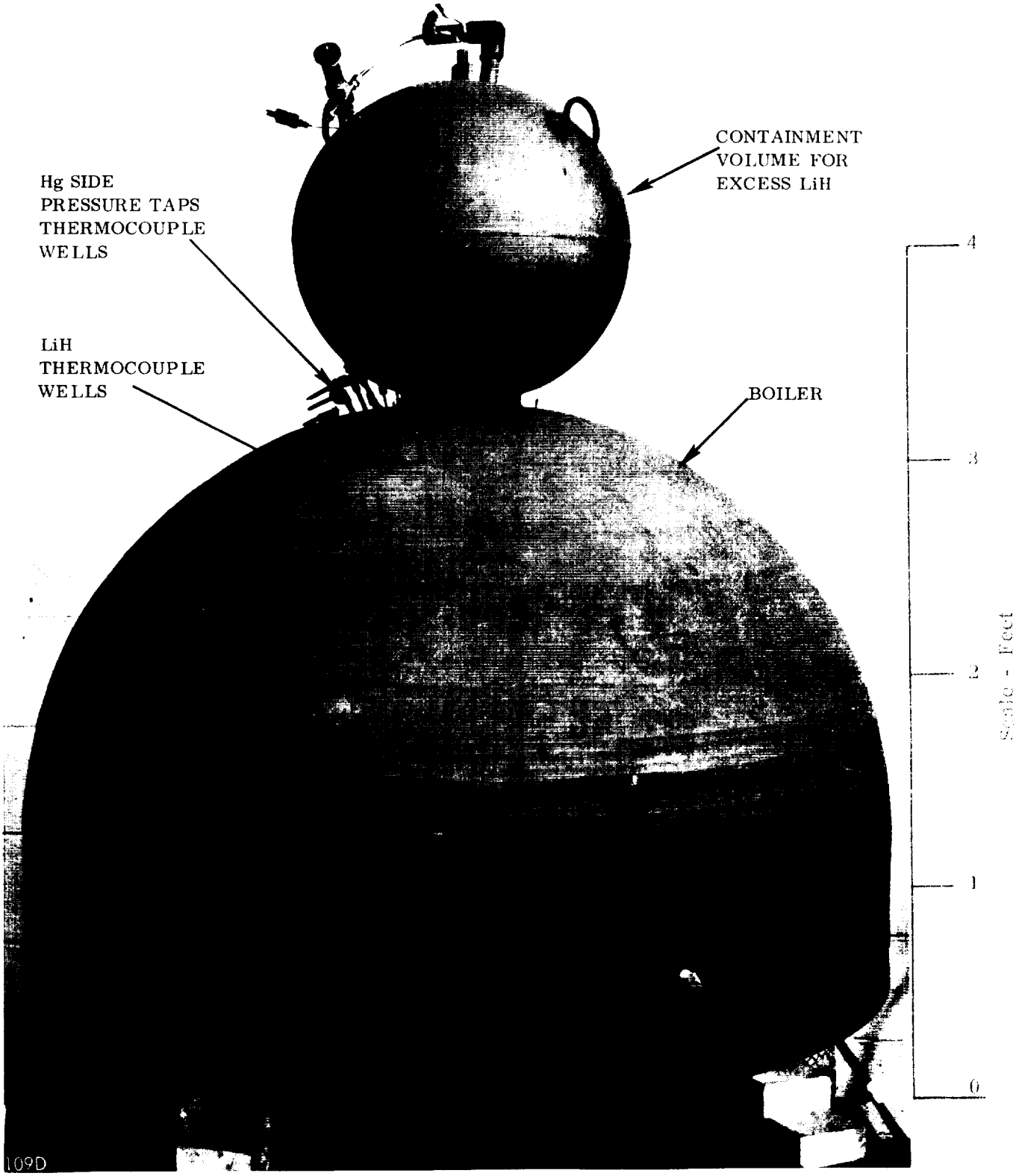
The configuration selected for the boiler heat storage designs is an internal cavity receiver of the form of (concentric) spherical shells with extended spherical aperture control doors. The lithium hydride heat storage material is contained within the space formed by the inner and outer shell. The thickness of the heat storage material is determined by the amount of material required and surface area for a conservative heat transfer flux profile. The design provides for a single tube boiling section contained in the heat storage material.

The BHS I-2 design incorporates an expansion volume to account for change in the lithium hydride density between solid and liquid phases. The purpose of the excess lithium hydride is to prevent the uncovering of the upper boiler coils in the 1 "g" gravity environment during the freezing of the lithium hydride. The tendency during zero gravity freezing will be for the lithium hydride to adhere to the cooling surfaces, creating void volumes between the tubes and shells. The heat flux utilized in the design of this boiler was derived from module testing and is conservative since the flux rates were obtained while transferring heat across a void which resulted from the settling action of the 1 "g" environment in the module tests. The BHS I-2 unit is shown in Figure 3.8. Not shown is the aperture control door assembly required for the flight system. This assembly attaches to the lower enclosure ring to form and vary the aperture size to incoming solar energy.

The presystem component tests of the BHS I-2 unit included startup test, steady state performance test and combination cyclic, heat-up and freeze-out tests. The startup tests were conducted to determine



SUNFLOWER BHS I-2

FIGURE 3.8

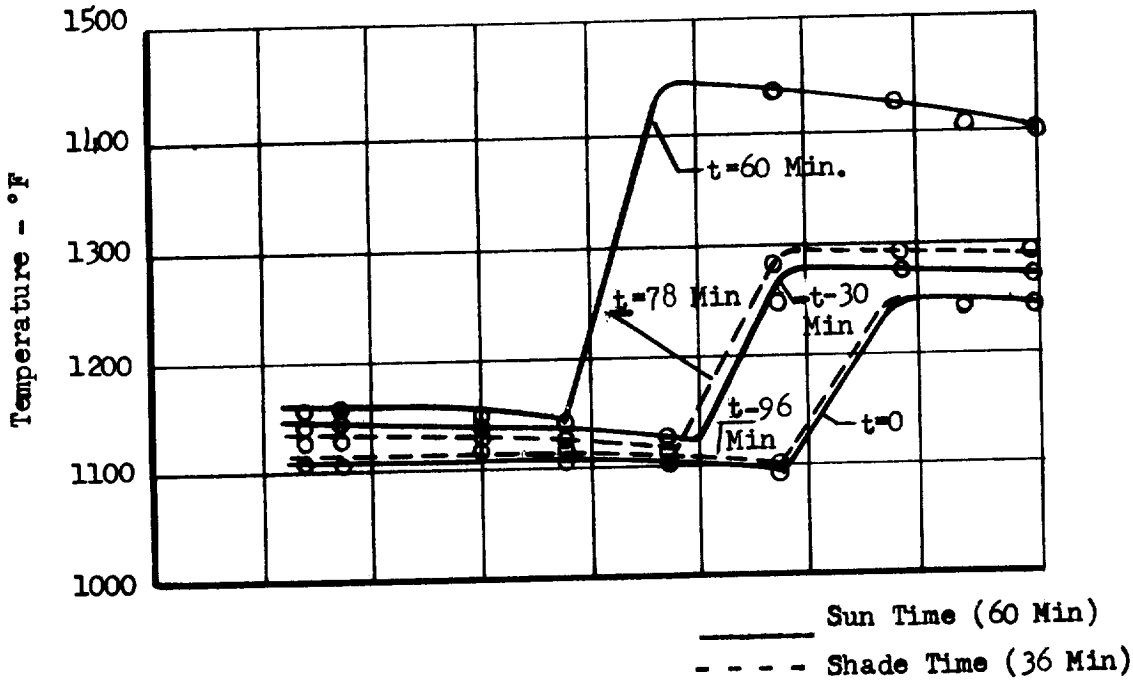
the characteristics of the BHS I-2 unit to orbital startup methods. These tests were conducted with a breadboard orbital start system coupled to the BHS I-2 unit. The results demonstrate the ability of the system to reach a final exit pressure at design system flow in a time of 18-30 seconds. The time variance to reach final conditions at the boiler discharge is a function primarily of the discharge orifice size used. The startup tests further demonstrated the stability of operation of the boiler throughout the transient period to final steady state conditions in the absence of or damping of existing pressure and flow fluctuations.

The cyclic heatup and freezout test simulate the heat transfer characteristics of orbital sun-shade cycles. These tests were conducted for the conditions of a 300 n-mile circular earth orbit at cycle flows to 15.5 ppm. Figure 3.9 illustrates typical results of these tests and demonstrates the ability of the BHS I-2 unit to supply superheated vapor at all times during the test cycle. The limiting condition occurs at the end of the shade period when the energy content of the heat storage material is a minimum and the resistance to heat transfer the highest.

Similar freezout test simulations for the higher 20,000 n-mile orbit were conducted to evaluate the thermal capacity of the BHS I-2 unit at the limiting conditions. The results demonstrate the ability of the BHS I-2 unit to supply superheated vapor for the 72 minute shade period at flows up to 16.0 ppm.

A comparison of the BHS I-2 performance achievements with design objectives is shown in Table 3.4.

BHS I-2 Transient Performance During a Low Orbit Thermal Cycle at 13.7 Lb/Min.



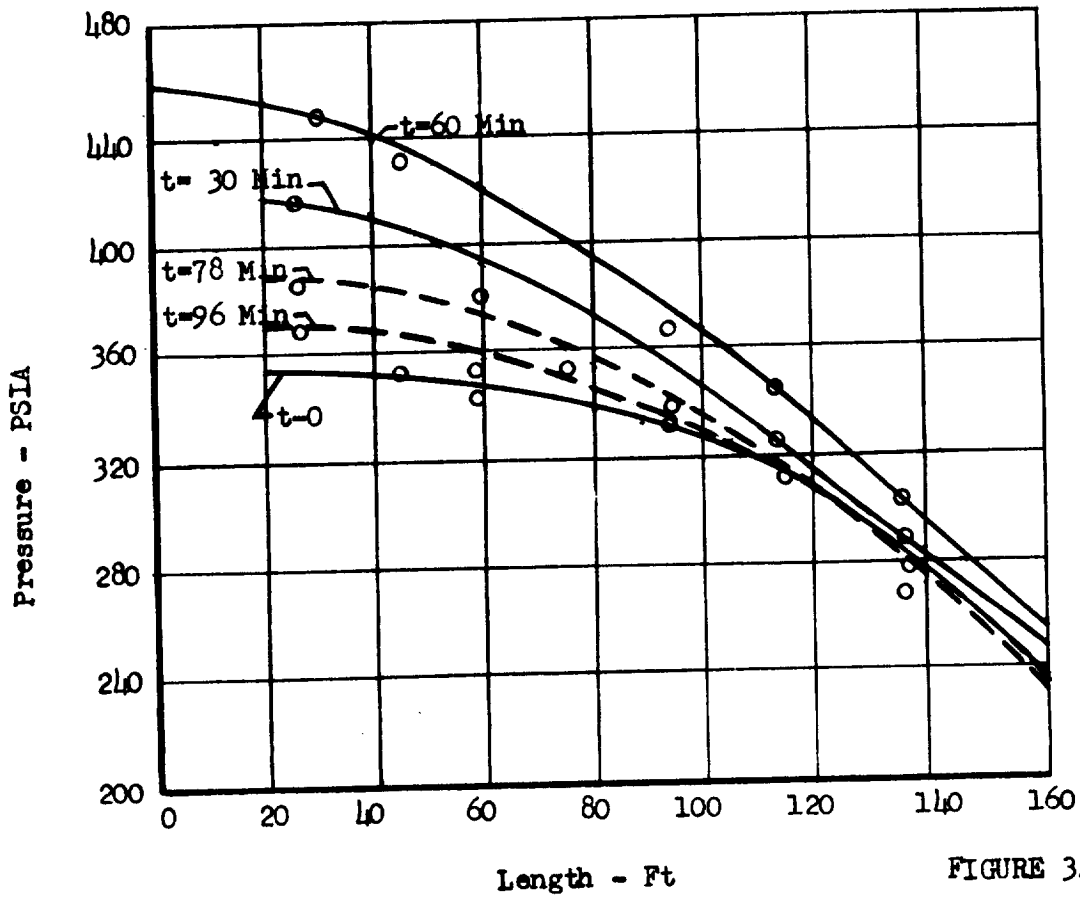


FIGURE 3.9

TABLE 3.4

BOILER HEAT STORAGE
STATUS SUMMARY

	WEIGHT		PERFORMANCE	
	TARGET	ACHIEVED	TARGET	ACHIEVED
BHS ASSEMBLY	260#	320# *		
ENERGY STORAGE AND TRANSMISSION			1) Absorb at 66.5 KW at $T_S \leq 1600°F$ 2) Operate for 72 Min with no external heat addition 3) Stable operation during cyclic heat supply	Confirmed ** Confirmed ** Confirmed **
START UP			To design outlet pressure in 30 Sec.	< 30 Sec - Stable
TEMPERATURE CONTROL			T Max $\leq$ 1600°F with Q_{in} = 74 KW & Unmodulated Q_{out} = 40 KW	Design Concept Completed
HYDROGEN CONTAINMENT			1.25 LB/YR H_2 Loss	$\leq$ 1.73 LB/YR extrapolated from 5000 Hr. Cyclic Temperature Test
ENDURANCE			1 Year 5800 Cycles	125 hours 25 cycles

* Weight estimate for flight unit based on extrapolation of data from component test

** 125 Hour Test BHS I-2

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CSC I-1A Condenser Subcooler

The CSC I-1A Condenser Subcooler component consists of a primary condensing section, a secondary condensing section and subcooler section. The primary condenser consists of ten (10) finned tube heat rejection sections. Each is fed by a common vapor inlet header and exhaust into a common exhaust header. The tubes have a linear diameter taper to maintain vapor velocity approximately constant along its length. The secondary condenser serves to reduce the low quality vapor from the primary condenser to the liquid state. This is provided in a single finned tube section. The tube section is rectangular in cross section and tapered. Figures 3.10 and 3.11 show the CSC I-1A unit in various stages of test preparation. .

