AEROJET GENERAL TIRE GENERAL

AEROJET-GENERAL CORPORATION

SACRAMENTO • CALIFORNIA

SACRAMENTO PLANT

17 May 1966
9410D:4040:SLS:eb

National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

N66 25246

Attention: Mr. Ward W. Wilcox
M-1 Project Manager
M-1 Engine Project Office

Subject: Technology Report, Cooldown of Large Diameter Liquid Hydrogen and Liquid Oxygen Lines

Dear Mr. Wilcox

1. The subject report (Enclosure 1) is forwarded for your information.

2. Additional reports have been distributed as delineated in the subject report.

Very truly yours,

AEROJET-GENERAL CORPORATION

S. L. Sachs

S. L. Sachs, Manager
Documentation
M-1 Program

Encl: (1) Technology Report, Cooldown of Large Diameter Liquid Hydrogen and Liquid Oxygen Lines

NASA CR-54809
AGC 8800-54

TECHNOLOGY REPORT

COOLDOWN OF LARGE-DIAMETER LIQUID HYDROGEN AND LIQUID OXYGEN LINES

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

20 April 1966

CONTRACT NAS3-2555

Prepared by:

AEROJET-GENERAL CORPORATION
LIQUID ROCKET OPERATIONS
SACRAMENTO, CALIFORNIA

AUTHOR: M. H. Schwartz
J. C. Commander

APPROVED: D. H. Clark, Manager
M-1 Test Program

Technical Management:

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO

TECHNICAL MANAGERS: C. Y. Young
L. T. Weise

APPROVED: W. F. Dankhoff
M-1 Project Manager

ABSTRACT

20-246

This report describes the chilldown of large cryogenic systems located in Test Zone E of the Aerojet-General M-1 Engine test complex. Theoretical analyses as well as actual experience are included.

Author

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

I. SUMMARY

This report concerns the analytical study and operational experience associated with the large cryogenic propellant systems used in Test Zone E of the M-1 test complex.(1) This facility was designated for cold flow development testing of the M-1 liquid hydrogen/liquid oxygen engine fuel and oxidizer turbopump assemblies. The test facility was designed by the AETRON Division of the Aerojet-General Corporation based upon criteria mutually established by NASA/LeRC and Aerojet-General Liquid Rocket Operations. Substantial support to the design effort in the area of thermal and stress analysis was provided by the Von Karman Center (division of Aerojet-General Corporation). A significant part of this report is concerned with the thermal and stress analysis study conducted at the Von Karman Center, using the Aerojet-developed thermal analysis computer. The remainder of the report deals with experience gained by Liquid Rocket Test Operations in operating the completed facility at Sacramento, California

The techniques applicable to initial chilldown of large diameter cryogenic piping systems are discussed; major consideration is given to liquid hydrogen and liquid oxygen propellant systems that utilize the cryogenic boil-off gases at a predetermined rate to effect system chilldown. The use of this technique reduces or eliminates the problem of thermal stress concentrations in the system materials during chilldown. The principal areas of discussion include:

A. Various methods considered for chilldown of cryogenic piping systems.

B. Analysis of thermal stress at selected points in liquid hydrogen and liquid oxygen piping systems where cross-section transitions produce maximum thermal gradients.

C. Analysis of system chilldown characteristics when cold gaseous cryogens are utilized to effect the initial reduction in system temperatures, including predictions of time in relationship to equilibrium temperature for systems exposed to various combinations of gas flow rate and initial temperature.

D. Analysis of the effects caused by cold shocking on critical cross-section transitions of the 18-in. liquid hydrogen discharge line which have stabilized at equilibrium temperatures of 260°R, 160°R, and 60°R.

Detailed thermal analyses of the liquid hydrogen and liquid oxygen propellant systems were performed with the Aerojet-General passive element thermal analyzer(2) to determine the transient behavior of the system

---

(1) The contents of this report are based upon an outline provided by Messrs. C. Y. Young and L. T. Weise of the Lewis Research Center, National Aeronautics and Space Administration, Cleveland, Ohio

(2) Aerojet-General Report No. 1654, Research Computer Laboratory, Space Technology Division, August 1959

at selected changes in section. Stress analyses were then made for the thermal conditions resulting from the worst case of cold shocking the system with liquid hydrogen from ambient conditions to the recommended prechilling of the system with cold gas prior to the introduction of the cryogen.

As a result of the study, the large-diameter liquid hydrogen and liquid oxygen piping systems were provided with bypass systems that used storage vessel boil-off gases to ensure proper chilldown. The system configuration is described, and the results of actual E-Zone operating experience as compared with the calculated data for the large diameter propellant systems are summarized.

II. INTRODUCTION

The purpose of this report is to analyze, in relationship to thermal-induced stress, the large diameter cryogenic piping systems associated with the E-Zone test facility; and to provide realistic, safe, and economical chilldown procedures for the piping systems. Abundant information exists relative to the cooldown of small-diameter systems; however, chilldown procedures for large 18-in. diameter lines are not within current technology because almost no previous research or experience is available for cryogenic systems of this size. Also, considerable difficulty has been experienced in achieving a uniform cooldown of large irregularly shaped masses (e.g., pipeline flanges, and valves). Nonuniform cooling of piping systems can create severe and undesirable thermal stresses which cause bowing, contraction, and yielding of the piping materials. It can also cause detrimental displacements of the system in relationship to supports, guides, and restraints.

Test Stands E-1 and E-3 comprise a two-position turbopump test complex (see Figures No. 1 through 5). Each of the two turbopump stands has a fourfold capability for accommodating gas generator testing, single liquid oxygen pump, single liquid hydrogen pump or system testing involving all three components simultaneously as an integrated system. Pump backpressure transient and steady-state characteristics are controlled by programed, highly responsive flow control valves.(3)

The cryogenic system in E-Zone consists of liquid hydrogen and liquid oxygen storage facilities and small-diameter transfer lines; off-stand liquid hydrogen and liquid oxygen vacuum-insulated run and catch vessels; on-stand liquid hydrogen and liquid oxygen transient run vessels supplying propellant through suction lines to the turbopump assembly (TPA) positions(4); on-stand high pressure liquid hydrogen and liquid oxygen gas generator assembly (GGA)

---

(3) Garcia, L. W., Friedland, H., and Lehmburg, A. E., Servo Control Systems and Analog Simulation in E-Zone, Aerojet-General Report No. 8800-61, 10 March 1966

(4) Ritter, J. A., Summary of Observed Results When Chilling the M-1 Fuel Turbopump Assembly to Liquid Hydrogen Temperature, Aerojet-General Report No. 8800-65, 22 April 1966

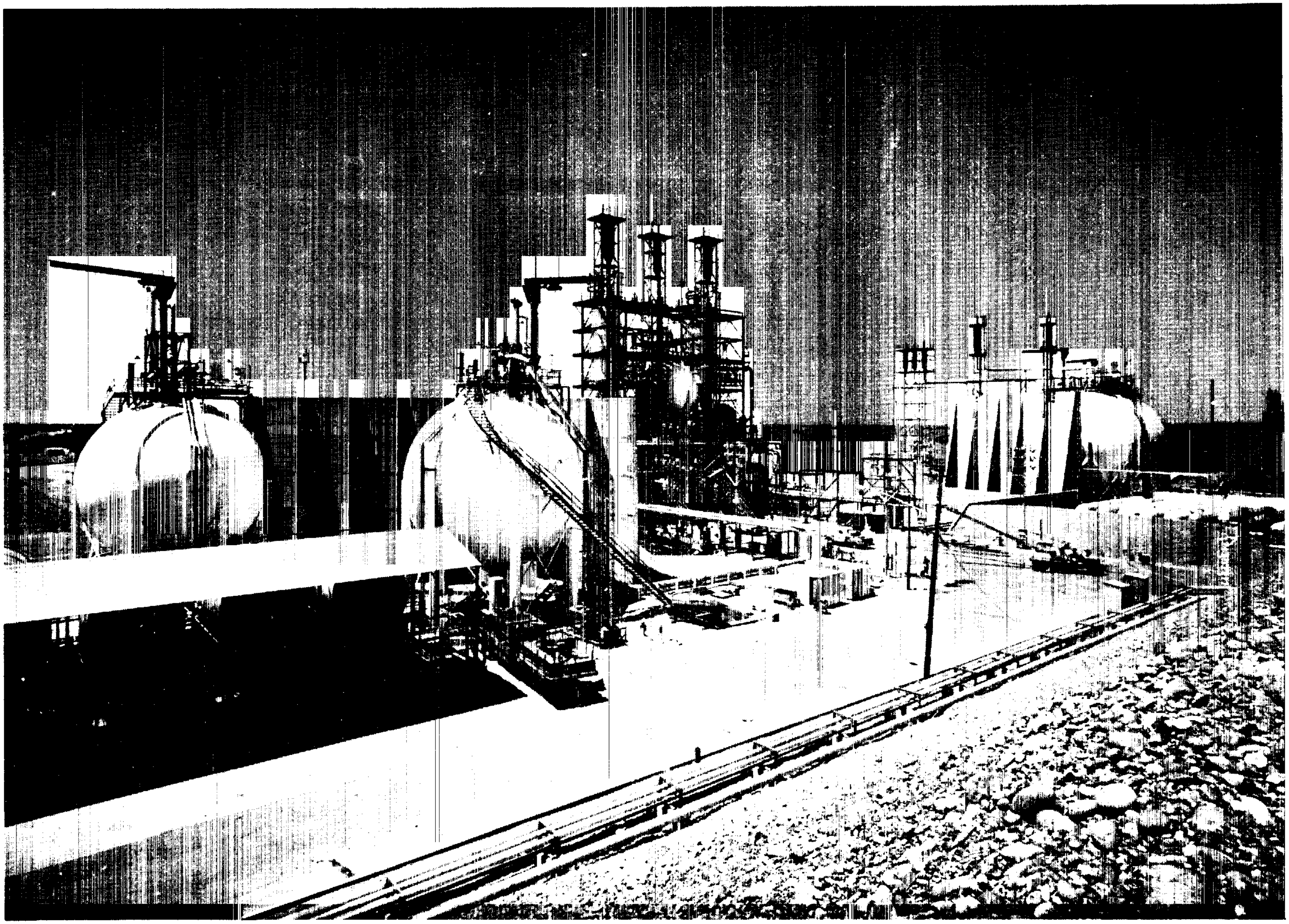


Figure 1

E-Zone, General View

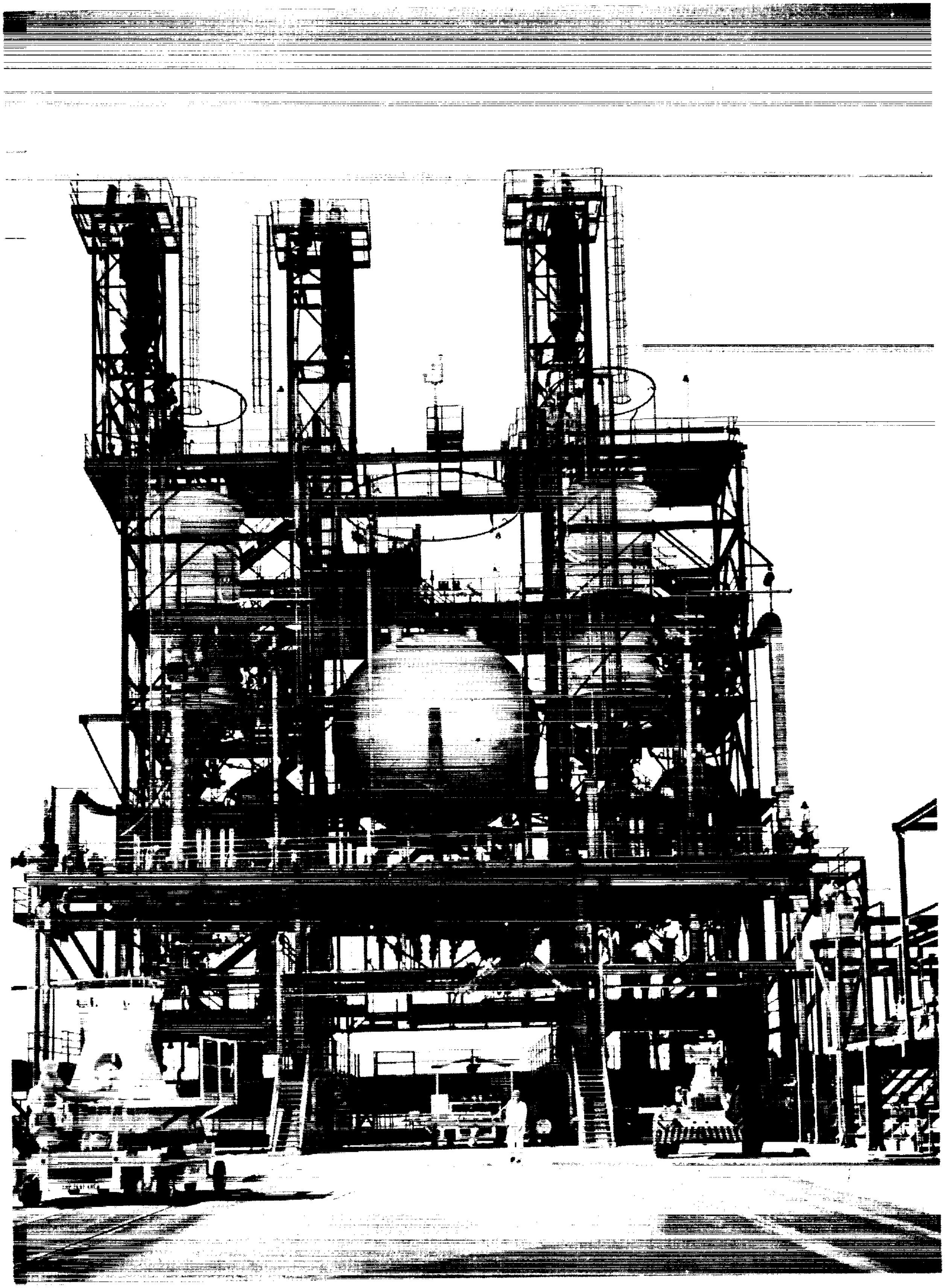


Figure 2

Test Stands E-1 and E-3

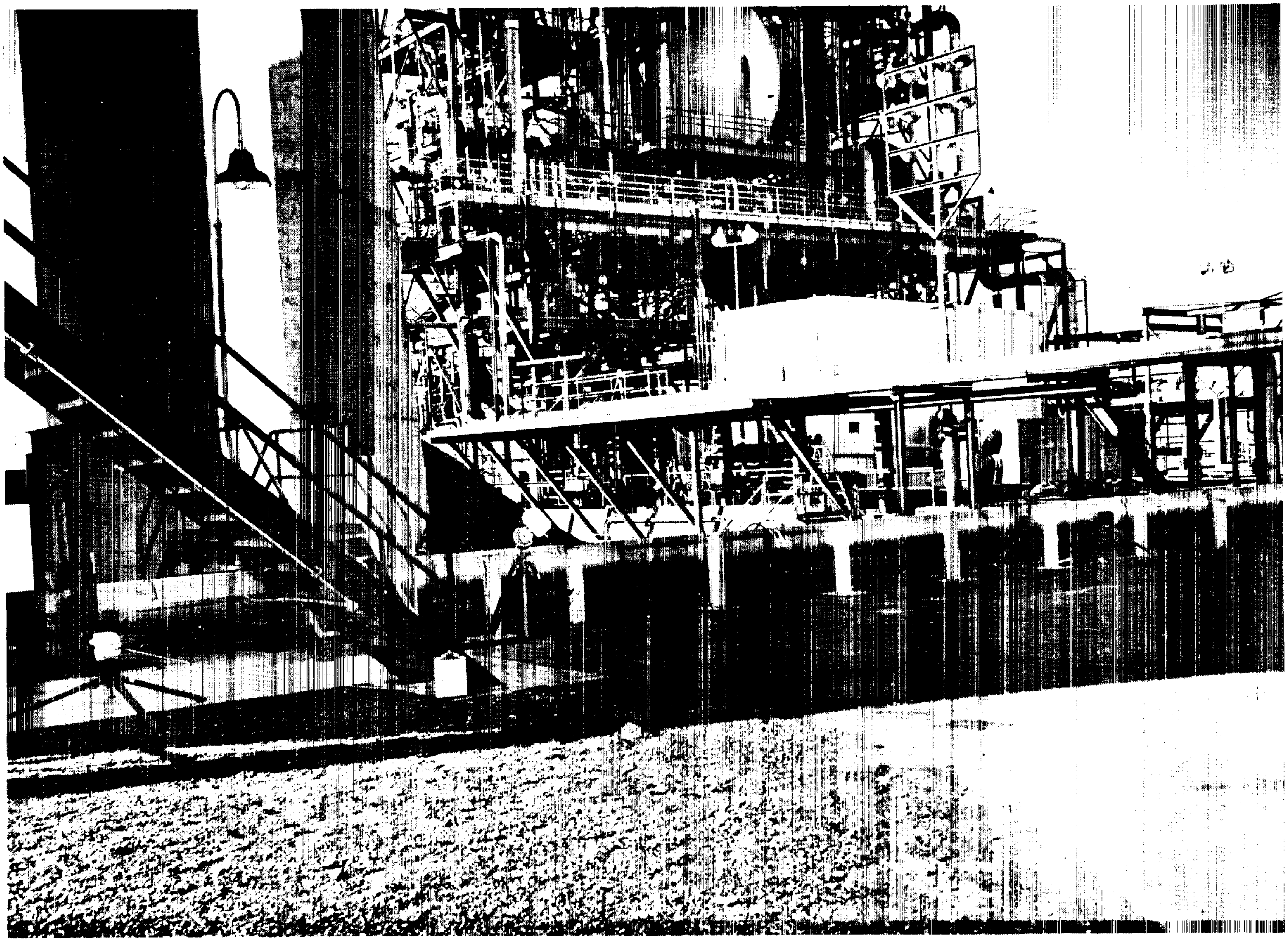


Figure 3

18-in. LO_2 Catch Line Between VE-11 and Test Stands E-1, E-3

Figure 4

18-in. Vacuum Jacketed LH_2 Run and Catch Lines

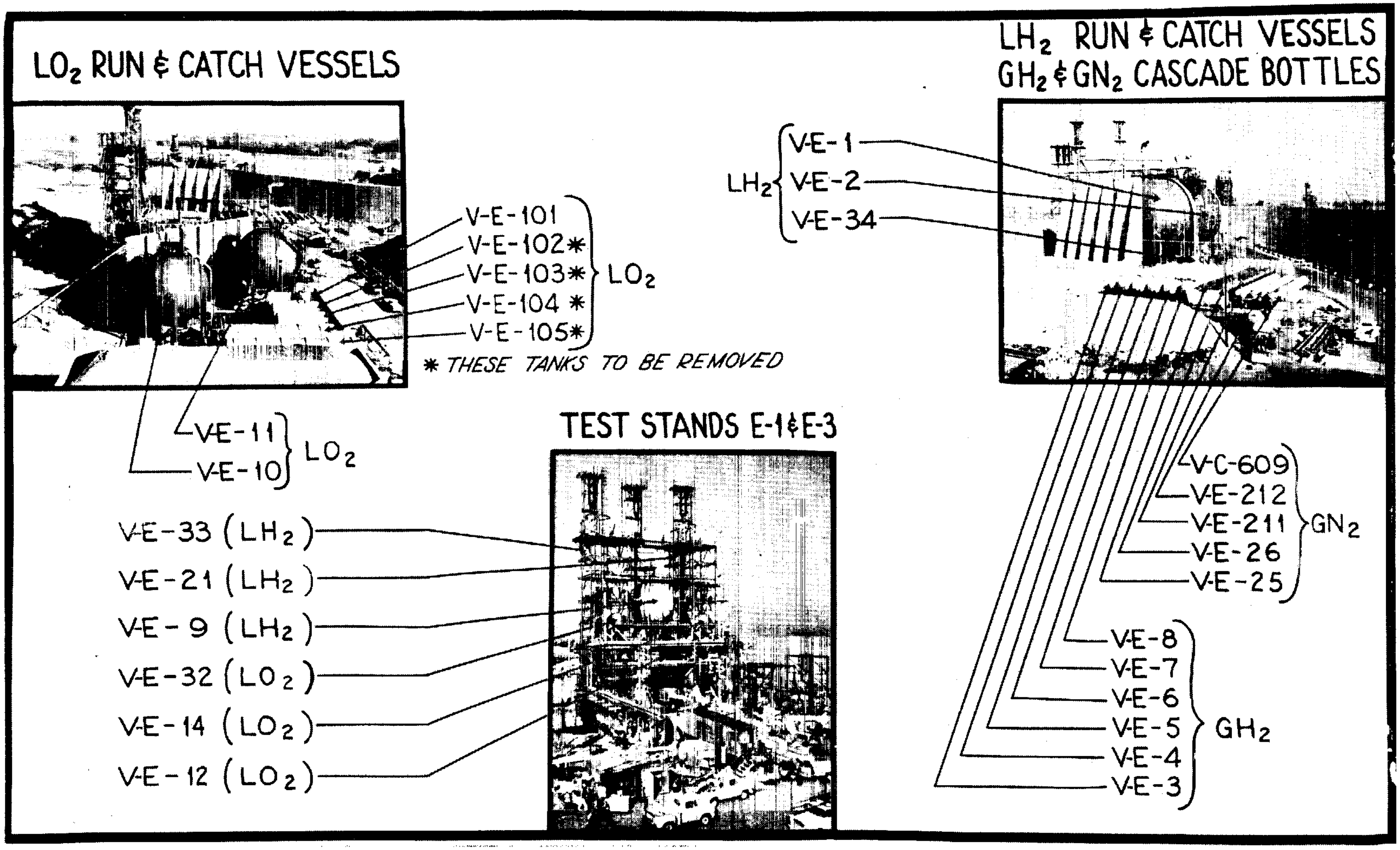


Figure 5

E-Zone Tank Locations

run vessels; large diameter liquid hydrogen and liquid oxygen run lines between off-stand and on-stand vessels; and large-diameter discharge lines from the turbopump assemblies to the respective catch vessels. The following are schematics of the liquid oxygen and liquid hydrogen systems. On-stand overhead tankage is used for short-duration pump tests while off-stand propellant systems, linked with on-stand systems, provide additional volumes of propellant to allow long-duration testing under closely controlled conditions. (This latter system was not completely activated and used because of M-1 Program termination.) These extensive capabilities also make this facility well-suited for flowmeter calibration tests.(5) Figures No. 6 and 7 are isometric drawings of the system showing propellant lines, vessels, vents, flare stacks, bypass lines, and pressurization lines. The recommended gaseous hydrogen and gaseous oxygen prechill system installations are included in these system configuration drawings. These systems were designed and installed based upon the two-directional, gas flow thermal analysis; thermal mapping; and thermal stress analysis discussed in this report and the references.

