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STUDY OF CONTAMINATION OF  
LIQUID OXYGEN BY GASEOUS NITROGEN  
CONTRACT NAS 8-11337

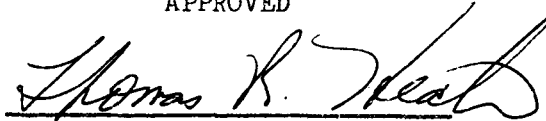
FIRST QUARTERLY PROGRESS REPORT  
1 July 1964 through 30 September 1964

October 1964

Prepared by

Dale A. Fester  
Philip J. Pizzolato  
John R. Wilde

APPROVED



Thomas R. Heaton  
Program Manager

MARTIN-MARIETTA CORPORATION  
MARTIN COMPANY  
Denver Division  
Denver, Colorado

**FOREWORD**

This document is submitted in accordance with Exhibit "A",  
Paragraph II, Sub-paragraph B, of Contract NAS 8-11337, dated June  
27, 1964.

## SUMMARY

Program progress on NASA Contract NAS 8-11337, "Study of Contamination of Liquid Oxygen by Gaseous Nitrogen," for the first quarterly reporting period from 1 July 1964 to 30 September 1964 is presented in this report.

A preliminary analytical model for the system has been developed which takes into account the applicable heat and mass transfer mechanisms. An existing Martin tank pressurization computer program is being modified to incorporate both the transfer processes in the analytical model and property data for liquid and gaseous oxygen and nitrogen over the wide range of conditions being studied. Of particular concern was the development of expressions for the transport properties of the ullage gases at pressure levels above the critical pressure. Most of the desired expressions have been developed and excellent correlation with experimental data has been obtained.

Design of the test system has been completed and procurement of tanks, components, and other material is proceeding. All test equipment will be on hand and construction of the test system will begin in mid-October. All sampling and analysis equipment has been acquired and calibration will be completed by mid-October. Start of testing is planned for the beginning of November.

A description of the test system, tests planned, and test procedure is presented together with the program schedule.

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I. INTRODUCTION

This report details the program progress on NASA Contract NAS 8-11337, "Study of Contamination of Liquid Oxygen by Gaseous Nitrogen," during the first quarterly reporting period from 1 July 1964 to 30 September 1964.

When nitrogen gas is used as the pressurant for LOX, it is absorbed and condensed by the LOX. This LOX dilution is undesirable since it produces the following effects:

- 1) Makes it difficult to maintain constant ullage pressure;
- 2) Yields inaccurate tank-level measurements;
- 3) Reduces engine performance.

In addition, an injector that sustains stable combustion with nitrogen-free LOX could become unstable with nitrogen-contaminated LOX. Since nitrogen gas is employed to pressurize LOX in some phases of the F-1 and J-2 engine programs, contaminated LOX could produce serious effects.

The objective of this program is to determine the extent of LOX contamination by gaseous nitrogen pressurant as a function of the pertinent parameters. Both analytical and experimental studies are being conducted. Empirical correlations of the experimental data will be incorporated in the analytical model to obtain an accurate method for predicting the dilution of LOX by nitrogen pressurant gas.

## II. ANALYTICAL STUDY

### A. ANALYTICAL MODEL

One of the objectives of this investigation is an analytical model permitting the prediction of pressurizing gas requirements as a function of time under a range of operating conditions. Since the extent and distribution of LOX contamination will be determined experimentally, the analytical study is intended to supplement actual pressurization system testing. The analytical model should be sufficiently detailed to predict test results with reasonable accuracy and permit correlation of test data.

The heat and mass transfer processes related to the gas requirements through a gas-phase energy balance are indicated in Figure 1. The energy balance involves terms for the following processes:

a) the addition of enthalpy to the system by entering pressurizing gas,  $h_{ge}, \dot{m}_{ge}$ ;

b) the change in internal energy of the gas phase,

$$\dot{U} = \dot{m}_{tg} u_{tg} + \dot{u}_{tg} m_{tg};$$

c) The loss of enthalpy from the system by mass transfer at the gas-liquid interface or condensation at the tank wall,

