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SHUTTLE

FINAL REPORT

SHUTTLE CRYOGENICS SUPPLY SYSTEM

OPTIMIZATION STUDY

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APPENDIX TO PROGRAMMERS MANUAL FOR MATH MODEL

PART 2

PRICES SUBJECT TO CHANGE

CONTRACT NAS9-11330

Prepared for Manned Spacecraft Center
by
Manned Space Programs, Space Systems Division

LOCKHEED MISSILES & SPACE COMPANY, INC.
A SUBSIDIARY OF LOCKHEED AIRCRAFT CORPORATION

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FINAL REPORT
SHUTTLE CRYOGENIC SUPPLY SYSTEM OPTIMIZATION STUDY

VOLUME VB-3
APPENDIX TO PROGRAMMERS MANUAL FOR MATH MODEL
PART 2

LOCKHEED MISSILES & SPACE COMPANY

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FOREWORD

This Final Report provides the results obtained in the Shuttle Cryogenics Supply System Optimization Study, NAS 9-11330, performed by Lockheed Missiles & Space Company (LMSC) under contract to the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas. The study was under the technical direction of Mr. T. L. Davies, Cryogenics Section of the Power Generation Branch, Propulsion and Power Division. Technical effort producing these results was performed in the period from October 1970 to June 1973.

The Final Report is published in eleven volumes*:

Volume I	– Executive Summary
Volumes I, III, and IV	– Technical Report
Volume V A-1 and V A-2	– Math Model – Users Manual
Volume V B-1, V B-2, V B-3, and V B-4	– Math Model – Programmers Manual
Volume VI	– Appendixes

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*The Table of Contents for all volumes appears in Volume I only. Section 12 in Volume III contains the List of References for Volumes I through IV.

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THE MATH MODELS

This Appendix presents the mathematical models for the major subroutines and supporting subprograms employed in Program TCIMM.

MATH MODEL FOR ACPS ANALYSIS

PURPOSE OF ANALYSIS

To provide a computational technique, which, when programmed for a digital computer, will permit rapid and accurate parametric analysis of current and advanced attitude control propulsion systems. The analytical capability of the calculational techniques employed is to include system sizing and weight determination procedures as well as the permitting of parametric perturbation of system functional constraints and performance criteria. Where applicable, the analysis is to generate time dependent energy requirement histories associated with reactant or propellant storage and utilization.

THE MATH MODEL

The ACPS concept system, upon which the model is based, was chosen from among similar concepts studied previously under this study contract (Ref 1.9-4, 5). The concept illustrated in Fig. M.M-1, is a cold helium pressurized, subcritical cryogen fluid supplied, bipropellant gas-fed attitude control propulsion system. The cryogen fluids are stored as liquids under low pressure and temperature conditions. Conversion of the liquid cryogen fluids to gases is accomplished through the use of high pressure liquid pumps which feed high pressure vaporizer consisting of gas generator fired heat exchangers. The resulting gaseous propellants are fed into high pressure accumulators for temporary storage until needed by the rocket engines. Propellant feed to the engines is through pressure regulator valves which drop the pressure to levels compatible with the engine operating requirements. Oxygen and hydrogen gas at the engine feed pressure and temperature are available to other systems via tap lines at the engine feed manifolds.

The Math Model, presented herein, gives in generalized equation form, the procedural technique employed in setting up the ACPS analysis program. As the program was developed, many detailed refinements were added to enhance analytical accuracy,

HIGH PRESSURE - SUBCRITICAL STORAGE
CONCEPT 1A

STORED HELIUM PRESSURIZATION

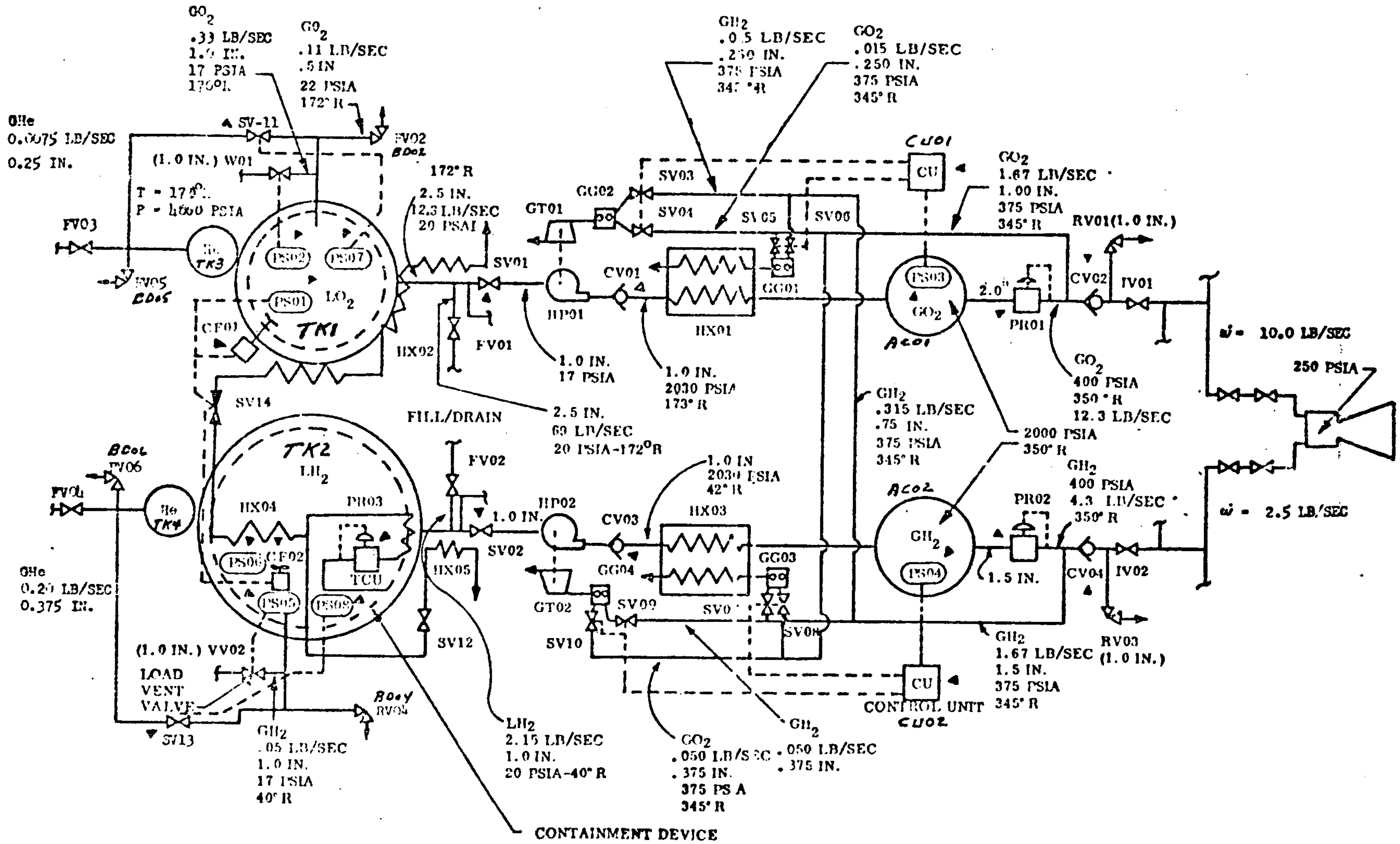

Fig. M. M-1 Attitude Control Propulsion System therefore, deviations will become apparent when comparing the model with the actual program listings. And, of course, it will be noted that the model was broken into quite a few subprograms, each of which are quite detailed as compared to the generalized model equations.

MATHEMATICAL PROCEDURES AND EQUATIONS

The following text presents the generalized procedures and equations employed in the mathematical model for the ACPS analysis program:

1. Propellant flow requirements:

   a) Input data required:

      $P_{E_{O_2}}$ = engine O_2 feed pressure, psia

      $P_{E_{H_2}}$ = engine H_2 feed pressure, psia

      $T_{E_{O_2}}$ = engine O_2 feed temperature, ^oR

      $T_{E_{H_2}}$ = engine H_2 feed temperature, ^oR

      $T_{t_{O_2}}$ = O_2 storage tank temperature, ^oR

      $T_{t_{H_2}}$ = H_2 storage tank temperature, ^oR

      F = engine thrust level, lbs per engine

      E_{max} = maximum number of engines operating simultaneously at any duty cycle point

      ISP = engine specific impulse, lbs/lb-sec

      MR_E = engine propellant mixture ratio, lbs O_2/lbs H_2

      MR_{HXGG} = heat exchanger gas generator mixture ratio, lbs O_2/lbs H_2

      MR_{TPGG} = turbopump gas generator mixture ratio, (lbs O_2/lbs H_2)

      Th_{in} = gas generator gas temperature to heat exchanger, ^oR

      Th_{out} = gas generator gas temperature out of heat exchanger, ^oR (≥ 700)

$P_{h_{in}}$ = gas generator gas pressure to heat exchanger, psia

$P_{h_{out}}$ = gas generator gas pressure out of heat exchanger, psia

DS_E = engine duty cycle, number of engines and time of operation

η_P = propellant pump efficiency, decimal fraction

η_T = propellant pump drive turbine efficiency, decimal fraction

ΔP_{EST} = trial assumption, maximum required pump ΔP, psi

PT_{in} = turbopump turbine gas inlet pressure, psia

PT_{out} = turbopump turbine gas outlet pressure, psia

TT_{in} = turbopump turbine gas inlet temperature, ^{o}R

γ_G = ratio of specific heats of gas generator exhaust productions

g = gravitational constant = 32,174 ft/sec^2

b) Maximum propellant flow rates to engines:

$\dot{W}_{O_{2_i}}$ = $F/ISP\ (MR_E/1 + MR_E)$ lb/sec per engine at any duty cycle point

$\dot{W}_{H_{2_i}}$ = $F/I_{SP}\ (1/1 + MR_E)$ lb/sec per engine at any duty cycle point

$$\dot{W}_{O_{2_i}} = \sum_{i=1}^{E_{max}} \dot{W}_{O_{2_i}} \text{ lb/sec maximum flow to all engines}$$

$$\dot{W}_{H_{2_E}} = \sum_{i=1}^{E_{max}} \dot{W}_{H_{2_i}} \text{ lb/sec maximum flow to all engines}$$

c) Maximum total propellant system flow rates:

$$\dot{W}_{O_{2_{tot}}} = \dot{W}_{O_{2_E}} + \dot{W}_{O_1} + \dot{W}_{O_2} \text{ lb/sec maximum}$$

$\dot{W}_{H_{2_{tot}}} = \dot{W}_{H_{2_E}} + \dot{W}_{H_1} + \dot{W}_{H_2}$ lb/sec maximum

$\dot{W}_{O_1}$ = O_2 flow rate to condition O_2, lb/sec

$\dot{W}_{O_2}$ = O_2 flow rate to condition H_2, lb/sec

$\dot{W}_{H_1}$ = H_2 flow rate to condition O_2, lb/sec

$\dot{W}_{H_2}$ = H_2 flow rate to condition H_2, lb/sec

$$\dot{W}_{O_1} = \frac{\dot{W}_{O_{2_E}} (K_1 K_4 - K_1) + \dot{W}_{H_{2_E}} (-K_1 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$\dot{W}_{O_2} = \frac{\dot{W}_{O_{2_E}} (-K_2 K_3) + \dot{W}_{H_{2_E}} (K_1 K_3 - K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$\dot{W}_{H_1} = \frac{\dot{W}_{O_{2_E}} (K_2 K_4 - K_2 + \dot{W}_{H_{2_E}} (-K_2 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$\dot{W}_{H_2} = \frac{\dot{W}_{O_{2_E}} (-K_2 K_4) + \dot{W}_{H_{2_E}} (K_1 K_4 - K_4)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$K_1 = \left[\frac{\left(h_{c_{out}} - h_{c_{in}}\right)_{O_2\ HX}}{\left(h_{h_{in}} - h_{h_{out}}\right)_{O_2\ HX}}\right] \left(\frac{MR}{1 + MR}\right)_{O_2\ HX\ GG}$$

$$+ \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LO_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{O_2\ TP} \left(\frac{MR}{1 + MR}\right)_{O_2\ TPGG}$$

$$K_2 = \left[\frac{\left(h_{c_{out}} - h_{c_{in}}\right)}{\left(h_{h_{in}} - h_{h_{out}}\right)}\right]_{O_2\ HX} \left(\frac{1}{1 + MR}\right)_{O_2\ HXGG}$$

$$+ \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LO_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{O_2\ TP} \left(\frac{1}{1 + MR}\right)_{O_2\ TPGG}$$

$$K_3 = \left[\frac{\left(h_{c_{out}} - h_{c_{in}}\right)}{\left(h_{h_{in}} - h_{h_{out}}\right)}\right]_{H_2\ HX} \left(\frac{MR}{1 + MR}\right)_{H_2\ HXGG}$$

$$+ \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LH_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{H_2\ TP} \left(\frac{MR}{1 + MR}\right)_{H_2\ TT\ GG}$$

$$K_4 = \left[\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}}\right]_{H_2\ HX} \left(\frac{1}{1 + MR}\right)_{H_2\ HXGG}$$

$$+ \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LH_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{H_2\ TP} \left(\frac{1}{1 + MR}\right)_{H_2\ TPGG}$$

$H_{c_{out}}$ = cold fluid outlet enthalpy, Btu/lb (obtained from Tables, vs $\Delta P_{EST} + 15,\ T_E$)

$H_{c_{in}}$ = cold fluid inlet enthalpy, Btu/lb (from Tables, vs $\Delta P_{EST} + 15,\ T_t$)

$h_{h_{out}}$ = hot fluid outlet enthalpy, Btu/lb (from Tables, vs $P_{h_{out}}$ and $T_{h_{out}}$)

$h_{h_{in}}$ = hot fluid inlet enthalpy, Btu/lb (from Tables, vs $P_{h_{in}}$ and $T_{h_{in}}$)

$h_{T_{out}}$ = gas outlet enthalpy from turbine, Btu/lb (from Tables, vs $P_{T_{out}}$ and $T_{T_{out}}$)

$h_{T_{in}}$ = gas inlet enthalpy to turbine, Btu/lb (from Tables, vs $P_{T_{in}}$ and $T_{T_{in}}$)

$$T_{T_{out}} = T_{T_{in}} - \eta_T T_{T_{in}} \left[1 - \left(\frac{P_{T_{out}}}{P_{T_{in}}} \right) \right]^{\frac{\gamma_G - 1}{\gamma_G}} \quad , \ {}^{o}R$$

2. <u>Computation of Propellant System ΔP Between Pump and Engines</u>:

Pressure drop is found only for the maximum flow case, since that is the condition which sizes the lines and fittings. The maximum flow case occurs with all engines operating. Each system element is treated in order of its occurrence, advancing upstream from the engines to the accumulator, the the heat exchanger, and the pump. Analysis is conducted for each operating engine in turn.

(a) Input data required:

(1) For each line segment element:

Numerical identity of the element in the system

L_i = line segment length, ft

D_i = line inside diameter, in.

Line function or location in system:

A – transports engine propellant only

B – transports engine and gas generator propellant

C – between accumulator and heat exchanger

D – between heat exchanger and pump

F – between pump and tank

G – between tank and helium sphere

H – transports propellants to HX gas generators

J – transports propellants to TP gas generators

K – transports gas from GG to HX

L – transports gas from GG to TP

Type of fluid flowing:

I – O_2

II – H_2

(2) Tabulation of f_i, (friction factor), versus Re, (Reynolds Number), for the type of pipe used.

(3) V_{Acc} = accumulator volume, ft^3

(4) P_S = pump actuation pressure switch (accumulator) pressure setting, psia

(5) P_{max} = accumulators pressure at pump shutoff, psia

(6) t_D = time from pump actuation to full pump output pressure (output check valve setting) at zero flow, seconds

(7) γ_f = ratio of specific heats for the fluid under consideration (O_2, H_2, He, or gas)

(8) For each two-outlet branch fitting element:

D_i = fitting inlet inside diameter, in.

N_o = number of outlets in operation

K_1 = pressure drop coefficient through outlet No. 1 (function of $(\dot{W}/A)_{in}$, $(\dot{W}/A)_1$, and diversion angle)

K_2 = pressure drop coefficient through outlet No. 2 (function of $(\dot{W}/A)_{in}$, $(\dot{W}/A)_2$, and diversion angle)

(9) For each pressure regulator element:

Numerical identity of the element

Minimum ΔP for regulation, psi

(10) For each valve element:

Numerical identity of the element

ΔP through valve, as function of fluid flow rate and state, and valve diameter

(11) For each single-outlet fitting element:

Numerical identity of the element

D_i = inside diameter of the fitting, in.

L_i = equivalent feet of pipe of the fitting, ft

(12) For each accumulator:

Numerical identity of the accumulator exit as a system pressure drop element

Numerical identity of the accumulator inlet as a system pressure drop element

D_{i_1} = accumulator exist inside diameter, in.

D_{i_2} = accumulator inlet inside diameter, in.

(13) For each heat exchanger:

Numerical identity of the heat exchanger as a system pressure drop element.

$\Delta P_{c_{HX}}$ = Heat exchanger cold fluid pressure drop $\leq 0.2\ P_{c_{in}} \leq 0.25\ P_{c_{out}}$

NOTE: $\Delta P_{h_{HX}}$ = heat exchanger hot fluid pressure drop $\leq 0.4\ P_{h_{in}} \leq 0.667\ P_{h_{out}}$

(14) R = gas constant for the fluid under consideration, ft/^{o}R

(b) Procedure for Analysis:

(1) Determine ΔP_i for each system element in order of its occurrence, advancing upstream from the engines, per the order of element numerical designation, for each system O_2 and H_2.

(2) Let subscript (i) designate the element under consideration, regardless of its type

(3) Let subscript (i - 1) designate the element which preceded (i) in the analysis, (the element which is immediately downstream of i), regardless of its type

(4) Sum pressure drops to the point of the pump exit, for each system, O_2 and H_2.

(5) Compare $\Sigma\Delta P_i$ found in (4) with the trial assumption of ΔP_{EST} which was input in operation 1a for the respective system, O_2 or H_2.

(6) If $\left|\frac{\Sigma\Delta P_i - \Delta P_{EST}}{\Sigma\Delta P_i}\right| \leq 0.01$, iteration not necessary

(7) If $\left|\frac{\Sigma\Delta P_i - \Delta P_{EST}}{\Sigma\Delta P_i}\right| > 0.01$, input $\Delta P_{EST} = \frac{\Sigma\Delta P_i + P_E + \quad _{EST}}{2}$

and recalculate $\dot{\omega}_{o_1}$, $\dot{\omega}_{o_2}$, $\dot{\omega}_{H_1}$, and $\dot{\omega}_{H_2}$, per operation 1c.

Recalculate $\Sigma\Delta P_i$

Recheck for $\left|\frac{\Sigma\Delta P_i - \Delta P_{EST}}{\Sigma\Delta P_i}\right| \leq 0.01$

Iterate as necessary until $\left|\frac{\Sigma\Delta P_i - \Delta P_{EST}}{\Sigma\Delta P_i}\right| \leq 0.01$ for each system O_2 and H_2.

(c) Compute pressure drop through a line segment element:

(1) $\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{i-1}$

$P_i = P_{i-1} + \Delta P_i$

Find fluid state for T_{i-1}, P_{i-1}, and type of propellant.

(2) If fluid is a liquid:

$$\Delta P_i = 4.64 \; (\dot{W}_i/\mu_i \, P_i)^{-0.2} \; (\dot{W}_i^{\,2} \, L_i/\rho_i \, D_i^{\,5})$$

$\rho_i = f\,(T_{i-1},\, P_{i-1},$ fluid type$)$, lb/ft^3

$\mu_i = f\,(T_{i-1},\, P_{i-1},$ fluid type$)$, lb/ft-sec

(3) If fluid is a gas, proceed as follows:

(i) Solve for M_2, from equation or input curve:

$$0.2245\left(\frac{\dot{W}_i \sqrt{R\,T_{i-1}}}{D_i^2 \, P_{i-1} \sqrt{\gamma_f}}\right) = M_2 \left(1 + \frac{\gamma_f - 1}{2} M_2^2\right)^{0.5}$$

(ii) Solve for $\left(\frac{4fL^*}{D}\right)_2$ from equation:

$$\left(\frac{4fL^*}{D}\right)_2 = \left[\frac{\left(1 - M_2^2\right)}{\gamma_f \, M_2^2}\right] + \frac{\gamma_f + 1}{2\,\gamma_f} \ln \frac{(\gamma_f + 1)\, M_2^2}{2\left(1 + \frac{\gamma_f - 1}{2} M_2^2\right)}$$

(iii) Solve for $\left(\frac{4fL^*}{D}\right)_1$ from equation:

$$\left(\frac{4fL^*}{D}\right)_1 = \left(\frac{4fL^*}{D}\right)_2 + \left(\frac{4\, f_i \, L_i}{D_i}\right)$$

f_i is found from tabulation of f_i vs Re, where

$$\mathrm{Re} = 15.27 \left(\frac{\dot{W}_i}{D_i \mu_i}\right)$$

μ_i = viscosity at T_i and P_i, lb/sec-ft

(iv) Solve for M_1 from equation or input curve:

$$\left(\frac{4fL^*}{D}\right)_1 = \left(\frac{1 - M_1^2}{\gamma_f M_1^2}\right) + \left(\frac{\gamma_f + 1}{2\gamma_f}\right) \ln \frac{(\gamma_f + 1) M_1^2}{2\left(1 + \frac{\gamma_f - 1}{2} M_1^2\right)}$$

(v) Solve for $\Delta P_i = P_i - P_{i-1}$

$$\Delta P_i = P_i - P_{i-1}$$

$$P_i = \frac{0.2245\left(\frac{\dot{W}_i \sqrt{R\, T_{i-1}}}{D_i^2 \sqrt{\gamma_f}}\right)}{M_1 \quad 1 + \left(\frac{\gamma_f - 1}{2} M_1^2\right)^{0.5}}$$

P_{i-1} = calculated P_i for the element which preceded this line segment in the analysis

(d) Compute pressure dropthrough a two-outlet branch fitting element: (Flag the outlets which feed the gas generators)

(1) Are both outlets operating?

(a) If no,

$$\dot{W}_i = \dot{W}_{i-1}$$

$$T_i = T_{i-1}$$

$$P_i = P_{i-1} + \Delta P_i$$

$$\Delta P_i = 3.63 \frac{K_1 W_i^2}{D_i^4 \rho_i}$$

where $K = K_1$ or $K = K_2$, as applicable.

(b) If yes, for outlet No. 1,

$$\dot{W}_i = (\dot{W}_{i-1})_1 + (\dot{W}_{i-1})_2$$

$$T_i = (T_{i-1})$$

$$P_i = (P_{i-1})_1 + \Delta P_i$$

$$(\Delta P_i)_1 = 3.63 \frac{K_1 W_i^2}{D_i^4 \rho_i}$$

(c) If yes, for outlet No. 2,

$$\dot{W}_i = (\dot{W}_{i-1})_2 + (\dot{W}_{i-1})_1$$

$$T_i = (T_{i-1})_2$$

$$P_i = (P_{i-1})_2 + \Delta P_i$$

$$(\Delta P_i)_2 = 3.63 \frac{K_2 W_i^2}{D_i^4 \rho_i}$$

(e) Compute pressure drop through a pressure regulator element:

$$\dot{W}_i = \dot{W}_{i-1}$$

$$T_i = f\,(P_i,\ h_{i-1}),\ \text{where}\ h_{i-1} = (\text{Enthalpy})_{i-1} = f\,(P_{i-1},\ T_{i-1})$$

$$P_i = P_{i-1} + \Delta P_i$$

Set $\Delta P_i = \Delta P_{min}$

$$\Delta P_i = \Delta P_{min}$$

(f) Compute pressure drop through a valve element:

$$\dot{W}_i = \dot{W}_{i-1}$$

$$T_i = T_{i-1}$$

$$P_i = P_{i-1} + \Delta P_i$$

$$\Delta P_i = f\,(W_i,\ \text{fluid, fluid state, and}\ D_{valve})$$

$$\Delta P_i = \Delta P_{valve}$$

(g) Compute pressure drop through single outlet fitting element:

(1) $\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{i-1}\ ;\ P_i = P_{i-1} + \Delta P_i$

$D_i = \text{I.D.}_{\text{Fitting}}$

Find fluid state for T_{i-1}, P_{i-1}, and type of fluid.

(2) If fluid is a liquid:

$$\Delta P_i = 4.64 \left(\frac{\dot{W}_i}{\rho_i D_i}\right)^{-0.2} \left(\frac{\dot{W}_i^2 L_E}{\rho_i D_i^5}\right)$$

$L_E = L_{\text{Equivalent}}$ of Fitting

(3) If fluid is a gas,

(i) Solve for M_2, from equation or input curve:

$$0.2245 \left(\frac{\dot{W}_i \sqrt{R\, T_{i-1}}}{D_i^2\, P_{i-1} \sqrt{\gamma_f}} \right) = M_2 \left(1 + \frac{\gamma_f - 1}{2} M_2^2 \right)^{0.5}$$

(ii) Solve for $\left(\frac{4fL^*}{D}\right)_2$ from equation:

$$\left(\frac{4fL^*}{D}\right)_2 = \left[\frac{\left(1 - M_2^2\right)}{\gamma_f M_2^2} \right] + \left(\frac{\gamma_f + 1}{2\,\gamma_f} \right) \ln \frac{(\gamma_f + 1)\, M_2^2}{2\left(1 + \frac{\gamma_f - 1}{2} M_2^2\right)}$$

(iii) Solve for $\left(\frac{4fL^*}{D}\right)_1$ from equation:

$$\left(\frac{4fL^*}{D}\right)_1 = \left(\frac{4fL^*}{D}\right)_2 + \left(\frac{4\, f_i\, L_E}{D_i} \right)$$

f_i is found from tabulation of f_i vs Re, where

$$Re = 15.27 \left(\frac{\dot{W}_i}{D_i\, \mu_i} \right)$$

L_E = equivalent pipe length of the fitting, ft

(iv) Solve for M_1 from equation or input curve:

$$\left(\frac{4fL^*}{D}\right)_1 = \left(\frac{1 - M_1^2}{\gamma_f M_1^2} \right) + \left(\frac{\gamma_f + 1}{2\,\gamma_f} \right) \ln \frac{(\gamma_f + 1)\, M_1^2}{2\left(1 + \frac{\gamma_f - 1}{2} M_1^2\right)}$$

(v) Solve for ΔP_i:

$$\Delta P_i = P_i - P_{i-1}$$

$$P_i = \frac{0.2245 \left(\frac{W_i \sqrt{R\, T_{i-1}}}{D_i^2 \sqrt{\gamma_f}} \right)}{M_1 \left(1 + \frac{\gamma_f - 1}{2} M_1^2 \right)^{0.5}}$$

P_{i-1} = calculated P_i for the element which preceded this fitting element in the analysis.

(h) Compute pressure drop through an accumulator:

$$\dot{W}_i = \dot{W}_{i-1}$$

$$T_i = T_{i-1}$$

$$P_i = P_{i-1} + \Delta P_i$$

$$\Delta P_i = \Delta P_I + \Delta P_O = \Delta P_{inlet} + \Delta P_{outlet}$$

$$\Delta P_I = 3.63 \left(\frac{\dot{W}_i^2}{{}_i\, D_i^4} \right) \left[1 - \left(\frac{D_i}{D_{Acc}} \right)^2 \right]^2$$

D_{Acc} = accumulator diameter, in.

$$\Delta P_O = 0.363 \left[\frac{\dot{W}_i^2}{\rho_i\, D_{i-1}^4} \right]$$

$$P_m = P_{i-1} + \Delta P_O$$

where

P_{i-1} = highest value of P_{i-1} found in the element immediately downstream of the accumulator for any engine.

(i) Compute pressure drop through a heat exchanger:

The heat exchanger design subroutine provides the possibility that pressure drop of the cold fluid (ΔP_i) may be as much as $0.2\ P_{c_{in}} = 0.25\ P_{cont}$ if ΔP_c is not specified.

Therefore

P_i = $0.25\ P_{i-1}$, or any input value lower than this.

Also, for the heat exchanger,

$\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{Tnk}$

where

$T_{Tnk} = T_{Tnk_{O_2}}$ for the O_2 system

$T_{Tnk} = T_{Tnk_{H_2}}$ for the H_2 system

$P_i = P_{i-1} + \Delta P_i$

(j) Perform summation of pressure drops of all elements:

$$\Delta P_P = \sum_{i=1}^{n} P_i$$

where

$$\sum_{i=1}^{n} \Delta P_i$$ = maximum pressure drop between the pump and any engine. Use nonsteady-state flow for elements where it results in a higher ΔP_i .

(k) Perform iteration:

Compare $\sum_{i=1}^{n} P_i$ with ΔP_{EST} per procedure outlined in Operation 2b, and iterate as necessary until $\frac{\Sigma \Delta P_i - \Delta P_{EST}}{\Delta P_i} \leq 0.01.$

3. Compute Propellant System ΔP From Pump into Storage Tank:

Pressure drop is found only for the maximum flow case, which occurs with all engines operating. Each system element is treated in order of its occurrence, advancing upstream from the pump to the storage tank.

(a) Input data required:

Provide inputs per Operation 2a, as applicable, for each pump-to-storage tank flow path.

(b) Procedure:

(1) Determine ΔP_i for each system element in order of its occurrence advancing upstream from the pump, per the order of element numerical designation, for each system, O_2 and H_2 .

(2) Let subscript (i) designate the element under consideration, regardless of its type.

(3) Let subscript (i-1) designate the element which preceded (i) in the analysis (the element which is immediately downstream of i), regardless of its type.

(4) Sum the pressure drops of all elements between the pump inlet and the inside of the storage tank, for each system, O_2 and H_2.

(c) Compute pressure drop through a line segment element:

(1) $\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{i-1}$

$P_i = P_{i-1} + \Delta P_i$

(2) By definition of subcritical system, fluid is a liquid. Is flow steady-state?

(i) If flow is steady-state,

$$\Delta P_i = 4.64 \left(\frac{\dot{W}_i}{\mu_i D_i} \right)^{-0.2} \left(\frac{\dot{W}_i^2 L_i}{\rho_i D_i^5} \right)$$

(ii) If flow is not steady-state,

$$\Delta P_i = 4.64 \left(\frac{\dot{W}_i}{\mu_i D_i} \right)^{-0.2} \left(\frac{\dot{W}_i^2 L_i}{\rho_i D_i^5} \right) + 0.0395 \left(\frac{\ddot{W} L_i}{D_i^2} \right)$$

where $\ddot{W}$ is found as follows:

For O_2:

$$\ddot{W} = \frac{\left(\dot{W}_{O_{2_E}} + \dot{W}_{O_1} + \dot{W}_{O_2}\right)^2}{2\, V_{Acc_{O2}} \left[\rho\left(P_{S_{O_2}}, T_{T_{O_2}}\right) - \rho\left(P_{m_{O_2}}, T_{T_{O_2}}\right)\right] - 2\, t_D \left(\dot{W}_{O2_E} + \dot{W}_{O1} + \dot{W}_{O2}\right)}$$

For H_2:

$$W = \frac{\left(\dot{W}_{H_{2_E}} + \dot{W}_{H_1} + \dot{W}_{H_2}\right)^2}{2\, V_{Acc_{H_2}} \left[\rho\left(P_{S_{H_2}}, T_{T_{H_2}}\right) - \rho\left(P_{m_{H_2}}, T_{T_{H_2}}\right)\right] - 2\, t_D \left(\dot{W}_{H2_E} + \dot{W}_{H1} + \dot{W}_{H2}\right)}$$

T_T = storage tank temperature, ^oR

(d) Compute pressure drop through a two-outlet branch fitting element:

Solve by same method as operation 2d.

(e) Compute pressure drop through a pressure regulator element:

Such an element would not normally be found in this section of a subcritical system. If such an element existed, it would be solved per operation 2e.

(f) Compute pressure drop through a valve element:

Solve by same method as operation 2f.

(g) Compute pressure drop through single outlet fitting element:

(1) $\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{i-1}$

$D_i = \text{I.D.}_{\text{Fitting}}$

(2) By definition of subcritical system, fluid is a liquid.

Is flow steady-state?

(i) If flow is steady-state,

$$\Delta P_i = 4.64 \left(\frac{\dot{W}_i}{\mu_i D_i}\right)^{-0.2} \left(\frac{\dot{W}_i^2 L_E}{\rho_i D_i^5}\right)$$

where

$L_E = L_{\text{Equivalent}}$ of Fitting

(ii) If flow is not steady-state,

$$P_i = 4.64 \left(\frac{\dot{W}_i}{\mu_i D_i}\right)^{-0.2} \left(\frac{\dot{W}_i^2 L_E}{\rho_i D_i^5}\right) + 0.0395 \left(\frac{\ddot{W} L_i}{D_i^2}\right)$$

where

$L_i = L_{\text{Actual}}$ of Fitting

$\ddot{W}$ = value found in operation 3c (2) (ii)

(h) Compute pressure drop through an accumulator:

No accumulator in this section of the system.

(i) Compute pressure drop through a heat exchanger:

No heat exchanger in this section of the system.

(j) Compute pressure drop through storage tank exit:

(1) $\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{i-1}$

$D_i = \text{I.D.}_{\text{Exit}}$

(2) By definition of subcritical system, fluid is a liquid.

Is flow steady-state?

(i) If flow is steady-state,

$$\Delta P_i = 0.363 \left(\frac{\dot{W}_i^2}{\rho_i D_{i-1}^4} \right)$$

(ii) If flow is not steady-state,

$$\Delta P_i = 0.363 \left(\frac{\dot{W}_i^2}{\rho_i D_{i-1}^4} \right) + 0.0395 \left(\frac{\ddot{W} L_i}{D_i^2} \right)$$

where

L_i = length of the outlet nipple

$\ddot{W}$ = value found in operation 3c (2) (ii)

(k) Compute pressure drop through propellant acquisition device:

$\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{i-1}$

D_i = equivalent orifice diameter of acquisition device

$L_i = L_{\text{Acq Dev}}$

$$\Delta P_i = 0.0395 \left(\frac{\ddot{W} L_i}{D_i^2} \right)$$

where

$\ddot{W}$ = value found in operation 3c (2) (ii)

(1) Compute storage tank pressure:

$$P_{Tnk} = \left(\sum_{i=1}^{n} \Delta P_i \right) + P_{SAT} + NPSP$$

where

P_{Tnk} = storage tank ullage pressure, psia

P_{SAT} = saturation pressure of the stored liquid corresponding to T_{Tnk}, psia

NPSP = net positive suction pressure at pump inlet (Input), psi

$\sum_{i=1}^{n} \Delta P_i$ = summation of pressure drops from inside of tank to pump inlet, psi. Use nonsteady-state flow for elements where it results in a higher ΔP_i .

4. Determine Pressure Drop From Pressurant Sphere to Inside of Storage Tank:

Pressure drop is found only for the maximum flow case, which occurs with all engines operating. Each system element is treated in order of its occurrence, advancing upstream from the storage tank to the pressurant tank.

(a) Inputs required:

Provide inputs per operation 2a, as applicable, for each storage tank-to pressurant sphere flow path.

(b) Procedure:

(1) Determine ΔP_i for each system element in order of its occurrence, advancing upstream from the inside of the storage tank, per the order of element numerical designation for the pressurant system.

(2) Let subscript (i) designate the element under consideration, regardless of its type.

(3) Let subscript (i-1) designate the element which preceded (i) in the analysis (the element which is immediately downstream of i), regardless of its type.

(4) Sum the pressure drops of all elements between the storage tank and the pressurant tank.

(5) It is assumed that the pressurant is stored cryogenically; therefore, temperature changes which tend to occur in the pressurant due to blowdown and subsequent pressure reduction are assumed to be nullified by the thermal influence of the cryogenic sink, especially after injection of the pressurant into the storage tank.

(6) Start from storage tank ullage conditions of:

$$T_i = T_{Tnk} \text{ (Input)}, \ {}^{o}R \quad ; \qquad P_i = P_{Tnk}, \text{ psia}$$

For the O_2 pressurant:

$$\dot{W}_{i_{(PR)}} = \dot{W}_{O_{2_{tot}}} \left(\frac{\rho_{PR}}{\rho_{O_2}} \right)$$

For the H_2 pressurant:

$$\dot{W}_{i_{(PR)}} = \dot{W}_{H_{2_{tot}}} \left(\frac{\rho_{PR}}{\rho_{H_2}} \right)$$

$$\rho_{PR} = f\,(T_i, P_{Tnk} - P_{SAT}) \ ; \ \rho_{O_2} = f\,(T_i, P_i) \ ; \ \rho_{H2} = f\,(T_i, P_i)$$

(c) Compute pressure drop through storage tank pressurant entry:

$$\Delta P_i = 3.63 \left(\frac{\dot{W}_i^2}{\rho_i \, D_i^4} \right) \left[1 - \left(\frac{D_i}{D_{Tnk}} \right)^2 \right]^2$$

where

$\rho_i = f\,(T_i, P_{Tnk})$

D_{Tnk} = storage tank diameter, in.

(d) Compute pressure drop through a line segment element:

Solve by same method as operation 2c (3).

(e) Compute pressure drop through a two-outlet branch fitting element:

Solve by same method as operation 2d.

(f) Compute pressure drop through a pressure regulator element:

$\dot{W}_i = \dot{W}_{i-1}$

$T_i = T_{i-1}$ (Assumed)

$\Delta P_i = \Delta P_{min}$ = Input, psi

(g) Compute pressure drop through a valve element:

Solve same method as operation 2f.

(h) Compute pressure drop through single outlet fitting element:

Solve by same method as operation 2g (3).

(i) Compute pressure drop through pressurant tank outlet element:

$$\Delta P_i = 0.363 \left(\frac{W_i^2}{{}_i\, D_{i-1}^4} \right)$$

$$P_{PR} = P_{i-1} + \Delta P_i$$

(j) Summation of pressure drops of all elements:

$$\Delta P_{PR} = \sum_{i=1}^{n} \Delta P_i$$

5. Determine Propellant Pressure Drop From Main Propellant Line Tap to a Gas Generator:

Pressure drop is found for the propellants flowing to the O_2 and H_2 conditioning gas generators which provide the turbopump drive gas and the hot fluid for the propellant conditioning heat exchangers.

(a) Inputs required:

Provide inputs per operation 2a, as applicable, for each gas generator propellant feed line.

(b) Procedure:

(1) Determine ΔP_i for each feed path element in order of its occurrence, advancing upstream from the gas generator to the main line tap point, per the order of element numerical designation, for each system, O_2 and H_2, and for each gas generator.

(2) Let subscript (i) designate the element under consideration, regardless of its type.

(3) Let subscript (i-1) designate the element which preceded (i) in the analysis (the element which is immediately downstream of i), regardless of its type.

(4) Sum the pressure drops of all elements between the point of departure from the main propellant line and the gas generator, for each propellant and gas generator.

(5) Determination of flow rate, $\dot{W}_i$:

(a) To heat exchanger gas generators:

O_2 flow rate to O_2 heat exchanger GG:

$$\dot{W}_{i_1} = \frac{\dot{W}_{O_{2_E}} (K_5 K_8 - K_5) + \dot{W}_{H_{2_E}} (-K_5 K_7)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

O_2 flow rate to H_2 heat exchanger GG:

$$\dot{W}_{i_2} = \frac{\dot{W}_{O_{2_E}} (-K_6 K_7) + \dot{W}_{H_{2_E}} (K_5 K_7 - K_7)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

H_2 flow rate to O_2 heat exchanger GG:

$$\dot{W}_{i_3} = \frac{\dot{W}_{O_{2_E}} (K_6 K_8 - K_6) + \dot{W}_{H_{2_E}} (-K_6 K_7)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

H_2 flow rate to H_2 heat exchanger GG:

$$\dot{W}_{i_4} = \frac{\dot{W}_{O_{2_E}} (-K_6 K_8) + \dot{W}_{H_{2_E}} (K_5 K_8 - K_8)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

$$K_5 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}} \right)_{O_2 \text{ HX}} \left(\frac{MR}{1 + MR} \right)_{O_2 \text{ HX GG}}$$

$$K_6 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}} \right)_{O_2 \text{ HX}} \left(\frac{1}{1 + MR} \right)_{O_2 \text{ HX GG}}$$

$$K_7 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}} \right)_{H_2 \text{ HX}} \left(\frac{MR}{1 + MR} \right)_{H_2 \text{ HX GG}}$$

$$K_8 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}} \right)_{H_2 \text{ HX}} \left(\frac{1}{1 + MR} \right)_{H_2 \text{ HX GG}}$$

(b) To turbopump gas generators:

O_2 flow rate to O_2 turbopump GG:

$$\dot{W}_{i_5} = \frac{\dot{W}_{O_{2_E}} (K_9 K_{12} - K_9) + \dot{W}_{H_{2_E}} (-K_9 K_{11})}{(K_9 + K_{12} + K_{10} K_{11} - K_9 K_{12} - 1)}$$

O_2 flow rate to H_2 turbopump GG:

$$\dot{W}_6 = \frac{\dot{W}_{O_{2_E}} (-K_{10} K_{11}) + \dot{W}_{H_{2_E}} (K_9 K_{11} - K_{11})}{(K_9 + K_{12} + K_{10} K_{11} - K_9 K_{12} - 1)}$$

H_2 flow rate to O_2 turbopump GG:

$$\dot{W}_7 = \frac{\dot{W}_{O_{2_E}} (K_{10} K_{12} - K_{10}) + \dot{W}_{H_{2_E}} (-K_{10} K_{11})}{(K_9 + K_{12} + K_{10} K_{11} - K_9 K_{12} - 1)}$$

H_2 flow rate to H_2 turbopump GG:

$$\dot{W}_8 = \frac{\dot{W}_{O_{2_E}} (-K_{10} K_{12}) + \dot{W}_{H_{2_E}} (K_9 K_{12} - K_{12})}{(K_9 + K_{12} + K_{10} K_{11} - K_9 K_{12} - 1)}$$

$$* \qquad K_9 = \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LO_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{O_2\ TP} \left(\frac{MR}{1 + MR}\right)_{O_2\ TP\ GG}$$

$$K_{10} = \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LO_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{O_2\ TP} \left(\frac{1}{1 + MR}\right)_{O_2\ TP\ GG}$$

$$K_{11} = \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LH_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{H_2\ TP} \left(\frac{MR}{1 + MR}\right)_{H_2\ TP\ GG}$$

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*Assume P_i at gas generator = P_E (Operation 1).

$$K_{12} = \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LH_2}\ \eta_P\ \eta_T\ (h_{T_{in}} - h_{T_{out}})}\right]_{H_2\ TP} \left(\frac{1}{1 + MR}\right)_{H_2\ TP\ GG}$$

(c) Compute pressure drop through a line segment element:

(1) $\dot{W}_i$ found per preceding operation

$T_i = T_{i-1}$ (main line fluid temperature)

$P_i = P_{i-1} + \Delta P_i$

(2) At this point in the system, fluid is a gas.

(3) Solve by same method as operation 2c (3).

(d) Compute pressure drop through a two-outlet branch fitting element:

Solve by same method as operation 2d.

(e) Compute pressure drop through a pressure regulator element:

Solve by same method as operation 2e.

(f) Compute pressure drop through a valve element:

Solve by same method as operation 2f.

(g) Compute pressure drop through a single outlet fitting element:

Solve by same method as operation 2g (3).

(h) Summation of pressure drops of all elements:

$$\Delta P_{GG_F} = \sum_{i=1}^{n} P_i$$

6. Determine Gas Generator Combustion Products Pressure Drop From a Gas Generator to the Gas User:

Pressure drop is found for the gas flowing to the O_2 and H_2 heat exchangers and the O_2 and H_2 turbopumps.

(a) Inputs:

Provide inputs per operation 2a, as applicable, for each gas flow line.

(b) Procedure:

(1) Determine ΔP_i for each gas flow path, element in order of its occurrence, advancing upstream from the point of inlet to the HX or turbopump, per the order of element numerical designation, for each gas flow line.

(2) Let subscript (i) designate the element under consideration, regardless of its type.

(3) Let subscript (i-1) designate the element which preceded (i) in the analysis (the element which is immediately downstream of i), regardless of its type.

(4) Sum the pressure drops of all elements between the point of exit from the gas generator and the user, for each propellant and each gas user.

(5) Determination of gas flow rate

Gas line to the O_2 heat exchanger:

$$\dot{W}_{i_{1+2}} = \left(\frac{\Delta h_c}{\Delta h_h}\right)_{O_2\ HX} \left(\dot{W}_{O_{2_{tot}}}\right)$$

Gas line to the H_2 heat exchanger:

$$\dot{W}_{i_{3+4}} = \left(\frac{\Delta h_c}{\Delta h_h}\right)_{H_2\ HX} \left(\dot{W}_{H_{2_{tot}}}\right)$$

Gas line to the O_2 turbopump:

$$\dot{W}_{i_{5+6}} = \left(\frac{0.185\,\Delta P_P}{LO_2\ \eta_P\ \eta_T \Delta h_T}\right)_{O_2\ TP} \left(\dot{W}_{O_{2_{tot}}}\right)$$

Gas line to the H_2 turbopump:

$$\dot{W}_{i_{7+8}} = \left(\frac{0.185\ \Delta P_P}{LH_2\ \eta_P\ \eta_T \Delta h_T}\right)_{H_2\ TP} \left(\dot{W}_{H_{2_{tot}}}\right)$$

(6) Start the analyses of the gas lines from gas generator exit conditions:

W_i = gas flow rate as found above

T_i = $T_{h_{in}}$ for heat exchanger gas flow

T_i = $T_{T_{in}}$ for turbopump gas flow

P_i = P_{i-1} - P_i, as found from operation 5h.

ρ_G = f (T_i, P_i, MR)

R_G = f (MR)

γ_G = f (MR)

C_{P_G} = f (T_i, MR)

(c) Compute pressure drop through a line segment element:

(1) $\dot{W}_i$, T_i, and P_i as found above.

(2) Fluid is a gas.

(3) Solve by same method as operation 2c(3).

(d) Compute pressure drop through a pressure regulator element:

Solve by same method as operation 2d.

(e) Compute pressure drop through a pressure regulator element:

Solve by same method as operation 2e.

(f) Compute pressure drop through a valve element:

Solve by same method as operation 2f.

(g) Compute pressure drop through a single outlet fitting element:

Solve by same method as operation 2g(3).

(h) Summation of pressure drops of all elements:

$$\Delta P_{GG_D} = \sum_{i=1}^{n} \Delta P_i$$

7. Size Heat Exchanger:

(a) Required input data for heat exchanger subroutine:

$\dot{W}_C$ = weight rate of flow of cold fluid, lb/sec $\left(\dot{W}_{O_{2_{tot}}} \text{ or } \dot{W}_{H_{2_{tot}}}, \text{ from operation 1c}\right)$

$T_{C_{in}}$ = cold fluid inlet temperature, $^{\circ}R$
($T_{t_{O_2}}$ or $T_{t_{H_2}}$ from operation 1a)

$P_{C_{in}}$ = cold fluid inlet pressure, psia
(ΔP_{EST} + 15 from operation 2j)

$T_{C_{out}}$ = cold fluid outlet temperature, $^{\circ}R$
($T_{E_{O_2}}$ or $T_{E_{H_2}}$ from operation 1a)

ΔP_c = cold fluid pressure drop in heat exchanger, psia
(Input maximum permissible value or 0.2 $P_{c_{in}}$
whichever is the smaller. If no P_c is input,
the heat exchanger subroutine will assume a value
which gives minimum heat exchanger weight or
volume.)