The CSC I-1A component test was divided into three general phases. The test was conducted in the Sunflower component test booth, and directed at defining the performance of the unit, condensing in a direction opposing gravity. The first phase of test involved testing of the primary condenser section to define performance as a function of inlet flow and quality and exit vapor velocity. Phase 2 involved the addition of the secondary condenser section and interface. In this phase, inlet conditions were varied and the operation of the unit evaluated at various combinations of inlet parameters. In the third phase, the compact heat exchangers for subcooling were added and the CSC I-1A unit tested for operational performance.

Figure 3.12 summarizes the operation performance of the CSC I-1A unit in terms of operating pressure as a function of vapor inlet weight flow. The results of test in air are used to predict the unit performance in an argon environment and compared to the design requirement.

PRIMARY CONDENSER DURING FABRICATION

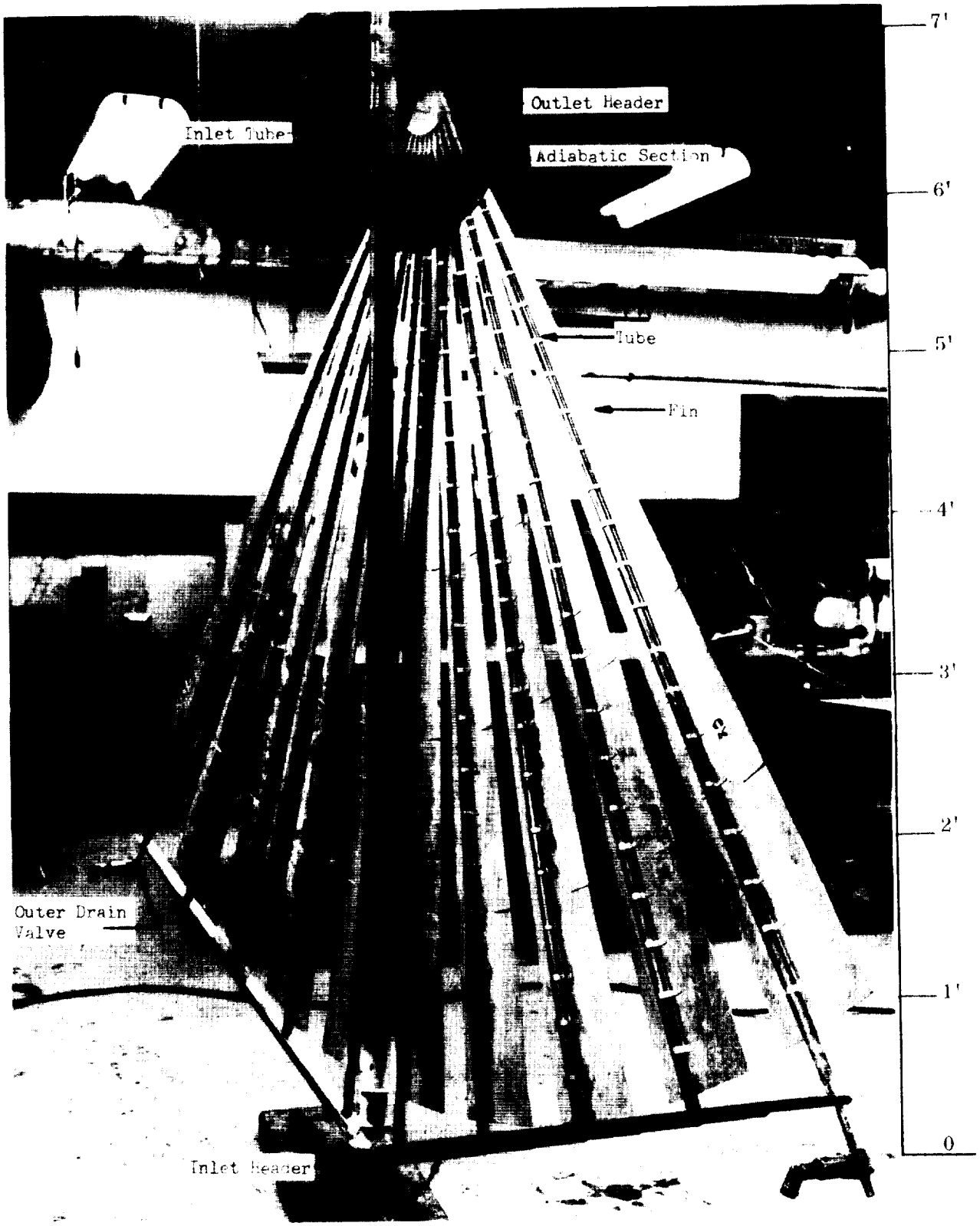
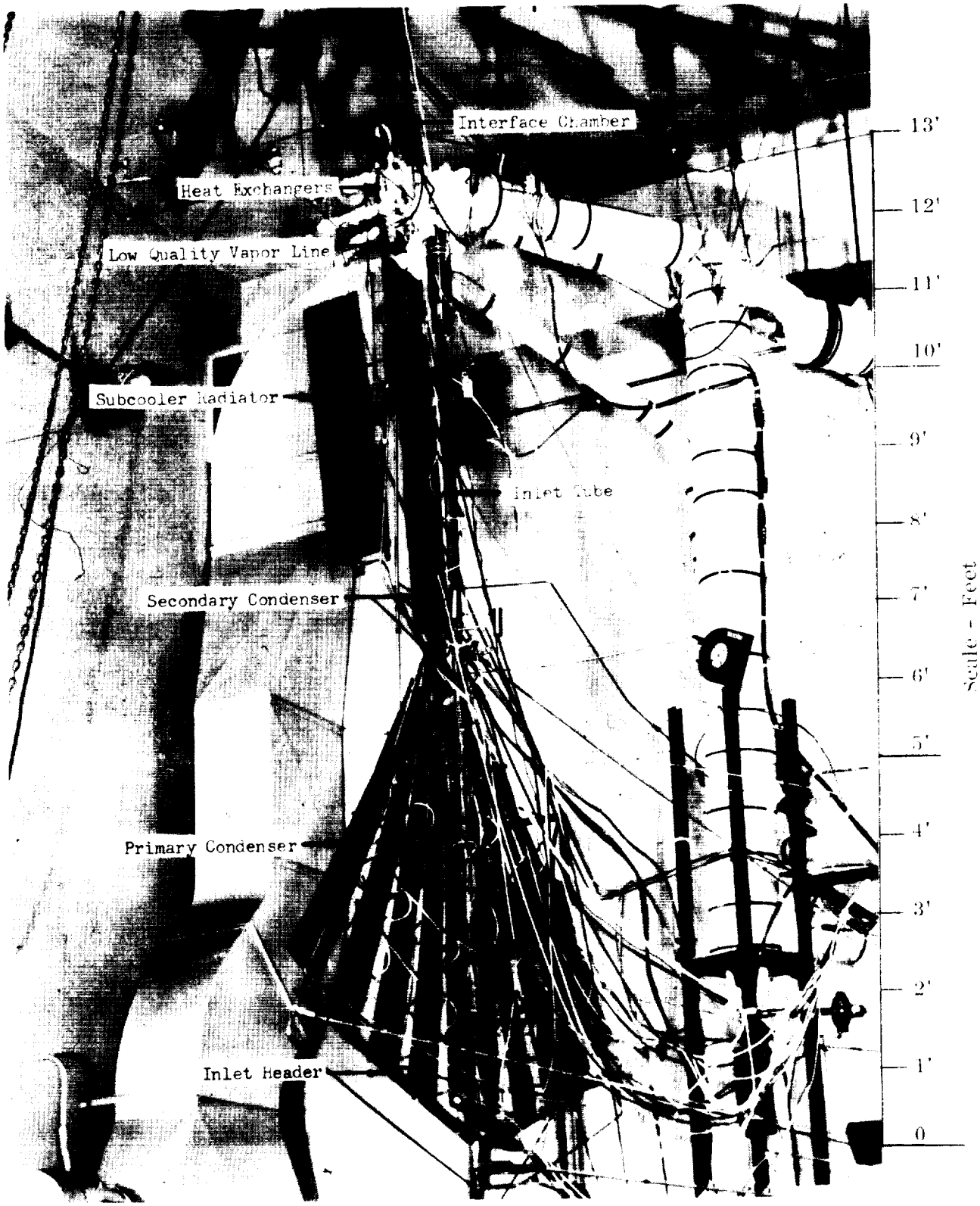