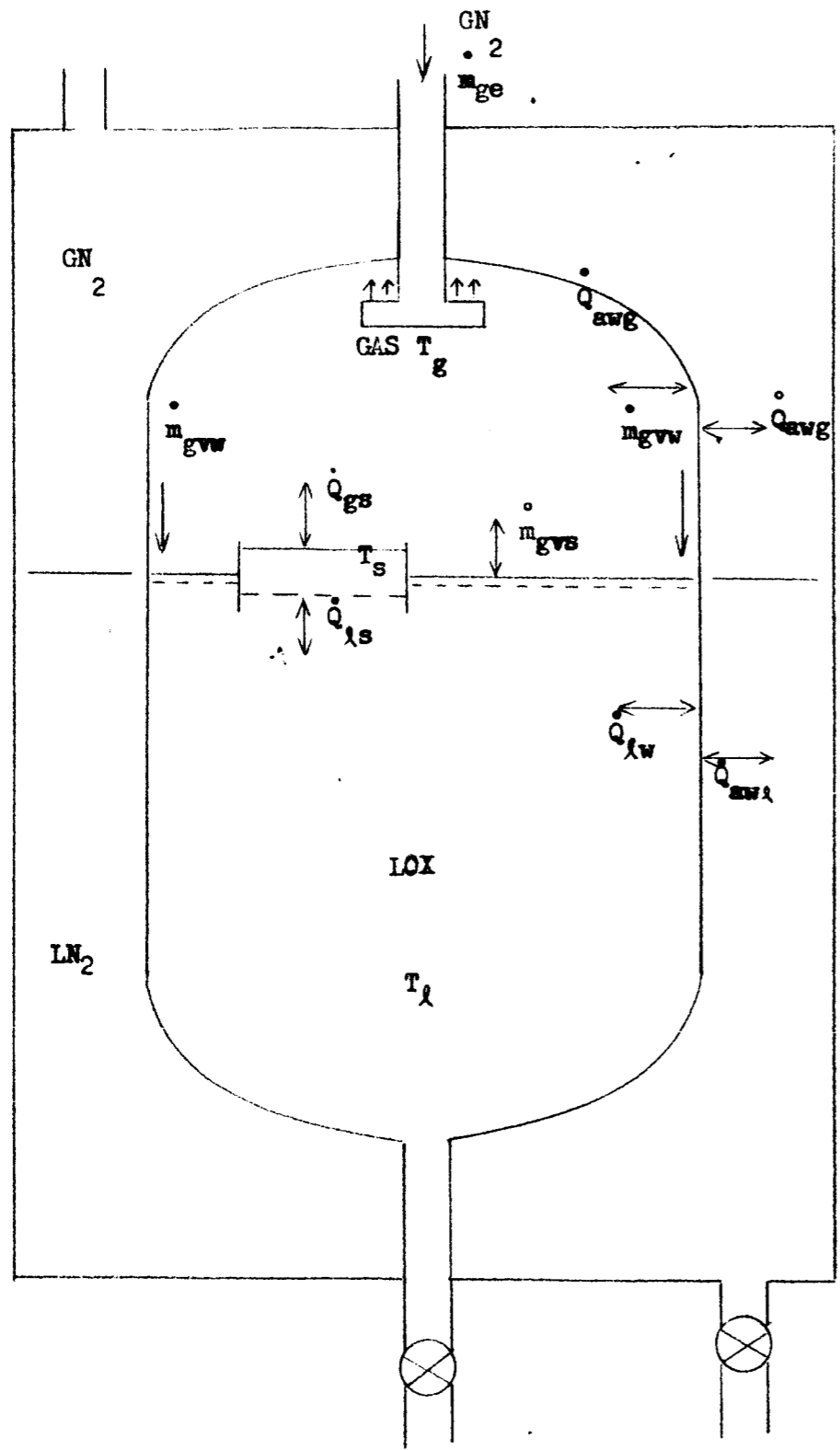
$$\sum h_{gv} \dot{m}_{gv}; \text{ and,}$$

d) the heat transfer from the gas phase to the surroundings, i.e., between the gas and liquid phases and between the gas and tank wall,  $\sum \dot{Q}_g$ .

By definition  $H = U + pV/J$ .



FIGURE 1



- $\dot{m}_{ge}$  = mass flow rate of entering gas
- $\dot{m}_{gvs}$  = mass transfer rate at interface via condensation or evaporation
- $\dot{m}_{gww}$  = mass transfer rate by condensation at tank wall
- $\dot{Q}_{lw}$  = heat exchange rate between liquid and wall adjacent to liquid
- $\dot{Q}_{ls}$  = heat exchange rate between liquid and liquid surface layer
- $\dot{Q}_{gs}$  = heat exchange rate between gas and liquid surface layer
- $\dot{Q}_{gw}$  = heat exchange rate between gas and wall adjacent to gas
- $\dot{Q}_{aw\lambda}$  = heat exchange rate between liquid nitrogen bath and wall adjacent to liquid
- $\dot{Q}_{awg}$  = heat exchange rate between surrounding and wall adjacent to gas

Since the propellant is not being discharged there is no expulsion work being done ( $\dot{pV}/J = 0$ ), the energy balance reduces to

$$\dot{H} = \dot{U} \quad \text{or,}$$

$$h_{ge} \dot{m}_{ge} + \sum h_{gv} \dot{m}_{gv} + \sum \dot{Q}_g = \dot{m}_{tg} u_{tg} + \dot{u}_{tg} \dot{m}_{tg}$$

For a given pressurizing gas inlet temperature and tank pressure, therefore, prediction of the total quantity of gas required for pressurization,  $\dot{m}_{ge}$ , over a given period of time involves determination of the gas phase enthalpy and internal energy changes, mass transfer at the interface and tank wall and heat transfer.

For a near-ideal gas, the enthalpy can be represented by  $c_p T$ , internal energy by  $c_v T$ , and internal energy change by  $c_v \Delta T$ , since  $c_p$  and  $c_v$  can be considered constant over the temperature ranges encountered.

Since two gases are present, the pertinent terms are obtained as the sum of the corresponding terms for each species. The following equations would be used to obtain the changes in total internal energy due to changes in specific internal energy and due to changes in total mass of each gas:

$$\dot{m}_{tg} \dot{u}_{tg} = \dot{m}_{tg} c_v \dot{T}_{tg} = \dot{T}_{tg} (\dot{m}_{go_2} c_{vgo_2} + \dot{m}_{gN_2} c_{vgN_2}) = \dot{T}_{tg} \sum \dot{m}_g c_{vg}$$

$$\dot{m}_{tg} u_{tg} = \sum \dot{m}_g u_g = \dot{m}_{go_2} u_{go_2} + \dot{m}_{gN_2} u_{gN_2}$$

Solutions of the above equations for  $\dot{m}_{tg}$  and  $\dot{T}_{tg}$  requires a knowledge of the thermodynamic properties of the gases concerned, the heat transfer rates, mass transfer rates and pressurant inflow rate and temperature.

It will be assumed that at any given time the ullage gas composition and temperature are uniform, the bulk liquid temperature and composition are uniform, and that the temperature of the liquid surface at any time greater than  $t=0$  is the saturation temperature corresponding to the pressure of nitrogen in the ullage. It will be assumed that the surface layer is pure liquid nitrogen, any oxygen condensed with the pressurizing nitrogen having been added instantaneously to the underlying bulk liquid.