W_h = weight rate of flow of hot fluid, lb/sec ($\dot{W}_i$ of hot
fluid is obtained from operation 5b(5)).

NOTE: As an alternative, $MR_{HX\ GG}$ can be input
and the heat exchanger subroutine will
calculate W_h.

$MR_{HX\ GG}$ = O_2/H_2 ratio of heat exchanger gas generator, lb/lb
(can be input as alternative to W_h)

$T_{h_{in}}$ = hot fluid inlet temperature, $^{\circ}R$
($T_{h_{in}}$, from operation 1a)

$T_{h_{out}}$ = hot fluid outlet temperature, $^{\circ}R$
($T_{h_{out}}$ from operation 1a)

$P_{h_{in}}$ = hot fluid inlet pressure, psia
($P_{h_{in}}$ from operation 1a)

$P_{h_{out}}$ = hot fluid outlet pressure, psia
(Input minimum permissible or 0.6 $P_{h_{in}}$, whichever
is the larger. If no $P_{h_{out}}$ is input, the heat exchanger
subroutine will assume a value which gives minimum
heat exchanger weight or volume.)

F_I = identity of cold fluid, O_2 or H_2

Which is preferred, minimum weight or minimum volume?

(b) Output data:

W_{tot} = heat exchanger weight, lb = W_{HX}

V_{tot} = heat exchanger volume, in.^{3}

$P_{h_{tot}}$ = hot fluid pressure drop, psi

$P_{h_{out}}$ = hot fluid outlet pressure, psia

$\Delta P_{c_{tot}}$ = cold fluid pressure drop, psi

$P_{c_{out}}$ = cold fluid outlet pressure, psia

8. Determine Total Weight of Propellants Delivered, $W_{F_{Del}}$:

(a) $W_{O_{2_{tot}}} = W_{O_{2_E}} + W_{O_1} + W_{O_2} = W_{O_{2_{Del}}}$

$W_{H_{2_{tot}}} = W_{H_{2_E}} + W_{H_1} + W_{H_2} = W_{H_{2_{Del}}}$

$W_{O_{2_E}}$ = total O_2 load for engine use, lb

W_{O_1} = total O_2 for O_2 conditioning, lb

W_{O_2} = total O_2 for H_2 conditioning, lb

$W_{H_{2_E}}$ = total H_2 load for engine use, lb

W_{H_1} = total H_2 for O_2 conditioning, lb

W_{H_2} = total H_2 for H_2 conditioning, lb

(1) Total engine propellant =

$$W_{P_E} = \sum_{i=1}^{n} (E_i) \left(\frac{F}{I_{SP}}\right) (\theta_i) \text{ lb}$$

where

E_i = number of engines operating during time period (i)

F = engine thrust, lb per engine

I_{SP} = engine specific impulse, lb/lb-sec

θ_i = operating time during time period (i), sec

$$\therefore \quad W_{O_{2_E}} = W_{P_E}\left(\frac{MR_E}{1 + MR_E}\right)$$

$$W_{H_{2_E}} = W_{P_E}\left(\frac{1}{1 + MR_E}\right)$$

$$\text{(2)} \quad \left.\begin{aligned}
W_{O_1} &= \frac{W_{O2_E}(K_1 K_4 - K_1) + W_{H2_E}(-K_1 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)} \\[2ex]
W_{O_2} &= \frac{W_{O2_E}(-K_2 K_3) + W_{H2_E}(K_1 K_3 - K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)} \\[2ex]
W_{H_1} &= \frac{W_{O2_E}(K_2 K_4 - K_2) + W_{H2_E}(-K_2 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)} \\[2ex]
W_{H_2} &= \frac{W_{O2_E}(-K_2 K_4) + W_{H2_E}(K_1 K_4 - K_4)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}
\end{aligned}\right\}$$

NOTE: These values of K_1, K_2, K_3 K_4 are different than those in operation 1c, because ΔP_{Eq} is used here.

$$K_1 = \left(\frac{\Delta h_c}{\Delta h_h}\right)_{O_2\ HX}\left(\frac{MR}{1 + MR}\right)_{O_2\ HX\ GG} + \left(\frac{0.185\ \Delta P_{Eq}}{\rho_{LO_2}\ \eta_P\ \eta_T\ \Delta h_T}\right)_{O_2\ TP}\left(\frac{MR}{1 + MR}\right)_{O_2\ TP\ GG}$$

$$K_2 = \left(\frac{\Delta h_c}{\Delta h_h}\right)_{O_2\ HX} \left(\frac{1}{1 + MR}\right)_{O_2\ HX\ GG} + \left(\frac{0.185\ \Delta P_{Eq}}{\rho_{LO_2}\ \eta_P\ \eta_T \Delta h_T}\right)_{O_2\ TP} \left(\frac{1}{1 + MR}\right)_{O_2\ TP\ GG}$$

$$K_3 = \left(\frac{\Delta h_c}{\Delta h_h}\right)_{H_2\ HX} \left(\frac{MR}{1 + MR}\right)_{H_2\ HX\ GG} + \left(\frac{0.185\ \Delta P_{Eq}}{\rho_{LH_2}\ \eta_P\ \eta_T \Delta h_T}\right)_{H_2\ TP} \left(\frac{MR}{1 + MR}\right)_{H_2\ TP\ GG}$$

$$K_4 = \left(\frac{\Delta h_c}{\Delta h_h}\right)_{H_2\ HX} \left(\frac{1}{1 + MR}\right)_{H_2\ HX\ GG} + \left(\frac{0.185\ \Delta P_{Eq}}{\rho_{LH_2}\ \eta_P\ \eta_T \Delta h_T}\right)_{H_2\ TP} \left(\frac{1}{1 + MR}\right)_{H_2\ TP\ GG}$$

In these expressions, $\left(\frac{\Delta h_c}{\Delta h_h}\right)$ has the same values as in operation 5b(5). P_{Eq} is found below.

(3) Determine ΔP_{Eq}:

(a) Find W_{BD_A} for O_2 and for H_2:

$$W_{BD_A} = V_{Acc}\ (\rho_{max} - \rho_m)$$

where

W_{BD_A} = weight of propellants used from accumulator during one pump-off blowdown period, lb

V_{Acc} = accumulator volume (input), ft^3

ρ_{max} = propellant density at T_E, P_{max}, lb/ft^3

ρ_m = propellant density at T_E, P_m, lb/ft^3 (P_m found in operation 2h)

(i) Calculate $W_{E_i} = (E_i)(F/I_{SP})(\theta_i)$ for each interval θ_i in the ACPS duty cycle.

(ii) Find $W_{E_{C_1}} = W_{E_1} + W_{E_2} + W_{E_3} + \ldots\ldots + W_{E_x}$ for intervals $_1$, $_2$, $_3$, ... $_x$, such that

$$W_{E_1} + W_{E_2} + W_{E_3} + \ldots\ldots + W_{E_x} \geq W_{BD_A}, \text{ but}$$

$$W_{E_1} + W_{E_2} + W_{E_3} + \ldots\ldots + W_{E_{x-1}} < W_{BD_A} .$$

One accumulator blowdown has occurred during the period θ_1 through θ_x, inclusive.

(iii) Find $W_{E_{C2}} = W_{E_{x+1}} + W_{E_{x+2}} + \ldots\ldots + W_{E_{x+y}}$ for intervals θ_{x+1}, θ_{x+2}, ... θ_{x+y}, such that

$$W_{E_{x+1}} + W_{E_{x+2}} + \ldots\ldots + W_{E_{x+y}} \geq W_{BD_A}, \text{ but}$$

$$W_{E_{x+1}} + W_{E_{x+2}} + \ldots\ldots + W_{E_{x+y-1}} < W_{BD_A} .$$

A second accumulator blowdown has occurred during the period θ_{x+1} through θ_{x+y}, inclusive.

(iv) Continue through the ACPS duty cycle with this procedure, and find the total number of accumulator blowdown events which occurs.

(v) Call the total number of accumulator blowdown events N_c. The number of pump startup cycles is then N_c, since the pump must charge the accumulator prior to each successive blowdown.

(c)

$$P_{Eq} = (P_m - P_p) + \frac{N_c V_{Acc}}{W_{P_E}} (\rho_{max} - \rho_m)(P_{max} - P_m)$$

where

P_P = pump inlet pressure for the propellant system being calculated, psia

W_{P_E} = $W_{O_{2_E}}$ for oxygen

W_{P_E} = $W_{H_{2_E}}$ for hydrogen

NOTE: The use of $W_{O_{2_E}}$ or $W_{H_{2_E}}$ for the calculation of ΔP_{Eq} is an approximation, and yields a conservatively high value of ΔP_{Eq}.

9. Determine Weight of Propellant Residuals in Accumulators:

$$W_{R_A} = V_{Acc} \; (\rho_m)$$

W_{R_A} is found for both the O_2 and H_2 systems.

10. Determine Weight of Propellant Residuals in O_2 and H_2 Lines, Fittings, and Valves:

$$W_{R_{LFV}} = V_{S_1} \rho_{S_1} + V_{S_2} \rho_{S_2} + V_{S_3} \rho_{S_3} + V_{S_4} \rho_{S_4}$$

where

V_{S_1} = volume of line system between storage tank and pump ft^3 (Input)

ρ_{S_1} = density of fluid between storage tank and pump = f (T_t, P_p), lb/ft^3

V_{S_2} = volume of line system between pump and heat exchanger, ft^3 (Input)

ρ_{S_2} = density of fluid between pump and heat exchanger = f (T_i, P_m), lb/ft^3

V_{S_3} = volume of line system between heat exchanger and engine flow pressure regulator; plus volumes of line systems between main line and gas generator pressure regulators or valves, ft^3 (Input)

ρ_{S_3} = density of fluid in V_{S_3} volume, = f (T_E, P_m), lb/ft^3

V_{S_4} = volume of line systems between engine flow pressure regulator and the engines, ft^3 (input)

ρ_{S_4} = density of fluid between engine flow regulator and the engines = f (T_E, P_E), lb/ft^3

11. Determine Weight of O_2 and H_2 Fluid Turbopumps:

A fixed gas temperature of 2000°R is assumed to the turbine:

(a) Required input data for turbopump subroutine:

W = flow rate through pump, lb/sec ($\dot{W}_{O_{2_{tot}}}$ or $\dot{W}_{H_{2_{tot}}}$ from operation 1c)

NPSP = net positive suction pressure, psi (Input)

ΔP = total pressure rise in pump, psia (ΔP_P from operation 2j)

T_t = fluid inlet temperature to pump, °R (Input)

(b) Output from pump subroutine:

W_{TP} = weight of turbopump, lb

η_P = pump efficiency, percent

η_T = turbine efficiency, percent

Δt_S = pump start time, sec

12. Determine Weight of H_2 Vent Requirements:

(a) Compute weight of H_2 vent required to absorb H_2 tank and pump heat leak:

$$W_{V_{H2_H}} = \left(\frac{1}{\Delta h_V}\right) \left[\left(\dot{q}_T A_T + \dot{q}_{LL} A_{LL} + \dot{q}_P A_P\right) \tau + N_c \Delta H_{TP} f_q\right]$$

where

Δh_V = heat of vaporization of hydrogen at $T_{t_{H_2}}$, Btu/lb

$\dot{q}_T$ = heat leak into tank, from heat leak subroutine, Btu/hr-ft^2

A_T = tank surface area, ft^2

$\dot{q}_P A_P$ = steady-state pump heat leak into pump, Btu/hr from heat leak subroutine

$\dot{q}_{LL}$ = heat leak into liquid lines, from heat leak subroutine, Btu/hr-ft^2

A_{LL} = liquid line surface area between tank and pump, ft^2

τ = total mission time to end of ACPS system use, hrs

N_c = number of accumulator charging events during the mission (from operation 8)

ΔH_{TP} = $(W_{TP}) (\overline{C_{p_{TP}}}) \left(\frac{T_G - T_t}{2}\right)$

W_{TP} = turbopump weight, lb (obtained from pump subroutine)

$\overline{C_{p_{TP}}}$ = turbopump material mean specific heat, Btu/lb-^{o}R (Input)

T_G = gas temperature to the turbopump, ^{o}R (Input)

f = decimal fraction of turbopump heat estimated to reach storage tank (Input)

(b) Compute weight of H_2 vent required to absorb O_2 tank and pump heat leak:

$$W_{V_{H_2O}} = \left(\frac{1}{\Delta h_{\Delta T}}\right) \left[\left(\dot{q}_T A_T + \dot{q}_{LL} A_{LL} + \dot{q}_T A_P \ \tau + N_c \Delta H_{TP} f_q\right)\right]$$

$$\Delta H_{\Delta T} = \Delta T_{H_2} \; \overline{Cp}_{H_2} = 130 \; \overline{Cp}_{H_2}$$

where

$\overline{Cp}_{H_2}$ = average specific heat of H_2 between 35°R and 165°R, (Btu/lb-°R)

(c) Perform iteration:

Compare $Wv_{H_{2_H}}$ and $Wv_{H_{2_O}}$:

If $Wv_{H_{2_H}} \geq Wv_{H_{2_O}}$, $Wv_{H_2} = Wv_{H_{2_H}}$

If $Wv_{H_{2_O}} < Wv_{H_{2_O}}$, $Wv_{H_2} = Wv_{H_{2_O}}$

13. Determine Weight of Loaded Propellant:

$$W_{F_L} = W_{F_T} + W_{F_A} + W_{F_{LFV}}$$

where

W_{F_L} = total loaded propellant

W_{F_T} = total propellant loaded in tank

W_{F_A} = total propellant loaded in accumulator

$W_{F_{LFV}}$ = total propellant loaded in lines, fittings, and valves

It is assumed that the propellants are loaded into the tanks, accumulators, and lines at the following conditions:

O_2: T_L = 159.7°R P_L = 14.7 psia

ρ_L = 71.6 lb/ft^3 2 percent ullage in tank

H_2: $T_L = 34.26^\circ R$ $P_L = 14.7$ psia

$\rho_L = 4.50$ lb/ft^3 3 percent ullage in tank

The propellants in the lines downstream of the pumps and in the accumulators are then brought to T_E and P_m by external, ground means which are not chargable to vehicle weight.

(a) Calculation of W_{F_A} :

$$W_{F_A} = V_{Acc}\,\rho_L$$

where

$\rho_L = 71.6$ for O_2

$\rho_L = 4.5$ for H_2

(b) Calculation of $W_{F_{LFV}}$:

$$W_{F_{LFV}} = \rho_L\,(V_{S_1} + V_{S_2} + V_{S_3} + V_{S_4})$$

where

$\rho_L = 71.6$ for O_2

$\rho_L = 4.5$ for H_2

(c) Calculation of W_{F_T} :

$$W_{F_T} = F_u\,V_{T_S}\,\rho_L$$

where

For O_2 :

$F_u = 0.98$, $\rho_L = 71.6$

$$V_{T_s} = \frac{W_{O2_{Del}} - \left(W_{O2_A} - W_{R_{AO_2}} \right)}{0.98\ \rho_L - \rho_{R_{O_2}}}$$

where

$W_{O2_{Del}}$ = from operation 8

W_{O2_A} = from W_{F_A}, above

$W_{R_{AO_2}}$ = from operation 9

$\rho_{R_{O_2}}$ = saturated vapor density at T_t

For H_2 :

$F_u = 0.97$, $\rho_L = 4.5$

$$V_{T_s} = \frac{W_{H2_{Del}} + W_{V_{H_2}} - \left(W_{H2_A} - W_{R_{AH_2}} \right)}{0.97\ \rho_L - \rho_{R_{H_2}}}$$

$W_{V_{H_2}}$ from operation 12.

14. Determine Weight of Residual Propellant:

$$W_{F_R} = W_{R_T} + W_{R_A} + W_{R_{LFV}}$$

(a) Calculation of W_{R_T}:

$$W_{R_T} = V_{T_s} \rho_R$$

(b) Calculation of W_{R_A}:

W_{R_A} calculated in operation 9.

(c) Calculation of $W_{R_{LFV}}$:

$W_{R_{LFV}}$ calculated in operation 10.

15. Determine Total Loaded Propellants:

$$W_{F_{L_{tot}}} = W_{O_{2_L}} + W_{H_{2_L}}$$

16. Determine Total Residual Propellants:

$$W_{F_{R_{tot}}} = W_{O_{2_R}} + W_{H_{2_R}}$$

17. Determine Storage Tank Weight:

W_T is obtained from the tank weight subroutine when V_T, P_{Tnk}, and T_T are input.

18. Determine Accumulator Weight:

W_A is obtained from the tank weight subroutine when V_{Acc}, P_{max} and T_E are input.

19. Determine Helium Sphere Weight:

(a) Compute volume of helium tank:

$$V_{T_{He}} = V_{T_S}\left(\frac{\rho_{He_s}}{\rho_{He_{max}} - \rho_{He_f}}\right)$$

where

$V_{T_{He}}$ = volume of helium tank, ft^3

ρ_{He_s} = density of helium at T_T $(P_{Tnk} - P_{SAT})$

$\rho_{He_{max}}$ = density of helium at T_T, $P_{He_{max}}$, where $P_{He_{max}}$ is input.

ρ_{He_f} = density of helium at conditions of:

$P_\epsilon = P_{Tnk} + \Delta P_{PR}$ (ΔP_{PR} from operation 4j)

$$T_f = T_T\left(\frac{P_f}{P_{He_{max}}}\right)^{\frac{x-1}{x}}$$

where

$1 \leqslant X \leqslant 1.67$

$X = 1.00$ for slow withdrawal

$X = 1.67$ for fast withdrawal

(b) Compute weight of helium sphere:

$W_{T_{He}}$ is obtained from the tank weight subroutine when $V_{T_{He}}$, $P_{He_{max}}$, and T_T are input.

20. Determine Weight of Loaded and Residual Helium:

(a) Compute Loaded Helium:

$$W_{L_{He}} = V_{T_{He}} \rho_{He_{max}}$$

(b) Compute Residual Helium:

$$W_{R_{He}} = \left(V_{T_{He}}\right)\left(\rho_{He_f}\right) + \left(V_{T_S} \rho_{He_s}\right)$$

(c) Compute residual in helium lines:

Neglected, because helium spheres are considered closed-coupled to propellant tanks.

21. Determine Weight of Gas Generator:

Enter program Table 13 with gas generator flow, P_c, and T_c and obtain gas generator weights; $W_{HX\ GG_{O_2}}$, $W_{HX\ GG_{O_2}}$, $W_{TP\ GG_{H_2}}$

Flow is obtained from operation 5b (5) as follows:

To O_2 HX GG: flow $= \dot{W}_{i_1} + \dot{W}_{i_2}$

To H_2 HX GG: flow $= \dot{W}_{i_3} + \dot{W}_{i_4}$

To O_2 HX GG: flow $= \dot{W}_{i_5} + \dot{W}_{i_6}$

To H_2 TP GG: flow $= \dot{W}_{i_7} + \dot{W}_{i_8}$

$P_c = P_{max} - P_{GG_F}$

T_c = GG output temperature $= T_{n_{in}}$ (operation 1)

22. Determine Weight of System Lines, Fittings, and Regulators:

W_{LFR} = input from subroutine CMPCAL

23. Perform Summation of Subcritical System Weight:

(a) Compute total system hardware weight:

$$W_{t_{HW}} = \left(W_{HX_{O_2}} + W_{HX_{H_2}}\right) + \left(W_{TP_{O_2}} + W_{TP_{H_2}}\right) + \left(W_{HX\,GG_{O_2}} + W_{HX\,GG_{H_2}}\right) + \left(W_{TP\,GG_{O_2}} + W_{TP\,GG_{H_2}}\right) + \left(W_{T_{O_2}} + W_{T_{H_2}}\right) + \left(W_{A_{O_2}} + W_{A_{H_2}}\right) + \left(W_{T_{He_{O_2}}} + W_{T_{He_{H_2}}}\right)$$

$\left(W_{HX_{O_2}} + W_{HX_{H_2}}\right)$	is obtained from operation 7
$\left(W_{TP_{O_2}} + W_{TP_{H_2}}\right)$	is obtained from operation 11
$\left(W_{HX\,GG_{O_2}} + W_{HX\,GG_{H_2}}\right)$	is obtained from operation 21
$\left(W_{TP\,GG_{O_2}} + W_{TP\,GG_{H_2}}\right)$	is obtained from operation 21
$\left(W_{T_{O_2}} + W_{T_{H_2}}\right)$	is obtained from operation 17
$\left(W_{A_{O_2}} + W_{A_{H_2}}\right)$	is obtained from operation 18
$\left(W_{T_{He_{O_2}}} + W_{T_{He_{H_2}}}\right)$	is obtained from operation 19

(b) Compute total weight of propellants loaded:

$$W_{t_{LDD}} = W_{L_{O_2}} + W_{L_{H_2}}$$

$$W_{t_{LDD}} = \left(W_{O_{2_T}} + W_{H_{2_T}}\right) + \left(W_{O_{2_A}} + W_{H_{2_A}}\right) + \left(W_{O_{2_{LFV}}} + W_{H_{2_{LFV}}}\right) + W_{V_{H_2}}$$

$\left(W_{O_{2_T}} + W_{H_{2_T}}\right)$ is obtained from operation 13c

$\left(W_{O_{2_A}} + W_{H_{2_A}}\right)$ is obtained from operation 13a

$\left(W_{O_{2_{LFV}}} + W_{H_{2_{LFV}}}\right)$ is obtained from operation 13b

$W_{V_{H_2}}$ is obtained from operation 12

(c) Compute total weight of helium loaded:

$$W_{t_{He}} = \left(W_{L_{He_{O_2}}} + W_{L_{He_{H_2}}}\right)$$

$\left(W_{L_{He_{O_2}}} + W_{L_{He_{H_2}}}\right)$ is obtained from operation 20a

(d) Compute total weight of residual propellants:

$$W_{t_R} = W_{R_{tot_{O_2}}} + W_{R_{tot_{H_2}}}$$

$$W_{t_R} = \left(W_{R_{T_{O_2}}} + W_{R_{T_{H_2}}}\right) + \left(W_{R_{A_{O_2}}} + W_{R_{A_{H_2}}}\right) + \left(W_{R_{LFV_{O_2}}} + W_{R_{LFV_{H_2}}}\right)$$

$\left(W_{R_{T_{O_2}}} + W_{R_{T_{H_2}}}\right)$ is obtained from operation 14a

$\left(W_{R_{A_{O_2}}} + W_{R_{A_{H_2}}}\right)$ is obtained from operation 9

$\left(W_{R_{LFV_{O_2}}} + W_{R_{LFV_{H_2}}}\right)$ is obtained from operation 10

(e) Compute total weight of residual helium:

$$W_{R_{He_t}} = \left(W_{R_{He_{O_2}}} + W_{R_{He_{H_2}}}\right)$$

$\left(W_{R_{He_{O_2}}} + W_{R_{He_{H_2}}}\right)$ is obtained from operation 20b

MATH MODEL FOR SUBROUTINE APUFL0

PURPOSE OF SUBROUTINE

Provide for computation of basic values required to perform on APU system parametric analysis for either a sub-critical cryogenic system, or a super-critical system.

PROCEDURE AND MODEL

1. INPUT APU DUTY CYCLE

DCYCLE(I)	Time duration of each constant power time interval (min).
DCYCLE(F+1)	Time duration of each non-operating time interval (min).
NEOP(I)	Number of units operating.
HP(I)	Total power extraction for each unit operating over each constant power time interval (horsepower).
PAMB(I)	Ambient pressure during each operating period. Must account for back pressure imposed (by exhaust duct and hot gas side of heat exchangers) upon APU turbine.

2. INPUT APU SYSTEM CHARACTERIZATION DATA

NAPU	Number of operating APU units.
HPR	Horsepower rating - each unit
FMR	APU Fuel Mixture Ratio
PGG	Pressure of gas generator inlet
TIT	Turbine Inlet Temperature
TD	Exhaust Discharge Temp of Heat Exchanger
MRGGCH	H2 Conditioning Gas Generator Mixture Ratio
MRGGC0	02 Conditioning Gas Generator Mixture Ratio
TDGGH	H2 Conditioning Heat Exchanger Discharge Temp
TDGG0	02 Conditioning Heat Exchanger Discharge Temp
TVH	Temp Residual H2 Vapor in Tank
TV0	Temp Residual 02 Vapor in Tank
TENV	Environmental Temperature Around APU System

3. COMPUTE THE APU FLØ PARAMETERS:

(a) TOTAL HORSEPOWER CAPABILITY

TØTHRP = NAPU x HPR

(b) % POWER FOR EACH DUTY CYCLE

$$\text{PCTHP(I)} = 100 \left(\frac{\text{HP(I)} \times \text{NEOP}}{\text{TØTHPR}} \right)$$

(c) CALCULATE TEMP OF FLUIDS AT APU GAS GENERATOR INLET (TPF)

For: TIT = 2060°R $\qquad \text{TPF} = \dfrac{1.17 - \text{FMR}}{.000563}$

TIT = 2260°R $\qquad \text{TPF} = \dfrac{1.27 - \text{FMR}}{.000556}$

(d) **FIND REFERENCE FLUID FLOW RATE (RR_i) for each constant power time interval of the duty cycle from Table I for TIT = 2060°R, and for appropriate value of PGG, FMR, (% Power)$_i$, and PAMB$_i$. Linear interpolation of Table values is employed.**

Table 1

Reference Fluid Flow Rate for Turbine Inlet Temp = 2200°R

PGG (psia)	FMR (Ratio)	% Power (%)	RR (PAMB = 14.7)	RR (PAMB = 0)
900	0.5	0	.762	0.00
900	0.5	100	6.650	6.42
900	1.0	0	.810	0.00
900	1.0	100	8.700	8.45
600	0.5	0	.840	0.0
600	0.5	100	7.130	6.53
600	1.0	0	.780	0.0
600	1.0	100	9.300	8.58
300	0.5	0	1.230	0.0
300	0.5	100	8.57	7.52
300	1.0	0	3.00	0.0
300	1.0	100	10.57	9.60

(1) The Reference Fluid Flow Rate (RR_i) is determined for each duty cycle interval (i):

$$RR_i = f\,(PGG,\ FMR,\ PAMB_i,\ PCTHP_i)$$

(2) Find total fluid flow rate over each interval (i) for TIT = 2260°R

$$WD_i = \left(\frac{TOTHPR}{300.}\right) \times RR_i$$

(3) Total fluid consumed over the entire duty cycle (Mission), for TIT = 2260°R

$$WDT = \frac{TOTHPR}{300.} \cdot \sum_{i=1}^{n} (RR_i)\ (KCYCLE_i)$$

where: $KCYCLE_i$ = Operating time part of DCYCLE ARRAY.

(e) FIND REFERENCE FLUID FLOW RATE CORRECTION FACTOR (KK_i) for each constant power time interval of the duty cycle from Table 2, if TIT is 2060°R. Linear interpolation of FMR, $PCTHP_i$, and $PAMB_i$ is employed.

Table 2

Reference Fluid Flow Rate Correction Factor (KK), for TIT = 2060°R

PGG	FMR	% POWER	KK	KK
900	0.5	0	1.052	1.050
900	0.5	100	1.088	1.040
900	1.0	0	1.047	1.068
900	1.0	100	1.068	1.068
600	0.5	0	1.050	1.087
600	0.5	100	1.082	1.087
600	1.0	0	1.044	1.067
600	1.0	100	1.064	1.067
300	0.5	0	1.037	1.078
300	0.5	100	1.069	1.078
300	1.0	0	1.035	1.062
300	1.0	100	1.055	1.062

(1) The Reference Fluid Flow Rate Correction Factor (KK_i) is determined for each duty cycle interval (i):

$$KK_i = f\,(PGG,\ FMR,\ PCTHP_i,\ PAMB_i)$$

(2) Find Corrected Total Flow Rate over each interval (i) for TIT = 2060°R.

$$\dot{WD}_i = \frac{TOTHPR}{300} \quad \times RR_i \times KK_i$$

(3) Corrected Total Fluid Consumed over the entire duty cycle (mission), for TIT = 2060°R

$$WDT = \left(\frac{TOTHPR}{300}\right) \quad \sum_{i=1}^{i=n} \quad (RR_i)\ (KK_i)\ (KCYCLE_i)$$

where: **KCYCLE is operating time part of the DCYCLE ARRAY.**

(f) CALCULATE SPECIFIC FLUID FLOW RATES AND TOTAL SPECIFIC FLUID FLOWS (O2 AND H2)

For Oxygen:

$$WDRH_i = \frac{WD_i}{(1 + FMR)} \quad ; \quad WDH = \frac{WDT}{(1 + FRM)}$$

For Hydrogen:

$$WDRO_i = \frac{WD_i}{\left(1 + \frac{1}{FMR}\right)} \quad ; \quad WDO = \frac{WDT}{1 + \frac{1}{FMR})}$$

(g) CALCULATE APU EXHAUST GAS TEMPERATURES FOR EACH DUTY CYCLE INTERVAL.

$$TE_i = \frac{(\dot{WD}_i)\ (Cp)_{CB}\ (TIT) - 42.42\ (HP_i)}{(\dot{WD}_i)\ (Cp)_{CB}}$$

where: Cp for the APU combustion products at Ø2 and H2 is computed from empirical data embodied in SUBROUTINE CSUPI

$$Cp_{CB} = f\ (FMR,\ TIT)$$

(h) Compute heat available from combustion products - available to heat exchangers:

$$(TE_i)_{mean} = TME_i = (TE_i + TD)/2.0$$

$$(Cp_{CB})_{mean} = CPE_i = f\ (TME_i,\ FMR)$$

$$D_i = CPE_i\ (TE_i - TD)$$

where D_i is heat available to heat exchangers each duty cycle interval.

NOTE: The nemonic nomenclature employed is compatible with the subroutine listing.

MATH MODEL FOR SUBROUTINE APUSUB

PURPOSE OF SUBROUTINE

Subroutine APUSUB takes the basic flow calculations performed in subroutine APUFL0 and proceeds to perform the sizing and weight calculations for a subcritical cryogen fluid supplied APU system. The subroutine is used in conjunction with subroutine CMPCAL to effect the sizing and weighing of the APU configuration and performance to a specified mission-duty cycle and performance constraints.

MATH MODEL SYMBOL DEFINITIONS

The symbols employed in the math model are defined in the following list.

Symbol	Definition
$\dot{q}_{4_{H_i}}$	Heat transfer rate in heat exchanger between H_2 accumulator and APU gas generator during time period θ_i, Btu/min
Cp_{SA_H}	Specific heat of H_2 in accumulator, Btu/lb-°R
T_{SA_H}	Temperature of H_2 in accumulator, °R
$\dot{W}_{DG_i}$	APU exhaust flowrate through H2 heat exchanger between accumulator and APU gas generator, lb/min
Cp_{G_i}	Specific heat of APU exhaust gas during θ_i, Btu/lb-°R
$\dot{q}_{6_{o_i}}$	Heat transfer rate in heat exchanger between O_2 accumulator and APU gas generator during time period θ_i, Btu/min
Cp_{SA_o}	Specific heat of O_2 in accumulator, Btu/lb-°R
T_{SA_o}	Temperature of O_2 in accumulator, °R
$\dot{W}_{D_{J_i}}$	APU exhaust flowrate through O_2 heat exchanger between accumulator and APU gas generator, lb/min
T_{GG_C}	Condition gas generator gas exit temperature, °R
MR_{GG_C}	Conditioning gas generator mixture ratio, O_2/H_2

$MR_{GG_{C_H}}$	H_2 conditioning gas generator mixture ratio, O_2/H_2
$MRGG_{C_O}$	O_2 conditioning gas generator mixture ratio, O_2/H_2
TGG_{C_H}	H_2 conditioning gas generator exit temperature, ^oR
TGG_{C_O}	O_2 conditioning gas generator exit temperature, ^oR
T_{ST_H}	Temperature of H_2 in storage tank, ^oR
P_{STH}	Pressure of H_2 in storage tank, ^oR
$E1_H$	Entropy of H_2 in storage tank at T_{STH} AND P_{STH}, Btu/lb-^oR
$T2_H$	Temperature of H_2 at P_{PD_H} and $E1_H$, ^oR
η_{PH}	H_2 pump efficiency, decimal fraction
$CpST_H$	Specific heat of H_2 at P_{STH} and T_{STH}, Btu/lb-^oR
ρST_H	Density of H_2 at P_{STH} and T_{STH}, lb/ft^3
T_{STO}	Temperature of O_2 in storage tank, ^oR
P_{STO}	Pressure of O_2 in storage tank, psia
$E1_O$	Entropy of O_2 in storage tank at T_{STO} and P_{STO}, Btu/lb-^oR
$T2_O$	Temperature of O_2 at P_{PD_O} and $E1_O$, ^oR
η_{PO}	O_2 pump efficiency, decimal fraction
C_{PST_O}	Specific heat of O_2 at P_{STO} and T_{STO}, Btu/lb-^oR
ρST_O	Density of O_2 at P_{STO} and T_{STO} , lb/ft^3
$\dot{q}_{5_{H_i}}$	Heat transfer rate in heat exchanger between H_2 pump and accumulator during time period θ_i , Btu/min
$\dot{W}_{GG_{H_i}}$	Total H_2 flowrate for the O_2 and H_2 conditioning gas generators during interval θ_i , lb/min
$H_{A_{H_i}}$	Enthalpy of H_2 out of heat exchanger between pump and accumulator, during interval θ_i , Btu/lb
T_{PDH}	Temperature of H_2 out of H_2 pump, ^oR
$H_{P_{H_i}}$	Enthalpy of H_2 out of H_2 pump during interval θ_i , Btu/lb

H_{AO_i}	Enthalpy of O_2 out of heat exchanger between pump and accumulator, during interval θ_i, Btu/lb
H_{PO_i}	Enthalpy of O_2 out of O_2 pump during interval θ_i, Btu/lb
K_1	Factor, defined in calculations, dimensionless
K_2	Factor, defined in calculations, dimensionless
K_3	Factor, defined in calculations, dimensionless
K_4	Factor, defined in calculations, dimensionless
H_{GGC_D}	Enthalpy of O_2 system conditioning gas generator exit gas, Btu/lb
H_{DO}	Enthalpy of O_2 system conditioning gas leaving heat exchanger, Btu/lb
Cp_{GG_D}	Specific heat of O_2 system conditioning gas generator exit gas, Btu/lb-°R
T_{DGG_O}	Exit temperature of O_2 conditioning gas generator products from heat exchanger, °R
H_{DH}	Enthalpy of H_2 system conditioning gas leaving heat exchanger, Btu/lb
Cp_{GG_H}	Specific heat of H_2 system conditioning gas generator exit gas, Btu/lb-°R
T_{DGG_H}	Exit temperature of H_2 conditioning gas generator products from heat exchanger, °R
H_{GGC_H}	Enthalpy of H_2 system conditioning gas generator exit gas, Btu/lb
$\dot{q}_{7O_i}$	Heat transfer rate in O_2 heat exchanger between pump and accumulator, Btu/min
W_{GGO_i}	Total O_2 flowrate for the O_2 and H_2 conditioning gas generator during interval θ_i, lb/min
P_{PD_O}	O_2 pump discharge pressure, psia
(ΔP_{SSO_i})	O_2 propellant system pressure drop between pump and APU at flowrate during interval θ_i, psia

$\left(\Delta P_{SSO_i}\right)_{max}$	Maximum O_2 propellant system pressure drop during any interval θ_i in the mission, psia
T_{PDO}	Temperature of O_2 out of O_2 pump, °R
V_{STH}	H_2 storage tank volume, ft^3
W_{GGH}	Total H_2 quantity used for H_2 and O_2 conditioning during the mission, lb
W_{SVH}	Total H_2 vented during the mission, lb
ρ_{VH}	Density of residual H_2 vapor in H_2 storage tank, lb/ft^3
P_{VH}	H_2 tank residual vapor pressure, psia
Z_{VH}	Compressibility factor of the tank residual H_2 vapor, dimensionless
T_{VH}	Temperature of the H_2 residual vapor in tank, °R
V_{STO}	O_2 storage tank volume, ft^3
W_{GGO}	Total O_2 quantity used for H_2 and O_2 conditioning during the mission, lb
W_{SVO}	Total O_2 vented during the mission, lb
ρ_{VO}	Density of residual O_2 vapor in O_2 storage tank, lb/ft^3
P_{VO}	O_2 tank residual vapor pressure, psia
Z_{VO}	Compressibility factor of the tank residual O_2 vapor, dimensionless
T_{VO}	Temperature of the O_2 residual vapor in tank, °R
HP_{PH}	H_2 pump power, horsepower
$\left(\dot{W}_{DH_i}\right)_{max}$	Maximum flowrate of H_2 to the APU during any interval θ_i in the mission, lb/min
$\dot{W}_{GGH_{i\ max}}$	Maximum flowrate of H_2 to the H_2 and O_2 conditioning gas generators during any interval θ_i in the mission, lb/min
W_{PH}	H_2 pump weight, lb
HP_{PO}	O_2 pump power, horsepower

$\left(\dot{W}_{DO_i}\right)_{max}$	Maximum flowrate of O_2 to the APU during any interval θ_i in the mission, lb/min
$\left(\dot{W}_{GGO_i}\right)_{max}$	Maximum flowrate of O_2 to the H_2 and O_2 conditioning gas generators during any interval θ_i in the mission, lb/min
W_{PO}	O_2 pump weight, lb
$W_{HX_{LH2_i}}$	Weight of H_2 heat exchanger between pump and accumulator for any interval θ_i, lb
$W_{HX_{LH_2}}$	Maximum value of $W_{HX_{LH2_i}}$ for any interval θ_i during the mission, lb
$W_{HX_{LO2_i}}$	Weight of $O2$ heat exchanger between pump and accumulator for any interval θ_i , lb
$W_{HX_{LO_2}}$	Maximum value of $W_{HX_{LO2_i}}$ for any interval θ_i during the mission, lb
W_{SA_H}	Weight of H_2 accumulator, lb
Z_{SA_H}	Compressibility factor for H_2 at conditions of P_{PD_H} and T_{SA_H} , dimensionless
$Z_{SA_{H_e}}$	Compressibility factor for H_2 at conditions of P_{GG} and T_{P_f}, dimensionless
Z_{SA_O}	Compressibility factor for O_2 at conditions of P_{PD_O} and T_{SA}
$Z_{SA_{O_e}}$	Compressibility factor for O_2 at conditions of P_{GG} and T_{P_f}
W_{RSA_H}	Residual propellant in H_2 accumulator, lb
W_{RSA_O}	Residual propellant in O_2 accumulator, lb
$W_{HX_{GH2_i}}$	Weight of H_2 heat exchanger between accumulator and APU, for any interval θ_i , lb
$W_{HX_{GH_2}}$	Maximum value of $W_{HX_{GH2_i}}$ for any interval θ_i during the mission, lb
$W_{HX_{GO2_i}}$	Weight of O_2 heat exchanger between accumulator and APU, for any interval θ_i , lb
$W_{HX_{GO_2}}$	Maximum value of $W_{HX_{GO2_i}}$ for any interval θ_i during the mission, lb
W_{SR_H}	Weight of residuals in H_2 storage tank, lb

W_{SRO}	Weight of residuals in O_2 storage tank, lb
W_{GGG_H}	Weight of H_2 conditioning gas generator, lb
W_{GGG_O}	Weight of O_2 conditioning gas generator, lb
W_{SH_2SYS}	Total weight of H_2 subcritical system, lb
W_{SO_2SYS}	Total weight of O_2 subcritical system, lb
W_{SPSYS}	Total weight of subcritical propellant system, lb

THE MATH MODEL EQUATIONS

The equations and calculational procedures required for the subroutine are given in the following subparagraphs:

1. Heat Exchanger Analysis Requirements

(a) Required input data for heat exchanger subroutine:

W_C = weight rate of flow of cold fluid, lb/sec

$T_{C_{in}}$ = cold fluid inlet temperature, ^oR

$P_{C_{in}}$ = cold fluid inlet pressure, psia

$T_{C_{out}}$ = cold fluid outlet temperature, ^oR

ΔP_C = cold fluid pressure drop across HX, psi (Input maximum permissible value or 0.2 $P_{C_{in}}$ whichever is the smaller. If no ΔPC is input, the heat exchanger subroutine will assume a value which gives minimum heat exchanger weight or volume.)

W_h = weight rate of flow of hot fluid, lb/sec

NOTE: As an alternative, MR can be input for the heat exchangers between the accumulators and APUs, and MR_{GG} for the gas generator-fed heat exchangers, and the heat exchanger subroutine will calculate W_h.

MR = O_2/H_2 ratio of the APU, lb/lb
(Can be input as alternative to W_h for the heat exchangers downstream of the accumulators.)

MR_{GG} = O_2/H_2 ratio of the gas generators, lb/lb
(Can be input as alternative to W_h for the gas generator-fed heat exchangers.)

$T_{h_{in}}$ = hot fluid inlet temperature, °R

$T_{h_{out}}$ = hot fluid outlet temperature, °R

$P_{h_{in}}$ = hot fluid inlet pressure, psia

$P_{h_{out}}$ = hot fluid outlet pressure, psia
(Input minimum permissible value or 0.6 $P_{h_{in}}$, whichever is the larger. If no $P_{h_{out}}$ is input, the subroutine will assume a value which gives minimum heat exchanger weight or volume.)

F_I = identity of cold fluid, O_2 or H_2

Which is preferred, minimum weight or minimum volume?

(b) Output:

W_{tot} = heat exchanger weight, lb

V_{tot} = heat exchanger volume, in.^{3}

$\Delta P_{h_{tot}}$ = hot fluid pressure drop, psi

$P_{h_{out}}$ = hot fluid outlet pressure, psia

$\Delta P_{c_{tot}}$ = cold fluid pressure drop, psi

$P_{c_{out}}$ = cold fluid outlet pressure, psia

2. Find Weight of Heat Exchanger Between H_2 Accumulator and APU

Find W_{HX_4}, ΔP_h, and ΔP_c for $(\dot{q}_{4_{H_i}})_{max}$, with input of H_2 fluid, 0.0166 $\dot{W}_{P_{H_i}}$, T_{SA_H}, T_{P_f}, P_{GG}, 0.0166 $W_{D_{G_i}}$, T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

$$\dot{q}_{4_{H_i}} = \dot{W}_{D_{H_i}} C_{p_{SA_H}} \left(T_{P_f} - T_{SA_H}\right)$$

where

$\dot{W}_{DH_i}$	is determined in calculation 8
$C_{p_{SA_H}}$	is taken from thermo tables for T_{SA_H}

Maximum heat exchange occurs when W_{DH_i} is maximum, for given values of T_{P_f} and T_{SA_H}.

$$\dot{W}_{D_{G_i}} = \frac{\left(\dot{q}_{4_{H_i}}\right)_{max}}{C_{p_{G_i}} (T_{E_i} - T_D)}$$

where

$C_{p_{G_i}}$	is obtained from H_2 - O_2 Combustion Products Table for T_{E_i} and MR
T_{E_i}	is determined in calculation 11
T_D	is input
T_{SA_H}	is input
T_{P_f}	is input
P_{TE}	is input, assumed value of APU turbine exhaust pressure at heat exchanger inlet
MR	is input

3. Find Weight of Heat Exchanger Between O2 Accumulator and APU

Find W_{HX_G}, ΔP_h and ΔP_c for $(\dot{q}_{GO_i\,max}$, with input of O_2 fluid, 0.0166 W_{DO_i}, T_{SA_O}, T_{P_f}, P_{GG}, 0.0166 W_{DJ_i}, T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

$$\dot{q}_{GO_i} = \dot{W}_{DO_i} C_{p_{SA_O}} \left(T_{P_f} - T_{SA_O}\right)$$

$$\dot{W}_{DJ_i} = \frac{\left(\dot{q}_{GO_i}\right)_{max}}{C_{p_{G_i}} \left(T_{E_i} - T_D\right)}$$

4. Gas Generator Temperature Vs Mixture Ratio Data

Input table, showing T_{GG} as a function of MR_{GG_C} and T_{SA_H}. Interpolate linearly for values of T_{GG_C} between MR_{GG_C} and T_{SA_H} values shown in Table 1.

Table 1

MR_{GG_C}, T_{SA_H}, AND T_{GG_C} VALUES

MR_{GG_C}	T_{SA_H}	T_{GG_C}
0.8	300	1742
0.9	300	1905
1.0	300	2068
1.1	300	2234
0.7	400	1674
0.8	400	1838
0.9	400	2002
1.0	400	2165
0.7	500	1764
0.8	500	1927
0.9	500	2092
1.0	500	2256

Table 1 (Cont'd)

MR_{GG_C}	T_{SA_H}	T_{GG_C}
0.6	600	1690
0.7	600	1857
0.8	600	2022
0.9	600	2188
0.5	700	1625
0.6	700	1788
0.7	700	1952
0.8	700	2116
0.9	700	2278

Use selected values of $MRGG_C$ and TSA_H to find TGG_C from Table 3. Note that TGG_{C_H} may be found for $MRGG_{C_H}$ for H_2, and TGG_{C_O} may be found for $MRGG_{C_O}$ for O_2.

