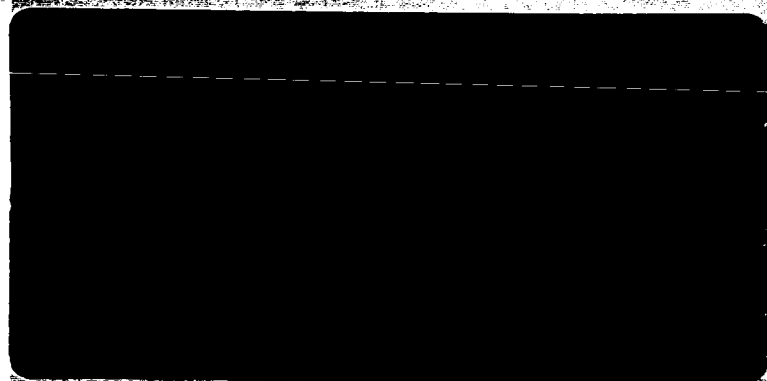


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STUDY OF CONTAMINATION OF
LIQUID OXYGEN BY GASEOUS NITROGEN
CONTRACT NAS 8-11337
THIRD QUARTERLY PROGRESS REPORT
1 January 1965 through 31 March 1965

April 1965

Prepared by

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FOREWORD

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

SUMMARY

22563

Program progress on NASA Contract NAS 8-11337, "Study of Contamination of Liquid Oxygen by Gaseous Nitrogen," for the third quarterly reporting period, from 1 January 1965 to 31 March 1965, is presented in this report.

The majority of work on the analytical portion of the program has been directed toward completion of the main computer program and its associated subroutines. In addition, special emphasis was placed on developing and improving the basic transport property relationships required. Portions of the computer program are in the check-out-debug phase where this can be accomplished by sections. Other work in progress includes some compiling and the coding of transport property relationships required for two of the subroutines.

Construction and check-out of the spherical tank system was accomplished and all of the planned test runs have been completed. The system is presently being held in standby condition. Only relatively minor problems were encountered during testing; these problems did not adversely affect successful completion of the experimental effort. Approximately 50 per cent of the data, recorded on strip charts, has been reduced to tabular and/or graphical form.

Detailed discussion of progress on both the analytical study and the experimental program is presented in the main body of the report.

Author

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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 third quarterly reporting period from 1 January 1965 to 31 March 1965.

When gaseous nitrogen is used as the pressurant for liquid oxygen, contamination of the liquid oxygen occurs through absorption and condensation of the nitrogen. Since the contamination can produce adverse effects in missile and booster performance both prior to and after launch, this program was undertaken to evaluate the magnitude of the contamination. The influence of liquid temperature, tank ullage pressure, inlet nitrogen gas temperature, liquid-vapor interfacial area, liquid-vapor volume ratio, and tank geometry is being assessed both experimentally and analytically. Empirical correlations of the experimental data will be combined in the analytical model to provide a method for predicting the dilution of LOX by nitrogen pressurant gas.

II. ANALYTICAL STUDY

Efforts on the analytical phase of this work during the past quarter have been directed mainly toward completion of the main computer program and its associated subroutines. The basic transport property relationships required by the computer program received special emphasis. Portions of the program are in the check-out-debug phase where this can be done by sections. Other work in progress includes some compiling and the coding of transport property relationships required for two of the subroutines.

A. COMPUTER PROGRAM FOR LOXCON ANALYTICAL MODEL

The bulk of the computer program to be used in the analytical phase of this study was coded and punched in the past quarter and about 50 per cent of the compiling has been accomplished. Completed portions include the main computer program together with its input and output sections, and the equation of state, tank geometry, and film coefficient subroutines. Compiled portions of the program are being checked and debugged. Completion of the transport properties subroutine has been delayed by recent changes in the viscosity and thermal conductivity equations aimed at improving the agreement between calculated and tabulated data over certain parts of the range of pressures and temperatures to be considered.

The relatively large equation of state subroutine has been compiled satisfactorily and is being debugged of minor errors in logic encountered in check-out.

The program has developed to fairly sizable proportions with the source deck now numbering about two thousand cards. Despite

the size of the computer program, running time for the calculations at any given time interval should be reasonably small. All main computer program calculations are done directly except for the pressurant gas flow which is calculated by iteration using the regula-falsi method. The acceptable error level is adjustable and is now set for 0.05%. Subroutine calculations are all direct except for that using the equation of state to determine density of the ullage gas when temperature and pressure are input. This calculation involves an iteration by the Newton-Raphson method backed up by the regula-falsi method.

A flow chart indicating the steps to be employed in the main computer program and how the various subroutines are to be used is presented in Figure 1.

Preliminary listings for the LOXCON main computer program, and for the tank geometry and equation of state subroutines have been reproduced as Appendices A, B, and C.

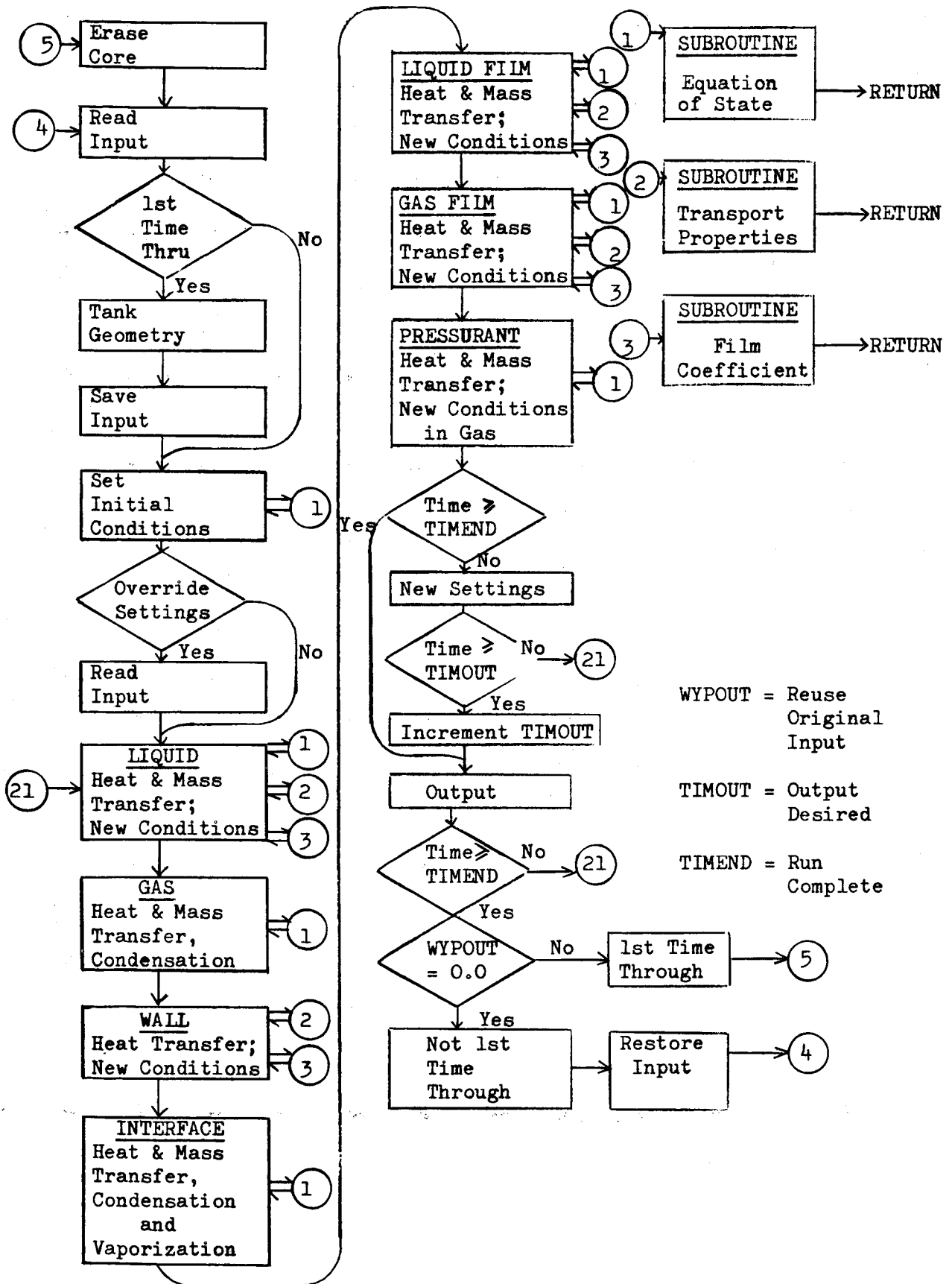


Figure 1 - LOXCON Computer Program Flow Chart

B. TRANSPORT PROPERTIES RELATIONSHIPS

The availability of reliable viscosity and thermal conductivity data for the combination of high pressures and low temperatures has been a requirement more or less peculiar to this particular study. The equations for the viscosity and thermal conductivity of gases as functions of temperature and pressure, presented in an earlier progress report (1)*, have been programmed for computer calculation and checked for agreement with tabulated data in the liquid and the high pressure-low temperature reaches of the two-phase region. Since observed discrepancies were significant, efforts have been underway to improve the accuracy of calculated data in these ranges by replacing one of the constants with a function of density involving adjustable constants.

One of the more important internal calculations of the main computer program involves determination of the heat and mass transfer rates for condensation or vaporization occurring at the gas-liquid interface. This calculation requires reliable estimates of the diffusion coefficients for the components in the gas and liquid interfacial films. Evaluation of techniques for estimating these coefficients has indicated that for gases for which reliable viscosity data are available the most accurate approach is the use of equations relating the coefficients of diffusion and viscosity. The relationship derived by Weissman and Mason (2) for binary mixtures of gases is being used in this work.

* Numbers in parentheses designate references.

It has the following form:

$$(p D_{12})^2 a + (p D_{12}) b + (p D_{12}) A_{12}^* c + A_{12}^* d = 0$$

where:

p = pressure, atm.,

A_{12}^* = ratio of collision integrals, i.e.,

$$A_{12}^* = \Omega^{(2,2)*} / \Omega^{(1,1)*}, \text{ which depends only}$$

weakly on the temperature and the force law,

and

$$a = (X_1 X_2)^2 (\mu_{\text{mix}} - \mu_1 - \mu_2) / \mu_1 \mu_2,$$

$$b = 2 X_1 X_2 (M_1 + M_2)^{-1} RT \left[\mu_{\text{mix}} (X_1^2 \mu_2 + X_2^2 \mu_1) - \mu_1 \mu_2 \right] / \mu_1 \mu_2,$$

$$c = \frac{6}{5} X_1 X_2 (M_1 + M_2)^{-1} RT \left[\mu_{\text{mix}} (X_1^2 M_1^2 \mu_2 + X_2^2 M_2^2 \mu_1) - (X_1 M_1 + X_2 M_2)^2 \mu_1 \mu_2 \right] / M_1 M_2 \mu_1 \mu_2$$

$$d = 3/5 (2 X_1 X_2 RT)^2 \mu_{\text{mix}} / M_1 M_2$$

X_1 and X_2 = mole fractions of components, dimensionless,

M_1 and M_2 = mol. weights of components, grams/gram-mole,

μ_1 and μ_2 = viscosities of components, poises,

μ_{mix} = viscosity of mixture, poises,

T = °K,

R = 82.0567 cm³-atm/mole-°K (gas constant).