FIGURE 3-10



C5[illegible]A CONDENSER SUBCOOLER ASSEMBLY

FIGURE 3-11

CSC I-1A Operating Curve

Inlet Pressure vs.
Inlet Vapor Wt. Flow

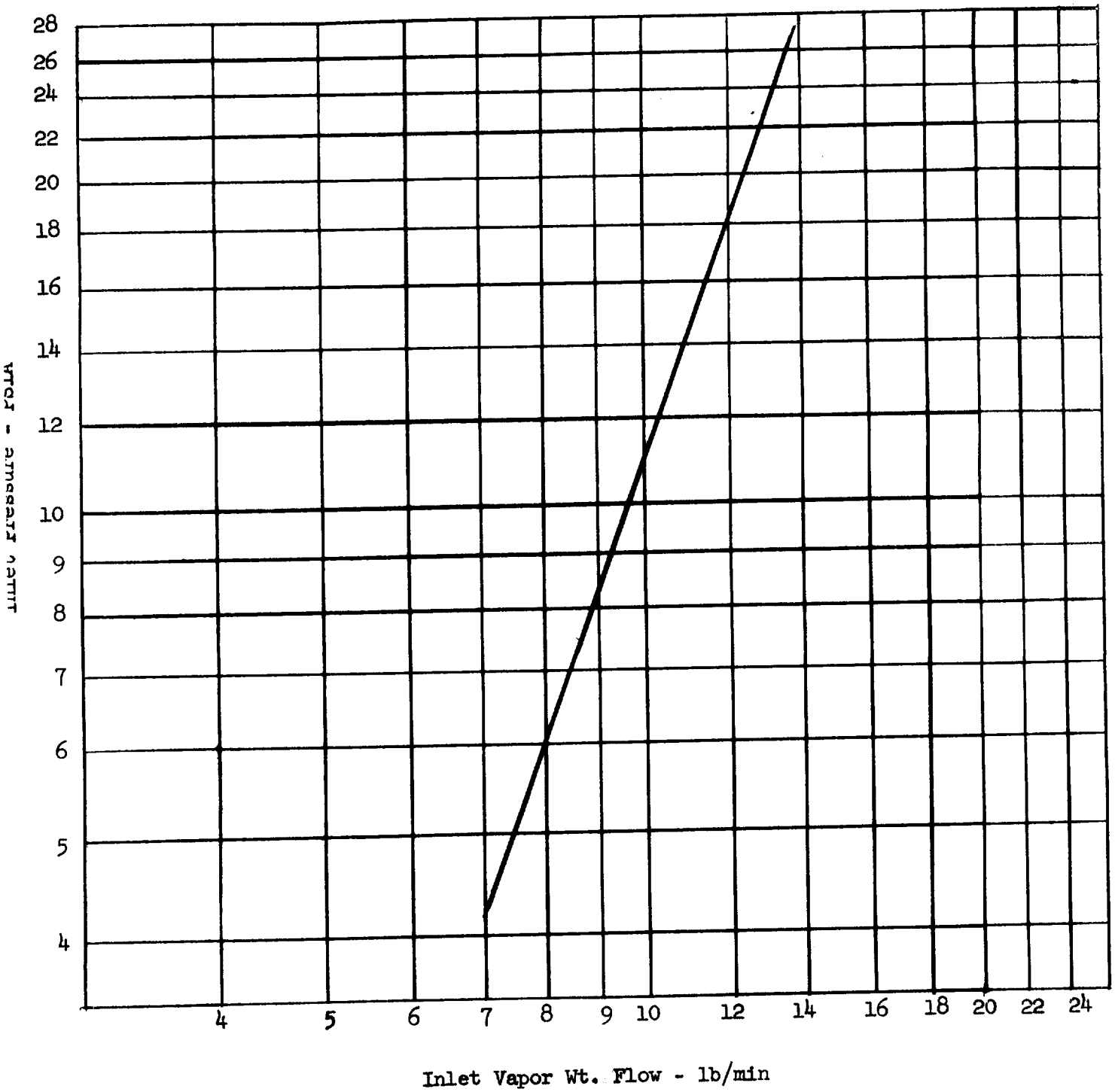


FIGURE 3.12

A comparison of the CSC design objectives to demonstrated performance is given in Table 3.5. The primary accomplishments included the demonstration of parallel flow stability in the CSC I-1A unit in a flow direction opposing gravity. The major requirement to be demonstrated is long term stable operation under the imposed environmental conditions. Of particular interest are the criteria associated with the condensing processes; i.e., drop formation, surface tension, adhesion, contact angle and degree of wetting experienced. Test results indicated the presence of a wetting phenomenon which was time dependent. The general characteristic in the presence of wetting is higher vapor velocity requirements to carry droplet formations with associated increased pressure drop to maintain stable operation. With the current CSC I-1A design the requirements necessitate a deviation from design parameters to both higher flow and inlet pressures to the unit.

The remaining deviation of CSC I-1A performance with design requirements is heat rejection capacity. The design of the CSC I-1A unit was based upon radiation and convection heat transfer in the presence of an inert argon environment. The deviation on heat rejection capacity at design inlet vapor pressure and temperature results from higher than design temperature drop between the vapor and tube wall. The

TABLE 3.5

CONDENSER SUBCOOLER
STATUS SUMMARY

	WEIGHT		PERFORMANCE	
	TARGET	ACHIEVED	TARGET	ACHIEVED
ASSEMBLY	62 lbs	90 lbs excluding heaters	Stable Thermal & Fluid Dynamic Operation in environment of $\pm$ 1g	Confirmed for nonwetting conditions* Design criterion established for fully wetted condition in -1 g operation
			$\Delta P \leq 1.8$ PSID	$\Delta P \simeq 2.5$ PSI
			X_E = 15% Primary Sect. V_E = 90 ft/sec	Confirmed*
			X_E = 1% Secondary Sect. V_E = 90 ft/sec	Confirmed*
			Startup with no auxiliaries except preheat	Confirmed
SINGLE TUBE			Stable Operation $X_E \geq$ 1% and $V_E \geq$ 60 ft/sec Against Gravity $\Delta P \geq$ 1 PSID	Confirmed down to X_E = 0% & $V_E \approx 0$ ft/sec Vertically up (and down) $\Delta P \leq$ 1 PSID
MULTIPLE TUBE			$X_E \geq$ 15% and V_E = 90 ft/sec Against Gravity	Three tube breadboard operable at $X_E \geq$ 15% at V_E as low as 12.5 ft/sec

* Present design adequate for 0 to +1 g and -1 g under nonwetting conditions.
For wetting conditions and -1 g operation - increased velocity and ΔP required.

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CSC I-1A thus rejects energy at an effectively lower temperature than originally designed.

These combining factors, the apparent progressive wetting of the CSC I-1A unit during component test and the less than design heat rejection capacity of the unit limit the operation of the CSC I-1A unit in integrated system test of the PCS I-1 to the following specifications:

Inlet pressure - 7.0 + 1.0 psia

Inlet temperature - 605°F + 19°F (continuous)

Inlet vapor flow - 8.4 - 8.9 ppm

Pressure drop - 7.0 psi maximum

3.3 System Performance Specification

The performance specification for PCS I-1 results from the integration of basic component performance data. The objective has been to maximize the performance of PCS I-1 within operation limits. The primary limitation is the environmental temperature of operation of the CSU alternator bore seal, which is determined by the operational temperature of the CSC I-1A condenser. The basic criterion in establishing the PCS I-1 specification has been to limit the CSC I-1A operational temperature to 605°F during long term operation.

Cycle Flow	8.4 ppm
Turbine Inlet Pressure	147 psia
Turbine Inlet Temperature	1250°F
Condenser Pressure, Inlet	7.0 psia
Condenser Temperature, Inlet	605°F
Boiler Inlet Temperature	560 ± 20°F
Bearing Inlet Temperatures	400-410°F
Bearing Flow	
Thrust	12.0 ppm
Turbine Journal	6.0 ppm
Alternator Journal	7.0 ppm
Speed	40,000
Electrical Power	1130 watts

4.0 SUNFLOWER PCS I-1 TEST

The objective of testing the PCS I-1 is to determine the integrated performance of all components. The specific test objectives include the following:

4.1 Test Plan Objectives

4.1.1 Pre-System Test Preparation

The system minus CSU I-1A is to be flushed with liquid mercury to clean and remove any foreign particles which may have entered into the system during assembly and to allow for a preconditioning of the system tubing. The boiler heat storage unit, BHS I-2, and

condenser-subcooler, CSC I-1A, are to be flushed individually before integration into the system. The flushing operation is to be conducted at a temperature of approximately 600°F, for a total period of nearly 116 hours, 100 hours for system flushing and 8 hours each for the boiler and condenser components.

During this flushing operation, heater valves and instrumentation are to be checked out to ascertain proper operation before actually progressing into the system testing.

4.1.2 PCS I-1 System Startup

System startup is to be conducted with the aid of the auxiliary mercury supply facilities. During start the pump is to supply liquid mercury to both the CSU bearings and the boiler.

The startup is to be preceded by bearing calibrations both cold and hot. Following, the sequence shall include preheat of the boiler heat storage unit, condenser unit, the CSU unit and system plumbing as required. Following the preheat, system charging of liquid mercury can occur. The sequence of operation after mercury flow is started will be to bring the CSU to a speed of 30,000 rpm. At this rated speed and power, data recording is to be initiated and maintained at selected intervals during the period required to achieve steady state or near steady state condition. The unit speed will then be increased to 40,000 rpm and the cycle flow raised to obtain the maximum power consistent with operating limitations.

4.1.3 Performance Test

At design speed and maximum electrical power output, a steady state performance test will be conducted. The objective shall be to conduct this test for the fully integrated system for a test duration approaching 100 hours. Data is to be recorded at 1 hour intervals or any other convenient period not greater than 1 hour.

4.1.4 Cycle Testing

Following the performance test, a test is to be conducted to simulate the sun-shade transients of orbital flight. Transients will be investigated which simulate operation at 300 and 20,000 nautical mile orbits. During this test, flow will be held constant and the boiler radiant heat input will be modulated to determine the effects of the cycling upon performance. The cycling test shall be conducted as expediently as possible with time available to establish steady state conditions between tests.

4.1.5 Endurance Testing

Upon the completion of system cyclic testing an endurance test will be conducted at the highest steady state power achievable within system operational limitations. The endurance test shall be directed toward the observation of long term characteristics of component and system performance. In addition, information regarding operation of the corrosion product separators and hydrogen diffusion affects upon system performance will be obtained.

The time duration of this test will be defined by mutual agree-

ment between TRW and NASA. Imperative to this decision will be the results of the system performance test and current system performance status during the endurance test.

4.2 PCS I-1 Test Installation

The Sunflower PCS I-1 test installation is shown schematically in Figure 4.1. Schematically, the PCS I-1 system is similar to the Sunflower flight system schematic given in Figure 2.2. The differences are minor modifications to PCS I-1 to account for the vapor-liquid interface design and location above the centerline of the CSU I-1A unit. In addition, the PCS I-1 system incorporates two (2) corrosion product separators to evaluate foreign particle separation from the working fluid. Individual separators are installed in the line feeding the boiler inlet and common line to the CSU I-1A bearing inlets. Other minor modification involves changes required for integration with the auxiliary mercury facilities. These are shown in Figure 4.1 and involve plumbing terminals for vacuum references and flow to and from the system.

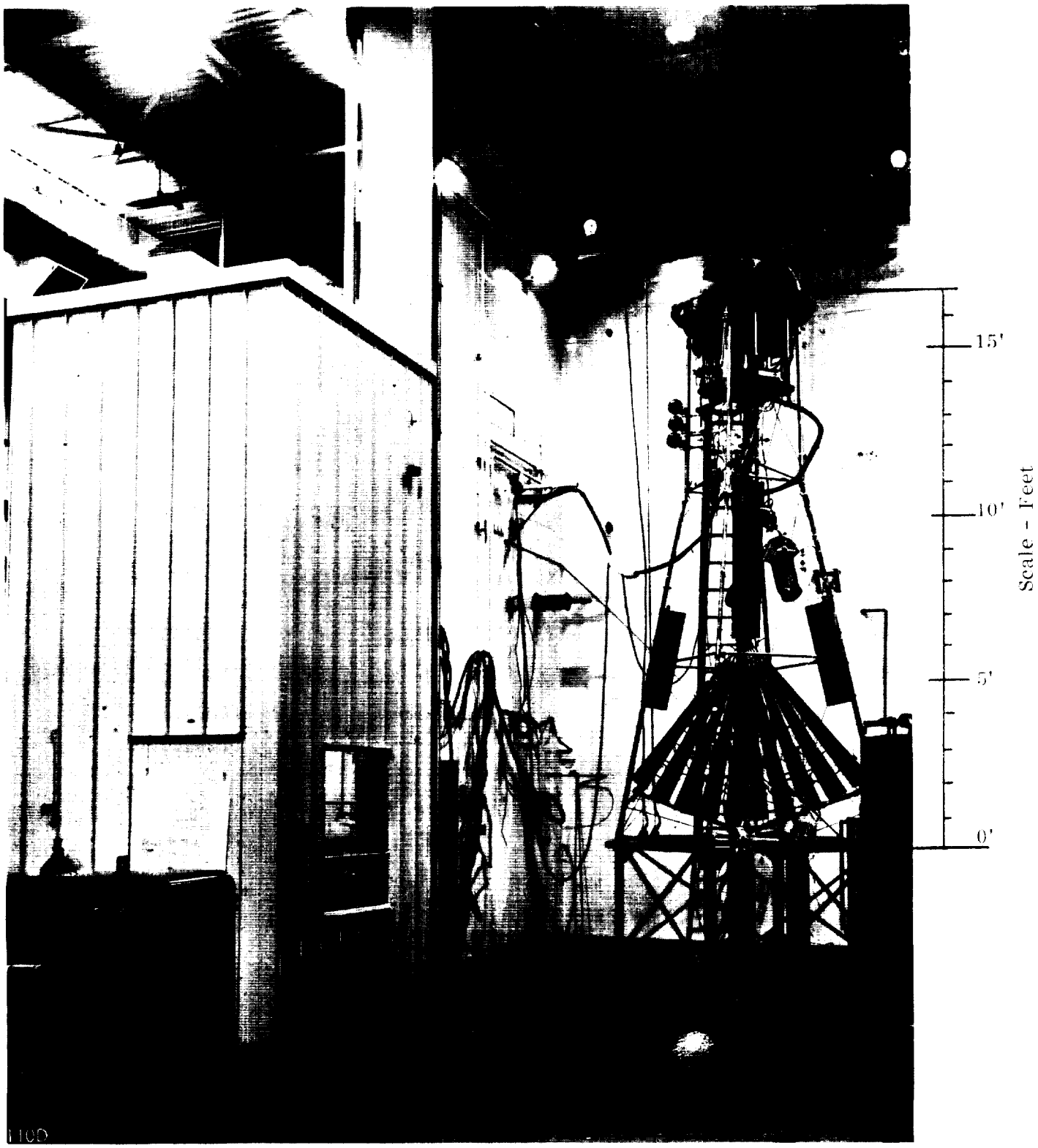
The system instrumentation provides for 120 automatic temperature readouts and 8 channels of oscillograph recordings. In addition; the instrumentation includes 12 static pressure references, for both vacuum and positive pressure monitoring and control indicators.