5. Calculation of $\left(\dot{W}GG_{H_i}\right)_{max}$ and $\left(\dot{W}GG_{O_i}\right)_{max}$

$$\left(\dot{W}GG_{O_i}\right)_{max} = \dot{W}_{O1} + \dot{W}_{O2}$$

$$\left(\dot{W}GG_{H_i}\right)_{max} = \dot{W}_{H_1} + \dot{W}_{H_2}$$

where

$\dot{W}_{O_1}$ = O_2 flow rate to condition O_2, lb/min

$\dot{W}_{O_2}$ = O_2 flow rate to condition H_2, lb/min

$\dot{W}_{H_1}$ = H_2 flow rate to condition O_2, lb/min

$\dot{W}_{H_2}$ = H_2 flow rate to condition H_2, lb/min

$$\dot{W}_{O_1} = \frac{\left(\dot{W}_{D_{O_i}}\right)_{max} (K_1 K_4 - K_1) + \left(\dot{W}_{D_{H_i}}\right)_{max} (-K_1 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$\dot{W}_{O_2} = \frac{\left(\dot{W}_{D_{O_i}}\right)_{max} (-K_2 K_3) + \left(\dot{W}_{D_{H_i}}\right)_{max} (K_1 K_3 - K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$\dot{W}_{H_1} = \frac{\left(\dot{W}_{D_{O_i}}\right)_{max} (K_2 K_4 - K_2) + \left(\dot{W}_{D_{H_i}}\right)_{max} (-K_2 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$\dot{W}_{H_2} = \frac{\left(\dot{W}_{D_{O_i}}\right)_{max} (-K_2 K_4) + \left(\dot{W}_{D_{H_i}}\right)_{max} (K_1 K_4 - K_4)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

$$K_1 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}}\right)_{O_2\ HX} \left(\frac{MR}{1 + MR}\right)_{O_2\ HX\ GG}$$

$$+ \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LO_2}\ \eta_P\ \eta_T \left(h_{T_{in}} - h_{T_{out}}\right)}\right]_{O_2\ TP} \left(\frac{MR}{1 + MR}\right)_{O_2\ TP\ GG}$$

NOTE: If the O_2 pump is motor driven instead of turbine driven, the value of the terms with a TP subscript is zero.

$$K_2 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}}\right)_{O_2\ HX} \left(\frac{1}{1 + MR}\right)_{O_2\ HX\ GG}$$

$$+ \left[\frac{0.185\ \Delta P_{EST}}{\rho LO_2\ \eta_P\ \eta_T \left(h_{T_{in}} - h_{T_{out}}\right)}\right]_{O_2\ TP} \left(\frac{1}{1 + MR}\right)_{O_2\ TP\ GG}$$

$$K_3 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}} \right)_{H_2\ HX} \left(\frac{MR}{1 + MR} \right)_{H_2\ HX\ GG}$$

$$+ \left[\frac{0.185\ \Delta P_{EST}}{\rho_{LH_2}\ \eta_P\ \eta_T \left(h_{T_{in}} - h_{T_{out}} \right)} \right]_{H_2\ TP} \left(\frac{1}{1 + MR} \right)_{H_2\ TP\ GG}$$

$$K_4 = \left(\frac{h_{c_{out}} - h_{c_{in}}}{h_{h_{in}} - h_{h_{out}}} \right)_{H_2\ HX} \left(\frac{1}{1 + MR} \right)_{H_2\ HX\ GG}$$

$$+ \left[\frac{0.185\ P_{EST}}{\rho_{LH_2}\ \eta_P\ \eta_T \left(h_{T_{in}}\ h_{T_{out}} \right)} \right]_{H_2\ TP} \left(\frac{1}{1 + MR} \right)_{H_2\ TP\ GG}$$

$$\Delta P_{EST} = \left(P_{GG} + \Delta P_{EST\ SYS} \right) - P_{ST}$$

where

P_{GG} = propellant pressure at APU, input

$\Delta P_{EST\ SYS}$ = estimated pressure drop of the flow system downstream of the pump, including pressure regulators and heat exchangers, input, psi

P_{ST} = storage tank pressure, input, psia

ρ_{LO_2} = density of O_2 at T_{ST_O} and P_{ST_O}

ρ_{LH_2} = density of H_2 at T_{ST_H} and P_{ST_H}

η_P = estimated pump efficiency, decimal fraction, input

η_T = estimated turbine efficiency, decimal fraction, input

$h_{c_{out}}$ = propellant outlet enthalpy, Btu/lb (from tables, for $\Delta P_{EST} + 15,\ T_{SA}$)

$h_{c_{in}}$ = propellant inlet enthalpy, Btu/lb (from tables, for $\Delta P_{EST} + 15,\ T_{ST}$)

$h_{h_{out}}$ = HX gas outlet enthalpy, Btu/lb (from tables, for 0.6 $P_{GG},\ T_D$)

$h_{h_{in}}$ = HX gas inlet enthalpy, Btu/lb (from tables, for $P_{GG},\ T_{GG_C}$)

$h_{T_{out}}$ = gas outlet enthalpy from turbine, Btu/lb (from tables, for $P_{AMB} + 10,\ T_{T_{out}}$)

$$T_{T_{out}} = T_{GG_C} - \eta_T\, T_{GG_C}\left[1 - \left(\frac{P_{AMB} + 10}{P_{GG}}\right)^{\frac{\gamma_G - 1}{\gamma_G}}\right] \ {}^{o}R$$

$h_{T_{in}}$ = gas inlet enthalpy to turbine, Btu/lb (from tables, for $P_{GG},\ T_{GG_C}$)

6. Find Weight of Heat Exchanger Between H2 Accumulator and H2 Pump

Find W_{HX_5}, ΔP_h and ΔP_c for $\dot{q}_{5H_i\,max}$, with input of H_2 fluid, 0.0166 $\dot{W}_{DH_i} + \dot{W}_{GGH_i\,max}$, T_{STH}, T_{SAH}, P_{PDH}, 0.0166 $\dot{W}_{GGHX_{iH}\,max}$ T_{GG_C}, T_D, P_{SA_H}, $MRGGC_H$, and ΔP of the cold and hot fluids if desired. Use heat exchanger subroutine.

$\left(\dot{W}_{GG_{HX_{iH}}}\right)$ from operation 5

P_{SA_H} from input accumulator pressure

P_{PD_H} = P_{SA_H}

$0.0166\left(\dot{W}_{D_{H_i}} + \dot{W}_{GG_{H_i}}\right)_{maximum}$ from operation 5

7. Find Weight of Heat Exchanger Between O_2 Accumulator and O_2 Pump

Find W_{HX_7}, ΔP_h and ΔP_c for $\dot{q}_{7_{O_i\,max}}$, with input of O_2 fluid, $0.0166\ \dot{W}_{D_{O_i}} + \dot{W}_{GG_{O_i\,max}}$, T_{ST_O}, T_{SA_O}, P_{PD_O}, $0.0166\ \dot{W}_{GG_{HX_{i_O}}\,max}$, T_{GG_C}, T_D, P_{SA_O}, $MR_{GG_{C_O}}$, and ΔP of the cold and hot fluids if desired. Use HX subroutine.

Values for the above quantities are found as in operation 6.

8. Calculate H_2 Vent Requirements

It is planned that the vented H_2 which absorbs the H_2 tank and pump heat leak will then be used to absorb the O_2 tank and pump heat leak before being vented overboard. Therefore, venting of H_2 only is considered, and the quantity of H_2 vented is determined by the higher requirement as established by the H_2 system and O_2 system heat leaks, respectively.

(a) Weight of H_2 required to absorb H_2 tank and pump heat leak:

$$W_{SV_{H_H}} = \frac{1}{\Delta h_V}\left[\left(\dot{q}_T A_T + \dot{q}_{LL} A_{LL} + \dot{q}_p A_p\right)\tau + N_c \Delta H_{TP} f_q\right]$$

where

Δh_V = heat of vaporization of H_2 at T_{ST_H}, Btu/lb

$\dot{q}_T$ = heat leak into the tank from heat leak subroutine, Btu/hr-ft^2 ~ f (Insulation, t_{INSUL})

A_T = H_2 tank surface area, ft^2

$$A_T = 4.84\left(V_{ST_{H_{EST}}}\right)^{2/3}$$

$$V_{ST_{H_{EST}}} = \frac{W_{D_H} + W_{GG_H}}{4.36 - \rho_{V_H}}$$

W_{D_H} from subroutine APUFLØ

$$W_{GG_H} = \sum_{i=1}^{n} \left(\dot{W}_{GG_{H_i}}\right)(\theta_i)$$

ρ_{V_H} = density of saturated vapor at T_{ST_H} and P_{ST_H}

$\dot{q}_p A_p$ = steady-state heat leak into H_2 pump, from heat leak subroutine, Btu/hr

$\dot{q}_{LL}$ = heat leak into liquid lines between tank and pump, from heat leak subroutine, Btu/hr-ft^2

A_{LL} = liquid line surface area between tank and pump, input, ft^2

τ = total mission time to end of APU system use, hrs

N_c = number of pump start cycles during the mission (number of APU system starts), input

$$\Delta H_{TP} = \left(W_{TP}\right)\left(\bar{C}_{p_{TP}}\right)\left(\frac{T_{GG_C} - T_{ST_H}}{2}\right)$$

W_{TP} = turbopump weight, lb (obtained from pump subroutine)

$\bar{C}_{p_{TP}}$ = turbopump material mean specific heat, input, Btu/lb-^oR

T_{GG_C} = gas temperature to the turbopump, ^oR

f_q = decimal fraction of turbopump heat estimated to reach storage tank, input

(b) Weight of H_2 required to absorb O_2 tank and pump heat leak:

$$W_{SV_{H_O}} = \left(\frac{1}{\Delta h_{\Delta T}}\right)\left[\left(\dot{q}_T A_T + \dot{q}_{LL} A_{LL} + \dot{q}_p A_p\right)\tau + N_c \Delta H_{TP} f_q\right]$$

$\dot{q}_T$, A_T, $\dot{q}_p A_p$, $\dot{q}_{LL}$, A_{LL}, τ, N_c, ΔH_{TP}, and f_q have the same definitions as in part (a), above, except as applied to the O_2 system.

$$\Delta h_{\Delta T} = \Delta T_{H_2} \bar{C}_{p_{H_2}} = 130 \ \bar{C}_{p_{H_2}} \quad .$$

$\bar{C}_{p_{H_2}}$ = average specific heat of H_2 between $35^{o}R$, and $165^{o}R$, Btu/lb-^{o}R

(c) Compare $W_{SV_{H_H}}$ and $W_{SV_{H_O}}$:

If $W_{SV_{H_H}} \geq W_{SV_{H_O}}$, $W_{SV_H} = W_{SV_{H_H}}$

If $W_{SV_{H_H}} < W_{SV_{H_O}}$, $W_{SV_H} = W_{SV_{H_O}}$

9. Calculate Weight of H_2 Storage Tank

$$V_{ST_H} = \frac{W_{D_H} + W_{GG_H} + W_{SV_H}}{4.35 - \rho_{V_H}}$$

W_{D_H} is found from calculation (8)

$$W_{GG_H} = \sum_{1}^{n} \left(\dot{W}_{GG_{H_i}}\right) (\theta_i)$$

W_{SV_H} is found from preceding operation 8.

ρ_{V_H} = density of saturated H_2 vapor at T_{ST_H} and PST_H

W_{ST_H} is found from the tank weight program.

10. Calculate Weight of O_2 Storage Tanks:

$$V_{ST_O} = \frac{W_{D_O} + W_{GG_O}}{70.0 - \rho_{V_O}}$$

W_{D_O} = is found from Subroutine APUFL0

$$W_{GG_O} = \sum_{i=1}^{n} \left(W_{GG_{Oi}} \right) (\theta_i)$$

ρ_{V_O} = density of saturated O_2 vapor at T_{ST_O} and P_{ST_O}

11. Calculate LH2 Pump Weight:

A turbine driven pump is assumed, and a gas temperature of 2000°R is assumed to the turbine. The turbopump subroutine is used.

(a) Required input data to turbopump subroutine:

$\dot{W}$ = flow rate through pump, lb/sec

$$\left(\dot{W}_{D_{H_i}} + \dot{W}_{GG_{H_i}}\right)_{max}$$

NPSP = net positive suction pressure, input, psi

ΔP = total pressure rise in pump, psi $(P_{PD_H} - 15)$

T_t = fluid inlet temperature to pump, °R (T_{ST_H})

(b) Output from pump subroutine:

W_{TP} = weight of turbopump, lb

η_P = pump efficiency, percent

η_T = turbine efficiency, percent

Δt_s = pump start time, seconds

12. Calculate LO2 Pump Weight

Same procedure as in operation 10, above, except for O_2 system.

13. Calculate Weight of H2 Accumulator

$$W_{SA_H} = 1.042 \left(P_{PD_H}\right)\left(\frac{HP_R \times R_{R_{FP}}}{\frac{P_{PD_H}}{Z_{SA_H} T_{SA_H}} - \frac{P_{GG}}{Z_{SA_{He}} T_{P_f}}}\right)\left(\frac{\rho}{F_{tu}}\right)_{SA_H}$$

where

$R_{R_{FP}}$ = reference propellant flow rate from Table 1, corresponding to 100 percent power, MR = 1.0, P_{AMB} = 14.7, and the value of P_{GG} selected in APUFL0.

$\left(\frac{\rho}{F_{t_u}}\right)_{SA_H}$ = the lesser value of the programmed curves of $\left(\frac{\rho}{F_{t_u}}\right)$ for steel and aluminum, respectively, corresponding to T_{SA_H}.

Z_{SA_H} = found from the programmed thermodynamic properties of hydrogen for P_{PD_H} and T_{P_f}.

$Z_{SA_{He}}$ = found from the programmed thermodynamic properties of hydrogen for P_{GG} and T_{P_f}.

14. <u>Calculate Weight of O_2 Accumulator</u>

$$W_{SA_O} = 0.0652 \left(P_{PD_O}\right) \left(\frac{HP_R \times R_{R_{FP}}}{\dfrac{P_{PD_O}}{Z_{SA_O}\, T_{SA_O}} - \dfrac{P_{GG}}{Z_{SA_{O_e}}\, T_{P_f}}} \right) \left(\frac{\rho}{F_{t_u}}\right)_{SA_O}$$

where

$R_{R_{FP}}$ = reference propellant flow rate from Table 1, corresponding to 100 percent power, MR = 1.0, P_{AMB} = 14.7, and the value of P_{GG} selected in APUFL0.

$\left(\frac{\rho}{F_{t_u}}\right)_{SA_O}$ = the lesser value of the programmed curves of $\left(\frac{\rho}{F_{t_u}}\right)$ for steel and aluminum, respectively, corresponding to T_{SA_O}.

Z_{SA_O} = found from the programmed thermodynamic properties of oxygen, for P_{PD_O} and T_{P_f}.

$Z_{SA_{O_e}}$ = found from the oxygen thermodynamic properties for P_{GG} and T_{P_f}.

15. Calculate Weight of H_2 Accumulator Residual Propellant

$$W_{R_{SA_H}} = \frac{W_{S_H} P_{GG}}{\left(\frac{P_{PD_H}}{Z_{SA_H} T_{SA_H}} - \frac{P_{GG}}{Z_{SA_{H_e}} T_{P_f}}\right) Z_{SA_{H_e}} T_{P_f}}$$

$$W_{S_H} = \frac{(HP_R)(R_{R_{FP}})}{36{,}000}$$

16. Calculate Weight of O_2 Accumulator Residual Propellant

$$W_{R_{SA_O}} = \frac{W_{S_O} P_{GG}}{\left(\frac{P_{PD_O}}{Z_{SA_O} - T_{SA_O}} - \frac{P_{GG}}{Z_{SA_{O_e}} - T_{P_f}}\right) Z_{A_{O_e}} T_{P_f}}$$

$$W_{S_O} = \frac{(HP_R)(R_{R_{FP}})}{36{,}000}$$

17. Calculate Weight of H_2 Storage Tank Residual Propellant

$$W_{SR_H} = \rho_{V_H} \left(\frac{W_{D_H} + W_{GG_H} + W_{SV_H}}{4.35 - \rho_{V_H}}\right)$$

W_{D_H} is found from subroutine APUFL0

$$W_{GG_H} = \sum_{1}^{n} \left(\dot{W}_{GG_{H_i}}\right)(\theta_i)$$

W_{SV_H} is found from the heat leak/vent program for the total mission duration.

ρV_H = density of saturated propellant (H_2) vapor at T_{ST_H} and P_{ST_H}

18. Calculate Weight of O_2 Storage Tank Residual Propellant

$$W_{SR_O} = \rho_{V_O} \left(\frac{W_{D_O} + W_{GG_O} + W_{SV_O}}{70 - \rho_{V_O}} \right)$$

W_D is found from subroutine APUFL0

$$W_{GG_O} = \sum_{1}^{n} \left(\dot{W}_{GG_{O_i}}\right)(\theta_i)$$

W_{SV_O} is found from the heat leak/vent program for the total mission duration

ρV_O = density of saturated O_2 propellant vapor at T_{ST_O} and P_{ST_O}

19. Weight of H_2 System Gas Generator

$W_{H_2 GG}$ is found from AiResearch data of gas generator weight, as a function of $\left(\dot{W}_{GG_{H_i}}\right)_{max}$ and $MR_{GG_{C_H}}$ and T_{SA_H}.

20. Weight of O_2 System Gas Generator

$W_{O_{2_{GG}}}$ is found from AiResearch data of gas generator weight, as a function of $\left(\dot{W}_{GG_{O_i}}\right)_{max}$, $MR_{GG_{C_O}}$, and T_{SA_H}.

21. Total Weight of H_2 System

$$W_{S_{H_2SYS}} = W_{D_H} + W_{ST_H} + W_{GG_H} + W_{SV_H} + W_{SR_H} + W_{P_H} + W_{HX_4} + W_{SA_H} + W_{R_{SA_H}} + W_{HX_5} + W_{H_{2_{GG}}} + W_{H_{2_{LINES\ AND\ FITTINGS}}}$$

22. Total Weight of O_2 System

$$W_{S_{O_2SYS}} = W_{D_O} + W_{ST_O} + W_{GG_O} + W_{SR_O} + W_{P_O} + W_{HX_6} + W_{SA_O} + W_{R_{SA_O}} + W_{HX_7} + W_{O_{2_{GG}}} + W_{O_{2_{LINES\ AND\ FITTINGS}}}$$

23. Total Weight of Subcritical Propellant System

$$W_{SP\ SYS} = W_{S_{H_2\ SYS}} + W_{S_{O_2\ SYS}}$$

MATH MODEL CONFIGURATION

The configuration concept upon which the subcritical APU model is based is illustrated in Fig. APUSUP-1.

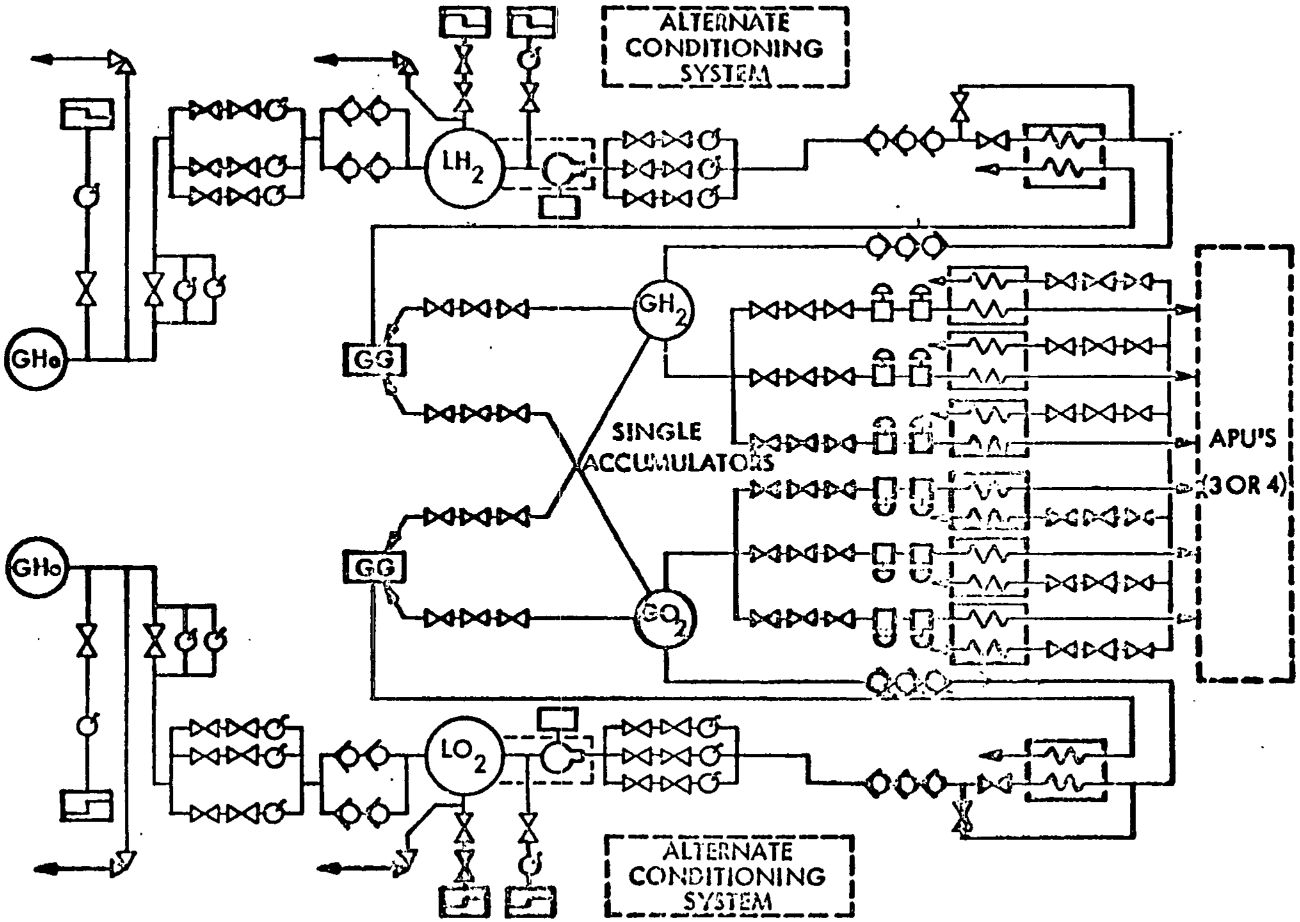


Fig. APUSUB-1 Subcritical APU Supply

MATH MODEL FOR SUBROUTINE APUSUP

PURPOSE OF SUBROUTINE

Subroutine in APUSUP taken as input the basic energy and flow calculations performed in subroutine APUFLO and procedes with the computations necessary for the sizing and weighing of component assemblies for a supercritical fluid supplied APU system. The subroutine computes the sizing and weight parameters for the major components (tanks, heat exchangers, gas generators, etc.). Subroutine CMPCAL then supplies the weight and pressure drop data for the minor components (lines, valves, etc.).

The routine configuration is analyzed to the specified input mission duty cycle and performance constraints.

MATH MODEL SYMBOL DEFINITIONS

The symbols employed in the math models are defined in the following list:

Symbol Definition

HP = total power extraction over a constant-power time interval, HP

HP_i = total power extraction over time interval Θ_i HP

HP_r = rated horsepower of each APU in operation, HP

P_{AMBi} + ambient pressure during interval (i), psia

N = number of APU's in operation

T_t = APU turbine inlet temperature, ^oR

MR = APU mixture ratio, O/F, dimensionless

P_{fH} = final H2 tank pressure, psia

T_{Pf} = temperature of delivered propellants at APU gas generator inlet, ^oR

T_{fH} = final H2 tank temperature, ^oR

P_{GG} = H2 and O2 pressure at APU gas generator inlet, psia

(% Power)i = percent of HPi relative to total available power, percent

R_R = Reference propellant flow rate, lbs/min.

R_{Ri} = Reference propellant flow rate during interval (i), lbs/min.

θ = Constant-power time interval, minutes
θ_i = Duration of time interval (i), minutes
WD_T = Total propellant flow to APU, lbs.
$\dot{w}_{Di}$ = Delivered flow rate over time interval θ_i, lbs/min
K_{Ki} = Correction factor to reference propellant flow rate for 2060°R turbine inlet temperature, for conditions during interval (i)
W_{DH} = Total H2 delivered to APU gas generator, lbs.
$\dot{w}_{DHi}$ = Weight rate of H2 flow during time period θi, lbs/min.
W_{Do} = Total 02 delivered to APU gas generator, lbs.
$\dot{w}_{DOi}$ = Weight rate of 02 flow during time period θi, lbs/min.
P_{fo} = Final 02 tank pressure, psia
T_{fo} = Final 02 tank temperature, °R
$(P_{CH})_{min}$ = H2 conditioned Propellant tank min. pressure, psia
$(P_{CO})_{min}$ = 02 Conditioned Propellant tank min pressure, psia
P_{CH} = Input value of H2 tank conditioned pressure, $\geq (P_{CH})$ min.
P_{Co} = Input value of 02 tank conditioned pressure, $\geq (P_{Co})$ min.
H_{Po} = enthalpy of H2 at T_{Pf} and P_{CH}, btu/lb
H_{PH} = enthalpy of H2 at T_{Pf} and P_{CH}, btu/lb
H_{Ao} = enthalpy of 02 at T_A. and P_{Co}, btu/lb
T_E = APU Trubine exhaust temperature, °R.
T_{Ei} = APU Turbine exhaust temperature over time interval θi, °R.
C_{P_T} = Specific heat of gas to the APU turbine, btu/lb °R
$\dot{q}_{Hi}$ = Heat transfer rate in Heat Exchanger between H2 accumulator and APU gas generator during time period θi, btu/min.
$C_{P_{AH}}$ = Specific Heat of H2 in H2 accumulator, btu/lb °R
T_{AH} = Temperature of H2 in H2 Accum., °R
$\dot{w}_{PAi}$ = APU exhaust flow rate through H2 heat exchanger between H2 Accumulator and APU gas generator during time period 0i, lbs/min
T_D = Exhaust discharge temperature from heat exchanger, °R
$C_{P_{Ei}}$ = Exhaust gas specific heat at conditions T_{Ei} and MR, btu/lb °R

$\dot{q}_{1Oi}$ = Heat transfer rate in Heat Exchanger between O2 accumulator and APU gas generator during time period θ_i, btu/min

C_{PAO} = Specific Heat of O2 in O2 accumulator, btu/lb °R

T_{AO} = Temperature of O2 in O2 Accum., °R

$\dot{w}_{DOi}$ = APU exhaust flow-rate through O2 heat exchanger between O2 accumlator and APU gas generator during time period θi, lbs/min

$\dot{q}_{2Hi}$ = Heat transfer rate in Heat Exchanger between H_2 tank and H2 accumulator during time period θi, btu/min

T_{THi} = Temperature of H2 in H2 tank during interval θ_i, °R

C_{PBHi} = Specific heat of tanked H2 during interval θ_i, btu/lb °R

$\dot{q}_{2Oi}$ = Heat transfer rate in Heat Exchanger between O2 tank and O2 accumulator during time period θ_i, btu/min

C_{PBOi} = Specific heat of tanked O2 during interval θ_i, btu/lb °R

T_{TOi} = Temperature of O2 in O2 tank during interval θ_i, °R

$\dot{w}_{DBi}$ = APU exhaust flow through H2 heat exchanger between H2 tank and H2 accumulator during time period θ_i, lbs/min

$\dot{w}_{DEi}$ = APU exhaust flow through O_2 heat exchanger between O_2 tank and O_2 accumulator during time period θ_i, lbs/min

$\dot{q}_{3Hi}$ = Heat transfer into H_2 tank during interval θ_i, btu/min

$(\Delta Q/\Delta W)_{Hi}$ = Heat transfer into H_2 tank during interval O_i, btu/lb withdrawn

$\dot{w}_{DCi}$ = APU exhaust flow through H_2 tank heat exchanger during time interval θ_i, lbs/min

$(\Delta Q/\Delta W)_{Oi}$ = Heat transfer into O_2 tank during interval θ_i, btu/min

= Heat transfer into O_2 tank during interval θ_i, btu/lb withdrawn

$\dot{w}_{DFi}$ = APU exhaust flow through O_2 tank heat exchanger during time interval θ_i, lbs/min

W_{CH} = Weight of H_2 tank heater circulating compressor, lbs

Z_{EH} = H_2 compressibility factor at P_{EH} and T_{EH}

Z_{FO} = O_2 compressibility factor at P_{FO} and T_{FO}

$(\dot{w}_{DH})_{max}$ = Max H_2 propellant consumption rate at any point in APU duty cycle, lbs/min

ρ_{Hf} = Tanked H_2 density at end of useable H_2 supply, lb/ft^3

C_{pHf} = Specific heat of tanked H_2 at end of useable H_2 supply, but/lb ^{o}R

W_{HXA_i} = weight of H_2 heat exchanger between H_2 accumulator and APU gas generator, required to meet the heat exchange demand over interval θ_i, lbs

W_{HXA} = max value of W_{HXA_i} over the APU duty cycle, lbs.

W_{HXD_i} = weight of O_2 heat exchanger between O_2 accumulator and APU gas generator, required to meet the heat exchange demand over interval θ_i, lbs.

W_{HXD} = max value of W_{HXD} over the APU duty cycle, lbs.

W_{HXB_i} = weight of H_2 heat exchanger between H_2 tank and H_2 accumulator, required to meet the heat exchange demand over interval θ_i, lbs.

W_{HXB} = max value of W_{HXB_i} over the APU duty cycle, lbs.

W_{HXE_i} = weight of O_2 heat exchanger between O_2 tank and O_2 accumulator, required to meet the heat exchange demand over interval θ_i, lbs.

W_{HXE} = max value of W_{HXE_i} over the APU duty cycle, lbs.

W_{HXC_i} = weight of H_2 tank conditioning heat exchanger, required to meet the conditioning demands over time interval θ_i, lbs.

W_{HXC} = max value of W_{HXC} over the APU duty cycle, lbs.

W_{HXF_i} = weight of O_2 tank conditioning heat exchanger required to meet the conditioning demands over time interval θ_i, lbs.

W_{HXF} = max value of W_{HXF_i} over the APU duty cycle, lbs.

W_{CO} = Weight of O_2 tank heater circulating compressor, lbs.

$(\dot{\omega}_{O})_{max}$ = Max O_2 propellant consumption rate at any point in APU duty cycle, lbs/min

ρ_{Ot} = Tanked O_2 density at end of useable O_2 supply, lb/ft^3

C_{pOf} = Specific heat of tanked O_2 at end of useable O_2 supply, btu/lb ^{o}R

W_{TO} = O_2 storage tank weight, lbs.

W_{TH} = H_2 storage tank weight, lbs.

W_{VH} = Weight of H_2 vented during mission, lbs.

$\left(\frac{\rho}{F_{tu}}\right)$ = Tank material density/strength ratio, ^{1}/in. x 10^{-6}

W_{RH} = Weight of Residual H_2 in storage tank, lbs.

W_{RO} = Weight of Residual O_2 in storage tank, lbs.

W_{AH} = Weight of H_2 accumulator, lbs.

$R_{R_{FP}}$ = Reference propellant flow-rate at 100% power, MR = 1.0, P_{AMB} = 14.7, and applicable value of P_{GG}

Z_{AH} = Hydrogen compressibility factor at P_{cH} and T_{AH}

Z_{AHe} = Hydrogen compressibility factor at P_{GG} and T_{AH}

W_{AO} = Weight of O_2 accumulator, lbs.

Z_{AO} = Oxygen compressibility factor at P_{cO} and T_{AO}

Z_{ADC} = Oxygen compressibility factor at P_{GG} and T_{AO}

W_{RAH} = Weight of H_2 accumulator residual propellant, lbs.

W_{S_H} = H_2 accumulator Hydrogen capacity, lbs.

W_{RAO} = Weight of O_2 accumulator residual propellant, lbs.

W_{S_O} = O_2 accumulator Oxygen capacity, lbs.

$W_{H_2\,sys}$ = Total weight of H_2 Supercritical System, lbs.

$W_{O_2\,sys}$ = Total weight of O_2 Supercritical System, lbs.

$W_{P\,sys}$ = Total weight of Supercritical Propellant System, lbs.

$\dot{\omega}_{GH_{ic}}$ = H_2 flow rate to supplemental gas generator, lbs/min (during period θ_i)

$\Delta\dot{\omega}_{DB_{ic}}$ = Reduction of $\dot{\omega}_{DB_i}$ during θ_i required to make sum of APU exhaust requirements equal to the value of APU exhaust available during period θ_i, if the sum required is larger than the available quantity.

H_{TH_i} = enthalpy of H_2 in tank at conditions T_{TH_i} and P_{cH}, btu/lb

H_{TC_i} = enthalpy of O_2 in tank at conditions T_{TC_i} and P_{CO} btu/lb

T_G = gas temperature from supplemental gas generator, °R

MR_G = mixture ratio to supplemental gas generator, O/F

C_{P_G} = gas specific heat from supplemental gas generator, btu/lb °R

$\dot{\omega}_{TH_i}$ = total H_2 flow rate to accumulator during θ_i, lbs/min

$\dot{\omega}_{TC_i}$ = total O_2 flow rate to accumulator during θ_i, lbs/min

$\dot{\omega}_{GC_{ic}}$ = O_2 flow rate to supplemental gas generator during θ_i, lbs/min

ΔH_i = enthalpy increase imparted to H_2 by supplemental gas during interval θ_i, btu/lb

$(P_{CH})_{min_c}$ = corrected value of (P_{CH})min to account for supplemental gas generator H_2 flow, psia

$(P_{CO})_{min_c}$ = corrected value of (P_{CO})min to account for supplemental gas generator O_2 flow, psia

$(\dot{\omega}_{THi})_{max}$ = max value of $\dot{\omega}_{THi}$ during any θ_i, lbs/min

$(\dot{\omega}_{TOi})_{max}$ = max value of $\dot{\omega}_{TOi}$ during any θ_i, lbs/min

$\dot{q}_{2Hi_c}$ = corrected value of $\dot{q}_{2Hi}$ to account for reduction in gas flow, and increase in H_2 flow due to supplemental gas gen H_2 flow, btu/min

$\dot{\omega}_{DBi_c}$ = corrected values of $\dot{\omega}_{DBi}$, lbs/min

$\dot{q}_{2Ci_c}$ = corrected value of $\dot{q}_{2Ci}$ to account for increase in O_2 flow due to gas gen. O_2 flow, btu/min

$\dot{\omega}_{DEi_c}$ = corrected value of $\dot{\omega}_{DEi}$ to account for flow rate change due to gas gen. O_2 flow, lbs/min

$\dot{q}_{3Hi_c}$ = corrected value of $\dot{q}_{3Hi}$ to account for increased flow due to gas gen. H_2 flow, btu/min

$\dot{\omega}_{DCi_c}$ = corrected value of $\dot{\omega}_{DCi}$ to account for flow rate change due to gas gen. H_2 flow, lbs/min

$\dot{q}_{3Oi_c}$ = corrected value of $\dot{q}_{3Oi}$ to account for increased flow due to gas gen. O_2 flow, btu/min

$\dot{\omega}_{DFi_c}$ = corrected value of $\dot{\omega}_{DFi}$ to account for flow rate change due to gas gen. O_2 flow, lbs/min

W_{GH} = sum of supplemental gas generator H_2 consumption over the duty cycle, bls.

W_{GO} = sum of supplemental gas generator O_2 consumption over the duty cycle, lbs.

W_{HXSi} = supplemental heat exchanger weight to accommodate requirements during any interval θ_i, lbs

W_{HXS} = max value of W_{HXSi} over the duty cycle, lbs.

W_G = supplemental gas generator weight, lbs.

$(\dot{\omega}_{GHi})_{max}$ = max value of $\dot{\omega}_{GHi}$ during any θ_i, lbs/min

$(\dot{\omega}_{GOi})_{max}$ = max value of $\dot{\omega}_{GOi}$ during any θ_i, lbs/ min

$(\Delta H_i)_{max}$ = max value of ΔH_i during any θ_i, btu/lb

$\dot{\omega}_{GHi}$ = Reference H_2 flow rate to supplemental gas generator, lbs/min.

$\Delta\dot{\omega}_{PBi}$ = Reference reduction of $\dot{\omega}_{PBi}$ during θ_i required to make sum of APU exhaust requirements equal to the value of APU exhaust available during θ_i

K5 = factor, defined in text

K6 = factor, defined in text

K7 = factor, defined in text

THE MATH MODEL EQUATIONS

The equations and calculational procedures required for the subroutine coding are presented in the following sub paragraphs. Repetitive terms appearing herein were isolated and given specific variable names in the coded program in order that repetitions programming might be avoided.

1. Input APU Duty Cycle:
   a) HP_i - Total power extraction over each constant-power time interval θ_i, horsepower
   b) θ_i = Time duration of each constant-power time interval, minutes
   c) P_{AMB_i} = Ambient pressure during each θ_i interval, psia. This input must include allowance for the back pressure imposed by the exhaust duct and heat exchangers upon the APU turbines.

1A. Input total number of APU's operating (N), and their maximum individual rating (HP_R)

2. Find percent power for each duty cycle point:

$$(\%\text{ Power})_i = 100\left(\frac{HP_i}{HP_R \times N}\right)$$

3. Input turbine inlet temperature: (T) = 2060°R or 2260°R
   a) Input mixture ratio: (MR)
   b) Calculate For $T_T = 2060\,^\circ R$ $\quad T_{P_f} = \dfrac{1.17 - MR}{0.000563}$

   For $T_T = 2260\,^\circ R$ $\quad T_{P_f} = \dfrac{1.27 - MR}{0.000556}$

4. Input pressure of H_2 and O_2 at APU (P_{GG}): (300, 600, or 900 psia)

5. Input Table 1
   a) Find reference propellant flow rate (R_{Ri}) for each constant-power time interval (θ_i) of the duty cycle from Table 1, for

T_T = 2060 or T_T = 2260°R, and for appropriate values of P_{GG}, MR, (% Power); and P_{AMB_i}. Interpolate linearly for MR, % Power, and P_{AMB}

TABLE 1

P_{GG}	MR	% Power	R_R @ P_{AMB} = 14.7	R_R @ P_{AMB} = 0
900	.5	0	.762	0
900	.5	100	6.65	6.42
900	1.0	0	.810	0
900	1.0	100	8.70	8.45
600	.5	0	.840	0
600	.5	100	7.13	6.53
600	1.0	0	.780	0
600	1.0	100	9.30	8.58
300	.5	100	8.57	7.52
300	1.0	0	3.00	0
300	1.0	100	10.57	9.60

6. Find total propellant flow rate over each interval θ_i, for T_T = 2260°R

   $\dot{\omega}_{Pi} = \frac{(N)(HP_R)}{300}(R_{Ri})$, over time interval θ_i

   a) Find total propellant used over the entire duty cycle, for T_T = 2260°R

$$W_{D_T} = \frac{(N)(HP_R)}{300} \sum_{i=1}^{n} (R_{Ri})(\theta_i)$$

7. Input Table 2

   a) Find total propellant flow rate over each interval θ_i, for T_T = 2060°R

$$\dot{\omega}_{Di} = \frac{(N)(HP_R)}{300}(R_{Ri})(K_{Ki})$$

   Interpolate linearly for MR, % Power, and P_{AMB}

   b) Find total propellant over the entire duty cycle, for T_T = 2060°R:

$$W_{D_T} = \frac{(N)(HP_R)}{300} \sum_{i=1}^{n} (R_{Ri})(\theta_i)(K_{Ki})$$

TABLE 2

Correction Factor for T,l,T, = 2060°R.

P_{GG}	MR	% Power	K_K @ P_{AMB} = 14.7	K_K @ P_{AMB} = 0
900	.5	0	1.052	1.09
900	.5	100	1.088	1.09
900	1.0	0	1.047	1.068
900	1.0	100	1.068	1.068
600	.5	0	1.050	1.087
600	.5	100	1.082	1.087
600	1.0	0	1.044	1.067
600	1.0	100	1.064	1.067
300	.5	0	1.037	1.078
300	.5	100	1.069	1.078
300	1.0	0	1.035	1.062
300	1.0	100	1.055	1.062

8. Calculate $\dot{\omega}_{DH_i}$ and $\dot{\omega}_{DO_i}$:

$$\dot{\omega}_{DH_i} = \frac{\dot{\omega}_{D_i}}{1+MR} \quad ; \qquad \dot{\omega}_{DO_i} = \frac{\dot{\omega}_{D_i}}{1+\frac{1}{MR}}$$

a) Calculate W_{DH} and W_{D_O}:

$$W_{DH} = \frac{W_{DT}}{1+MR} \quad ; \qquad W_{DO} = \frac{W_{DT}}{1+\frac{1}{MR}}$$

9. Determmine min. required Propellant Tank pressure, psia:

$(P_c)_{min} = P_{GG} + (\Delta P_s)_{max}$ where $(\Delta P_s)_{max}$ is found for $(\dot{\omega}_{DH_i})_{max}$

10. Determine APU exhaust gas temperature:

$$T_{E_i} = \frac{\dot{\omega}_{D_i} C_{P_T} T_T - 42,42(HP_i)}{W_{D_i} C_{P_T}}$$, where

C_{P_T} is found from the graphical data of the combustion products of Hydrogen and Oxygen, as a function of MR and T_T

11. Size H_2 heat exchanger between H_2 Accumulator and APU gas generator.

$$\dot{q}_{1Hi} = \dot{w}_{DHi} \left(H_{PH} - H_{AH} \right)$$

$\dot{w}_{DHi}$ is determined in calculation 8.

H_{PH} is taken from tables for T_{Pf} and P_{cH}

H_{AH} is taken from tables for T_{AH} and P_{cH}

(Max heat exchange occurs when $\dot{w}_{DHi}$ is maximum, for given values of T_{Pf} and T_{AH}).

$$\dot{w}_{DAi} = \frac{\dot{w}_{DHi} \left(H_{PH} - H_{AH} \right)}{C_{FEi} \left(T_{Ei} - T_D \right)}$$

C_{PEi} is found from H_2-O_2 Combustion Prods. table for $\frac{T_{Ei} + T_D}{2}$ and MR

T_{Ei} is determined in calculation (10)

T_D is input

12. Size O_2 Heat Exchanger between O2 Accumulator and APU gas generator:

$$\dot{q}_{1Oi} = \dot{w}_{DOi} \left(H_{PO} - H_{AO} \right)$$

$\dot{w}_{DO}$ is determined in calculation (8)

H_{PO} is taken from tables for T_{Pc} and P_{cO}

H_{AO} is taken from tables for T_{AO} and P_{cO}

$$\dot{w}_{DOi} = \frac{\dot{w}_{DOi} \left(H_{PO} - H_{AO} \right)}{C_{PAi} \left(T_{Ei} - T_D \right)}$$

C_{PEi} is found from H_2-O_2 Combustion Prods. Table for $\frac{T_{Ei} + T_D}{2}$ and MR

T_{Ei} is determined in calculation (10)

T_D is input

13. Size H_2 Heat Exchanger between H_2 Tank and H_2 Accmulator:

$$\dot{q}_{2Hi} = \dot{w}_{DHi} \left(H_{AH} - H_{THi} \right)$$

$\dot{w}_{DHi}$ is determined in calculation (8)

H_{THi} is found from tabulated thermo properties of H_2, corresponding to T_{THi} and P_{cH}

T_{TH_i} is found from the tabulated values of T_{TH_i} vs. H_2 density, as a function of P_{cH} and of percent usable H_2 withdrawn from the tank to that point in the mission.

Note that percent usable withdrawn = $f(P_{fH}, T_{fH}, Z_{fH})$

Z_{fH} is found from thermo tables for P_{fH} and T_{fH}

$$\dot{w}_{DB_i} = \frac{\dot{w}_{DH_i}(H_{AH} - H_{TH_i})}{C_{PE_i}(T_{E_i} - T_D)}$$

C_{PE_i}, T_{E_i}, T_D are found as in calc. (11)

14. Size O_2 Heat Exchanger between O_2 Tank and O_2 Accumulator:

$$\dot{q}_{2O_i} = \dot{w}_{DO_i}(H_{AO} - H_{TO_i})$$

$\dot{w}_{DO_i}$ is determined in calculation (8)

H_{TO_i} is found from tabulated thermo properties of O_2, corresponding to T_{TO_i} and P_{cO}

T_{TO_i} is found from the tabulated values of T_{TO_i} vs. O_2 density, as a function of percent usable O_2 withdrawn to that point in the mission, and as a function of P_{fO}, T_{fO}, Z_{fO}, and P_{cO}.

Z_{fO} is found from thermo tables for P_{fO} and T_{fO}.

$$w_{DE_i} = \frac{\dot{w}_{DO}(H_{AO} - H_{TO_i})}{C_{PE_i}(T_{E_i} - T_D)}$$

C_{PE_i}, T_{E_i}, T_D are found as in calc. (12)

15. **Size H_2 Tank Heat Exchanger:**

$\left(\frac{\Delta Q}{\Delta W}\right)_{H_i}$ is taken from the graphical data of vs. Density for H_2 Supercritical Storage, as applicable for time period θ_i, as a function of P_{CH}, P_{fH}, T_{fH}, and percent usable H_2 withdrawn.

$$\dot{q}_{3_{H_i}} = (\Delta Q/\Delta W)_{H_i} \; (\dot{\omega}_{D_{H_i}})$$

$\dot{\omega}_{D_{H_i}}$ is determined in calculation (8)

$$W_{D_{C_i}} = \frac{(\Delta Q/\Delta W)_{H_i} \left(\dot{\omega}_{D_{H_i}}\right)}{C_{P_{E_i}} \quad (T_{E_i} - T_D \quad)}$$

$C_{P_{E_i}}$, T_{E_i}, & T_D are found as in calculation (11)

16. Size O_2 Tank Heat Exchanger:

$\left(\frac{\Delta Q}{\Delta W}\right)_{O_i}$ is taken from the graphical data of $(\Delta Q/\Delta W)$ vs. Density for O_2 Supercritical Storage, as applicable for time period θi, as a function of P_{CC}, P_{fO}, T_{fO}, and percent usable O_2 withdrawn.

$$\dot{q}_{3_{O_i}} = \left(\frac{\Delta Q}{\Delta W}\right)_{O_i} \left(\dot{\omega}_{D_{O_i}}\right)$$

$\dot{\omega}_{D_{O_i}}$ is determined in calculation (8).

$$\dot{w}_{D_{F_i}} = \frac{\left(\Delta Q/\Delta W\right)_{o_i} \left(\dot{w}_{D_{o_i}}\right)}{C_{P_{E_i}} \left(T_{E_i} - T_D\right)}$$

$C_{P_{E_i}}$, T_{E_i}, & T_D are found as in calculation (12).

17. Check adequacy of exhaust products for conditioning:

Find $\sum(\dot{w}_{D_{A_i}} + \dot{w}_{D_{B_i}} + \dot{w}_{D_{C_i}} + \dot{w}_{D_{D_i}} + \dot{w}_{D_{E_i}} + \dot{w}_{D_{F_i}})$ and compare with the value of $\dot{w}_{D_i}$ for each interval (i) in the mission.

If the $\sum_{x=A}^{F} (\dot{w}_{D_{x_i}}) \leq \dot{w}_{D_i}$ for all points in the duty cycle, proceed to operation 17B. If $\sum_{x=A}^{F} (\dot{w}_{D_{x_i}}) > \dot{w}_{D_i}$ for any point in the duty cycle, then the use of a supplementary gas generator and a supplementary heat exchanger (added to the Supercritical System schematic) must be brought into play at that point. This reduces the value of $\dot{w}_{D_{B_i}}$ and increases the value of $\dot{w}_{D_{C_i}}$, $\dot{w}_{D_{E_i}}$, and $\dot{w}_{D_{F_i}}$, since an additional quantity of H_2 and O_2 must be conditioned for use in the supplementary gas generator.

17A. For the case where $\sum_{x=A}^{F} (\dot{w}_{D_{X_L}}) > \dot{w}_{D_L}$:

$\dot{w}_{G_{H_i}}$ = H_2 flow increment to the supplementary gas generator.

$\dot{w}_{G_{O_i}}$ = O_2 flow increment to the supplementary gas generator.

$\dot{w}'_{D_{A_i}}$ = $\dot{w}_{D_{A_i}}$ unchanged.

$\dot{\omega}_{D_{D'_{i_C}}} = \dot{\omega}_{D_{D_i}} =$ unchanged.

$\dot{\omega}_{D_{B_{i_C}}} =$ new value of exh gas to HX(B).

$\dot{\omega}_{D_{E_{i_C}}} =$ new value of exh gas to HX(E).

$\dot{\omega}_{D_{C_{i_C}}} =$ new value of exh gas to HX(C).

$\dot{\omega}_{D_{F_{i_C}}} =$ new value of exh gas to HX (F).

$$\dot{\omega}_{D_{B_{i_C}}} = \dot{\omega}_{D_i} - \dot{\omega}_{D_{A_{i_C}}} - \dot{\omega}_{D_{D_{i_C}}} - \dot{\omega}_{D_{F_{i_C}}} - \dot{\omega}_{D_{C_{i_C}}} - \dot{\omega}_{D_{F_{i_C}}}$$

$\dot{\omega}_{D_i} =$ unchanged by addition of suppl. GG (cal. from #7A).

$\dot{\omega}_{D_{A_i}} =$ calc. from #12.