For the diffusion coefficient of liquid mixtures the Wilke-Chang (3) correlation is being used. This expression is written:

$$D_{12} = 7.4 \times 10^{-8} \frac{(XM)^{1/2} T}{\mu V_1^{0.6}}$$

where:

D_{12} = diffusion coefficient of solute 1 in solvent 2 at temperature T, cm²/sec,

M = molecular weight of solvent, gram/gram-mole,

T = temperature, °K,

μ = viscosity of solution, centipoises,

V_1 = molal volume of solute at normal boiling point, cm³/g mole,

X = "association" parameter of solvent;
for unassociated solvents, X = 1.0.

By use of the coefficient of viscosity, μ , calculated for the mixture at the operating pressure, the effect of pressure on the diffusion coefficient is taken into account.

C. FUTURE EFFORT

The coding, compilation, and check-out of subroutines will be continued. When all parts of the program have been completed and satisfactorily checked out, the overall operation of the program will be tested with representative input data. This phase of the work should begin in about two weeks.

After satisfactory operation of the overall program has been established, program output will be compared with actual test data at various levels of operating conditions to determine what adjustments in the program will be required to bring calculated results into reasonable agreement with the observed test data.

Effort on the final report will begin in approximately one month.

III. EXPERIMENTAL PROGRAM

During the past quarter, effort on the experimental portion of the program was concentrated on completion of the 23 planned test runs with the spherical tank. After performance of the final run, the test system was placed in standby condition to obviate reconstruction should additional programs with this system prove desirable. An extensive amount of data was recorded on strip charts during the course of testing. This data is presently being reduced from strip-chart to tabular and/or graphical form; approximately 50 per cent of this work has been accomplished.

A. TEST SYSTEM AND PROCEDURE

Construction of the test system for the spherical tank tests was completed the week of 11 January 1965. The system included the inverted containers for fine control of the IN_2 level in the jacketing tank which were discussed in detail in the Second Quarterly Progress Report (4). To circumvent leakage problems, all fittings were seal welded to the spherical tank. This welding was required since tool chatter marks on the tank port sealing surfaces prevented effective use of K-seals. The system was leak checked by submerging the tank in IN_2 and pressurizing with helium to 500 psia. Observation of the tank substantiated that a leak proof system had been obtained. Leak checks to higher pressures were delayed until after all runs at 500 psia or lower had been completed, i.e., Runs 4 through 19. Prior to Run 20, the tank system was locked up at 5000 psia and the pressure was monitored. No appreciable pressure decay occurred during a 30-minute hold period, thereby indicating that

leakage was negligible. The sample system, including the pressure lock inlets for the snap samplers, was leak checked prior to every run by evacuating the entire system and watching for vacuum decay. Any leaks were immediately isolated and repaired.

The level control mechanism in the IN_2 jacket allowed maintenance of the liquid level within 1/4-inch of that desired. The system was employed in the following manner:

- 1) The IN_2 jacket was intentionally filled above the desired run level during IN_2 loading.
- 2) After LOX had been loaded to the desired level in the inner tank, the jacket vent was closed and the IN_2 allowed to warm to the desired temperature (indicated by jacketing tank pressure).
- 3) The inverted containers in the level control system were filled with IN_2 by back-bleeding GN_2 from the containers through the helium injection line. This provided the maximum amount of liquid for later displacement into the jacket.
- 4) The GN_2 backflow was maintained and the jacket level was lowered to that desired, i.e., jacket level same as LOX level in inner tank. This resulted in the IN_2 level in the containers being above the level in the jacket.
- 5) At this point the run was initiated. To maintain a constant jacket level, it was necessary to displace IN_2 from the containers into the jacket at the same rate that IN_2 was vaporized and vented from the jacket. As long as the container level was above the jacket level, this was accomplished by controlling the GN_2 backflow rate at a value lower than the vaporization rate in the containers.

- 6) When the liquid level in the containers had dropped to the jacket level, GN_2 backflow was stopped and flow of pressurized helium into the containers was begun.
- 7) Control of the helium inlet rate allowed continuation of the constant jacket level. When all LN_2 was displaced from the containers, jacket level control was lost and the run was terminated.

LOX loading to a precise level was accomplished by employing the two thermocouple rakes in the inner tank as liquid level sensors. Location of the thermocouple rakes is shown schematically in Figure 2. During loading, LOX was introduced into the evacuated inner tank at or above its ambient boiling temperature of -300°F . All thermocouples immediately sensed this temperature. When flow ceased, thermocouples not submerged in LOX dropped rapidly toward the lower LN_2 temperature in the jacketing tank. This cooling was due to heat transfer from the ullage gas to the surrounding LN_2 which nearly submerged the inner tank due to the overfilling described previously. By loading in a stepwise fashion with short flow periods, the desired LOX level was obtained by observing the thermocouple reactions. During LOX loading for three or four of the runs, the thermocouples did not react in normal fashion and LOX level exceeded that desired. In these cases, the excess LOX was removed by slight, momentary pressurization with the LOX tank drain open.