III. TECHNICAL DISCUSSION

Original designs for large liquid hydrogen and liquid oxygen piping systems were subjected to flexibility analysis (6),(7) and the systems were determined adequate with regard to contraction and expansion caused by steady-state thermal variations. This design relied upon a one-piece flexible system instead of flexible couplings to absorb the transient and thermal stresses. Early recognition that precooling techniques are required for the large propellant lines and heavy wall vessels resulted in the consideration of several methods for step cooldown for liquid hydrogen and liquid oxygen systems; this was done to minimize system propellant losses and transient stresses caused by high-temperature gradients in the pipe or vessel wall. This report is concerned primarily with the childown of the large liquid hydrogen and liquid oxygen piping systems.

A. CONSIDERATION OF DIFFERENT CHILLDOWN METHODS

One of the first methods considered was that of using liquid nitrogen to precool the liquid hydrogen system to 140°R. This approach offered a savings when compared to chilling with liquid hydrogen because liquid nitrogen is relatively inexpensive and easy to handle. However, to effectively introduce liquid nitrogen into the system would add considerably to the facility and operations cost, and proper evacuation of the liquid nitrogen from a complicated system of piping, valves, and vessels could prove costly as well as time

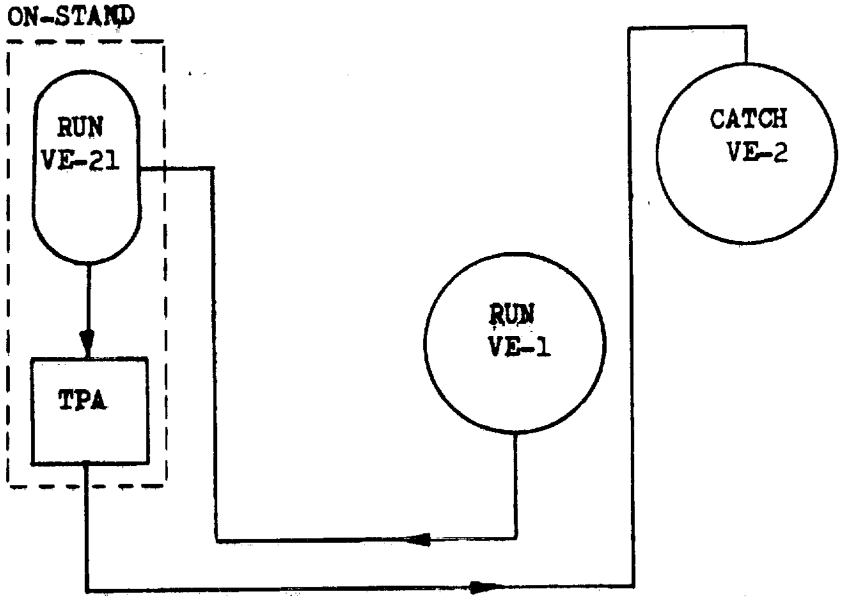
---

(5) Deppe, G. R., Large Size Flowmeter Technology, Aerojet-General Report No. 8800-60, 8 April 1966

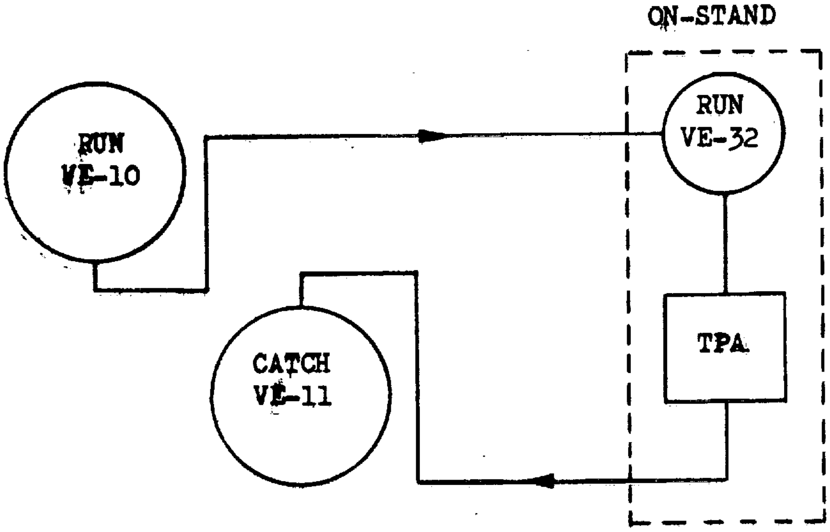
(6) Aerojet-General Corporation AETRON Division Report No. 2816, AETRON Pipe Flexibility Analysis Program, March 1964

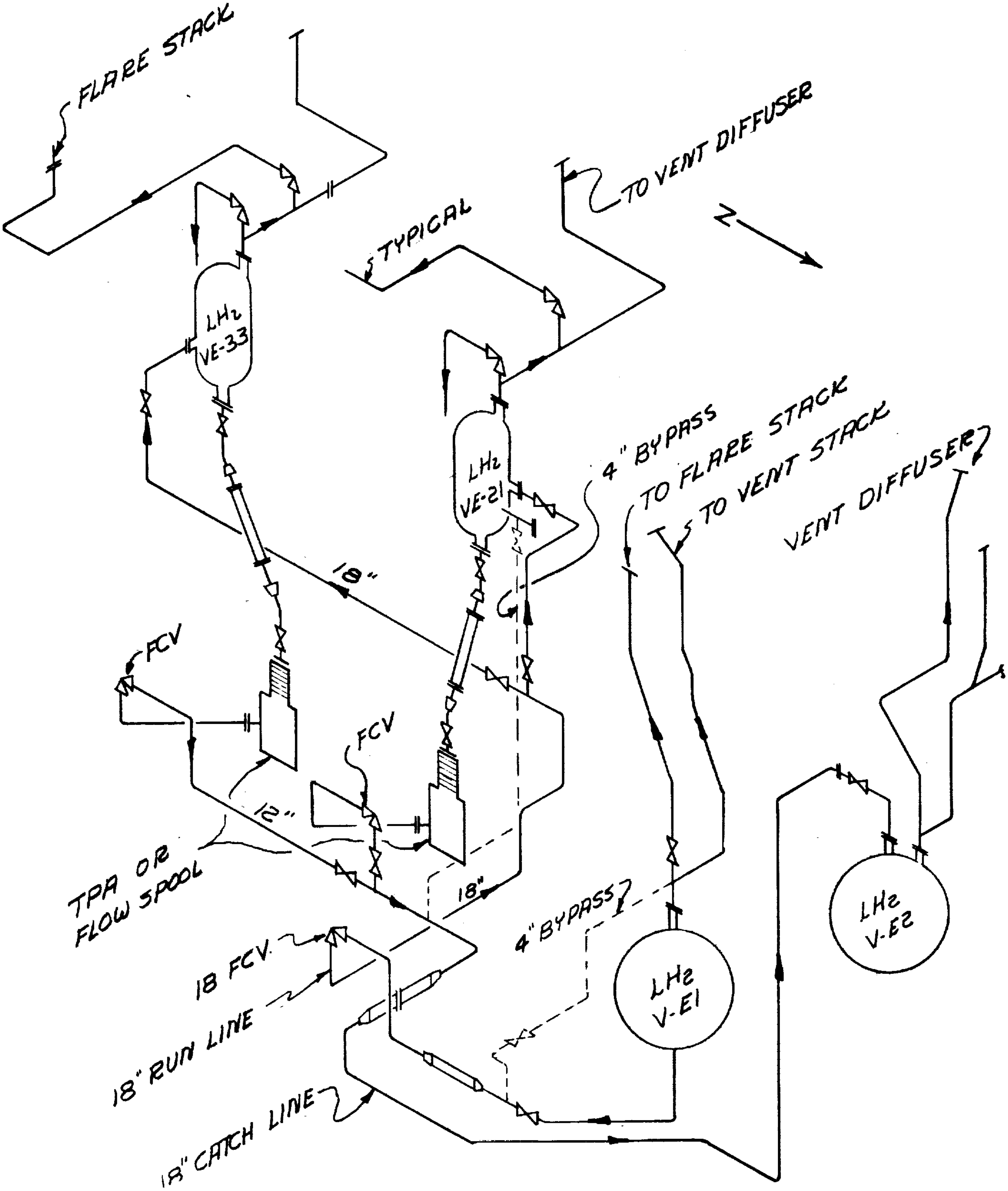
(7) Contract No. LAE 174828, Associated Piping and Engineering Company

LIQUID HYDROGEN SYSTEM



LIQUID OXYGEN SYSTEM





Test Stands E-1 and E-3 LH_2 System

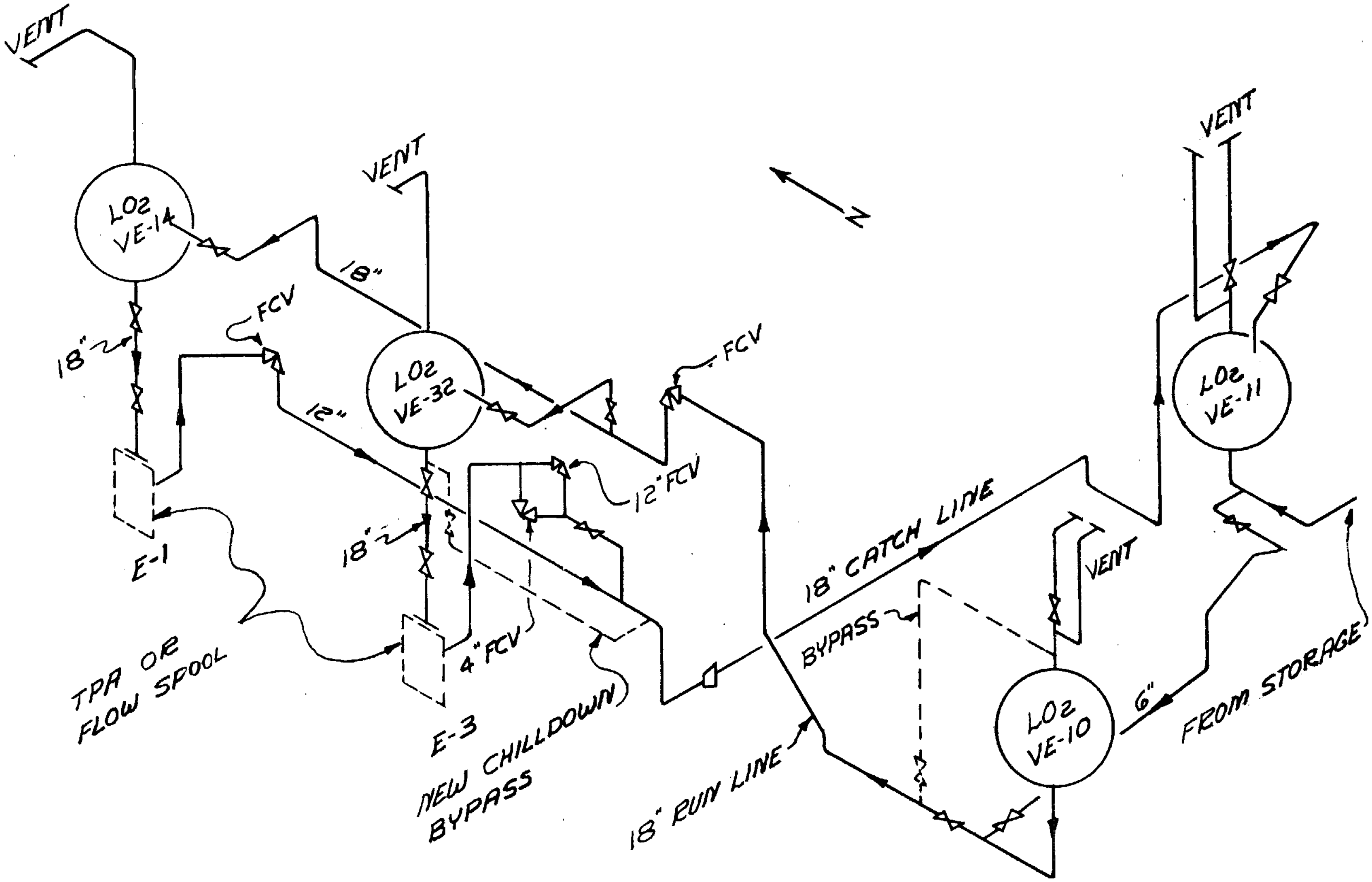


Figure 7

Test Stands E-1 and E-3 LO_2 System

consuming. The possibility of not solving all stress problems still existed. Furthermore, it would be difficult to determine, with any degree of assurance, when the liquid nitrogen/gaseous nitrogen was thoroughly evacuated (in preparation for introduction of liquid hydrogen).

Another method considered was that of shocking the ambient temperature piping system with a fast-moving front of liquid hydrogen or liquid oxygen. If this liquid front were moving at sufficient velocity, bowing could be prevented because of the absence of stratified, two-phase flow. This method had the obvious disadvantage of being difficult to control. This lack of control presented the risk of exposing the piping cross-sections to extreme temperature differentials, thereby creating possible overstresses in the piping.

A third method considered was that of applying a saturated liquid hydrogen or liquid oxygen vapor to the interior of the piping system by establishing atomization stations along the piping. This method proved expensive to design and build. It also created maintenance difficulties.

The use of sparging line, axially supported within the large-diameter, vacuum-insulated piping systems, was also considered. This line would allow simultaneous injection of liquid hydrogen or liquid oxygen in a uniform spray at many points within the system. The method had the disadvantages of unreasonable facility cost as well as maintenance difficulties. The internal, axial sparging line would also interrupt the propellant flow pattern and increase pressure drop throughout the system.

The fifth method considered was that of precooling the piping system to a predetermined cryogenic temperature with cold gaseous hydrogen for liquid hydrogen systems and gaseous oxygen for liquid oxygen systems. This method has the advantages of utilizing vessel boiloff which was otherwise vented and allowing closer control over the chilldown time-temperature characteristics. It was the method selected for the thermal and stress analysis discussed in this report. Cooldown studies completed by the Computer Sciences Division of Aerojet-General Von Karman Center were utilized to develop the procedures for cooldown of the liquid hydrogen and liquid oxygen systems.

B. THERMAL AND STRESS ANALYSIS OF CHILLDOWN USING GASEOUS HYDROGEN/GASEOUS OXYGEN BOILOFF

1. Assumptions and Procedures

A preliminary thermal analysis was made for directly flowing liquid hydrogen (at 60°R) through the liquid hydrogen piping system while the system is at ambient temperature (550°R). Results of this thermal analysis indicated that cold-shocking the system with liquid cryogenics at ambient temperature would induce excessively high thermal stresses. Therefore, a slower precooling period is required to reduce the system equilibrium temperature before cold-shocking the system.

The heavy 18-in. and 20-in. flanges are assumed to be the most critical parts in the system with respect to severe thermal stresses. All major fittings and equipment (e.g., flanges, valves, and flowmeters) in the system were considered as part of the pipe for analytical purposes. The mass of these components was converted to an equivalent pipe wall thickness corresponding to the appropriate inside pipe diameter and combined with the mass of the pipe at appropriate locations.

To perform the analysis, an arbitrary mass flow rate was used during the gaseous precooling period. The selection of this flow rate was based upon a nominal initial exit velocity of 50 fps at each hydrogen and oxygen line size. During the initial gaseous hydrogen or oxygen flow, the systems and media at the system exit are assumed to be at ambient temperature (550°R). As precooling proceeds, the temperature of the piping systems and gases at the system exit decreases. The gaseous hydrogen temperature at the inlet is assumed to be 50°R, and the gaseous oxygen temperature at the inlet is assumed to be 162°R.

Liquid hydrogen line heat leaks are not taken into account in the analysis because this line is vacuum-jacketed. This results from a preliminary calculation of the effect of heat leaks through the liquid hydrogen lines that indicates an increase in a steady-state gas exit temperature of less than 10°R. The liquid oxygen lines are uninsulated, and the heat leak (a temperature-dependent variable) between ambient air and the pipe outer surface is included.

When the desired temperature of the gas at an arbitrarily selected location (the exits of the piping systems were used in this analysis) is reached, the precooling period is terminated. Liquid hydrogen or liquid oxygen is then bled into the system upstream of the test hardware and flow is initiated at the respective rates required for hardware testing (2980 lb/sec for liquid oxygen and 600 lb/sec for liquid hydrogen). This is the so-called "liquid cold-shocking."

Thermal stresses induced during the gaseous precooling phase are assumed to be of relatively low magnitude, below the yield strength of the material. This can be verified by inspecting the continuous experimental time-temperature curves for all locations examined(8). The maximum rate of average metal temperature change is calculated to be approximately 9°R/min. No attempt was made to determine the temperature differential between the inner and outer surfaces of the piping systems during the period of gaseous prechill. It is possible that certain combinations of transient-temperature distribution and metal thickness could result in high transient thermal stress during the gas-cooled prechill. However, this situation could be easily avoided by lowering

---

(8) Aerojet-General Report No. 153:R102 (with Supplements 1, 2, and 3), <u>Thermal Stress Analysis and Cooldown Procedures for LH_2 and LO_2 Systems</u>, 2 January 1964

the prechill gaseous flow rate. When the system is cooled slowly enough with a gas, and when the systems reach their respective equilibrium temperature, there should be no thermal stress in the system. The effects of over-all shrinkage are accounted for by the built-in flexing capability of the system.

The thermal stress analysis discussed in this report is concentrated upon the period beginning with the introduction of the cryogen into the system. Because the worst thermal differential conditions are assumed to be in the heavy flanges, the stress analysis is based upon an initial average flange temperature equal to the average metal temperature at the piping exit at the completion of the gaseous prechill phase. The actual locations of the flanges are upstream of the exit points; therefore, the flanges are cooler than the pipe at the exit, thereby giving an additional margin of safety. A transient thermal analysis of the pipe flanges was made under the above conditions to determine temperature gradients occurring in the flanges. These temperature gradients were then used to determine stress levels. To simplify stress calculations, only primary stresses were determined. Numerous steps and computations were required before even these primary stresses could be resolved. If the maximum thermal stresses, transient or steady state, produced in the flanges were below the yield strength of the material, the selected precooled equilibrium termination temperature was considered to be safe. It is probable that two-phase flow (gas and liquid) exists at the piping system exit for a period of time during the initial introduction of liquid cryogen into the system. The maximum heat transfer coefficients between the liquid media and the pipe inner surfaces are used to give conservative (high) thermal gradients in the flanges. These maximum coefficients would occur during pure liquid flow, which would be an unlikely situation during the initial cold-shocking period because of the gas film that will form at the interface between the pipe and the liquid.

2. Description of Analytical Methods Used

a. Thermal Analysis

The Aerojet-General thermal analyzer described in Section III, C, was used for most of the thermal analysis discussed in this report. This thermal analyzer is an analog device with passive electrical components for direct simulation of thermal and diffusional phenomena. The hardware to be analyzed (in this study, the flanges of the piping systems) is divided into convenient nodes (shells) and a temperature-time history is obtained for each node. This information was then used in conjunction with the well-known and commonly-used Dittus-Boelter Correlation to evaluate the heat transfer coefficients between the pipe inner wall and the propellant in either the liquid or gaseous state. The Dittus-Boelter Correlation is:

$$\frac{hD}{K} = 0.024\left(\frac{GD}{\mu}\right)^{0.8}\left(\frac{C_p\mu}{K}\right)^{0.4}$$

Where:

h = Heat transfer Coefficient, BTU/hr-ft^2-°F

D = Pipe diameter, ft.

K = Thermal conductivity, BTU/hr-ft-°F

G = Mass flow rate, lb/hr-ft^2

μ = Viscosity, lb/hr-ft.

Cp = Specific heat, BTU/lb-°F

This correlation applies where flow is turbulent, as is the case with the systems under study.

A question exists as to whether this correlation prevails for the cryogens which are used in this analysis. Numerous projects are now being conducted in various companies to evaluate heat transfer coefficients for cryogenic fluids under specific conditions.

Until these results are collected and published, the Dittus-Boelter correlation or something very similar to it will remain the best compromise for most situations. However, high accuracy computation is neither required nor the intent of this analysis. Furthermore, as it is shown in the detailed discussion in the following sections, the internal conductance of the pipe material in this case is considerably less than the boundary conductance. As a result, the boundary heat transfer coefficient has relatively small affect upon the over-all problem.

b. Stress Analysis

To facilitate calculation of internal stresses in the flanges induced by temperature differential throughout the flange body, the flanges were divided into concentric rings corresponding to the node points used in the thermal analysis. The temperature within each ring is assumed to be uniform and equal to the temperature obtained for the nodal point of the ring from the thermal analysis at any particular time. This temperature varies from ring to ring at any particular time and also varies within a particular ring with the passage of time. It will also vary within a particular ring with the passage of time.

To obtain internal loads upon each ring for one particular instant of time, compatibility equations are solved for the rings. This is accomplished by applying moments and shear forces to the boundaries of the rings to make the radial deformations consistent.(9) Solving these

---

(9) ibid

equations yields the moments and shear forces upon the rings. When all loads for each ring are known, stresses in the rings can be solved by applying standard stress analysis equations.

This procedure is repeated for as many time instances as required to establish a stress-time curve for each individual ring. An envelope of maximum stress versus time can be determined. This maximum stress versus time relationship applies when the system is exposed to a liquid cryogen at one particular precooling termination temperature. Additional calculations are made for different degrees of precooling until a sufficiently low maximum stress is obtained. This gives the minimum precooling termination temperature that is required for the system.

3. Results of Analysis

a. Liquid Hydrogen Discharge Line Thermal Analyses

The liquid hydrogen discharge line was divided into eleven axial sections. The masses of line components were combined to represent equivalent pipe thicknesses at appropriate locations; the inner diameters of the pipes were kept at the nominal values listed in the specifications. The nodal locations in the pipe wall and the gas stream as well as the electrical analog used in the simulation are shown in Figure No. 8. The 20-in., 900 lb flange is located at Node No. 7.