$\dot{\omega}_{D_{D'_i}} =$ calc. from #13.

$$\dot{\omega}_{D_{E_{i_C}}} = \dot{\omega}_{D_{E_i}} \left(\frac{\dot{\omega}_{D_{O_i}} + \dot{\omega}_{G_{O_i}}}{\dot{\omega}_{D_{O_i}}} \right)$$

$$\dot{w}_{D_{C_{i_c}}} = \dot{w}_{D_{C_i}} \left(\frac{\dot{w}_{D_{H_i}} + \dot{w}_{G_{H_i}}}{\dot{w}_{D_{H_i}}} \right)$$

$$\dot{w}_{D_{F_{i_c}}} = \dot{w}_{D_{F_i}} \left(\frac{\dot{w}_{D_{O_i}} + \dot{w}_{G_{O_i}}}{\dot{w}_{D_{O_i}}} \right)$$

$$\dot{w}_{D_{B_{i_c}}} = \dot{w}_{D_i} - \dot{w}_{D_{A_i}} - \dot{w}_{D_{D_i}} - \dot{w}_{D_{C_i}} \left(1 + \frac{\dot{w}_{G_{H_i}}}{\dot{w}_{D_{H_i}}}\right) - \left(\dot{w}_{D_{E_i}} + \dot{w}_{D_{F_i}}\right) \left(1 + \frac{\dot{w}_{G_{O_i}}}{\dot{w}_{D_{O_i}}}\right)$$

Since $\dot{w}_{G_{O_i}} = \dot{w}_{G_{H_i}} MR_G$,

$$\dot{w}_{D_{B_{i_c}}} = \dot{w}_{D_i} - \dot{w}_{D_{A_i}} - \dot{w}_{D_{D_i}} - \dot{w}_{D_{C_i}} \left(1 + \frac{\dot{w}_{G_{H_i}}}{\dot{w}_{D_{H_i}}}\right) - \left(\dot{w}_{D_{E_i}} + \dot{w}_{D_{F_i}}\right) \left(1 + \frac{\dot{w}_{G_{H_i}} MR_G}{\dot{w}_{D_{O_i}}}\right)$$

and the only unknowns are $\dot{w}_{D_{B_{i_c}}}$ and $\dot{w}_{G_{H_i}}$

Now, the reduction in enthalpy change in heat exchanger (B) is equal to the enthalpy change in the supplementary gas generator.

$$\Delta H_{B_i} = \Delta \dot{w}_{D_{B_{i_c}}} \; Cp_{E_i} \left(T_{E_i} - T_D \right) = \dot{w}_{G_{H_i}} \left(1 + MR_G\right) Cp_G \left(T_G - T_D\right)$$

Also, $\Delta \dot{w}_{D_B} = \dot{w}_{D_{B_i}} - \dot{w}_{D_{B_{i_c}}}$

$$\left(\dot{w}_{D_{B_i}} - \dot{w}_{D_{B_{i_c}}}\right) Cp_{E_i} \left(T_{E_i} - T_D\right) = \dot{w}_{G_{H_i}} \left(1 + MR_G\right) Cp_G \left(T_G - T_D\right)$$

$$w_{D_B}\, Cp_{E_i} (T_{E_i} - T_D) - \dot{w}_{D_{B_{ic}}}\, Cp_{E_i} (T_{E_i} - T_D) = \dot{w}_{G_{H_i}} (1 + MR_G)\, Cp_G (T_G - T_D)$$

$$\dot{w}_{D_{B_{ic}}} = \frac{\dot{w}_{D_{B_i}}\, Cp_{E_i} (T_{E_i} - T_D) - \dot{w}_{G_{H_i}} (1+MR_G)\, Cp_G (T_G - T_D)}{Cp_{E_i} (T_{E_i} - T_D)}$$

Let $K_6 = Cp_{E_i} (T_{E_i} - T_D)$

$K_7 = Cp_G (T_G - T_D)$

$$\dot{w}_{D_{B_{ic}}} = \dot{w}_{D_{B_i}} - \dot{w}_{G_{H_i}} (1+ MR_G) \left(\frac{K_7}{K_6}\right)$$

Combining equations,

$$\dot{w}_{D_{B_i}} - \dot{w}_{G_{H_i}} (1+MR_G)\left(\frac{K_7}{K_6}\right) = \dot{w}_{D_i} - \dot{w}_{D_{A_i}} - \dot{w}_{D_{D_i}} - \dot{w}_{D_{C_i}} \left(1+\frac{\dot{w}_{G_{H_i}}}{\dot{w}_{D_{H_i}}}\right) - (\dot{w}_{D_{E_i}} + \dot{w}_{D_{F_i}}) \left(1+ \frac{\dot{w}_{G_{H_i}}\, MR_G}{\dot{w}_{D_{O_i}}}\right)$$

$K_8 = (1 + MR_G)$

Let $K_9 = \dot{w}_{D_i} - \dot{w}_{D_{A_i}} - \dot{w}_{D_{D_i}} - \dot{w}_{D_{B_i}}$

$$\dot{w}_{G_{H_i}} (K_8)\left(\frac{K_7}{K_6}\right) = -K_9 + (\dot{w}_{D_{C_i}} + \dot{w}_{D_{E_i}} + \dot{w}_{D_{F_i}}) + \dot{w}_{G_{H_i}} \left[\frac{\dot{w}_{D_{C_i}}}{\dot{w}_{D_{H_i}}} + \frac{\dot{w}_{D_{E_i}}\, MR_G}{\dot{w}_{D_{O_i}}} + \frac{\dot{w}_{D_{F_i}}\, MR_G}{\dot{w}_{D_{O_i}}}\right]$$

Let $K_{10} = \dot{\omega}_{D_{C_i}} + \dot{\omega}_{D_{E_i}} + \dot{\omega}_{D_{F_i}}$

Let $K_{11} = \left(\frac{\dot{\omega}_{D_{C_i}}}{\omega_{D_{H_i}}} + \frac{\dot{\omega}_{D_{E_i}} MR_G}{\omega_{D_{O_i}}} + \frac{\dot{\omega}_{D_{F_i}} MR_G}{\omega_{D_{O_i}}} \right)$

$$\dot{\omega}_{G_{H_i}} (K_8) \left(\frac{K_7}{K_6}\right) = K_{10} - K_9 + \dot{\omega}_{G_{H_i}} (K_{11})$$

$$\dot{\omega}_{G_{H_i}} (K_8) \left(\frac{K_7}{K_6}\right) - \dot{\omega}_{G_{H_i}} (K_{11}) = K_{10} - K_9$$

$$\dot{\omega}_{G_{H_i}} = \frac{K_{10} - K_9}{K_8 \left(\frac{K_7}{K_6}\right) - K_{11}}$$

$$\dot{\omega}_{G_{H_i}} = \frac{K_9 - K_{10}}{K_{11} - K_8 \left(\frac{K_7}{K_6}\right)}$$

$$= \frac{\dot{\omega}_{D_i} - \dot{\omega}_{D_{A_i}} - \dot{\omega}_{D_{D_i}} - \dot{\omega}_{D_{B_i}} - \dot{\omega}_{D_{C_i}} - \dot{\omega}_{D_{E_i}} - \dot{\omega}_{D_{F_i}}}{K_{11} - K_8 \left(\frac{K_7}{K6}\right)}$$

$$\dot{\omega}_{G_{H_i}} = \frac{\dot{\omega}_{D_i} - \sum_{X=A}^{F} (\dot{\omega}_{D_{X_i}})}{K_{11} - K_8 \left(\frac{K_7}{K_6}\right)}$$

(2) Step 2:

As solved for , $\dot{\omega}_{G_{H_i}} = \dot{\omega}_{G_{H_{i_C}}}$ $\dot{\omega}_{G_{O_i}} = MR_G \, \dot{\omega}_{G_{H_i}}$, and

$$\dot{\omega}_{G_{O_{i_c}}} = MR_G \, \dot{\omega}_{G_{H_{i_C}}}$$

17B. Solve for corrected values of heat exchanger exhause requirements:

If step 17A is omitted, $\dot{w}_{D_{B_{i_C}}} = \dot{w}_{D_{B_i}}$ and $\dot{w}_{D_{C_{i_C}}} = \dot{w}_{D_{C_i}}$

$$\dot{w}_{D_{B_{i_c}}} = \dot{w}_{D_{B_i}} \text{ minus } \dot{w}_{G_{H_i}} \left(\frac{K_8 - K_7}{K_6} \right)$$

$$\dot{w}_{D_{i_c}} = \dot{w}_{D_{c_i}} \left(\frac{\dot{w}_{D_{H_i}} + \dot{w}_{G_{H_{i_c}}}}{\dot{w}_{D_{H_i}}} \right)$$

If step 17A is omitted, $\dot{w}_{D_{E_{i_c}}} = \dot{w}_{D_{E_i}}$ and $\dot{w}_{D_{F_{i_c}}} = \dot{w}_{D_{F_{i_c}}}$

$$\dot{w}_{D_{E_{i_c}}} = \dot{w}_{D_{E_i}} \left(\frac{\dot{\omega}_{D_{O_i}} + \dot{\omega}_{G_{O_c}}}{\dot{w}_{D_{O_i}}} \right)$$

$$D_{F_{i_c}} = \dot{\omega}_{D_{F_i}} \left(\frac{\dot{\omega}_{D_{\phi_i}} + \dot{\omega}_{G_{\phi c_i}}}{\dot{\omega}_{D_{\phi_i}}} \right)$$

17C. If step 17A was performed, recheck for adequacy of APU exhaust when supplementary gas generator is used:

Check for $\sum_{X=A}^{F} \left(\dot{w}_{D_{X_{i_c}}} \right) \leq \dot{w}_{D_i}$ for all points in the duty cycle.

If not, check for errors in steps 17A and 17B. If $\sum_{X=A}^{F} \dot{w}_{D_{X_{i_c}}} \leq \dot{w}_{D_i}$, go to step 17D.

17D. Total H_2 flow to accumulator:

$\dot{w}_{T_{H_i}} = \dot{w}_{D_{H_i}} + \dot{w}_{G_{H_{i_c}}}$; If step 17A was omitted, $\dot{w}_{G_{H_{i_c}}} = 0$

17E. Total O_2 flow to accumulator:

$\dot{w}_{T_{O_i}} = \dot{w}_{D_{O_i}} + \dot{w}_{G_{O_{i_c}}}$; If step 17A was omitted, $\dot{w}_{G_{O_{i_c}}} = 0$

17F. Correction to calculation of H_2 heat exchanger between tank and accumulator: (Ignore if $\dot{w}_{G_{H_{i_c}}} = \dot{w}_{G_{O_{i_c}}} = 0$)

$$\dot{q}_{2_{H_{i_c}}} = (\dot{w}_{D_{B_i}} - \Delta \dot{w}_{D_{B_{i_c}}}) C_{p_{E_i}} (T_{E_i} - T_D)$$

$\dot{w}_{D_{B_{i_c}}}$ defined in operation 17B

17G. Correction to calculation of O_2 heat exchanger between tank and accumulator: (Ignore if $\dot{w}_{G_{A_{i_c}}} = \dot{w}_{G_{O_{i_c}}} = 0$)

$$\dot{q}_{2_{O_{i_c}}} = \dot{w}_{T_{O_i}} (H_{A_o} - H_{T_{O_i}})$$

$\dot{w}_{T_{O_i}}$ defined in operation 17E.

17H. Correction to calculation of H_2 tank heat exchanger:

$$\dot{q}_{3_{H_{i_c}}} = \left(\frac{\Delta Q}{\Delta W}\right)_{Hi} \left(\dot{w}_{T_{Hi}}\right)$$

$\dot{w}_{D_{C_{i_c}}}$ defined in (17B).

17I. Correction to calculation of O_2 tank heat exchanger:

$$\dot{q}_{3_{O_{i_c}}} = \left(\frac{\Delta Q}{\Delta W}\right)_{Oi} (\dot{w}_{T_{O_i}})$$

$\dot{w}_{D_{F_{i_c}}}$ defined in (17B)

18. Use of Heat Exchanger subroutine:

For the six heat exchangers which are investigated in the following six operations, the heat exchanger subroutine is used. Inputs and outputs for the subroutine follow:

(a) Inputs:

Type of fluid, O_2 or H_2.

$\dot{w}_c$ = rate of flow of cold fluid, lbs/sec.

$T_{c\ in}$ = cold fluid inlet temp, ^{o}R.

$T_{c\ out}$ = cold fluid outlet temp, ^{o}R.

Pc_{in} = cold fluid inlet press, psia.

Pc_{out} = cold fluid outlet press., psia, (optional, see Note)

$\dot{W}h$ = hot fluid rate of flow, lbs/sec. (See Note)

Th_{in} = hot fluid inlet temp., ^{o}R.

Th_{out} = hot fluid outlet temp., ^{o}R.

Ph_{in} = hot fluid inlet press., psia.

Ph_{out} = hot fluid outlet press., psia, (Optional, See Note).

OF = hot fluid gas generator O/F ratio, $\frac{\text{lbs Oz}}{\text{lbs Hz}}$ (See Note)

Note: (1) If Wh is given but OF is not, the sub-routine will calculate OF, and vice-versa.

(2) For each heat exchanger, Pc_{out} cannot be less than 0.8 Pc_{in}, and Ph_{out} cannot be less than 0.6 Ph_{in}, to avoid choking effects. If $\Delta P = P_{in} - P_{out}$ is not specified for the cold fluid or the hog fluid, the subroutine will use and output a value of ΔP which results in a minimum size heat exchanger.

(b) Output:

The subroutine will generate the following output:

W_{tot} = weight of the heat exchanger, lbs
V_{tot} = volume of the heat exchanger, in ^{3}
$\Delta P_{h\,tot}$ = hot fluid pressure drop, psi
$P_{h\,out}$ = hot fluid outlet pressure, psia
Pc_{tot} = cold fluid pressure drop, psi
Pc_{out} = cold fluid outlet pressure, psia

19. Weight and Characteristics of Heat Exchanger HX_A:

Find W_{HXA}, ΔPh and ΔPc for $(\dot{q}_{H_i})$ max with input of H_2 Fluid, $.0166\,\dot{w}_{D_{H_i}}$, T_{A_H}, P_{GG}, $.0166\,\dot{\omega}_{HX_A}$, T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

P_{TE} = input, assumed value of APU turbine exhaust pressure at heat exchanger inlet.

Δ P = input, allowable ΔP of the cold fluid and/or the hot fluid, if it is desired to specify this value.

20. Weight and characteristics of Heat Exchanger HX_D:

Find W_{HXD}, ΔP_h and Pc for $(\dot{q}_{1O_i})$max, with input of O_2 Fluid, $.0166\,\dot{w}_{D_{O_i}}$, T_{A_O}, T_{P_f}, P_{GG}, T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

21. Weight and characteristics of Heat Exchanger HX_B:

Find $\dot{W}_{HX_B}$, ΔPh and ΔPc for $(\dot{q}_{2H_i})$max or $(\dot{q}_{2H_{ic}})$max, as applicable, with input of H_2 Fluid, $.0166\,W_{T_{H_i}}$, $T_{T_{H_i}}$, T_{A_H}, Pc_H,

T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

22. Weight and characteristics of Heat Exchanger HX_E:

Find W_{HX_E}, ΔPh and ΔPc for $(\dot{q}_{io_i})$max or $(\dot{q}_{io_{i_c}})$max, as applicable, with input of O_2 Fluid, .0166 $\dot{\omega}_{T_{o_i}}$, $T_{T_{o_i}}$, T_A, Pco, T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

23 Weight and characteristics of Heat Exchanger HX_c:

Find W_{HXc}, and ΔPh and ΔPc for $(\dot{q}_{3_{H_{i_c}}})$max, with input of H_2 Fluid, .0166 $\dot{\omega}_{CR_H}$, $T_{T_{H_i}}$, $T_D - 100$, Pc_H, T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

$$\dot{\omega}_{CR_H} = \frac{\left(\frac{\Delta Q}{\Delta W}\right)_{H_f} \left(\dot{\omega}_{T_{H_i}}\right)_{max}}{Cp_{f_H} \left(T_D - 100 - T_{t_H}\right)}$$

$\left(\frac{\Delta Q}{\Delta W}\right)_{H_f}$ is obtained from tables of $\left(\frac{\Delta Q}{\Delta W}\right)_H$ vs stored density and tank pressure as a function of percent consumable propellant consumed.

$\dot{\omega}_{T_{H_i}}$ is obtained from operation 18D

$Cp_{f_H} = f\left(T_{f_H}, P_{f_H}\right)$

TD-100 = assumed outlet temp of cold fluid, °R.

24. Weight and characteristics of Heat Exchanger HX_F:

Find W_{HX_F}, ΔPh and ΔPc for $(\dot{q}_{3_{o_{i_c}}})$max, with input of O_2 Fluid,

.0166 $\dot{w}_{CR_o}$, $T_{T_{Oi}}$, TD -100, P_{c_o}, T_{E_i}, T_D, P_{TE}, MR, and ΔP of the cold and hot fluids if desired.

$$\dot{\omega}_{CR_o} = \frac{\left[\left(\frac{\Delta Q}{\Delta W}\right)_{o_i}\left(\dot{\omega}_{T_{o_i}}\right)\right]_{max}}{Cp_{to}\left(T_D - 100 - T_{to}\right)}$$

25. Weight and characteristics of Supplemental Heat Exchanger, if required, HX_S:

Find W_{HX_s}, ΔPh and ΔPc for $(\dot{q}_{s_i})$max, with input of H_2 Fluid, .0166 $W_{T_{H_i}}$, $T_{S_{m_i}}$, T_{A_H}, P_{C_H}, T_G, T_D, P_G, MR_G, and ΔP of the cold and hot fluids if desired.

$$\left(\dot{q}_{si}\right)_{max} = \left(\dot{\omega}_{G_{Hi_c}} + \dot{\omega}_{G_{Oi_c}}\right)_{max} Cp_G\left(T_G - T_D\right)$$

$$Cp_G = f\left(T_G, MR_G\right), \text{ from tables}$$

$$T_G = \text{input}$$

$$T_{SIN_i} = T_{A_H} - \frac{\left(\dot{\omega}_{G_{H_i}} + \dot{\omega}_{G_{O_i}}\right)K_7}{\left(\dot{\omega}_{T_{H_i}}\right)\left(Cp_{B_{H_i}}\right)}$$

25A. Calc. weight of Propellant tank heater circulating compressor:

This calculation is based upon the following assemputions:

Compressor assembly weighs 2 lbs/HP

Compressor efficiency is 60%

Tank nearly empty of usable propellant

Compressor, pressure rise = ΔP_{COMPR}

Cold fluid outlet temp from tank heat exchanger is 100°R less than hot fluid outlet temp

Max APU flow requirement

$$W_{COMPR} = .01455\, \dot{w}_{CR} \frac{\Delta P_{COMPR}}{\rho_f}$$ where

$$\dot{w}_{CR} = \frac{\left[\left(\frac{\Delta Q}{\Delta W}\right)_f \left(\dot{w}_{T_i}\right)\right]_{max}}{Cp_f \left(T_D - 100 - T_f\right)}$$

$\left(\frac{\Delta Q}{\Delta W}\right)_f$ is obtained from tables of $\left(\frac{\Delta Q}{\Delta W}\right)$ vs stored density and tank pressure as a function of percent consumable propellant consumed.

$\dot{w}'_{T_i}$ is obtained from operation 17D and 18E

$C_{P_f} = f\ (T_f, P_f)$

ΔP_{COMPR} = input, or the value of HX ΔP_c obtained from the heat exchanger subroutine for the tank heat exchanger. It may be desirable to set ΔP_{COMPR} quite low to minimize W_{COMPR}, and compressor power, and accept the resultant heat exchanger weight.

$\rho_f = f\ (T_f, P_f)$

26. Calculate Weight of H_2 storage tank:

$$W_{T_H} = 7000 \left(\frac{W_D + W_G + W_V}{4.35 - \rho_{HP}}\right) P_{C_H} \left(\frac{\rho}{F t_u}\right)$$ where

W_{D_H} is found from calculation (8)

W_{V_H} is found from the Heat Leak/Vent program for the total mission duration (see Calc. 35)

$$W_{G_H} = \sum_{i=1}^{n} \left(\dot{w}_{G_{H_{i_c}}}\right)\left(\theta_i\right)$$

P_{C_H} is found from calculation (9)

$\left(\frac{\rho}{F_{tu}}\right)$ is found as the lesser value of the programmed curves of $\frac{\rho}{F_{tu}}$ for steel and aluminum, respectively, corresponding to T_{P_f}.

27. Calculate Weight of O_2 storage tank:

$$W_{T_H} = 7000 \left(\frac{W_{D_O} + W_{G_O} + W_{V_O}}{70 - \rho_{of}} \right) P_{C_O} \left(\frac{\rho}{F_{tu}} \right)$$

W_{D_O} is found from calculation (8)

W_{V_O} is found from Heat Leak/Vent program for the total mission duration

$$W_{G_O} = \sum_{i=1}^{n=1} MR_G \left(\dot{\omega}_{GH_i}\right)\left(\theta_i\right)$$

P_{C_O} is found from calculation (10)

$\left(\frac{\rho}{F_{tu}}\right)$ is found as the lesser values of the programmed curves of $\left(\frac{\rho}{F_{tu}}\right)$ for steel and aluminum, respectively, corresponding to T_{P_f}

28. Calculate weight of H_2 tank Residual Propellant:

$$W_{R_H} = \rho_{Hf} \left(\frac{W_{D_H} + W_{G_H} + W_{V_H}}{4.35 - \rho_{Hf}} \right)$$

29. Calculate weight of O_2 tank Residual Propellant:

$$W_{R_O} = \rho_{of} \left(\frac{W_{D_O} + W_{G_O} + W_{V_O}}{70 - \rho_{of}} \right)$$

30. Calculate weight of H_2 accumulator:

$$W_{A_H} = 1.042 \left(P_{C_H}\right) \left(\frac{HP_R \; R_{R_{FP}} \; T_{A_H}}{\frac{P_{C_H}}{Z_{A_H}} - \frac{P_{f_H}}{Z_{A_{Hf}}}} \right) \left(\frac{\rho}{Ftu} \right)_{A_H} \quad \text{where}$$

$R_{R_{FP}}$ = Reference propellant flow rate from Table 1, corresponding to 100% power, MR = 1.0, P_{AMB} = 14.7, and the value of P_{GG} selected in calculation step (4)

$\left(\frac{\rho}{Ftu}\right)_{A_H}$ is found as the lesser value of the programmed curves of $\left(\frac{\rho}{Ftu}\right)$ for steel and aluminum, respectively, corresponding to T_{A_H}

Z_{A_H} is found from the programmed thermo-dynamic properties of Hydrogen, for P_{C_H} and T_{A_H}

31. Calculate weight of O_2 Accumulator:

$$W_{A_O} = .0652 \left(\frac{HP_R \; R_{R_{FP}} \; T_{A_O}}{\frac{P_{C_O}}{Z_{A_O}} - \frac{P_{GG}}{Z_{A_{Of}}}} \right) P_{C_O} \left(\frac{\rho}{Ftu} \right)_{A_O}, \quad \text{where}$$

$R_{R_{FP}}$ = Reference propellant flow rate from Table 1, corresponding to 100% power, MR = 1.0, P_{AMB} = 14.7, and the value of P_{GG} selected in calculation step (4)

$\left(\frac{\rho}{Ftu}\right)_{A_O}$ is found as the lesser value of the programmed curves of (ρ/Ftu) for steel and aluminum respectively, corresponding to T_{A_O}

Z_{A_O} is found from the programmed thermo-dynamic properties of Oxygen, for P_{C_O} and T_{A_O}

$Z_{A_{o_f}}$ is found from the programmed thermo-dynamic properties of Oxygen, for P_{f_o} and T_{A_o}

32. Calculate weight of H_2 accumlator residual Propellant:

$$W_{R_{A_H}} = \frac{W_{S_H} \; P_{f_H}}{Z_{A_{H_f}}\left(\frac{P_{c_H}}{Z_{A_H}} - \frac{P_{f_H}}{Z_{A_{H_f}}}\right)} \qquad W_{S_H} = \frac{(HP_R)(R_{R_{FP}})}{36,000}$$

33. Calculate weight of O_2 accumulator residual propellant:

$$W_{R_{A_o}} = \frac{W_s \; P_{f_o}}{Z_{A_{o_f}}\left(\frac{P_{c_o}}{Z_{A_o}} - \frac{P_{f_o}}{Z_{A_{o_f}}}\right)} \qquad W_{S_o} = \frac{(HP_R)(R_{R_{FP}})}{36,000}$$

34. Calculate weight of H_2 vented during mission:

(a) Weight of H_2 Vent required to absorb H_2 Tank leak:

There is no interest in heat leak below the temperature T_{f_H} since that is the temperature being sought in the tanks. Also, there is no interest in heat leak while the APU's are in operation, since heat is input into the tanks during these periods intentionally.

$$W_{V_{H_H}} = \sum_{i=1}^{n} W_i \left[1 + \frac{5.4\,\Delta H_i}{P_{c_H} V_{T_H}} - \sqrt{1 + \left(\frac{5.4\,\Delta H_i}{P_{c_H} V_{T_H}}\right)^2}\right.$$

where

$$\Delta H_i = \dot{q}_{T_i} A_{T_H} \tau_i$$

τ_i = a time increment between APU burns, during which the H_2 tank temperature is T_{f_H}, hrs (obtained from duty cycle and tables of $T_{T_{H_i}}$ vs stored density)

A_{T_H} = tank area, ft^2 (obtained from approximate value of V_{T_H} for spherical tank)

$$V_{T_H} \cong \left(\frac{W_{D_H} + W_{G_H}}{4.35 - \rho_{H_f}} \right)$$ (see operation 26)

$\dot{q}_{T_i}$ is obtained from vent subroutine as a function of T_{f_h}, ambient temperature, and type and thickness of insulation, $\frac{btu}{hr\text{-}ft^2}$

V_{T_H} = approximate volume of H_2 tank, ft^3 (obtained above)

P_{C_H} = input tank pressure, psia

W_i = weight of H_2 in tank at start of time period τ_i, lbs

(B) Weight of H_2 vent required to absorb O_2 Tank leak:

The same rationale applies as for the H_2 tank vent case.

$$W_{V_{H_O}} = \sum_{i=1}^{n} \frac{\dot{q}_{T_i} A_{T_O} \tau_i}{C_{P_{H_i}} \left(T_{f_O} - T_{T_{H_i}} \right)}$$, where

$C_{P_{H_i}}$ = specific heat of H_2 at $T_{T_{H_i}}$ and P_{C_H}

τ_i = a time increment between APU burns during which the O_2 tank temperature is T_{f_O}, hrs

(c) Resultant total weight of vented H_2:

If $W_{V_{H_H}} \geq W_{V_{H_O}}$, $W_{V_H} = W_{V_{H_H}}$

If $W_{V_{H_H}} < W_{V_{H_O}}$, $W_{V_H} = W_{V_{H_O}}$

35. Weight of Supplemental Gas Generator:

Call subroutine GASGEN with $(\dot{w}_{G_{H_{ic}}} + \dot{w}_{G_{O_{ic}}})$max, P_{C_H}, and T_G, and obtain gas generator weight, W_G

36. Total weight of H_2 System:

$$W_{H2_{sys}} = W_{D_H} + W_{C_H} + W_{HX_C} + W_{HX_B} + W_{HX_A} = W_{T_H} + W_{V_H}$$

$$+ W_{R_H} + W_{A_H} + W_{R_{A_H}} + W_{\substack{LINES,\\ FTTGS_H}} + W_{HX_S} + W_G + W_{G_H}$$

37. Total weight of O_2 System:

$$W_{O_{sys}} = W_{D_O} + W_{C_O} = W_{HX_F} + W_{HX_E} + W_{HX_D} + W_{T_O} + W_{R_O}$$

$$+ W_{A_O} + W_{R_{A_O}} + W_{\substack{LINES,\\ FTTGS_O}} + W_{G_O}$$

38. Total weight of supercritical APU Propellant System:

$$W_{P\ sys} = W_{H_{2_{sys}}} + W_{O_{2_{sys}}}$$

Math Model Configuration

The configuration concept employed in the modeling of the supercritical APU calculations is illustrated in Figure APUSUP-1.

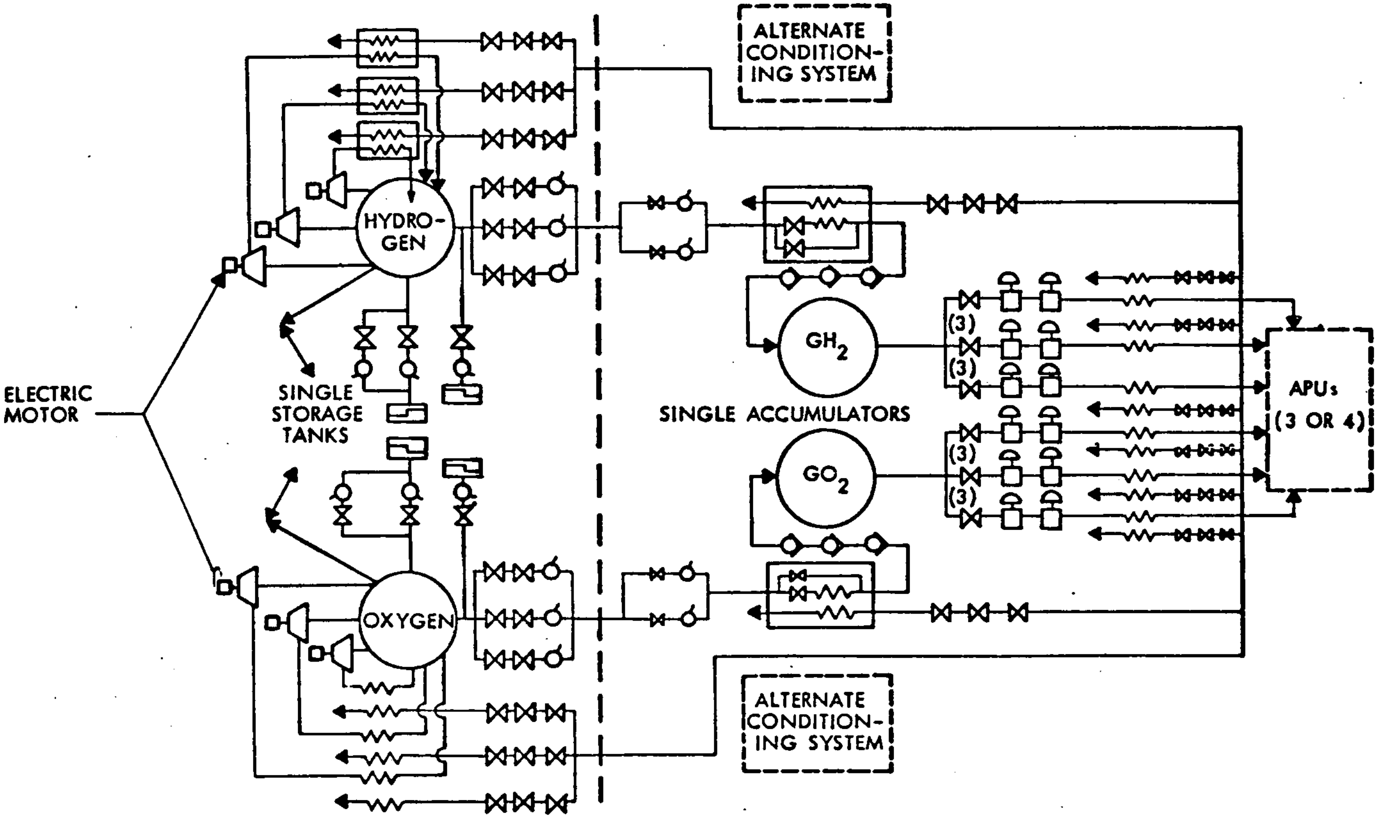


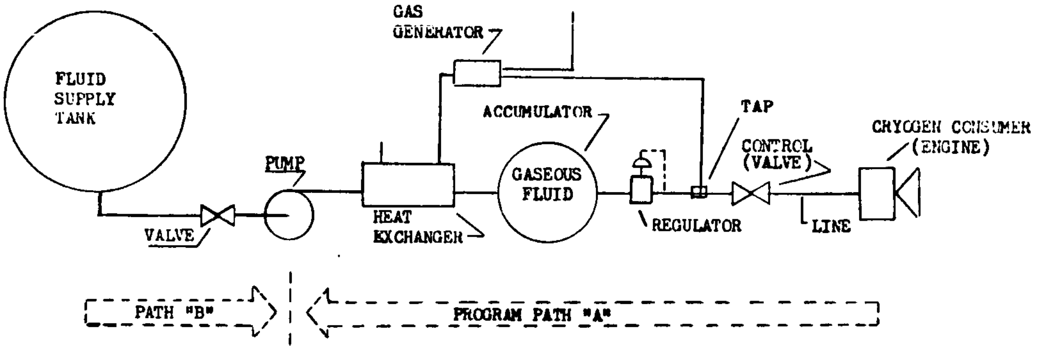
FIGURE APUSUP-1 SUPERCRITICAL APU SUPPLY SYSTEM

MATH MODEL FOR SUBROUTINE CMPCAL

PURPOSE OF SUBROUTINE

The subroutine provides in one package the necessary equations, evidence, constants and procedural techniques for the computation of the flow rate, flow conditions, component sizing and component item weight required for a configuration analysis. The subroutine makes use of a number of subprograms which supply specific or specialized computations for the larger component assemblies such as pumps heat exchangers, etc. Significant variables employed in the subroutine are defined and described in the subroutine description (Sec. 1.9).

The manner in which CMPCAL is programmed to carry through its calculation is illustrated in the following sketch and explanation:



Subroutine CMPCAL starts with the cryogen consummer, in this case an engine, and takes each component in turn as it goes along Path "A" toward the fluid supply tank. When the subroutine encounters a pump, it searches ahead until it finds a tank, it then obtains the tank temperature, pressure, flow-rate and resets the value of ISIGN to (-1) and returns via PATH "B" to the pump. The calculations then proceed for each component up to and including the tank and pressurization subsystem if one is in use. CMPCAL performs the computations for each fluid subsystem leg separately taking into account all gas generator requirements in both fluid legs of the total system.

SUBPROGRAMS AND SYMBOLS REFERENCED IN THE MATH MODEL

Subroutines, functions and data lock-up table numbers are referenced with the using equations and procedures contained in this model. The asterisk (*) implies quantity multiplication, the slash (/) denotes division of quantities and the paranthesis ( ) serve to group a set of terms.

Data transfer to and from subroutine CMPCAL is effect through the use of INCLUDE statements which bring in the appropriate PDP element defining the required labeled COMMON storage areas.

1. INPUT REQUIREMENTS AND VARIABLES NAMES

1.1 INPUT REQUIRED FROM DUTY CYCLES:

NAME	DESCRIPTION
DCYCLE (I) = $\theta(I)$	Time duration for operating interval (sec)
DCYCLE (I+1) = $\gamma(I)$	Time duration for non-operating interval (sec)
NEOP (I)	Number of units operating in interval

1.2 INPUT REQUIRED FROM CONFIGURATION DATA:

NAME	DESCRIPTION
ICNF	Number of configuration data cards input
IDX	Configuration item index
ISIGN	Analysis directional index

NAME	DESCRIPTION
CFUNCT	Integer Corresponding to Configuration Item Function
CFTYPE	Integer Corresponding to Function Type
CMTYPE	Integer Corresponding to Material Type
CITYPE	Integer Corresponding to Insulation Type
CNOPER	Number of units operating
CNSTBY	Number of units on standby
FRCOEF	Characteristic Friction Factor for Flow Region
LØD	Length over Diameter, or, Length
DIAM	Diameter
ITHIK	Insulation Thickness
NBAR	Number of Layers of insulation per inch
CØDE	Identification Code for Config. Unit

1.3 VARIABLES EMPLOYED IN MODEL EQUATIONS:

NAME	DESCRIPTION
IGAS	Integer Corresponding to Fluid Kind
GSTATE	Integer Corresponding to Fluid State
PRES	Fluid Peessue at Each Point in System
TEMP	Fluid Temp at each point in System
WDØTN	Fluid Flowrate at each print in system
WDØTI	Input Fluid Max. Flow Rate at Consumer
PLSNØM	Input Fluid Pressure at Consumer
TLSNØM	Input Fluid Temperature at Consumer
FLD	$\frac{fL}{D}$ for Configuration Unit Considered
IDV	Integer Pointer for Control Mass Characteristic
LDV	Integer Pointer for Fitting and Tap Configuration
RHØ	Fluid Density when a gas
DELP	Fluid Pressure Drop across Component
A	Cross Sectional Area of Flow Region

NAME	DESCRIPTION
WEIGHT	Weight of Configuration Component Considered
APRES	Accumulator Pressure (if used)
INDXAC	Accumulator Index (if used)
INDXTK	Fluid Tank Index-Set to IDX
SIPRES	Fluid Tank Initial Pressure
SITEMP	Fluid Tank Initial Temperature
WTTOT	Fluid Tank Weight
WDOTCF	Fluid Heat Exchanger Flow Rate
UCØDE	Fluid Heat Exchanger I.D. Code
HEXCIT	Fluid Heat Exchanger Cold Inlet Temp
HXCDLP	Fluid Heat Exchanger Delta-P
WHXTØT	Fluid Heat Exchanger Weight
MACH	Fluid Mach No.
MFLG	Fluid Mach No. Flag
JØPTN	Option for Minimum Wgt or Minimum Power Pump
PTEMP	Pump Fluid Inlet Temperature
PPRES	Pump Fluid Inlet Pressure
PPDCH	Pump Fluid Outlet Pressure
PPDEL	Pump DELTA-P (each fluid)
PPWDT	Pump Flow Rate (each fluid)
PPRHØ	Pump Inlet Fluid Density
PNPSH	Pump NPSH for Each Fluid
PMPEFF	Calculated Pump Efficiency (each fluid)
PMPVØL	Calculated Pump Volume (each fluid)
PMPØW	Calculated Pump Power (each fluid)
PSPD	Calculated Pump Speed (each fluid)
PSTAGE	Calc. Number Pump Stages (each fluid)
PNPSPR	Calc. NPSP Required (each fluid)
PWEGHT	Calculated Pump Weight (each fluid)
TWEGHT	Calculated Turbine Weight (each fluid)

NAME	DESCRIPTION
TITEMP	Turbine Inlet Temperature (each fluid)
TØTEMP	Turbine Outlet Temperature (each fluid)
TMRATØ	Turbine Gas. Gen. Mixture Ratio (each fluid)
GWEGHT	Fluids Required to Run Turbine Gas Generator
WGTGGA	Weight of Gas Generator Assy (each fluid)
TPDELP	Transfer Pump Delta-P (each fluid)
TPEFF	Transfer Pump Efficiency (each fluid)
TPNPSH	Transfer Pump NPSH (each fluid)
TPWDØT	Transfer Pump Flow Rate (each fluid)
TPWGHT	Transfer Pump Weight (each fluid)
HP	Calc Horse Power for Electric Motor
MSS	Input Motor Speed
MTYPE	Input Motor Type
PDNSTY	Battery Power Density
EMWGT	Electric Motor Weight
BWEGHT	Battery Weight
WCIRCP	Weight Fluid Circulating Pumps
WTTØT	Fluid Tank Weights (from Tank, etc)
WDØTCF	Cold Fluid Flowrate - Heat Exchangers
UCØDE	Heat Exchanger I.D. Code
HXCØDE	Input Heat Exchanger I.D. Code
HXCIT	Fluid Heat Exchanger Cold Inlet Temp
HXCDLP	Fluid Heat Exchanger - Delta P
WHXTØT	Fluid Heat Exchanger Weight
MACH	Fluid Mach Number
MFLG	Fluid Mach Number Flat

1.4 Constants Required:

PI = = 3.14159265

Gravity= G = 32.172

C1 = 1152.0/(GRAVITY*PI*PI)

2. MAJOR MATH MODEL EQUATIONS

Much of the coding in subroutine CMPCAL is required for setting-up component sequencing indices, temperatures, pressures, component identity and dimensions, as well as fluid identity and state. Most of this coding is obvious as to its meaning by simple inspection and tracking at the branching variable, therefore, only the more significant equations will be treated.

2.1 PRESSURE DROP AND WEIGHT CALCULATIONS:

Pressure drop calculations are performed by CMPCAL for all lines, fittings, taps and controls such as valves and check-valves. The line pressure drop calculation will serve to illustrate the computation procedure, taking the first line encountered after the cryogen-common, which will be assumed to be an engine.

2.1.1 PROCESS A LINE:

```
    FLD = FRCOEF(IDX)*LOD(IDX)/DIAM(IDX)
    LDV = CFTYPE/10
    CFTYPE = CFTYPE - LDV * 10
    WDOTN(IDX) = WDOTN(IDX-ISIGN)
    TEMP(IDX) = TEMP(IDX-ISIGN)
    PRES(IDX) = PRESS(IDX-ISIGN)
    IX = IDX - ISIGN
    GO TO (520,550), GSTATE
        ***** DELTA PRESSURE WHEN GASEOUS
                  CALC. RHO OF GAS
520 CALL GSDNST (IGAS,TEMP(IX),PRES(IX),RHO)
    DELP = CI*FLD*(WDOTN(IX)/CNOPER)**2/(RHO*DIAM(IDX)**4)

        ***** IF PCT. OF PRESSURE CHANGE EXCEEDS ONE PCT. - RECOMPUTE
        ***** DELTA-P, IF NOT, COMPUTE THE NEW PRESSURE
    IF(DELP/(PRES(IX) * DELP) - 0.01)560,560,530
```

```
                    CALC. RHO OF GAS
530 CALL GSDNST (IGAS,TEMP(IX),PRES(IX)+DELP/2.0,RHO)
    DELP = CI*FLD*(WDOTN(IX)/CNOPER)**2/(RHO*DIAM(IDX)**4)

       ***** AGAIN CHECK PCT. OF PRESSURE CHANGE.  IF PCT. EXCEEDS
           * 2.8 PCT. COMPUTE THE DELTA-P BY USE OF THE COMPRESSIBLE
       ***** FLOW EQUATIONS.  (REF.-RPL-TDR-64-25.VOL.L,REV.D)

    IF (DELP/PRES(IX) + DELP) - 0.028)560,560,540

540 A = PI*DIAM(IDX)**2/576.0
    CALL COMFLO(IDX,PRES(IX),TEMP(IX),FLD,A,WDOTN(IX)/CNOPER,IGAS.
   1 DELP)
    PRES(IDX) = PRES(IX) + ISIGN * DELP
    GO TO 561

      ***** DELTA PRESSURE WHEN LIQUID

550 CALL RHOLIQ(TEMP(IX),IGAS,RHO)
    DELP = CI*FLD*(WDOTN(IX)/CNOPER)**2/(RHO*DIAM(IDX)**4)

      ***** COMPUTE NEW PRESSURE

560 PRES(IDX) = PRES(IX) + ISIGN*DELP

      ***** COMPUTE THE GAS MACH NUMBER

    IF (GSTATE.EQ.2) GO TO 561

                      CALC. RHO OF GAS
    CALL GSDNST (IGAS,TEMP(IX),PRES(IDX),RHO)

    IF (GSTATE.EQ.1) CALL VGVS(IDX,RHO,IGAS)

561 CONTINUE

      ***** COMPUTE LINE WEIGHT

    CALL LWEGHT(IDX,LDV)
```

The line weight is automatically stored in the correct component weight array position designated by the component index IDX. If, instead of a line, a control fitting **or tap** were being processed then the component weight would be computed by Function CFTW as follows:

```
                         570 WEIGHT(IDX) = CFTW(DIAM(IDX),PRES(IDX,IOV)
```

2.1.2 PROCESS AN ACCUMULATOR:

```
600 PRES(IDX) = APRES(IGAS)
    TEMP(IDX) = TEMP(IDX - ISIGN)
    WDOTN(IDX) = WDOTN(IDX - ISIGN)
    INDXAC(IGAS) = IDX
```

The index INDXRAC(IGAS) is used to retrieve the **accumulator** weight from the ouput array of subroutine WTACC.