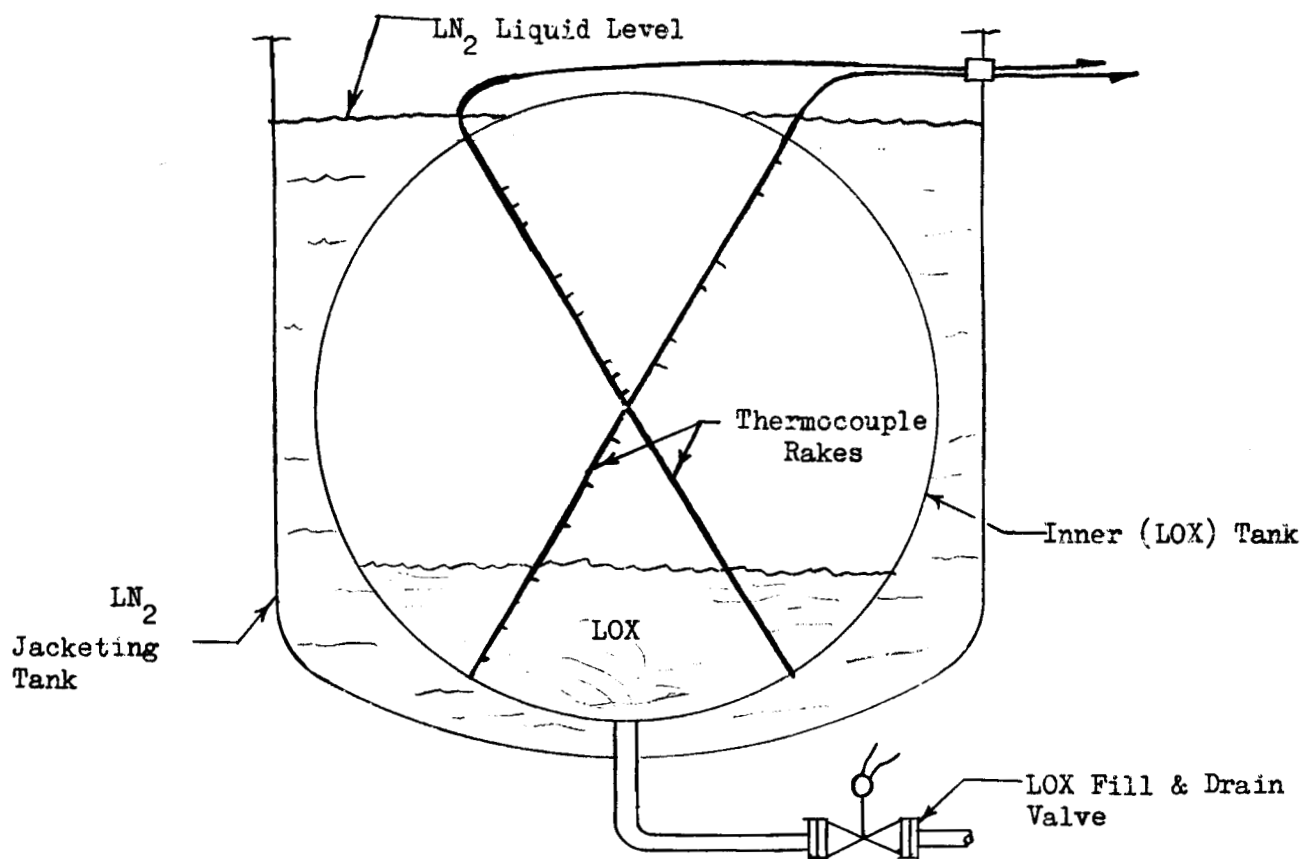


FIGURE 2

Schematic Diagram of Thermocouple Rake Arrangement

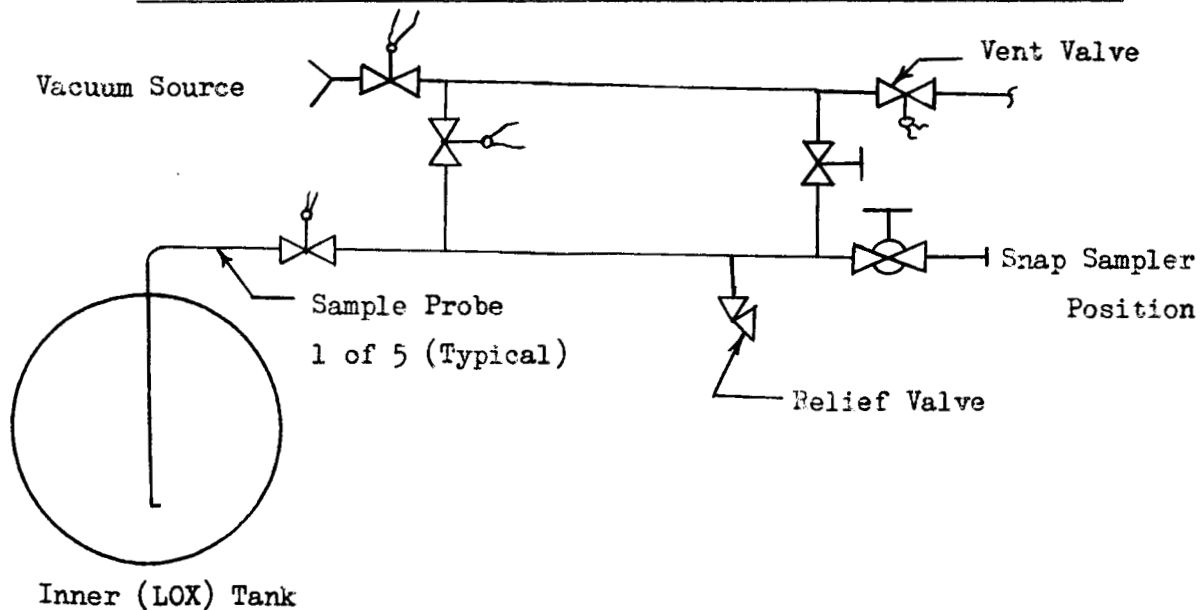


FIGURE 3

Schematic Diagram of Sample System

B. TESTING

For most efficient utilization of test time, the check-out run on the spherical tank system was conducted at the conditions for Run 4 to allow accomplishment of this run if the system performed satisfactorily. Conducted on 15 January 1965, the run proceeded through initial pressurization as system check-out. The system performed excellently with no difficulties being encountered. At this time it was designated Run 4 and continued. Originally, the conditions set for Run 4 were 15 psia and -297°F . Since the vapor pressure of LOX at this temperature was equal to the planned system pressure, the run conditions were changed prior to pressurization to allow positive inflow of GN_2 pressurant. The fact that GN_2 inflow results in condensation on the liquid interface which produces an interfacial temperature and LOX vapor pressure higher than those of the bulk liquid was also taken into account. The conditions chosen were 18 psia ullage temperature and -310°F LOX temperature. For the first two hours a positive, but steadily decreasing, inflow of GN_2 pressurant was obtained. However, at the end of the second hour, pressurant inflow ceased. The run was continued for an additional hour; during this time backflow of GOX was experienced through the flowrators in the pressurization line. At the end of the third hour, the fourth set of LOX samples was taken and the run was terminated.

Runs 5 through 10 were essentially trouble-free with only small difficulties normal to any test program being encountered. Test duration averaged approximately five hours depending upon the length

of time IN_2 level control could be sustained in the jacketing tank.

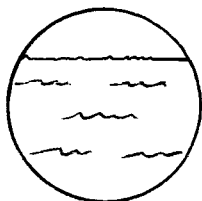
As experience was gained, the time required to prepare for a run decreased. Preparations involved instrumentation warm-up and calibration, cooldown of IN_2 transfer lines and jacketing tank and loading IN_2 , LOX loading, and warm-up of IN_2 in the jacket to run temperature. Initially, run preparation and conduction required $1\frac{1}{2}$ shifts on a single day. Beginning with Runs 11 and 12 on 29 January 1965, two runs were conducted during a single, 2-shift day. Seven sets of double runs were subsequently conducted; after Run 10, only Runs 17 and 22 were single runs. This is noted in Table 1.

For Runs 15, 16, and 17, an automatic electric heater was installed in the pressurant supply line to increase the inlet temperature of the gaseous nitrogen. Runs 15 and 16 were conducted with an initial heater outlet temperature of approximately 100°F and Run 17 had an outlet temperature approaching 150°F . However, use of the heater is believed to have had little effect on the actual temperature of the GN_2 entering the LOX tank ullage after initial pressurization when N_2 flow rate had diminished to a very low value. The test system configuration required the pressurant gas to flow through the ullage region of the jacketing tank. Under low flow conditions, this passage required sufficient time for the gas to cool to or below its original temperature.

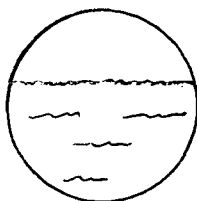
The LOX tank ullage pressure was cycled between 150 psia and 100 psia for Runs 18 and 19 and between 5000 psia and 4000 psia for Run 26. Cycling was accomplished by pressurizing to the high level and then closing the tank pressurization valve to stop

TABLE 1
SPHERICAL TANK TESTS

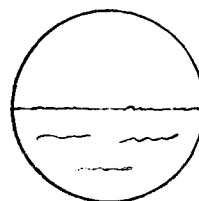
RUN NO.	DATE COMP.	ULLAGE PRESS. PSIA	LOX TEMP. (°F)	$\frac{V_L}{V_U}$ ^a	A_S ^b	GN ₂ INLET TEMP. (°F)
CYLINDRICAL TANK						
1	12/18	100	-297	Case 3	Case 3	Ambient
2	12/22	100	-297	Case 2	Case 3	Ambient
3	12/28	100	-297	Case 1	Case 3	Ambient
SPHERICAL TANK						
4	1/15	18	-308	Case 1	Case 1	Ambient
5	1/19	100	-297	Case 1	Case 1	Ambient
6	1/20	100	-290	Case 1	Case 1	Ambient
7	1/21	100	-285	Case 1	Case 1	Ambient
8	1/22	500	-290	Case 1	Case 1	Ambient
9	1/27	500	-285	Case 1	Case 1	Ambient
10	1/28	500	-297	Case 1	Case 1	Ambient
11] e	1/29	500	-297	Case 2	Case 2	Ambient
12]	1/29	100	-297	Case 2	Case 2	Ambient
13]	2/2	500	-297	Case 3	Case 3	Ambient
14]	2/2	100	-297	Case 3	Case 3	Ambient
15]	2/3	100	-297	Case 1	Case 1	100
16]	2/3	100	-297	Case 1	Case 1	100
17	2/4	100	-297	Case 1	Case 1	150
18]	2/5	Cycling ^c	-297	Case 1	Case 1	Ambient
19]	2/5	Cycling ^c	-297	Case 1	Case 1	Ambient
20]	2/9	1000	-297	Case 1	Case 1	Ambient
21]	2/9	3000	-297	Case 1	Case 1	Ambient
22	2/10	3700	-297	Case 1	Case 1	Ambient
23]	2/11	5000	-290	Case 1	Case 1	Ambient
24]	2/11	5000	-285	Case 1	Case 1	Ambient
25]	2/12	5000	-297	Case 2	Case 2	Ambient
26]	2/12	Cycling ^d	-297	Case 3	Case 3	Ambient



Case 1



Case 2



Case 3

a Ratio of liquid volume to ullage volume.

b Liquid-vapor interfacial area.

c For Runs 18 and 19, the system was pressurized to 150 psia, allowed to decay to 100 psia, and then repressurized to 150 psia. This was repeated continuously during the run.

d For Run 26, the system was cycled between 5000 psia and 4000 psia, similar to Runs 18 and 19.

e Double runs were performed where brackets indicate.

inflow of GN_2 . The ullage pressure was allowed to decay to the low level through absorption, condensation, and cooldown of the ullage gases. When the low pressure level was reached, the GN_2 pressurization valve was opened and the tank was again pressurized to the high level. This procedure was repeated throughout the run with cycle periods increasing with time.

Failure of a flange seal at 4500 psia during initial pressurization for Run 22 required temporary suspension of the run. After the seal had been replaced and a fresh load of LOX had been obtained, a second attempt to reach 5000 psia was made. A maximum pressure of 4500 psia was obtained when the hand loader used to control the high pressure GN_2 regulator malfunctioned. Pressure rapidly decayed to 3700 psia and the run was conducted at this pressure. The hand loader was replaced after Run 22 and the planned 5000 psia ullage pressure was obtained for the last four runs.

The last two runs, Runs 25 and 26, were completed on 12 February 1965. At the conclusion of the test program the system was shut-down and left in standby condition.

C. SAMPLING AND ANALYSIS

Samples of the contaminated LOX in the inner tank were obtained by flashing a small amount of liquid into an evacuated sample line. Complete vaporization of the liquid sample assured that the gaseous sample contained the same ratio of nitrogen to oxygen as the liquid. Special sampling devices inserted in the lines prior to the flashing operation were employed for trapping and holding the gaseous samples under pressure for subsequent gas chromatographic analysis. These devices, called "snap samplers", are manufactured by Micro Tek Instruments, Inc. Samplers having volumes of 20 and 30 microliters were employed. Some leakage from the snap samplers was encountered when the time span between sampling and analysis exceeded 8 or 10 minutes. Leakage of the samplers presented no problem because relative and not absolute quantities of the sample constituents was the desired information.

A Beckman GC-2 gas chromatograph was used to measure sample concentrations during the cylindrical tank runs and for Runs 4, 5, and 6 with the spherical tank. To obtain greater sensitivity, use of a Perkin-Elmer 154D gas chromatograph was started with Run 7. The Perkin-Elmer instrument provided greater accuracy for sample analysis and broadened the band of measurable concentrations (5).

The sampling system used to obtain samples of LOX in the inner tank is shown schematically in Figure 3. No changes were made in this system during the course of the test program. However, the sampling procedure was varied to determine if the procedure used had an effect on measured nitrogen concentration and whether the sampling system was functioning properly.

When unexpectedly high nitrogen concentrations were measured in samples taken immediately after pressurization during the 500 psia runs, the possibility developed that non-representative samples were being obtained either from the tank or by nitrogen being introduced inadvertently into the sampling system. In seeking an explanation for these seemingly erroneous findings, sample repeatability was scrutinized by altering the sampling procedure and observing any changes in recorded nitrogen concentrations. Alteration of both the number and size of purge cycles employed to clear the residual liquid from the sample lines inside of the tanks, produced no noticeable effect on nitrogen concentration. Variations in the method of relieving excess pressure in the outer (holding) portion of the sample system also produced no effect. At this point it was concluded that:

- 1) the sampling system was functioning properly;
- 2) the sampling procedure was sound;
- 3) representative samples were being obtained.

Two possibilities remained for explaining the high nitrogen concentrations in samples taken just after pressurization during Runs 8, 9, and 10. These were:

- 1) The chemical analysis of the fresh LOX load for each run, furnished by the supplier, was in error.
- 2) Most of the contamination occurred during initial pressurization.

After discussing the first possibility with the LOX supplier, it was discarded and the second possibility was investigated.

Observation of the chromatograms for samples from Runs 4, 5, and 6 had previously shown that the samples contained a low nitrogen content and that little growth in nitrogen concentration occurred as a run progressed (5). Run 7 also showed a low level of nitrogen in the samples.

Runs 5, 6, and 7 were performed at 100 psia and Run 4 was conducted at 18 psia. Examination of the chromatograms from Runs 8, 9, 10 and 11, which were all conducted at 500 psia, showed nitrogen concentrations in the first samples after pressurization were five to ten times greater than those measured during the 100 psia runs. It was concluded that initial pressurization was producing most of the contamination and that contamination level increased with system pressure. This conclusion was substantiated by the results observed during the remaining runs. The cycling runs, i.e., Runs 18, 19, and 26, developed still greater contamination than their non-cycling counterparts. A final contamination level of approximately 30% was produced in Run 26 which was a cycling run between 4000 and 5000 psia.