Gaseous hydrogen flow rates were determined for an exit velocity of 50 ft/sec. During the early cooldown period, the exiting gas will be at ambient temperature. The mass flow rates were calculated using gaseous hydrogen property values at 550°R. As exit temperature decreases, the velocity will also decrease. Mass flow rates were calculated for normally directed flow (TPA to VE-2) and reverse flow (VE-2 to TPA); see Figure No. 6. Calculations of Reynolds numbers for the discharge lines indicated turbulent flow. Additional turbulence induced by such changes as the flow area at orifices and flowmeters was not considered. Therefore, the calculated heat transfer coefficients will be lower than actual values, resulting in conservative cooldown times. The heat transfer coefficients from the gas to the pipe wall for the gaseous precooling period were determined from the Dittus-Boelter correlation previously referenced (Section III, B, 2, a). Property values for an average temperature of 300°R were used for the entire cooling phase and the following heat transfer coefficients were determined for gaseous hydrogen flow:

	h, Btu/hr-ft^2-°F	
Inner Diameter, In.	1500 lb/Hr.	500 lb/hr.
17.2	8.0	3.3
15.8	13.9	5.6
10.3	28.7	11.9

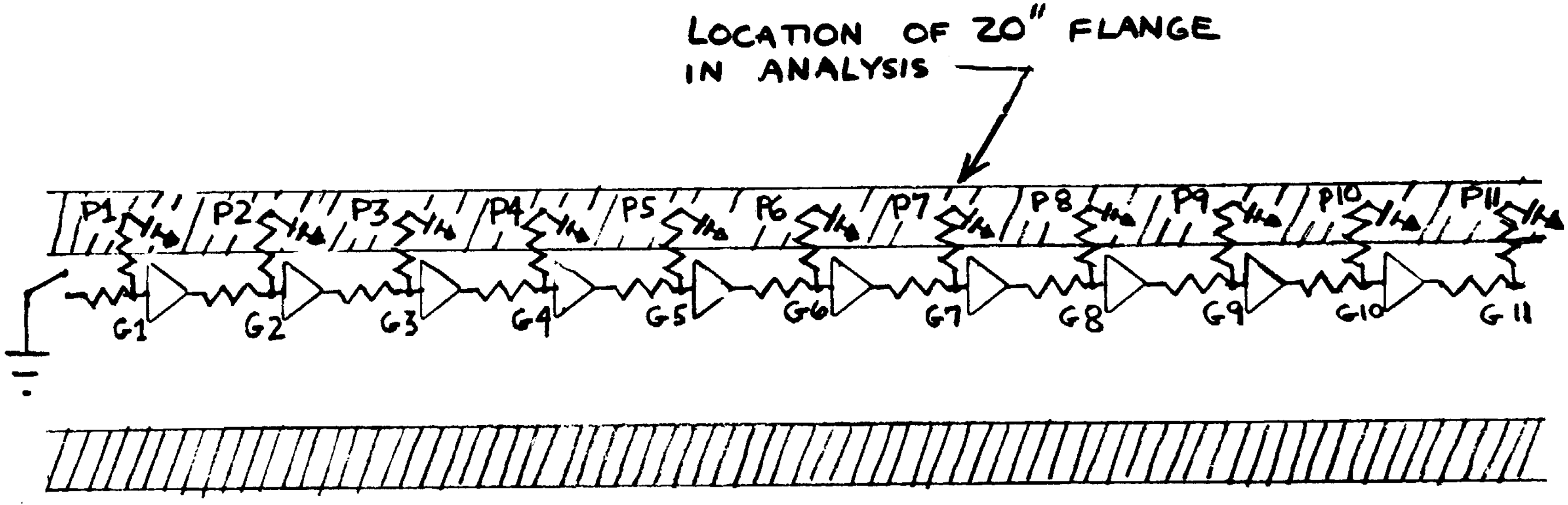


Figure 8

Node Locations and Electrical Model for LH_2 Discharge Line

The results of computer runs have been compiled(10) for the gaseous hydrogen precooling, showing average pipe wall and gas stream time temperature curves at each of the eleven axial sections for each flow rate. The results of these computer runs relating to nodal point temperatures for flow at 500 lb/hr from VE-2 to the turbopump assembly and for 1500 lb/hr from the turbopump assembly to VE-2 are presented in Tables I and II. Point G-11 gives the gas temperature at the exit of the system and this is then used as the boundary condition for the analysis of the flange. Evaluation of the results indicates that the normal liquid hydrogen flow operation (cold-shocking) can start when the exit gas temperature reaches 200°R. A summary of cooldown information is presented in Table III.

b. Liquid Oxygen Discharge Line Thermal Analyses

The analysis procedure for this system was the same as that used for the liquid hydrogen discharge line. The eight node locations and the electrical analog used in the simulation are shown in Figure No. 9. Heat transfer coefficients for gaseous oxygen obtained from the Dittus-Boelter Relationship are:

Inner Diameter, In.	h, BTU/hr-ft^2-°F
11.06	5.2
17.50	2.3

In this system, which is uninsulated, the heat leak has a significant effect upon the steady-state temperatures. The boundary conductance between the ambient air and the outer pipe surface will gradually decrease between the time that cooldown is initiated and the time that the operational flow reaches steady-state. This is because of the condensation and freezing of air and the water vapor present in the air on the exposed pipe.

Typical values for these boundary conductances used(11) were:

(1) Natural convection (560 to 460°R), 2 BTU/hr-ft^2-°F.

(2) Condensation and Icing (460 to 360°R), 1.2 BTU/hr-ft^2-°F

(3) Icing (360°R to 160°R), 0.9 BTU/hr-ft^2-°F

These values are conservative, thereby resulting in a high heat leak. The above values were switched into the electrical model (at the appropriate times) as functions of temperature.

---

(10) ibid

(11) ibid

TABLE I

TIME-TEMPERATURE DATA FOR LH_2 DISCHARGE LINE THERMAL ANALYSIS

(GH_2 AT 500 lb/hr FROM VE-2 TO TPA)

TEMPERATURE (°R)

POINTS	TIME (HR)											
	START	1	2	3	4	5	6	7	8	9	10	11
G-1	175	160	130	100	80	70	60	55	50	50	50	50
P-1	550	400	290	220	160	130	100	80	75	65	60	50
G-2	290	210	150	120	90	80	70	60	55	50	50	50
P-2	550	330	210	150	110	90	70	60	55	50	50	50
G-3	360	270	190	140	100	90	70	60	55	50	50	50
P-3	550	370	250	180	130	100	80	70	60	55	50	50
G-4	450	310	220	170	130	100	80	70	60	55	50	50
P-4	550	420	300	210	150	115	90	75	65	60	50	50
G-5	480	360	260	190	150	110	90	75	70	60	50	50
P-5	550	450	330	250	180	135	110	90	70	65	55	50
G-6	510	400	290	230	165	140	100	80	70	60	50	50
P-6	550	465	370	270	200	150	115	95	80	70	60	50
G-7	530	430	330	250	180	135	110	85	70	60	50	50
P-7	550	490	400	310	235	170	140	100	80	70	60	50
G-8	540	450	365	290	230	170	135	110	90	75	60	50
P-8	550	520	470	410	360	300	250	200	160	130	110	90
G-9	550	465	380	310	240	185	150	120	100	80	65	55
P-9	550	520	470	400	310	250	200	150	120	100	80	70
G-10	550	490	420	350	280	220	170	135	110	90	75	60
P-10	550	520	460	380	320	250	200	150	130	100	80	65
G-11	550	520	460	400	330	270	220	170	140	110	90	70
P-11	550	540	500	450	370	320	250	210	170	140	110	90

TABLE II

TIME-TEMPERATURE ANALYSIS OF LH_2 DISCHARGE LINE

FLOWING 1500 LB/HR GH_2 FROM TPA TO VE-2

Temperature (°R)

	Time (Hrs)					
Points	Start	1	2	3	4	5
G-2	400	140	70	50	50	50
P-2	550	200	90	60	50	50
G-3	420	150	75	60	50	50
P-3	550	270	120	70	60	50
G-4	450	180	90	70	50	50
P-4	550	375	220	130	80	60
G-5	470	220	110	80	60	50
P-5	550	280	130	80	70	60
G-6	500	250	130	75	60	50
P-6	550	310	150	85	70	60
G-7	510	270	130	75	60	50
P-7	550	330	170	90	70	60
G-8	520	290	150	90	70	60
P-8	550	360	180	100	75	60
G-9	530	320	160	90	65	60
P-9	550	380	200	110	70	60
G-10	540	330	170	90	65	60
P-10	550	400	210	110	70	60
G-11	550	380	230	130	80	60
P-11	550	475	330	220	125	80

TABLE III

COOLDOWN INFORMATION SUMMARY

		TPA to VE-2	VE-2 to TPA
1.	Inlet gas temperatures, °R	50	50
2.	Gas flow rate, lb/hr	1500	500
3.	Time for exit gas to reach 200°R, hr	2.2	6.4
4.	Total weight of GH_2 required, lb	3300	3200

The results of this analysis are shown in Table IV. A difference of 85°R exists between the steady-state exit temperatures in the two flow directions. A stress analysis similar to that conducted for the liquid hydrogen system 20-in. flange (Section III,B,3,c) shows that the 360°R temperature is sufficiently low to prevent overstressing of the flange.(12) The thermal properties and dimensions of the flange are such that a steady-state distribution will occur approximately 1.5 hours after a sink temperature is applied to it. That is, 1.5 hours after Tg (exit gas temperature) reaches a steady-state value, the flange will be at equilibrium.

This differs from the vacuum-jacketed liquid hydrogen line chilldown characteristics because the liquid oxygen line is uninsulated.

c. Liquid Hydrogen System 20-in. Flange Thermal and Stress Analysis

The 20-in., 900-lb flange located between the turbopump assembly and VE-2 was analyzed to determine the minimum amount of precooling required to avoid producing permanent set in the piping system. The time-dependent pre-chill average metal temperature at the piping exit is taken as the average flange temperature at the moment of cold shocking for the flange thermal/stress analysis. Separate thermal analyses are made of the

---

(12) ibid, (Supplement 1)

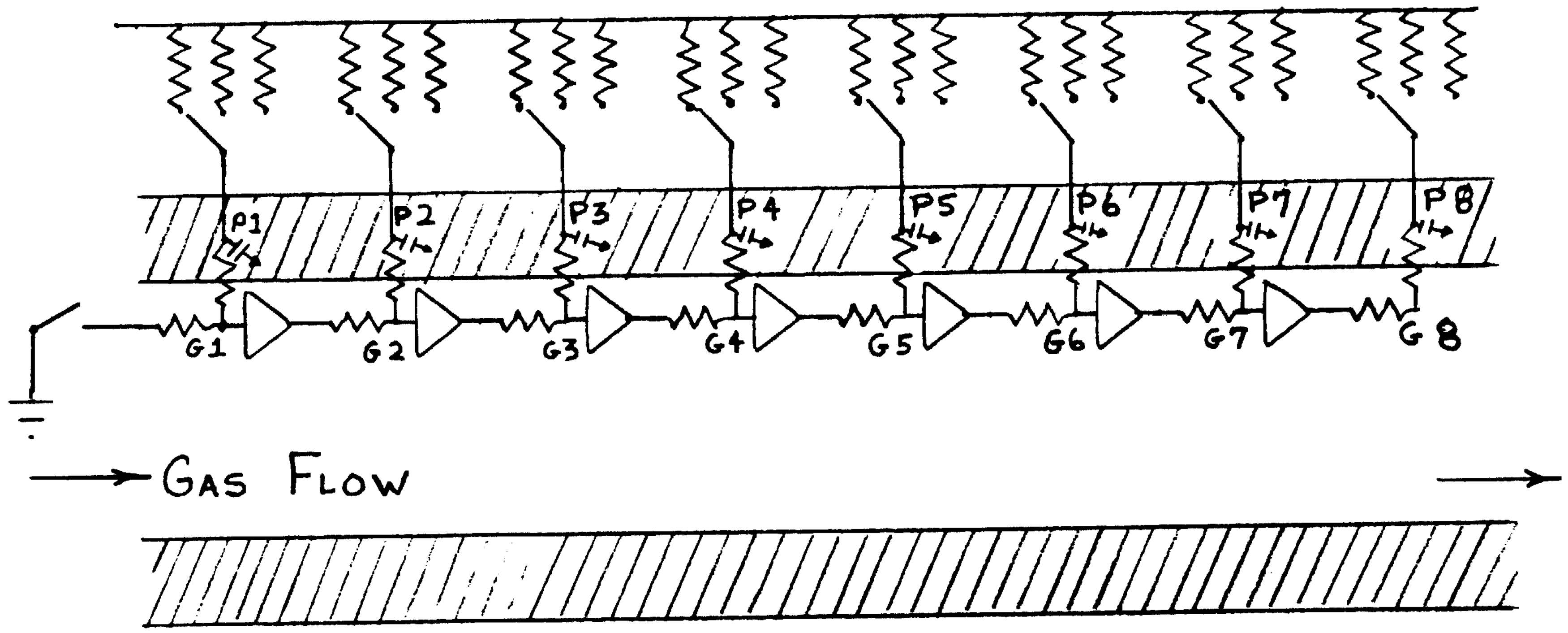


Figure 9

Node Locations and Electrical Model for LO_2 Discharge Line

TABLE IV

LIQUID OXYGEN DISCHARGE LINE THERMAL ANALYSIS RESULTS

		TPA to VE-11	VE-11 to TPA
1.	Inlet gas temperature, °R	162	162
2.	Gas flow, lb/hr	21,000	6,900
3.	Steady-state exit gas temperature: °R	275	360
4.	Time for exit gas to reach steady-state, hr.	1.4	4
5.	Total weight of GO_2 required, lb	29,400	27,600

flange, assuming a constant gas flow rate and successively larger pre-chill periods prior to cold shocking. This transient thermal analysis is directed towards determining the temperature gradients within the flange, both during and after cold shocking with the cryogen. At some point during the successive analyses, the maximum thermal gradient (i.e., stress) remains within the established safe limits. It is at this point in time that the system is considered adequately pre-chilled as measured by the exit gas temperature. The electrical model for the flange thermal analysis is shown in Figure No. 10 and is described in Section III, C of this report. The maximum heat transfer coefficient of 540 BTU/hr-ft^2-°F for liquid flow was used to provide conservative maximum temperature gradients in the flange. Table V shows the results from one of the computer runs relating to the flange nodal point temperatures. In this example, cold shocking with the liquid cryogen occurs with an exit gas temperature of 250°R. For the stress analysis, the flange was divided into eleven rings (Figure No. 11) corresponding to the eleven node points used in the thermal analysis, and each ring was assumed to be at a uniform temperature. The temperature gradient resulting from the thermal analysis was then incorporated directly into the stress program. The resulting radial deformation was made consistent by applying moments and shears at each ring as shown in Figure No. 12. The sign convention for the moments and shears is shown in Figure No. 13. Additional assumptions made were that all cross-sections remain plane and undeformed and that all dilation effects are neglected.

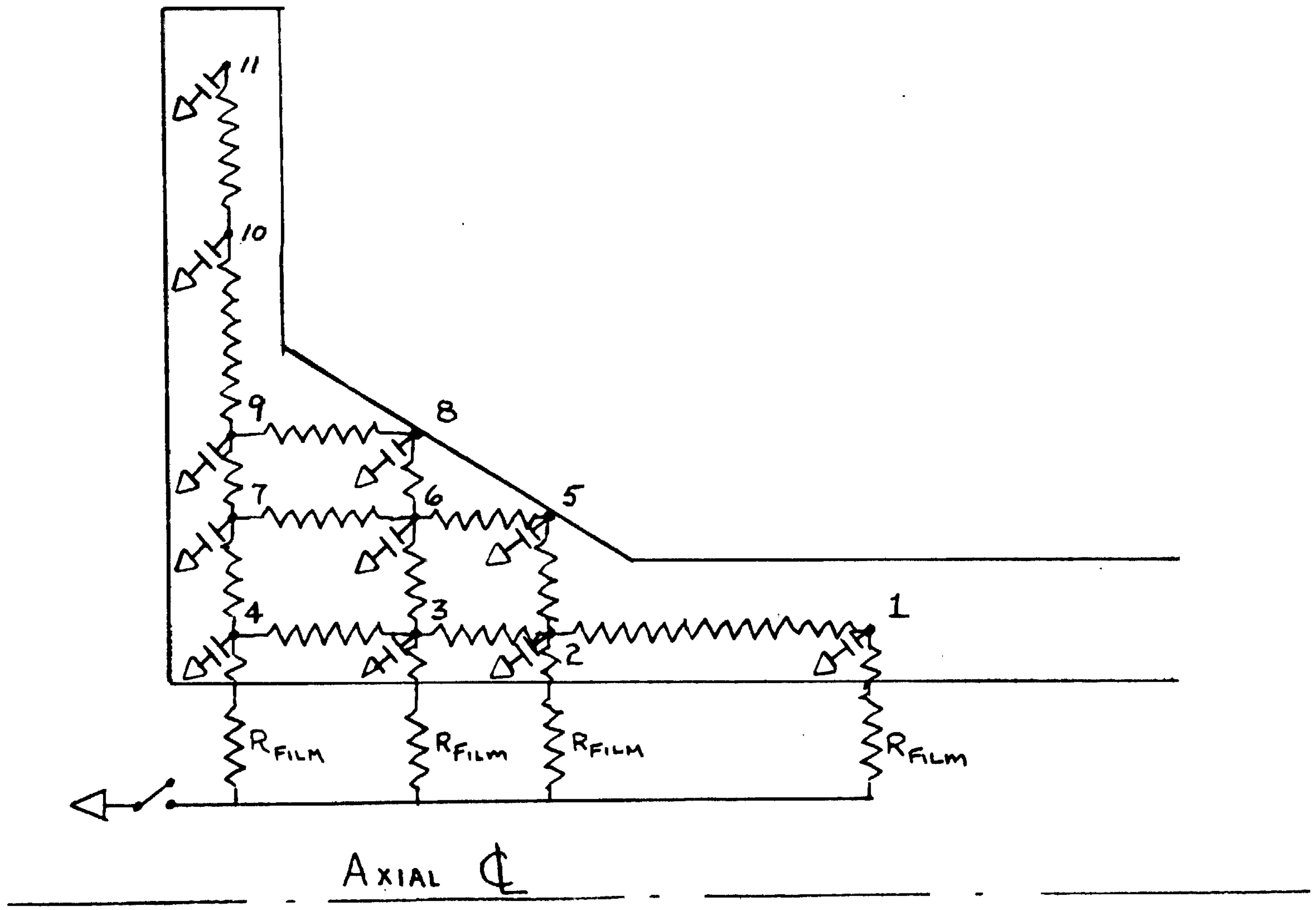


Figure 10

Nodal Locations and Electrical Model of Flange

NODES	TEMPERATURE (°R)												
	TIME (HR)												
	START	1	2	3	4	5	6	7	8	9	10	11	12
1	550	530	490	440	380	320	55	50	50	50	50	50	50
2	550	535	500	450	390	330	60	60	55	55	55	55	55
3	550	535	500	450	395	335	75	65	60	55	50	50	50
4	550	535	505	455	395	340	95	70	60	55	50	50	50
5	550	535	500	445	385	330	65	60	55	55	55	55	55
6	550	535	505	460	405	350	100	75	60	55	50	50	50
7	550	540	510	470	415	360	150	95	70	55	50	50	50
8	550	535	510	465	415	350	115	75	70	55	50	50	50
9	550	545	520	480	435	380	200	125	85	70	60	55	55
10	550	540	525	490	450	400	265	150	100	75	65	55	55
11	550	545	535	500	460	410	300	175	105	80	65	55	50
FLANGE COLD-SHOCKED AT 5.35 HRS. WHEN EXIT GAS TEMP. = 250°R													

TABLE V

Time-Temperature Data for LH_2 Discharge Line 20-in. Flange Thermal Analysis (Cold-Shocked When Exit Gas Temperature = 250°R)