2.1.3 PROCESS A HEAT EXCHANGER UNIT:

Since heat exchanger and heat exchanger heat source data are stored in doubly **subscripted** arrays the index JX is used to keep track of which unit is being considered, IGAS specifies the fluid and IDX is the exchanger position index in the configuration array. The temperature, pressure and flow rate are picked up at the heat exchanger outlet point and the calculations proceed as follows:

```
900 IF(ISIGN.GT.0) GO TO 910
    WRITE (IOT,6005) ISIGN
910 CONTINUE
    JX = JX + 1
    JHX = JX
    WDOTN(IDX) = WDOTN(IDX-ISIGN)
    WDOTCF(JX,IGAS) = WDOTN(IDX)
    UCODE(JX,IGAS) = CODE(IDX)

    HXDLP = HEXCIP(JX,IGAS) - HEXCOP(JX,IGAS)

    IF(HXDLP,GT,0.0) TO TO 911
    UCODE(JX,IGAS) = 6HNONE    )
    PRES(IDX) = PRES(IDX-1)     }   Resets T & P if Heat Exchanger
    TEMP(IDX) = TEMP(IDX-I)     }      is a Dummy Unit.
    GO TO 1000                 )

911 CONTINUE
    HEXCOP(JX,IGAS) = PRES(IDX - 1)
    HEXCIP(JX,IGAS) = HEXCOP(JX,IGAS) + HXDLP
    IF (SCRIT .EQ. 1) TO TO 913
    IF (SYSNUM .EQ. @ .OR. SYSNUM .EQ. 4) GO TO 912
```

```
913 CONTINUE
                        COMPUTE HEATEX PARAMETERS
      CALL HEATEX(IGAS,JHX,WDOTN(IDX),HEXHIT(JF,IGAS),HEXCIT(JX,IGAS),
     1 HEXHOT(JX,IGAS),HEXCOT(JX,IGAS),HEXHIP(JX,IGAS),HEXCIP(JX,IGAS),
     2 HEXHOP(JX,IGAS),HEXCOP(JX,IGAS),HXMRAT(JX,IGAS),WDOTH (JX,IGAS),
     3 WHXTOT(JX,IGAS))

        ***** COMPUTE THE GAS GENERATOR ASSEMBLY WEIGHT *****

      CALL GASGEN(JX,IGAS)

912 CONTINUE

      TEMP(IDX) = HEXCIT(JX,IGAS)
      DLPRES = HEXCIP(JX,IGAS) - HEXCOP(JX,IGAS)
      PRES(IDX)= PRES(IDX-ISIGN) + DLPRES*ISIGN
      WEIGHT(IDX) = WHXTOT(JX,IGAS)
```

2.1.4 PROCESS A PUMP OR TANK PUMP UNIT:

When a pump is encountered, CMPCAL will always check to see if there is a tank down stream. If no tank is found the program will execute an automatic termination. If a tank exists, the temperature, pressure and tank flow rates are retrieved for use. This segment of CMPCAL processes high pressure pumps, turbo pumps and transfer pumps with electric motor drives. The coded equations are as follows:

```
        ***** CHECK ISIGN TO SEE IF THE CONDITIONS ON BOTH SIDES OF
        ***** THE PUMP HAVE BEEN CALCULATED.

800 IF(ISIGN,LT,0) GO TO 825
      ISIGN = -1

        ***** SEARCH FORWARD IN LINE FOR A SOURCE TANK

      DO 810 12=IDX,ICNF
      CALL GETCON(12)
      IF(CFUNCT.EQ.12) GO TO 820
```

```
810 CONTINUE

    WRITE(6,6010) IDX  }      Termination if no tank can
    CALL EXIT          }           be found.

      ***** WHEN A SOURCE TANK IS FOUND, SETUP PRESSURE, TEMPERATURE,
      ***** FLOW RATE AND FLAG TO CONTINUE THE CALCULATIONS.

820 WDOTN(12) = WDOTN(IDX-1)
    IDT = 12 - 1
    IDX = 12

    PRES(IDX) = SIPRES(IGAS,1)
    TEMP(IDX) = SITEMP(IGAS,1)
    GO TO 1000

      ***** COMPUTE THE WEIGHT OF THE PUMP, TURBINE, PROPELLANT AND
      ***** MOTOR DEPENDING ON THE TYPE OF PUMP.

      ***** CHECK CFTYPE FOR HIGH OR LOW PRESSURE PUMP

825 ISIGN = 1
    PRES(IDX) = PRES(IDX+1)
    TEMP(IDX) = TEMP(IDX+1)
    WDOTN(IDX) = WDOTN(IDX+1)

    JOPTIN = CFTYPE/10
    CFTYPE = CFTYPE - JOPTN * 10

    IF(CFTYPE.EQ.2) GO TO 840

      ***** PROCESS THE HIGH PRESSURE PUMP
      ***** COMPUTE THE PUMP OR TURBOPUMP WEIGHT

    JJOPT(IGAS) =JOPTN
    PTEMP(IGAS) =TEMP(IDX
    PPRES(IGAS) =PRES(IDX)
    PPDCH(IGAS) = PRES(IDX-1)
    PDELP = ABS(PRES(IDX-1) - PRES(IDX))
    PPDEL(IGAS) =PDELP
    PWDOT = WDOTN(IDX)/CNOPER
    PPWDT(IGAS) =PWDOT
    CALL RHOLIQ(TEMP(IDX),IGAS,RHO)
    PPRHO(IGAS) =RHO
                 CALCULATE PUMP PARAMETERS
```

```
 CALL PARPMP(IGAS,JOPTN,PDELP,PWDOT,PNPSH(IGAS),RHO,PMEF,V,
1 E, WT, PNSG, NSTG, NPSPR)
 PMPEFT(IGAS) = PMEF
 PMPVOL(IGAS) = V
 PMPOW(IGAS) = E
 PSPD(IGAS) = PNSG
 PSTAGE(IGAS) = NSTG
 PNPSPR(IGAS) = NPSPR
 PWEGHT(IGAS) = WT * (CNOPER + CNSTBY)

   ***** CHECK PTYPE FOR PUMP OR TURBOPUMP *****

 IF(PTYPE.EQ.1) GO TO 830

   ***** COMPUTE THE TURBINE WEIGHT

 CALL TURBN(IGAS,TRBWGT)
 TWEGHT(IGAS) = TRBWGT * (CNOPER + CNSTBY)

   ***** COMPUTE THE FLOWRATE OF THE GAS GENERATOR AND ITS WEIGHT

 TMEAN1 = (TITEMP(1) - TOTEMP(1))/2.0
 TMEAN2 = (TITEMP(2) - TOTEMP(2))/2.0
 CALL CSUBP1(TMEAN1,TMRATO(1),CPEPI)
 CALL CSUBPi(TMEAN2,TMRATO(2),CPEP2)
 DLHTPI = CPEPI * (TITEMP(1) - TOTEMP(1))
 DLHTP2 = CPEP2 * (TITEMP(2) - TOTEMP(2))
 CALL RHOLIQ(SITEMP(1,1),RHOLQ1)
 CALL RHOLIQ(SITEMP(2,1),2,RHOLQ2)
 BRACI = (0.185 * PPDEL(1))/(RHOLQI * PMPEFF(1) * TEFF(1) *  DLHTP1)
 C1 = TMRATO(1)/(1.0 + TMRATO(1))
 C2 = 1.0/(1.0 + TMRATO(1))
 IF(PPDEL(2).EQ.0.0) PPDEL(2) = EPDELP(2)
 IF(PMPEFF(2).EQ.0.0) PMPEFF(2) = PEFF(2)
 BRAC2 = (0.185 * PPDEL(2))/(RHOLQ2 * PMPEFF(2) * TEFF(2) * DLHTP2)
 C3 = TMRATO(2)/(1.0 + TMRATO(2))
 C4 = 1.0/(1.0 + TMRATO(2))
 C5 = BRACI * C1
 C6 = BRACI * C2
 C7 = BRAC2 * C3
 C8 = BRAC2 * C4
 D1 = (C5 + C8 + C6*C7 - C5*C8 - 1.0)
 WFLO1 = (WDOTI(1) * (C5*C8-C5) + WDOTI(2) * (-C5*C7))/DI * CNOPER
 WFLO2 = (WDOTI(1) * (-C6*C7) + WDOTI(2) * (C5*C7 - C7))/D1*CNOPER
 WFLO3 = (WDOTI(1) * (C6*C8 - C6) + WDOTI(2) * (-C6*C7))/DI*CNOPER
 WFLO4 = (WDOTI(1) * (-C6*C8) + WDOTI(2) * (C5*C8 - C8))/DI*CNOPER
 WDGGFR(1) = (WFLO1 + WFLO3) * CNOPER
 WDGGFR(2) = (WFLO2 + WFLO4) * CNOPER
```

```
      KK = 0
      WDOTG1 = 0.0
      WDOTG2 = 0.0

      DO 835 12 = 1,NDCYCL,2
      KK = KK + 1
      WFL05 = (WDOTJ(KK,1) * (C5*C8-C5) + WDOTJ(KK,2) * (-C5*C7))/D1
      WFL06 = (WDOTJ(KK,1) * (1-C6*C7) + WDOTJ(KK,2) * (C5*C7 -C7))/D1
      WFL07 = (WDOTJ(KK,1) * (C6*C8 - C6) + WDOTJ(KK,2) * (-C6*C7))/D1
      WFL08 = (WDOTJ(KK,1) * (-C6*C8) + WDOTJ(KK,2) * (C5*C8 -C8))/DI
      WFL057 = (WFL05 + WFL07)/CNOPER
      WFL068 = (WFL06 + WFL08)/CNOPER
      WDOTG1 = WDOTG1 + WFL057 * DCYCLE(12)
      WDOTG2 = WDOTG2 + WFL068 * DCYCLE(12)
  835 CONTINUE

      GWEGHT(1) = WDOTG1 * CNOPER

      GWEGHT(2) = WDOTG2 * CNOPER

        ***** COMPUTE SYSTEM WEIGHT

      ATERM = 13.824204 - (0.01117823*TGGPC( IGAS   )) + (1.8632927E-5 *
     1(TGGPC( IGAS  )**2)) - (1.108423E-8 * (TGGPC( IGAS  )**3))

      BTERM = 7.9470262 - (.035636198*TGGPC( IGAS  )) + (6.4684644E-5 *
     1(TGGPC(IGAS    )**2)) - (3.7946E-8 * (TGGPC(   )**3))

      WTGGA = ATERM + BTERM * WDGGFR(IGAS)/CNOPER
      WGTGGA(IGAS) = WTGGA * (CNOPER + CNSTBY)
      WEIGHT(IDX) = PWEGHT(IGAS) + TWEGHT(IGAS) +WGTGGA(IGAS)

      GO TO 999

  830 CONTINUE
      WEIGHT(IDX) = PWEGHT(IGAS)

      GO TO 999

        *****PROCESS LOW PRESSURE SYSTEM
        *****FLUID TRANSFER PUMP

  840 CONTINUE
      IF((SYSNUM.EQ.@.OR.SYSNUM.EQ.$) .AND. (SCRIT.EQ.2)) GO TO 841
      CALL FINTAB (NTBID(15)+IGAS)
      XTAB(1) = TPEFF(IGAS)*100.0         }
      XTAB(2) = TPNPSH(IGAS)              }  Table 14 for 02
      IF(TPDELP(IGAS))860,850,860         }  Table 15 for H2
```

```
850 TPDELP(IGAS) = PRES(IDX) - PRES(IDX-1)
860 IF(TPWDOT(IGAS))880.870.880
870 TPWDOT(IGAS) = WDOTN(IDX)/CNOPER
880 XTAB(3) = TPDELP(IGAS)
    XTAB(4) = TPWDOT(IGAS)
    TPWGHT(IGAS) = MIPE(4,XTAB)*(CNOPER + CNSTBY)

      ***** ELECTRIC MOTOR FOR TRANSFER PUMP

    CALL FINTAB (NTBID(16))                    - Table No. 16
    CALL RHOLIQ(TEMP(IDX),IGAS,RHO)
    HP = 144.0*WDOTN(IDX)*(PRES(IDX) - PRES(IDX-1))/(550.0*PEFF*RHO*
   1     MEFF)
    XTAB(1) = HP
    XTAB(2) = MSS
    EMWGT = MIPE(2,XTAB) * (CNOPER + CNSTBY)
    WEIGHT(IDX) = EMWGT + TPWGHT(IGAS)

    KK = 0
    BWEGHT(IGAS) = 0.0
    DO 890 12 = 1,NDCYCL,2
    KK = KK + 1
    HP = 144.0*WDOTJ(KK,IGAS)*(PRES(IDX) - PRES(IDX - 1))/(550.0*PEFF*
   1     RHO*MEFF)
    PB = HP*746.0*DCYCLE(12)/3600.0
    BWEGHT(IGAS) = BWEGHT(IGAS) + PB/PDNSTY
890 CONTINUE
    GO TO 999

841 CONTINUE
    WEIGHT(IDX) = WCIRCP(IGAS)
    GO TO 999
```

At statement 841, CMPCAL picks up the weight of a circulating pump calculated in another subroutine. (For super-critical systems only). **Statement 999 in the WRITE statement which outputs the computed values.**

MATH MODEL FOR SUBROUTINE CØMFLØ

PURPOSE OF SUBROUTINE

To provide a subprogram which solves the compressible flow equations for the determination of pressure drops of gaseous fluids in long ducts. The equations employed are taken from References 1.9-15 and 1.9-16.

THE BASIC MATH MODEL

The analysis is reversed to the normal method of solution to the compressible flow problem as shown in the following sketch:

Flow ⟶

M_1)) M_2, P_2.

⟵ Analysis

P_2, M_2 and $\frac{fL}{D}$ are known, M_1 and P_1 are not known.

From Shapiro, pp 167 (Ref 1.9-16), the length of duct L required for the flow to pass from a given initial MACH No. M_1 to a final MACH No. M_2 is found from the expression:

$$\frac{fL}{D} = F(M_1) - F(M_2) \tag{1}$$

where

$$F(M) = \frac{1 - M^2}{\gamma M^2} + \frac{\gamma + 1}{2\gamma} \ln \left[\frac{(\gamma + 1) M^2}{2 \left(1 + \frac{\gamma + 1}{2} M^2 \right)} \right] \tag{2}$$

If $\frac{fL}{D}$ and M_2 are given, then M_1 (which is less than M_2) can be found from Eq. (1) by solving (on a trial and error basis) for the value of M_1, such that:

$$\left| \delta (M_1) \right| = \left| F (M1_{Assumed}) - \left[F (M_2) + \frac{fL}{D} \right| < \epsilon \right] \qquad (3)$$

where ϵ = a small value ≈ 0.00005.

Since $M_2 > M_1$, the value of $F (M_2) < F (M_1)$. That is, F (M) decreases as M increases for $0.0 < M \lesssim 1.0$. (Note that F (M) is undefined for $M = 0.$) Thus a positive error ($\delta > 0.0$), implies that an increase in M_1 (assumed) is required, and vice versa. Setting $(M1)_{Min}$ to 10^{-10} and $(M1)_{Max}$ to 1.0, and $\epsilon = 0.00005$, a solution can usually be found in less than twenty iterative loops of Eq. (3).

With M_1 known, the pressure drop can be determined. From Shapiro, pp 168 and pp 169, (Ref 1.9-16):

$$\left(\frac{P_2}{P_1}\right) = \left(\frac{M_1}{M_2}\right) \left(\frac{1 + \frac{\gamma - 1}{2} M_1^2}{1 + \frac{\gamma - 1}{2} M_2^2}\right)$$

where

$$\Delta P = P_1 - P_2 = P_2 \left(\frac{P_1}{P_2}\right) - 1 = P_2 \left(\frac{1}{P_2/P_1} - 1\right)$$

and the compressible flow solution has been obtained.

MATH MODEL FOR SUBROUTINE ECLSS

PURPOSE OF SUBROUTINE

The subroutine provides in integrated subprogram package which permits the computation of the basic life support system parameters for dynamic and parametric system analysis. The analytical capability of the subprogram package includes system sizing and weight generation computational techniques for the system components, as well as the capability for computing the dynamic energy-requirement history associated with consumables storage and utilization.

SUBPROGRAMS AND SYMBOLS REFERENCED IN MATH MODEL

Subroutine, functions and data lookup table numbers are referenced with the using equations and procedures contained in this math model. The asterisk (*) implies quantity multiplication and the paranthesis ( ) serve to group a set of mathematical terms.

PROCEDURE AND MODEL

1. Input Required for Life Support Duty Cycle

DCYCLE(I)	– Time duration of each interval requiring life support operation (hrs)
DCYCLE(I+1)	– Time duration of each nonoperating life suppport interval (hrs)
RPRTIM	– Time duration of interval during which cabin or airlock repressurization is required

2. Input Required for Life Support System Characterization

MDAYS	– Mission duration — Days
NCREW	– Number of Men in Crew
NRPRES	– Number of cabin or airlock repressurizations required

NDARES – Number of days supply of reserve gases

$Ø_2$FNØM – Oxygen consumed per man day (lb/day)

GLKRAT – Vehicle gas leakage rate (lb/day)

TLSNØM – Delivered gas nominal temperature (^{o}R) – O_2 or N_2

RHØBEG – Cryogen gas fill density (lb/cu ft) – O_2 or N_2

TKFTEM – Gas storage tank final temperature (^{o}R) – O_2 or N_2

TKFPR5 – Gas storage tank final pressure (psia) – O_2 or N_2

TENVR – Environmental temperature around life support gas storage systems

CABVØL – Airlock or cabin volume (cu ft)

LINDIA – Diameter of inlet line to gas heat exchanger (inches) – O_2 or N_2

HTRFLX(1) – Electric heater manufacturer's energy output rating for heat exchanger heating units (Btu/H_2-ft^2-^{o}R) – O_2 and N_2

HTRFLX(2) – Electric heater manufacturer's energy output rating for tank heater units, (Btu/hr-ft^2-^{o}R) – O_2 and N_2

PLSNØM – Delivered gas pressure (psia) – O_2 or N_2

HTRDIA – Heater diameter for tank heater units, (1) for O_2 tank, (2) for H_2 tank

HTRLNG – Heater length for tank heater units (1) for O2 tank, (2) for H_2 tank

PSET1 – Oxygen tank lower pressure limit-pressure setting (psia)

PSET2 – Hydrogen tank lower pressure limit-pressure setting (psia)

PØPØ2 – Oxygen tank operating pressure

PØPN2 – Nitrogen tank operating pressure

PVPØ2 – Oxygen tank vent pressure

PVPN2 – Nitrogen tank vent pressure

TØ2IN – Initial $Ø_2$ tank temperature

TN2IN – Initial N_2 tank temperature

3. Compute Quantity of Fluids Consumed for Life Support for Each Duty Cycle Interval and Total Gas Requirements

Let Θ = Operating Duty Cycle Periods

Let τ = Nonoperating Duty Cycle Periods

$$\text{Ø2MWT(I)} = \left(\frac{\text{Ø2FNØM}}{24}\right) * \text{NCREW} * \theta(\text{I})$$

$$\text{O2LWT(I)} = 0.21 * \left(\frac{\text{GLKRAT}}{24}\right) * \theta(\text{I})$$

$$\text{N2LWT(I)} = 0.79 * \left(\frac{\text{GLKRAT}}{24}\right) * \theta(\text{I})$$

$$\text{Ø2MCØN} = \sum_{\text{I}=\theta_1}^{\text{I}=\theta_f} \text{Ø2MWT(I)}$$

$$\text{Ø2LCØN} = \sum_{\text{I}=\theta_1}^{\text{I}=\theta_f} \text{Ø2LWT(I)}$$

$$\text{N2LCØN} = \sum_{\text{I}=\theta_1}^{\text{I}=\theta_f} \text{N2LWT(I)}$$

$$\text{GASWGT} = \frac{\text{CABVØL}}{\bar{V}_{\text{AIR}}} \qquad \text{Sp Vol Air} = \bar{V} = 13.2743$$

$$\text{O2REPR} = 0.21 * \text{NRPRES} * \text{GASWGT}$$

$$\text{N2REPR} = 0.79 * \text{NRPRES} * \text{GASWGT}$$

$$\text{Ø2CØNS} = \text{Ø2MCØN} + \text{Ø2LCØN} + \text{Ø2REPR}$$

$$\text{N2CØNS} = \text{N2LCØN} + \text{N2REPR}$$

4. Compute Reserve Gases Required for the Mission

$$\text{Ø2MRES} = \text{Ø2FNØN} * \text{NCREW} * \text{NDARES}$$

$$\text{Ø2LRES} = 0.21 * \text{GLKRAT} * \text{NDARES}$$

$$\text{N2LRES} = 0.79 * \text{GLKRAT} * \text{NDARES}$$

$$\text{Ø2RES} = \text{Ø2MRES} + \text{Ø2LRES}$$

$$\text{N2RES} = \text{N2LRES}$$

5. Compute Usable Gas Consumables Total

Ø2TØTU = Ø2CØNS + Ø2RES

N2TØTU = N2CØNS + N2RES

6. Compute Nominal Flowrate, Repressurization Flowrate, Maximum Flowrate and Quantity Consumed — Each Interval

WDØTØN(I) = $\left[\frac{\text{Ø2MWT(I) + Ø2LWT(I)}}{\epsilon\text{(I)}}\right]$

WDOTNN(I) = $\frac{\text{N2LWT(I)}}{\theta\text{(I)}}$

WPØTØR(I) = (Ø2REPR/NRPRES)/RPRTIM(I)

WDØTNR(I) = (N2REPR/NRPRES)/RPRTIM(I)

WDTØ2(I) = WDØTØN(I) + WDØTØR(I)

WDTN2(I) = WDØTNN(I) + WDØTNR(I)

WTØ2(I) = WDØTØN(I) * θ(I) + WDØTØR(I) * RPRTIM(I)

WIN2(I) = WDØTNN(I) * ϵ(I) + WDØTNR(I) * RPRTIM(I)

WDTØMX = WDTØ2(MAX)

WDINMX = WDTN2(MAX)

WDØTI(I) = WDTØMX/3600.00 = WDØTT(I)

WDØTI(2) = WDTNMX/3600.00 = WDØTT(2)

(1) = O_2 ; (2) = N_2

7. Determine Initial Tank Conditions

TEMPØ2 = f (PØPØ2, RHØBEG(1))

Table 5

TEMPN2 = f (PØPN2, RHØBEG(2))

Table 19

CISBVØ = f (TEMPØ2, PØPØ2, 1) Function CSUBV

CISBVN = f (TEMPN2, PØPN2, 18) Function CSUBV

8. Compressibility at Final Tank Conditions

ZFØ = f (TKFTEM(1), TKFPRS(1), 1) Function ZGET

ZFN = f (TKFTEM(2), TKFPRS(2), 18) Function ZGET

9. Compute Tank Conditions for Each Duty Cycle Interval

(a) Percent Usable Fluid Withdrawn:

TKØW = TKØW + WTØ2(I)

TKØ2DP(I) = TKØW

$$\text{PCOXWD(I)} = \frac{\text{TKØ2DP(I)}}{\text{Ø2TØTU}}$$

TKNW = TKNW + WTN2(I)

TKN2WD(I) = TKNW

$$\text{PCN2WD(I)} = \frac{\text{TKN2DP(I)}}{\text{N2TØTU}}$$

(b) Density of Fluids As Function of Percent Withdrawn

$$\text{C1} = \left(\frac{144.0}{\text{RHOBEG(1)}}\right) * \left(\frac{1544.2546}{31.9988}\right)$$

$$\text{C2} = \left(\frac{144.0}{\text{RHOBEG(2)}}\right) * \left(\frac{1544.2546}{28.0134}\right)$$

$$\text{C3} = 1 - \left(\frac{\text{C1 * TKFPRS(1)}}{\text{ZFØ * TKFTEM(1)}}\right)$$

$$\mathrm{C4} = 1 - \left(\frac{\mathrm{C2} * \mathrm{TKFPRS(2)}}{\mathrm{ZFN} * \mathrm{TKFTEM(2)}}\right)$$

$$\text{Ø2RHØ(I)} = \text{RHØBEG(1)} * \left\{1 - \left[\text{PCØXWD(I)} * \text{C3}\right]\right\}$$

$$\text{N2RHØ(I)} = \text{RHØBEG(2)} * \left\{1 - \left[\text{PCN2WD(I)} * \text{C4}\right]\right\}$$

(c) Fluid Temperature In Tanks:

Ø2TEMP = f [PØPØ2, Ø2RHØ(I)]

Table 5

N2TEMP = f [POPN2, N2RHO(I)]

Table 19

(d) Specific Heat Input (DQ/DM) and Energy Derivative (DP/DU):

From subroutine PHTHØN(Ø2TEMP(I), Ø2RHØ(I), 1, PHI, THETA)

DQDMØ2(I) = THETA
DPDUØ2(I) = PHI

From subroutine PHTHØN(N2TEMP(I), N2RHØ(I), 18, PHI, THETA)

DQDMN2(I) = THETA
DPDUN2(I) = PHI

(e) Size Conditioning Heat Exchangers for Fluids:

Enthalpy of Delivered Gases

HLSØ = f (PØPØ2, TLSNØM(1))

Function ØXENTH

HLSN = f (PØPN2, TLSNØM(2))

Function NIENTH

Enthalpy of Gas — Each Interval

Ø2H(I) = f (PØPØ2, Ø2TEMP(I))

Function ØXENTH

N2H(I) = f (PØPN2, N2TEMP(I))

Function NIENTH

QDTØR(I) = WDTØ2(I) * (HLSØ - Ø2H(I))
QDTØMX = f (QDTØMX, QDTØR(I))

Function AMAX1

QDTNR(I) = WDTN2(I) * (HLSN-N2H(I))
QDTNMX = f (QDTNMX, QDTNR(I))

Function AMAX1

(f) Power Required to Provide Energy in Heat Exchanger — Each Interval and Total:

HWATØ2(I) = QDTØR(I) * 0.293
HWTØMX = AMAXI (HWTØMX, HWATØ2(I))

$$\text{HWTØTT} = \sum_{I=\theta_1}^{I=\theta_f} \text{HWATØ2(I)}$$

HWATN2(I) = QDTNR(I) * 0.293
HWTNMX = AMAXI (HWTNMX, HWATN2(I))

$$\text{HWTØTT} = \sum_{I=\theta_1}^{I=\theta_f} \text{HWATN2(I)}$$

(g) Size O2 and N2 Tank Heat Requirements:

QDTTKØ(I) = WDTØ2(I) * DQDMØ2(I)
QDTTKN(I) = WDTN2(I) * DQDMN2(I)

(h) Power to Provide Energy to Tanks:

TWATØ2(I) = QDTTKØ(I) * 0.293

TWTØMX = AMAXI (TWTØMX, TWATØ2(I))

$$\text{TWTØTT} = \sum_{I=\theta_1}^{I=\theta_f} \text{TWATØ2(I)}$$

TWATN2(I) = QDTTKN(I) * 0.293

TWTNMX = AMAXI (TWTNMX, TWATN2(I))

$$\text{TWTNTT} = \sum_{I=\theta_1}^{I=\theta_f} \text{TWATN2(I)}$$

TØTWMX = HWTØMX + HWTNMX + TWTØMX + TWTNMX

TØTWAT = HWTØTT + HWTNTT + TWTØTT + TWTNTT

TØTPØW = TØTWAT/1000.0 (KW)

(i) Calculate Tank Heater Ratings Required:

$$\text{HTRRAI} = \frac{(\text{TWTØMX}/0.293)}{(\pi \ * \ \text{HTRDIA(I)} \ * \ \text{HTRLNG(1)})}$$

$$\text{HTRRA2} = \frac{(\text{TWTNMX}/0.293)}{(\pi \ \text{x} \ \text{HTRDIA(2)} \ * \ \text{HTRLNG(2)})}$$

(These values are used later only if HTRFLX(2) = 0.0.)

10. Compute Fluid Densities At Final Conditions

RHØEND(1) = f (Ø2TEMP(MAX), TKFPRS(1), IGAS)
Subroutine DENSØN

RHØEND(2) = f (N2TEMP(MAX), TKFPRS(2), IGAS)
Subroutine DENSØN

11. Compute Weight of Residual Fluids in Tanks

$$\text{WTRSID(1)} = \left(\frac{\text{RHØEND(1)}}{\text{RHØBEG(1)}}\right) * \left(\frac{1}{1 - \dfrac{\text{RHØEND(1)}}{\text{RHØBEG(1)}}}\right) * (\text{Ø2CØNS} + \text{Ø2RES})$$

$$\text{WTRSID(2)} = \left(\frac{\text{RHØEND(2)}}{\text{RHOBEG(2)}}\right) * \left(\frac{1}{1 - \dfrac{\text{RHØEND(2)}}{\text{RHØBEG(2)}}}\right) * (\text{N2CØNS} + \text{N2RES})$$

12. Compute Volume and Surface Area of Tanks

$$\text{VOLTK(1)} = \frac{\text{Ø2TØTU} + \text{WTRSID(1)}}{0.97 * (\text{RHOBEG(1)} - \text{RHOEND(1)})}$$

$$\text{VØLTK(2)} = \frac{\text{N2TØTU} + \text{WTRSID(2)}}{0.97 * (\text{RHØBEG(2)} - \text{RHØEND(2)})}$$

$$\text{ARETK(1)} = 4.84 * (\text{VØLTK(1)})^{0.667}$$

$$\text{ARETK(2)} = 4.84 * \text{VØLTK(2))}^{0.667}$$

13. Compute Heat Leak Into Fluid Tanks

TØCND(I) = f (TENVR,Ø2TEMP(I),SNBAR(1),SITHIK(1),SITYPE(1))
Subroutine TCØND

TNCND(I) = f (TENVR,N2TEMP(I),SNBAR(2),SITHIK(2),SITYPE(2))
Subroutine TCØND

$$\text{QØ2LK(I)} = \text{TØCND(I)} * \text{ARETK(1)} * \theta\text{(I)}$$

$$\text{QN2LK(I)} = \text{TNCND (I)} * \text{ARETK(2)} * \theta\text{(I)}$$

$$\text{QLKØTK} = \sum_{I=\theta_1}^{I=\theta_f} \text{QØ2LK(I)}$$

$$\text{QLKNTK} = \sum_{I=\theta_1}^{I=\theta_f} \text{QN2LK(I)}$$

14. Compute Quantity of Fluids Vented During Each Interval and Total Fluid Vented

$$\text{CSBV02(I)} = \text{CSUBV(02TEMP(I), P0P02, 1)}$$

$$\text{CSBVN2(I)} = \text{CSUBV(N2TEMP(I), P0PN2, 18)}$$

$$\text{QREQD0(I)} = \left(\frac{\text{V0LTK(1)} * \text{CSBV02(I)}}{48.3}\right) (\text{PVNT0} - \text{P0P02}) * 144.0$$

$$\text{QREQDN(I)} = \left(\frac{\text{V0LTK(2)} * \text{CSBVN2(I)}}{54.9}\right) * (\text{PVNTN} - \text{P0PN2}) * 144.0$$

$$\text{DELQ(I)} = \text{Q02LK(I)} - \text{QREQD0(I)}$$

$$\text{WVNT0(I)} = \frac{\text{DELQ(I)}}{\text{CSBV02(I)} * \text{O2TEMP(*)} * \left(\frac{\text{PVNT0}}{\text{P0P02}}\right) - 1}$$

$$\text{WV02} = \sum_{I=\theta_1}^{I=\theta_f} \text{WVNT0(I)}$$

$$\text{DELQN(I)} = \text{QN2LK(I)} - \text{QREQDN(I)}$$

$$\text{WVNTN(I)} = \frac{\text{DELQN(I)}}{\text{CSNVN2(I)} * \text{N2TEMP(I)} * \left(\frac{\text{PVNTN}}{\text{P0PN2}}\right) - 1}$$

$$\text{WVN2} = \sum_{I=\theta_1}^{I=\theta_f} \text{WVNTN(I)}$$

15. Total Fluids Loaded Into Tank

$$\text{T0TWTL(1)} = \text{02T0TU} + \text{WTRSID(1)} + \text{WV02}$$

$$\text{T0TWTL(2)} = \text{N2T0TU} + \text{WTRSID(2)} + \text{WVN2}$$

16. Diameter of Fluid Tanks — Assumed Spherical

$$DITK(1) = 1.9098 * \left(\frac{T0TWTL(1)}{RH0BEG(1)}\right)^{0.33} * 12.0$$

$$DITK(2) = 1.9098 * \left(\frac{T0TWTL(2)}{RH0BEG(2)}\right)^{0.33} * 12.0$$

17. Fluid Tank Insulation Weight

$$TIWT(1) = \frac{ARETK(1) * RH0I(SITYPE(1)) * SITHIK(1)}{12.0}$$

$$TIWT(2) = \frac{ARETK(2) * RH0I(SITYPE(2)) * SITHIK(2)}{12.0}$$

18. Diameter of Fluid Tank Vacuum Jackets

$$DIVJ(1) = DITK(1) + 1.60$$

$$DIVJ(2) = DITK(2) + 1.85$$

19. Compute Weight of Tank Pressure Vessels

$$R0FTU(1) = \frac{RH0L(SMTYPE)/1728.0}{FTUX}$$

FTUX = f (SMTYPE)

See Table (21 + SMTYPE)

$$R0FTU(2) = \frac{RH0L(SMTYPE)/1728.0}{FTUX}$$

FTUX = f (SMTYPE)

See Table (21 + SMTYPE)

$$WTPV(1) = 7000 * \left(\frac{T0TWTL(1)}{RH0BEG(1)}\right) * P0P02 * R0FTU(1)$$

$$WTPV(2) = 7000 * \left(\frac{T0TWTL(2)}{RH0BEG(2)}\right) * P0PN2 * R0FTU(2)$$

20. Compute Weight of Vacuum Jackets

SPWTI = f (DIVJ(1))
Table 17

SPWT2 = f (DIVJ(2))
Table 17

WTVJØ = SPWT1 * ARETK(1)

WTVJN = SPWT2 * ARETK(2)

21. Total Weight of Tank Assembly

WTTØT(1) = WTPV(1) + WTVJØ + TIWT(1)

WTTØT(2) = WTPV(2) + WTVJN + TIWT(2)

22. Weight of Heat Exchangers

WHXTØT(1) = f (TEMPØ2, TLSNUM(1),PØPØ2, HTRFLX(1), LINDIA(1), WDTØMX, Ø2RHØ(MAX),IFIN)
From subroutine HEXELC

WHXTØT(2) = f (TEMPN2, TLSNØM(2), PØPN2, HTRFLX(1), LINDIA(2), WDTNMX, N2RHØ(MAX), IFIN)
From subroutine HEXELC

23. Compute Tank Energy History and Heater Duty Cycle

The tank energy history and heater duty cycle model parallels closely to the model employed in subroutine FUELCL. By using that model, or, by inspection of the coding given in the ECLSS listing, the model may be readily understood. Hence, it will not be repeated here.

MATH MODEL FOR SUBROUTINE FLØRAT

PURPOSE OF SUBROUTINE

To provide for the calculation of cryogen flow rates required in supplying fuel and oxidizer to gas generators which are not primary cryogen consumers in any given system. Such gas generator may be required for heat exchanger heat sources or to power turbine driven equipments. The calculations provide a means of arriving at the total cryogen consumption for the primary system consumer and its ancillary support system.

SUBPROGRAMS AND SYMBOLS REFERENCED IN MATH MODEL

The subprograms and symbols used are referenced with the equations employed in the model. The asterisk (*) implies multiplication and parenthesis ( ) serve to group a set of mathematical manipulations.

PROCEDURE AND EQUATIONS

1. Variable Definitions:

Model	Program	Definition
$\dot{W}_{OC}$	WDOTI(1)	O_2 max flow rate to consumer
$\dot{W}_{HC}$	WDOTI(2)	H_2 max flow rate to consumer
$\dot{W}_{O1}$	WFLO1	O_2 flow rate to condition O_2
$\dot{W}_{O2}$	WFLO2	O_2 flow rate to condition H_2
$\dot{W}_{H1}$	WFLO3	H_2 flow rate to condition O_2
$\dot{W}_{H2}$	WFLO4	H_2 flow rate to condition H_2
$\dot{W}_{O3}$	WFLO5	O_2 flow rate to drive O_2 turbine

Model	Program	Definition
$\dot{W}_{O4}$	WFLO6	O_2 flow rate to drive H_2 turbine
$\dot{W}_{H3}$	WFLO7	H_2 flow rate to drive O_2 turbine
$\dot{W}_{H4}$	WFLO8	H_2 flow rate to drive H_2 turbine
H_{CIN}	—	Enthalpy at cold fluid inlet
H_{COUT}	—	Enthalpy at cold fluid outlet
H_{AIN}	—	Enthalpy at hot fluid inlet
H_{HOUT}	—	Enthalpy at hot fluid outlet
H_{TIN}	—	Enthalpy at turbine hot gas inlet
H_{TOUT}	—	Enthalpy at turbine hot gas outlet
ΔP_{EST}	DELHTP	Pump pressure rise
ρ_{LO2}	RHOLQ(1)	Density liquid oxygen
η_P	PEFF	Pump efficiency
η_T	TEFF	Turbine efficiency
H_{TIN}	—	Enthalpy turbine inlet gas
H_{TOUT}	—	Enthalpy turbine outlet gas
ρ_{LH2}	RHOLQ(2)	Density liquid hydrogen
MR_{HEX}	TMRATO	Mixture ratio (0/H) HEX
MR_{TBN}	TMRATC	Mixture Ratio (0/H) Turbine
HXGG	—	Heat exchanger gas generator
TBGG	—	Turbine gas generator

2. Equations for Fluid Flow Rates

The equations which express the fluid species flow rates for fluids to power the heat exhanger gas generator and turbine gas generators were derived originally for the combined heat exchanger and turbine gas generators. In coding the equations for the subroutine it was found that splitting out the heat exchanger and turbine gas generator portions of the equations provided more flexibility in calculational technique and checkout. Therefore, the model will be shown in its revised form since this permits a better appreciation of the gas generator requirements on a system.

The equations are as follows:

(1) Fluid Flow Rates for Heat Exchanger Gas Generators —

(a) O_2 flow rate to O_2 HEX gas generator:

$$\dot{W}_{O1} = \frac{\dot{W}_{OC}(K_1 K_4 - K_1) + \dot{W}_{HC}(-K_1 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

(b) O_2 flow rate to H_2 HEX gas generator:

$$\dot{W}_{O2} = \frac{\dot{W}_{OC}(-K_2 K_3) + \dot{W}_{HC}(K_1 K_3 - K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

(c) H_2 flow rate to O_2 HEX gas generator:

$$\dot{W}_{H1} = \frac{\dot{W}_{OC}(K_2 K_4 - K_2) + \dot{W}_{HC}(-K_2 K_3)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

(d) H_2 flow rate to H_2 HEX gas generator:

$$\dot{W}_{H2} = \frac{\dot{W}_{OC}(-K_2 K_4) + \dot{W}_{HC}(K_1 K_4 - K_4)}{(K_1 + K_4 + K_2 K_3 - K_1 K_4 - 1)}$$

where:

$$K_1 = \left(\frac{H_{CONT} - H_{CIN}}{H_{HIN} - H_{HOUT}}\right)_{02HX} * \left(\frac{MR}{1 + MR}\right)_{02HXGG}$$

$$K_2 = \left(\frac{H_{CONT} - H_{CIN}}{H_{HIN} - H_{HOUT}}\right)_{02HX} * \left(\frac{1}{1 + MR}\right)_{02HXGG}$$

$$K_3 = \left(\frac{H_{CONT} - H_{CIN}}{H_{HIN} - H_{HOUT}}\right)_{H2HX} * \left(\frac{MR}{1 + MR}\right)_{H2HXGG}$$

$$K_4 = \left(\frac{H_{CONT} - H_{CIN}}{H_{HIN} - H_{HOUT}}\right)_{H2HX} * \left(\frac{1}{1 + MR}\right)_{H2HXGG}$$

(2) Fluid Flow Rates for Turbine Gas Generators —

The turbine considered herein is part of a turbopump assembly.

(a) O_2 flow rate to O_2 turbopump gas generator:

$$\dot{W}_{O3} = \frac{\dot{W}_{OC} (K_5 K_8 - K_5) + \dot{W}_{HC} (-K_5 K_7)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

(b) O_2 flow rate to H_2 turbopump gas generator:

$$\dot{W}_{O4} = \frac{\dot{W}_{OC} (-K_6 K_7) + \dot{W}_{HC} (K_5 K_1 - K_1)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

(c) H_2 flow rate to O_2 turbopump gas generator:

$$\dot{W}_{H3} = \frac{\dot{W}_{OC} (K_6 K_8 - K_6) + \dot{W}_{HC} (-K_6 K_7)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

(d) H_2 flow rate to H_2 turbopump gas generator:

$$\dot{W}_{H4} = \frac{\dot{W}_{OC} (-K_6 K_8) + \dot{W}_{HC} (K_5 K_8 - K_8)}{(K_5 + K_8 + K_6 K_7 - K_5 K_8 - 1)}$$

where

$$K_5 = \left[\frac{0.185 * \Delta P_{EST}}{\rho_{LO2} * \eta P * \eta T * (H_{TIN} - H_{TOUT})}\right]_{02TP} * \left(\frac{MR}{1 + MR}\right)_{02TPGG}$$

$$K_6 == \left[\frac{0.185 * \Delta P_{EST}}{\rho_{LO2} * \eta P * \eta T * (H_{TIN} - H_{TOUT})}\right]_{02TP} * \left(\frac{1}{1 + MR}\right)_{02TPGG}$$

$$K_7 = \left[\frac{0.185 * \Delta P_{EST}}{\rho_{LH2} * \eta P * \eta T * (H_{TIN} - H_{TOUT})}\right]_{H2TP} * \left(\frac{MR}{1 + MR}\right)_{H2TPGG}$$

$$K_8 = \left[\frac{0.185 * \Delta P_{EST}}{\rho_{LH_2} * \eta P * \eta T * (H_{TIN} - H_{TOUT})}\right]_{H2TP} * \left(\frac{1}{1 + MR}\right)_{H2TPGG}$$

(3) Combined Flow Rate to Heat Exchanger Gas Generators –

Oxidizer:

$$WDHXT0 = \dot{W}_{O1} + \dot{W}_{O2}$$

Fuel:

$$WDHXTF = \dot{W}_{H1} + \dot{W}_{H2}$$

(4) Combined Flow Rate to Turbopump Gas Generators —

Oxidizer:

$$WDTPT0 = \dot{W}_{O3} + \dot{W}_{O4}$$

Fuel:

$$WDTPTF = \dot{W}_{H3} + \dot{W}_{H4}$$

(5) Total Flow Rates, Consumer Plus All Gas Generators —

Oxidizer:

$$WD0TT(1) = WD0TI(1) + WDHXT0 + WDTPT0$$

Fuel:

$$WD0TT(2) = WD0TI(2) + WDHXTF + WDTPTF$$

MATH MODEL FOR SUBROUTINE FUELCL

PURPOSE OF SUBROUTINE

To provide an integrated subprogram package which permits the computation of basic fuel cell reactant supply system parameters for dynamic and parametric system analysis. The analytical capability of the subprogram package is to include system sizing and weight generation techniques for the system components, as well as the capability for computing the dynamic energy-requirement history associated with reactant storage and utilization.

SUBPROGRAMS AND SYMBOLS REFERENCED IN MATH MODEL

Subroutines, functions and data look-up table numbers are referenced with the using equations and procedures contained in this math model. The asterisk (*) implies quantity multiplication and parentheses () serve to group a set of mathematical manipulations.

PROCEDURE AND MODEL

1. Input Required for Fuel Cell Duty Cycle

DCYCLE (I) - Time Duration of Each Constant-Power Time Interval (Hrs.)
DCYCLE (I +1) - Time Duration of Each Non-operating Time Interval (Hrs.)
NE0P (I) - Number of Units Operating Each Time Interval
PKW (I) - Power Level of Each Operating Unit - Each Interval (KW)

2. Input Required for Fuel Cell System Characterization

MRFC - Mixture Ratio (0/F) for Fuel Cell(s)
SRCFC - Specific Reactant Consumption for Fuel Cell Under Consideration
QDTFC - Nominal Heat Rejection Rate for Fuel Cell (BTU/KW-HR @ Rated Power)
SPWTFC - Specific Weight for Fuel Cell (LBS/KW @ Rated Power)
TFCNOM - Fuel Cell Nominal Temperature - Each Fluid (°R)
TF21IN - F21 Temperature Available to System (°R)
TF210U - F21 Temperature Leaving System (°R)
TF0FC - Final 02 Tank Temperature (°R)
TFHFC - Final H2 Tank Temperature (°R)

PFØFC - Final Ø2 Tank Pressure (PSIA)

PFHFC - Final H2 Tank Pressure (PSIA)

RHØFIL - Fill Density - Each Fluid (LB/CU FT)

WØVENT - Estimated Ø2 Vented (LBS)

WHVENT - Estimated H2 Vented (LBS)

DELTCP - Tank Circulating Pump Delta-P (PSI)

TENV - Fuel Cell System Environment Temperature (^{o}R)

PRFCØP - Fuel Cell Operating Pressure (PSIA)

PØWNØM - Fuel Cell Nominal Operating Power (KW)

NFCØP - Number of Fuel Cells Operating

NFCSTB - Number of Fuel Cells on Standby

PLSETI - Ø2 - Tank Lower Pressure Limit (PSIA)

PLSET2 - H2 - Tank Lower Pressure Limit (PSIA)

VJANUL - Reactant Tank Vacuum Jacket Annulus - Each Tank (IN_1)

TKMXDI - Reactant Tank Pressure Vessel Maximum Diameter - Each Tank (IN_1)

FCVØLT - Fuel Cell Average Voltage Level (Volts)

PRGRAT - Fuel Cell Purge Gas Flow Rate - Each Reactant (LBS/HR)

PRGTIM - Fuel Cell Purge Time - Each Purge - Each Gas (HRS)

PRGINT - Fuel Cell Purge Interval (Ampere Hours)

3. <u>Computer Total Power Supplied for Mission</u>

$$P\O WT\O T = \sum_{i=1}^{(n,\ 2)} (PKW_i)\ (DCYCLE_i)$$

4. <u>Compute Reactant Required for Power and Reactant Flow Rates</u>

<u>Each Interval</u>: (LBS)

$$WRP_i = PKW_i \times DCYCLE_i \times NFC\O P$$

<u>Total Reactant</u>: (LBS)

$$WRF\O RP = \sum_{i=1}^{n} WRP_i$$

Oxygen for Power: (LBS-Total)

$$\text{WØCØNS} = \text{WRFORP} * \left(\frac{\text{MRFC}}{\text{MRFC} + 1}\right)$$

Hydrogen for Power: (LBS - Total)

$$\text{WHCØNS} = \text{WRFØRP} * \left(\frac{1}{1 + \text{MRFC}}\right)$$

Ø2 Each Interval: (LBS)

$$\text{WØRFP}_i = \text{WRP}_i * \left(\frac{\text{MRFC}}{\text{MRFC} + 1}\right)$$

H_2 Each Interval: (LBS)

$$\text{WHRFP}_i = \text{WRP}_i * \left(\frac{1}{1 + \text{MRFC}}\right)$$

O2 and H2 Flow Rates - Each Interval: (LBS/HR)

$$\text{WDTFCØ}_i = \text{PKW}_i * \text{SRCFC} * \left(\frac{\text{MRFC}}{\text{MRFC} + 1}\right)$$

$$\text{WDTFCH}_i = \text{PKW}_i * \text{SRCFC} * \left(\frac{1}{1 + \text{MRFC}}\right)$$

Maximum Ø2 and H2 Flow Rates: (LBS/HR)

$$\text{WDUTMX (Ø2)} = \text{SRCFC} * \text{PKW}_{\text{MAX}} * \left(\frac{\text{MRFC}}{\text{MRFC} + 1}\right)$$

$$\text{WDØTMX (H2)} = \text{SRCFC} * \text{PKW}_{\text{MAX}} * \left(\frac{1}{1 + \text{MRFC}}\right)$$

5. Determine Average Heat of F21 Hot Fluid

$$\text{TMF21} = \frac{\text{TF21IN} + \text{TF21OU}}{2}$$

$C_p\text{F21}_{avg}$ = f(TMF21) (See Function CSPF21)

QF21 = C_pF21 (TF21IN - TF21ØU) (BTU/LB)

6. Compute Total Heat Rejected by Fuel Cell and Heat Rejected for Each Operating Interval.

QAVAIL_i = QDTFC (PKW_i) (DCYCLE_i) (NEØP_i)

$$\text{QFCTØT} = \sum_{i=1}^{n} \text{QAVAIL}_i \qquad \text{(BTU)}$$

Hot Fluid Flow Rate - Each Interval

$$\text{WDTF21}_i = \frac{\text{QAVAIL}_i}{\text{QF21}} \qquad \text{(LBS/HR)}$$

7. Determine Reactant Tank Conditions - Initial and for Each Duty Cycle Interval

Enthalpy of Fluids Feeding Fuel Cell

HFLØ = f (PCØFC, TFCNØM (1)) (See Function QXENTH)

HFCH = f (PCHFC, TFCNØM (2)) (See Function HYENTH)

Initial Tank Temperatures

TEMPØ2 = f (PCØFC, RHØFIL (1)) (See Data Table -5)

TEMPH2 = f (PCHFC, RHØFIL (2)) (See Data Table -6)

Initial C_V Values In Fluid Tanks

CISBVØ = f (TEMPØ2, PCØFC, Fluid))

CISBVH = f (TEMPH2, PCHFC, Fluid))- See Function CSUBV

COMPUTE COMPRESSIBILITY OF Ø2 AND H2 AT FINAL CONDITIONS

ZFØ = f (TFØFC, PFØFC, Fluid) (See Function ZGET)

ZFH = f (TFHFC, PFHFC, Fluid) (See Subroutine ZFIND)

QUANTITY AND PERCENT OF USABLE REACTANTS WITHDRAWN UP TO EACH INTERVAL IN THE MISSION - FOR ALL INTERVALS

(For i = 1 to i = n)

$$\text{TKØ2WD}_i = \left((\text{WDTFCØ}_i * \text{DCYCLE}_i) + \text{TKØWD}_{i-1} \right)$$

$$\text{TKH2WD}_i = \left((\text{WDTFCH}_i * \text{DCYCLE}_i) + \text{TKH2WD}_{i-1} \right)$$

PERCENT WITHDRAWN INCLUDING ESTIMATED 20% RESOURCE REACTANT

$$\text{PCWDØ2} = \frac{\text{TKØ2WD}_i}{(\text{WØCØNS} + 0.2 * \text{WØCØNS})}$$

$$\text{PCWDH2} = \frac{\text{TKH2WD}_i}{(\text{WHCØNS} + 0.2 * \text{WHCØNS})}$$

COMPUTE DENSITY OF FLUIDS AS FUNCTION OF PERCENT FLUID WITHDRAWN

First Compute Density Modifiers:

$$\text{C1} = \left(\frac{144.0}{\text{RHØFIL(1)}}\right) * \left(\frac{1544.2546}{31.9988}\right)$$

$$\text{C2} = \left(\frac{144.0}{\text{RHØFIL(2)}}\right) * \left(\frac{1544.2546}{2.01594}\right)$$

$$\text{C3} = 1.0 - \left(\frac{\text{C1*PFØFC}}{\text{ZFØ*TFØFC}}\right)$$

$$\text{C4} = 1.0 - \left(\frac{\text{C2*PFHFC}}{\text{ZFH*TFHFC}}\right)$$

Then Compute Density as f (PCWD):

$$\text{RHØT2}_i = \text{RHØFIL(1)*(1.0-(PCWDØ2}_i\text{*C3))}$$

$$\text{RHØT2}_i = \text{RHØFIL(2)*(1.0-(PCWDH2}_i\text{*C4))}$$

REACTANT FLUID TEMPERATURES FOR EACH INTERVAL

$\mathrm{TK0}_i = f\ (\mathrm{PC0FC},\ \mathrm{RH0T02})$ (See Data Table - 5)
$\mathrm{TKH}_i = f\ (\mathrm{PCHFC},\ \mathrm{RH0TH2})$ (See Data Table - 6)

REACTANT FLUID SPECIFIC HEAT INPUT (THETA) EACH INTERVAL

$\mathrm{DQDW0}_i = f\ (\mathrm{TK0}_i,\ \mathrm{RH0T02}_i)$ (See Subroutine PHTH0N)

$\mathrm{DQDWH}_i = f\ (\mathrm{PCHFC},\ \mathrm{RH0TH2}_i)$ (See Data Table - 4)

REACTANT FLUID ENERGY DERIVATIVE (PHI) FOR EACH INTERVAL

$\mathrm{PHIF02}_i = f\ (\mathrm{TK0}_i,\ \mathrm{RH0T02}_i)$ (See Subroutine PHTH0N)

$\mathrm{PHIFH2}_i = f\ (\mathrm{PCHFC},\ \mathrm{RH0TH2}_i)$ (See Data Table - 18)

8. SIZE REACTANT FLUID TANK HEAT REQUIREMENTS - FOR EACH DUTY CYCLE INTERVAL

$\mathrm{Q20DTR}_i = \mathrm{WDTFC0}_i * \mathrm{DQDW0}_i$

$\mathrm{Q2HDTR}_i = \mathrm{WDTFCH}_i * \mathrm{DQDWH}_i$

$$\mathrm{WDT2F0}_i = \frac{\mathrm{Q20DTR}_i}{\mathrm{QF21}}$$

$$\mathrm{WDT2FH}_i = \frac{\mathrm{Q2HDTR}_i}{\mathrm{QF21}}$$

9. SIZE REACTANT FLUID CONDITIONING HEAT EXCHANGERS - FOR EACH DUTY CYCLE INTERVAL

ENTHALPY OF FLUIDS LEAVING TANKS:

$\mathrm{HTH0}_i = f\ (\mathrm{PC0FC},\ \mathrm{TK0i})$ (See Function 0XENTH)

$\mathrm{HTKH}_i = f\ (\mathrm{PCHFC},\ \mathrm{TKH}_i)$ (See Function HYENTH)

HEAT REQUIRED TO CONDITION FLUIDS:

$$\mathrm{Q10DTR}_i = \mathrm{WDTFC0}_i * (\mathrm{HFC0} - \mathrm{HTK0}_i)$$

$$\mathrm{Q1HDTR}_i = \mathrm{WDTFCH}_i * (\mathrm{HFCH} - \mathrm{HTKH}_i)$$

$$\mathrm{WDT1F0}_i = \frac{\mathrm{Q10DTR}_i}{\mathrm{QF21}}$$

$$\mathrm{WDT1FH}_i = \frac{\mathrm{Q1HDTR}_i}{\mathrm{QF21}}$$

10. CHECK TO SEE IF ADEQUATE SUPPLY OF FUEL CELL REJECT HEAT IS AVAILABLE FOR ALL DUTY CYCLE INTERVALS

$$\mathrm{QSUMR}_i = \mathrm{Q10DTR}_i + \mathrm{Q1HDTR}_i + \mathrm{Q20DTR}_i + \mathrm{Q2HDTR}_i$$

$$\mathrm{QT0TR} = \sum_{i=1}^{n} \mathrm{QSUMR}_i$$

$$\mathrm{DQNET}_i = \mathrm{QAVAIL}_i - \mathrm{QSUMR}_i$$

$$\mathrm{QEXCES} = \mathrm{QFCT0T} - \mathrm{QT0TR}$$

11. FIND MAXIMUM REQUIRED HOT FLUID FLOW RATE:

$\mathrm{WF21MX} = f\,(\mathrm{WDT1F0}_i, \mathrm{WDTIFH}_i, \mathrm{WDT2F0}_i, \mathrm{WDT2FH}_i)$ (See Function AMAXI)

12. COMPUTE WEIGHT OF REACTANT FLUID TANK HEATER CIRCULATING COMPRESSOR

FIRST COMPUTE MAX. HEAT FLOW REQUIRED INTO TANKS

$$\left.\begin{array}{lcl} \mathrm{QMXTK0} & = & \mathrm{AMAXI}\,(\mathrm{AMXTK0}, \mathrm{Q20DTR}_i) \\ \mathrm{QMXTKH} & = & \mathrm{AMAXI}\,(\mathrm{QMXTKH}, \mathrm{Q2HDTR}_i) \\ \mathrm{TK0MAX} & = & \mathrm{AMAXI}\,(\mathrm{TK0MAX}, \mathrm{TK0}_i) \\ \mathrm{TKHMAX} & = & \mathrm{AMAXI}\,(\mathrm{TKHMAX}, \mathrm{TKH}_i) \end{array}\right]_{i=1}^{i=n}$$

where: Initial value of all max. variables is zero and n is number of duty cycle intervals. (See Function AMAXI).