A second parametric effect noted was that contamination increased as V_L/V_U , the ratio of liquid volume to ullage volume, decreased. For the spherical tank, variations in V_L/V_U correspond to variations in A_S , the liquid-vapor interfacial area, negating any direct correlations. Future refined analysis should separate the effect caused by varying A_S from that caused by varying V_L/V_U .

Cursory analysis of the chromatograms also showed the existence of an irregular nitrogen concentration gradient in the LOX tank. The contribution of convection to the mass and heat transfer occurring in the LOX tank requires assessment if subsequent detailed analysis supports these unexpected gradients.

D. DATA REDUCTION

Fifteen of the twenty-six runs were selected for initial data reduction to facilitate the earliest possible preparation of data for correlation with the analytical model. To date, all 15 have been reduced to tabular form; conversion of the tabular data to graphical form is 80 per cent complete. The data consists of 24 temperatures, two pressures, and GN_2 flowrates. The flowrates were recorded by two turbine meters. On the low pressure runs, i.e. up to 100 psia, pressurant flow rates were measured by a bank of 4 flowrators after initial pressurization. Temperature and static pressure were recorded at the point of flow measurement. All temperatures for the 15 runs have been converted to graphical form and 10 of the flowrates have been completely reduced and plotted as weight flow rate versus time.

Of the remaining 11 runs, half of the temperature data has been reduced to tabular form. Work will continue on these runs at a reduced level until the first 15 runs are complete at which time emphasis will be placed on finishing these runs with maximum dispatch.

E. FUTURE EFFORT

Data reduction will be completed in two weeks. Data analysis will commence in a week to 10 days and continue through April. This effort will be essentially complete by the end of April and work on the portion of the final report devoted to the experimental program will then be initiated.

IV. REFERENCES

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4. Fester, et. al., "Study of Contamination of Liquid Oxygen by Gaseous Nitrogen", Second Quarterly Progress Report on Contract NAS 8-11337, Martin CR-64-51 (Issue 6), Martin Company, Denver, Colorado (January 1965).
5. Fester, et. al., "Study of Contamination of Liquid Oxygen by Gaseous Nitrogen", Seventh Monthly Progress Report on Contract NAS 8-11337, Martin CR-64-51 (Issue 7), Martin Company, Denver, Colorado (January 1965).

APPENDIX A

LOXCON MAIN COMPUTER PROGRAM

```

C LOXCEN, MAIN PROGRAM
C PAUL A. FRIEDMAN      26 MARCH 1965
COMMON A,ASAVE
DIMENSION A(500),ASAVE(500)
EQUIVALENCE (A(1),TIMEI),A(2),TIMEND),A(3),ADDATA),A(4),WYPOUT)
  ,A(15),TIMED),A(9),OUTPUT),A(13),GRAVITY),A(17),P),A(18),T),A
  (19),TLI),A(20),VLI),A(21),XMWP),A(22),XMI),A(23),ZLFI),A(24)
  ,ZGFI),A(25),HXCG),A(26),HXCL),A(27),HXEXG),A(28),HXEXL),A(2
  9),HWGTE),A(30),TE),A(31),TR),A(32),TDH),A(33),TBH),A(34),TZ)
  ,A(35),WTBA),A(36),ROBIAR),A(37),CPTA),A(38),CPTB),A(39),CRTC
  ),A(40),STG),A(44),ALGI),A(48),ZP),A(52),DZPBDV),A(119),VT),A
  (139),ST)
  DMY1=EQSTAT(0.,0.,0.,0.,0.,0.)
2 DO 3 I=1,500
  A(I)=0.0
3 ASAVE(I)=0.0
  IDMY1=0
  GO TO 5
1 DO 4 I=1,500
4 A(I)=ASAVE(I)
5 CALL SLITE(0)
  WRITE(6,109)
  IDMY3=0
  CALL FORTN2(M)
  IF(IDMY1.NE.0)GO TO 7
  CALL TANK(TR,TDH,TBH,TZ)
  DO 6 I=1,500
6 ASAVE(I)=A(I)
7 IDMY=1
C SECTION 1      INITIAL CONDITIONS
  TL=TLI
  TG=TL
  TGR=TL
  TLF=TL
  XMPPL=1.0
  XMPPLF=1.0
  XMPPGF=1.0
  XMPPG=1.0
  ZLF=ZLFI
  ZGF=ZGFI

```



```

ZGFW=ZGFI
TIME=TIMEI
TIMOUT=TIMEI
SUMQL=0.
SUMWDI=0.
PG=EQSTAT(0.,0.,0.,TL,0.,1)
RHOL=EQSTAT(1.,PG,TL,0.,4)
RHOLF=RHOL
DMY1=VT-VLI
CALL PAFTAB(DMY1,STG,41)
CALL PAFTAB(DMY1,ALGI,45)
VLF=ALGI*ZLF
WPLF=RHOLF*VLF
VL=VLI-VLF
WPL=VL*RHOL
RHOG=EQSTAT(1.,PG,TG,0.,3)
RHOGF=RHOG
VGF=ALGI*ZGF
WPGF=VGF*RHOG
VG=VT-VL-VLF-VGF
WPG=VG*RHOG
IFCADATA.EQ.0.0) GO TO 91
CALL FORTN2(M)
GO TO 91
C SECTION 2 LIQUID
21 XMPL=WPL/(XMWP*VL)
XMPLF=WPLF/(XMWP*VLF)
DIFFL=DIFFL/(XMPLF+XMFPL)/2.,PG,((TL+TLP)/2.),1)
WDPL=DIFFL*(XMPLF-XMPL)*ALGI*TIMED*XMWP*2./ZLF
XMIL=WIL/(XMWI*VL)
XMILF=WILF/(XMWI*VLF)
WDIL=DIFFL*(XMILF-XMIL)*ALGI*TIMED*XMWI*2./ZLF
WPL=WPL+WDPL
WIL=WIL+WDIL
XMFPL=(WPL/XMWP)/(WPL/XMWP+WIL/XMWI)
XMFIL=1.-XMFPL
RHOL=EQSTAT(XMFPL,PG,TL,0.,4)
VL=(WPL+WIL)/RHOL
DMY1=EQSTAT(1.,PG,TL,0.,4)
DMY2=EQSTAT(1.,PG,TL,0.,4)
QDPL=WDPL*(EQSTAT(1.,PG,TL,DMY1,7)-EQSTAT(1.,PG,TL,DMY2,7))
DMY1=EQSTAT(0.,PG,TL,0.,4)
DMY2=EQSTAT(0.,PG,TL,0.,4)
QDIL=WDIL*(EQSTAT(0.,PG,TL,DMY1,7)-EQSTAT(0.,PG,TL,DMY2,7))
TF=(TLF+TL)/2.
XMFPF=(XMFPL+XMFPLF)/2.

```

```

XMFU=VISCOS*(XMFPPF,PG,TF,1)
XKF=THCOND*(XMFPPF,PG,TF,1)
RHOF=EQSTAT*(XMFPPF,PG,TF,0,4)
DMY2=EQSTAT*(XMFPPF,PG,TF,5,0,4)
DMY1=EQSTAT*(XMFPPF,PG,TF,5,0,4)
BETAF=(1./DMY2-1./DMY1)*RHOF/10.
CPE=(EQSTAT*(XMFPPF,PG,TF,5,DMY2,6)-EQSTAT*(XMFPPF,PG,TF,5,DMY1,6))/
*10.
HXFC=HXCL*XKF/(2.*TR)*((2.*TR)**3*RHOF**2*GRAVITY*BETAF*(TLF-TL)*CP
F/UXMUF*XKF)**HXEXL
QDLFTL=HXFC*ALG*(TLF-TL)*TIMED
IF(WDPL.GT.0.0) SUMQL=SUMQL+QDPL
IF(WIPL.GT.0.0) SUMQL=SUMQL+QDIL
SUMQL=SUMQL+QDLFTL
SECTION 3 GAS
DIFF6=DIFF((XMFPG+XMFPGF)/2.),PG,(TG+TGF)/2.,0)
XMRG=WPG/(XWWP*VGF)
XMRGF=WPGF/(XWWP*VGF)
WDRG=DIFF*(XMPGF-XMPG)*ALG*(TIMED*XWWP*2./ZGF
XMRG=WIG/(XMWI*VGF)
XMRGF=WIGF/(XMWI*VGF)
WDIG=DIFF*(XMIGF-XMIG)*ALG*(TIMED*XMWI*2./ZGF
DMY1=WPG+WDPG)/XWWP/(WPG+WDPG)/XWWP+(WIG+WDIG)/XMWI)*PG
DMY2=EQSTAT(1.,DMY1,TG,0,3)
DMY3=WPGF-WDPG)/XWWP/(WPGF-WDPG)/XWWP+(WIGF-WDIG)/XMWI)*PG
DMY4=EQSTAT(1.,DMY3,TGF,0,3)
QDRG=WDPG*(EQSTAT(1.,DMY1,TG,DMY2,6)-EQSTAT(1.,DMY3,TGF,DMY4,6))
DMY1=PG-DMY1
DMY2=EQSTAT(0.,DMY1,TG,0,3)
DMY3=PG-DMY3
DMY4=EQSTAT(0.,DMY3,TGF,0,3)
QDIG=WDIG*(EQSTAT(0.,DMY1,TG,DMY2,6)-EQSTAT(0.,DMY3,TGF,DMY4,6))
WDRCW=0.0
QDPCW=0.0
QDRCLF=0.0
WDRICW=0.0
QDRICW=0.0
QDRICLF=0.0
DMY1=EQSTAT(0.,0.,TWG,0,1)
IF(DMY1.GE.(XMFPG*PG))GO TO 31
DMY2=EQSTAT(1.,XMFPG*PG,TG,0,3)
DMY3=EQSTAT(1.,PG,TWG,0,4)