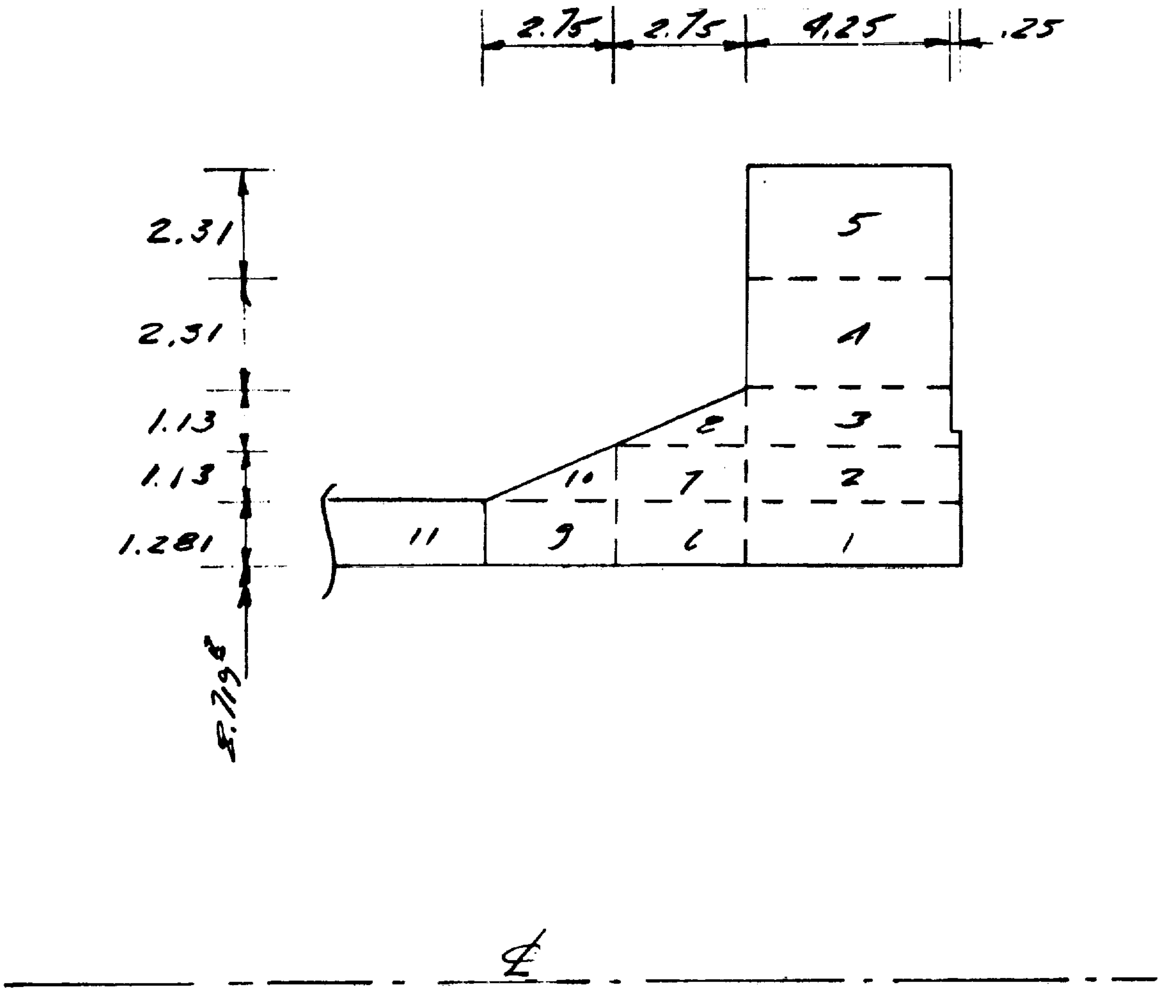


Figure 11

20-in., 900-lb Flange Geometry

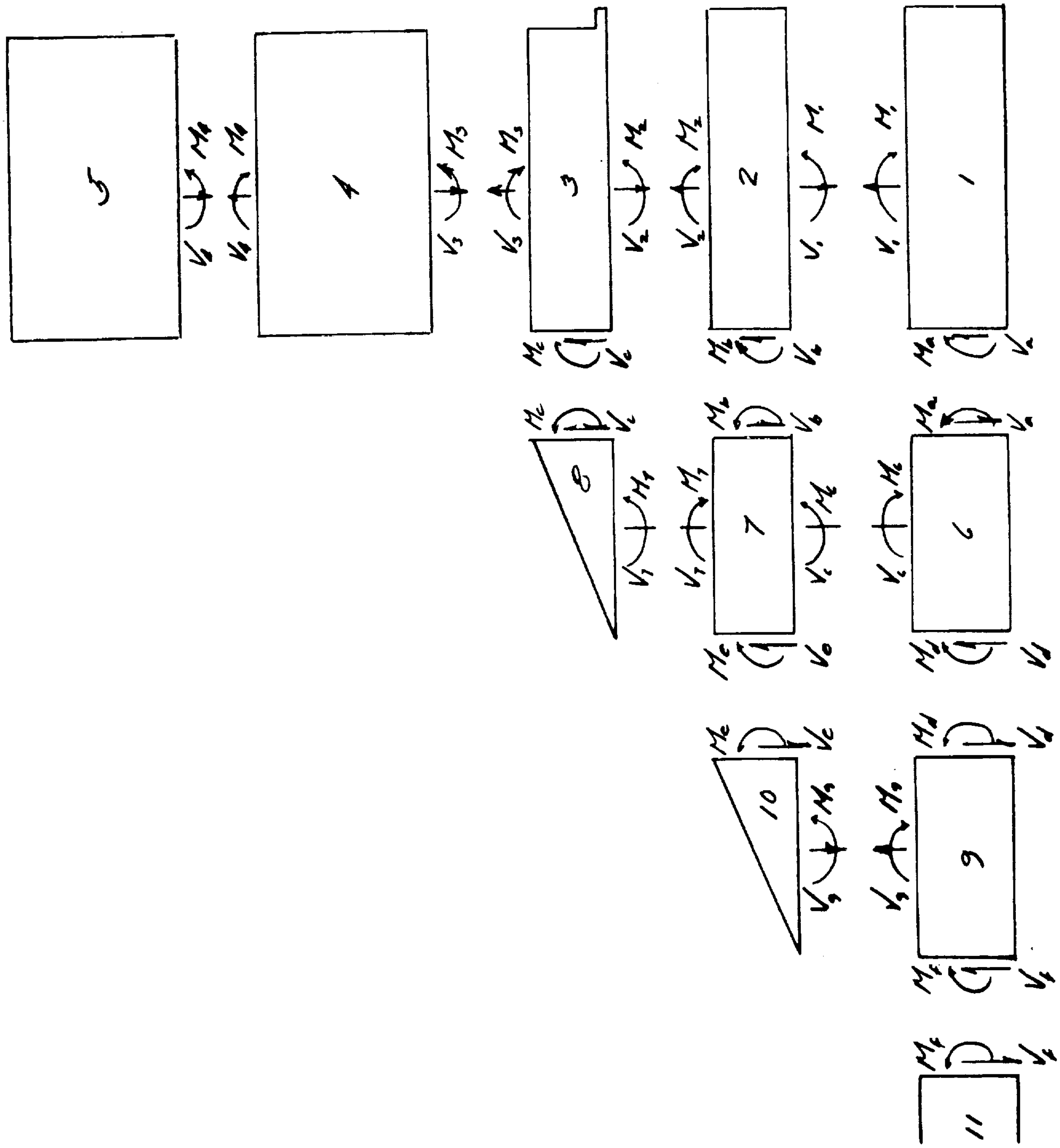


Figure 12

Flange Load Identification Diagram

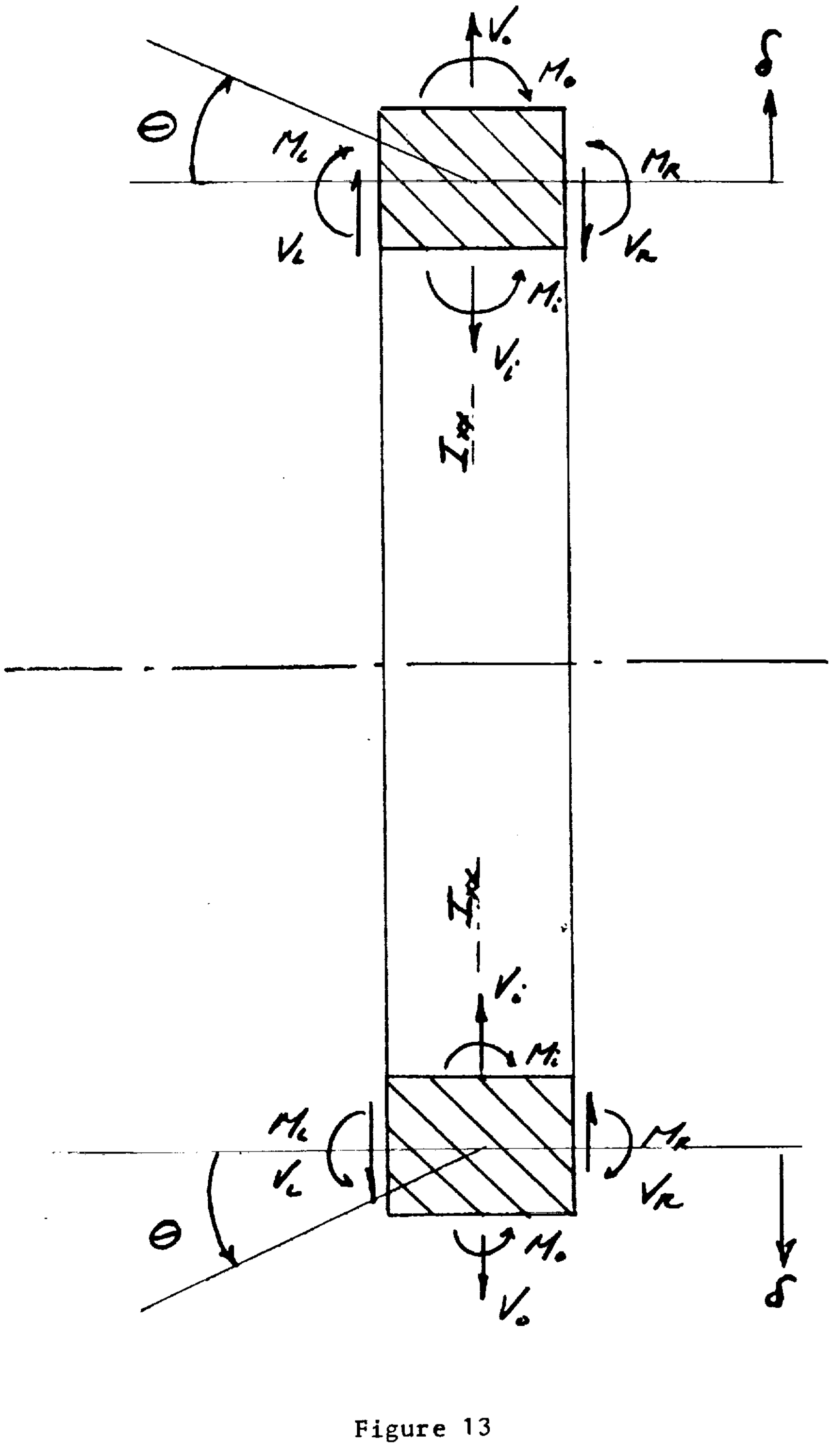


Figure 13

Positive Load Convention

Equations used in the stress analysis are as follows (see Section IV for nomenclature):

DEFORMATION EQUATIONS

(1) Ring

$$\delta L = \left[-V_R + V_L + V_o - V_i\right] \frac{R^2}{AE} + (a-\bar{y})\ \theta - (\Delta L/Lo - \Delta 1/1_o)R$$

$$\delta R = \left[-V_R + V_L + V_o - V_i\right] \frac{R^2}{AE} - \bar{y}\ \theta(\Delta L/L_o - \Delta 1/1_o)R$$

$$\delta i = \delta_o = \left[-V_R + V_L + V_o - V_i\right] \frac{R^2}{AE} - (\Delta L/L_o - \Delta 1/1_o)R$$

$$\theta = \left[-M_R + M_L + M_o - M_i + V_R\ (\bar{y}) + V_L\ (a-\bar{y}) + (V_o - V_i)(\frac{a}{2} - \bar{y})\right] \frac{R^2}{EI_{XX}}$$

(2) Pipe

$$\delta R = \frac{V}{2D\lambda^3} + \frac{M}{2D\lambda^2} - (\Delta L/L_o - \Delta 1/1_o)\ R$$

$$\theta R = + \frac{V}{2D\lambda^2} - \frac{M}{\lambda D}$$

(3) Compatibility

$$\delta d - \delta a = \theta_a$$

$$\delta e - \delta b = \theta_a$$

$$\delta f - \delta d = \theta_a$$

STRESS EQUATIONS

(1) Ring

$$S_h = \frac{MR\bar{y}}{I_{xx}} + \frac{VR}{A}$$

(2) Pipe Hoop Stress

$$S_h = \frac{2\lambda R}{t}\ e^{-\lambda x} \left[(\lambda M - V)\ \cos \lambda x - \lambda\ M \sin \lambda\ x\right]$$

Set derivative equal to zero and solve for x to obtain points of maximum hoop stress.

$$\frac{ds}{dx} = \left[- (\lambda M-V) - \lambda M\right] \cos \lambda x + \left[\lambda M - (\lambda M-V)\right] \sin \lambda x = 0$$

$$\left[\lambda M + (\lambda M-V)\right] \cos \lambda x = \left[\lambda M - (\lambda M-V)\right] \sin \lambda x$$

$$\tan \lambda x = \frac{\lambda M + (\lambda M-V)}{\lambda M - (\lambda M-V)}$$

$$\lambda x = \tan^{-1} \left\{\frac{2\lambda M-V}{V}\right\}$$

(3) Pipe Longitudinal Stress

$$S_1 = \frac{6}{t^2} \left[\frac{V}{\lambda} e^{-\lambda x} \sin \lambda x - Me^{-\lambda x} (\cos \lambda x + \sin \lambda x)\right]$$

Set derivative equal to zero and solve for x to obtain point of maximum longitudinal stress.

$$\frac{ds}{dx} = \frac{6}{\lambda t^2} \left\{- \lambda e^{-\lambda x} \left[(V- \lambda M) \sin \lambda x- \lambda M \cos \lambda x\right] + \lambda e^{-\lambda x} \left[(V - \lambda M) \cos \lambda x + \lambda M \sin \lambda x\right]\right\}$$

$$V \cos \lambda x + (-V +2 \lambda M) \sin \lambda x = 0$$

$$\lambda x = \tan^{-1} \left\{\frac{V}{V-2 \lambda M}\right\}$$

The variation of maximum stress with respect to time for each of the three precooling temperatures of 200°R, 250°R and 350°R is shown in Figure No. 14. Precooling to 250°R or lower to maintain stress levels below 30,000 psi is indicated in Figure No. 15. Because the liquid oxygen line is smaller and thinner than the liquid hydrogen line, the same temperature gradients are expected to produce lower stresses.

C. ANALOG COMPUTER STUDY

The Aerojet-General Corporation Thermal Analyzer was used for the thermal analysis discussed in this report.(13) This analyzer is a passive-element direct analog type computer, which solves problems of dissimilar physical systems by relating their direct analogs upon the basis of two-term

---

(13) Aerojet-General Report No. 1654, op.cit.

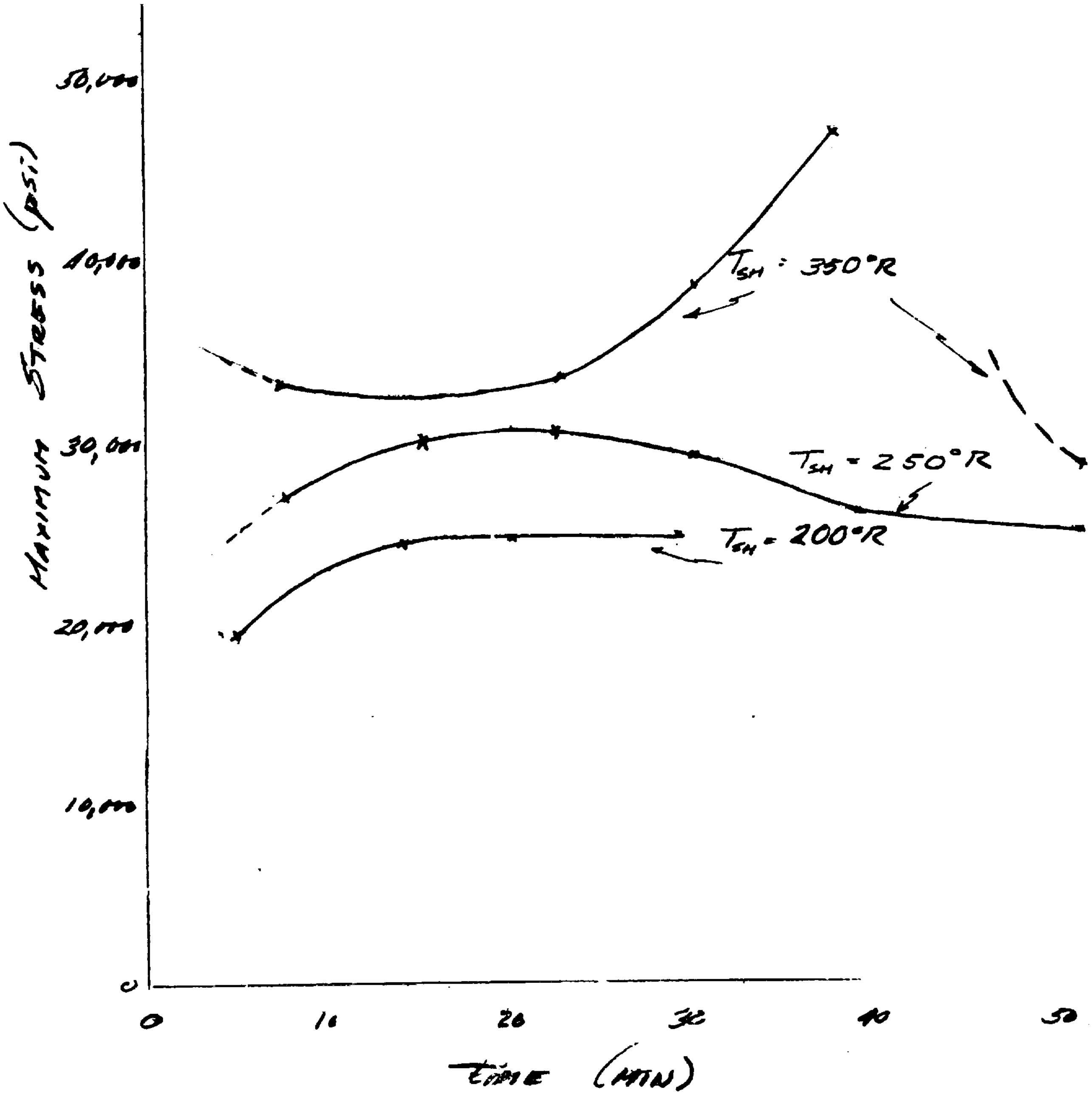


Figure 14

Maximum Stress vs Time for Flange

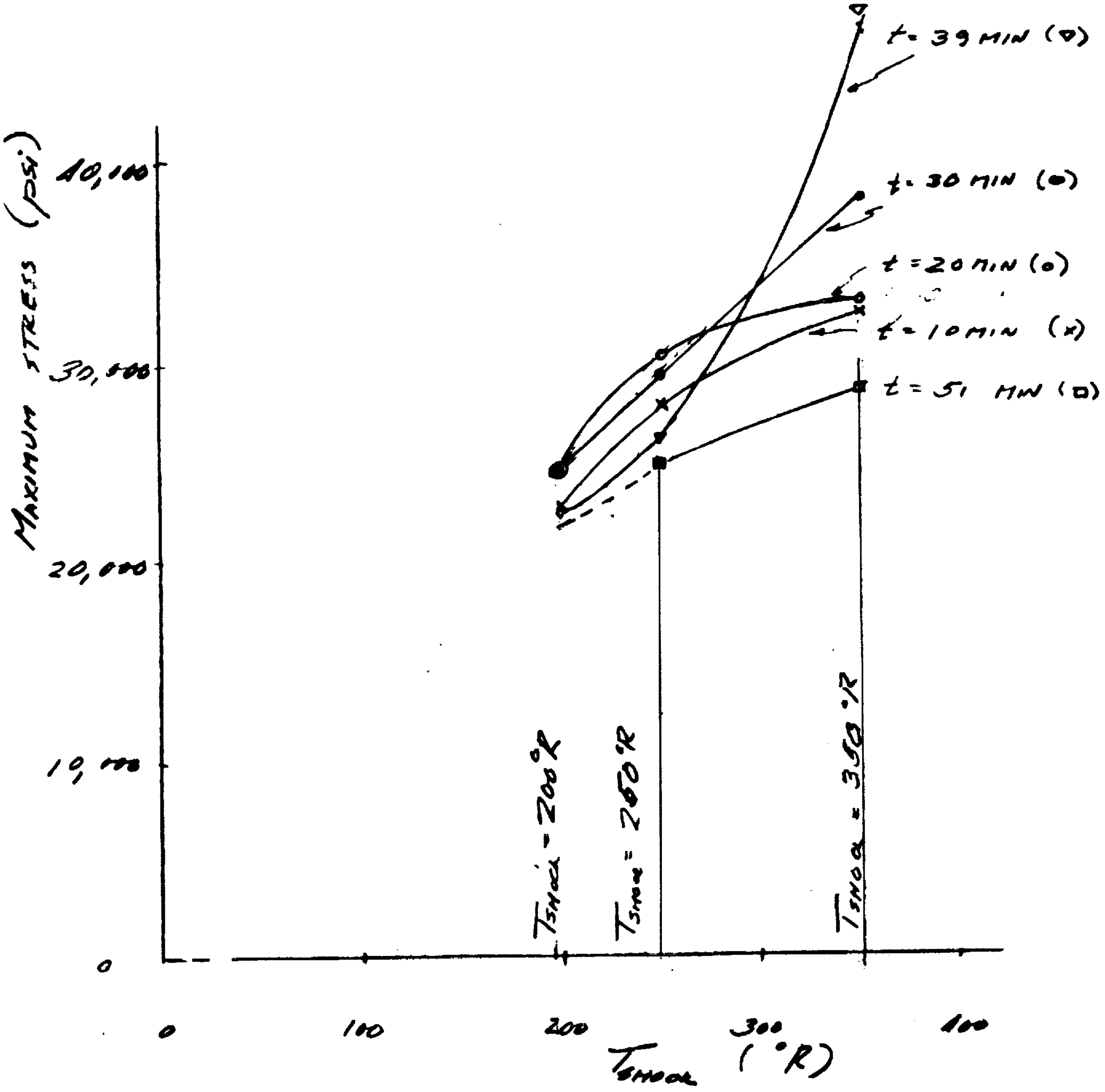


Figure 15

Maximum Stress vs T-Shock for Flange

algebraic equations. Many of the problems solved with the computer involve heat flow and other thermal phenomena; therefore, its name, "Thermal Analyzer." In the process of problem solution, the thermal system is first considered as made of many nodes or lumps as an approximation of the real continuous system. The thermal properties of heat capacitance and conduction of the nodes represent the corresponding value of that portion of the continuous system lumped into the node. This lumping permits the use of lumped parameter mathematical expressions in place of the partial differential equations required for the continuous system.

The lumped parameter equations of a thermal system have a one-to-one analogy in the equations of an electrical network made of resistors and capacitors. Voltages are the direct analog of temperatures, currents are heat flows, capacitors are used for heat capacities, and resistance is the reciprocal of heat conductance. The thermal analyzer provides up to 800 nodes that can be connected with a wide variety of resistors and capacitors. Voltage sources can be connected to any node by means of a convenient plug-in board. Voltages at the variable nodes can be read on several convenient reading meters and recorders.

The usual procedure is to scale the problem so that reasonable voltages and impedances are useable, make the required connections, and finally, apply the boundary voltages representing the fixed or controlled temperatures. The resulting transient in voltages represents transient temperatures at the nodes, and the difference between adjacent node voltages divided by the connecting resistor represents the heat flow between the two nodes. Initial temperatures are obtained by introducing an initial charge on the capacitors. If the thermal system has time-varying parameters, this can be simulated by switching the parameters from one value to another during the run. Nonlinearities can be treated in a similar fashion.

Application of passive electrical networks in thermal analysis is based upon the diffusion equation being as follows:

$$\nabla^2 \phi = K \frac{\partial \phi}{\partial T}$$

where: ∇^2 = Laplacian operator $\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \right)$

ϕ = Potential function (voltage or temperature)

T = Time

K = System parameter (time constant or inverse of thermal diffusivity)

This diffusion equation describes both thermal and electrical systems. Thus, the electrical solution of this equation (using appropriate initial and boundary conditions) can be transformed into the solution of a thermal system by means of the proper scalar quantities.

Finite-difference techniques are used to reduce the left side of the diffusion equation to a form that can be utilized to synthesize networks for discrete fields. The right side of the equation remains a continuous-time derivative.

The network illustrated in Figure No. 10 is typical of the type used in the flange analysis. The resistors are electrical equivalents of the thermal resistance between adjacent nodal points. The capacitors are analogous to the heat storage capability or the thermal capacitance of the discrete element.

Since this study was performed, the use of high-speed digital computers for thermal analysis problems has been developed. Several programs now exit that can perform the same functions as the thermal analyzer. The equations solved are also the lumped parameter equations as used in the thermal analyzer; however, the convenience, speed, tabulated results, and flexibility inherent with the digital computer has resulted in entirely using the digital computer for solving heat transfer problems. Nonlinearities as well as time-varying parameters and boundaries can be accommodated. Subroutines that calculate the conduction and heat capacity of the nodes also are available; thus eliminating a tedious detail. Also, a number of runs can be stacked and this provides a parameter study with one pass through the computer. Any additional study in this or similar programs should probably be done using the digital computer.

D. OPERATIONAL EXPERIENCE

A number of tests have been conducted at Test Stands E-1 and 3 using both the large liquid oxygen and liquid hydrogen propellant systems. Initial flow tests, using liquid nitrogen rather than liquid oxygen, were started in December 1964 at the oxidizer turbopump position. A flow spool, (Figure No. 7) was installed in place of the pump to complete the flow circuit. After a series of facility flow tests, the pump was installed and tests were initiated using gaseous nitrogen to drive the turbopump. Subsequent tests were conducted with a pressure-fed liquid hydrogen/liquid oxygen gas generator driving the turbopump. All tests were conducted with liquid nitrogen as the pumped fluid; liquid oxygen was never introduced into the large liquid oxygen propellant lines. This was done to minimize the hazards associated with such considerations as possible pump impeller rubbing during the initial tests. Budgetary problems forced cancellation of subsequent tests with liquid oxygen.