COMPUTE RH$_o$ AND C$_p$ AT FINAL TANK TEMPERATURE AND PRESSURE

Ø2: RHØFIN (1) = f (TKØMAX, PFOFC, Fluid) See Subroutine DENSØN
CDFØ = f (TKØMAX, PFØFC, Fluid) See Subroutine CSUBP

H2: RHØFIN(2) = f (TKHMAX, PFHFC, Fluid) See Subroutine GSDNST
CPFH = f (TKHMAX,PFHFC, Fluid) See Subroutine CSUBP

COMPUTE CIRCULATING COMPRESSOR FLOW RATE FOR TANKS:

$$\text{WDTCFØ} = \frac{\text{QMXTKO}}{\text{CPFØ*(TF21IN-100.-TKØMAX)}}$$

$$\text{WDTCFH} = \frac{\text{QMXTKH}}{\text{CPFH*(TF21IN-125.-TKHMAX)}}$$

COMPUTE CIRCULATING COMPRESSOR WEIGHT

ASSUMPTIONS: Compressor weight is 2 lb/HP
Compressor efficiency is 60%
Compressor pressure rise is input.
Tank is near final conditions.

$$\text{WØCMP} = \text{WDTCFØ*} \frac{\text{DELPCP*144.0*2.0}}{\text{RHOFIN(1)*33000} \times 0.6}$$

$$\text{WØCMP} = \frac{\text{WDTCFØ*0.01455*DELPCP}}{\text{RHØFIN(1)}}$$

$$\text{WHCMP} = \frac{\text{WDTCFH*0.01455} \times \text{DELCP}}{\text{RHØFIN(2)}}$$

13. COMPUTE RESERVE REACTANT QUANTITY - EACH REACTANT

FIND MISSION EXTRAPOLATED MAX. POWER VALUE:

$$\text{PØWMAX} = \text{PKWMAX*NFCØP*} \sum_{i=1}^{n} \text{DCYCLE}_i$$

FIND TOTAL RESERVE AND RESERVE REACTANT BY SPECI

Set pressure at 11.5% of mission extrapolated max. power reactant requirement. Change value when defined specific mission

$$\text{WRRSRV} = \text{SRCFC*PØWMAX*}\ 0.115$$

$$\text{WØRSRV} = \text{WRRSRV*}\left(\frac{\text{MRFC}}{\text{MRFC} + 1.0}\right)$$

$$\text{WHRSRV} = \text{WRRSRV} * \left(\frac{1}{1.0 + \text{MRFC}}\right)$$

14. COMPUTE WEIGHT OF RESIDUAL REACTANTS

FOR Ø2:

$$\text{WTRES}(1) = \frac{\text{RHØFIN}(1)}{\text{RHØFIL}(1)} * \left[\frac{1.0}{1.0\ \frac{\text{RHØFIN}(1)}{\text{RHØRIL}(1)}}\right] * (\text{WØCØNS} + \text{WØRSRV} + \text{WØVENT})$$

For H2:

$$\text{WTRES}(2) = \frac{\text{RHØFIN}(2)}{\text{RHØFIL}(2)} * \left[\frac{1.0}{1.0\ \frac{\text{RHØFIN}(2)}{\text{RHØFIL}(2)}}\right] * (\text{WHCØNS} + \text{WHRSRV} + \text{WMVENT})$$

15. COMPUTER WEIGHT OF PURGE REACTANTS REQUIRED

$$\text{AMPHRS} = \frac{\text{PØWTØT} * 1000.0}{\text{FCVØLT}}$$

For Ø2:

$$\text{PURGAS}(1) = \text{PRGRAT}(1) * \text{PRG TIM}(1) * \frac{\text{AMPHRS}}{\text{PRGINT}(1)}$$

For H2:

$$\text{PURGAS}(2) = \text{PRGRAT}(2) * \text{PRGTIM}(2) * \frac{\text{AMPHRS}}{\text{PRGINT}(2)}$$

NUMBER OF PURGES REQUIRED:

For Ø2:

$$\text{NPRGE1} = \frac{\text{AMPHRS}}{\text{PRGINT(1)}}$$

For H2:

$$\text{NPRGE 2} = \frac{\text{AMPHRS}}{\text{PRGINT(2)}}$$

16. COMPUTE VOLUME AND SURFACE AREA OF TANKS

For Ø2:

$$\text{VOLTNK(1)} = \frac{(\text{WØCØNS} + \text{WØRSRV} + \text{WØVENT} + \text{WTRES(1)} + \text{PURGAS(1)}\ )}{0.97 * (\text{RHØFIL(1)} - \text{RHØFIN(1)}\ )}$$

$$\text{AREATKI} = 4.84 * (\text{VØLTNK(1)}\ )^{0.66}$$

For H2:

$$\text{VOLTNK(2)} = \frac{(\text{WHCØNS} + \text{WHRSRV} + \text{WHVENT} + \text{WTRES(2)} + \text{PURGAS(2)}\ )}{0.98 * (\text{RHØFIL(2)} - \text{RHØFIN(2)}\ )}$$

$$\text{AREATK2} = 4.84 * (\text{VØLTNK(2)}\ )^{0.66}$$

17. COMPUTE HEAT LEAK INTO REACTANT TANKS FOR EACH NON-OPERATING INTERVAL AND TOTAL

COMPUTE THERMAL CONDUCTIVITY OF INSULATION EACH CYCLE

$$\text{TØCØND}_i = f\ (\text{TENV},\ \text{TKØ}_i,\ \text{SNBAR(1)},\ \text{SITHIK(1,1)},\ \text{SITYPE(1,1)}\ )$$

$$\text{THCØND}_i = f\ (\text{TENV},\ \text{TKH}_i,\ \text{SNBAR(2)},\ \text{SITHIK(2,1)},\ \text{SITYPE(2,1)}\ )$$

(See Subroutine TCØND)

For Ø2:

$$\mathrm{QLK\text{Ø}}_i = \mathrm{T\text{Ø}C\text{Ø}ND}_i * \mathrm{AREATK(1)} * \mathrm{DCYCLE}_{i+1}$$

$$\mathrm{QLEAK\text{Ø}} = \sum_{i=1}^{n} \mathrm{QLK\text{Ø}}_i$$

For H2:

$$\mathrm{QLKH}_i = \mathrm{THC\text{Ø}ND}_i * \mathrm{AREATK(2)} * \mathrm{DCYCLE}_{i+1}$$

$$\mathrm{QLEAKH} = \sum_{i=1}^{n} \mathrm{QLKH}_i$$

18. COMPUTE WEIGHT OF REACTANTS VENTED EACH INTERVAL AND TOTAL VENTED FOR MISSION

Compute C_v:

$$\left.\begin{aligned} \mathrm{CSBV\text{Ø}2}_i &= f\ (\mathrm{TK\text{Ø}}_i,\ \mathrm{PCOFC},\ \mathrm{Fluid}) \\ \mathrm{CSBVH2}_i &= f\ (\mathrm{TKH}_i,\ \mathrm{PCHFC},\ \mathrm{Fluid}) \end{aligned}\right] \text{(see function CSUBV)}$$

COMPUTE HEAT REQUIRED TO REACH VENT PRESSURE

$$\mathrm{QRQD\text{Ø}2}_i = \frac{\mathrm{V\text{Ø}LTNK(1)} * \mathrm{CSBV\text{Ø}2}_i}{48.3} * (\mathrm{SVPRES(1,1)} - \mathrm{PC\text{Ø}FC}) * 144.0$$

$$\mathrm{QRQDH2}_i = \frac{\mathrm{V\text{Ø}LTNK(1)} * \mathrm{CSBV\text{Ø}2}_i}{776.5} * (\mathrm{SVPRES\ (2,1)} - \mathrm{PCHFC}) * 144.0$$

TEST TO SEE IF HEAT LEAK IS GREATER THAN QRØDXX:

IF, $\mathrm{QRQD\text{Ø}2}_i > \mathrm{QLK\text{Ø}}_i$; then $\mathrm{WVENT\text{Ø}}_i = 0.0$

IF, $\mathrm{QRQDH2}_i > \mathrm{QLKH}_i$; then $\mathrm{WVENTH} = 0.0$

IF NOT - COMPUTE WEIGHT REACTANT VENTED AND TOTAL VENTED:

For O2:

$$\mathrm{DELQ}_i = \mathrm{QLKØ}_i - \mathrm{QRQDØ2}_i$$

$$\mathrm{WVENTØ}_i = \frac{\mathrm{DELQi}}{(\mathrm{CSBVØ2}_i * \mathrm{TKØ}_i * \left(\frac{\mathrm{SVPRES(1,1)}}{\mathrm{PCØFC}} -1.0 \right)}$$

$$\mathrm{WØVENT}_{\mathrm{TOT}} = \sum_{i=1}^{n} \mathrm{WVENTØ}_i$$

For H2:

$$\mathrm{DELQH}_i = \mathrm{QLKH}_i - \mathrm{QRQDH2}_i$$

$$\mathrm{WVENTH}_i = \frac{\mathrm{DELQH}_i}{\mathrm{CSBVH2}_i * \mathrm{TKH}_i * \left(\frac{\mathrm{SVPRES(2,1)}}{\mathrm{PCHFC}} -1.0 \right)}$$

$$\mathrm{WHVENT}_{\mathrm{TOT}} = \sum_{i=1}^{n} \mathrm{WVENTH}_i$$

19. TOTAL REACTANT LOADED INTO TANKS
(Ø2 = Index 1, H2 = Index 2, PI = π)

WRTØTL (1) = WØCØNS + WØRSRV + WØVENT + WTRES(1) + PURGAS(1)

WRTOTL(2) = WHCØNS + WØRSRV + WHVENT + WTRES(2) + PURGAS(2)

20. SIZE AND WEIGH REACTANT TANK ASSEMBLIES

TANK PRESSURE VESSEL DIAMETERS: (Assume Spheres)

$$DIATK(1) = \left(\frac{6.0}{PI}\right) * \left(\frac{WRT0TL(1)}{RH0FIL(1)}\right)^{0.33} * 12.0$$

$$DIATK(2) = \left(\frac{6.0}{PI}\right) * \left(\frac{WRT0TL(2)}{RH0FIL(2)}\right)^{0.33} * 12.0$$

TANK INSULATION WEIGHT:

$$TIWT(1,1) = \frac{N0P(1,1) * AREATK(1) * RH0I(SITYPE(1,1)) * SITHIK(1,1)}{12.0}$$

$$TIWT(2,1) = \frac{N0P(1,1) * AREATK(2) * RH0I(SITYPE(2,1)) * SITHIK(2,1)}{12.0}$$

DIAMETER OF TANK VACUUM JACKETS:

$$DIAVJ(1) = DIATK(1) + (VJANUL(1) * 2.0)$$

$$DIAVJ(2) = DIATK(2) + (VJANUL(2) * 2.0)$$

WEIGHT OF TANK PRESSURE VESSELS:

FIND $\left(\frac{RH0}{FTU}\right)$ - FOR TANK MATERIAL (SMTYPE(1,1):

$$RH0FTU(1) = f\,(TK0MAX, SMTYPE(1,1))$$

$$RH0FTU(2) = f\,(TKHMAX, SMTYPE(2,1))$$

See Data Tables - Table No. (21 + SMTYPE(-,-))

COMPUTE PRESSURE VESSEL WEIGHT:

$$WTPVT(1) = 7000.0 * \left(\frac{WRT0TL(1)}{RH0FIL(1)}\right) * PCHFC * RH0FTU(1)$$

$$WTPVT(2) = 7000.0 * \left(\frac{WRTOTL(2)}{RH0FIL(2)}\right) * PCHFC * RH0FTU(2)$$

WEIGHT OF TANK VACUUM JACKETS:

Assumes jacket is aluminum honeycomb sandwich material.

Find Spec Weight of Vacuum Jacket Material:

$$\left.\begin{array}{l} \mathrm{SPWT(1)} = f\ (\mathrm{DIAVJ(1)}) \\ \\ \mathrm{SPWT(2)} = f\ (\mathrm{DIAVJ(2)}) \end{array}\right] \quad \text{(See Data Table Number 17)}$$

$$\mathrm{WTVJ(1)} = \mathrm{SPWT(1)} * \mathrm{PI} * (\mathrm{DIAVJ(1)})^2$$
$$\mathrm{WTVJ(2)} = \mathrm{SPWT(2)} * \mathrm{PI} * (\mathrm{DIAVJ(2)})^2$$

TOTAL WEIGHT OF REACTANT TANK ASSEMBLIES:

$$\mathrm{WTT0T(1)} = \mathrm{WTPVT(1)} + \mathrm{WTVJ(1)} + \mathrm{TIWT(1,1)}$$
$$\mathrm{WTT0T(2)} = \mathrm{WTPVT(2)} + \mathrm{WTVJ(2)} + \mathrm{TIWT(2,1)}$$

21. COMPUTE WEIGHT OF FUEL CELLS

$$\mathrm{FCWGT} = \mathrm{PKWMAX} * \mathrm{SPWTFC} * (\mathrm{NFC0P} + \mathrm{NFCSTB})$$

22. COMPUTE WEIGHT OF HEAT EXCHANGERS

FIND MAX. HOT FLUID FLOW RATE:

$$\mathrm{WDTFMX} = f\ \left.(\mathrm{WDTFMX},\ \mathrm{WDTIF0}_i,\ \mathrm{WDTIFH}_i,\ \mathrm{WDT2F0}_i,\ \mathrm{WDT2FH}_i)\right]_{i=1}^{n}$$

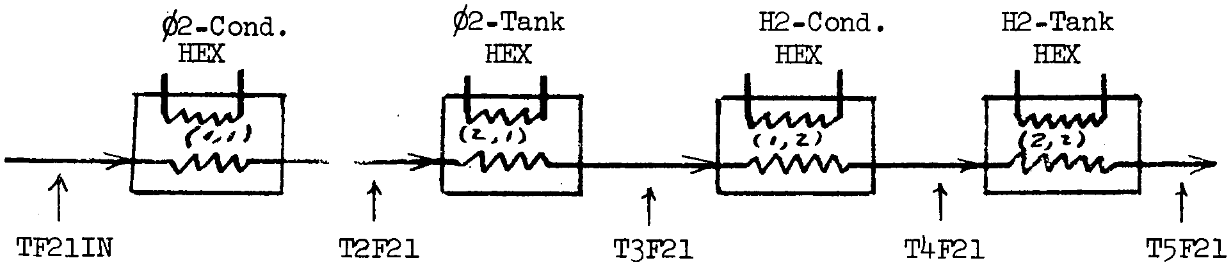
(See Function AMAXI)

FIND MAX. HEAT REQUIRED IN FLUID CONDITIONING HEAT EXCHANGERS:

$$\left.\begin{array}{l} \mathrm{Q10DMX} = f\ (\mathrm{Q10DMX},\ \mathrm{Q10DTR}_i) \\ \mathrm{Q1HDMX} = f\ (\mathrm{Q1HDMX},\ \mathrm{Q1HDTR}_i) \end{array}\right]_{i=1}^{n}$$

(See Function AMAXI)

FIND UNKNOWN TEMPERATURES FOR FUEL CELL SYSTEM SERIES HEAT EXCHANGERS: (max. hot fluid flow condition)



$$\text{T2F21} = \text{TF21IN} - \left(\frac{\text{Q1ØDMX}}{\text{CF21*WDTFX}}\right)$$

$$\text{T3F21} = \text{T2F21} - \left(\frac{\text{QMXTKØ}}{\text{CF21*WDTFMX}}\right)$$

$$\text{T4F21} = \text{T3F21} - \left(\frac{\text{Q1HDMX}}{\text{CF21*WDTFMX}}\right)$$

$$\text{T5F21} = \text{T4F21} - \left(\frac{\text{QMXTKH}}{\text{CF21*WDTFMX}}\right)$$

COMPUTE WEIGHT OF Ø2 AND H2 CONDITIONING HEAT EXCHANGERS:

WHXTØT(1,1) = f (fluid, Q1ØDMX, PCØFC)

WHXTØT(1,2) = f (fluid, Q1HDMX, PCHFC) (See subroutine HEXF21)

COMPUTE WEIGHT OF Ø2 AND H2 TANK HEAT EXCHANGERS:

WHXTØT (2,1) = f (fluid, QMXTKØ, (PCØFC + DELTCP))

WHXTØT (2,2) = f (fluid, QMXTKH, (PCHFC + DELTCP))

(See subroutine HEXF21)

23. COMPUTE TANK ENERGY HISTORY AND HEATER DUTY CYCLE

The tank history portion of the fuel cell subprogram provides the capability for examining the energy history and tank heater duty cycle in subintervals of each major duty cycle interval. For convenience, the major duty cycle is subdivided into ten (10) minute intervals. If the duty cycle is less than ten minutes in length, it is subdivided into one (1) minute intervals. Further, the odd minutes left over beyond full ten minute subintervals, are evaluated on a per minute basis. Fractions of minutes are not considered.

The tank history and heater duty cycle calculations are similar to those performed earlier in the system sizing calculations except for using smaller incremental steps. The calculations are set up to operate in a three (3) level "nested" loop, having two (2) defined nested loops with the thinest loop being an implied loop, controlled by IF statements within the second loop program.

The nemonic symbology is, for most symbols, quite close to those previously used in subsections 1 through 12. Additional nemonics employed are as follows:

Nemonic	Meaning
CTIM	Number of minutes in a given major duty cycle interval
NTP	Integer number of (either 10 minute, or, 1 minute) subintervals being considered in intter loop calculations. Value of NTP is set on the outer loop.
WDTØ30	Weight flow of Ø2 in subinterval, either - lbs/10 min., or lbs/min.
WDTH30	Weight flow of H2 in subinterval, either - lbs/10 min., or lbs/min.
TIME	Cumulative time counting index, adds appropriate time interval for each calculational pass made through inner loop. Increments of 10 min, or 1 min, as defined.
PTIME	Total time index - total current interval plus preceding accumulated TIME. (minutes).
DTIME	Time in current interval remaining to be used in calculations. (minutes)
IK2	Integer value of DTIME - used in the implied third loop for odd minute calculations.
Q1CUM	Summed heat input required (for Ø2 withdrawn from tank) to restore Ø2 tank pressure to operating level
Q2CUM	Summed heat input required (for H2 withdrawn from tank) to restore H2 tank pressureto operating level.
BETAØ	Volume expansivity for Ø2 at temperature and density existing in subinterval
BETAH	Volume expansivity for H2 at temperature and pressure exising in subinterval.
CPØ	Cp of Ø2 at temperature and pressure existing in subinterval.

Nemonic	Meaning
CPH2	Cp of H2 at temperature and pressure existing in subinterval
DELP1	Calculated tank pressure drop due to loss of energy from 02 withdrawn during subinterval
DELP2	Calculated tank pressure drop due to loss of energy from H2 withdrawn during subinterval
PTANK1	02 tank pressure at any subinterval time point
PTANK2	H2 tank pressure at any subinterval time point
QHSF21	Heat available in tank heat exchanger (BTU/MIN)
PLSET1	Lower Pressure limit for 02 TANK HEATER switch
PLSET2	Lower pressure limit for H2 tank heater switch
TIMINC	Number of time subintervals considered in DELP1 or DELP2 calculation
IK2	Integer index used to keep track of odd time (minutes) which must be accounted for in duty cycle subinterval. Is integer value of DTIME when DTIME is less than 10 minutes.

(a) SETUP ARRAY OF TIME VARIABLES FOR EACH OF THE MAJOR OPERATING DUTY CYCLE INTERVALS:

$$TIM_k \Big]_{k=1}^{n} = DCYCLE \Big]_{i=1}^{n,2}$$

(b) SETUP INCREMENTAL ARRAY FOR SUBINTERVALS OF EACH MAJOR DUTY CYCLE WITH BRANCHING TO 10 MINUTE INTERVALS OR 1 MINUTE INTERVALS AS REQUIRED:

$$CTIM = TIM_K * 60.0$$

(1) IF CTIM IS > 10 MINUTES; SETUP OUTER LOOP FOR 10 MINUTE INTERVALS:

$NTP = (TIM_K * 6.0) + 0.6$ (number of subintervals)

$WDT030_i = WDTFC0_K/6.0$ (lbs/10 min)

$WDTH30_i = WDTFCH_K/6.0$ (lbs/10 min)

(2) IF CTIM < 10 MINUTES; SETUP OUTER LOOP FOR 1 MINUTE INTERVALS:

$NTP = CTIM + 0.6$ (number of subintervals)

$WDT030_i = WDTFC0_K/60.0$ (lbs/min)

$WDTH30_i = WDTFCH_K/60.0$ (lbs/min)

NOTE: The value 0.6 is added to the calculation for NTP to insure that the octal representation of (TIM_R x 6.0) or CTIM will yield the next whole integer when converted.

(example: 3.6 converts to integer 3, while
3.6 + 0.6 converts to integer 4)

(c) SETUP TIME COUNTER FOR INNER CALCULATIONAL LOOP: (BE SURE TIME IS SET TO ZERO INITIALLY)

(1) If CTIM > 10 minutes, then,

$$\text{TIME} = \text{TIME} + 10.0$$

(2) If CTIM < 10 minutes, then,

$$\text{TIME} = \text{TIME} + 1.0$$

(d) PROCEED WITH SUBINTERVAL CALCULATIONS:

(1) WGT. REACTANTS WITHDRAWN EACH SUBINTERVAL(i):

$$\text{TKØDP} = \text{TKØDP} + \text{WDTØ30}_i$$

$$\text{TKHDP} = \text{TKHDP} + \text{WDTH30}_i$$

(2) PERCENT REACTANTS WITHDRAWN EACH SUBINTERVAL(i):

$$\text{PCØXW}_i = \frac{\text{TKØDP}}{(\text{WØCØNS} + \text{WORSRV})}$$

$$\text{PCH2W}_i = \frac{\text{TKHDP}}{(\text{WHCØNS} + \text{WHRSRV})}$$

(3) DENSITY OF REACTANTS IN TANK AT SUBINTERVAL(i):

$$\text{ØRHØ}_i = \text{RHØFIL}(1) * \left[1.0 - \text{PCØXW}_i * \left(1.0 - \frac{(0.0425 * \text{PFØFC})}{(\text{ZFØ} * \text{TFØFC})}\right) \right]$$

$$\text{HRHØ}_i = \text{RHØFIL}(2) * \left[1.0 - \text{PHC2W}_i * \left(1.0 - \frac{(0.0427 * \text{PCHFC})}{(\text{ZFH*TFHFC})} \right) \right]$$

(4) TEMPERATURE OF REACTANTS IN TANK AT SUBINTERVAL(i):

$\text{ØXTEM}_i = f\ (\text{PTANK1}_i,\ \text{ØRHØ}_i)$ (Table lookup - Table No. 5)

$\text{H2TEM}_i = f\ (\text{PTANK2}_i,\ \text{HRHØ}_i)$ (Table lookup - Table No. 6)

(5) SPECIFIC HEAT INPUT AND ENERGY DEVIATION OF REACTANTS IN TANK AT INTERVAL(i):

For Ø2:

$\text{DQDM1}_i = f\ (\text{ØTEM}_i,\ \text{ØRHØ}_i,\ \text{Fluid})$, for THETA

$\text{DPDU1}_i = f\ (\text{ØXTEM}_i,\ \text{ØRHØ}_i,\ \text{Fluid})$, for PHI

(See subroutine PHTHØN)

For H2:

$\text{DQDM2}_i = f\ (\text{PTANK2}_i,\ \text{HRHØ}_i)$

(Table Lookup - Table No. 3)

$\text{DPDU2}_i = f\ (\text{PTANK2}_i,\ \text{HRHØ})$

(Table Lookup - Table No. 18)

(6) HEAT REQUIRED TO RESTORE REACTANT TANK PRESSURE TO OPERATING PRESSURE:

For Ø2:

$\text{QDTTK1}_i = \text{WDTØ30}_i * \text{DQDM1}_i$

$\text{Q1CUM} = \text{Q1CUM} + \text{QDTTK1}_i$

For H2:

$\text{QDTTK2}_i = \text{WDTØ30}_i * \text{DQDM2}_i$

$\text{Q2CUM} = \text{Q2CUM} + \text{QDTTK2}_i$

(7) COMPUTE VOLUME EXPANSIVITY OF REACTANTS IN TANK AT INTERVAL(i): (BETA)

$\text{BETAØ}_i = f(\text{ØXTEM}_i, \text{ØRHØ}_i, \text{Fluid})$ (see Subroutine BETAB)

$\text{BETAH}_i = f(\text{PTANK2}_i, \text{H2TEM}_i)$ (Table Lookup - Table No. 46)

(8) COMPUTE SPECIFIC HEAT OF REACTANT FLUIDS IN TANKS AT INTERVAL(i):

$$\left.\begin{array}{l} \text{CPØ}_i = f(\text{ØXTEM}_i, \text{PTANK1}_i, \text{Fluid}) \\ \text{CPH}_i = f(\text{H2TEM}_i, \text{PTANK2}_i, \text{Fluid}) \end{array}\right\}$$

(See Subroutine CSUBP)

(9) COMPUTE REACTANT TANK PRESSURE DROP DUE TO REACTANT WITHDRAWN: (Do for Each Interval with TIMINC = 1.0)

For Ø2:

$$\text{DELP1}_i = 1.0 * \left(\frac{\text{DPDU1}_i}{\text{VØLTNK(1)}}\right) * \left(\frac{-\text{CPØ}_i}{\text{BETAØ}_i}\right) * \text{WDTØ30}_i$$

For H2:

$$\text{DELP2}_i = 1.0 * \left(\frac{\text{DPDU2}_i}{\text{VØTNK(2)}}\right) * \left(\frac{-\text{CPH2}_i}{\text{BETAH}_i}\right) * \text{WDTH30}_i$$

(10) ADJUST REACTANT TANK PRESSURES:

$\text{PTANK1}_i = \text{PTANK1}_i + \text{DELP1}_i$

$\text{PTANK2}_i = \text{PTANK2}_i + \text{DELP2}_i$

(11) COMPUTE ESTIMATED HEAT AVAILABLE TO HEAT FLUID IN REACTANT TANK AT ANY TIME IN SUBINTERVAL:

$$\text{QHSF21} = \left(\frac{\text{QDTFC} * \text{PKW}_K * \text{NEØP}_K}{60.0}\right) * 0.75$$

(BTU/MIN)

(12) TEST TO SEE IF REACTANT TANK PRESSURE HAS DROPPED BELOW LOWER PRESSURE LIMIT SET POINT:

For Ø2:

If, $\text{PTANK1}_i < \text{PLSETI}$:

(a) Calculate number of minutes heating circuit is ØN to add required heat to tank:

$$\text{HTRØNI} = \frac{\text{Q1CUM}}{\text{QHSF21}} \quad ; \quad \frac{\text{(BTU-Req'd)}}{\text{(BTU/Min-Avail)}}$$

(b) Set heater cycle counter -

$$\text{ICHT0} = \text{ICHT0} + 1$$

IF $\text{PTANK1}_i > \text{PLSETI}$: Skip (a) and (b)

For H2:

If $\text{PTANK2}_i < \text{PLSET2}$:

(c) $\text{HTR0N2} = \dfrac{\text{Q2CUM}}{\text{QHSF21}}$

(d) $\text{ICHTH} = \text{ICHTH} + 1$

If, $\text{PTANK2}_i > \text{PLSET2}$: Skip (c) and (d).

(13) <u>OUTPUT CALCULATED VALUES AND RESET VARIABLES WHERE REQUIRED</u>:

If, $\text{PTANKI}_i < \text{PLSET1}$:

Reset, $\text{HTR0N1} = 0.0$
Reset, $\text{Q1CUM} = 0.0$
Reset, $\text{PTANK1}_i = \text{PC0FC}$

If, $\text{PTANK2}_i < \text{PLSET2}$:

Reset, $\text{HTR0N2} = 0.0$
Reset, $\text{Q2CUM} = 0.0$
Reset, $\text{PTANK2}_i = \text{PCHFC}$

Proceed through loop again for next time subinterval.

(14) Test to see if DTIME is less than 10 minutes, but, greater than 0.0 - to pickup odd minutes in duty cycle sub-interval

If, $\text{DTIME} < 10.0$, and $\text{DTIME} > 0.0$:

Reset - TIME increment, WDT030, WDTH30 and Index for Odd TIME REMAINING, as follows:

$$\text{TIME} = \text{TIME} + 1.0$$

$$\text{WDT030}_i = \frac{\text{WDTFC0}_K}{60.0}$$

$$\text{WDTH30}_i = \frac{\text{WDTFCH}_K}{60.0}$$

$$\text{IK2} = \text{DTIME}_i - 1$$

Return to 23d.(1) and perform calculations 23d.(1) through 23d.(13) until the value of both IK2 and $DTIME_i$ are zero. At which point the calculations return to 23b. for consideration of the next major duty cycle time interval. When all major duty cycle intervals are exhausted the subprogram ends.

MATH MODEL FOR SUBROUTINE GASGEN

PURPOSE OF SUBROUTINE

To provide a procedure for the computation of realistic weights for gas generators. The equations employed were developed by Aerojet Liquid Rocket Company in support of a study for McDonald-Douglas on GO_2/GH_2 gas generators. (Ref: 1.9-3)

PROCEDURE AND MODEL

The data employed are based upon a gas generator using a coaxial flow injector operating at a mixture ratio (O_2/H_2) of approximately 1.1 to produce an exhaust temperature of $2200^{\circ}R$. Flow range was 1.0 lb/sec to 10.0 lb/sec. Chamber pressure ranged from 100 to 500 psia.

The general equation derived in the study presents the gas generator weight (WT_{GG}) as a function of chamber pressure (P_c) and flow rate $(\dot{W})$.

$$WT_{GG} = C + K (\dot{W})$$

where

$$C = 13.824204 - 0.011178226 (P_c) + 1.8632927 \times 10^{-5} (P_c)^2 - 1.108423 \times 10^{-8} (P_c)^3$$

and

$$K = 7.9470262 - 0.035636198 (P_c) + 1.8632927 \times 10^{-5} (P_c)^2 - 3.7946 \times 10^{-8} (P_c)^3$$

The equation is represented as being accurate over the range of mixture ratios of 0.7 to 1.25.

MATH MODEL FOR SUBROUTINE HEATEX

PURPOSE OF SUBROUTINE

The mathematical model for the heat exchanger subroutine is essentially a heat exchanger design model in that given certain input parameters which define the performance of the devices, the model will seek to generate an exchanger that fits the input parameters. The model provides a rapid and reasonably accurate means of determining the weight and hot fluid requirements of heat exchangers which use the combustion products of hydrogen and oxygen to condition the cryogenic hydrogen and oxygen working fluids.

PROCEDURE AND MODEL

The model employed is based upon AiResearch Report No. 71-7505-10, "Heat Exchanger Parametric Data," dated August 31, 1971. The data and procedures contained in this report were reformatted and modified, as required, to permit the construction of a model which could be programmed for a computer. The procedure employed is iterative in nature with respect to establishing the heat exchanger design point. The scaling parameters which produce the heat exchanger sub-unit, and unit, weights are said to reflect the AiResearch experience in realistic heat exchanger weights for specific design points.

A general flow chart of the Heat Exchanger analysis procedure is given in Figure HEATEX-1.

1. DEFINE SYSTEM INTERFACE WITH HEAT EXCHANGER

The following parameters are defined prior to attempting to determine the weight of the heat exchanger:

$\dot{\omega}_c$	cold fluid flow rate
T_c in	cold fluid inlet temperature
P_c, in	cold fluid inlet pressure
T_c, out	cold fluid outlet temperature

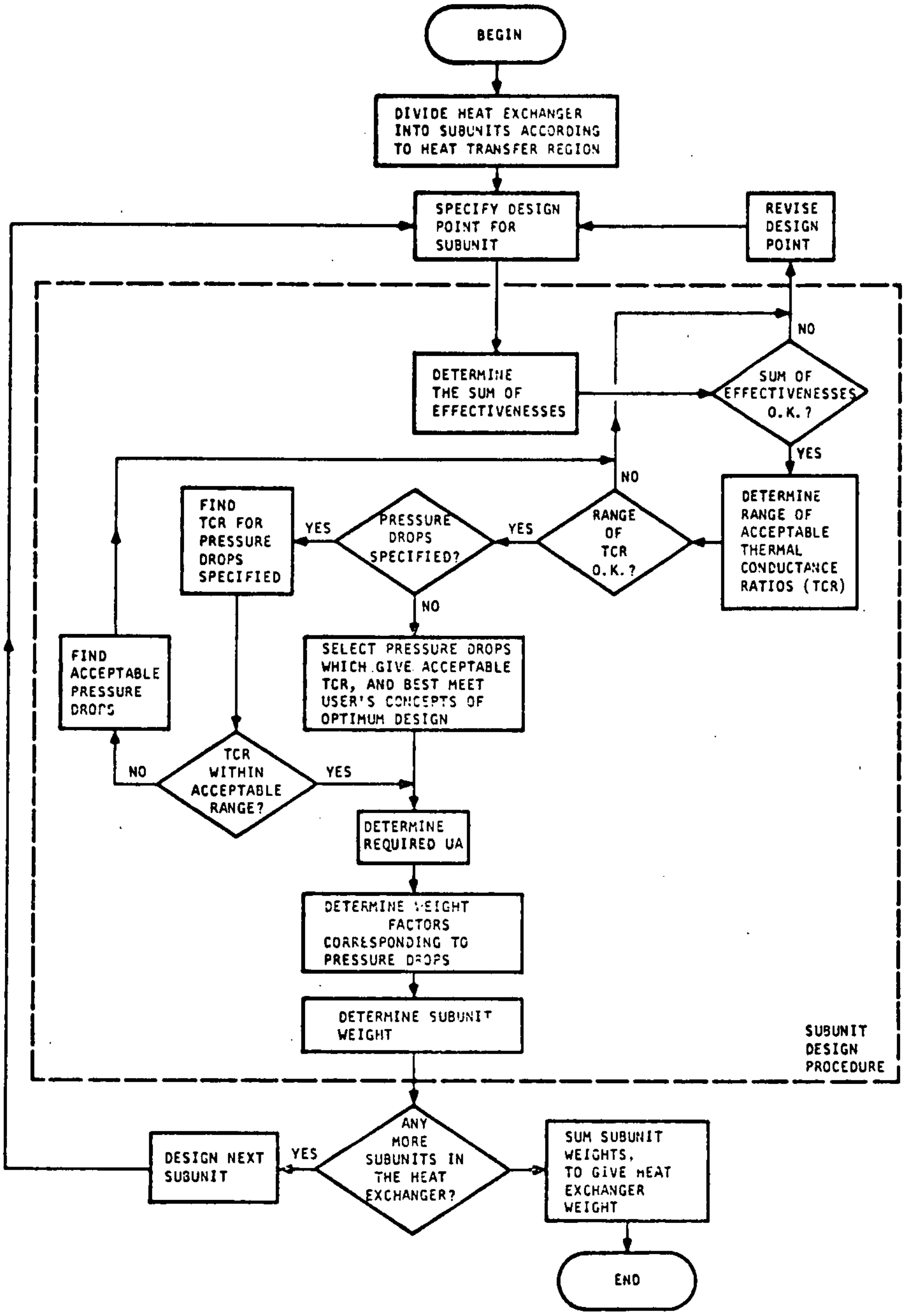


FIGURE HEATEX-1 OUTLINE OF METHOD USED FOR DETERMINING WEIGHT OF HEAT EXCHANGERS.

P_c, out	cold fluid outlet pressure (optional- can be calculated)
$\dot{\omega}_H$	hot fluid flow rate (optional - can be calculated)
T_H, in	hot fluid inlet temperature
P_H, in	hot fluid inlet pressure
T_H, out	hot fluid outlet temperature
P_H, out	hot fluid outlet pressure (optional – can be calculated)
ØF	gas generator oxidizer to fuel ratio (optional - can be calculated)

2. AIRESEARCH (AR) DATA MODIFICATIONS

(a) The AR Thermal Conductance Ratio (TCR) data curves are replaced by equations which characterize the curves.

(b) Heat exchanger volume calculations are not to be included in the model, as a means of subroutine size and complexity.

(c) The AR-W/UA curves are replaced by equations which characterize each applicable set of curves.

3. COMBUSTION PRODUCTS DATA:

Input table of combustion products of hydrogen and oxygen, in the form of C_p versus temperature for a family of OF ratios.

4. TO CALCULATE ØF RATIO:

If W_h is input but ØF is not, find ØF:

$$i_h = \frac{W_c}{W_h} (\Delta i_c)$$

$$i_c = (\text{Enthalpy})_{C_{out}} - (\text{Enthalpy})_{C_{in}}$$

Enthalpy of "C" fluid is found from the tables of thermodynamic properties of the cold fluid, (Hydrogen or Oxygen, as applicable), corresponding to the respective outlet and inlet pressures and temperatures. If $P_{C_{out}}$ is not specified, let $P_{C_{out}} = P_{C_{in}}$.

$$\bar{C}_{P_h} = \frac{\Delta i_h}{\Delta T_h}$$

$$\Delta T_h = T_{h_{in}} - T_{h_{out}}$$

From table of combustion products of hydrogen and oxygen, find ØF corresponding to $\bar{C}_{P_h}$ and $\frac{T_{h_{out}} + T_{h_{in}}}{2}$.

5. TO CALCULATE $\dot{W}_H$:

If ØF is input but W_h is not, find W_h:

From Table of combustion products of hydrogen and oxygen, find $\bar{C}_{P_h}$ corresponding to ØF and $\frac{T_{h_{out}} + T_{h_{in}}}{2}$.

$$\Delta i_h = \bar{C}_{P_h} \quad T_h$$

$$W_h = W_c \left(\frac{\Delta i_c}{\Delta i_h}\right)$$

Δi_c is found as in operation (4) above.

6. SET VALUE OR LIMIT FOR $T_{H_{in}}$:

Check to assure that $T_{H_{in}} \leq 3500°R$. If not, set $T_{H_{in}} = 3500°R$.

7. SET VALUE OR LIMIT FOR $T_{H_{out}}$:

Check to be sure that $T_{H_{out}} \geq T_{sat} + 30°R$

$$P_{sat} = 0.126 \, P_{tot}(ØF)$$

If $P_{H_{out}}$ is specified, use $P_{tot} = P_{H_{out}}$

If $P_{H_{out}}$ is not specified, use $P_{tot} = 0.6 \, P_{H_{in}}$

Find T_{sat} corresponding to P_{sat} from table of thermodynamic properaties of steam, for saturated vapor.

Check for $T_{H_{out}} = \geq T_{sat} + 30^\circ$. If so, go to operation 8.

If $T_{H_{out}} < T_{sat} + 30^\circ$, either $T_{H_{out}}$ must be raised or $P_{H_{out}}$ must be raised. If $T_{H_{out}}$ may be raised, set $T_{H_{out}} = T_{sat} + 30^\circ$.

If $T_{H_{out}}$ may not be raised and $P_{H_{out}}$ is specified, then $P_{H_{out}}$ must be raised. From the Steam Tables, find a value of P_{tot} for which $T_{H_{out}} = T_{sat} + 30^\circ$. Call it P_{totR}.

Then the revised value of $P_{H_{out}}$ must be,

$$P_{H_{outR}} = P_{H_{out}} \left(\frac{P_{sat_R}}{P_{sat}}\right)$$

If $T_{H_{out}}$ may not be raised and $P_{H_{out}}$ was not specified, it now becomes specified, as, $P_{H_{out_R}} = 0.6\ P_{H_{in}} \left(\frac{P_{sat_R}}{P_{sat}}\right)$.

8. SET VALUE OR LIMIT FOR T_c OUT:

Check to assure that $T_{C_{out}} \leq 1800^\circ R$. If not, set $T_{C_{out}} = 1800^\circ R$.

9. FIND SUM OF EFFECTIVENESSES:

$$\sum \epsilon = \epsilon_H + \epsilon_C = \frac{T_{H_{in}} - T_{H_{out}} + T_{C_{out}} - T_{C_{in}}}{T_{H_{in}} - T_{C_{in}}}$$

If $\sum \epsilon < 0.5$, set $T_{H_{out}} = T_{sat} + 30^\circ$ and recheck $\sum \epsilon$

If $\sum \epsilon < 0.5$, when $T_{H_{out}} = T_{sat} + 30°$, increase $T_{c_{out}}$ until $\sum \epsilon = 0.5$. Call the new value $T_{C_{out_R}}$ and solve for revised flow rate of cold fluid through the heat exchanger, W_{C_R}, as follows:

$$W_{C_R} = W_C \left(\frac{T_{C_{out}} - T_{C_{in}}}{T_{C_{out_R}} - T_{C_{in}}} \right)$$

The balance of the original W_C will bypass the heat exchanger.

10. CHECK FOR ACCEPTABLE PRESSURE DROP (IF SPECIFIED):

Is $P_H \leq 0.4 \, P_{H_{in}}$; if not, set $P_H = 0.4 \, P_{H_{in}}$

Is $P_C \leq 0.2 \, P_{C_{in}}$; if not, set $P_C = 0.2 \, P_{C_{in}}$

Note that $P_H = P_{H_{in}} - P_{H_{out}}$; $P_C = P_{C_{in}} - P_{C_{out}}$

11. IDENTIFY REVISED HEAT EXCHANGER REQUIREMENTS:

W_c , as specified in operation 2 or modified in operation 9.

$T_{C_{in}}$, as specified in operation 2

$T_{C_{out}}$, as specified in operation 2 or modified in Operation 9.

$P_{C_{in}}$, as specified in operation 10 **Cold Fluid Type**

W_H, if specified, or as found by operation 5.

$T_{H_{in}}$, as specified in operation 2, or as modified in operation 6.

$T_{H_{out}}$, as specified, or as modified by operation 7

$P_{H_{in}}$, as specified in Operation 2.

$P_{H_{out}}$, if specified,or as modified by operations 7 or 10.

ØF, if specified,or as found by operation 4.

12. SUBDIVIDE HEAT EXCHANGER ACCORDING TO HEAT TRANSFER REGIONS:

(Note that Super-critical and boiling regions will not coexist in one HX)

(a) Find $\epsilon = \dfrac{C_c\,(T_{C_{out}} - T_{C_{in}})}{C_{min}\,(T_{H_{in}} - T_{C_{in}})}$, or $\epsilon = \dfrac{C_H\,(T_{H_{in}} - T_{H_{out}})}{C_{min}\,(T_{H_{in}} - T_{C_{in}})}$

$$\left.\begin{aligned} C_c &= (W\,\overline{C}_p)_c\ (3600) \\ C_H &= (W\,\overline{C}_p)_h\ (3600) \end{aligned}\right\}\quad C_{min} = \mathrm{MIN}\,(C_c,\ C_h)$$

$\overline{C}_{p_h}$ found from $\dfrac{\Delta i_h}{\Delta T_h}$; $\overline{C}_{p_c}$ found from $\dfrac{\Delta i_c}{\Delta T_c}$

(b) If the cold fluid is hydrogen:

(1) Is $200 \leqslant P_{C_{in}} \leqslant 2000$

Is $35 \leqslant T_{C_{in}} < 90$

Is $T_{C_{out}} \leqslant 90$

If all "yes", the HX has a supercritical subunit only.