The PCS I-1 system installation in the system test booth is shown in Figure 4.2. The vertical orientation, simulates the system specification of -1 "g" operation. Under this condition of test, which represents the most severe condition, condensing and the transportation of liquid

FIGURE 4.1

Located in Jacket at End

of Report



SUNFLOWER PCS I-1 TEST INSTALLATION

FIGURE 4.2

droplets to the vapor-liquid interface occurs against the opposition of gravity. The affect of gravity on system pressure distributions is illustrated schematically in Figure 4.3. The system test cell is designed and constructed to minimize leaks for inert atmosphere testing. The cell is provided with three 20" diameter blow-off stacks in the roof, which release at 2.8" of water pressure differential. One side of the cell is composed of removable panels as can be seen in Figure 4.2. The normal procedure in preparing the cell for test is to first assemble and seal the panels, then with the use of "shop air" the cell is checked for leaks and to establish a satisfactory leak rate. The cell is then inerted with argon gas, requiring approximately a 1½ volume purge to achieve a volume of O_2 contant less than ½ percent.

The temperature and pressure of the cell are controlled automatically to maintain a slightly positive pressure. The rate matches the cell leakage which is nominally 80 cu. ft. per hr. The temperature is controlled by the actuation of a 25 ton refrigeration unit which is located within the cell.

The facility provides for the supply of liquid mercury to meet a wide range of process flow, pressure and temperature conditions. High pressure mercury flow is provided by a 7½ CFH Chempump. A second pump in parallel is automatically actuated in case of failure of the primary pump.

Flows are recorded and automatically controlled by Taylor pneumatic recorder controllers. The various required pressures are readout

PCS I-1 SYSTEM TEST RIG

LIQUID LEVEL RELATIONSHIPS

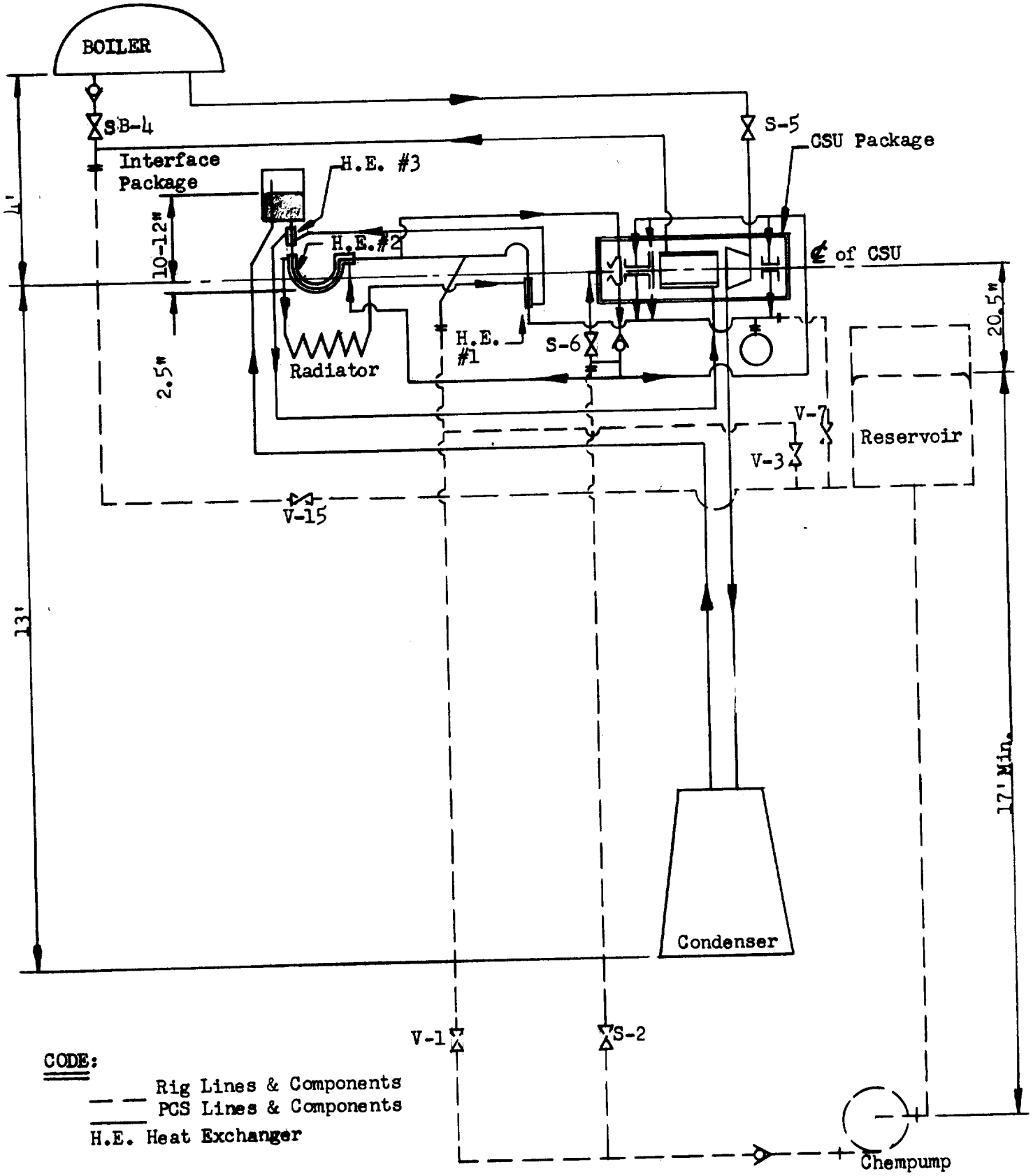


Fig. 4.3

and recorded on gauges, Taylor chart recorders and on Offner Dynagraph recorder. Temperatures are printed on Brown Electronic recorders. Figure 4.4 shows the control console with the various instruments mentioned above.

During the testing O_2 content is automatically evaluated and recorded by means of a Leeds and Northrup Oxygen analyzer. Automatically, gas samples are taken from eight (8) locations within the cell to determine and record O_2 content as a function of station location and time.

4.3 PCS I-1 Test Results

The Sunflower PCS I-1 test was initiated with the goal of performing the test objectives defined in paragraph 4.1. The specific accomplishments include:

1. Twelve individual system startups and programmed shutdowns, with a total accumulation of 47 hours of system performance test experience.
2. Sun-shade cyclic test.
3. Simulated system squirt startup.

The test consisted of three individual tests designated as PCS I-1-1, PCS I-1-2 and PCS I-1-3. Each test is discussed as well as specific objectives and conclusions reached.

The pretest operations included hot liquid mercury flushing of individual components, followed by a system flush minus the CSU I-1A unit. The BHS I-2 unit and CSC I-1A unit were flushed for a period of eight hours.

SUNFLOWER PCS I-1 TEST CONSOLE

FIGURE 4.4

Temperatures were maintained at an average 500°F for the BHS I-2 unit and 400°F for the CSC I-1A unit. Following, the units were plumbed into the system and flushed for 100 hours with average temperatures of the individual components maintained at the stated values. At the completion of the flushing operation, the CSU I-1A unit was installed into the system and preparations for the system test initiated. These include the following sequence of functions or operations performed:

1. CSU I-1A bearing calibrations.
2. Test cell argon inert in conjunction with BHS I-2 preheat to 700-800°F.
3. BHS I-2 preheat to 1350-1400°F in conjunction with CSC I-1A preheat to 600°F.
4. CSU I-1A housing preheat.
5. Mercury inventory charging and start.

4.3.1 PCS I-1-1 Test

1. Test Description:

Start No. 1 - Startup was initiated at 10:30 hours on 27 November 1962 by manually opening the boiler inlet flow control valve to pass 4 lbs. per minute of mercury flow. The objective was to achieve 30,000 or 1500 cps at minimum load. At approximately 22 seconds after the start of boiler flow, indication of turbine speed was received, followed by acceleration to a plateau of 1120 cps and minimum manual load as seen by the alternator. At this state, turbine inlet pressure was 60-65 psig corresponding

to a flow of 4.8 to 5.1 lbs per minute. At approximately 10:32 hours, flow was increased to obtain 1800 cps. The behavior of the boiler inlet flow control valve was erratic at this time resulting in the attainment of a lower flow and speed for the new setting. At the fixed setting of the boiler flow control valve, a gradual increase in flow was experienced. At approximately 10:39 hours, flow began to increase rapidly as the valve opened fully. The valve would not respond to manual efforts to close it. At 10:45 hours, due to increasing temperature at the turbine exhaust, action was taken to bypass a portion of flow to lower turbine inlet pressure and flow. During this transient, turbine inlet pressure was recorded at a maximum of 206 psig, at a speed of 1478 cps and power slightly in excess of 2000 watts. The action of bleeding the boiler flow through the boiler bypass was effective in reducing pressure and thus flow, however, the sharp transients in flow prior to and during bleed down apparently introduced instability in the CSC I-1A unit with the general result of increasing turbine exhaust temperature and discontinuity of temperatures in the various sections. Under these operational conditions, at 10:48 hours a programmed shut down was initiated when the turbine exhaust temperature reached a maximum of 710°F. The results of the first start and test indicated a problem with the boiler inlet flow control valve. Also, it was concluded that some difficulty was experienced with the rotational speed control. The inability to achieve the first

speed plateau was in part a function of parasitic load capacity during startup attributed to low battery output of the bias circuit in the control.

With the experience obtained from the first start, a second start was planned. Use of supplemental boiler flow control was planned by means of the parallel flow path through the alternator coolant test rig return line.

Start No. 2 - The conditions of the second start were similar to the first. At 12:10 hours, flow of 5-6 ppm was initiated to the boiler with the first indication of speed at approximately 12 seconds from start. A rapid acceleration to 750 cps was experienced in 10 seconds followed by gradual decay to 350 cps. At this time a step increase in flow was executed providing a steady state speed of 1125 cps at a turbine inlet pressure of approximately 58 psig. Following data point No. 4, at a time of approximately 40 minutes following start, a rapid increase in turbine inlet pressure to 185 psig was experienced. The cause was due to the boiler inlet valve apparently opening to a near full open position. Attempts to again manually close the valve were uneventful and an initial attempt was made to control flow by diverting flow in a parallel path through the alternator coolant test rig return line. The effectiveness of this control appeared to be limited although a positive result in lowering turbine inlet pressure was observed. This control action

was performed gradually over the duration of data points No. 5, 6 and 7 with the primary objective of reducing flow to lower turbine exhaust temperature and pressure. At the higher turbine inlet pressure rotational speed was increased to 40,000 rpm at 13:21 hours between data points No. 5 and 6. The unit ran very smoothly at 40,000 rpm with no apparent problems. The only concern was that of higher than design turbine exhaust pressure of 2.5 to 3.0" Hg vacuum. Following data point No. 7 at approximately 14:55 hours, the boiler inlet valve began to act erratic again and shortly afterward popped closed. This was immediately reflected in a reduced turbine inlet pressure. The system was allowed to follow a normal decay path. As flow reduced the accompanying speed decay was allowed to follow until 20,000 rpm or 1000 cps was reached, at which time the turbine inlet valve was closed causing a gradual spin down to zero rpm.

Following the stop a post calibration check of the bearings was conducted which correlated very closely to pretest bearing calibrations. Under these conditions it was decided to terminate the test and to correct the boiler inlet flow control valve before attempting another start.

2. Results and Discussion

This test was the first attempt to operate the Sunflower PCS I-1 system as an integrated unit of the basic component hardware. The test consisted of two each, system starts

and stops and an accumulation of 3 hours of test experience. The test served to identify the boiler inlet valve problem, as well as other minor modification requirements and to provide important operational experience.

Following the termination of the PCS I-1-1 test, the boiler inlet valve was removed and bench tested. The valve behavior experienced in the system was duplicated in bench tests, substantiating the general opinion the valve was oversized to provide adequate control in the flow range of 4 to 6 ppm. The "F" trim was replaced with an "L" trim size in the valve body and valve rechecked by bench test to verify adequacy of the new trim size to control flow in the range of 4 to 6 ppm. After test the boiler inlet valve with "L" trim size was reassembled into the system.