Initial facility flow tests at the fuel turbopump position were begun in April 1964, with liquid hydrogen as the pumped fluid. Fuel turbopump tests were subsequently conducted with both the gaseous nitrogen and the gas generator drive. All tests (both fuel and oxidizer systems) were conducted using only the on-stand vessels for propellant supply. The off-stand run systems were not used to increase test durations because of the M-1 Program termination.

Extensive measurements of facility propellant system temperatures and pressures were made during the chilldown and testing phases. However, no measurements of gas flow rates or chilldown liquid flow rates were made. Photographic coverage of line movements during system chilldown and initial testing provided considerable data regarding structural characteristics. The use of mechanical scribers attached to the line proved ineffective because of the nature of the line displacements during chilldown.

1. Liquid Oxygen Propellant System Performance

a. Initial Liquid Oxygen System Chilldown with Facility Flow Spool in Place

A 4-in. line, bypassing the pump, was installed to facilitate system chilldown as recommended for E-Zone cryogenic piping systems.(14) This line is shown in Figure No. 16. Initial system chilldown was attempted using the line and the recommended procedures.(15) Minor modifications to these procedures were required because certain facility items had not been activated at the time of initial chilldown.

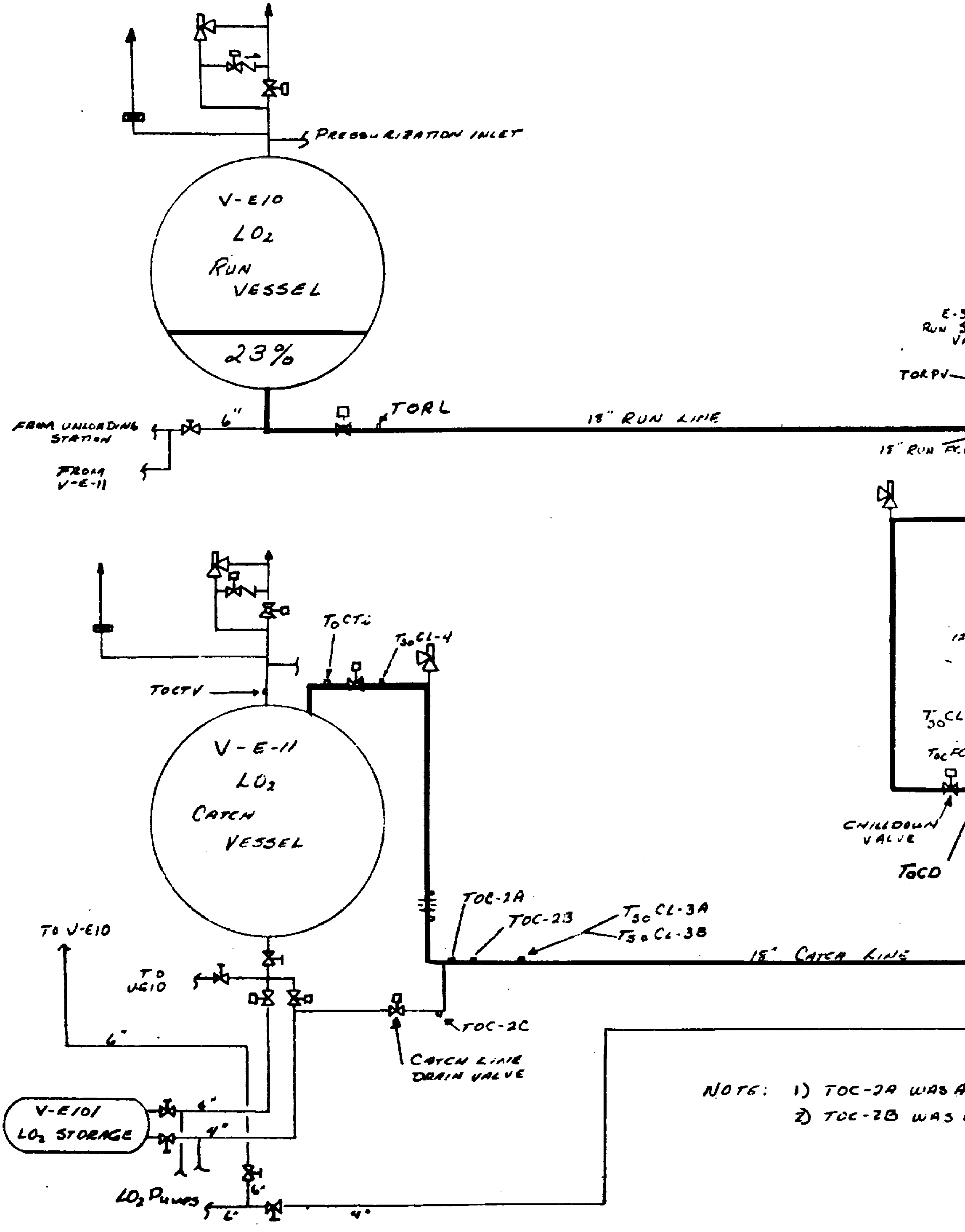
The first chilldown of the liquid oxygen system with liquid nitrogen was conducted on 4 December 1964. This chilldown was initiated by pressurizing the 30% full off-stand catch vessel (VE-11) to 28 psig (see Figure No. 16). After stabilizing the gas temperature (approximately six hours), the chilled gaseous nitrogen was vented through the 18-in. catch line (in the counter direction to normal flow), the chilldown bypass system, and out the on-stand tank vent. System temperatures, both before and after this flow, were as follows:

	Before Chilling	Elapsed Time	After Chilling
18-in. catch line discharge into VE-11 (T_oCT_i)	513°R	1.5 hr	293°R
18-in. catch line at junction with 4-in. chilldown bypass line (T_oCD)	513°R	1.5 hr	477°R

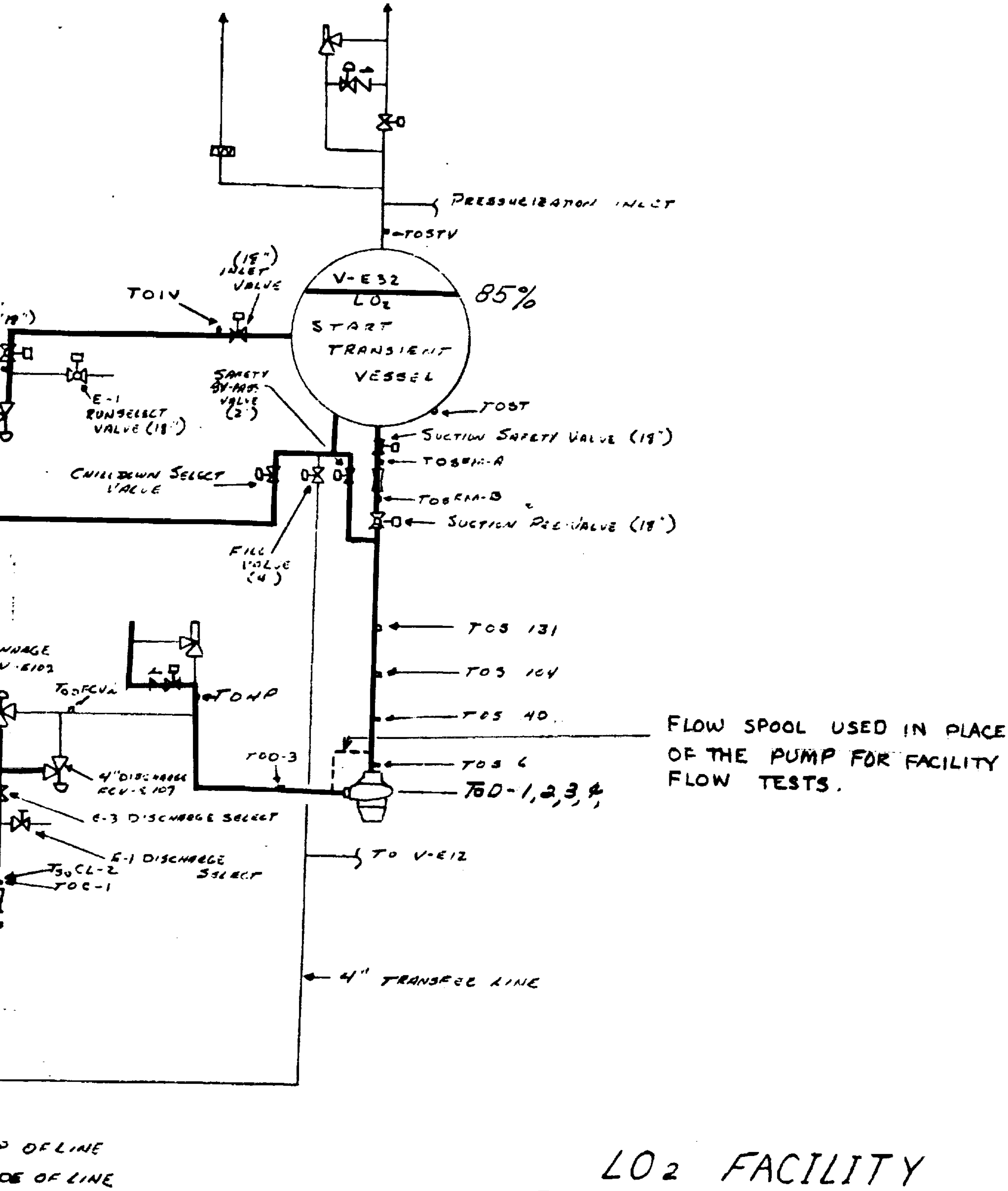
---

(14) Aerojet-General AETRON Division Report, Recommended Cooldown Procedures for E-Zone Cryogenic Piping Systems

(15) ibid.



NOTE: 1) TOC-2A WAS A
2) TOC-2B WAS



LO2 FACILITY
INSTRUMENTATION SCHEMATIC

Figure 16

Test Stands E-1 and E-3 LO_2 System Instrumentation Schematic

2

An evaluation of these temperatures showed that this quantity of chilled gaseous nitrogen was insufficient to prechill the 18-in. catch line prior to introducing liquid nitrogen. The results of the thermal and stress analyses previously discussed showed that a maximum steady-state exit gas temperature of 360°R must be reached prior to cold-shocking the system (Table IV). To complete the system prechill, it was necessary to transfer liquid nitrogen to the on-stand start transient vessel (VE-32). Boil-off gas from chilldown of this vessel was then passed through the 18-in. catch line, in the direction of normal flow, to further prechill the system. Because this system was not insulated, the boil-off-gas chilling effect was insufficient to complete prechilling of the catch line. To complete the chilldown, it was necessary to introduce liquid nitrogen into the 4-in. chilldown bypass line and let it flash-off into the 18-in. catch line until fluid temperatures at ToC-2A, -2B and 2C indicated 310°R. Liquid nitrogen was then bled into the catch line, and the chilled condition was maintained by intermittently flowing liquid nitrogen through the bypass into the catch line.

This initial chilldown showed that significantly greater quantities of chilled gas were required to properly prechill the catch line than were available from VE-11. This required a higher initial pressure for VE-11. The pointer scribe system installed on the propellant line to determine horizontal and vertical movements of the line was not adequate. The long horizontal run of 18-in. pipe bowed upward approximately 6-in. at the center. The U-bolt tiedowns in the horizontal pipe runs had to be loosened to allow the line to seek its own position during the chilldown. Available data indicated that a faster gas and liquid chilldown would probably result in less line distortion during future chilldowns. The elapsed time required to chilldown the propellant system for this initial flow test was approximately six hours.

b. Revised Liquid Oxygen System Chilldown Procedures

Preparation for the subsequent series of chilldown tests with the 18-in. catch line included installation of a new grid and pointer system to show line movements. Three movie cameras were positioned to take pictures of the grid and pointer systems to show this line movement. Liquid nitrogen in VE-11 was pressurized to 65 psig with gaseous nitrogen and the gas temperature allowed to stabilize for nine hours prior to the initiation of system chilldown.

System temperatures both before and after the initial gas flow from VE-11 through the 18-in. catch line were as follows:

	Before Chilling	Elapsed Time	After Chilling
18-in. catch line discharge into VE-11 (T_oCT_i)	511°R	1.9 hr	259°R
18-in. catch line at junction with 4-in. childown bypass line (T_oCD)	509°R	1.9 hr	440°R

This amount of system prechilling was still considered inadequate. Liquid nitrogen was then transferred to the on-stand tank (VE-32) at the continuous rate of approximately 1700 lb/min. During this transfer, liquid nitrogen was allowed to center the chilldown bypass system and subsequently chill the 18-in. catch line to the desired temperatures. Thermocouple readings were monitored during the chilldown and lines were observed to prevent excessive displacements.

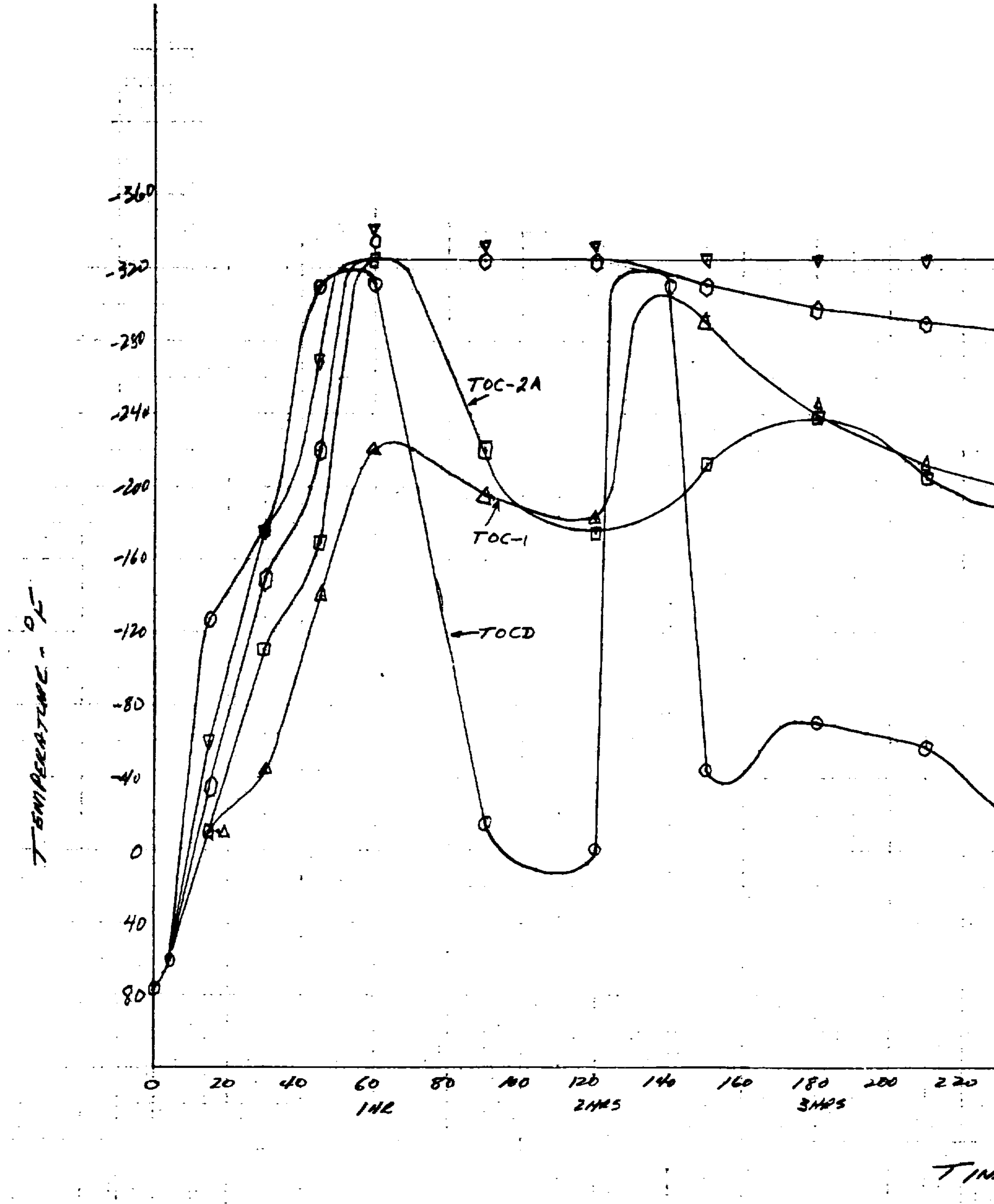
The improved line displacement measuring techniques showed a maximum line displacement of 3-in. vertically and 2.25-in. sideways at the center of the long horizontal run of the 18-in. catch line (Figure No. 3). This was a significant improvement over the approximate 6-in. displacement noted during the initial chilldown. The distance between the anchor points in this section of line is approximately 130 ft.

The elapsed time for this chilldown was approximately three hours. The existing data indicated that an even faster chilldown appeared feasible.

c. Liquid Oxygen System Catch Line Chilldown with the Turbopump Assembly in Position

System chilldown was initiated directly by transferring liquid nitrogen to the on-stand vessel and allowing the boil-off gas to flow through the bypass line, the 18-in. catch line, and into VE-11. This procedure bypassed the previous step of initial chill of the 18-in. line by flowing chilled gaseous nitrogen from VE-11 to the on-stand tank. As chilldown progressed, liquid nitrogen began to remain in the on-stand vessel and eventually, the bypass line and 18-in. catch line were bled-in (See Figure No. 17 for time temperature data.) Line displacements were of approximately the same magnitude as before and the elapsed time for facility propellant line chilldown was again approximately three hours. The chilldown of the oxidizer turbopump assembly and the inlet and discharge lines required an additional two and one-half hours.

Subsequent chilldowns were conducted in the same manner as the previous one except that the pump and facility systems were chilled concurrently with a total elapsed time of three and one-half hours. Once liquid nitrogen remained in the line, it was necessary to maintain the



○ - TOCD
□ - TOC-2A
⬡ - TOC-2B
▽ - TOC-2C
△ - TOC-1

NOTE: CATCH LINE WAS INS
FIBER GLASS INSULAT
THIS TEST SERIES,
INSULATION THICKN
APPROX. 1 INCH

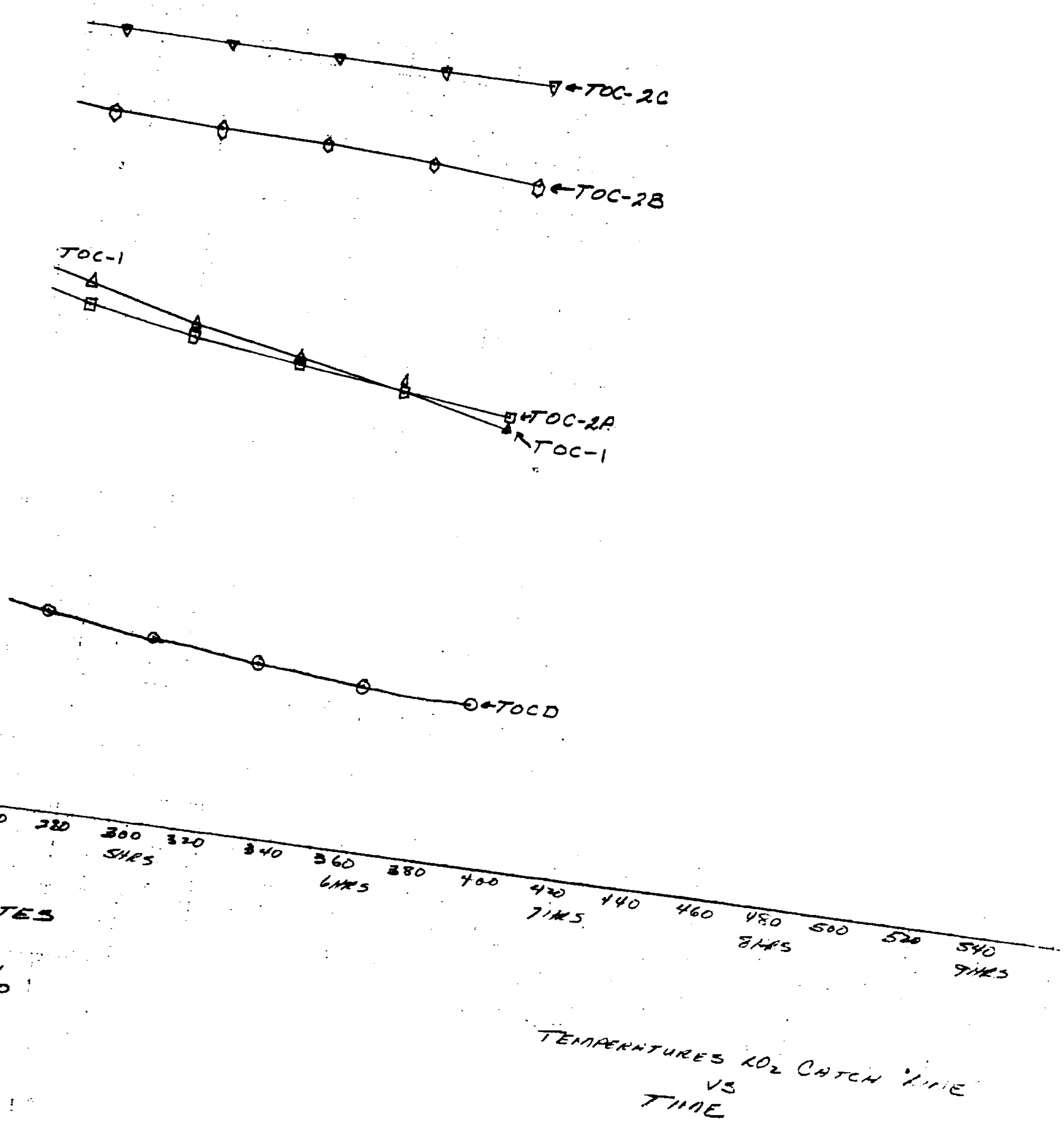


Figure 17

LO_2 Catch Line Internal Temperatures vs Time

long horizontal runs of 18-in. line in a full bleed-in condition to prevent bowing caused by the top of the line becoming warm.

d. Childown of the Run Line Between VE-10 and the On-Stand Run Vessel

The 18-in. run line from VE-10 to VE-32 was chilled by slowly bleeding liquid nitrogen into the run line and then allowing it to boil-off and cool the remainder of the line. Whenever the temperature at ToRL indicated 210°R or warmer (Figure No.13), the safety valve (tank outlet) was recycled to bring the temperature at ToRL back down to liquid temperature (140°R). Complete chilldown of the line was thus achieved with minimum line distortion. Liquid nitrogen was then transferred through this line to the on-stand vessel (VE-34) and the remainder of the system was chilled as before. Total elapsed time, including the chilldown of the run line, was four and one-half hours.