#### B. COMPUTER PROGRAM

Part of the effort during this report period was devoted to consideration of several pressurization system computer programs available at Martin to determine which, if any, might be adapted to this analytical study. Of the three programs evaluated, the Martin  $\emptyset$ DO41, "Tank Pressurization Program," written for the IBM 7094 appeared to be the most readily adaptable to this application. This program makes predictions of time histories for gas pressure, temperature, weight, volume and other pertinent parameters in a propellant tank during missile operation. It provides for pressurization by propellant vapor pressure with or without an inert gas. When the program was employed to describe the performance of an actual pressurization system for a cryogenic propellant, the calculated data showed excellent agreement with test results. Heat transfer is considered between the gas and liquid phases, between the gas phase and the tank wall, and between the tank wall and the surroundings. Mass transfer is considered for surface condensation or evaporation at the gas-liquid interface, for bulk boiling within the liquid phase and for cloud condensation within the gas phase.

Values of C and n (equation 2) determined from curve fitting heat flux rate versus X for vertical and horizontal surfaces and laminar as well as turbulent flow are available from standard heat transfer references.

## 2. Mass Transfer

For the case of a volatile propellant in contact with its vapor, the program considers the most common types of mass transfer - surface evaporation and condensation, and condensation at the tank wall - and also cloud condensation and bulk boiling of the liquid.

The surface temperature is taken as the saturation temperature corresponding to the partial pressure of the vapor above the surface. The direction and extent of surface mass transfer are determined from the enthalpy change between phases and the heat transfer rates between the surface and each phase

$$\dot{m}_{gvs} = \left( \dot{Q}_{ls} - \dot{Q}_{gs} \right) / \left( h_{vg} - h_l \right)$$

For the case of condensation at the tank wall when the wall temperature is below the dew-point of a condensible constituent, standard equations for condensing vapors have been modified for use in the program.

$$h_{cw} = C_c \left[ k_{tg}^3 \Delta h_v \rho_{tg}^2 g/L_w \mu_g (T_{vc} - T_w) \right]^{1/4}$$

$$\dot{Q}_{cw} = h_{cw} A_w (T_w - T_{vc})$$

$$\dot{m}_{gvw} = \dot{Q}_{cw} / (h_{vg} - h_l)$$

### 3. Program Changes and Additions

The chief limitations of the computer program referred to above, in its present form, when considered for application to the LOX contamination analytical study are concerned with the assumptions of

- 1) a single component or pure liquid phase, and
- 2) complete and instantaneous mixing of the bulk liquid via convective transfer leading to a uniform bulk liquid temperature.

The presence of a second condensible gas nitrogen in the gas phase requires the addition of equations describing mass transfer processes involving the pressurant and the data for pressurant gas and liquid properties that are required for the solution of these equations. While the assumptions of complete and instantaneous mixing in the gas phase appears reasonable for the LOX contamination model, extension of this assumption to the liquid phase would lead to calculated pressurizing gas requirements which are controlled by the equilibrium data for the particular conditions of propellant temperature and ullage pressure. Experience has shown that such values based on the vapor-liquid equilibrium data for the binary system are far in excess of the nitrogen absorption or contamination actually observed in pressurization when precautions are taken to avoid direct impingement of entering pressurant on the liquid surface or other conditions leading to liquid turbulence. The equilibrium value of nitrogen in LOX for given conditions of LOX temperature and tank pressure represents an upper bound not likely to be approached under static conditions. Apparently, the ability of the main body of liquid to exchange heat energy with

the gas phase is limited by the low thermal conductivity of the liquid. Bowersock and Reid (2) point out, however that temperature measurements made in and near the liquid surface during pressurization of cryogenic liquid storage tanks, have shown temperature - depth gradients to be smaller than would be predicted from treatment of the bulk liquid as a semi-infinite slab whose surface temperature was increased instantaneously from the bulk temperature to the saturation temperature at a new ullage pressure. This discrepancy is believed to be the result of an increase in heat flux due to the presence of some convective heat transfer accompanying the conductive transfer. To more closely approximate the heat flow to the liquid, Bowersock and Reid proposed a "film model." In this model the original liquid surface is assumed to remain at the bulk temperature and the rate of heat transfer is assumed to be limited by conduction through the film of liquid condensed on the original liquid surface. The following expression was derived for the heat transfer to the bulk liquid

$$Q_L = A_L \left[ 2t (T_s - T_L) \Delta hr (k\rho)_f \right]^{1/2}$$

The proportionality constant,  $r$ , provides for modification of the theory to fit existing data, thereby allowing for variations in system parameters, fluid properties, pressurization levels and time.

The computer program  $\emptyset$ DO41 was designed for use with systems operating over the relatively narrow pressure range of ambient to 150 psia. Since the effect of pressure on the gas transport properties  $\mu$  and  $k$ , and on  $p$  and  $Z$  is small over this range, the effect of pressure on these properties has been neglected in the

interest of simplicity.

Over the range of pressures to be considered in this study up to 5000 psia, however, the effect of pressure on these gas properties must be taken into account. Adaptation of the computer program will require inclusion of equations which compute the gas properties as a function of pressure as well as temperature.