4.3.2 PCS I-1-2 Test

PCS I-1 test No. 2 was initiated on December 4, 1962. The test was a continuation of the PCS I-1-1 test terminated on 27 November. Physical changes to equipment were as follows:

1. The boiler inlet control valve was modified to an "L" trim size for flow control capability at flows of 4-8 ppm.

2. The battery bias of the RSC III-1 was modified and relocated outside the system booth. This provided access for servicing of the bias power supply for

conditions of multiple starts.

3. Instrumentation changes.

The test included ten (10) individual starts and programmed shut downs with accumulation of 44 hours of system performance testing. The objectives of these tests were to accumulate data and to gain basic test experience.

1. Test Description

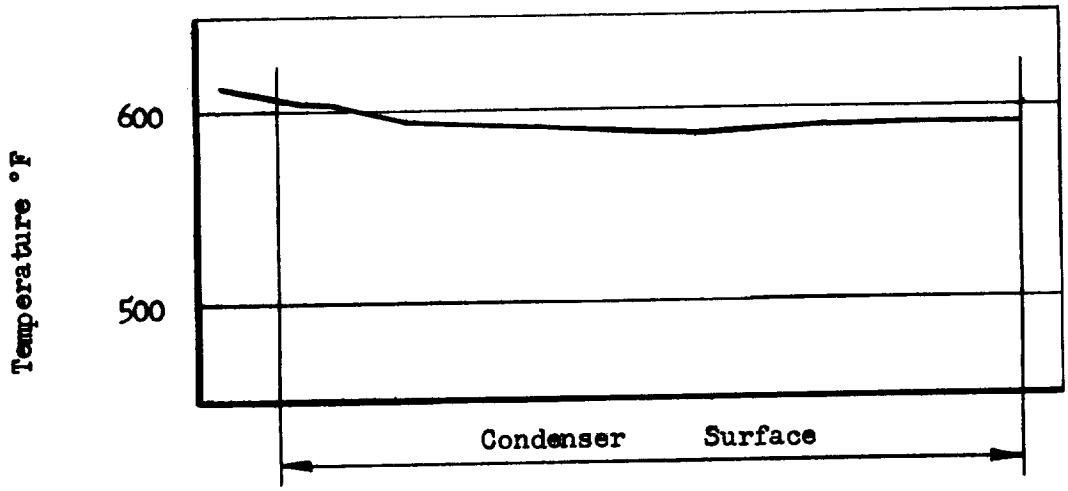
Start No. 1 - Startup was initiated by introducing liquid flow into the boiler at a rate of approximately 5 ppm. An indication of speed was obtained at approximately 10 seconds following the start of flow, followed by acceleration to a first speed plateau of 1486 cps and a condition of minimum useful load. To achieve 30,000 rpm, flow was increased to approximately 8.0 ppm and a lock-on-speed corresponding to 1488 cps obtained. This was followed by a second change in speed to 35,000 rpm at constant flow. A lock-on-speed of 1716 cps was experienced providing a total useful power of 1070 watts at conditions of turbine inlet pressure of 137 psia and condenser pressure of approximately 7.0 psia. At these conditions data point No. 2 was taken at 10:58 hours, or 00:21 hours following start. The system was allowed to stabilize with only minor adjustements to flow and condenser preheat.

Modifications to the RSC III-1 unit bias power supply resulted in negligible electrical parasitic power consumption in accelerating over the frequency span to the first speed plateau. Also, the modifications to the boiler inlet flow control valve resulted in good control of flow during the startup.

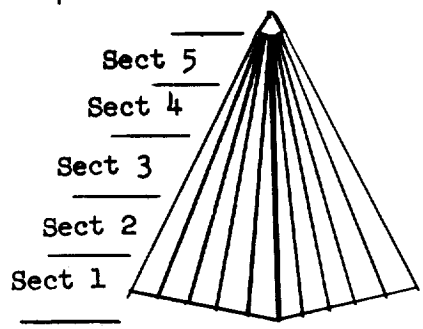
The start procedures applied to CSC I-1A unit included the immediate termination or adjustment of sectional preheat power inputs upon indications of flow. The preheater power inputs at data point No. 2 are shown in Figure 4.5. Figure 4.5 illustrates the additional capacity for heat rejection available at these conditions with all preheat power being restricted to the lower or inlet sections of the primary condensers. Heater inputs to sections 1, 2 and 3 were at relative settings of 69, 46 and 16 percent.

At approximately one (1) minute following data point No. 4, speed was increased from 35,000 rpm to 40,000 rpm design speed at conditions of constant flow. In making the change the parasitic power of the rotating components consumed approximately 360 watts. No immediate attempt was made to correct the loss of power by increasing flow in accordance to the test plan objectives. Compensation for

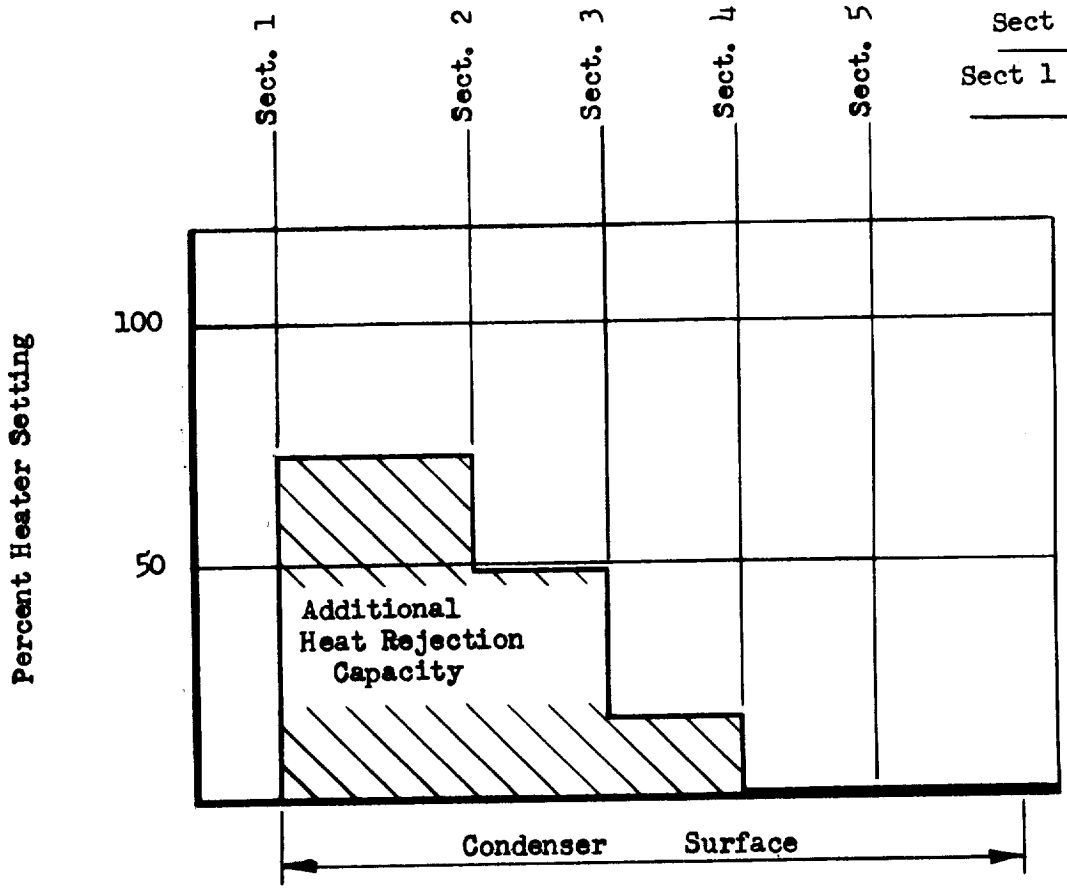
CSC I-1A Preheat Settings vs. Station Location



Condenser Temperature Profile



CSC I-1A



Heater Setting

FIGURE 4.5

higher flow could have been made by adjustment of the heater inputs in various sections of the primary condenser. At this condition of flow and maximum power complete integration of the system would require directing the bearing discharge return to the test rig into heat exchanger No. 1 to combine it with the interface bundle, and final transfer to CSU I-1A pump operation by actuating a solenoid allowing flow to be directed to the jet pump.

During the time between data point No. 4 and 5, the general observation was made of inventory accumulation in the CSC I-1A collector accumulator. (Sunflower Test Rig Schematic Figure 4.1). The leakage could be contributed to either leakage across the inlet header drain valves or vapor leakage through the degas valve in the vacuum reference to the interface. Determining the source became an immediate point of interest and concern. Although it was recognized that this leakage flow was occurring no apparent change in condenser performance could be observed in terms of changes in temperature profiles with time. This in itself supported a post test evaluation of drain valve leakage which showed the inlet header drain valves to be sealing effectively. Attempts were

made to correlate the amount of inventory volume accumulation versus time data using difference gauge readings as an indication of head. The results were not conclusive and lacked consistency in numerical value.

In checking for the source of leakage, the manual degas valve in the reference line to the interface was closed at 13:47 hours following data point No. 5. This precipitated an immediate change in temperature profiles in the CSC I-1A condenser. In particular, the uniformity of temperatures was lost and a general spreading of temperature to lower values experienced. Temperature of the interface and secondary condenser immediately began to drop off from a steady state value of 550 and 560°F respectively. At the same time the inlet line temperatures began increasing from a steady state values of 610°F to highs of 650°F. Temperature variation in the sections of the condenser suggested the occurrence of slugging. In view of this result, the immediate action was to open the manual degas valve followed by opening the inlet header outer drain valves to the various sections of the CSC I-1A unit. This action tended to correct the situation, lowering the inlet line temperature to 630°F, interface and secondary

temperature profile. Various attempts to return the CSC I-1A unit to its previous operational status by closing the outer drain valves in the inlet header resulted in similar disturbances in temperature profile and return to a running condition with the drain valves open. Operation under these conditions continued without success. The temperature unbalance became progressively worse. At 19:55 hours prior to data point No. 12, cycle flow was increased to 10 ppm to increase vapor velocity through the condenser tubes in an attempt to stop apparent liquid slugging. The results were not beneficial, actually raising temperature level in the inlet and individual sections. At 20:30 hours following data point No. 12, initial shutdown procedures were initiated. At 20:34 hours spin down of the CSU I-1A unit was complete and application of preheat to system components was initiated in preparation to another start.

The post test operations included a test to determine the source of CSC I-1A leakage detected during the test. The unit was pressurized with nitrogen gas at about 2 psig. The inlet header drain valves and degas valves in the vacuum reference to the interface were closed and a high vacuum applied to the test rig side of all valves.

No decay in condenser pressure resulted and with time the pressure level in the condenser showed only gradual decay. Following, the manual degas valve which is located intermediate to the interface and the automatic degas valve was opened and a rapid decay in pressure level was experienced, confirming a leakage past the pneumatically operated valve.

A post test calibration of the CSU I-1A unit bearings was made and showed no concernable deviations from the pre-test calibration and preparations were completed for the second start.

Start No. 2 - At 02:53 hours on 4 December, the second start of PCS I-1-2 test was initiated. The first indication of speed occurred at 12 seconds after the initiation of flow of 6 ppm to the boiler. With full load, acceleration to approximately 750 cps occurred within 6 seconds followed by a gradual acceleration to 1711 cps or 34,000 rpm within one minute while reducing manual load. The CSC I-1A unit was operating at an inlet pressure of 5 psia with the outer header valves open. At approximately 02:58 hours the outer drain valves were closed, followed by opening at 03:03 hours due to observed cooling in the

upper section of the primary condenser. Some apparent slugging was also observed to be occurring in the secondary condenser unit and low quality vapor line. Temperature of the upper section of the primary condenser continued to indicate sporadic cooling although temperatures in the secondary condenser and low quality vapor line tended to stablize. The true influence of this action is unknown due to simultaneous adjustments in heater power input to various sections of the CSC I-1A unit to correctively affect apparent slugging.

At approximately 03:12 hours a slight increase in flow to 8 ppm was experienced with an accompanying change in lock-on frequency to 1717 cps. Data point 14 was taken at 03:21 hours - speed 1717 cps, flow 8 ppm, useful power 980 watts, condenser pressure 6.5 psia. Another attempt was made to close the outer drain valves on the inlet header of the CSC I-1A unit. The results were similar to the first attempt and return to operation with the drain valves opened was executed.