```

C

```

DMY3=EQSTAT(1.,PG,TWG,DMY3,7)
QVAPP=EQSTAT(1.,XMFPG*PG,TG,DMY2,6)-DMY3
XMRGF=WP*DMY1/(XMFPG*PG*XMW*VG)
DIFEG=DIFF((XMFPG+DMY1/PG)/2.,PG,TG,0)
WDRCW=DIFFEG*(XMPG+XMPGF)*STG*TIMED*XMW/ZGFW
QDRCW=WDPCW*QVAPP
DMY2=EQSTAT(1.,PG,TLF,0.,4)
QDRCLF=WDPCW*(DMY3-EQSTAT(1.,PG,TLF,DMY2,7))
31 DMY1=EQSTAT(0.,0.,TWG,0.,2)
   IF(DMY1.GE.(XMF*PG))GO TO 39
DMY2=EQSTAT(0.,XMF*PG,PG,TG,0.,3)
DMY3=EQSTAT(0.,PG,TWG,0.,4)
DMY3=EQSTAT(0.,PG,TWG,DMY3,7)
QVAPI=EQSTAT(0.,XMF*PG,PG,TG,DMY2,6)-DMY3
DIFEG=DIFF((XMF*PG+DMY1/PG)/2.,PG,TG,0)
XMRGF=WP*DMY2/(XMF*PG*XMW*VG)
WDRCW=DIFFEG*(XMF-XMIG)*STG*TIMED*XMW/ZGFW
QDRCW=WDICW*QVAPI
DMY2=EQSTAT(0.,PG,TLF,0.,4)
QDRCLF=WDICW*(DMY3-EQSTAT(0.,PG,TLF,DMY2,7))
39 CONTINUE

C SECTION 4 WALL
TF=TWG+TWG)/2.
XMUF=VISCOS(XMFPG,PG,TF,0)
XKF=THCOND(XMFPG,PG,TF,0)
RHOF=EQSTAT(XMFPG,PG,TF,0.,3)
DMY2=EQSTAT(XMFPG,PG,TF+5.,0.,3)
DMY1=EQSTAT(XMFPG,PG,TF-5.,0.,3)
BETA=(1./DMY2-1./DMY1)*RHOF/10.
CPF=EQSTAT(XMFPG,PG,TF+5.,DMY2,6)-EQSTAT(XMFPG,PG,TF-5.,DMY1,6))/
10.
HXFC=HXCG*XKF/(2.*TR)*(12.*TR)**3*RHOF**2*GRAVITY*BETA*{(TG-TWG)*CP
F/(XMUF*XKF)}**HXEXG
QDGTWG=HXFC*STG*(TG-TWG)*TIMED
QDWTG=HWGTE*STG*ROBIAR*{(TWG-TE)*TIMED
SUMQW=QDGTWG-QDWTG+QDPCW+QDICW
CPI=CPTA+CPIB*TWG**CPTC
DMY1=TWG+SUMQW/(STG*WTBA*CPT)
CPT=CPTA+CPIB*{(TWG+DMY1)/2.}*CPTC
TWG=TWG+SUMQW/(STG*WTBA*CPT)
SECTION 5 INTERFACE HEAT AND MASS TRANSFER
DMY1=EQSTAT(0.,0.,TLF,0.,1)*XMFPLF
WDPLF=0.0
QDPLFL=0.0
QDRLFS=0.0
QDRGFS=0.0

```

```

51 IF(DMY1-XMFPGF*PG) 51,53,52
   DMY2=WPGF*DMY1/(XMFPGF*PG*XMWP*VGF)
   DIRFG=DIFF((XMFPGF+DMY1/PG)/2.)*PG,TGF,0)
   WDPLF=DIFFG*(DMY2-XMPGF)*ALGI*TIMED*XMWP*2./ZGF
   DMY2=EQSTAT(1.,PG*XMFPGF,TGF,0.,3)
   DMY3=EQSTAT(1.,PG,TGF,0.,4)
   DMY3=EQSTAT(1.,PG,TGF,DMY3,7)
   QDRLEL=-WDPLF*(EQSTAT(1.,PG*XMFPGF,TGF,DMY2,6)-DMY3)
   DMY2=EQSTAT(1.,PG,TLF,0.,4)
   QDRLES=-WDPLF*(DMY3-EQSTAT(1.,PG,TLF,DMY2,7))
   GO TO 53

52 WDRLE=WPGF*DMY1/(XMFPGF*PG)-WPGF
   DMY2=EQSTAT(1.,PG,TLF,0.,4)
   DMY3=EQSTAT(1.,DMY1,TLF,0.,3)
   DMY3=EQSTAT(1.,DMY1,TLF,DMY3,6)
   QDRLEL=-WDPLF*(DMY3-EQSTAT(1.,PG,TLF,DMY2,7))
   DMY2=EQSTAT(1.,DMY1,TFG,0.,3)
   QDRGFS=WDPLF*(EQSTAT(1.,DMY1,TGF,DMY2,6)-DMY3)
   DMY1=EQSTAT(0.,0.,TLF,0.,2)*XMFILF
   WDRGF=0.0
   QDRLEL=0.0
   QDRLES=0.0
   QDRGFS=0.0

   IF(DMY1-XMFIGF*PG)54,56,55
54 DIRFG=DIFF((XMFIFG+DMY1/PG)/2.)*PG,TGF,0)
   DMY2=WIGF*DMY1/(XMFIFG*PG*XMWI*VGF)
   WDRGF=DIFFG*(XMFIFG-DMY2)*ALGI*TIMED*XMWI*2./ZGF
   DMY2=EQSTAT(0.,XMFIFG*PG,TGF,0.,3)
   DMY3=EQSTAT(0.,PG,TGF,0.,4)
   DMY3=EQSTAT(0.,PG,TGF,DMY3,7)
   QDRLEL=WDIGF*(EQSTAT(0.,PG*XMFIGF,TGF,DMY2,6)-DMY3)
   DMY2=EQSTAT(0.,PG,TLF,0.,4)
   QDRLES=WDIGF*(DMY3-EQSTAT(0.,PG,TLF,DMY2,7))
   GO TO 56

55 WDRGF=WIGF-WIGF*DMY1/(XMFIFG*PG)
   DMY2=EQSTAT(0.,PG,TLF,0.,4)
   DMY3=EQSTAT(0.,DMY1,TLF,0.,3)
   DMY3=EQSTAT(0.,DMY1,TLF,DMY3,6)
   QDRLEL=WDIGF*(DMY3-EQSTAT(0.,PG,TLF,DMY2,7))
   DMY2=EQSTAT(0.,DMY1,TGF,0.,3)
   QDRGFS=-WDIGF*(EQSTAT(0.,DMY1,TGF,DMY2,6)-DMY3)

56 CONTINUE

```

C SECTION 6 LIQUID FILM
 WPLF=WPLF-WDPLF-WDPL*WDPCW
 WILF=WILF+WDIGF-WDIL+WDICW
 XMEPLF=(WPLF/XMWP)/(WPLF/XMWP+WILF/XMWI)
 XMRILF=1.-XMEPLF
 TF=(TGF+TLF)/2.
 XMUF=VISCOS(XMFPGF,PG,TF,0)
 XKF=THCOND(XMFPGF,PG,TF,0)
 RHOF=EQSTAT(XMFPGF,PG,TF,0,3)
 DMY2=EQSTAT(XMFPGF,PG,TF,5,0,3)
 DMY1=EQSTAT(XMFPGF,PG,TF,5,0,3)
 BETAF=(1./DMY2-1./DMY1)*RHOF/10.
 CPF=(EQSTAT(XMFPGF,PG,TF+5.,DMY2,6)-EQSTAT(XMFPGF,PG,TF-5.,DMY1,6))/10.
 HXFC=HXCG*XKF/(2.*TR)*((2.*TR)**3*RHOF**2*GRAVITY*BETAF*(TGF-TLF)*C
 PPF/(XMUF*XKF))*HXEXG
 QDGETL=HXFC*ALGI*(TGF-TLF)*TIMED
 TF=(TGF+TGF)/2.
 XMFPF=(XMEPG+XMFPGF)/2.
 XMUF=VISCOS(XMFPF,PG,TF,0)
 XKR=THCOND(XMFPF,PG,TF,0)
 RHOF=EQSTAT(XMFPF,PG,TF,0,3)
 DMYL=EQSTAT(XMFPF,PG,TF+5.,0,3)
 DMY1=EQSTAT(XMFPF,PG,TF-5.,0,3)
 BETAF=(1./DMY2-1./DMY1)*RHOF/10.
 CPF=(EQSTAT(XMFPF,PG,TF+5.,DMY2,6)-EQSTAT(XMFPF,PG,TF-5.,DMY1,6))/10.
 HXFC=HXCG*XKF/(2.*TR)*((2.*TR)**3*RHOF**2*GRAVITY*BETAF*(TG-TGF)*C
 PPF/(XMUF*XKF))*HXEXG
 QDGTGF=HXFC*ALGI*(TG-TGF)*TIMED
 QDGETL=HF*ALGI*(TGF-TLF)*TIMED
 SUMQLF=QDGETL-QDLFTL
 IF(WDPL,0,0) SUMQLF=SUMQLF+QDPL
 IF(WDIL,0,0) SUMQLF=SUMQLF+QDIL
 DMY1=EQSTAT(XMPLF,PG,TLF,0,4)
 DMY1=EQSTAT(XMPLF,PG,TLF,DMY1,7)
 DMY2=EQSTAT(XMPLF,PG,TLF+10.,0,4)
 DMY2=(EQSTAT(XMPLF,PG,TLF+10.,DMY2,7)-DMY1)/10.
 DMY3=TLF+SUMQLF/DMY2
 DMY2=EQSTAT(XMPLF,PG,DMY3,0,4)
 DMY2=(EQSTAT(XMPLF,PG,DMY3,DMY2,7)-DMY1)/(DMY3-TLF)
 TLF=TLF+SUMQLF/DMY2
 RHOLF=EQSTAT(XMPLF,PG,TLF,0,4)
 VLF=UNPLF+WILF)/RHOLF
 ZLF=VLF/ALGI

```

WPGF=WPGF+WDPLF-WDPG
WIGF=WIGF-WDIG-WDIG
XMEPGF=(WPGF/XMWP)/(WPGF/XMWP+WIGF/XMWI)
XMRIGF=1.-XMEPGF
SUMQGF=QDGTGF-QDGTGF+QDPPGF+QDPPGF
IF(WDIG.LT.0.0) SUMQGF=SUMQGF+QDIG
IF(WDPG.LT.0.0) SUMQGF=SUMQGF+QDPG
DMY1=EQSTAT(XMEPGF,PG,TGF,0.03)
DMY1=EQSTAT(XMEPGF,PG,TGF,DMY1,6)
DMY2=EQSTAT(XMEPGF,PG,TGF+10.0,0.03)
DMY2=EQSTAT(XMEPGF,PG,TGF+10.0,DMY2,6)-DMY1/10.0
DMY3=TGF+SUMQGF/DMY2
DMY2=EQSTAT(XMEPGF,PG,DMY3,0.03)
DMY2=EQSTAT(XMEPGF,PG,DMY3,DMY2,6)-DMY1/(DMY3-TGF)
TGF=TGF+SUMQGF/DMY2
RHOGF=EQSTAT(XMEPGF,PG,TGF,0.03)
VGF=(WPGF+WIGF)/RHOGF
ZGF=VGF/ALG1
SECTION 8 PRESSURANT
VG=VT-VL-VLF-VGF
WPG=WPG+WDPG-WDPCW
WIG=WIG+WDIG-WDICW
RHOG=(WPG+WIG)/VG
SUMQG=-QDGTGF-QDGTGF
IF(WDPG.GT.0.0) SUMQG=SUMQG+QDPG
IF(WDIG.GT.0.0) SUMQG=SUMQG+QDIG
DMY1=(WPG/XMWP)/(WPG/XMWP+WIG/XMWI)
DMY2=EQSTAT(DMY1,PG,TG,RHOG,6)
DMY3=EQSTAT(DMY1,PG,TG+10.0,RHOG,6)-DMY2/10.0
DMY4=TG+SUMQG/DMY3
DMY3=EQSTAT(DMY1,PG,DMY4,RHOG,6)-DMY2/(DMY3-TG)
TG=TG+SUMQG/DMY3
PG=EQSTAT(DMY1,0.0,TG,RHOG,5)
WDI=0.0
IDMY2=0
IF(LPGE.(10.995*P))GO TO 87
DMY1=(WPG+WIG)*P/PG-WPG-WIG
RHOG=(DMY1+WPG+WIG)/VG
DMY8=EQSTAT(0.0,P-PG,TI,0.03)
DMY9=EQSTAT(0.0,P-PG,TG,0.03)
QI=EQSTAT(0.0,P-PG,TI,DMY8,6)-EQSTAT(0.0,P-PG,TG,DMY9,6)
DMY8=(WPG/XMWP)/(WPG/XMWP+(WIG+DMY1)/XMWI)