Expressions for the variation of viscosity and thermal conductivity of gases with temperature and pressure have been developed at the Martin Company (3). For the coefficient of viscosity the equation is

$$\mu_{T,P} = \mu_{T_0,P_0} \left( \frac{T}{T_0} \right)^{3/2-B} \left[ \frac{1 + \left( \frac{S}{T_0} \right)^B - \int \left( \frac{S}{T_0} \right)}{1 + \left( \frac{S}{T} \right)^B - \int \left( \frac{S}{T} \right) \left( \frac{\rho RT}{P_0} \right)} \right]$$

$$T_0 = 273.2 \text{ } ^\circ\text{K}, \quad P_0 = 1 \text{ atm.} = 14.7 \text{ psi}$$

Gas	$\mu_{T_0, P_0}$ micropoises	S(°K)	n	$\int$	$B = \frac{n-3}{n-1}$
O <sub>2</sub>	192.33	119.9	$\infty$	0.00430*	1.000
N <sub>2</sub>	165.85	90.0	92.9	0.00550	0.9782
*Estimated					

A similar expression applies to the coefficient of thermal conductivity

$$k_{T,P} = k_{T_0,P_0} \left( \frac{T}{T_0} \right)^{3/2-B} \left[ \frac{1 + \left( \frac{S}{T_0} \right)^B - \int \left( \frac{S}{T} \right)}{1 + \left( \frac{S}{T} \right)^B - \int \left( \frac{S}{T} \right) \left( \frac{\rho RT}{P_0} \right)} \right]$$

GAS	$k_{T_0,P_0}$ $\left( \frac{\text{cal}}{\text{cm-sec-}^\circ\text{K}} \times 10^{-6} \right)$	S( $^\circ\text{K}$ )	n	$\int$	$B = \frac{n-3}{n-1}$
O <sub>2</sub>	58.73	106.4	13.9	0.00430*	0.3333
N <sub>2</sub>	57.92	117.6	26.3	0.00550	0.9209

\*Estimated

The compressibility factor, Z, at high pressures will be determined from Enshog's dense gas theory using viscosities at high pressures calculated as indicated above. This will require use of the equation of state to insure the compatibility of the compressibility and density data.

For the determination of specific heat,  $C_p$ , at elevated pressures, a relationship between  $C_p$  and Prandtl number is being sought in order that the elevated pressure  $\mu$  and k data obtained as indicated above can be used in evaluating  $C_p$  from the expression

$$N_{Pr} = C_p \frac{\mu}{k}$$



### C. FUTURE EFFORT

When the modifications and additions described in the preceding section have been made to the computer program being adapted for this study, the preliminary analytical model and modified program will be checked by comparison of calculated pressurizing gas requirements with test data taken in early runs in the test phase of the study. Based on the results of such comparisons, refinements will be made in the analytical model and the associated computer program until calculations based on the model agree satisfactorily with test data.

III. EXPERIMENTAL PROGRAM

#### A. OBJECTIVES

The objective of the experimental program is to provide accurate data for correlation with the analytical model on the contamination of Liquid Oxygen by Gaseous Nitrogen. The extent of contamination must be primarily determined by experimentation because of the many complex processes involved which are not amenable to direct theoretical analysis.

## B. DESCRIPTION OF SYSTEM

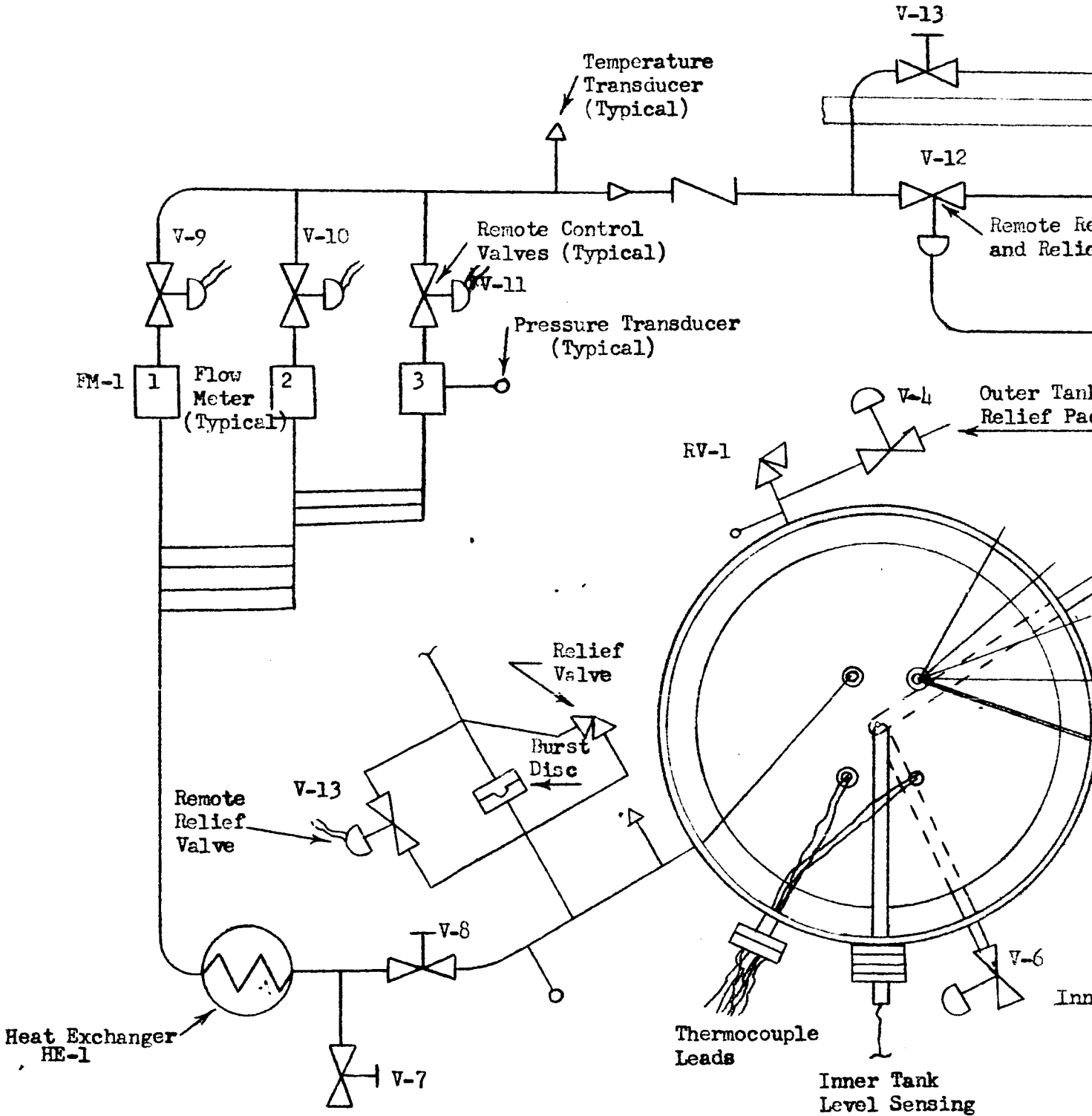
The experimental system to be used in conducting the planned 26 test runs is shown in Figures 2 and 3. Two different inner tank configurations, one spherical and one cylindrical, have been designed and fabricated in order to obtain information on the effects of tank configuration on contamination.