(2) Is $200 \leq P_{C_{in}} \leq 2000$

Is $35 \leq T_{C_{in}} < 90$

Is $\sum \epsilon \leq 0.91$

If all "yes", the HX has a supercritical submit and a gas parallel-flow subunit only.

(3) Is $200 \leq P_{C_{in}} \leq 2000$

Is $35 \leq T_{C_{in}} < 90$

Is $T_{C_{out}} > 500$

Is $\epsilon < 0.9$

If all "yes," the HX has a supercritical subunit, a gas parallel-flow subunit, and a gas counter-flow subunit.

(4) Is $10 \leq P_{C_{in}} \leq 180$

Is $35 \leq T_{C_{in}} < T_{C_{sat}}$

Is $T_{C_{out}} \leq T_{C_{sat}}$

If all "yes" the HX has a boiling subunit only.

Find $T_{C_{sat}}$ corresponding to $P_{C_{out}}$ from table of thermodynamic properties of hydrogen, for saturated vapor. If $P_{C_{out}}$ not input, use $P_{C_{in}}$.

(5) Is $10 \leq P_{C_{in}} \leq 180$

Is $35 \leq T_{C_{in}} < T_{C_{sat}}$

Is $T_{C_{sat}} < T_{C_{out}} \leq 500$

Is $\sum \epsilon \leq .91$

If all "yes", the HX has a boiling subunit and a gas parallel-flow subunit only.

(6) Is $10 \leq P_{C_{in}} \leq 2000$

Is $35 \leq T_{C_{in}} < T_{C_{sat}}$

Is $T_{C_{out}} > 500$

Is $\epsilon < 0.9$

If all "yes", the HX has a boiling subunit, a gas aprallel-flow subunit, and a gas counter-flow subunit.

(7) Is $10 \leq P_{C_{in}} \leq 2000$

Is $P_{C_{in}} < 188.1$, is $500 > T_{C_{in}} \geqslant T_{C_{sat}}$

Is $P_{C_{in}} > 188.1$, is $500 > T_{C_{in}} \geqslant 90$

Is $\sum \epsilon \leq 0.91$

If all "yes", the HX has a gas parallel-flow subunit only.

(8) Is $10 \leq P_{C_{in}} \leq 2000$

Is $P_{C_{in}} < 188.1$, is $500 > T_{C_{in}} \geq T_{C_{sat}}$

Is $P_{C_{in}} > 188.1$, is $500 > T_{C_{in}} \geqslant 90$

Is $T_{C_{out}} > 500$

Is $\epsilon < 0.9$

If all "yes ", the HX has a gas parallel-flow subunit and a gas counter-flow subunit only.

(9) Is $10 \leq P_{C_{in}} \leq 2000$

Is $T_{C_{in}} \geqslant 500$

Is $\epsilon < 0.9$

If all "yes", the HX has a gas counter-flow subunit only.

(10) Is $\epsilon \geq 0.9$, $T_{H_{out}}$ must be increased or $T_{C_{out}}$ must be decreased.

(c) <u>IF THE COLD FLUID IS OXYGEN:</u>

(1) Is $800 \leq P_{C_{in}} \leq 2000$

Is $160 \leq T_{C_{in}} < 320$

Is $T_{C_{out}} \leq 320$

If all "yes", the HX has a super-critical subunit only.

(2) Is $800 \leq P_{C_{in}} \leq 2000$

Is $160 \leq T_{C_{in}} < 320$

Is $320 < T_{C_{out}} \leq 500$

Is $\Sigma\epsilon \leq 0.91$

If all "yes," the HX has a super-critical subunit and a gas parallel-flow subunit only.

(3) Is $800 \leq P_{C_{in}} \leq 2000$

Is $160 \leq T_{C_{in}} < 320$

Is $T_{C_{out}} > 500$

Is $\epsilon < 0.9$

If all "yes", the HX has a super-critical subunit, a gas parallel-flow subunit, and a gas counter-flow subunit.

(4) Is $10 \leq P_{C_{in}} \leq 700$

Is $160 \leq T_{C_{in}} < T_{C_{sat}}$

Is $T_{C_{out}} \leq T_{C_{sat}}$

If all "yes", the HX has a boiling subunit only.

Find $T_{C_{sat}}$ corresponding to $P_{C_{out}}$ from table of thermodynamic properties of oxygen, for saturated vapor. If $P_{C_{out}}$ not input, use $P_{C_{in}}$.

(5) Is $10 \leq P_{C_{in}} \leq 700$

Is $160 \leq T_{C_{in}} < T_{C_{sat}}$

Is $T_{C_{sat}} < T_{C_{out}} \leq 500$

Is $\Sigma\epsilon \leq 0.91$

If all "yes", the HX has a boiling subunit and a gas parallel-flow subunit only.

(6) Is $10 \leq P_{C_{in}} \leq 700$

Is $160 \leq T_{C_{in}} < T_{C_{sat}}$

Is $T_{C_{out}} > 500$

Is $\epsilon < 0.9$

If all "yes", the HX has a boiling subunit, a gas parallel-flow subunit, and a gas counter-flow subunit.

(7) Is $10 \leq P_{C_{in}} \leq 2000$

Is $P_{C_{in}} < 731$, is $500 > T_{C_{in}} \geq T_{C_{sat}}$

Is $P_{C_{in}} > 731$, is $500 > T_{C_{in}} \geq 320$

Is $320 < T_{C_{out}} \leq 500$

Is $\Sigma\epsilon \leq 0.91$

If all "yes", the HX has a gas parallel-flow subunit only.

(8) Is $10 \leq P_{C_{in}} \leq 2000$

Is $P_{C_{in}} < 731$, is $500 > T_{C_{in}} \geq T_{C_{sat}}$

Is $P_{C_{in}} > 731$, is $500 > T_{C_{in}} \geq 320$

Is $T_{C_{out}} > 500$

Is $\epsilon < 0.9$

If all "yes", the HX has a gas parallel-flow subunit and a gas counter-flow subunit only.

(9) Is $10 \leq P_{C_{in}} \leq 2000$

Is $T_{C_{in}} \geq 500$

Is $\epsilon < 0.9$

If all "yes", the HX has a gas counter-flow subunit only

(10) If $\epsilon \geq 0.9$, $T_{H_{out}}$ must be increased or $T_{C_{out}}$ must be decreased.

13. DEFINITION OF DESIGN POINTS FOR INDIVIDUAL SUBUNITS:

(actual values are derived from the data of operation 11)

(a) Supercritical subunit: (low-temperature)

The subscript "S" will refer to the supercritical subunit; the subscript "tot" will refer to the entire heat exchanger.

$$(T_{C_{in}})_S = (T_{C_{in}})_{tot}$$

$$(T_{H_{in}})_S = (T_{H_{in}})_{tot}$$

If cold fluid is hydrogen:

If $(T_{C_{out}})_{tot} > 90$, set $(T_{C_{out}})_S = 90$

If $(T_{C_{out}})_{tot} \leq 90$, $(T_{C_{out}})_S = (T_{C_{out}})_{tot}$

If cold fluid is oxygen:

If $(T_{C_{out}})_{tot} > 320$, set $(T_{c_{out}})_S = 320$

If $(T_{C_{out}})_{tot} \leq 320$, $(T_{C_{out}})_S = (T_{C_{out}})_{tot}$

$$(T_{H_{out}})_S = (T_{H_{out}})_{tot}$$

$$(W_C)_S = (W_C)_{tot}$$

$$(W_H)_S = (W_C)_{tot} \frac{(\Delta i_c)_S}{(\Delta i_h)_{tot}}$$

$(\Delta i_c)_S$ found from tables of thermo properties of cold fluid, corresponding to $P_{C_{in}}$, $(T_{C_{in}})_S$, $(T_{C_{out}})_S$, and $(P_{C_{out}})_S$ if specified. If $(P_{C_{out}})$ not specified, set $(P_{C_{out}})_S = P_{C_{in}}$

$$(P_{H_{in}})_S = (P_{H_{in}})_{tot}$$

$$(P_{C_{in}})_S = (P_{C_{in}})_{tot}$$

If pressure drops are specified:

$$(\Delta P_H)_S = (\Delta P_H)_{tot}$$

$$(\Delta P_C)_S = 0.5 \ (\Delta P_c)_{tot} \ \frac{(\Delta i_c)_S}{(\Delta i_c)_{tot}}$$

(b) Boiling subunit: (low temperature)

The subscript "B" will refer to the boiling subunit; the subscript "tot" will refer to the entire heat exchanger:

$$(T_{C_{in}})_B = (T_{C_{in}})_{tot}$$

$$(T_{H_{in}})_B = (T_{H_{in}})_{tot}$$

If the cold fluid is hydrogen:

If $(T_{C_{out}})_{tot} > T_{C_{sat}}$, set $(T_{C_{out}})_B = T_{C_{sat}}$

If $(T_{C_{out}})_{tot} = T_{C_{sat}}$, set $(T_{C_{out}})_B = (T_{C_{out}})_{tot}$

If the cold fluid is oxygen:

If $(T_{C_{out}})_{tot} > T_{C_{sat}}$, set $(T_{C_{out}})_B = T_{C_{seat}}$

If $(T_{C_{out}})_{tot} = T_{C_{sat}}$, $(T_{C_{out}})_B = (T_{C_{out}})_{tot}$

$$(T_{H_{out}})_B = (T_{H_{out}})_{tot}$$

$$(T_{H_{in}})_B = (T_{H_{in}})_{tot}$$

$$(W_C)_B = (W_C)_{tot}$$

$$(W_H)_B = (W_c)_{tot} \frac{(\Delta i_c)_B}{(\Delta i_h)_{tot}}$$

$$(P_{H_{in}})_B = (P_{H_{in}})_{tot}$$

$$(P_{C_{in}})_B = (P_{C_{in}})_{tot}$$

$(\Delta i_c)_B$ found from tables of thermo properties of cold fluid corresponding to $P_{C_{in}}$, $(T_{C_{in}})$ and $(P_{C_{out}})_B$ if specified. If $(P_{out})_B$ not specified, set $(P_{C_{out}})_B$ = $P_{C_{in}}$.

If pressure drops are specified:

$$(\Delta P_H)_B = (\Delta P_H)_{tot}$$

$$(\Delta P_C)_B = 0.5 \ (\Delta P_C)_{tot} \frac{(\Delta i_c)_B}{(\Delta i_c)_{tot}}$$

(c) Gas parallel-flow subunit:

The subscript "GP" will refer to gas parallel subunit; the subscript "tot" will refer to the entire heat exchanger.

$$(T_{H_{in}})_{GP} = (T_{H_{in}})_{tot}$$

If no supercritical or boiling subunit exists,

$$(T_{C_{in}})_{GP} = (T_{C_{in}})_{tot}$$

If a supercritical subunit exists,

$$(T_{C_{in}})_{GP} = (T_{C_{out}})_{S}$$

If a boiling subunit exists,

$$(T_{C_{in}})_{GP} = (T_{C_{out}})_{B}$$

$$(T_{H_{out}})_{GP} = (T_{H_{out}})_{tot}$$

If no gas counter-flow subunit exists,

$$(T_{C_{out}})_{GP} = (T_{C_{out}})_{tot}$$

If a gas counter-flow subunit exists,

$$(T_{C_{out}})_{GP} = 500$$

$$(W_C)_{GP} = (W_C)_{tot}$$

$$(W_H)_{GP} = (W_C)_{tot} \frac{(\Delta i_c)_{GP}}{(\Delta i_h)_{tot}}$$

$$(P_{H_{in}})_{GP} = (P_{H_{in}})_{tot}$$

$(\Delta i_c)_{GP}$ found from tables of thermo properties of cold fluid correspond to $(P_{c_{in}})_{GP}$, $(T_{C_{in}})_{GP}$, $(T_{C_{out}})_{GP}$, and $(P_{C_{out}})_{GP}$. If $(P_{C_{out}})$ is not specified set $(P_{C_{out}})_{GP} = P_{C_{in}}$.

If no supercritical or boiling subunit exists,

$$(P_{C_{in}})_{GP} = (P_{C_{in}})_{tot}$$

If a supercritical subunit exists,

$$(P_{C_{in}})_{GP} = (P_{C_{in}})_{S} - \Delta P_{C_S}$$

If a boiling subunit exists,

$$(P_{C_{in}})_{GP} = (P_{C_{in}})_{B} - \Delta P_{C_B}$$

If pressure drops are specified,

$$(\Delta P_H)_{GP} = (\Delta P_H)_{tot}$$

$$(\Delta P_C)_{GP} = (\Delta P_C)_{tot} \frac{(\Delta i_c)_{GP}}{(\Delta i_c)_{tot}}$$

(d) Gas Counter-flow subunit:

The subscript "CF" refers to the gas counter-flow subunit; the subscript "tot" refers to the entire heat exchanger.

$$(T_{H_{in}})_{CF} = (T_{H_{in}})_{tot}$$

If no gas parallel-flow subunit exists,

$$(T_{C_{in}})_{CF} = (T_{C_{in}})_{tot}$$

If a gas parallel-flow subunit exists,

$$(T_{C_{in}})_{CF} = (T_{C_{out}})_{GP}$$

$$(T_{H_{out}})_{CF} = (T_{H_{out}})_{tot}$$

$$(T_{C_{out}})_{CF} = (T_{C_{out}})_{tot}$$

$$(W_c)_{CF} = (W_C)_{tot}$$

$$(W_H)_{CF} = (W_C)_{tot} \frac{(\Delta i_c)_{CF}}{(\Delta i_h)_{tot}}$$

$(\Delta i_c)_{CF}$ is found from tables of thermo properties of the cold fluid, corresponding to $(P_{C_{in}})_{CF}$, $(T_{C_{in}})_{CF}$, and $(P_{C_{out}})_{CF}$. If $(P_{C_{out}})_{CF}$ not specified, set $(P_{C_{out}})_{CF} = (P_{C_{in}})_{CF}$.

$$(P_{H_{in}})_{CF} = (P_{H_{in}})_{tot}$$

If no Gas-Parallel flow Subunit,

$$(P_{cin})_{CF} = (P_{cin})_{tot}$$

If a Gas-Parallel flow subunit exists,

$$(P_{C_{in}})_{CF} = (P_{C_{in}})_{GP} - \Delta P_{c_{GP}}$$

If pressure drops are specified,

$$(\Delta P_H)_{CF} = (\Delta P_H)_{tot}$$

$$(\Delta P_C)_{CF} = (\Delta P_C)_{tot} - (\Delta P_c)_{GP} - (\Delta P_c)_S - (\Delta P_c)_B$$

Note that if no gas-parallel subunit exists,

$$(\Delta P_c)_{GP} = 0$$

If no supercritical subunit exists,

$$(\Delta P_c)_S = 0$$

If no boiling subunit exists,

$$(\Delta P_c)_B = 0$$

14. IDENTIFY SUBUNITS REQUIRED IN THE HEAT EXCHANGER:

(a) Note that, for either hydrogen or oxygen as the cold fluid, nine possible combinations of subunits exist for a heat exchanger, depending on the cold fluid inlet and outlet conditions. Operation 12 shows these conditions to be:

(1) A supercritical subunit only.
(2) A supercritical and a gas parallel subunit.
(3) A supercritical, a gas parallel, and a gas counter-flow subunit.
(4) A boiling subunit only.
(5) A boiling subunit and a gas parallel subunit.
(6) A boiling, a gas parallel, and a gas counter-flow subunit.
(7) A gas-parallel subunit only.
(8) A gas-parallel and a gas counter-flow subunit.
(9) A gas counter-flow subunit only.

(b) The following order of subunit design must be observed:

(1) Supercritical or boiling subunit, if required.
(2) Gas parallel subunit, if required.
(3) Gas counter-flow subunit.

Each subunit must be fully designed before going on to the next subunit.

(c) After all subunits have been designed, their weights, volumes, and pressure drops are combined to obtain overall heat exchanger characteristics.

(d) Referring to operations 11 and 12, identify the subunits required. Place them in proper of analysis, per operation 14b, above.

(e) Identify individual subunit requirements, using the values of operation 11, and the design point definitions of operation 13.

15. DETERMINE TEMPERATURE - DEPENDENT LIMITATIONS:

For supercritical, boiling, or gas parallel subunits,

$$TCR_{min} = MAX \left(\frac{T_{H_{in}} - 1800}{1800 - T_{C_{in}}} , \frac{T_{H_{out}} - 1800}{1800 - T_{C_{out}}} \right)$$

If any terms are negative, set them equal to zero

$$TCR_{max} = MIN \left(\frac{T_{H_{in}} - 550}{550 - T_{C_{in}}} , \frac{T_{H_{out}} - 550}{550 - T_{C_{out}}} \right)$$

If any terms are negative, ignore them.

For gas counter-flow subunits,

$$(TCR\ min)_{CF} = MAX\left(\frac{T_{H_{in}} - 1800}{1800 - T_{C_{out}}} , \frac{T_{H_{out}} - 1800}{1800 - T_{C_{in}}} \right)$$

If any terms are negative, set them equal to zero

$$(TCR_{max})_{CF} = \text{MIN} \left(\frac{T_{H_{min}} - 550}{550 - T_{C_{out}}} , \frac{T_{H_{out}} - 550}{550 - T_{C_{in}}} \right)$$

If any terms are negative, ignore them.

If $TCR_{min} \geqslant TCR_{max}$, an impossible situation exists, and the design point must be changed.

16. DETERMINE THE NUMBER OF HEAT TRANSFER UNITS:

For supercritical or gas parallel subunits,

$$NTU = \frac{- \ln (1 - \epsilon - C_r \epsilon)}{1 + C_r}$$

For boiling subunits,

$$NTU = -\ln (1 - \epsilon)$$

For Gas counter-flow subunits,

$$NTU = \frac{1}{C_r - 1} \quad \ln \frac{1 - \epsilon}{1 - C_r \epsilon}$$

Expressions for the terms above are as follows, using values for specific subunits as determined from operation 13:

$$\epsilon = \text{MAX} \left(\frac{T_{H_{in}} - T_{H_{out}}}{T_{H_{in}} - T_{C_{in}}} , \frac{T_{C_{out}} - T_{C_{in}}}{T_{H_{in}} - T_{C_{in}}} \right)$$

$$C_r = \frac{C_{min}}{C_{max}}$$

$$C_{min} = \text{MIN} \quad (C_c, C_h)$$

$$C_{max} = \text{MAX} \quad (C_c, C_h)$$

$$C_c = 3600\, \dot{W}_c\, \overline{C_{P_c}}$$

$$C_h = 3600\, \dot{W}_h\, \overline{C_{P_h}}$$

$$\overline{C_{P_c}} = \frac{\Delta i_c}{\Delta T_c}$$

$$\overline{C_{P_h}} = \frac{\Delta i_h}{\Delta T_h}$$

17. DETERMINE UA FOR EACH SUBUNIT:

$$UA = (NTU)\,(C_{min})$$

18. DETERMINE CORRECTION FACTOR FOR (ØF) OTHER THAN 1.0:

If the (ØF) identified in operation 11 does not have the value 1.0, correction factors must be calculated and applied to the values obtained from the data curves which were input in operation 1.

(a) Correction for hot fluid pressure drop:

$$\left(\frac{\Delta P}{P}\right)_{h_1} = \left(\frac{\Delta P}{P}\right)_{h_0} \left(\frac{M_x}{M_{1.0}}\right), \text{ where}$$

$\left(\frac{\Delta P}{P}\right)_{h_1} = \left(\frac{\Delta P_h}{P_{h_{in}}}\right)$ = actual normalized pressure drop corresponding to ØF = X

M_X = hot fluid molecular weight at ØF = X

$M_{1.0}$ = hot fluid molecular weight at ØF = 1.0

$M_{1.0} = 4.016$

$M_X = 2.016\,(ØF_X) + 2.0$

(b) Correction for thermal conductance ratio (TCR):

$$TCR_1 = TCR_0 \left(\frac{\alpha_x}{\alpha_{1.0}} \right)$$

TCR_1 = Actual TCR corresponding to $\phi F = X$

TCR_0 = TCR obtained from the curves

$$\alpha_X = \frac{(P_r)^{2/3}}{\bar{C}_{P_h}} \quad \text{corresponding to } \phi F = X$$

19. DESIGN PROCEDURES FOR SUPERCRITICAL SUBUNIT:

Applicable only if a supercritical subunit exists in the heat exchanger, as determined by operation 12. If so, the supercritical subunit design point is taken from operation 13a.

(a) From specified pressure drops, find $\frac{W}{UA}$:

(1) $\Delta P_{c_1} = \Delta P_{C_S} \dfrac{350}{(T_{C_{out}})_S}$ if cold fluid is hydrogen

$\Delta P_{C_1} = \Delta P_{C_S} \dfrac{500}{(T_{C_{out}})_S}$ if cold fluid is oxygen

Subscript "1" denotes the value of P_C to be used in entering the data curves. Subscript "S" applies to the specified value for the supercritical subunit.

(2) Find $\left(\dfrac{\Delta P}{P}\right)_{C_1} = \dfrac{\Delta P_{C_1}}{(P_{C_{in}})_S}$, and $\left(\dfrac{\Delta P}{P}\right)_{h_S} = \dfrac{\Delta P_{h_S}}{(P_h)_{in}}$

(3) Using $(P_{C_{in}})_S$; $(P_{h_{in}})_S$, $\left(\dfrac{\Delta P}{P}\right)_{C_1}$ and $\left(\dfrac{\Delta P}{P}\right)_{h_S}$ as inputs, enter the appropriate gaseous curves of operation 1 to determine the evalue of W/UA as outlined in the steps which follow.

(4) If interpolation between P_c values in the tables is necessary, interpolate linearly to find W/UA:

If TCR $>$ 10., set TCR = 10.

$$W = \left(\frac{W}{UA}\right) * UA * \left(\frac{1 + TCR}{1 + TCR_{max}}\right) * \left(\frac{TCR_{max}}{TCR}\right)$$

(5) If interpolation between values of $\left(\frac{\Delta P}{P}\right)_C$ or $\left(\frac{\Delta P}{P}\right)_h$ is outside the range of values for which curves exist, extrapolate log-log.

(b) Find W for the supercritical subunit:

$$W = \left(\frac{W}{UA}\right) \quad (UA)$$

$\left(\frac{W}{UA}\right)$ is obtained from (a), above

(UA) is obtained from operation 17.

(c) Find ΔP_{C_S}:

ΔP_{C_S} = value of P_{C_S} found in operation 13

(d) Find ΔP_{H_S}:

ΔP_{H_S} = Value of P_{H_S} found in operation 13.

(e) Now go to the design of the gas parallel subunit, if one exists.

20. DESIGN PROCEDURE FOR BOILING SUBUNITS:

(a) Use data only from the boiling curves.

(b) Using specified pressure drops, find

$$\left(\frac{\Delta P}{P}\right)_{C_B} = \frac{\Delta P_{C_B}}{P_{C_{in_B}}} \quad ; \quad \left(\frac{\Delta P}{P}\right)_{h_B} = \frac{\Delta P_{h_B}}{P_{h_{in_B}}}$$

(c) Using $P_{C_{in_B}}$, $P_{h_{in_B}}$, $\left(\frac{\Delta P}{P}\right)_{C_B}$ and $\left(\frac{\Delta P}{P}\right)_{h_B}$, find TCR_5 from the applicable TCR relationship:

(1) For extrapolation of TCR from the values of $\left(\frac{\Delta P}{P}\right)_C$ and $\left(\frac{\Delta P}{P}\right)_h$ for which the TCR relation is expressed, proceed as follows:

(a) Find the value of TCR corresponding to $(P_{C_{in}})_B$ and $(P_{h_{in}})_B$, from the TCR relation.

(b) First extrapolate with respect to $\left(\frac{\Delta P}{P}\right)_h$:

$$TCR_5 = TCR_1 \left[\frac{\left(\frac{\Delta P}{P}\right)_{h_1}}{\left(\frac{\Delta P}{P}\right)_{h_B}} \right]^{.232} \quad , \text{ where}$$

$\left(\frac{\Delta P}{P}\right)_{h_1}$ = hot fluid pressure drop value for the TCR relation from which the extrapolation is made.

$\left(\frac{\Delta P}{P}\right)_{h_B}$ = the hot fluid pressure drop to which the extrapolation is made

TCR_1 = TCR value from which the extrapolation is made.

TCR_5 = Intermediate TCR value in the double extrapolation.

(c) Next, extrapolate with respect to $(\frac{\Delta P}{P})_C$:

$$TCR_6 = TCR_5 \left[\frac{(\frac{\Delta P}{P})_{C_B}}{(\frac{\Delta P}{P})_{C_O}} \right]^{.364}$$, where

$(\frac{\Delta P}{P})_{C_B}$ = the cold fluid pressure drop to which the extrapolation is made.

$(\frac{\Delta P}{P})_{C_o}$ = The cold fluid pressure drop value for the TCR relation from which the extrapolation is made.

TCR_5 = intermediate TCR_1 value in the double extrapolation, from (ii), above

TCR_6 = the value of TCR corresponding to $(\frac{\Delta P}{P})_{C_B}$ and $(\frac{\Delta P}{P})_{h_B}$

(d) If the specified values of $(\frac{\Delta P}{P})_{C_B}$ and $(\frac{\Delta P}{P})_{h_B}$ result in a value of TCR_6 which is less than TCR_{min} or greater than TCR_{max} (from operation 15), proceed as follows:

(1) Input which pressure drop is most limited by system considerations.

(2) Identify a new TCR, designated TCR_7

(3) If ΔP_{C_B} is most limited, set $TCR_7 = TCR_{min}$

Hold $(\frac{\Delta P}{P})_{C_B}$ at its specified value, and solve for a new value of $(\frac{\Delta P}{P})_{h_B}$ which corresponds to TCR_7:

$$(\frac{\Delta P}{P})_{h_2} = (\frac{\Delta P}{P})_{h_1} \left[\frac{TCR_1}{TCR_7} \right]^{4.31}$$, where

$(\frac{\Delta P}{P})_{h_2}$ = extrapolated value of $(\frac{P}{P})_h$ required for TCR_7

$(\frac{\Delta P}{P})_{h_1}$ = hot fluid pressure drop value for the TCR relation-from which the extrapolation is made.

TCR_1 = TCR value from which the extrapolation is made.

Solve for $P_{h_{out_B}} = P_{h_{in_B}} - (\frac{\Delta P}{P})_{h_2} * (P_{h_{in_B}})$

If $P_{h_{out_B}} < 0.6 \; P_{h_{in_B}}$, or if

$P_{h_{out_B}} < P_{h_{out_R}}$ determine by operation 7, whichever is the larger, then set $P_{h_{out_B}}$ equal to the larger of the two and find $(\frac{\Delta P}{P})_{h_3}$ from

$$(\frac{\Delta P}{P})_{h_3} = \frac{P_{h_{in_B}} - \text{MAX}\ (0.6\ P_{h_{in_B}},\ P_{h_{out_R}})}{P_{h_{in_B}}}$$

Then find a new value of $(\frac{\Delta P}{P})_{C_B}$ as follows:

$$(\frac{\Delta P}{P})_{C_{B_2}} = (\frac{\Delta P}{P})_{C_B} \left[\frac{TCR_7}{TCR_8}\right]^{2.75}$$

$$TCR_8 = TCR_7 \left[\frac{(\frac{\Delta P}{P})_{h_2}}{(\frac{\Delta P}{P})_{h_3}}\right]^{.232}$$

(4) If ΔP_{h_B} is most limited, set $TCR_7 = TCR_{max}$. Hold $\left(\frac{\Delta P}{P}\right)_{h_B}$ at its specified value, and find the value of TCR in the which corresponds to TCR_7:

$$\left(\frac{\Delta P}{P}\right)_{C_{B_3}} = \left(\frac{\Delta P}{P}\right)_{C_o} \left[\frac{TCR_7}{TCR_1}\right]^{2.75}$$

$\left(\frac{\Delta P}{P}\right)_{C_{B_3}}$ = extrapolated value of $\left(\frac{\Delta P}{P}\right)_C$ required for TCR_7

$\left(\frac{\Delta P}{P}\right)_{C_o}$ = cold fluid pressure drop value for the TCR relation from which the extrapolation is made.

TCR_1 = TCR value from which the extrapolation is made.

If the value of ΔP_c corresponding to $\left(\frac{\Delta P}{P}\right)_{C_{B_3}}$ exceeds the value $0.1 \left(P_{c_{in}}\right)_B \ast \left[\frac{\Delta i_{c_B}}{\Delta i_{c_{tot}}}\right]$, then set ΔP_c equal to this value and calculate $\left(\frac{\Delta P}{P}\right)_{C_{B_4}} = 0.1 \frac{(\Delta i_{c_B})}{(\Delta i_{c_{tot}})}$

Then find $\left(\frac{\Delta P}{P}\right)_{h_4}$:

$$\left(\frac{\Delta P}{P}\right)_{h_4} = \left(\frac{\Delta P}{P}\right)_{h_B} \left[\frac{TCR_8}{TCR_7}\right]^{4.31}$$

(e) Find $\frac{W}{UA}$ for the boiling subunit:

Enter the appropriate boiling curves of $\frac{W}{UA}$ to obtain a value of $\frac{W}{UA}$ using $(P_{C_{in\ B}})$, $(P_{h_{in\ B}})$, and one of the following sets of pressure drop factors:

(1) $(\frac{\Delta P}{P})_{C_B}$ and $(\frac{\Delta P}{P})_{h_B}$, from operation 20b.

(2) $(\frac{\Delta P}{P})_{C_B}$ and $(\frac{\Delta P}{P})_{h_2}$, or $(\frac{\Delta P}{P})_{C_{B_2}}$ and $(\frac{\Delta P}{P})_{h_3}$, whichever set is applicable, from operation 20d (3).

(3) $(\frac{\Delta P}{P})_{C_{B_3}}$ and $(\frac{\Delta P}{P})_{h_B}$, or

$(\frac{\Delta P}{P})_{C_{B_4}}$ and $(\frac{\Delta P}{P})_{h_4}$, whichever set is applicable, from operation 20(d) (4).

(4) If interpolation between P_c values in the tables is necessary, interpolate linearly to find $\frac{W}{UA}$.

(5) If interpolation between values of $(\frac{\Delta P}{P})_C$ or $(\frac{\Delta P}{P})_h$ is necessary, interpolate log-log.

(6) If the value of $(\frac{\Delta P}{P})_C$ or $(\frac{\Delta P}{P})_h$ is outside the range of values for which curves exist, extrapolate log-log.

(f) Find W for the boiling subunit:

$$W = (\frac{W}{UA})\ (UA)$$

$(\frac{W}{UA})$ is obtained from (e), above

(UA) is obtained from operation 17.

(g) Find ΔP_{C_B} :

$$\Delta P_{C_B} = \left(\frac{\Delta P}{P}\right)_C \left(P_{C_{in}}\right)_B, \text{ where}$$

$$\left(\frac{\Delta P}{P}\right)_C = \text{Either } \left(\frac{\Delta P}{P}\right)_{C_B} \text{ from operation 20 b,}$$

or $\left(\frac{\Delta P}{P}\right)_{C_{B_2}}$ from operation 20d(3),

or $\left(\frac{\Delta P}{P}\right)_{C_{B_3}}$ from operation 20d (4),

or $\left(\frac{\Delta P}{P}\right)_{C_{B_4}}$ from operation 20d(4)

(h) Find ΔP_{h_B} :

$$\Delta P_{h_B} = \left(\frac{\Delta P}{P}\right)_h \left(P_{h_{in}}\right)_B, \text{ where}$$

$$\left(\frac{\Delta P}{P}\right)_h = \text{either } \left(\frac{\Delta P}{P}\right)_{h_B} \text{ from operation 20b,}$$

or $\left(\frac{\Delta P}{P}\right)_{h_2}$ from operation 20d(3),

or $\left(\frac{\Delta P}{P}\right)_{h_3}$ from operation 20d(3),

or $\left(\frac{\Delta P}{P}\right)_{h_4}$ from operation 20d (4).

(i) Now go to the design of the gas parallel subunit, if one exists.

21. DESIGN OF GAS PARALLEL SUBUNITS:

(a) Follow precisely the same procedures as were followed in operation 20, except as follows:

(1) Take all curve data from the gaseous curves instead of the boiling curves.

(2) Change all subscripts "B" to "GP".

(3) If the value of ΔP_c corresponding to $\left(\frac{\Delta P}{P}\right)_{GP_3}$, from operation 20d(4), exceeds the value $0.2\,(P_{C_{in}})_S \frac{(\Delta i_c)_{GP}}{(\Delta i_c)_{tot}}$ or $0.2\,(P_{C_{in}})_B \ast \frac{(\Delta i_c)_{GP}}{(\Delta i_c)_{tot}}$, depending on whether a supercritical or a boiling subunit precedes the gas parallel subunit, or $0.2\,(P_{C_{in}})_{GP} \ast \frac{(\Delta i_c)_{GP}}{(\Delta i_c)_{tot}}$ if nothing precedes the gas parallel subunit. If ΔP_c exceeds one of the se values, set it equal to the applicable value and calculate as follows:

$$\left(\frac{\Delta P}{P}\right)_{C_{GP_4}} = 0.2\left[\frac{(P_{C_{in}})_S}{(P_{C_{in}})_{GP}}\right] \ast \left[\frac{(\Delta i_c)_{GP}}{(\Delta i_c)_{tot}}\right] \text{ or}$$

$$\left(\frac{\Delta P}{P}\right)_{C_{GP_4}} = 0.2\left[\frac{(P_{C_{in}})_B}{(P_{C_{in}})_{GP}}\right] \ast \left[\frac{(\Delta i_c)_{GP}}{(\Delta i_c)_{tot}}\right], \text{ or}$$

$$\left(\frac{\Delta P}{P}\right)_{C_{GP_4}} = 0.2\left[\frac{(\Delta i_c)_{GP}}{(\Delta i_c)_{tot}}\right], \text{ as applicable.}$$

(b) Now go to the design of the gas counter-flow subunit, if one exists.

22. DESIGN OF GAS COUNTER-FLOW SUBUNITS:

(a) Follow precisely the same procedures as were followed in operation 20, except as follows:

(1) Take all curve data from the gaseous curves, instead of the boiling curves.

(2) Change all subscripts from "B" to "CF"

(3) Does the value of ΔP_c corresponding to $(\frac{\Delta P}{P})_{C_{CF_3}}$, from operation 20d(4), exceed the value of $0.2\,(P_{C_{in}})_B - (\Delta P_c)_S - (\Delta P_c)_{GP} - (\Delta P_c)_B$, where θ = S, B, GP, or CR = identity of the first subunit in the heat exchanger? If so, set ΔP_c equal to this value, and calculate $(\frac{\Delta P}{P})_{C_{CF_4}}$:

$$(\frac{\Delta P}{P})_{C_{CF_4}} = \frac{0.2\,(P_{C_{in}})_\theta - (\Delta P_c)_{GP} - (\Delta P_c)_S - (\Delta P_c)_B}{(P_{C_{in}})_{CF}}$$

(b) Now go to the calculation of the overall heat exchanger characteristics.

23. CALCULATION OF OVERALL HEAT EXCHANGER CHARACTERISTICS:

(a) Overall heat exchanger weight:

$$W_{tot} = \sum_{J=1}^{m} W_J \quad \text{lbs, where}$$

W_J = each individual subunit weight, from operations 19, 20, 21, and 22

m = number of subunits

<u>NOTE</u>: If $W_{tot} < 5$ lbs, set $W_{tot} = 5$ lbs.

(b) Overall heat exchanger pressure drop:

$$\Delta P_{h_{tot}} = \max \quad (\Delta P_h)_J$$

$$P_{h_{out}} = P_{h_{in}} - \Delta P_{h_{tot}}$$

$$\Delta P_{C_{tot}} = \sum_{J=1}^{m} (\Delta P_c)_J$$

$$P_{C_{out}} = P_{C_{in}} - \Delta P_{c_{tot}}$$

MATH MODEL FOR SUBROUTINE HEXELC

PURPOSE OF SUBROUTINE

The subroutine computes the weight and pressure drop values for an electrically heated heat exchanger. The subroutine essentially designs the exchanger unit based upon two preset design configurations established by the Airesearch Mfg. Co. in the course of a NASA funded study (Ref. 1.9-7). The subroutine incorporates data permitting the spplication of the heat exchanger to the use of providing thermal energy for three gaseous fluids; oxygen, hydrogen and nitrogen. The subroutine then has direct application to both Fuel Cell and Life Support Systems.

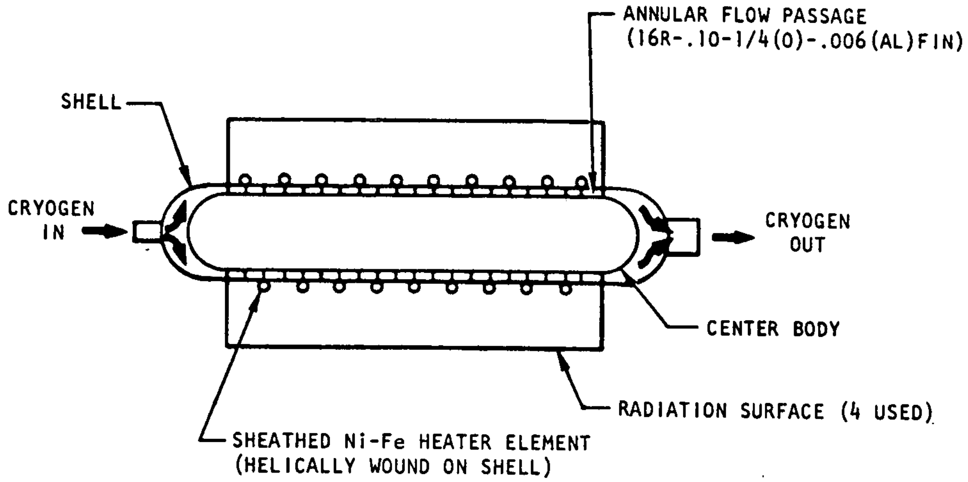
HEAT EXCHANGER DESIGN CONSIDERATIONS

The heat exchanger type considered here is an electrical resistance heater driven unit. The configuration, as illustrated in Figure HEXELC-1, employes a cylindrical annular cryogen flow passage with the heater element attached to the outer cylindrical shell.

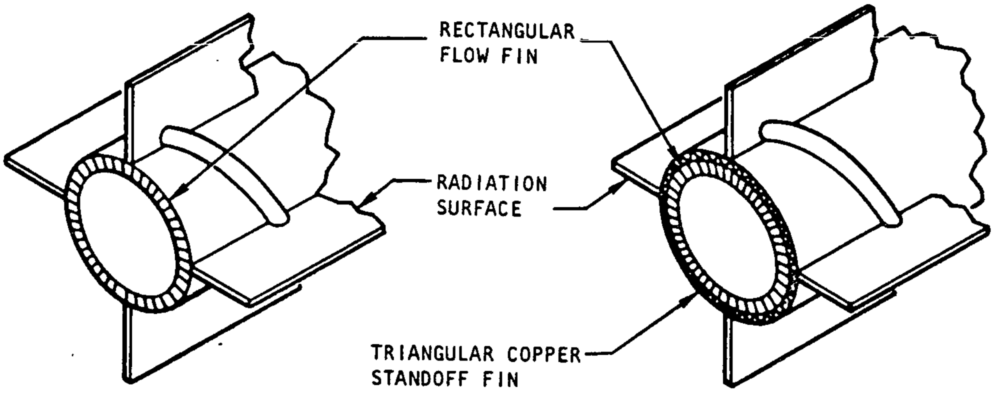
The heater element is Ni-Fe alloy, which was chosen because of the direct proportionality between resistance rise and temperature rise provided by this material. This characteristic acts to reduce power dissipation as heater temperature rises. This feature, coupled with extended external surfaces to enhance radiative heat rejection, allows heater temperature to be limited to 1000°R even under conditions of zero cryogen flow. Danger of heater burnout is thus virtually absent.

Heat transfer from the heated outer shell to the cryogen is improved by use of a rectangular offset fin within the annular flow passage. This fin, a 16-per-in., 0.006-in. thickness aluminum configuration, fixes the annulus radial thickness at 0.10 in.

The concept adopted for the oxygen heater unit differs from that of the hydro-



BASIC HEATER UNIT CONFIGURATION



SINGLE ANNULUS DESIGN FOR HYDROGEN AND NITROGEN

DOUBLE ANNULUS DESIGN FOR ISOLATION OF HEATER ELEMENT FROM OXYGEN STREAM

S-67096

FIGURE HEXELC-1 ELECTRICAL HEAT EXCHANGER CONFIGURATION gen and nitrogen units in that an additional cylindrical shell is located between the outer surface, to which the resistance element is brazed, and the oxygen flow passage. The barrier space thus formed is evacuated; the outer wall of the flow passage and the outer shell are thermally connected by a 0.05-in.-high triangular copper fin surface. This standoff construction prevents a single failure (of either the surface to which the heater is attached or the flow passage wall) from cuasing the heating element to be exposed to oxygen.

The procedure for design of electrical heater units is essentially closed-form, having a single degree of geometric freedom. It is necessary to select the outside diameter of the flow passage. For each diameter chosen, a heater design is defined. However, experimentation with this dimension may be needed in order to choose the most beneficial value for a particular application.

HEATING ELEMENT CONSIDERATIONS

For this application, it is desirable to have a resistance element capable of providing a large heat flux per unit wall area and having a resistivity characteristic that rises rapidly with temperature. This last requirement causes power dissipation to be decreased as heater temperature rises, a valuable trait with respect to safety of operation and radiator surface requirements. The 5.24-percent, nickel-iron alloy chosen for use in the heater provides a 63-percent decrease in power dissipation as temperature rises from 360°R to 1000°R, compared with the 27-percent decrease to be expected with Nichrome over the interval.

The relationship of temperature to resistivity ratio is given by the expression:

$$\left(\frac{R}{R_{360}}\right) = \left(\frac{T}{360}\right)^{n}$$

where R is the resistivity at the variable temperature and R_{360} is the resistivity at a 360°R reference condition.

SUBPROGRAMS AND SYMBOLS REFERENCED IN MATH MODEL

Subroutines, functions and data look-up table numbers are referenced with the using equations and procedures contained in this math model. The asterisk (*) implies multiplication and the paranthesis ( ) serve to group a set of mathematical manipulations.