```

```

DMY9=EQSTAT(DMY8,P,TG,RHOG,6)
DMY10=(EQSTAT(DMY8,P,TG+10,RHOG,6)-DMY9)/10.
DMY7=TG+DMY1*QI/(DMY1+WPG+WIG)*DMY10)
DMY10=(EQSTAT(DMY8,P,DMY7,RHOG,6)-DMY9)/(DMY7-TG)
DMY7=TG+DMY1*QI/(DMY1+WPG+WIG)*DMY10)
DMY4=EQSTAT(DMY8,0,DMY7,RHOG,5)
IF(L0.005*P).LT.ABS(DMY4-P).)GO TO 81
WDI=DMY1
TG=DMY7
PG=DMY4
IDMY2=1
GO TO 87
81 DMY2=DMY1*(R-PG)/(DMY4-PG)
RHOG=(DMY2+WPG+WIG)/VG
DMY8=(WPG/XMWP)/(WPG/XMWP+(WIG+DMY2)/XMWI)
DMY9=EQSTAT(DMY8,P,TG,RHOG,6)
DMY10=(EQSTAT(DMY8,P,TG+10,RHOG,6)-DMY9)/10.
DMY7=TG+DMY2*QI/(DMY2+WPG+WIG)*DMY10)
DMY10=(EQSTAT(DMY8,P,DMY7,RHOG,6)-DMY9)/(DMY7-TG)
DMY7=TG+DMY2*QI/(DMY2+WPG+WIG)*DMY10)
DMY5=EQSTAT(DMY8,0,DMY7,RHOG,5)
IF(L0.005*P).LT.ABS(DMY5-P).)GO TO 82
TG=DMY7
PG=DMY5
WDI=DMY2
IDMY2=2
GO TO 87
82 00 85 IDMY2=2,12
DMY3=DMY2+(DMY1-DMY2)*(P-DMY5)/(DMY4-DMY5)
RHOG=(DMY3+WPG+WIG)/VG
DMY8=(WPG/XMWP)/(WPG/XMWP+(WIG+DMY3)/XMWI)
DMY9=EQSTAT(DMY8,P,TG,RHOG,6)
DMY10=(EQSTAT(DMY8,P,TG+10,RHOG,6)-DMY9)/10.
DMY7=TG+DMY3*QI/(DMY3+WPG+WIG)*DMY10)
DMY10=(EQSTAT(DMY8,P,DMY7,RHOG,6)-DMY9)/(DMY7-TG)
DMY7=TG+DMY3*QI/(DMY3+WPG+WIG)*DMY10)
DMY6=EQSTAT(DMY8,0,DMY7,RHOG,5)
IF(L0.005*P).GE.ABS(DMY6-P).)GO TO 86
IF(L0.005*P).LT.ABS(DMY6-P).)GO TO 84
83 DMY1=DMY2
DMY2=DMY3
DMY4=DMY5
DMY5=DMY6
GO TO 85
84 IF(L0.005*P).GE.ABS(DMY6-P).)GO TO 83
DMY2=DMY3

```

```

DMY5=DMY6
85 CONTINUE
86 TG=DMY7
PG=DMY6
WDB=DMY3
87 SUMWDI=SUMWDI+WDI
WIG=WIG+WDI
XMFRG=(WPG/XMWP)/(WPG/XMWP+WIG/XMWI)
XMFRG=1.-XMFRG
SECTION 9 END
CALL SL4TET(1,DELETE)
GO TO (94,91),DELETE
91 TIME=TIME+TIMED
IF(TIME-GE-TIMEND) GO TO 92
CALL PAFTAB(TIME,TIMED,6)
CALL PAFTAB(TIME,GRAVITY,14)
CALL PAFTAB(VG+VGF,STG,41)
CALL PAFTAB(VG+VGF,ALGI,45)
IF(TIME-LT-TIMOUT) GO TO 21
CALL PAFTAB(TIME,OUTPUT,10)
TIMOUT=TIMOUT+OUTPUT
92 IF(IDMY3-LT-9)GO TO 93
WRITE(6,101)
WRITE(6,102)
IDMY3=0
93 DMY1=WDN/TIMED
WRITE(6,103)TIME,PG,SUMWDI,DMY1
WRITE(6,104)VG,TG,WPG,XMFRG,WIG,ZGFW
WRITE(6,105)VGF,TGF,WPGF,XMFRPGF,WIGF,ZGF
WRITE(6,106)VLF,TLF,WPLF,XMFRPLF,WILF,ZLF
WRITE(6,107)VL,TL,WPL,XMFRPL,WIL,SUMQL
IF(TIME-LT-TIMEND) GO TO 21
WRITE(6,108)
94 IF(WYPOUT-LE-0.0) GO TO 1
GO TO 2
101 FORMAT(1H114X4HTIME5X5HPRESS4X10HPRESSURANT4X6HVOLUME3X4HTEMP5X10H
,PROPELLANT5X5HINERT3X7HFILM HT3X5HSUMQL)
102 FORMAT(1H 14X5H(SEC)3X6H(PSIA)2X4H(LB)2X8H(LB/SEC)3X4H(CF)5X3H(R)3
,X4H(LB)6X4H(MF)4X4H(LB)5X4H(FT)4X5H(BTU))
103 FORMAT(1H013XF7.1,2XF6.1,2XF7.1)
104 FORMAT(1H 8HBULK 6AS38XF6.2,2XF6.1,2XF7.2,2XF5.3,2XF7.2,2XF7.4)
105 FORMAT(1H 8HGAS FILM38XF6.2,2XF6.1,2XF7.2,2XF5.3,2XF7.2,2XF7.4)

```



```
106 FORMAT(1H 11HLIQUID FILM35XF6.2,2XF6.1,2XF7.2,2XF5.3,2XF7.2,2XF7.4
  )
107 FORMAT(1H 11HBULK LIQUID35XF6.2,2XF6.1,2XF7.2,2XF5.3,2XF7.2,11XF7.
  )
108 FORMAT(1H 36HRUN EXECUTED AND TERMINATED NORMALLY)
109 FORMAT(1H158HLOXCON MATHEMATICAL MODEL FOR BINARY OXYGEN-NITROGEN
  )SYSTEM)
  STOP
  END
```

APPENDIX B
TANK GEOMETRY SUBROUTINE

C
 SUBROUTINE TANK(R,H,B,Z)
 PAUL A. FRIEDMAN 25 MARCH 1965
 COMMON A,VGP,SPTG,ALGP,ZP,DZBDV
 DIMENSION A(500),VGP(20),SPTG(20),ALGP(20),ZP(20),DZBDV(20)
 EQUIVALENCE (A(100),VGP), (A(120),SPTG), (A(140),ALGP), (A(160),ZP), (A(180),DZBDV)
 DMY1=1.5708
 DMY2=R**2
 DMY3=DMY2*H**2.
 DMY4=R/H
 DMY5=DMY4**2
 IF(R=H) 1,2,1
 1 DMY6=H**2
 DMY7=DMY2-DMY6
 DMY8=DMY6**2
 DMY9=SQRT(DMY7*DMY6+DMY8)
 DMY10=SQRT(DMY7)
 DMY11=3.1416*DMY4*DMY9
 DMY12=H*DMY10+DMY9
 DMY13=3.1416*R*DMY6/DMY10
 2 VGP(1)=0.
 SPTG(1)=0.
 ALGP(1)=0.
 ZP(1)=H+B+H+Z
 DZBDV(1)=-10.
 DO 6 I=2,10
 DMY1=DMY1-1.5708/9.
 DMY14=H*SIN(DMY1)
 DMY15=DMY14**2
 VGP(I)=1.0472*(DMY3-3.**DMY14*DMY2+DMY5*DMY14**3)
 IF(R=H) 3,4,3
 3 DMY16=SQRT(DMY7*DMY15+DMY8)
 DMY17=DMY14*DMY10+DMY16
 SPTG(I)=DMY11-3.1416*R*DMY14*DMY16/DMY6+DMY13*ALOG(DMY12/DMY17)
 GO TO 5
 4 SPTG(I)=6.2832*R*(R-DMY14)
 5 ALGP(I)=3.1416*(DMY2-DMY15*DMY5)
 ZP(I)=DMY14+B+H+Z
 6 DZBDV(I)=1./I3.1416*(DMY15*DMY5-DMY2)
 IF(B) 9,9,7
 7 VGP(11)=VGP(10)+3.1416*DMY2*B
 SPTG(11)=SPTG(10)+6.2832*R*B

```
ALGP(11)=ALGP(10)
ZP(11)=H+Z
DZBDV(11)=DZBDV(10)
DO 8 I=12,20
K=21-I
VGP(I)=VGP(10)+VGP(11)-VGP(K)
SPTG(I)=SPTG(10)+SPTG(11)-SPTG(K)
ALGP(I)=ALGP(K)
ZP(I)=ZP(1)-ZP(K)+Z
8 DZBDV(I)=DZBDV(K)
GO TO 11
9 DO 10 I=11,19
K=20-I
VGP(I)=VGP(10)+VGP(10)-VGP(K)
SPTG(I)=SPTG(10)+SPTG(10)-SPTG(K)
ALGP(I)=ALGP(K)
ZP(I)=ZP(1)-ZP(K)+Z
10 DZBDV(I)=DZBDV(K)
11 XI=I-1
A(41)=XI
A(45)=XI
A(49)=XI
A(53)=XI
IF(1.EQ.21)GO TO 12
VGP(20)=VGP(19)
SPTG(20)=SPTG(19)
12 RETURN
END
```