The spherical tank, with an inside diameter of 24 inches, has a volume of approximately 4.2 cubic feet. It was designed for a working pressure of 5000 psig per the ASME code for unfired pressure vessels. The cylindrical tank has the same diameter and consists of a one foot barrel section and two elliptical heads. Overall length is 2.5 feet. This tank has a working pressure ranging from 0 psia to 100 psig. Six pierce points have been incorporated in each tank, five in the top dome and one in the bottom. Loading and draining operations will be conducted through the bottom port with all other functions accomplished through one or more of the five top ports. Temperature and liquid level of the LOX will be monitored with two thermocouple rakes but an additional port has been incorporated for a float mechanism should the thermocouple technique of liquid level sensing prove inadequate. The two remaining pierce points are for the sample lines and the pressurization line.

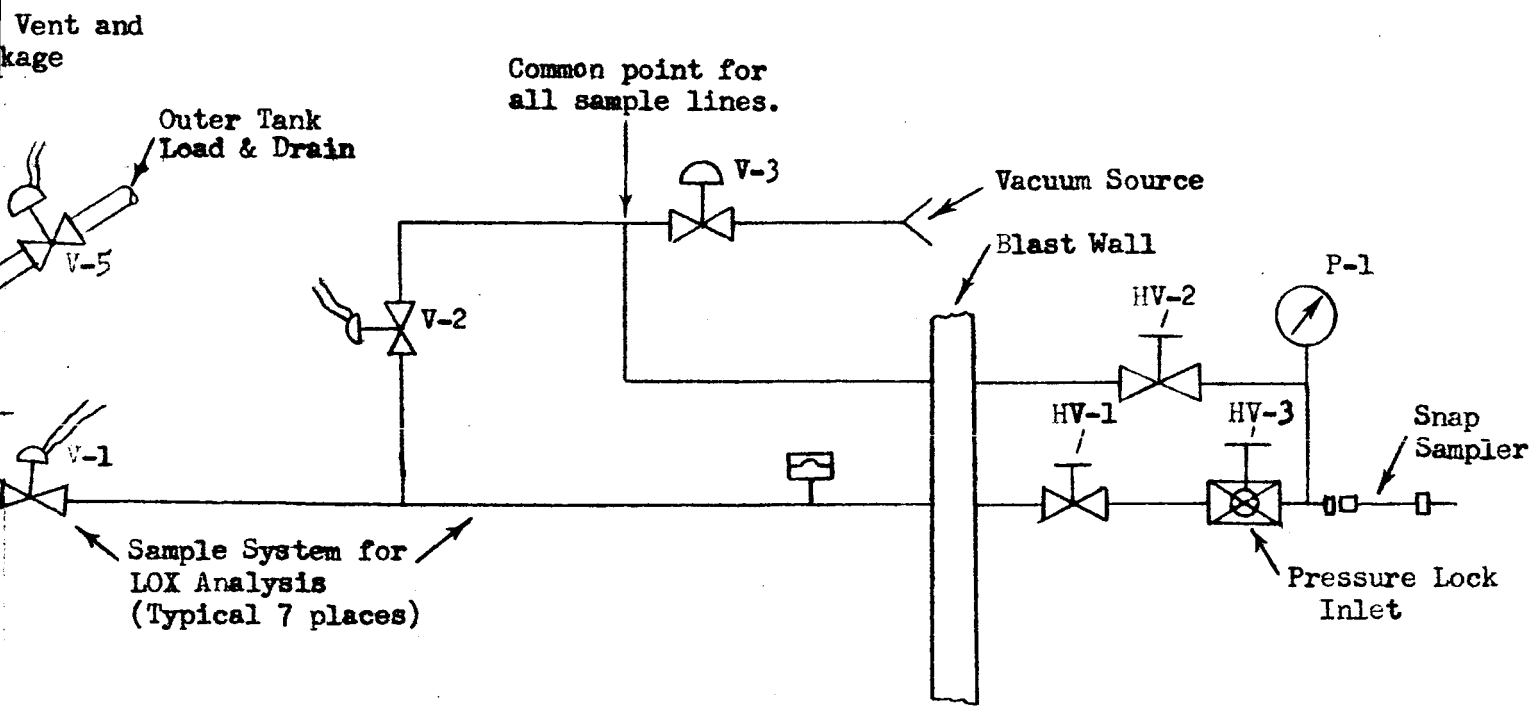
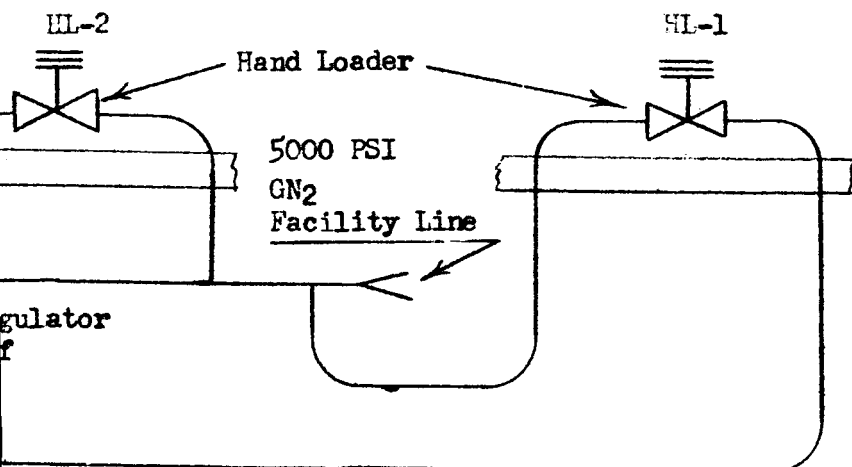
A second and larger cylindrical tank is used as a liquid nitrogen bath to control the temperature of the LOX in the smaller vessel. This tank completely encloses the smaller vessel and is pressurized to control the boiling point of the contained liquid nitrogen and consequently the LOX temperature. Standardized mountings allow either LOX vessel to