e. Final Chilldown Procedure

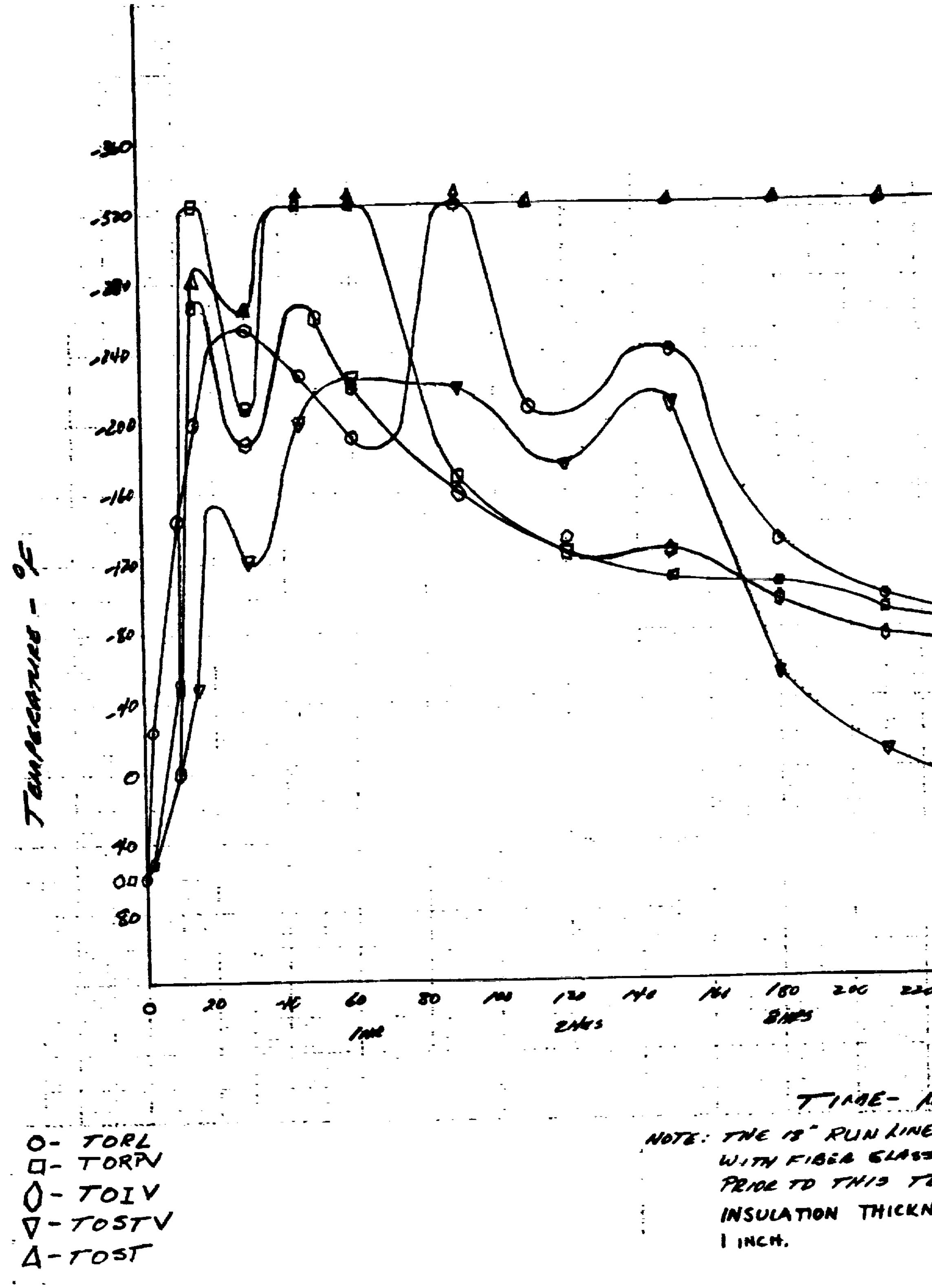
The final chilldown procedure is substantially the same as previously described, except that the 4-in. chilldown bypass is not used because of the simultaneous chilldown of the turbopump and the 18-in. catch line. Liquid nitrogen is transferred into VE-32 as before, but subsequent system chilldown is accomplished by slowly flowing liquid nitrogen from VE-32 through the turbopump assembly into the 18-in. catch line and finally into VE-11. This speeds the total system chilldown and takes advantage of the heat capacity of the gaseous nitrogen. The turbopump assembly is an excellent heat sink for generating boil-off gas (gaseous nitrogen) for prechilling the catch line. The elapsed time for this chilldown is two and one-half hours.

f. Summary

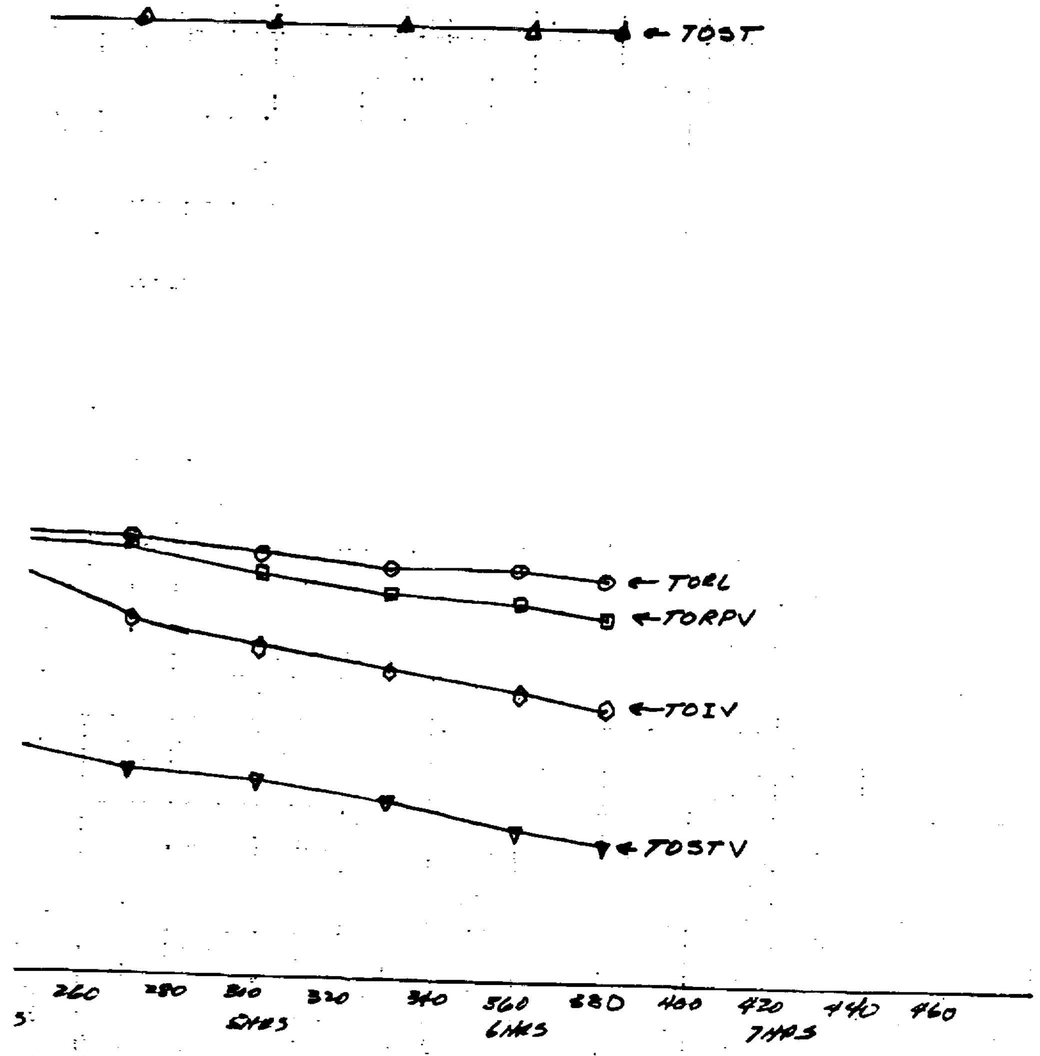
The final chilldown procedure varies significantly from the recommended procedure.(16) This is primarily because of the lack of a sufficient quantity of chilled gaseous nitrogen for catch-line chilldown when using the pressurant from VE-10 and VE-11. The limited use of the chilldown by-pass system was partially the result of the low testing rate in the reduced program scope. Higher rates of testing would most likely result in the advantageous use of the chilldown system to maintain the lines in a prechilled condition between tests, utilizing the vessel boil-off that is otherwise vented to the atmosphere. Line temperatures and displacements were carefully monitored during chilldown to ensure the degree of prechill recommended in the previous discussion on thermal and stress analysis. No adverse effects upon the large facility piping systems were detected when the direct chilldown procedure was used, although the supports, guides and restraints had to be loosened during the initial chilldown to permit the line to move freely.

---

(16) ibid.



NOTE: THE 18" RUN LINE
WITH FIBER GLASS
PRIOR TO THIS T
INSULATION THICKN
1 INCH.



ES
INSULATED
ION
ERIES.
S APPROX.

TEMPERATURES LO2 RUN LINE & START TRANSIENT VESSEL
VS TIME

Figure 18

LO_2 Run Line and Start Transient Vessel Temperatures vs Time

It can be concluded that cryogenic propellant lines of this size should be arranged to eliminate, as much as possible, long horizontal sections of line. Also, all such lines should be insulated (preferably vacuum jacketed) to minimize both childown and normal losses. This significantly reduces the required prechill period and minimizes the amount of propellant bleed required to maintain the system in a chilled condition. Although the advantages are attractive, the economics of propellant and operational cost savings in relationship to increased system cost must be considered.

Although the system was designed for liquid oxygen and the heat transfer calculations were based upon liquid oxygen properties, the thermal characteristics of liquid nitrogen are sufficiently similar to liquid oxygen that the results should apply to either.

2. Liquid Hydrogen Propellant System Performance

a. Initial Liquid Hydrogen System Chilldown With the Facility Flow Spool in Place

The initial chilldown was performed in accordance with recommended procedures(17), except that the off-stand run vessel (VE-1) and associated systems had not been activated and could not be utilized in the 18-in. hydrogen catch line chilldown. This was because of the abbreviated program that resulted from budgetary limitations.

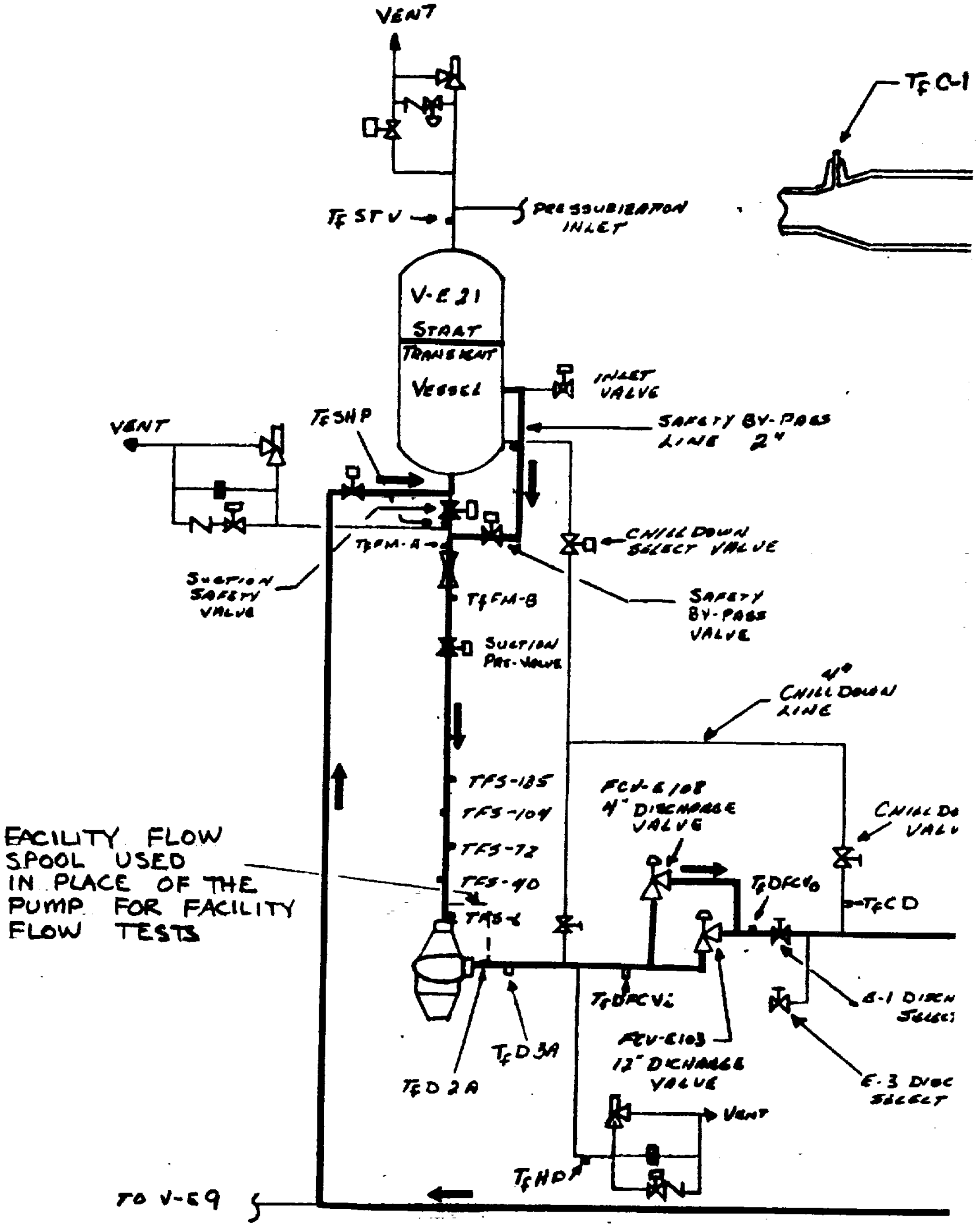
Vessel VE-2 was pressurized to 45 psig with gaseous hydrogen and allowed to stabilize for six hours. The chilled gas was then flowed in cycles through the 18-in. catch line in the reverse direction to normal liquid flow and into the on-stand vessel, VE-21 (see Figure No. 19). The pressure in VE-2 was depleted in approximately two hours; at which time approximately 300 lb of gaseous hydrogen had flowed through the system. Typical system temperatures both prior to and after this initial flow were:

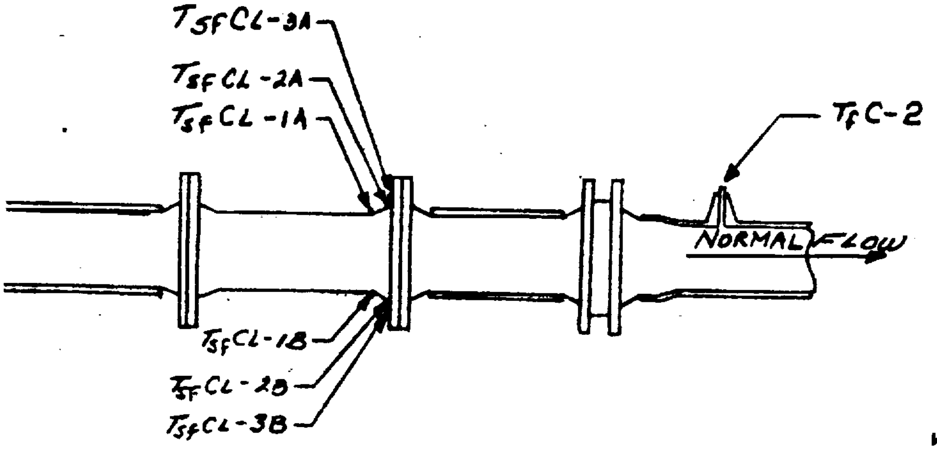
	Before Flow	Elapsed Time	After Flow
VE-2 catch line inlet (T_fCT_i)	492°R	1.8 hr	290°R
Chilldown bypass line junction with catch line (T_fCD)	492°R	1.8 hr	400°R

Following the gaseous hydrogen prechill of the catch line, liquid hydrogen was introduced into the on-stand, start-transient vessel (VE-21). The cold gaseous hydrogen resulting from the chilldown of this vessel was routed through the bypass line, the 18-in. catch line, and

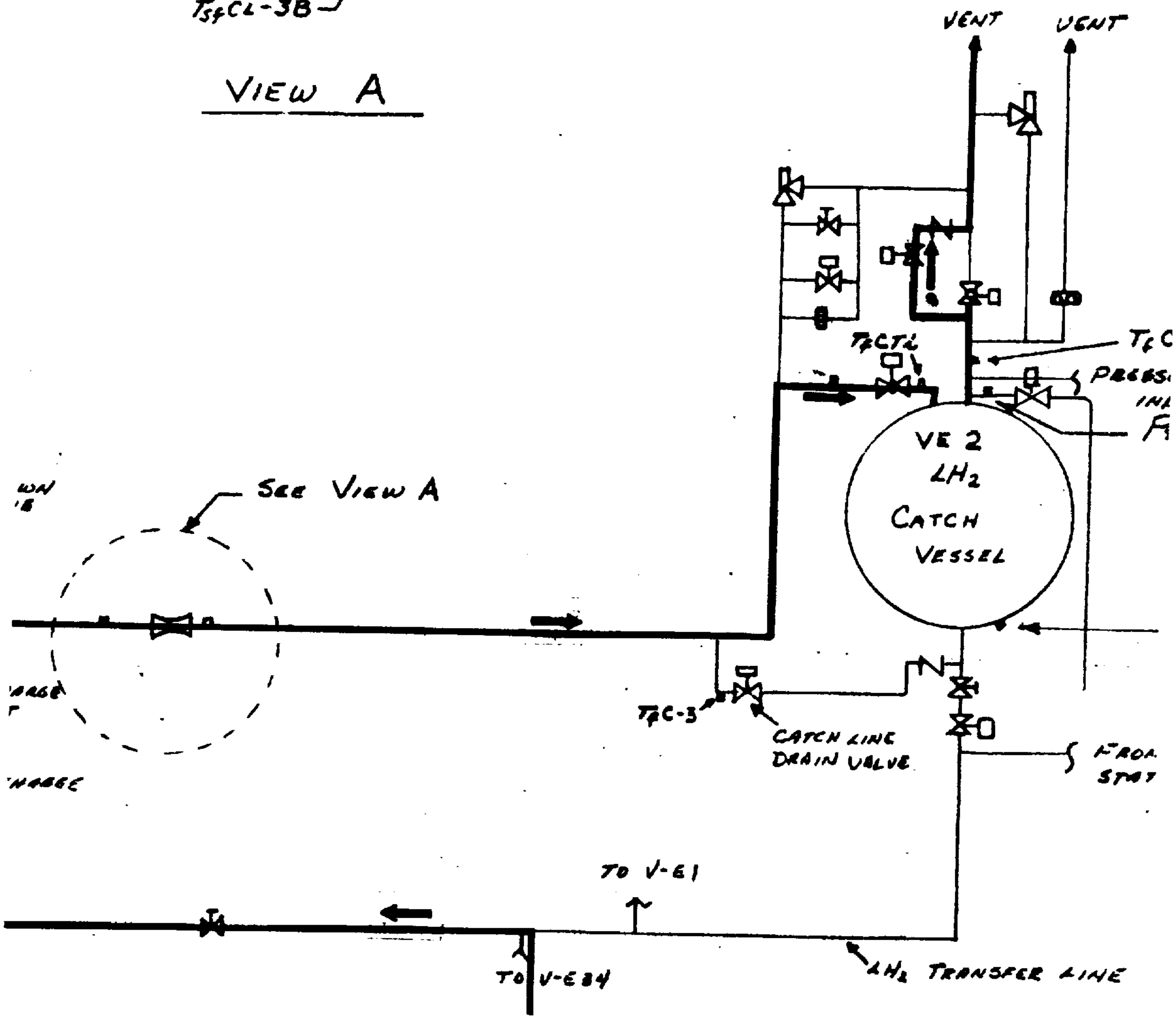
---

(17) ibid.


VENT
T$_{F}$C-1
T$_{F}$ STV
PRESSURIZATION INLET
V-E21 START TRANSIENT VESSEL
INLET VALVE
VENT
T$_{F}$SHP
SAFETY BY-PASS LINE 2"
T$_{F}$FM-A
CHILL DOWN SELECT VALVE
SUCTION SAFETY VALVE
T$_{F}$FM-B
SAFETY BY-PASS VALVE
SUCTION PRE-VALVE
4" CHILL DOWN LINE
TFS-135
TFS-104
TFS-72
TFS-40
TFS-6
FCV-E108 4" DISCHARGE VALVE
CHILL DO VALV
T$_{F}$DFCV$_{0}$
T$_{F}$CD
FACILITY FLOW SPOOL USED IN PLACE OF THE PUMP FOR FACILITY FLOW TESTS
T$_{F}$DFCV$_{i}$
E-1 DISCH SELEC
FCV-E103 12" DISCHARGE VALVE
T$_{F}$D3A
T$_{F}$D2A
E-3 DISC SELECT
VENT
T$_{F}$HDP
TO V-E9



VIEW A



43 2

Test Stand

TV
URIZATION
ET
ECT

TECT

TRUCK UNLOADING
ION

II

INSTRUMENTATION SCHEMATIC
TEMPERATURES ONLY
FTPA-FACILITY

——— GH_2/LH_2 flow from VE-21 to VE-2

Figure 19

s E-1 and E-3 LH_2 System Instrumentation Schematic

3

into VE-2 in the normal direction of flow. Upon attainment of the necessary prechill temperatures as measured by both internal and external surface thermocouples, liquid hydrogen was introduced into the system.