Following data point No. 15 at 04:02 hours, the manual degas valve was initially closed. It was planned to close the valve in increments of one quarter turns;

With the outer drain valves open, the condenser was operating satisfactorily with only the upper section of the primary condenser operating cold. The temperature profile of the condenser remained consistent and apparently unaffected by the valve closing until the valve was fully closed. At which time, several location temperatures in the upper sections of the CSC I-1A unit began to drop, showing signs of apparent instabilities. This was accompanied by increasing inlet pressure and temperature. Opening the manual degas valve did not correct the situation and a system shut down was performed at 04:13 hours.

Start No. 3 - At 06:05 hours on 4 December, the third start was initiated. As in the previous starts a first speed plateau of 1700 cps or 35,000 rpm was selected. Similarly, the acceleration to 750 cps occurred within seconds followed by gradual acceleration to 1700 cps within a minute from start with decreasing manual load. The CSU I-1A pump characteristics were different.

As in previous starts, the pump began to provide discharge pressure between 15 to 30 seconds from the start of rotation. Rather than the previously experienced gradual increase in head with speed,

pressure began to build irregularly and within 14 seconds from start dropped-off to a very low value. Following, the characteristic was a oscillation of discharge pressure between 10-60 psig for the rest of the run. This was accompanied by similar higher frequency oscillations superimposed on a lower frequency distrubance in the parasitic and total phase current.

After start, the CSC I-1A unit did not catch hold and at 06:10 hours a system shut down was initiated.

Start No. 4

This startup was similar to the second and third starts of this test with acceleration to a first speed plateau of 1711 cps. The start was initiated at 06:27 hours following shut down of start No. 3. As in previous tests, with exception to the first start, the test was characterized by indications of local cooling and apparent liquid slugging in closing the outer drain valves on the inlet header of the CSC I-1A unit.

At 06:47 hours, speed was increased to 40,000 rpm at constant flow. A lock-on speed of 1990 cps was obtained. Data point 17 followed at 07:05 hours. At 40,000, the CSU I-1A unit was delivering a total useful power of 660 watts at a turbine inlet

pressure of 139 psia or flow of 8.4 ppm and corresponding back pressure of 8.4 psia.

At 08:02 hours the CSU I-1A package pump began to intermittently overtake the test rig chempump across the common check valve feeding the PCS I-1 system. To correct this situation the speed was reduced to 36,000 rpm followed by a further reduction to 35,000 rpm at 08:50 hours.

The first attempt was made during this test to restrict the bearing drain return to the test rig and to cause the flow to pass into heat exchanger 1, up over the center line of the CSU package and return through the primary, condensate return. This is provided by closing valve V-7 shown in Figure 4.1. The event was accompanied by very little change in useful power, approximately one half amp. of parasitic current. The condition was maintained for 2 to 3 minutes. Because of indications of local cooling in the outer tube sections of the primary condenser, the system was returned to the previous operating conditions.

The system operation was maintained at these conditions for a period of approximately 4 hours. Similar to other tests, there was experienced a

gradual increase in bearing drain line pressure with time. At approximately 1300 hours a rather sudden increase in turbine back pressure was experienced. This led to a steady increase in pressure to a point corresponding to approximately 675°F. Due to the general inability to reduce back pressure of the CSU I-1A turbine exhaust, a shut down was initiated at 14:00 hours. This was complete at 14:05 hours.

Start No. 5, 6, and 7

Starts No. 5 and 6 were similar; each initiated with a nominal flow of 5 to 6 ppm and each achieving a first speed plateau of 30,000 rpm. This was followed by incremental increases in flow to 8 to 9 ppm and an increase in speed to 35,000 rpm during the course of test. Start No. 5 was initiated at 16:40 hours and terminated at 21:23 hours after experiencing a condenser malfunction shortly after data point 26 at 21:03 hours. Start No. 6 followed at 23:25 hours and terminated at 02:09 hours on December 5, 1962 for similar reasons of condenser performance. Start No. 7 was initiated at 02:37 hours with shut down shortly after 04:15 hours.

Again the apparent correlation between condenser malfunction and increasing CSU I-1A bearing drain

line pressure was observed. At data point 26, the bearing drain line pressure had increased to approximately 2" of Hg vacuum from a value of 15" Hg vacuum after start. Also, the characteristics of the condenser malfunction included sudden cooling in the interface, low quality vapor line and secondary condenser, followed by general temperature discontinuity through sections of the CSC I-1A unit.

In the test following start No. 5, the CSU I-1A exhaust was at an indicated superheat state. Increases in flow were found to reduce the amount of superheat and provide closer correlation of saturated pressure and temperature in the condenser inlet line. For these running conditions; however, indications of liquid presence in the CSC I-1A inlet line was noted: By placing one's ear close to the inlet header, inner drain valve stems, a distinct pinging could be heard. The same indications were not heard at the outer drain valve stems. This introduced the thought of liquid spillage from the CSU I-1A unit, in view of the present superheat from the turbine exhaust.

At 04:15 hours following start No. 7, the bearing drain, test rig return valve (V-7) was closed for the second time. As before, the restricted bearing

drain flow was forced to pass through heat exchangers No. 1, up over the center line of the CSU I-1A unit and return through the primary condenser return (V-3). The results were similar to those previously experienced. Initial cooling in the upper sections of the CSC I-1A followed by increasing temperature disturbance and an overall malfunction. A drop in alternator coolant inlet temperature from 600°F to approximately 400°F was experienced at this time due to the absence of preheat to the coolant in passing through the low heat exchanger 3.

Start No. 8

At 05:26 hours, flow of 7 ppm was introduced to the boiler for another startup. A speed of 35,000 rpm was achieved. At 06:06 hours, flow was increased to 9 ppm at constant speed and all preheat to the condensing sections of the CSC I-1A unit removed. Data point 32 followed at 06:18 hours. A total useful power of 1200 watts, electrical was obtained at a back pressure of 8.6 psia.

Following data point 33 at 07:32 hours, speed was increased to 40,000 rpm to observe the affects upon pump performance. A condition resulted in which the system flow was supplied simultaneously by

the test rig chempump and the CSU I-1A package pump. At a total system flow of 35 ppm, a flow supply of 17 ppm was indicated by the test rig pump. Wide temperature disturbances were experienced due to this condition, and speed was reduced to 35,000 rpm to lower the performance of the CSU I-1A package pump.

At 08:47 hours, the start of the first boiler sun-shade cyclic test was initiated. Boiler heater input power was reduced from 57 KW to 27 KW electrical. The boiler cycle flow was maintained at 9.6 ppm. At 09:23 hours, corresponding to data point 34, the shade cycle was complete and the boiler heater input set at 68 KW. This was followed by a period of 60 minutes of heat-up at 68 KW of boiler heater input. It was observed that the general temperature level of the boiler heat storage material was low after the 60 minute heat-up period and was attributed to insufficient heat input to compensate for oil coolant losses of the heater. A second test to evaluate freeze-out characteristics was initiated at 10:23 hours and the boiler heater input reduced to 25 KW. At 10:59 hours, corresponding to data point 6, the second freeze-out was complete and the boiler heater increased to 75 KW for a duration of 60 minutes. At 11:59 hours the third 36 minute freeze-out test was

initiated. The test was terminated at 12:23 hours due to a condenser temperature unbalance. A programmed shutdown was initiated and at 12:36 hours the system shutdown was complete.

Start No. 9 - Following the preceding system shutdown, boiler heater power was increased to a value of 65 KW to bring the temperature of the heat storage material up to prestart values. At 13:58 hours startup was executed taking speed to 35,000 rpm. At a corresponding turbine inlet of 169 psia, a total useful power of 1590 watts electrical was achieved.

At 15:15 following data point 40, the boiler heater power was reduced to start a 70 minute shade period simulation of a high altitude sun-shade cycle. At 16:25 hours the freeze-out was complete and heatup of the boiler to approximately 1400°F average started. A simulation of an equivalent sun period and second shade period was not executed.

Steady state performance at conditions of maximum capacity followed. Cycle flow had been increased to a maximum of 10 ppm at a turbine inlet pressure and temperature of 189 psia and 1240°F. At this

flow, the boiler inlet flow control valve was full open, and limiting further increases. Also, resulting operating conditions of 630°F and 9 psia of the CSC I-1A unit with no heater power, provided further limitations for extended operation. Total power realized was 1310 watts electrical at data point 45. Evidence of useful power decay was evident with increasing bearing drain line pressure. At data point 45, this read 4.2" of Hg vacuum, approaching the apparent critical value of approximately 2" of Hg vacuum coincident with past condenser malfunctions.

Starting at 20:10 hours, calibrations were made of inventory accumulation in the CSC I-1A drain pots. The method used was static head versus time correlation for a calibrated volume. Flows of 11 and 14 ppm were indicated for the two consecutive measurements. This data was recorded over a period of 7.2 and 6.0 minutes respectively at a cycle flow of 10.3 ppm. The results were suggestive of leakage flow from the CSU I-1A unit into the condenser inlet either from the alternator cavity drain or turbine vapor by-pass lines.

Between data points 47 and 48 a severe temperature disturbance of the condenser was experienced. At the time the bearing drain line pressure was approxi-

mately 1.5" of Hg vacuum and a rather noticeable increase in condenser collector pot inventory and head was experienced. At 22:14 hours system shut down procedures were initiated with shut down achieved within minutes following.

Start No. 10

The primary objective of this start was to evaluate the startup characteristic of the CSU I-1A unit under no load. The manual electrical load was set to zero and the unit rotational speed control was set at 30,000 rpm. A flow of 6 ppm was selected.

A second purpose was to attempt a start with the outer drain valves on the inlet header of the CSC I-1A unit closed, to simulate the results of the first start of this series. At the start, the inner drain valves were open-followed by closing soon after start.

At 00:10 hours on 6 December, flow was introduced to the boiler. At approximately 14 seconds rotational speed was experienced with acceleration to 1434 cps in 36 seconds. The flow stablized out at approximately 5.7 ppm. During acceleration, the rotational speed control bias of the parasitic load was excellent, resulting in no electrical load

upon the unit during acceleration. At 1434 cps, the first indication of parasitic power consumption occurred, increasing gradually as flow and power approached steady state at a shaft speed of 1448 cps. Total electrical power was low however, between 250 and 300 watts.

After startup the temperatures of the CSC I-1A rapidly stablized about 600°F with the interface and low quality vapor line temperatures running lower. Over a period of 4 to 5 minutes no indication of slugging was observed and it appeared that the CSC I-1A unit would enter into a condition of stable performance, simulating the results of the first start of this test series. However, at about 6 minutes after start, a spreading of temperatures was observed at a gradually increasing rate. Shortly after, the outer drain valves on the inlet header were opened to see if this would correct the situation. This had no corrective affect and at 00:23 hours preparations for a shut down were started. At 00:25 hours the shut down was complete.

The repeated difficulty in ability to operate the PCS I-1 system continuously for extended periods led to the decision to terminate the PCS I-1-2 test.

2. Results and Discussion

The PCS I-1-2 test consisted of a series of ten (10) short duration performance tests. Each test was initiated with a system startup and concluded with a programmed shut down. The number of individual tests result from either, or combination of the following factors:

a. The affects of non-condensable gases on PCS I-1 system operation.
b. The affect of "wetting" on CSC I-1A performance.
c. The affect of inlet vapor quality on CSC I-1A performance.