FIGURE 2

SCHEMATIC INSTAL



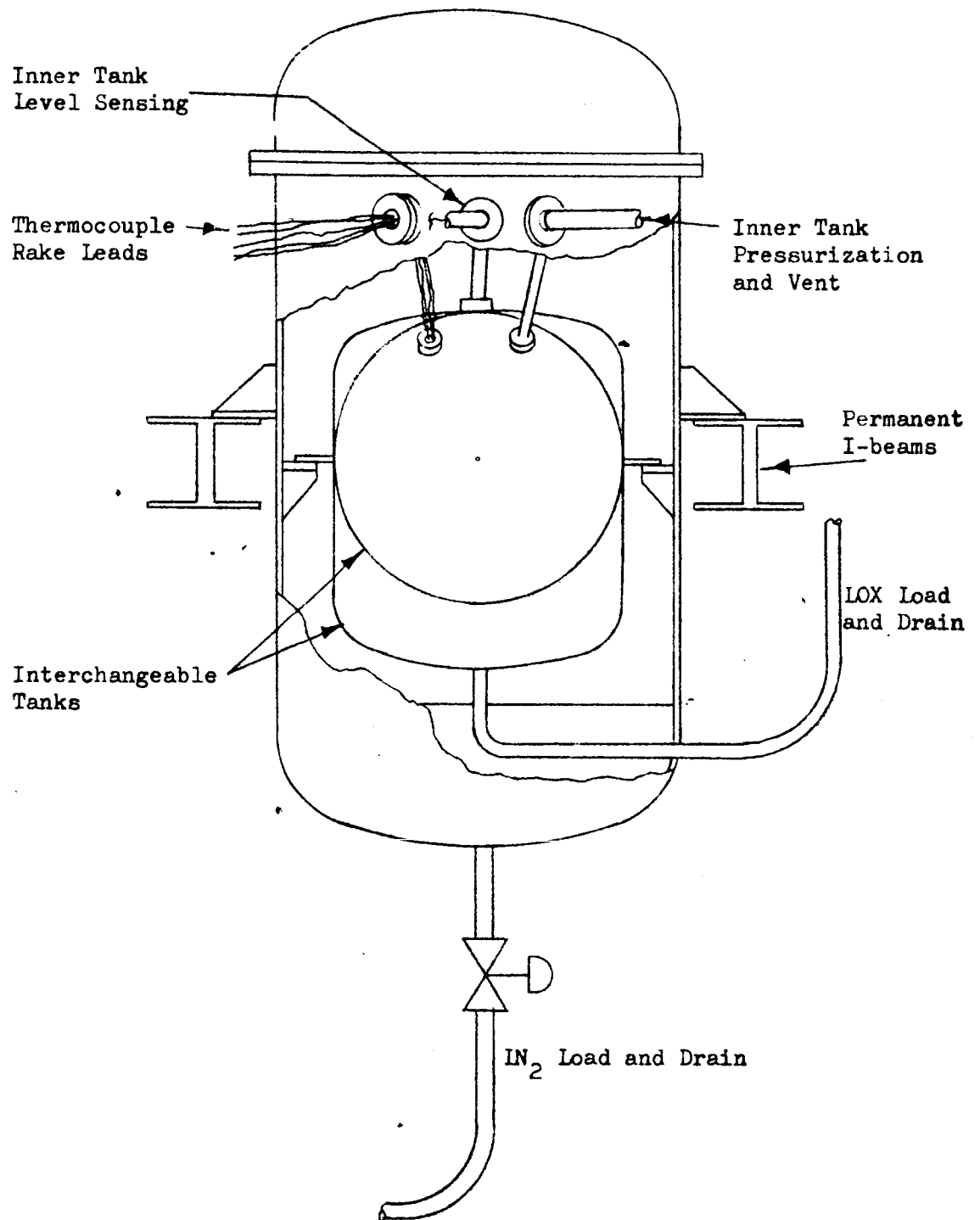
ATION DRAWING



er Tank Load & Drain

FIGURE 3

## TANK DETAIL



be used without modifications to the tankage. Magnetic float switches along the wall of the outer tank monitor the boil-off rate of the nitrogen. The nitrogen is replenished remotely through the bottom port in the jacketing tank. The vaporized nitrogen is discharged from the tank through a relief valve set at the appropriate pressure level, thereby providing the desired liquid nitrogen temperature.