While most of the system was vacuum jacketed or foam insulated, the sections that were uninsulated created a serious problem because of liquid air forming on the pipe surface. Line displacements noted during this chilldown were as expected except for greater-than-expected upward and sideward movement of the 18-in. catch line near VE-2.

b. Subsequent Liquid Hydrogen System Chilldown

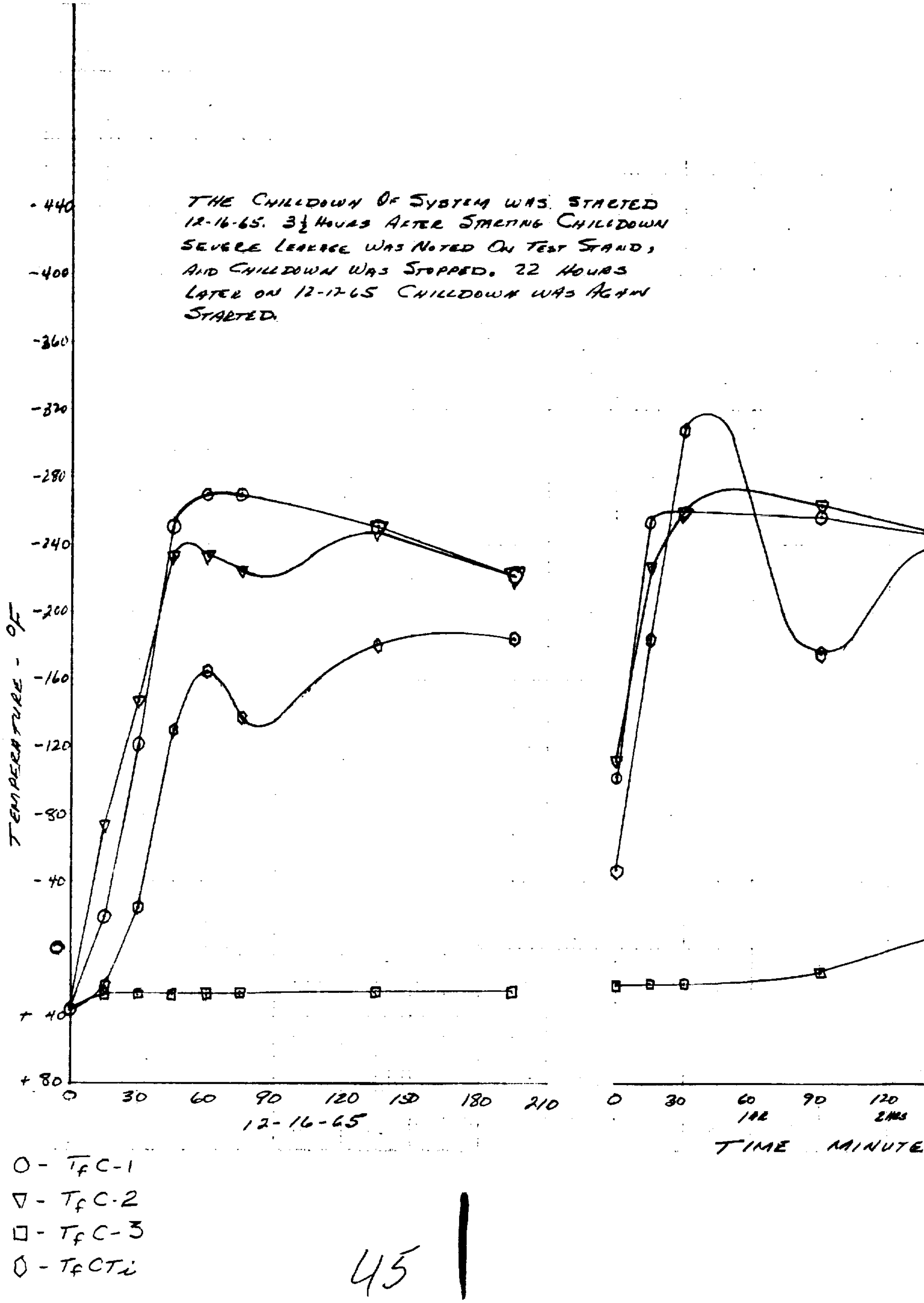
The former method of backflowing chilled gaseous hydrogen from VE-2 through the 18-in. catch line was not used. After further evaluation, a more direct method of chilling the entire system (i.e., suction line, flow spool, discharge line and catch line as shown in Figure No. 19 was selected. The on-stand run vessel VE-21 was filled with liquid hydrogen prior to the start of the liquid hydrogen flow system chilldown. Liquid hydrogen was then admitted directly into the suction line where it flashed-off into chilled gaseous hydrogen. This chilled gas then flowed through the 18-in. catch line to VE-2, progressively chilling it. Once liquid hydrogen was bled into the suction, flow spool, and discharge lines, the 18-in. catch line prechill was maintained by periodically admitting liquid hydrogen into the catch line through the 4-in. flow control valve. Elapsed time for this chilldown was approximately one and one-half hours. The temperature-time history of a typical chilldown is shown in Figures No. 20 and No. 21.

This procedure was used for all subsequent chilldowns and no adverse operational problems were encountered.

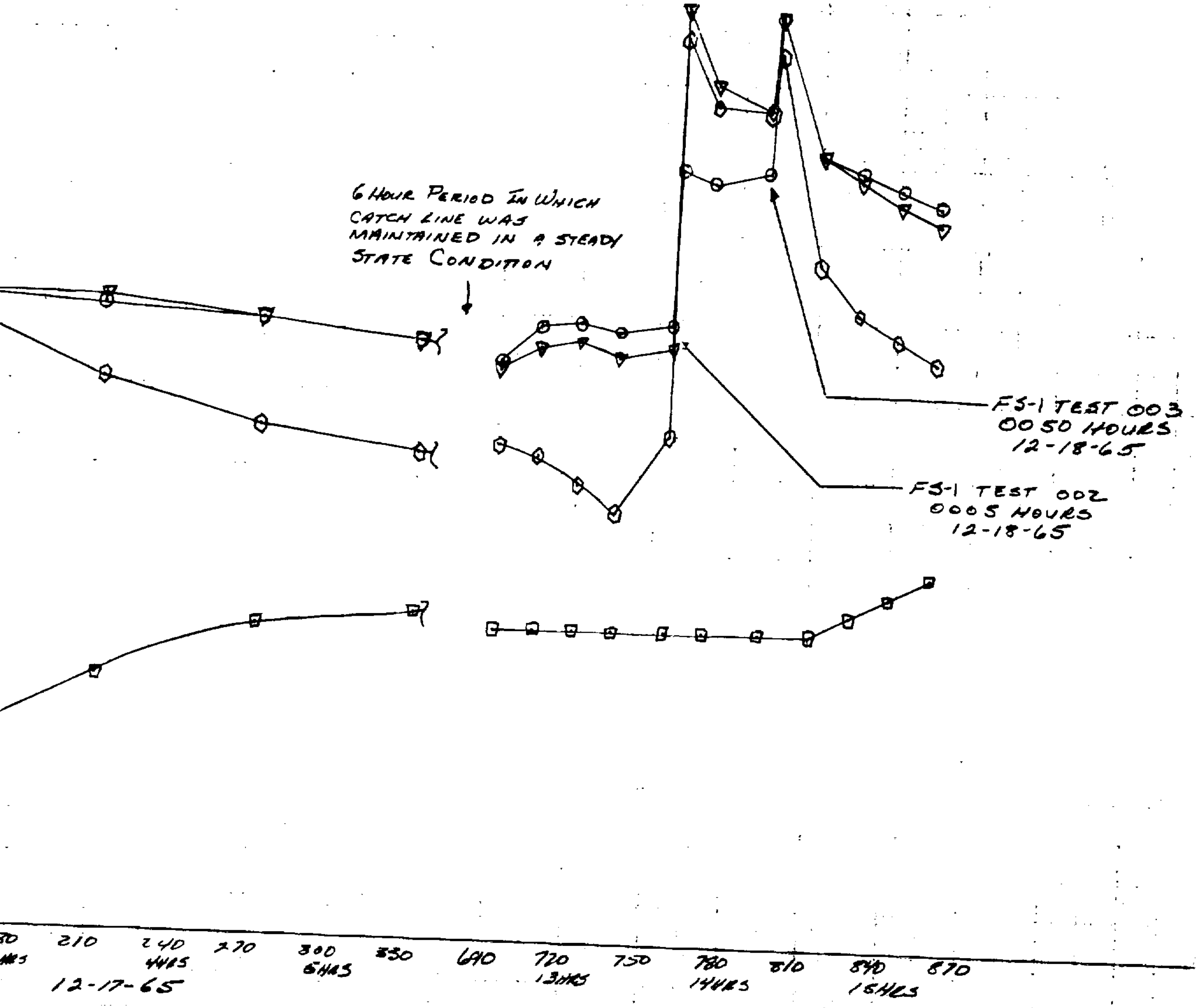
c. Liquid Hydrogen Catch Vessel (VE-2) Performance

This 370,000-gallon, 100-psi vacuum-insulated vessel is one of the largest liquid hydrogen storage vessels now in use. The 45.5-ft diameter stainless steel inner sphere is supported within a 55.5-ft diameter carbon steel outer sphere. The annulus is packed with perlite insulation and all air is evacuated.

The boil-off rate specified in the design is not to exceed 0.25% (220 lb/day). As shown in Figure No. 22, the vessel required approximately 60 days to stabilize after the initial fill. The declining boil-off rate results from the insulation approaching thermal equilibrium. The boil-off rate described by the curve in Figure No. 22 was plotted by measuring the absolute losses over incremental periods ranging from a few days to several weeks. The losses were determined by taking periodic inventory readings by means of the liquid level capacitance probe. This method was used in lieu of a formal boil-off test that was to be performed by the vessel manufacturer. Considering that the level readings can



THE CHILLDOWN OF SYSTEM WAS STARTED 12-16-65. 3½ HOURS AFTER STARTING CHILLDOWN SEVERE LEAKAGE WAS NOTED ON TEST STAND, AND CHILLDOWN WAS STOPPED. 22 HOURS LATER ON 12-17-65 CHILLDOWN WAS AGAIN STARTED.

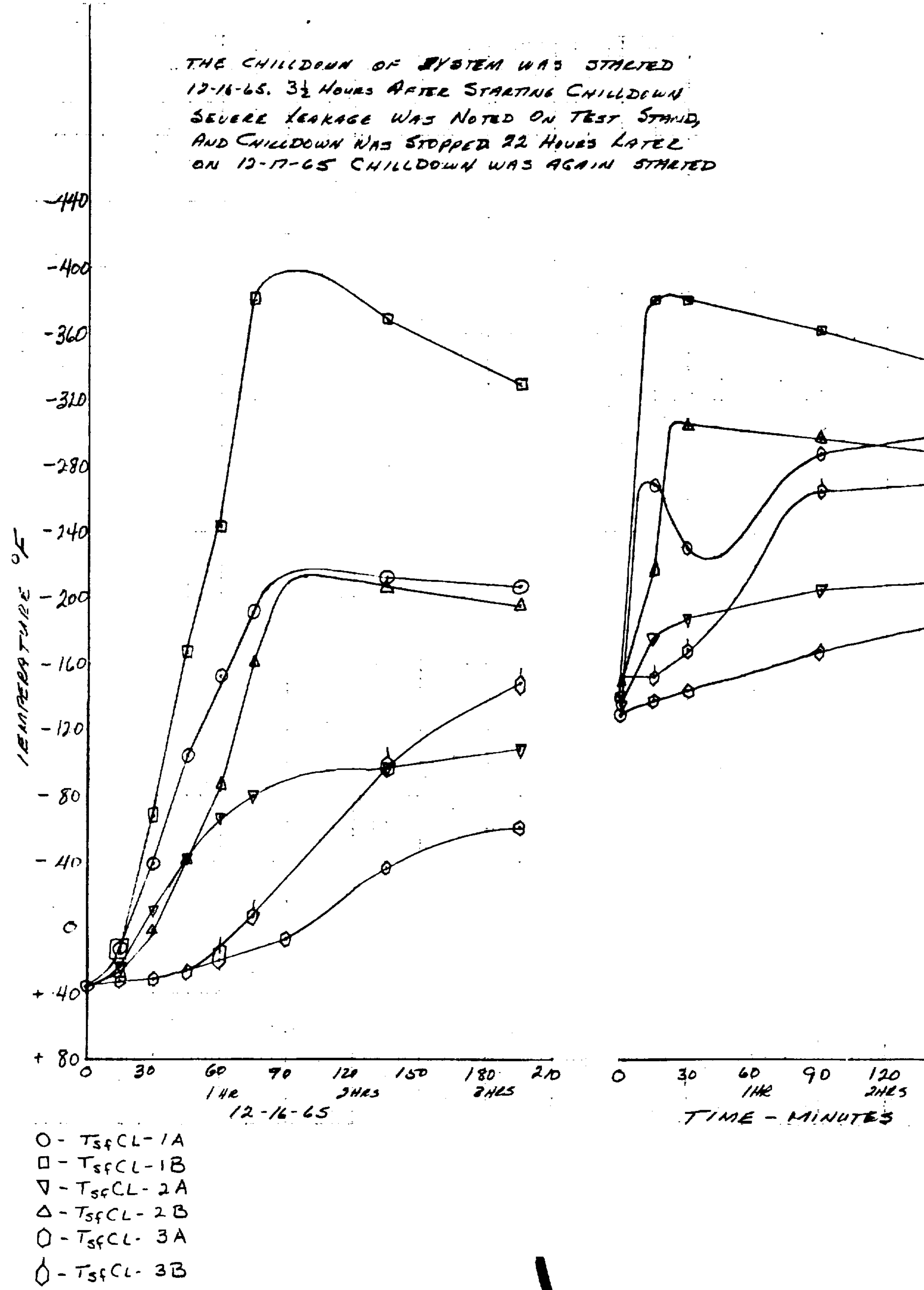


1-2-10-EHP-002 & -003

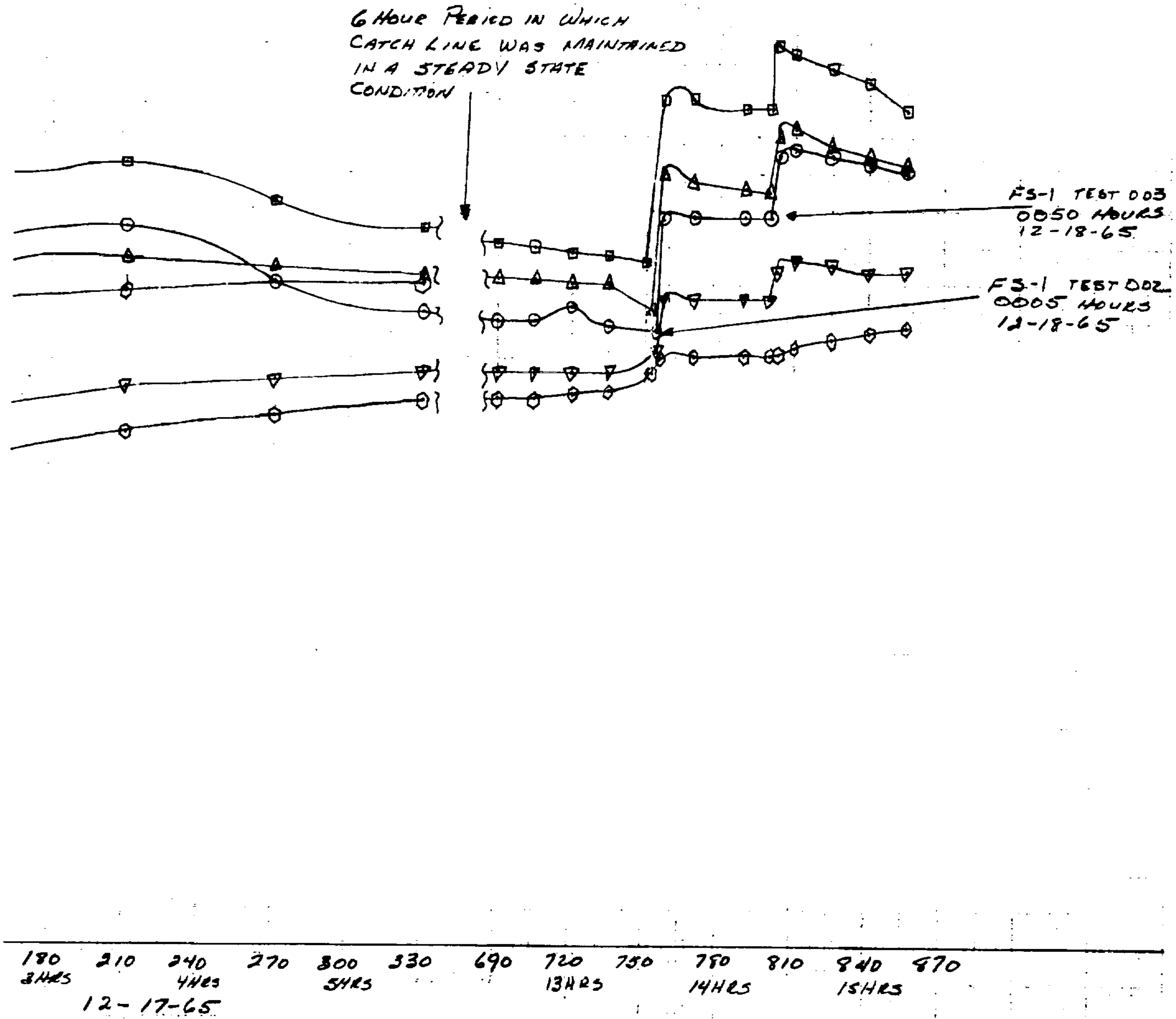
Catch Line Internal Temperatures VS Time

Figure 20

LH_2 Catch Line Internal Temperatures vs Time



THE CHILLDOWN OF SYSTEM WAS STARTED 12-16-65. 3½ HOURS AFTER STARTING CHILLDOWN SEVERE LEAKAGE WAS NOTED ON TEST STAND, AND CHILLDOWN WAS STOPPED 22 HOURS LATER ON 12-17-65 CHILLDOWN WAS AGAIN STARTED



6 HOUR PERIOD IN WHICH CATCH LINE WAS MAINTAINED IN A STEADY STATE CONDITION

FS-1 TEST 003
0050 HOURS
12-18-65

FS-1 TEST 002
0005 HOURS
12-18-65

CATCH LINE SKIN TEMPERATURES
VS
TIME

1.2-10-EHP-002 & -003

M J Rieb 12-30-65

Figure 21

LH_2 Catch Line Skin Temperatures vs Time

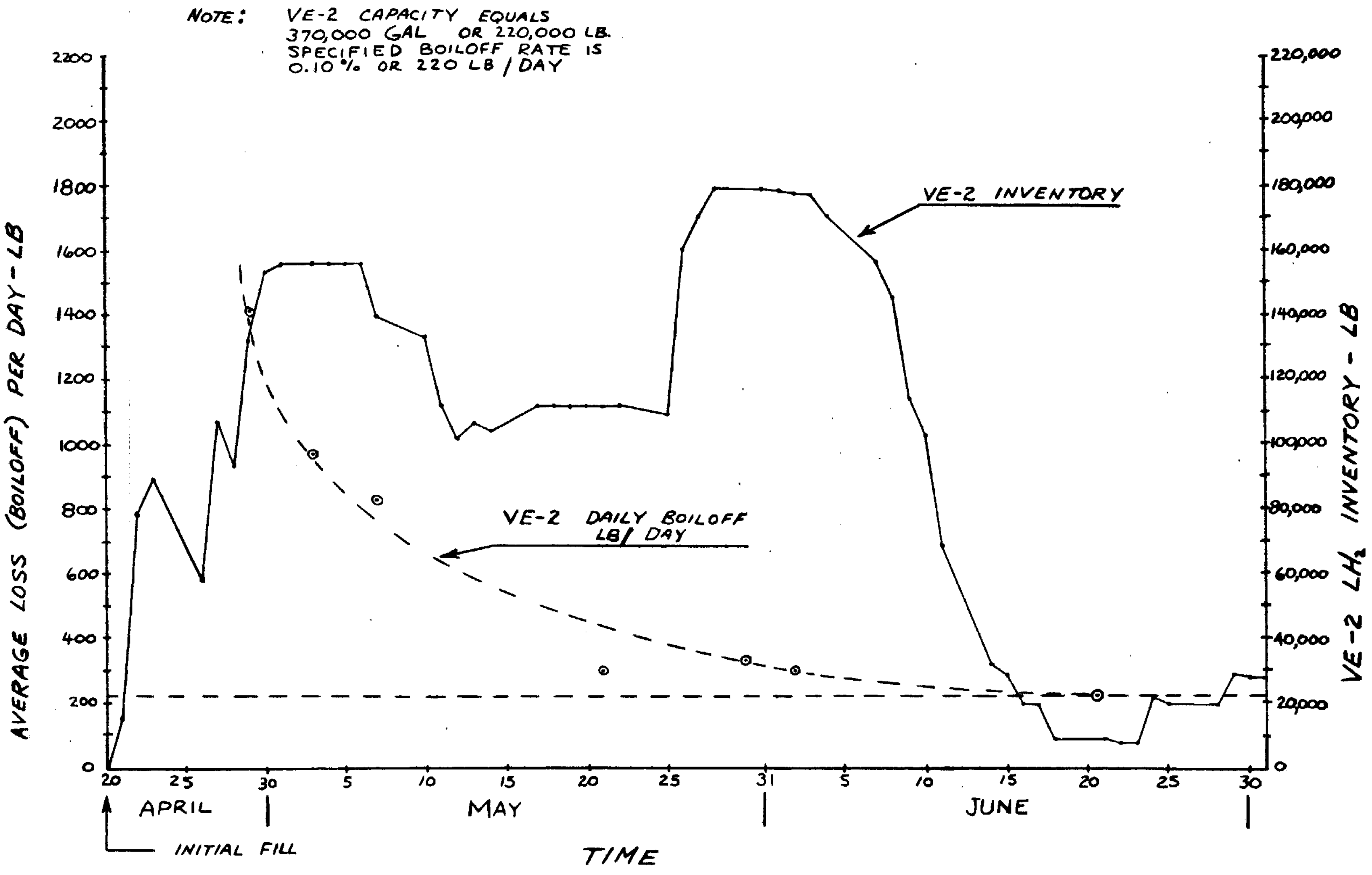


Figure 22

Liquid Hydrogen Catch Vessel (VE-2) Daily Boiloff Loss Rate be obtained to the nearest 1%, the accuracy of this method is limited. However, as seen from Figure No. 22, the limited data fits a smooth curve and shows that the actual boil-off rate approaches the specified rate of 220 lb/day.

d. Summary

The final large hydrogen line chilldown procedure utilized the cold gas prechill prior to cold-shocking the system with liquid hydrogen. However, the former method of backflowing chilled gaseous hydrogen from VE-2 to the stand was disregarded in favor of a more direct method of chilldown. This consisted of directly injecting liquid hydrogen into the pump suction line and allowing the boil-off to progressively chill the pump or flow spool and the 18-in. catch line. This had the advantages of permitting a faster chilldown and of using the liquid/gaseous hydrogen to chill the pump or flow spool as well as the discharge line. As in the liquid oxygen system, only limited use was made of the chilldown by-pass system. With increased testing rates, this by-pass system could be used advantageously to maintain the lines in a pre-chilled condition between tests, utilizing the vessel boil-off gases otherwise vented to the atmosphere.