APPENDIX C:

EQUATION OF STATE SUBROUTINE

```

C OXYGEN (PROPELLANT) AND NITROGEN (INERT PRESSURANT)
C PHYSICAL, THERMODYNAMIC AND P-V-T PROPERTIES
C I=0, LOAD CONSTANTS
C I=1, PROPELLANT VAPOR PRESSURE (PURE), PSIA
C I=2, INERT PRESSURANT VAPOR PRESSURE (PURE), PSIA
C I=3, VAPOR DENSITY (MIXTURE), LBS/CU-FT
C I=4, LIQUID DENSITY (MIXTURE), LBS/CU-FT
C I=5, PRESSURE (MIXTURE), PSIA
C I=6, VAPOR ENTHALPY (MIXTURE), BTU/LB
C I=7, LIQUID ENTHALPY (MIXTURE), BTU/LB
C PAUL A. FRIEDMAN 30 MARCH 1965
C XMFP = MOLE FRACTION PROPELLANT
C RHO = DENSITY, LBS/CUBIC FOOT
C P = PRESSURE, PSIA
C T = TEMPERATURE, DEGREES RANKINE
C FUNCTION EQSTAT(XMFP,P,T,RHO,I)
C DIMENSION XP(17),PVP(5),PCPO(5),XIVP(7),XICPO(5),A(17),B(17)
C ),X(7),Y(7)
C IF(I.GT.7)GO TO 3
C IF(I.LE.0)GO TO 1
C WRITE(6,2)
C 3 FORMAT(1H 46HILLEGAL ENTRY TO FUNCTION EQSTAT. CASE DELETED)
C CALL SLITE(1)
C EQSTAT=1.
C RETURN
C 1 IF(I.NE.0)GO TO 100
C LOAD CONSTANTS
C OXYGEN (PROPELLANT) EQUATION OF STATE CONSTANTS
C XP(1) = 0.36684115E-01
C XP(2) = -0.10091340E+01
C XP(3) = -0.59581958E+02
C XP(4) = -0.39091633E+04
C XP(5) = 0.12405065E+08
C XP(6) = 0.87258515E-03
C XP(7) = -0.11885929E-01
C XP(8) = 0.29165708E-05
C XP(9) = 0.12473562E+04
C XP(10) = -0.61007363E+05
C XP(11) = -0.46185178E+07
C XP(12) = -0.10379526E+01
C XP(13) = 0.66183734E+03
C XP(14) = -0.22051320E+05
C XP(15) = 0.73071820E-06
C XP(16) = 0.37656816E-02
C XP(17) = 0.0820797
C OXYGEN (PROPELLANT) VAPOR PRESSURE CONSTANTS
EQSTAT(C,0,0,0,0,0,0,0)
EQSTAT(0,0,0,0,0,0,0,1)
EQSTAT(0,0,0,0,0,0,0,2)
EQSTAT(XMFP,P,T,0,0,3)
EQSTAT(XMFP,P,T,0,0,4)
EQSTAT(XMFP,0,0,T,RHO,5)
EQSTAT(XMFP,P,T,RHO,6)
EQSTAT(XMFP,P,T,RHO,7)

```

PVP(1)= 0.13750055E-03
 PVP(2)=-0.54998814E-01
 PVP(3)= 0.66564191E+01
 PVP(4)= 0.17023470E+01
 PVP(5)=-0.94512173E+03
 OXYGEN (PROPELLANT) CPO CONSTANTS
 PCRO(1)= 0.29136250E+02
 PCRO(2)=-0.56902405E-03
 PCPO(3)= 0.68011222E-05
 PCPO(4)=-0.48441742E-07
 PCPO(5)= 0.13818407E-09
 OXYGEN (PROPELLANT) MISCELLANEOUS CONSTANTS

C

TCP=154.78
 PCP=50.14
 TTR=54.352
 PTP=0.14473684E-02
 TOP=90.
 HOP=11405.399
 RHOC=13.437876
 XMWP=32.
 NITROGEN (INERT PRESSURANT) EQUATION OF STATE CONSTANTS

C

XI(1)= 0.33716084E-01
 XI(2)=-0.57719429
 XI(3)=-0.11421081E+03
 XI(4)= 0.85226349E+03
 XI(5)= 0.34401762E+07
 XI(6)= 0.16503659E-02
 XI(7)=-0.15789059E-01
 XI(8)= 0.41683569E-05
 XI(9)= 0.32115491E+03
 XI(10)= 0.10801205E+06
 XI(11)=-0.10666579E+08
 XI(12)=-0.33044892E+01
 XI(13)= 0.12236936E+04
 XI(14)=-0.56935390E+05
 XI(15)= 0.16751672E-05
 XI(16)= 0.0056
 XI(17)= 0.0820574
 NITROGEN (INERT PRESSURANT) VAPOR PRESSURE CONSTANTS

C

XIVP(1)= 0.12153159E+01
 XIVP(2)=-0.70245744E-01
 XIVP(3)= 0.37857034

XIVP(4)=-0.72276315E-02
XIVP(5)= 0.68748520E-04
XIVP(6)=-0.32785261E-06
XIVP(7)= 0.63033916E-09

C NITROGEN (INERT PRESSURANT) CPO CONSTANTS

XICPO(1)= 0.29109996E+02
XICPO(2)=-0.80820995E-03
XICPO(3)= 0.86142037E-05
XICPO(4)=-0.36893228E-07
XICPO(5)= 0.56750880E+10

C NITROGEN (INERT PRESSURANT) MISCELLANEOUS CONSTANTS

TCI=126.194
PCI=33.499
TTI=63.15
PTI=0.123
TOI=77.364
HOI=6476.9792
RHOCI=8.55
XMWI=28.
EQSTAT=0.0
RETURN

100 T=T/1.18

IF(U,NE.1)GO TO 200
EQSTAT=14.696*VPP(T,PVP)

RETURN

200 IF(U,NE.2)GO TO 300

EQSTAT=14.696*VPI(T,XIVP)

RETURN

300 P=P/14.696

XMW=XMFP*XMWP+(1.-XMFP)*XMWI

CALCULATE MIXTURE CONSTANTS

PC=XMFP*PCP+(1.-XMFP)*PCI

TC=XMFP*TCP+(1.-XMFP)*TCI

PT=XMFP*PTP+(1.-XMFP)*PTI

TT=XMFP*TTP+(1.-XMFP)*TTI

RHO=RHO/(XMW*0.06243)

IF(XMFP,NE.0.0)GO TO 302

DO 301 N=1,17

301 A(N)=XI(N)

RHOC=RHOCI

GO TO 306

302 IF(XMFP,NE.1.0)GO TO 304

DO 303 N=1,17

303 A(N)=XP(N)

RHOC=RHOCPC

GO TO 306


```

304 DO 305 N=1,17
305 A(N)=XMFP*XP(N)+(1.-XMFP)*XI(N)
    RHOC=PC/(.3*A(17)*TC)
306 IF(LP.GT.200.)WRITE(6,307)
307 FORMAT(1H 42HPRESSURE ABOVE RANGE FOR EQUATION OF STATE)
    IF(LP.LT.1.)WRITE(6,308)
308 FORMAT(1H 42HPRESSURE BELOW RANGE FOR EQUATION OF STATE)
    IF(CT.GT.300.)WRITE(6,309)
309 FORMAT(1H 45HTEMPERATURE ABOVE RANGE FOR EQUATION OF STATE)
    IF(LT.LT.85.)WRITE(6,310)
310 FORMAT(1H 45HTEMPERATURE BELOW RANGE FOR EQUATION OF STATE)
    IF(L.NE.3)GO TO 400
    IF(P.LT.PC)GO TO 311
    I=4
    GO TO 400
311 P2=XMFP*VPP(TC,PVP)+(1.-XMFP)*VPI(TC,XIVP)
    P1=XMFP*VPP(TT,PVP)+(1.-XMFP)*VPI(TT,XIVP)
    IF(LP.GT.PT)GO TO 312
    TS=TC
    GO TO 315
312 BX=ALOG(P2/P1)/(1./TC-1./TT)
    AX=ALOG(P2)-BX/TC
    TEST=BX/(ALOG(P)-AX)
    DO 313 N=1,20
    PCAL=XMFP*VPP(TEST,PVP)+(1.-XMFP)*VPI(TEST,XIVP)
    Z=PCAL-P
    ZZ=DRVBDI(XMFP,TEST,PVP,XIVP)
    DELT=-Z/ZZ
    TEST=TEST+DELT
    DPR=Z/P
    DTOT=DELT/TEST
    IF(ABS(DPP).LE.0.00005)GO TO 314
313 IF(ABS(DTOT).LE.0.00005)GO TO 314
314 TS=TEST
315 IF(CT.GE.TS)GO TO 316
    I=4
    GO TO 400
316 RHOEST=RHOVR((TS-1.)/TC)*RHOC
    EQSTAT=ROTT(P,RHOEST,A)*XMW*0.06243
    RETURN
400 IF(L.NE.4)GO TO 500
    RHOEST=RHOEST(TT)

```

```

EQSTAT=RO(T,P,RHOEST,A)*XMW*0.06243
RETURN
500 IF(I.NE.5)GO TO 600
EQSTAT=14.696*PRESS(T,RHO,A)
RETURN
600 IF(I.NE.6)GO TO 700
HP=0.
HI=0.
IFLXMFPEQ.0.0)GO TO 601
HP=CPOINT(T,TO,PCPO)+HOP
601 IF(XMFPEQ.1.1)GO TO 602
HI=CPOINT(T,TO,XICPO)+HOI
602 H=XMFP*HP+(1.-XMFP)*HI+DELHRO(T,P,RHO,A)
EQSTAT=H*.4536*.948/XMW
RETURN
700 PS=XMFP*VPP(T,PVP)+(1.-XMFP)*VPI(T,XIVP)
ROVEST=RHOVR(T-1.)/TC)*RHOC
ROWEST=RHOLS(T-1.)
RHOSV=RO(T,PS,ROVEST,A)
RHOSL=RO(T,PS,ROLEST,A)
HCROS=T*101.3278*01./RHOSV-1./RHOSL)*DPVBDT(XMFP,T,PVP,XIVP)
HP=0.
HI=0.
IFLXMFPEQ.0.1)GO TO 701
HP=CPOINT(T,TO,PCPO)+HOP
701 IF(XMFPEQ.1.1)GO TO 702
HI=CPOINT(T,TO,XICPO)+HOI
702 H1=DELHRO(T,PS,RHOVS,A)
H2=DELHP(P,RHO,PS,RHOLS,T,A)
EQSTAT=(H1+H2-HCROS+XMFP*HP+(1.-XMFP)*HI)*.4536*.948/XMW
RETURN
END
C OXYGEN (PROPELLANT) VAPOR PRESSURE CALCULATION
FUNCTION VPP(T,X)
DIMENSION X(5)
VPR=EXP(X(1)*T+X(2)*T+X(3)+X(4)*ALOG(T)+X(5)/T)
IF(T.GT.154.78)WRITE(6,2)
IF(T.LT.54.352)WRITE(6,3)
2 FORMAT(1H 63HTEMPERATURE ABOVE CRITICAL IN OXYGEN VAPOR PRESSURE C
ALCULATION)
3 FORMAT(1H 67HTEMPERATURE BELOW TRIPLE POINT IN OXYGEN VAPOR PRESSU
RE CALCULATION)
RETURN
END
C NITROGEN (INERT PRESSURANT) VAPOR PRESSURE CALCULATION
FUNCTION VPI(T,X)