The LOX tank in use will be pressurized with dry nitrogen gas from the existing facility supply tanks. The gas will be controlled by one of two hand regulators mounted behind the blast wall (Figure 2). Temperature conditioning will be accomplished before tank entry in a line heat exchanger using electrically heated air as the control fluid. Flow rates of the  $\text{GN}_2$  will be measured by one of three flowmeters in parallel to provide accurate measurement of nitrogen gas charged to the system over the planned flow-rate range. Samples of the contaminated LOX will be taken through five of the seven sampling lines positioned to provide good cross-sectional samples of the liquid. Seven points have been found necessary to obtain adequate data for all twenty six runs due to the variation in liquid-vapor interface position from run to run. Only five of these points will be necessary for any given run, the remaining two will be capped at the tank outlet ports. The equipment necessary for a typical sampling point is shown in Figure 2. All of the equipment in the blast wall enclosed test cell is remotely operated and has sufficient safety provisions to relieve any undue pressure build up. A detailed report of this system is given in the procedure section of this chapter. Not shown in the Figures, but present in the test cell area, is a gas chromatograph which will be used to analyze the samples taken.



## C. TESTS PLANNED

Twenty-six test runs and two checkout runs are planned for the experimental effort. The amount and distribution of dissolved nitrogen in LOX will be determined as a function of:

- 1) Tank pressure (constant and cycling) over a range from 15 psia to 5000 psia;
- 2) LOX temperature;
- 3) Exposure time;
- 4) Liquid/gas volume ratio;
- 5) Liquid/gas interfacial area;
- 6) Gaseous nitrogen inlet temperature;
- 7) Tank geometry.

A list of the planned test runs with the parameters to be held constant for each run is given in Table I. These tests are specifically designed to provide information for the analytical model.

Three runs with the cylindrical tank will be accomplished first, preceeded by a checkout run. Installation and checkout of the spherical tank system will follow the cylindrical tank tests. The spherical tank runs, comprising the major portion of the experimental effort, will be accomplished last.

TABLE I. PLANNED TEST RUNS

RUN NO.	ULLAGE PRESSURE (PSIA)	LOX TEMPERATURE ( $^{\circ}$ F)	$V_L/V_U$	$A_s$ (Ft $^2$ )	Gaseous Nitrogen Inlet Temperature ( $^{\circ}$ F)
CYLINDRICAL TANK					
1	100	-297	7.02	3.14	Ambient
2	100	-297	2.34	3.14	Ambient
3	100	-297	1.00	3.14	Ambient
SPHERICAL TANK					
4	15	-297	1.00	3.14	Ambient
5	100	-297	1.00	3.14	Ambient
6	500	-297	1.00	3.14	Ambient
7	1000	-297	1.00	3.14	Ambient
8	3000	-297	1.00	3.14	Ambient
9	5000	-297	1.00	3.14	Ambient
10	100	-290	1.00	3.14	Ambient
11	500	-290	1.00	3.14	Ambient
12	5000	-290	1.00	3.14	Ambient
13	100	-285	1.00	3.14	Ambient
14	500	-285	1.00	3.14	Ambient
15	5000	-285	1.00	3.14	Ambient
16	15	-297	2.34	2.90	Ambient
17	100	-297	2.34	2.90	Ambient
18	5000	-297	2.34	2.90	Ambient
19	15	-297	7.02	2.16	Ambient
20	100	-297	7.02	2.16	Ambient
21	5000	-297	7.02	2.16	Ambient
22	cycling*	-297	1.00	3.14	Ambient
23	cycling*	-297	1.00	3.14	Ambient
24	100	-297	1.00	3.14	35
25	100	-297	1.00	3.14	75
26	100	-297	1.00	3.14	150

\* Pressure will be cycled between 50 and 100 psig for duration of run.

NOTE: 1.  $V_L/V_U$  = Ratio of LOX volume to gaseous nitrogen volume.

2.  $A_s$  = Liquid/gas interfacial area.

#### D. TEST PROCEDURE

The tests will be conducted according to the following general procedure. This sequential list does not contain the detail required to conduct the test but does present a comprehensive procedure for all major functions. The detailed checklist will be prepared by the test group and submitted to the program manager for approval before the next monthly reporting period.

The steps for a typical test run, referring to Figure 2, are:

- (1.) Verify by visual inspection that the system is installed in accordance with the installation drawings.
- (2.) Verify that the instrumentation is calibrated at ambient temperature and pressure and that all functions are operating properly.
- (3.) Evacuate the inner (LOX) tank through the sample lines by opening valves V-1, 2, and 3.
- (4.) Close valve V-1 and load the outer (bath) tank with liquid nitrogen through valve V-5. Valve V-4 must be open to vent the outer tank during loading operations.
- (5.) Loading will be completed by closing Valve V-5 when the float switch on the outer tank wall indicates the LN<sub>2</sub> level has reached the predetermined level. The operations will then be put in a hold condition to allow the LN<sub>2</sub> to reach the desired temperature which will be indicated by the relief valve RV-1 discharging GN<sub>2</sub>.

- (6.) Open Valve V-6 and commence to load the premeasured LOX into the inner tank. Terminate loading by closing valve V-6 when the proper quantity of LOX has been loaded as indicated by the level in the tank.
  - (7.) Take one sample of LOX for analysis from each of the five applicable sample points, (a detailed procedure for sampling is presented in the last half of this section).
  - (8.) Pressurize the LOX tank as follows:
    - (a) Close valves V-7, 10, 11, 12 and 13.
    - (b) Open valves V-8 and 9.
    - (c) Actuate the heat exchanger, HE-1
    - (d) Slowly open regulator V-12 with Hand Loader HL-1. V-12 should be brought up to full pressure slowly so as not to overspeed the flowmeter, FM-1.
    - (e) When V-12 has reached full pressure and flow has dropped to 5% of full scale on FM-1 open valve V-10 and close V-9 switching flow through the smaller flowmeter FM-2.
- NOTE:** If flow should drop to 5% of full scale on FM-2, repeat the switching operation to bring FM-3 into use.
- (9.) When tank pressure has reached the full test level, record the time and take samples of the LOX for later analysis.
  - (10.) Take samples every subsequent hour for the remainder of the run.
  - (11.) At the end of the run, close regulator V-12 and vent the LOX tank through valve V-13.
  - (12.) Unload the LOX through valve V-6 into the catch reservoir outside of the immediate test area.