It was found that system exit gas temperatures could be significantly warmer at the instant of cold-shocking than recommended in the thermal analysis. This is a result of the conservative assumption that the flange temperature was the same as that of the exit pipe, where in reality the flange is upstream and is at a colder temperature. The time allowed for chilldown also has a marked affect upon this recommended temperature. The analysis determined that, for a gas flow rate of 1500 lb/hr, 2.2 hours would be required to obtain the necessary exit gas temperature of 200°R. In actual practice, the prechill period was extended to as long as 14 hours in some cases. This was necessary to allow other operations connected with the pump test to be conducted. Liquid/gas was admitted to the catch line periodically during this time to maintain the prechill condition. No measurements of gas flow rate were made although it can be assumed that the rate was considerably less than 1500 lb/hr.

No abnormal line displacements were noted during the operations associated with the liquid hydrogen line. The high confidence in the revised chilldown procedure was partially a result of the experience gained during the liquid oxygen system. The only operating problem was the formation of liquid air on uninsulated portions of the system.

E. CONCLUSIONS AND RECOMMENDATIONS

The results of this thermal and stress analysis of the large cryogenic systems exposed to cold-shocking by liquid hydrogen and liquid oxygen show that a prechill at a predetermined rate and temperature is required before cold-shocking. The use of the cold gas propellant boil-off will prechill the system to the proper temperature before shocking the system and will prevent yielding of the material. The bypass systems of piping shown in Figures No. 6 and No. 7 were not necessary for prechilling the discharge line under the limited test program; however, they aided operationally in maintaining a chilled condition. With higher testing rates, these systems could be used advantageously to maintain the lines in a chilled condition between tests.

Operating experience with the hydrogen system shows that the calculated system prechill temperatures were conservative in that cold shocking was accomplished with exit temperatures less than recommended without adverse effects.

Tables III and IV are summaries of cooldown information resulting from the analysis. Faster cooldown of the system can be attained by increasing gas flow; however, no data are available to substantiate flow rates for comparison to calculated figures. Table VI is a summary of the comparison between actual and theoretical data at selected points.

It is recommended that all large cryogenic systems be insulated, preferably with vacuum jacketing. Noninsulated oxygen systems require constant attention to prevent deformation when filled with liquid. It is mandatory that liquid hydrogen systems be insulated.

IV. NOMENCLATURE

A. NOMENCLATURE PERTAINING TO THEORETICAL CALCULATIONS

1. Symbols

a = Ring width

t = Ring and sphere thickness

A = Ring cross-section area

R = Ring and sphere radius

M = Moment

V = Shear

δ = Ring and sphere deflection (Radial)

θ = Rotation of ring cross-section

E = Young's Modulus

p = Pressure on sphere

ν = Poisson's Ratio

TABLE VI

COMPARISON BETWEEN THEORETICAL AND ACTUAL GAS PRECHILL CHARACTERISTICS

		Theoretical	Actual
1.	Exit gas temperature at time of cold shocking:		
	a. LH_2 catch line (TPA to VE-2)	200°R	280°R (T_fCT_i)
	b. LO_2 catch line (TPA to VE-11)	275°R	324°R (TOC-2A)
2.	Time required to pre-chill to minimum necessary calculated temperature:		
	a. LH_2 catch line (TPA to VE-2)	2.2 hr	1.8 hr
	b. LO_2 catch line (TPA to VE-11)	1.4 hr	1 hr
3.	Total Weight of gas required to chill line:		
	a. LH_2 catch line (TPA to VE-2)	3,300 lb	5,400 lb*
	b. LO_2 catch line (TPA to VE-11)	29,400 lb	67,000 lb**

---

* Includes TPA chilldown.

** Includes chilldown of run line, VE-32, TPA and catch line.

D = Cylinder coefficient = $Et^3/12(1 - \nu^2)$

λ = Cylinder coefficient = $\sqrt[4]{3(1-\nu^2)/R^2t^2}$

T = Temperature in °R

I_{xx} = Area moment of inertia

$\bar{y}$ = Location of cg

x = Distance along pipe axis

S = Stress

$\Delta L/L_o$ = Expansion Coefficient at 560°R

$\Delta l/l_o$ = Expansion Coefficient at T

2. <u>Subscripts</u>

L = Left side of ring

R = Ring side of ring

i = Inner surface of ring and sphere

o = Outer surface of ring and sphere

1,2,3,etc. = Inner and outer surfaces of respective rings and respective spheres

a,b,c,etc. = Left and right edges of respective rings

h = Hoop direction

l = Longitudinal direction

B. NOMENCLATURE PERTAINING TO FACILITY INSTRUMENTATION

1. <u>General</u>

FS_1-FS_2	Fire Switch
RSD	Remote Command Shutdown
ESS	Emergency Command Shutdown
OST	Overspeed Trip

OPS	Overpressurization Switch
LLP	Liquid Level Probe
FCV	Flow Control Valve

2. <u>Fuel Turbopump Assembly Testing</u>

P_{FCTi}	Pressure - Fuel Catch Tank Inlet
T_{fST}	Temperature - Fuel Start Tank
T_{fC-1}	Temperature - Catch Line
T_{fC-2}	Temperature - Catch Line
T_{fC-3}	Temperature - Catch Line
T_{fSHP}	Temperature - High Point Bleed (Suction)
T_{fHP}	Temperature - High Point Bleed
T_{fSTV}	Temperature - Start Transient Vessel Vent
T_{fCTV}	Temperature - Catch Tank Vent
T_{fDFCVi}	Temperature - Flow Control Valve Inlet
T_{fDFCVo}	Temperature - Flow Control Valve Outlet
T_{fCTi}	Temperature - Catch Tank Inlet
$T_{SFCL-1A}$ through	
$T_{SFCL-3B}$	Skin Temperature - Fuel Catch Line
T_{FS}	Temperature - Pump Suction Line
T_{fD}	Temperature - Pump Discharge Line
T_{fCT}	Temperature - Fuel Catch Tank
T_{fFM}	Temperature - At Fuel Suction Flowmeter
T_{fHP}	Temperature - Fuel High Point Bleed
T_{fCD}	Temperature - Fuel Chilldown Bypass

3. Oxidizer Turbopump Assembly Testing

T_{oRL}	Temperature - Oxidizer Run Line
T_{oC}	Temperature - Oxidizer Catch Line
T_{oCD}	Temperature - Oxidizer Childown Bypass
T_{soCL}	Skin Temperature - Oxidizer Catch Line
T_{oCTV}	Temperature - Oxidizer Catch Tank Vent
T_{oCTi}	Temperature - Oxidizer Catch Tank Inlet
T_{oSTV}	Temperature - Start Transient Vessel Vent
T_{oS}	Temperature - Oxidizer Pump Suction Line
T_{oCFCV}	Temperature - Oxidizer Catch Line Flow Control Valve
T_{oST}	Temperature - Oxidizer Start Transient Vessel
T_{oSFM}	Temperature - At Oxidizer Suction Flowmeter
T_{oD}	Temperature - Oxidizer Pump Discharge
T_{oHP}	Temperature - High Point Bleed
T_{oIV}	Temperature - Oxidizer Run Line Inlet Valve
T_{oRPV}	Temperature - Oxidizer Run Line at Select Valve

Note; All temperatures are fluid temperatures except those with the small "s" subscript. These are designated as skin or line surface temperatures.

BIBLIOGRAPHY

1. Deppe, G. R., Large Size Flowmeter Technology, Aerojet-General Report No. 8800-60, 8 April 1966

2. Garcia, L. W., Friedland, H., and Lehmburg, A. E., Servo Control System and Analog Simulation in E-Zone, Aerojet-General Report No. 8800-61, 10 March 1966

3. Ritter, J. A., Summary of Observed Results When Chilling the M-1 Fuel Turbopump Assembly to Liquid Hydrogen Temperature, Aerojet-General Report No. 8800-65, 22 April 1966

4. Aerojet-General Report No. 153:R102 (with Supplements 1, 2, and 3), Thermal Stress Analysis and Cooldown Procedures for LH_2 and LO_2 Systems, 2 January 1964

5. Aerojet-General Report No. 1654, Research Computer Laboratory, Space Technology Division, August 1959

6. Aerojet-General AETRON Division Report, Recommended Cooldown Procedures for E-Zone Cryogenic Piping Systems, December 1963

7. Aerojet-General AETRON Division Report No. 2816, AETRON Pipe Flexibility Analysis Program, March 1964

8. Contract No. LAE174828, Associated Piping and Engineering Company

J. Christian

WEEKLY PROGRESS REPORT ON CURRENT FINAL REPORTS

May 13,1966, Through May 19, 1966

CODE	FILE	AUTHOR	NUMBER PAGES	STAR CAT.	PRINT	EST. OUT	MAILED
TN D-3427	E-3326	Smith,etc.	16	3	4-28		5-13
TN D-3228	E-2726	Olsen	40		4-28		5-16
CR - 439		Clark	76	32	4-26		5-13
CR - 479		Varauja	64	19	5-5		5-16
CR - 470		Honeywell,Inc.	124	10	5-5		5-13
TN D-3405	M-649	A. Dabul	88	7	4-28		5-19
TN D-3428	E-3167	Johnston,etc.	28	17	5-4		5-17
TN D-3429	E-3170	Schevermann,etc.	44	17	5-4		5-17
TN D-3441	M-412	Cortez	66	24	5-4		5-19
TN D-3426	E-3194	Yound,etc.	36	17	5-2		5-17
CR - 476		Robbins	38	23	5-12		5-19
CR - 480		Schulman	46	3	5-12		5-19
TT F-424		Guz',etc.	12	32	5-10		5-18
TT F-423		Savin,etc.	16	32	5-12		5-18
CR - 478		Wilson	48	19	5-12		5-19
TT F-389		Skuridin	834	30	4-8		5-16
CR- 459	E-3 370	Manson	166	3	4-11		5-18
CR- 464		Stapleford,etc.	174	31	4-14		5-18
TT F-380		Babenko,etc.	522	12	4-13		5 19
TN D-3402	A-2118	Callas,etc.	36	30	5-3	5-20	
CR - 485	L-	D'Anna,etc.	84	32	5-11	5-20	
CR - 484		Lake	64	10	5-11	5-20	
TN D-3421	L-4398	Jones,etc.	50	12	5-9	5-20	
TN D-3419	L-3314	Re,etc.	38	2	5-12	5-20	
TN D-3420	L-4023	Harvey	18	30	5-11	5-23	
CR - 481		Oman	52	12	5-12	5-23	
CR - 483		Bohachevsky,etc.	34	1	5-12	5-23	
CR - 489		Krall	10	19	5-12	5-23	
CR - 490		Dunn,etc.	26	14	5-12	5-23	
33 TN D-3446	A-2256	White	34	30	5-12	5-23	
TN D-3448	E-3401	Morris	14	10	5-12	5-23	
TN D-3445	E-3237	Orange	16	17	5-12	5-23	
CR - 495		Breeden,etc.	42	14	5-18	5-23	
CR - 497		Dickens	68	9	5-18	5-23	
CR - 491		Hyver	92	10	5-18	5-24	
CR - 496	Ames	Foster	58	6	5-18	5-24	
TN D-3391	G-687	Stark	46	14	5-12	5-24	
TN D-3439	M-204	Kurtz,etc.	56	7	5-12	5-24	
TN D-3452	M-415	Watkins	48	19	5-11	5-24	
TR R-237	L-4688	Holloway,etc.	40	30	5-18	5-25	
TN D-3418	L-4828	Huston	42	2	5-19	5-25	
TN D-3434	L-4846	Mascitti	46	1	5-19	5-25	
TM X-1239	E-3098	Lantz	18	22	5-12	5-25	
TM X-1236	L-4735	Carlson,etc.	38	2	5-19	5-25	
TN D-3456	E-3199	Stepka	18	32	5-16	5-26	
TN D-3353	G-703	Carr	34	31	5-12	5-26	
TN D-3453	E-3269	Schoenberg	54	3	5-16	5-26	
TN D-3447	H-390	Palitz	46	2	5-12	5-26	
TN D-3414	H-391	Patten,etc.	34	4	4-18	5-26	
CR-62027		Project 2110422	22		5-10	5-27	
CR - 453	Ames	Peschon,etc	200	10	4-26	5-26	
CR - 457	Ames	Friedlander	142	21	4-26	5-26	
CR - 460		Spacelabs,Inc.	192	5	4-28	5-26	
CR - 461		Texas Inst Inc	138	3	4-28	5-26	
CR - 472		Lardi,etc.	156	12	5-5	5-31	
CR-54436	E-3160	Holdeman,etc.	172	3	5-9	5-31	
CR - 473		Sperry Rand	254	11	5-10	5-31	
CR - 486	L-	Speaker,etc.	156	12	5-10	5-31	
CR - 488		Beam	322	8	5-11	6-3	
TT F-356		Bobkov,etc.	422	29	5-12	6-3	
CR - 482		Barrington,etc.	146	13	5-17	6-10	
CR-62026 VOL.1		Rothman,etc.	274		5-16	5-27	
TN D-3146	E-3149	Manson, etc.	22		11-22	HOLD	
TN D-3239	E-3198	Gahn, etc.	18		1-11	HOLD	
TN D-3372	E-2942	Stankiewicz	26	25	3-17	HOLD	

CR - 502	Langley	Eckstrom	5-13
CR - 503	Langley	Goodyear Aero. Corp.	5-13
CR - 504		Celentano,etc.	5-13
CR - 448		Hughes Aircraft	5-19

WEEKLY PROGRESS REPORT ON CURRENT FINAL REPORTS

REPORTS FROM LEWIS, AMES, GODDARD, MARSHALL, FLIGHT AND MSC

CODE	FILE	AUTHOR	NEGATIVES	PRINT ORDER	REMARKS
TN D-3087	M-332	Mead		10-14	
TN D-3451	M-331	Thompson, etc.	10-25	5-12	
TN D-	E-3134	Peoples, etc.	12-17		
TN D-	H-417	Taylor, etc.	12-29		
TN D-	G-689	Harris, etc.	2-21		
TN D-3359	G-696	Busse, etc.		2-28	
TN D-	A-2231	Hopkins, etc.	3-1		
	G-704-N	Snively	3-14		
TN D-3091	G-677	Cospar Meeting		3-15	
TN D-3127	G-699-N	Allison, etc.		3-21	
TN D-3313	G-663	Wagner		3-23	
TN D-3315	G-665-N	Wagner		3-23	
TN D-3316	G-666	Wagner		3-21	
TN D-	A-2080	Merrick, etc.	4-5		
TN D-3411	G-702-N	Habib.etc.		4-12	
TN D-	E-3280	Lorenzo	4-11		
TN D-	E-3327	Faeth	4-11		
TM X-1240	H-426	Andrews	4-11	5-12	
TN D-	A-1098	Stewart,etc.	5-2		
TN D-3430	M-205	Vogt		4-29	
TN D-3415	S-71	Kimzey		4-29	
TN D-3440	M-129	Platzer,etc.		4-29	
TN D-3450	M-130	Burns		5-12	
TN D-3431	A-2286	Rolls,etc.	5-11	5-18	
TN D-	A-2254	Giulianetti,etc.	5-16		
TN D-3458	E-3245	Dewitt,etc.	5-16	5-19	
TN D-3457	E-2949	Krawec	5-16	5-19	
TN D-3314	G-664	Wagner	5-17		
TN D-	A-2307	Cole	5-18		
TM X-1244	E-3134	Peoples,etc.		5-19	
TR R-239	E-3357	Bogart,etc.		5-19	
TR R-240	E-2863	Bogart		5-19	
TM X-1244	E-3134	Peoples,etc.		5-19	

MISCELLANEOUS PUBLICATIONS

	EST. OUT	MAILED
S-CSTAR 6B		5-16
S-CSTAR 9B		5-16
SP-7003(02)		5-13
SAB 28		5-16
CARA NO.3		5-18
SP-3024 Vol. 2		5-17
TT LIST 37		5-18
PAR NO. 13		5-17
CSTAR NO. 9A		5-18
Tech Briefs-66-10193,10200, 10203,10109	5-20	
Tech Briefs-10115,189,191,10210	5-23	
Tech Briefs-10112,179,182,192, 10220,223,224,225	5-24	
SP-7004(02)	5-24	
Tech Briefs-10186,181,187	5-25	
Tech Briefs-66-10110,111, 10221,227	5-26	
SP-7011(20)	5-26	
SP-7011(23)	5-26	
Aerospace Medicine-Index	5-26	
Index To Flash Sheets	5-27	
CStar NO. 10	5-31	
SAB NO. 29	5-31	
SP-3026	6-1	

Dr. J. F. Masi, SREP (1 Copy)
Air Force Office of Scientific
Research
Washington, D. C. 20333

AEOIM (1 Copy)
Arnold Engineering Development
Center
Air Force Systems Command
Tullahoma, Tennessee 37389

AFRSTD (1 Copy)
Headquarters, U. S. Air Force
Washington, D. C. 20330

Security Office (1 Copy)
Allied Chemical Corporation
General Chemical Division
P. O. Box 405
Morristown, New Jersey 07960

AMCRD-RC (1 Copy)
Department of the Army
U. S. Army Material Command
Washington, D. C. 20315

Chief, Document Section (1 Copy)
U. S. Army Missile Command
Redstone Scientific Information Center
Redstone Arsenal, Alabama 35808

Arthur D. Little, Incorporated (1 Copy)
Acorn Park
Cambridge, Massachusetts

T. Reinhardt (1 Copy)
Bell Aerosystems Company
P. O. Box 1
Buffalo, New York 14205

Ruth E. Peerenboom (1 Copy)
The Boeing Company
Aerospace Division
P. O. Box 3707
Seattle, Washington 98124

H. W. Carhart (1 Copy)
Director (Code 6180)
U. S. Naval Research Laboratory
Washington, D. C. 20390

J. L. Waisman (1 Copy)
Douglas Aircraft Company, Incorp.
Missile and Space Systems Division
3000 Ocean Park Boulevard
Santa Monica, California 90406

Garrett Corporation (1 Copy)
Airesearch Manufacturing Division
9857 Sepulveda Boulevard
Los Angeles, California

General Dynamics/Astronautics (1 Copy)
Library and Information Services (128-00)
P. O. Box 1128
San Diego, California 92212

C. Day (1 Copy)
General Electric Company
Apollo Support Department
P. O. Box 2500
Daytona,Beach, Florida 32015

Flight Propulsion Laboratory Department (1 Copy)
General Electric Company
Cincinnati, Ohio

Technical Information Center (1 Copy)
Lockheed Missiles and Space Company
P. O. Box 504
Sunnyvale, California

The Marquardt Corporation (1 Copy)
16555 Saticoy Street
Box 2013 - South Annex
Van Nuys, California 91409

Martin Division (1 Copy)
Martin Marietta Corporation
Baltimore, Maryland

Library (1 Copy)
National Aeronautics and Space
Administration
John F. Kennedy Space Center
Cocoa Beach, Florida 32931

Technical Information Center (1 Copy)
(D/096-722 (AJ01)
Space and Information Systems Division
12214 Lakewood Boulevard
Downey, California 90242

Rocketdyne (1 Copy)
(Library Department 596-306)
Division of North American Aviation
6633 Canoga Avenue
Canoga Park, California 91304

Dr. H. W. Schulz (1 Copy)
Office of the Director of Defense
Research and Engineering
Washington, D. C. 20301

Pratt and Whitney Aircraft
Corporation (1 Copy)
Florida Research and Development
Center
P. O. Box 2691
West Palm Beach, Florida 33402

STL Technical Library Document
Acquisitions (1 Copy)
Space Technology Laboratory, Inc.
1 Space Park
Redondo Beach, California 90200

Stanford Research Institute (1 Copy)
333 Ravenswood Avenue
Menlo Park, California 94025

Chemical Propulsion Information
Agency (1 Copy)
Johns Hopkins University
Applied Physics Laboratory
8621 Georgia Avenue
Silver Spring, Maryland 20910

REPORT NASA CR 54809 DISTRIBUTION LIST

W. F. Dankhoff (2 Copies)
NASA
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135
Mail Stop 500-305

W. W. Wilcox (1 Copy)
Mail Stop 500-305

W. H. Rowe (1 Copy)
Mail Stop 500-305

L. T. Weise (2 Copies)
Mail Stop 500-120

C. Y. Young (2 Copies)
Mail Stop 60-4

J. A. Durica (1 Copy)
Mail Stop 500-210

Patent Counsel (1 Copy)
Mail Stop 77-1

Lewis Library (2 Copies)
Mail Stop 3-7

Lewis Technical Information Division (1 Copy)
Mail Stop 5-5

Lewis Research Center Staff Members (1 Copy)
NASA
Cleveland, Ohio 44135

E. F. Baehr (1 Copy)
Mail Stop 500-116

P. M. Ordin (4 Copies)
Mail Stop 500-1

E. R. Jonash (1 Copy)
Mail Stop 500-103

Major E. H. Karalis (1 Copy)
AFSC Liaison Office
Mail Stop 4-1

Lewis Office of Reliability and Quality Assurance (1 Copy)
NASA
Cleveland, Ohio 44135

NASA Headquarters (6 Copies)
NASA Scientific and Technical Information Facility
Box 5700
Bethesda, Maryland

Library (1 Copy)
NASA
Ames Research Center
Moffett Field, California 94035

Library (1 Copy)
NASA
Flight Research Center
P. O. Box 273
Edwards AFB, California 93523

Library (1 Copy)
NASA
Goddard Space Flight Center
Greenbelt, Maryland 20771

Library (1 Copy)
NASA
Langley Research Center
Langley Station
Hampton, Virginia 23365

Library (1 Copy)
NASA
Manned Spacecraft Center
Houston, Texas 77058

Library (1 Copy)
NASA
George C. Marshall Space Flight Center
Huntsville, Alabama 35812

Library (1 Copy)
NASA
Western Operations
150 Pico Boulevard
Santa Monica, California 90401

Library (1 Copy)
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91103

A. O. Tischler (1 Copy)
NASA Headquarters
Code RP
Washington, D. C. 20546

J. W. Thomas, Jr. (5 Copies)
NASA
George C. Marshall Space Flight Center, Y-E-E
Huntsville, Alabama 35812

E. W. Gomersall (1 Copy)
NASA
Mission Analysis Division
Office of Advanced Research and Technology
Moffett Field, California 94035

G. Hennings (1 Copy)
NASA
Lewis Research Center
Plum Brook Station
Sandusky, Ohio 44871

F. Edeskuty (2 Copies)
Los Alamos Scientific Laboratory
CMF-9
P. O. Box 1663
Los Alamos, New Mexico

A. Schmidt (1 Copy)
National Bureau of Standards
Cryogenic Division
Boulder, Colorado

Dr. A. Acosta (1 Copy)
California Institute of Technology
1201 East California Street
Pasadena, California

Dr. E. B. Konecci (1 Copy)
National Aeronautics and Space Council
Executive Office of the President
Executive Office Building
Washington, D. C.

H. V. Main (1 Copy)
Air Force Rocket Propulsion Laboratory
Edwards Air Force Base
Edwards, California

Library-Documents (1 Copy)
Aerospace Corporation
2400 East El Segundo Boulevard
P. O. Box 95085
Los Angeles, California 90045