The characteristic of the CSU I-1A bearing exhaust pressure in the PCS I-1-2 test with test time suggests the accumulation of noncondensable gases in the bearing exhaust line. The bearing drain system is shown schematically in Figure 4.6. Unrestricted, the bearing flows discharge into a relatively fixed volume which acts as a reservoir for any noncondensable gases which may be present. The effects of continuous accumulation will be to raise the liquid height on heat exchanger No. 2 and 3. The ultimate result is liquid accumulation in the interface and spill-back into the CSC I-1A condenser. This

PCS I-1 Bearing Drain Line-Condensate Return Schematic

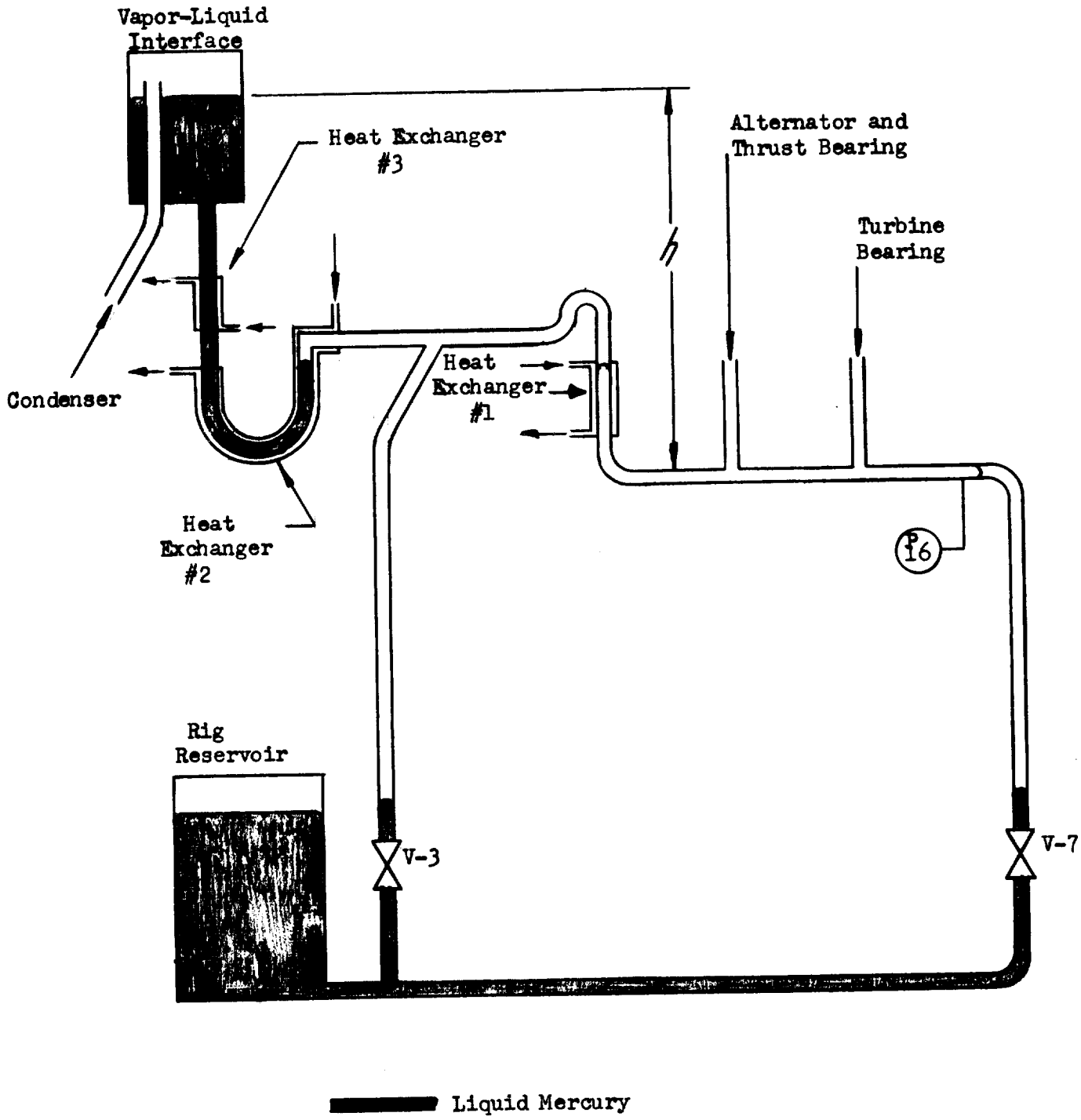


Fig. 4.6

would result in the general unbalance of the CSC I-1A operation which was noted and observed in test.

The existence of these conditions is supported by the PCS I-1-2 systems test data. Table 4.1 illustrates the relationship between bearing drain line and interface temperature and pressure. The point of interest is between data points 10 to 11. It is noted that the interface immersion temperature takes a sharp drop from 549°F at data point 10, to 390°F at data point 11. Also the corresponding saturation temperature at the interface pressure of 26 in. Hg vacuum is approximately 486°F or approximately 100°F higher than the measured temperature. The data is supporting evidence of liquid in the interface at data point 11. Unfortunately, due to malfunction of the closed circuit video monitoring the interface, this was not visually observed during test to verify the data.

TABLE 4.1

PCS I-1-2

Bearing Drain - Interface Temperature Pressure Relationships

DP	Pressure Interface -in Hg	Temperature Interface-°F	Temp - Saturation Corresponding to Interface Pressure	Bearing Drain Line Press. In - Hg	Δ H In - Hg
2	20.0	564	565	15	5.0
3	21.0	550	555	13.3	7.7
4	21.0	552	555	11.7	9.3
5	21.0	548	555	10.3	10.7
6	21.0	548	555	7.3	13.7
7	21.0	567	555	6.8	13.2
8	21.0	543	555	3.2	18.0
9	21.0	549	555	2.2	18.5
10	21.0	549	555	3.0	18.0
11	26.0	390	486	3.0	23.0
12	26.0	397	486	2.2	23.8

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This position is also further supported by the bearing drain, interface pressure relationship. From Table 4.1 it is noted that at data point 10 the differences in pressure correspond to differential height of 18.0 in of Hg. Physically, the height between the bearing drain centerline and top of the condensate inlet tube in the interface is 17.5 in. The data thus supports the position of gradual accumulation of inventory into the interface with time, which when reaching the height of the condensate inlet tube resulted in spillage or back flow into the CSC I-1A unit.

This condition is similar to that imposed upon CSU units in component tests to evaluate performance with flooded bearing drain lines. Such tests have always been accompanied by a drop in useful power of 400 to 500 watts when subjected to 12 inches of Hg head above the centerline of the CSU packages. This provides some insight as to the general decay of useful power experience with increasing bearing drain line pressure. The influence of this parameter on useful power is shown in Figure 4.7. The data is standardized to the same turbine inlet and condensing pressures.

The source of noncondensable gas in the bearing drain is limited to either the leakage of argon

PCS I-1-2 Power vs. Bearing Drain Pressure

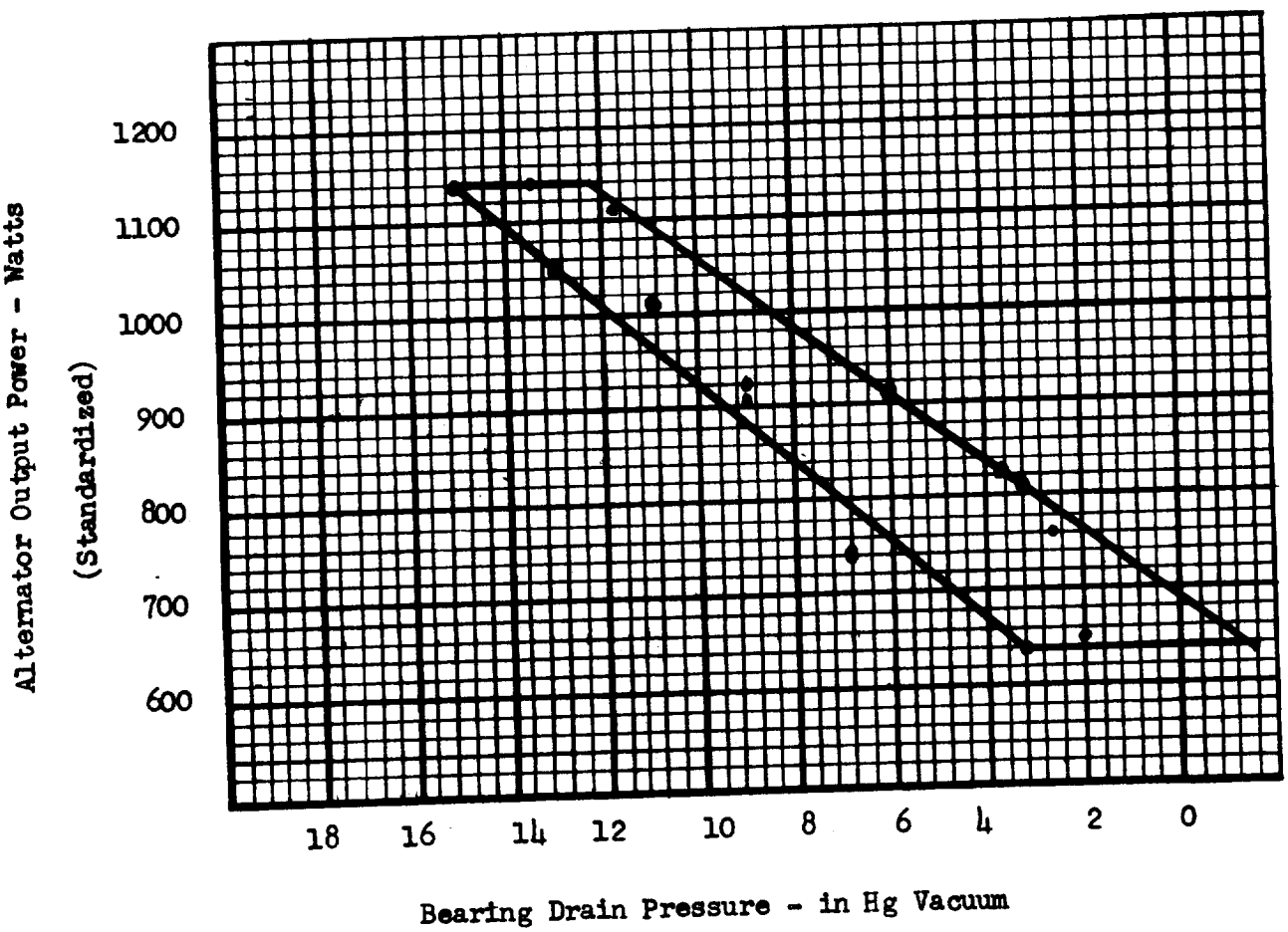


FIGURE 4.7

gas from the test cell atmosphere or to internal permeation of hydrogen gas into the system from dissociated hydrogen gas from lithium hydride heat storage material in the BHS I-2. Argon leakage into the system appears to be the more logical source although hydrogen permeation is a definite possibility. The liquid accumulation in the heat exchangers Nos. 2 and 3 would limit the path of hydrogen into the bearing drain system to the high pressure vapor leakage from the CSU I-1A first stage turbine wheel into the turbine bearing cavity. Hydrogen gas in the normal cycle vapor flow would tend to accumulate in the vapor-liquid interface. Since the interface during test was normally referenced to a vacuum source, hydrogen gas or other noncondensable gases would be drawn off continuously. If not removed, the liquid column in heat exchangers Nos. 3 and 2 would restrict passage to the bearing drain system and result in general rise of condenser pressure with time.

The general characteristic of CSC I-1A unit operation was the inability to provide complete integration of the unit with the other system components. After the first start, extended periods of satisfactory operation of the unit with the inlet header drain valves and interface degas valve closed were not obtained. The reason may be due to the singular or combining conditions given as

follows:

a) A progressive condition of tube "wetting."
The existence of this condition would required a progressive increase in vapor velocity to support and transfer condensate in the film until a fully wetted condition was developed. At this condition the condenser would continue to operate satisfactorily provided the sufficient vapor velocity was maintained. The fabricated CSC I-1A design was not based upon a fully wetted condition. Thus, if wetting did occur and became progressively worse, slugging and associated temperature unbalance would be expected to occur as observed in the test. The condition, if existent, is further aggravated by off-design testing of lower flows and corresponding vapor velocities.

b) The effect of high liquid content of the vapor into the CSC I-1A inlet.
The reason is due to the potential for liquid leakage into the CSC I-1A inlet line from sources within the CSU I-1A unit. The normal source of liquid is in the spent vapor from the turbine exhaust. This liquid quantity is low, within 5 to 7 percent and within the design requirements of the CSC I-1A unit. Other sources of liquid leakage are the alternator cavity, through the alternator cavity drain line and spillage of turbine

bearing flow, through the turbine vapor by-pass line. The turbine bearing flow leakage is dependent upon turbine bearing drain pressure and can occur with liquid build-up in the bearing cavity to the point of spillage past the inboard end of the bell shaped heat shield which protects the turbine bearing from the hot vapor leakage from the turbine first stage wheel.

During the test attempts were made to determine the amount of leakage flow accumulation in a calibrated drain accumulator. For two separate correlations, indications of leakage flow of 10.4 and 14.0 ppm were obtained. This data was taken at the end of the No. 2 test at a maximum system flow of 10.0 ppm. The data was accumulated with the CSC I-1A inner drain valves closed and the outer drain valves and degas valve opened. The data thus tends to support the existence of leakage since the indicated leakage flow was higher than the actual system flow.

c) An inconsistency and sensitivity to CSC I-1A preheat during startup.