- (13.) Unload the liquid nitrogen in the outer tank into a similar reservoir.
- (14.) Close down the system and make a visual inspection of the equipment.

The LOX sampling system has been designed for this particular application and is the critical element in the test. Care has been taken in designing the system to assure representative samples, but procedural juggling will be necessary if the system is to be used correctly. The initial procedure to be attempted on the first checkout run is as follows.

- (1) Place the snap sampler in the pressure lock inlet with valve HV-3 in the open position.
- (2) Open valves V-2, V-3, HV-1, and HV-2 and evacuate the system up to valve, V-1.
- (3) Close valves V-2 and HV-2.
- (4) Open and close valve V-1 to let a small sample of LOX into the sample lines. After vaporization a predetermined pressure reading on gauge P-1 will indicate that the sample line in the tank has been completely purged.
- (5) Evacuate the system through Valve V-2 and HV-2.
- (6) Close valves V-2 and HV-2 and open and close valve V-1 trapping a representative sample of LOX.
- (7) Allow the sample to vaporize and come to room temperature.
- (8) Trap a sample in the snap sampler and retract the stem from HV-3.

- (9) Close HV-3 and open HV-2 until gauge P-1 indicates ambient pressure.
- (10) Remove the snap sampler and analyse the gas trapped.
- (11) After analysis of the sample reinstall the snap sampler in the system and open valve HV-3. This will prepare the system for the next sampling.

Minor modifications in this procedure will be necessary as the peculiarities of the system are discovered through use.

## E. PROGRESS TO DATE

The effort expended on the experimental portion of the program during the first quarter was concentrated on designing the system and procuring components. The design has been completed (Martin drawing series CFL610077X) with only minor areas amenable to modification. These areas are subject to the requirements of the analytical model; consequently design provisions have been incorporated for some later modification without excess cost or schedule slippage. An example of this type of designing is found in the probe used to obtain samples from the LOX tank. The probe will be fabricated but the exact positions of the probe inlets will not be fixed until just prior to testing.

Component delivery dates extend through Oct. 17. However, 90% of the components will be on hand by Oct. 8 allowing build to begin Oct. 12. Cell 2 of the Cold Flow Laboratory has been cleared of past test equipment and the tank mounts have been welded in position in preparation for tank delivery and installation.

All sample analysis equipment has been procured and is ready for calibration. Preliminary checkout runs with samples of air indicate satisfactory performance will be obtained and the desired accuracy will be achieved. The gas chromatograph, a Beckman Model GC-2, is in position and calibration equipment has been set up with the exception of a vacuum pump. The pump is being cleaned as part of the process in making it compatible with gaseous oxygen. Calibration of the gas chromatograph will be accomplished prior to completion of the test system installation.

IV. PROGRAM SCHEDULE



PROGRAM SCHEDULE

	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
Development of Analytical Model	[Solid bar from Jul to Oct]											
Test Fixture Design and Procurement	[Solid bar from Aug to Nov]											
Test Fixture Fabrication	[Solid bar from Sep to Dec]											
Design and Fabrication of Cylindrical Tank	[Solid bar from Oct to Feb]											
Cylindrical Tank Installation and Checkout	[Solid bar from Nov to Mar]											
Checkout of Sample Analysis Technique	[Solid bar from Dec to Apr]											
Cylindrical Tank Tests	[Solid bar from Jan to May]											
Design and Fabrication of Spherical Tank	[Solid bar from Feb to Jun]											
Spherical Tank Installation and Checkout	[Solid bar from Mar to Jun]											
Spherical Tank Tests	[Solid bar from Apr to Jun]											
Analytical Model Refinements	[Solid bar from May to Jun]											
Reporting	○	○	○	●	○	○	○	○	○	○	○	○
												◆

○ Monthly  
● Quarterly  
◆ Final

V. NOMENCLATURE

A	=	area
a	=	acceleration
C	=	Constant
$c_p$	=	specific heat capacity at constant pressure
$c_v$	=	specific heat capacity at constant volume
H	=	total enthalpy
h	=	specific enthalpy, or heat transfer coefficient
J	=	Joule constant
k	=	thermal conductivity
L	=	length
M	=	molecular weight
m	=	mass
$N_{pr}$	=	Prandtl number
n	=	number of moles
p	=	pressure
Q	=	heat quantity
$R_u$	=	universal gas constant
r	=	proportionality constant
s	=	entropy, or Sutherland constant
T	=	temperature
t	=	time
U	=	total internal energy
u	=	specific internal energy
V	=	total volume, or velocity
v	=	specific volume
X	=	product of Grashof and Prandtl numbers
Z	=	compressibility factor

- $\beta$  = thermal coefficient of volumetric expansion  
 $S$  = constant in equation for viscosity and thermal conductivity at high pressures  
 $M$  = absolute viscosity  
 $\rho$  = mass density

## subscripts

- c = condensation (e.g.,  $Q_{cw}$ )  
e = entering  
f = film  
g = gas  
i = initial  
l = liquid  
s = static or surface  
t = tank or total  
v = vapor or vaporization  
w = wall

## superscripts

- . = first derivative with respect to time  
n = exponent

VI. REFERENCES

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3. Simon, W. E., Martin-Denver, private communication, Sept. 24, 1964.