```

```

DIMENSION X(7)
VPI=EXP(X(1)+X(2)/T+X(3)*T+X(4)*T**2+X(5)*T**3+X(6)*T**4+X(7)*T**5)
IF(T.GT.126.194)WRITE(6,2)
IF(T.LT.63.15)WRITE(6,3)
2 FORMAT(IH 65HTEMPERATURE ABOVE CRITICAL IN NITROGEN VAPOR PRESSURE
  * CALCULATION)
3 FORMAT(IH 69HTEMPERATURE BELOW TRIPLE POINT IN NITROGEN VAPOR PRES
  *SURE CALCULATION)
RETURN
END

```

C

```

DPV/DT
FUNCTION DPVBDT(XMFP,T,X,Y)
DIMENSION X(5),Y(7)
PP=0.
PI=0.
DPVP=0.
DPVI=0.
IF(XMFP.EQ.0.)GO TO 1
PP=EXP(X(3)+X(5)/T+X(2)*T+X(4)*ALOG(T)+X(1)*T)
DPVD=PP*(2.*X(1)*T+X(2)+X(4)/T-X(5)/(T*T))
1 IF(XMFP.EQ.1.)GO TO 2
PI=EXP(Y(1)+Y(2)/T+Y(3)*T+Y(4)*T**2+Y(5)*T**3+Y(6)*T**4+Y(7)*T**5)
DPVI=(Y(2)/(T*T)+Y(3)+2.*Y(4)*T+3.*Y(5)*T**2+4.*Y(6)*T**3+5.*Y(7)*
  *T**4)*PI
2 DPVBDT=XMFP*DPVP+(1.-XMFP)*DPVI
RETURN
END

```

C

```

REDUCED VAPOR DENSITY
FUNCTION RHOVR(TR)
IF(TR.LT.0.65)GO TO 1
RHOVR=1.+0.75*(1.-TR)-7./4.*(1.-TR)**(1./3.)
RETURN
1 RHOVR=EXP(5.29-5.31/TR)*.3/TR
RETURN
END

```

C

```

DENSITY VS TEMPERATURE AND PRESSURE USING STROBRIDGE EQUATION
FUNCTION ROFT,P,RHO,A)
DIMENSION A(17)
RHO1=RHO
DO 1 N=1,15
Z=PRESS(T,RHO1,A)-P
ZZ=DPBDROFT,RHO1,A)

```

```

RH01=RH01-Z/ZZ
IF(ABS(Z/P).LE.0.00005)GO TO 3
1 IF(ABS(Z/(ZZ*RH01)).LE.0.00005)GO TO 3
WRITE(6,2)
2 FORMAT(1H 77HNEWTON-RAPHSON METHOD FAILED TO PRODUCE FOUR FIGURE A
.CCURITY IN 15 ITERATIONS)
GO TO 4
3 RO=RH01
RETURN
4 RH0UP=RH0
RHODN=RH0
DO 5 N=1,50
RH0UP=RH0UP*1.05
RHODN=RHODN/1.05
ZUP=PRESS(T,RH0UP,A)-P
ZDN=PRESS(T,RHODN,A)-P
IF(ZUP/ZDN).7,16,5
5 CONTINUE
WRITE(6,6)RH0UP,RHODN
6 FORMAT(1H 43HNO SOLUTION FOUND, TERMINATE PROGRAM RH0UP=F10.3,6HRH
.ODN=F10.3)
RO =0.0
RETURN
7 ZUP1=PRESS(T,RH0UP/1.02,A)-P
IF(ZUP/ZUP1)9,16,8
8 RH02=RHODN*1.02
RH01=RHODN
GO TO 10
9 RH02=RH0UP
RH01=RH0UP/1.02
10 DO 13 N=1,25
Z1=PRESS(T,RH01,A)-P
Z2=PRESS(T,RH02,A)-P
RH03=RH01+(RH02-RH01)*(Z1)/(Z1-Z2)
IF(ABS((RH01-RH02)/RH01).LE.0.00005)GO TO 15
IF(ABS((Z1-Z2)/(Z1+P)).LE.0.00005)GO TO 15
Z3=PRESS(T,RH03,A)-P
IF(Z3/Z1)11,15,12
11 Z2=Z3
RH02=RH03
GO TO 13
12 Z1=Z3
RH01=RH03
13 CONTINUE
WRITE(6,14)
14 FORMAT(1H 75HREGULA-FALSI METHOD FAILED TO PRODUCE FOUR FIGURE ACC

```

ACCURACY IN 25 ITERATIONS)

15 RO =RH03

RETURN

16 RO =RH0UP

RETURN

END

C

PRESSURE VS TEMPERATURE AND DENSITY USING STROBRIDGE EQUATION

FUNCTION PRESS(T,RHO,A)

DIMENSION A(17),B(15)

RH02=RHO*RHO

RH03=RH02*RHO

RH04=RH03*RHO

RH05=RH04*RHO

RH06=RH05*RHO

T2=T*T

T3=T2*T

T4=T3*T

EX=EXP(-A(16)*RH02)

B(1)=A(17)*T*RHO2

B(2)=RH02

B(3)=RH02/T

B(4)=RH02/T2

B(5)=RH02/T4

B(6)=A(17)*T*RHO3

B(7)=RH03

B(8)=T*RHO4

B(9)=EX*RHO3/T2

B(10)=EX*RHO3/T3

B(11)=EX*RHO3/T4

B(12)=EX*RHO5/T2

B(13)=EX*RHO5/T3

B(14)=EX*RHO5/T4

B(15)=RH06

PRESS=A(17)*T*RHO

DO I K=1,15

1 PRESS=PRESS+A(K)*B(K)

RETURN

END

C

DP/RHO AT CONSTANT T STROBRIDGE EQUATION

FUNCTION DPDRHO(T,RHO,A)

DIMENSION A(17),B(15)

RH02=RHO*RHO

```

RHO3=RHO2*RHO
RHO4=RHO3*RHO
RHO5=RHO4*RHO
RHO6=RHO5*RHO
T2=T*T
T3=T2*T
T4=T3*T
EX=EXP(-A(16)*RHO2)
B(1)=2.*A(17)*T*RHO
B(2)=2.*RHO
B(3)=B(2)/T
B(4)=B(2)/T2
B(5)=B(2)/T4
B(6)=3.*A(17)*T*RHO2
B(7)=3.*RHO2
B(8)=4.*T*RHO3
B(9)=3.*RHO2-2.*A(16)*RHO4)*EX/T2
B(10)=B(9)/T
B(11)=B(9)/T2
B(12)=(5.*RHO4-2.*A(16)*RHO6)*EX/T2
B(13)=B(12)/T
B(14)=B(12)/T2
B(15)=6.*RHO5
DPBDR0=A(17)*T
DO 1 N=1,15
1 DPBDR0=DPBDR0+A(N)*B(N)
RETURN
END
C SATURATED LIQUID DENSITY
FUNCTION RHOLS(T)
RHOP=0.
RHOI=0.
IF(XMFP.EQ.0.)GO TO 1
RHOP=1.+(154.*78-T)**.4/(17.106+.0038*T)*.43)*1000.028*.43/32.
1 IF(XMFP.EQ.0.)GO TO 2
R=(1.-T/126.*26)**(1./3.)
RHOI=11.2302+21.*0821*R-9.81774*R**2+27.7904*R**3-11.7647*R**4
2 RHOLS=XMFP*RHOP+(1.-XMFP)*RHOI
RETURN
END
C INTEGRATE CPO FROM T-TO
FUNCTION CPOINT(T,T0,CPO)
DIMENSION CPO(5),Y(5)
CPOINT=0.0
DO 1 N=1,5
X=N

```

```

Y(N)=(T**N-TO**N)/X
1 CPOINT=CPOINT+CPO(N)*Y(N)
RETURN
END
C ISOTHERMAL ENTHALPY CHANGE FROM ZERO DENSITY TO RHO
FUNCTION DELHRO(T,P,RHO,A)
DIMENSION A(17)
EX=EXP(-A(16)*RHO*RHO)
DELHRO=101.3278*(P/RHO-A(17))*T+RHO*(A(2)+2.*A(3)/T+3.*A(4)/T**2+5.*
A(5)/T**4)+A(7)*RHO*RHO/2.-(3.*A(9)/T**2+4.*A(10)/T**3+5.*A(11)/T
**4)*EX/(2.*A(16))-(RHO*RHO/(2.*A(16))+1./(2.*A(16)**2))*(3.*A(12)
/T**2+4.*A(13)/T**3+5.*A(14)/T**4)*EX+A(15)*RHO**5/5.+(3.*A(9)/T**
2+4.*A(10)/T**3+5.*A(11)/T**4)/(2.*A(16))+(3.*A(12)/T**2+4.*A(13)/
T**3+5.*A(14)/T**4)/(2.*A(16)**2)
RETURN
END

```

C ISOTHERMAL ENTHALPY CHANGE FROM PV,RHOLS TO P,RHO

```

FUNCTION DELHP(R2,D2,P1,D1,T,A)
P=R1
D=D1
DELHP=0.
DO 1 N=1,2
H1=P/D+D*(A(2)+2.*A(3)/T+3.*A(4)/T**2+5.*A(5)/T**4)+A(7)*D*D/2.
H2=-03.*A(9)/T**2+4.*A(10)/T**3+5.*A(11)/T**4)
H3=EXP(-A(16)*D*D)/(2.*A(16))
H4=-0D*D/(2.*A(16))+1./(2.*A(16)**2)
H5=13.*A(12)/T**2+4.*A(13)/T**3+5.*A(14)/T**4)
H6=EXP(-A(16)*D*D)+A(15)*D**5/5.
DELHP=H1+H2*H3+H4*H5*H6-DELHP
P=R2
D=D2
1 RETURN
END

```