This results due to the affect of preheat upon vapor quality distribution in the condenser and the effects on vapor velocity. Figure 4.5 illustrates the relative CSC I-1A heater inputs for each section during the first start of the PCS I-1-2 test. It was during this test

that complete integration of the CSC I-1A unit was achieved.

4.3.3 PCS I-1-3 Test

The test was initiated 19 December 1962. Modifications to further aid system performance evaluations include the following:

1. Redirecting CSU I-1A alternator cavity drain from the turbine exhaust to the CSC I-1A collector drain accumulator for flow measurements.

2. Added sight gage and scale to CSC I-1A collector drain accumulator for flow measurements.

3. Modified CSU I-1A test rig bearing return line for flow measurements by head versus time correlations using the CSC I-1A collector drain accumulator.

4. Modified CSU I-1A bearing drain system for degasing by vacuum reference to a test rig reservoir.

Test Description:

Following normal pretest preparations, start-up was initiated at 16:21 hours at a selected flow of 5 ppm and speed plateau of 30,000 rpm. An indication of speed was received at approximately 30 seconds from start. After reaching a few thousand rpm in magnitude, the speed suddenly dropped to zero. At this

point immediate action was taken to close the turbine inlet valve and return all systems to prestart conditions.

An evaluation of the bearing flow and pressure requirements showed no concernable deviations from prestart values. This correlation indicated absence of bearing damage and suggested other reasons for the loss of speed shortly after start. The possibility of sudden liquid accumulation and drag on the shaft was considered.

At 20:17 hours a second start was attempted at the same condition of flow of the previous start. Rotation was not obtained and at 20:19 hours the turbine inlet valve was closed. During the period of flow, some vapor flow through the CSU I-1A package occurred as evidenced by responses in turbine exhaust and condenser inlet temperatures. The characteristic, however, suggested the magnitude of the flow to be small and possibly insufficient to overcome the inertia and nominal friction on the shaft.

It was observed during the course of flow to the boiler that some of the mercury immersion thermocouples rose to values exceeding the surrounding lithium hydride bath temperatures. Secondly, the pressure gage in the boiler bleed line failed to respond to record boiler pressure with flow to the boiler. These conditions suggested an internal leak in the BHS I-2

component with a resulting chemical reaction between mercury and lithium hydride and possible tube plugging due to this.

Following shutdown a sample of mercury was taken from the PCS I-1 inventory for chemical analysis. The results confirmed the presence of lithium metal in the mercury. Upon disassembly of the BHS I-2 unit from the system structure, it was noted that a short section line exterior to the boiler on the discharge or vapor side was completely plugged. Also plugged was the boiler bleed off exterior to the boiler. Radiographs of the boiler were taken to identify conditions within the boiling tube. For the most part, the boiler tube appeared clean, free of foreign elements except one section in the preheater which was partially plugged. The radiographs, however, fail to show a positive identification of tube malfunction. One area of the preheater tube appears suspicious of a possible crack as evidenced by apparent mercury contamination of the lithium hydride in this area. Confirmation of this possibility will not be obtained until the boiler is cleaned of hydride and sectioned for analysis purposes.

4.4 Startup Characteristics

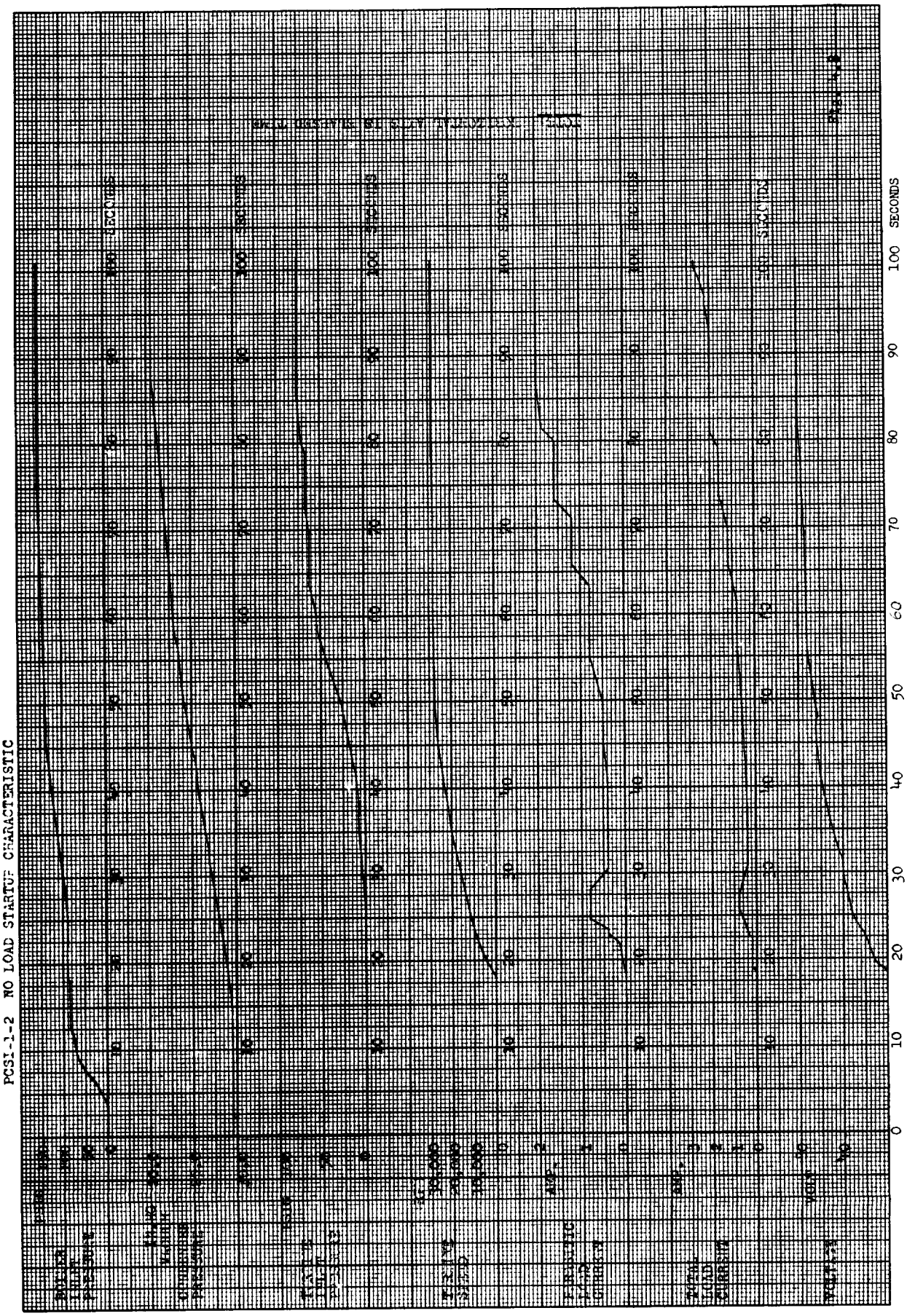
The startup characteristic of the PCS I-1 system is well within requirements of short duration start methods. The startups are characterized by stable operation throughout the startup transients and high pressure build-up. In each of the ten starts of the PCS I-1-2 test, a first indication of speed was obtained within 15 seconds from the initiation of

flow into the boiler - with some starts providing rotation at 10 seconds. Figure 4.8 illustrates the final startup under conditions of no load and flow of 6 ppm. The time of acceleration to rated speed is approximately 36 seconds. The lag in turbine inlet pressure shown is characteristic of the pressure readout system and does not give a true indication of actual pressure with time. Noted also is the excellent functioning of the parasitic control in biasing the parasitic element of load during acceleration.

The simulated starts were performed using the auxiliary mercury test facilities. This provides for the use of a high capacity mercury pump supply in place of a pressurized mercury start tank system for orbital startup. The difference in the start methods is due primarily to the effective infinite capacity at a relatively constant supply pressure of the auxiliary test rig pump as compared to a fixed inventory for a flight startup system.

A preprototype flight startup system was designed and tested in component tests of the BHS I-2 unit. The relationship of the start system to the BHS I-2 component demonstrated the basic feasibility of the start system and adaptability to further power system test.

PCSI-1-2 NO LOAD STARTUP CHARACTERISTIC



5.0 PCS I-1 TEST CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be drawn regarding component and system performance of PCS I-1.

1. The integration of the PCS I-1 system test installation provides for frequent starts and stops with minimum elapsed time. This feature proved to be very beneficial in view of the number of starts and stops required.

2. The boiler heat storage component, BHS I-2, combined shaft unit, CSU I-1A, and rotational speed control, RSC III-1, demonstrated basic integration compatibility and operational integrity.

3. System performance was characterized by sensitivity of the CSC I-1A unit to operating conditions. Factors influencing the CSC I-1A performance include the following:

   a) Probability of progressive tube wetting and condensation against gravity with effective decreasing vapor velocities. Operation of the CSC I-1A unit, thus, generally required running with the inlet header drain valves and interface degas valve open.

   b) External influences of potential liquid leakage from the alternator cavity drain and turbine vapor by-pass line.

   c) The affects of bearing drain line pressure with time. CSC I-1A malfunctions were correlated to this parameter in the general range of 5 to 2 inches of mercury vacuum. Indications of liquid accumulation and eventual spillage backwards through the condenser from the interface is thought to cause the malfunction. Secondly, the effects of increasing bearing drain line pressure contributes to increasing

vapor by-pass leakage by diverting turbine bearing flow because of the higher resistance of the bearing discharge line.

4. The operation of the CSC I-1A was shown to limit maximum heat rejection capacity below design and, in general, support the conclusion of previous component test of this unit.

5. The CSU I-1A unit performance in the PCS I-1 system test was below predicted performance and component test data. In general, there is good agreement between predicted and actual component test data of each of the CSU I-3, CSU I-3A and CSU I-1A fabricated to date. The discrepancy in useful power in system integration and test of the CSU I-1A unit is attributed to liquid accumulation and drag on the shaft caused by difference in bearing drain conditions.

6. The phenomenon of increasing pressure in the CSU I-1A bearing drain line can be attributed to noncondensable gas. The source of such gases is thought to come either from the ambient argon environment by leakage into the system or by permeation of H_2 gas from the lithium hydride boiler heat storage material.

6.0 PCS I-1 TEST RECOMMENDATIONS

1. Perform a failure analysis of BHS I-2 unit to determine source and nature of failure. The results of this finding should be used to evaluate modifications required in the BHS II-1 unit prior to fabrication and lithium hydride filling.

2. Integration of the CSU condensate pump should be modified to provide independent operation of the condensate pump. This will involve modification to the valving and plumbing to prevent the condensate pump over pressuring the auxiliary Chempump at rated speed. The modification should provide for direct return of the condensate pump discharge to the test rig reservoir and the ability to transfer to system operation by proper valving.

3. Provide for direct return of the CSU I-1A alternator cavity drain and vapor by-pass drain to the test rig reservoir, or replacement with a CSU incorporating drain provisions. Provisions should be made to measure these drain flows and attempt made to evaluate the nature of the flow in terms of either vapor or liquid.

4. Review CSU seal designs to evaluate adequacy of alternator bearing-cavity seal and incorporate a similar seal on the turbine end of the shaft to restrict liquid by-pass from the bearing cavity through the by-pass line. This effort should be complimented by considerations of a more effective thermal barrier to heat transfer from the turbine vapor by-pass to the turbine bearing cavity.

5. Reactivate system testing to determine effectiveness of recommendations (1) through (3), in particular with reference to CSC I-1A performance and component integration. Similarly, the test would resolve the question of wetting and influence upon performance of the CSC I-1A unit. A lack of improvement in performance would indicate the need of redesign of the CSC unit for full wetting in 1 "g" attitudes.

6. If required redesign of the condenser-subcooler should take into account the following factors:

   a) Change in system specification from ± 1 "g" in any direction to 0 "g" with a predicted "g" force in a known direction to be more consistent with the actual orbital environment.

   b) Consideration of improved heat-up techniques consistent with system startup methods.

7. Test turboalternator units in component fashion to evaluate performance improvements as outlined in item 4 above. After checkout install into power conversion system for checkout and compatibility with other components, particularly in regards to fluid spillage into the condenser component.

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NOTE: All Reports have been published as Topical Reports on contract NAS 5-462, "Sunflower Power Conversion System," and copies can be obtained through:

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