PROCEDURE AND MODEL

1. INPUT VALUES REQUIRED:

NGAS - Fluid Gas Identity; 1 = Oxygen
2 = Hydrogen
3 = Nitrogen
TIN - Gas Inlet Temperature (°R)
TØUT - Gas Outlet Temperature (°R)
PIN - Inlet Gas Pressure (Psia)
HF - Heater Heat Flux Rating - (BTU/Hr - Sq. In. @ 360°R)
LDIA - Exchanger Inlet Line Diameter (In.)
WDØT - Gaseous Fluid Flow Rate (Lbs/hr)
RHØGAS - Gaseous Fluid Density (Lb/cu.ft.)
IFIN - Anti-Burnout Fin Index; 0 = No fins
1 = With fins

2. CONSTANTS REQUIRED IN MODEL:

PI - 3.141593
TREF - 360.0 (°R)
PCI - 736.9 (psia) Critical Pressure - Oxygen
PC2 - 187.5 (psia) Critical Pressure - Hydrogen
PC3 - 492.2 (psia) Critical Pressure - Nitrogen

3. CALCULATE THE MASS VELOCITY: (MASVEL)

MASVEL = WDØT/(PI * DH)

4. CALCULATE THE OVERALL HEAT TRANSFER COEFFICIENT: (UØA)

For this step, the data presented in Figures HEXELC-2 and -3 have been converted into Data Tables for data look-up:

Table 20 was derived from Fig. HEXELC-2
Table 21 was derived from Fig. HEXELC-3

For Hydrogen:
UØA = f (PIN, MASVEL) Table 20

For Oxygen and Nitrogen:
UØA = f (PIN, MASVEL) Table 21

5. CALCULATE THE HEAT EXCHANGER LENGTH:

The basic equation for heat exchanger length as given in Ref. 1.9-7 is as follows:

$$L = (\dot{w}_c/\pi D) * \bar{C}_p * \left[\frac{T_1^2 - T_2^2}{2B/\pi D} + \beta \frac{\ln(T_1/T_2)}{U} \right]$$

Let:

$$\phi_1 = \frac{T_1^2 - T_2^2}{2B/\pi D} \qquad \phi_2 = \frac{\ln(T_1/T_2)}{U}$$

Then:

$$L = (\dot{w}_c/\pi D) * \bar{C}_p * (\phi_1 + \beta \phi_2)$$

Where: L = HLNGTH = Heater Length
$\dot{w}_c$ = WDØT - Cryogen Gas Flow Rate

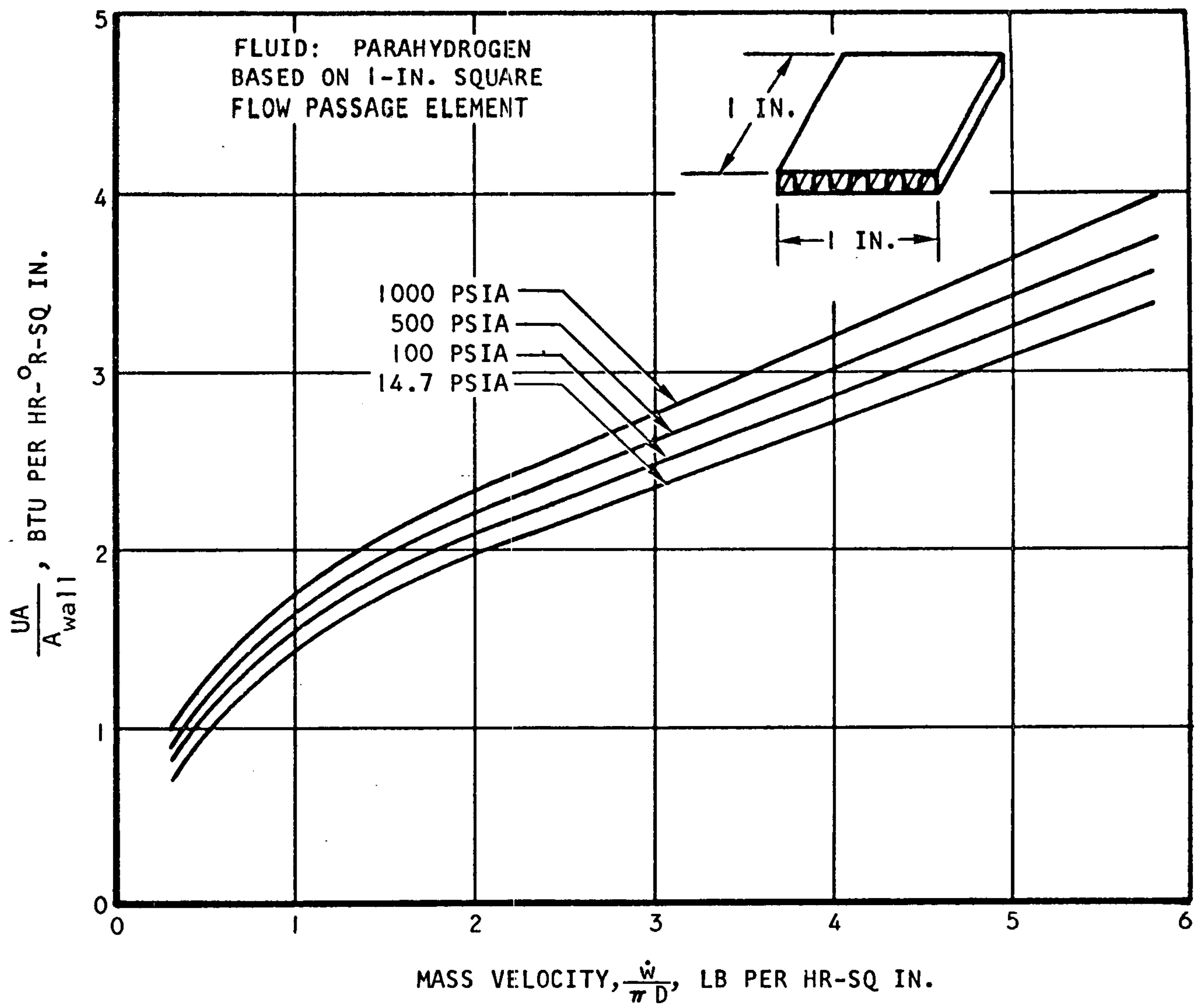


FIGURE HEXELC-2 HYDROGEN ELECTRICAL HEATER HEAT TRANSFER PERFORMANCE

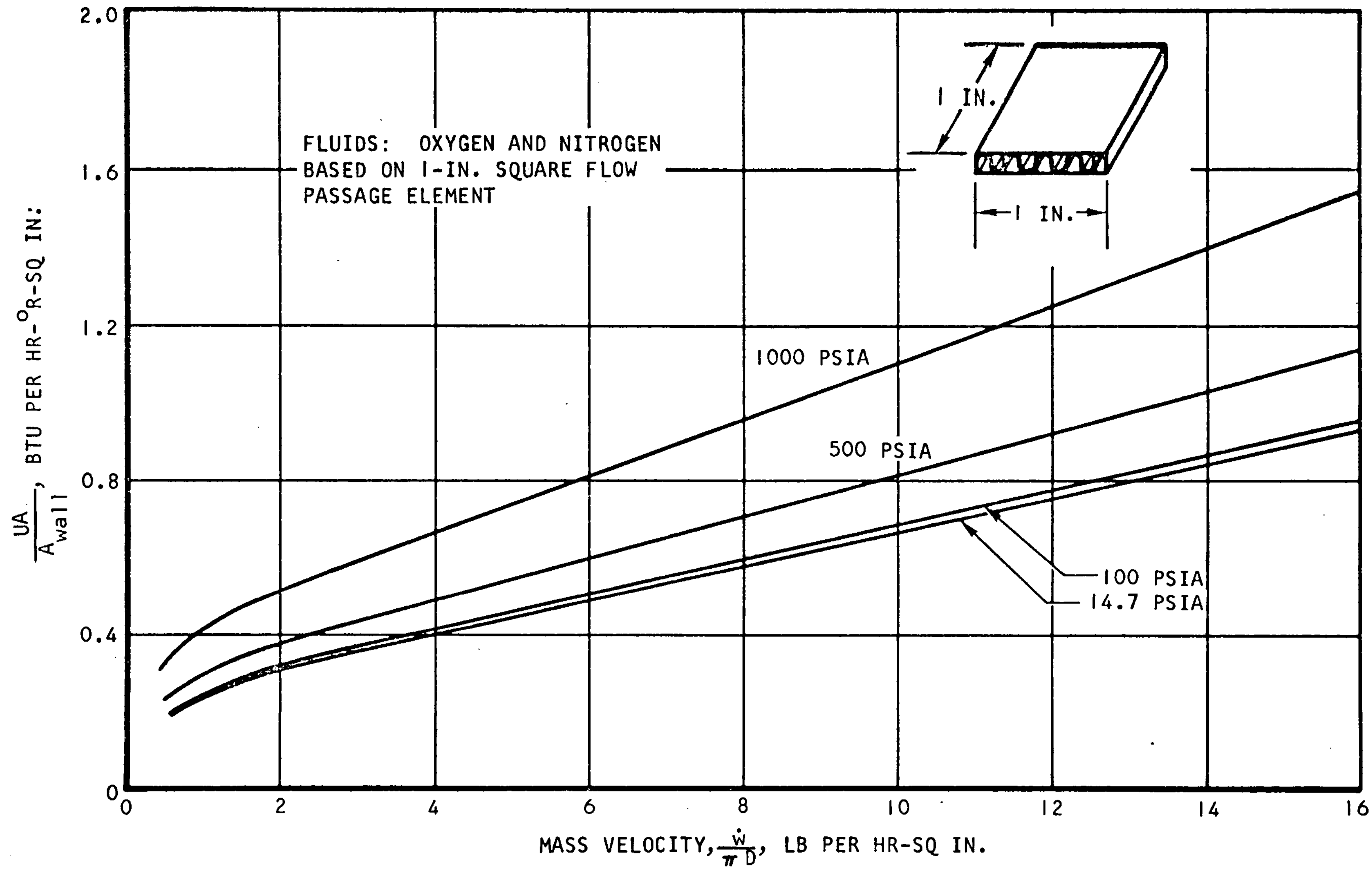


FIGURE HEXELC-3 OXYGEN AND NITROGEN ELECTRICAL HEATER HEAT TRANSFER PERFORMANCE

D = DH = Exchanger Outer Annulus Diameter

$\bar{C}_p$ = CPBAR - Mean Spec. Heat. of Cryogen Gas

T2 = TIN - Gas Inlet Temp

T_1 = TØUT - Gas Outlet Temp

β = BETA - Correction Factor for ϕ_2

B_1 = BØNE - Heater Power Per Unit Area

U = UØA - Overall Thermal Conductance of Heat Exchanger Surface

ϕ_1 = PHIØNE - As Defined Above

ϕ_2 = PHITWØ - As Defined Above

Further:

$$B_1 = \pi * D * B_o$$

Where:

$$B_o = \left(\frac{q}{A}\right)_{REF} * T_{REF} = HF * TREF$$

$\left(\frac{q}{A}\right)_{REF}$ or HF, in the manufacturers heater energy rating at a reference temperature

Since:

$$MASVEL = \frac{\dot{w}}{\pi D}$$

The model and subroutine equation becomes:

HLNGTH = MASVEL * CPBAR * (PHIØNE + BETA * PHITWØ)

Values for BETA are derived from Figure HEXELC-4, which has been converted to table look-up data as Table 44 in the Data Tables.

$$\text{BETA} = f\left(\frac{P}{Pc}\right) \qquad \text{Table 44}$$

where P is the gas pressure and P_c is the critical pressure of the same gas.

6. CALCULATE THE HEAT EXCHANGER WEIGHT:

The heat exchanger weight versus diameter and length curves presented in the reference study (Ref. 1.9-7) have been reduced to equation form as follows:

For Oxygen Heat Exchangers:

$$\text{HEXWGT} = 0.1519984 * \text{DH}^{1.05379} * \text{HLNGTH}$$

For Hydrogen and Nitrogen Heat Exchangers:

$$\text{HEXWGT} = 0.0950445 * \text{DH}^{1.061} * \text{HLNGTH}$$

7. CALCULATE THE ANTI-BURNOUT FIN WEIGHT:

The fin weight versus heater diameter graphic data presented in the referenced study has been reduced to equation form as follows:

If fins are required - then:

$$\text{FINWGT} = 0.2068721 * \text{DH}^{3.19204} * \text{HLNGTH}$$

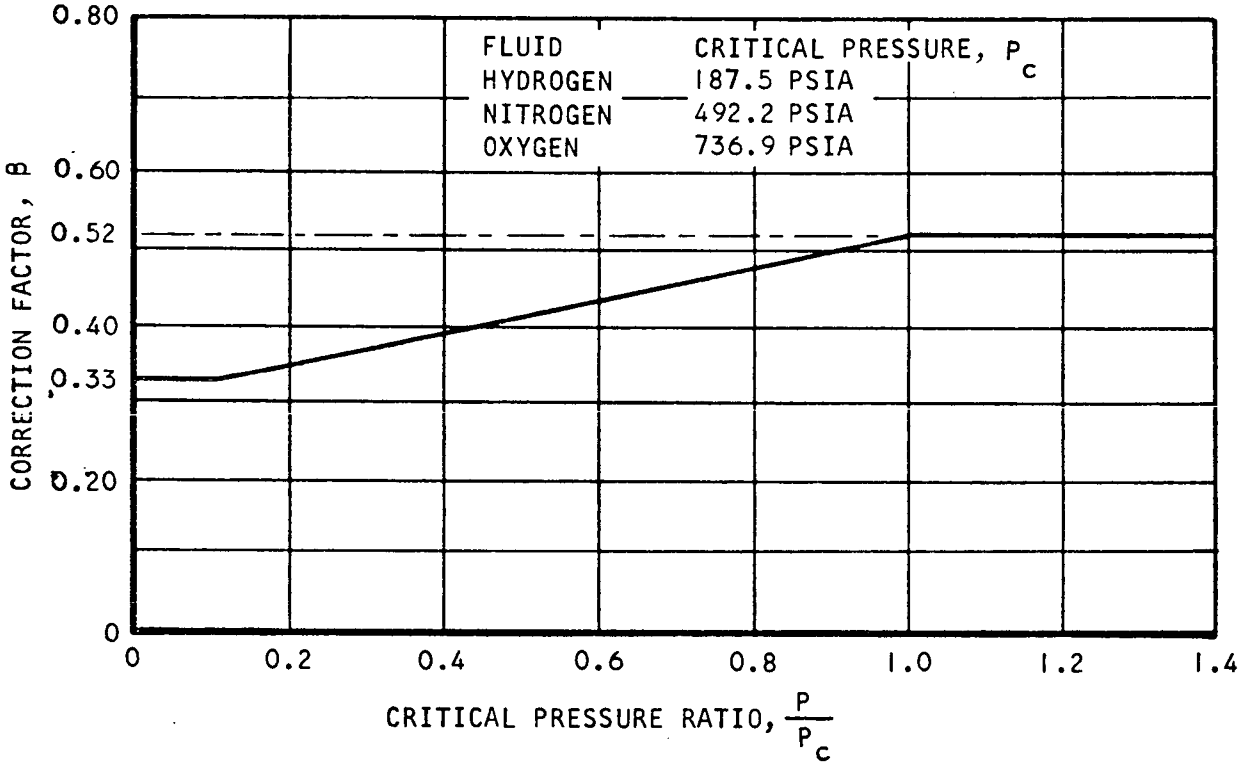


FIGURE HEXELC-4 PRESSURE CORRECTION FACTOR FOR HEATER LENGTH EQUATION

8. CALCULATE TOTAL HEAT EXCHANGER WEIGHT:

$$\text{HEXWGT} = \text{HEXWGT} + \text{FINWGT}$$

9. CALCULATE THE HEAT EXCHANGER PRESSURE DROP FOR THE FLUID GAS CONSIDERED:

The heat exchanger pressure loss characteristics as a function of fluid mass velocity is presented in Figure HEXELC-5. This data has also been converted to a look-up Table for use by the subroutine.

$$\sigma \Delta P = \text{SIGDLP} = f\ (\text{MASVEL, HLNGTH})$$

from Table - 45

Then:

$$\text{DELTAP} = \text{SIGDLP}/\ (\text{RH0GAS}/0.0765)$$

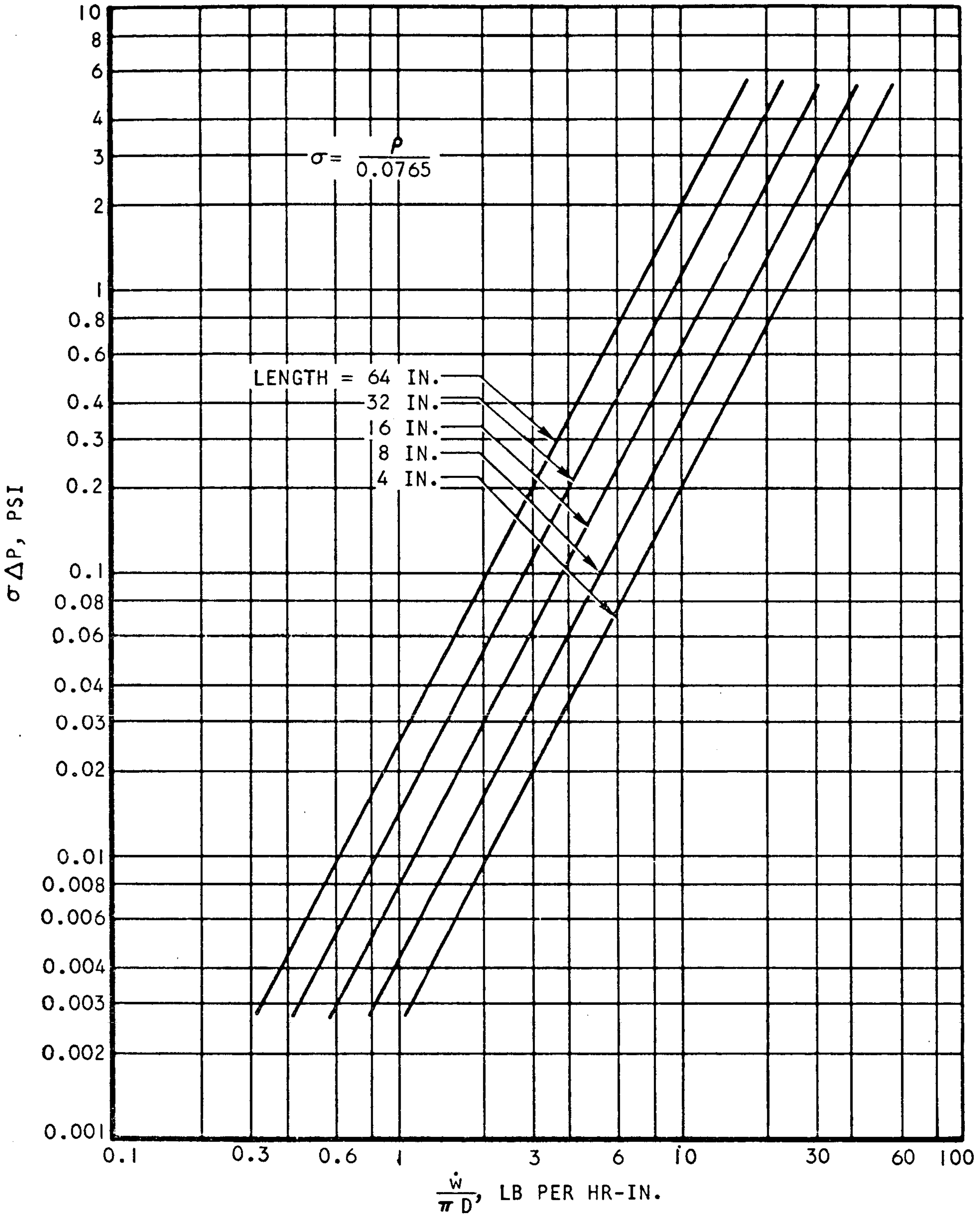


FIGURE HEXELC-5 ELECTRICAL HEATER PRESSURE LOSS CHARACTERISTICS

MATH MODEL FOR SUBROUTINE PARPMP

PURPOSE OF SUBROUTINE

To provide for the calculation of pump parameters required in support of other subprograms needing such computed parameters. The subroutine in essence designs a pump to fit the input values, and, where necessary, will revise certain of the input values to meet built-in design constraints.

The subroutine requires as input the following:

Type of Fluid:	Oxygen (as liquid) Hydrogen (as liquid)
Design Option:	Minimum Power Design Minimum Weight Design

Required Pump Pressure Rise
Required Delivered Flow Rate
Net Positive Suction Pressure Available
Fluid Density (as liquid)

The subroutine is to output the following variables:

Pump Efficiency
Pump Power
Pump Weight
Pump Speed
Number of Pump Stages
Computed NPSP Required by Pump

The math model employed is based upon an AiResearch Manufacturing Company study performed under subcontract for LMSC (Ref. 1-9-6).

MATH MODEL SYMBOLS AND SOURCE INFORMATION

Symbols and source information used in the math model are presented in the following subparagraphs along with the pertinent mathematical procedures and equations. Note that the asterisk (*) is used to denote multiplication and parenthesis ( ) serve to group a set of mathematical manipulations.

PROCEDURES AND EQUATIONS

1. Variable Definitions

Symbol	Description	Dimensions
D	Pump Diameter	in.
d	Impeller Diameter	in.
E	Power Requirement	horsepower
g_c	Gravitational Constant	32.17 ft-lbm/lbf-sec^2
H	Head Rise Per Stage	ft-lbf/lbm
L	Pump Length	in.
N	Rotational Speed	rpm
n	Number of Stages	—
NPSH	Net Positive Pressure Head	ft-lbf/lbm
NPSP	Net Positive Suction Pressure	psi
N_s	Specific Speed	rpm (gpm)$^{0.5}$/(ft-lbf/lbm)$^{0.75}$
P	Scroll Pressure	psi
Q	Volumetric Flow Rate	gpm
S	Suction Specific Speed	rpm (gpm)$^{0.5}$/(ft-lbf/lbm)$^{0.75}$
u	Impeller Tip Speed	ft/sec
V	Pump Volume	cu in.
W	Weight	lb
ΔP	Total Pressure Rise in Pump Module	psi
η	Pump Hydraulic Efficiency	—
(η/η_o)	Efficiency Quotient	—
η_o	Adiabatic Efficiency	—
μ	Fluid Viscosity	lbm/sec-ft
π	Pi	3.14159

Symbol	Description	Dimensions
	Fluid Density	lbm/cu ft
	Flow Coefficient	—
	Head Coefficient	—
	Flow Rate	lbm/sec

2. Equations for Pump Math Model

The equations which essentially design a pump are presented in order of utilization.

2.1 Design Point Input Requirements

Type of Fluid, H_2 or O_2

Flow Rate $(\dot{\omega})$, lb/sec

Required Pressure Rise (ΔP), psi

Fluid Density (ρ), lb/ft^3

Net Position Suction Pressure Available (NPSP), psi

2.2 Source Information Required

Data presented in the AiResearch curves (Figs. 3-1 through 3-5) is to be reduced to equation form (mean values) for use in the model. Curves are appended at end of model.

2.3 Calculate N_{max}:

(a) If (NPSP) > 0,

$$N_{max} = (S) \left(449 \; \frac{\omega}{\rho}\right)^{-0.5} \left(\frac{144 \; [NPSP]_A}{\rho}\right)^{0.75}$$

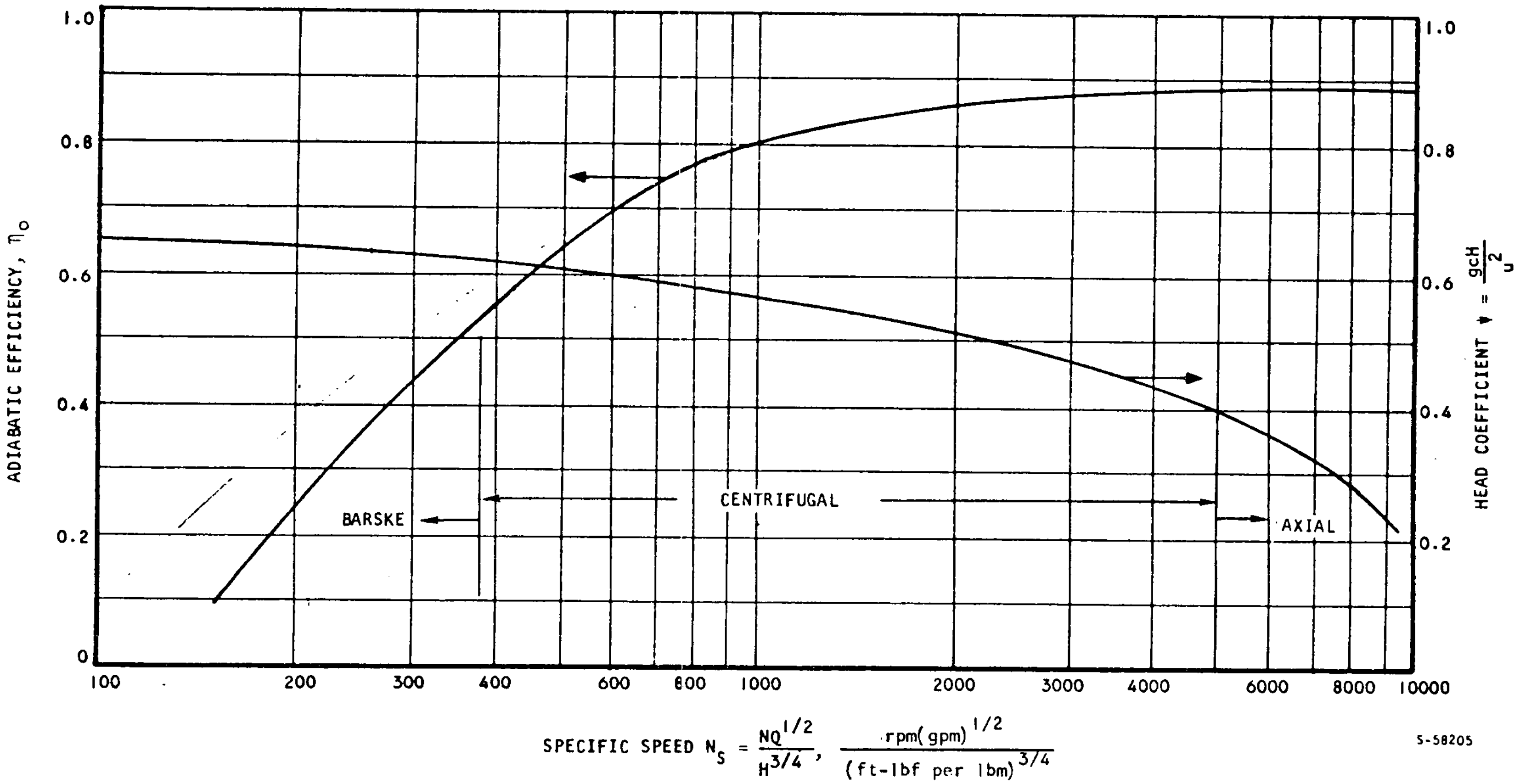


Figure 3-1. Pump Efficiency and Head Coefficient, at a Reynolds Number of 10^6

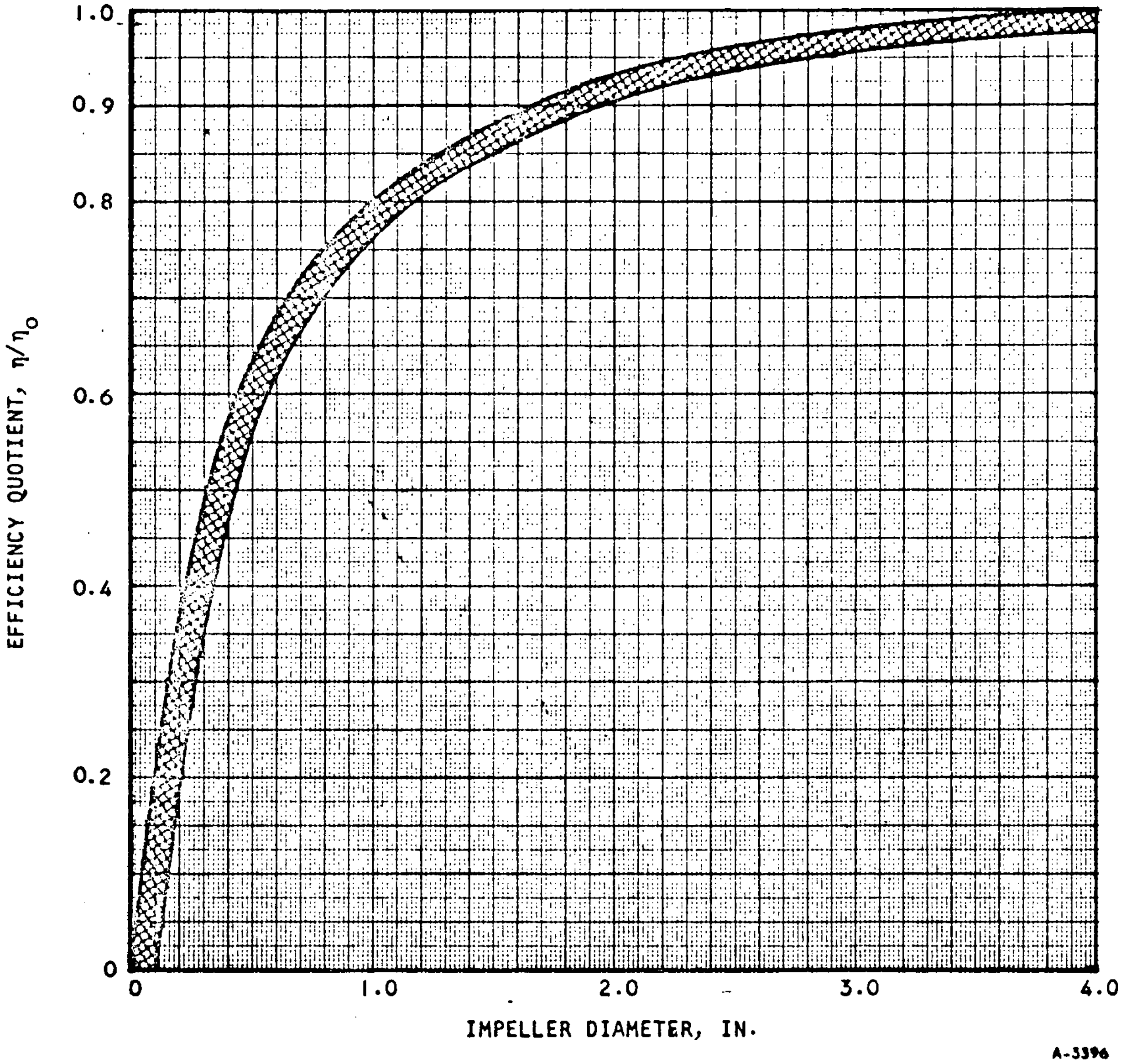


Figure 3-2. Effect of Impeller Size on Efficiency

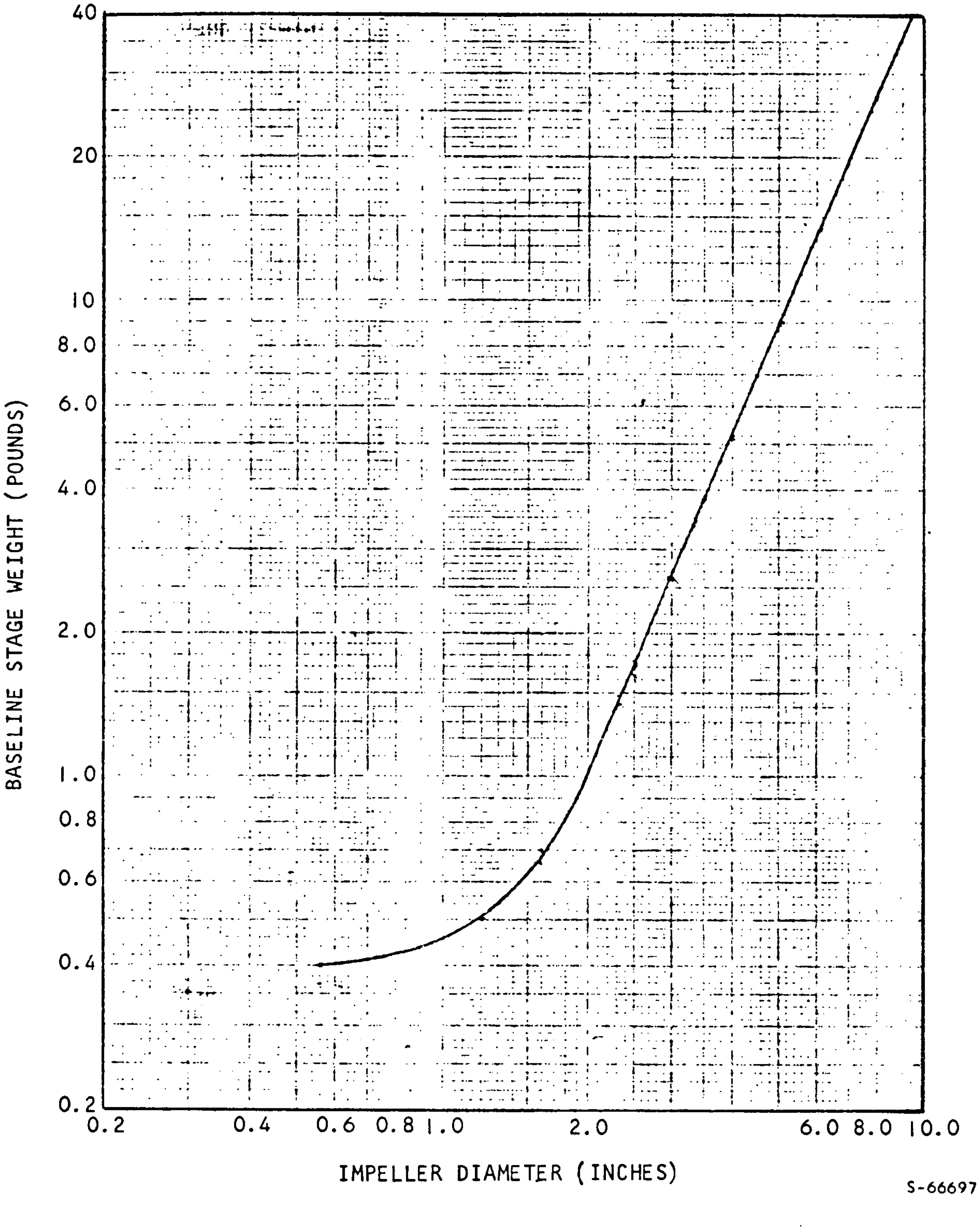


Figure 3-3. Baseline Pump Weights

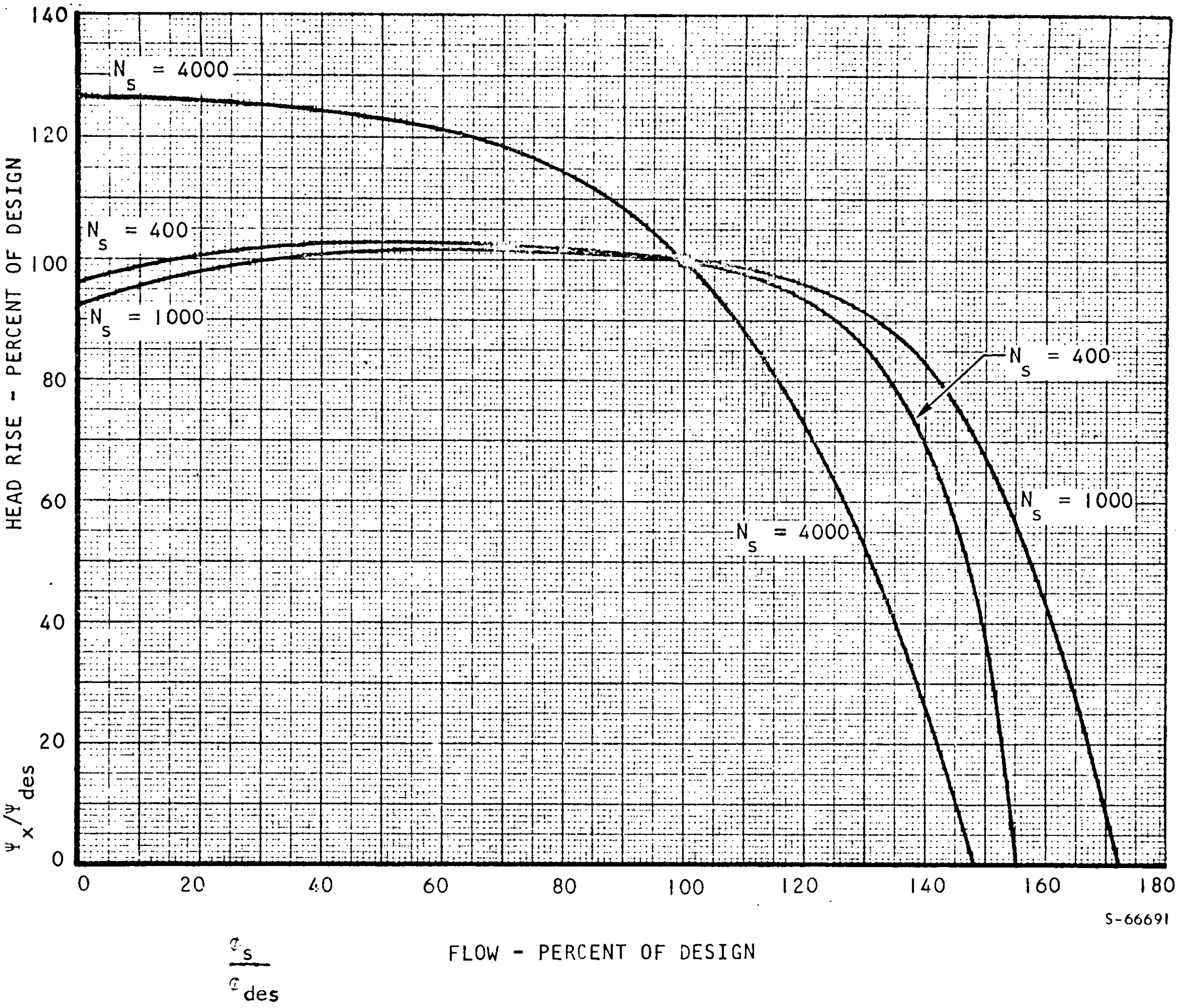


Figure 3-4. Normalized Head Coefficient vs Normalized Flow Coefficient for Off-Design Pump Performance

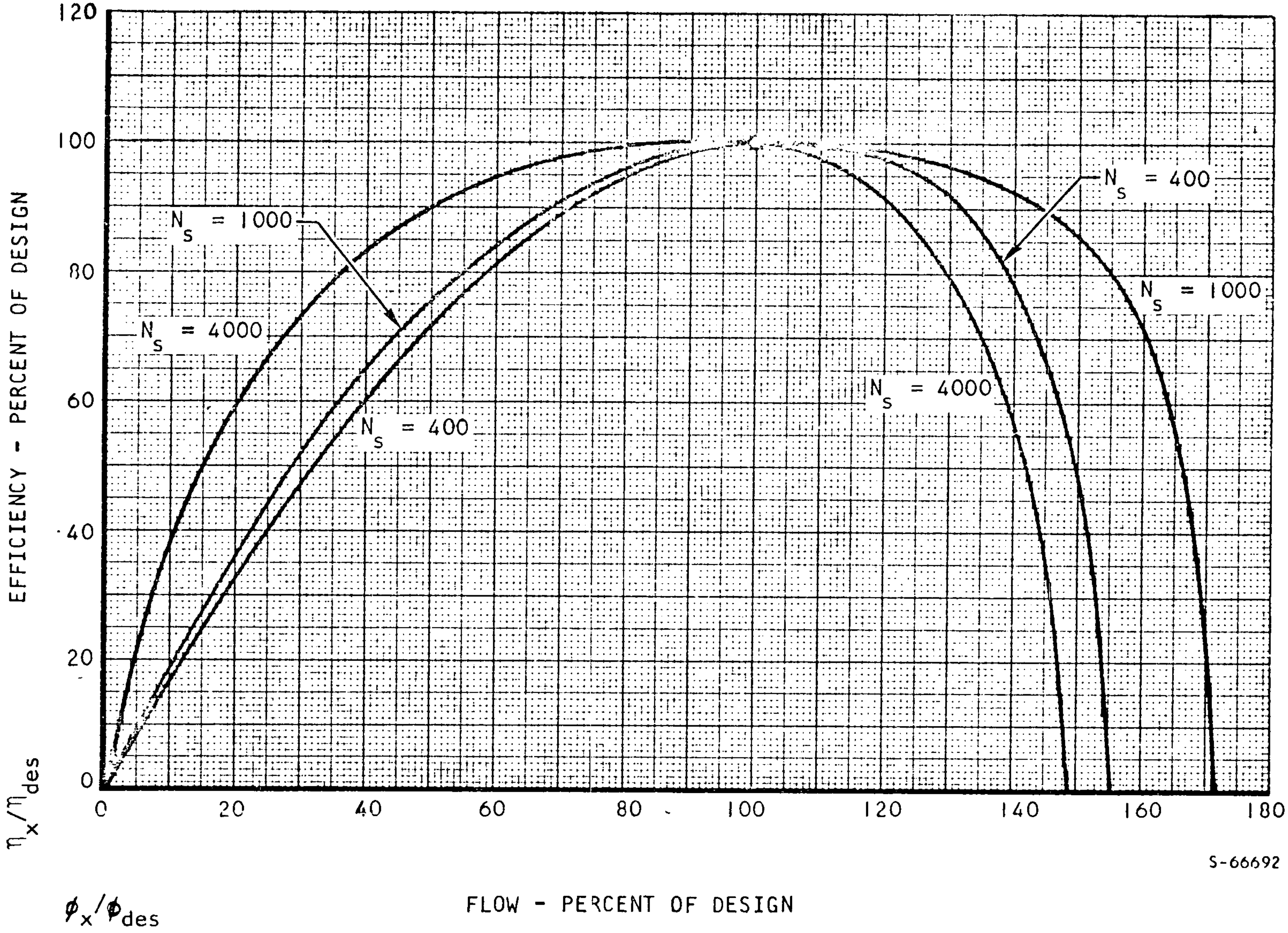


Figure 3-5. Normalized Efficiency vs Normalized Flow Coefficient for Off-Design Pump Performance

where

$S = 300{,}000$ for hydrogen

$S = 50{,}000$ for oxygen

If $N_{max} > 100{,}000$, set $N_{max} = 100{,}000$

(b) If $(NPSP)_A = 0$, set $N_{max} = 100{,}000$

2.4 Set Up Iteration for Computation of Number of Pump Stages (n)

Let $n = 1, 2, 3, 4, 5$ in that order, with 5 as the maximum number of stages. The iteration loop will encompass calculations 2.4 through 2.23 which follow.

2.5 Calculate Head Rise Per Stage

$$H = \frac{144\ \Delta P}{n\ \rho}$$

2.6 Calculate Specific Speed (Ns)

$$N_s = 0.508\ N\ (\rho)^{0.25}\ \frac{(\omega)^{0.5}}{(\Delta P)^{0.75}}$$

N = unknown

2.7 Find Head Coefficient (ψ)

$$\psi = \phi_1 (N_s)\ , \text{ from Fig. 3-1}$$

2.8 Find Adiabatic Efficiency (η_o)

$$\eta_o = \phi_2\ (N_s) \text{ from Fig. 3-1}$$

2.9 Find Impeller Tip Speed (u)

$$u = \left(\frac{32.2H}{\psi}\right)^{0.5} = \left[\frac{32.2H}{\phi_2\,(N_s)}\right]^{0.5}$$

2.10 Find Impeller Diameter (d)

$$d = \frac{229u}{N} = \frac{229}{N}\left[\frac{32.2H}{\phi_2\,(N_s)}\right]^{0.5}$$

N = unknown

2.11 Find Efficiency Quotient (η/η_o)

$$(\eta/\eta_o) = \theta_1\,(d)$$

From Fig. 3-2

$$(\eta/\eta_o) = \theta_1\left\{\frac{229}{N}\left[\frac{32.2H}{\phi_2\,(N_s)}\right]^{0.5}\right\}$$

2.12 Find Pump Hydraulic Efficiency (η)

$$\eta = (\eta/\eta_o)\;\eta_o = \left[\phi_2\,(N_s)\right]\left[\theta_1\left\{\frac{229}{N}\;\frac{32.2H}{\phi_2\,(N_s)}^{\;0.5}\right\}\right]$$

2.13 Find Values of N_s, N, and η

Maximize η as a function of N_s

η = η_{max}
N_s = value of N_s which provides η_{max}
N = value required to provide η_{max}

2.14 Is the value of N acceptable?

If $N \leq N_{max}$, go to operation 2.15.

If $N > N_{max}$, set $N = N_{max}$, and recalculate operations 2.6 through 2.12; then ship operation 2.13 and go to operation 2.15.

2.15 Calculate Pump Total Efficiency (t)

$$\eta_t = (\eta)\left(\frac{1}{1 + 0.05\,\frac{n-1}{n}}\right)$$

(η) is found by operation 2.12, unless modified by operation 2.14.

2.16 Identify Type of Pump

If $N_s \leq 375$, pump is type B.

If $375 < N_s \leq 5000$, pump is type C.

If $N_s < 5000$, pump is type A.

2.17 Calculate Pump Diameter (D)

If pump is type A or type C,

$$D = 1.7\ (d)$$

If pump is type B,

$$D = 1.4\ (d)$$

2.18 Calculate Pump Length (L)

If pump is type A or type C:

If $n = 1$:

For $d \leq 1.5$, $L = 2.5\,(d)$
For $1.5 < d \leq 2.0$, $L = 2.25\,(d)$
For $d > 2.0$, $L = 2.0\,(d)$

If $n = 2$:

For $d \leq 1.5$, $L = 3.5\,(d)$
For $1.5 < d \leq 2.0$, $L = 3.25\,(d)$
For $d > 2.0$, $L = 2.75\,(d)$

If $n \geq 3$:

For $d < 1.5$, $L = 3.5\,(d) + 0.5\,(d)\,(n-2)$
For $1.5 < d \leq 2.0$, $L = 3.25\,(d) + 0.5\,(d)\,(n-2)$
For $d > 2.0$, $L = 2.75\,(d) + 0.5\,(d)\,(n-2)$

If pump is type B:

If $n = 1$, $L = 2.0\,(d)$
If $n = 2$, $L = 3.0\,(d)$
If $n \geq 3$, $L = 3.0\,(d) + 0.5\,(d)\,(n-2)$

2.19 Calculate Pump Weight (W_t)

$$W_t = W_i + W_h + W_s$$

If pump is type A or type C,

$$W_i = 0.1\, n\, W_b \left(\frac{W}{W_b}\right)^{0.25}$$

$$W_h = 0.55\, W_b\, (n)^{0.33}$$

$$W_s = 0.35\, W_b \left(\frac{W}{W_b}\right)^{0.25} \left(\frac{P}{P_b}\right)$$

W_b is found from Fig. 3-3, vs (d)

W_b = 3.0 for hydrogen

W_b = 50.0 for oxygen

$$P = NPSP + \triangle P$$

P_b = 1000

If pump is type B,

$$W_i = 0.05\, n\, W_b$$

$$W_h = 0.35\, W_b\, (n)^{0.33}$$

$$W_s = 0.35\, W_b\, (n)^{0.75} \left(\frac{W}{W_b}\right)^{0.25} \left(\frac{P}{P_b}\right)$$

2.20 Calculate Pump Volume (V)

$$V = 0.25\, \pi\, D^2\, L$$

2.21 Calculate Pump Power (E)

$$E = \frac{W\,H\,n}{550\ \eta_t}$$

2.22 Calculate Net Positive Suction Pressure Required $(NPSP)_R$

$$(NPSP)_R = \frac{\rho (N)^{1.33}\ (Q)^{0.66}}{144\ (S)^{1.33}}$$

Ignore $(NPSP)_R$ for cases where $(NPSP)_A = 0$.

For cases where $(NPSP)_A > 0$, if $(NPSP)_R > (NPSP)_A$, set $(NPSP)_R = (NPSP)_A$ and solve above equation for N. Then recalculate operations 2.6 through 2.12 and 2.14 through 2.21.

2.23 Select Number of Stages in Pump (n)

(a) Discard any values of n for which $u > 1700$.

(b) Input which is of greater importance, W_t, V, or E.

(c) Select pump configuration and performance corresponding to the value of n which provides minimum W_t, V, or E, as selected in b above.

2.24 Off-Design Pump Performance

(a) This calculation may be used to determine off-design performance for any pump whose design point and physical configuration were determined by operations 2.1 through 2.23.

(b) Input AiResearch curves, Figs. 2-53, 2-54, and 2-55.

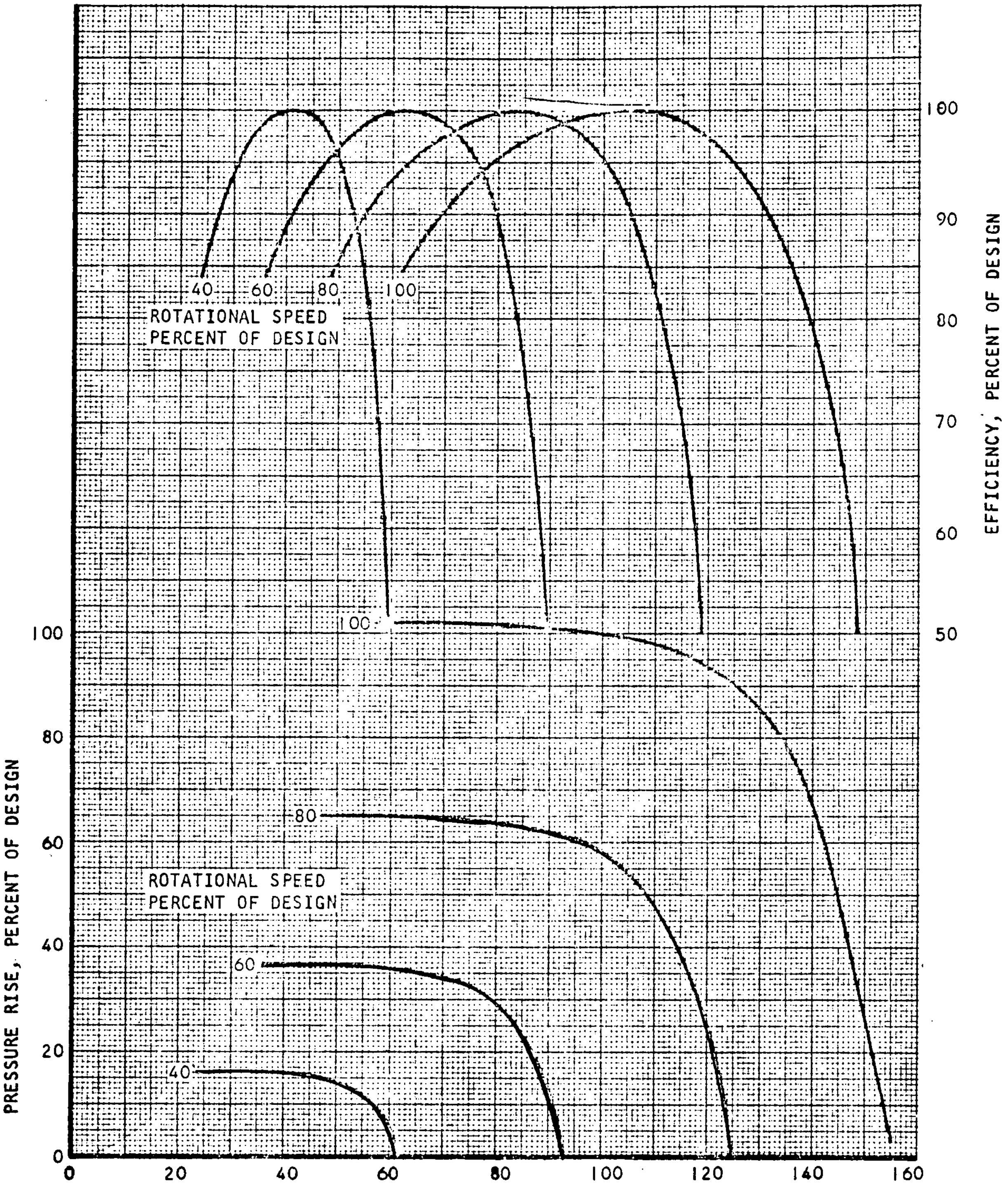


Figure 2-53. Off-Design Performance of Pumps Operating at a Design Specific Speed of 400 rpm

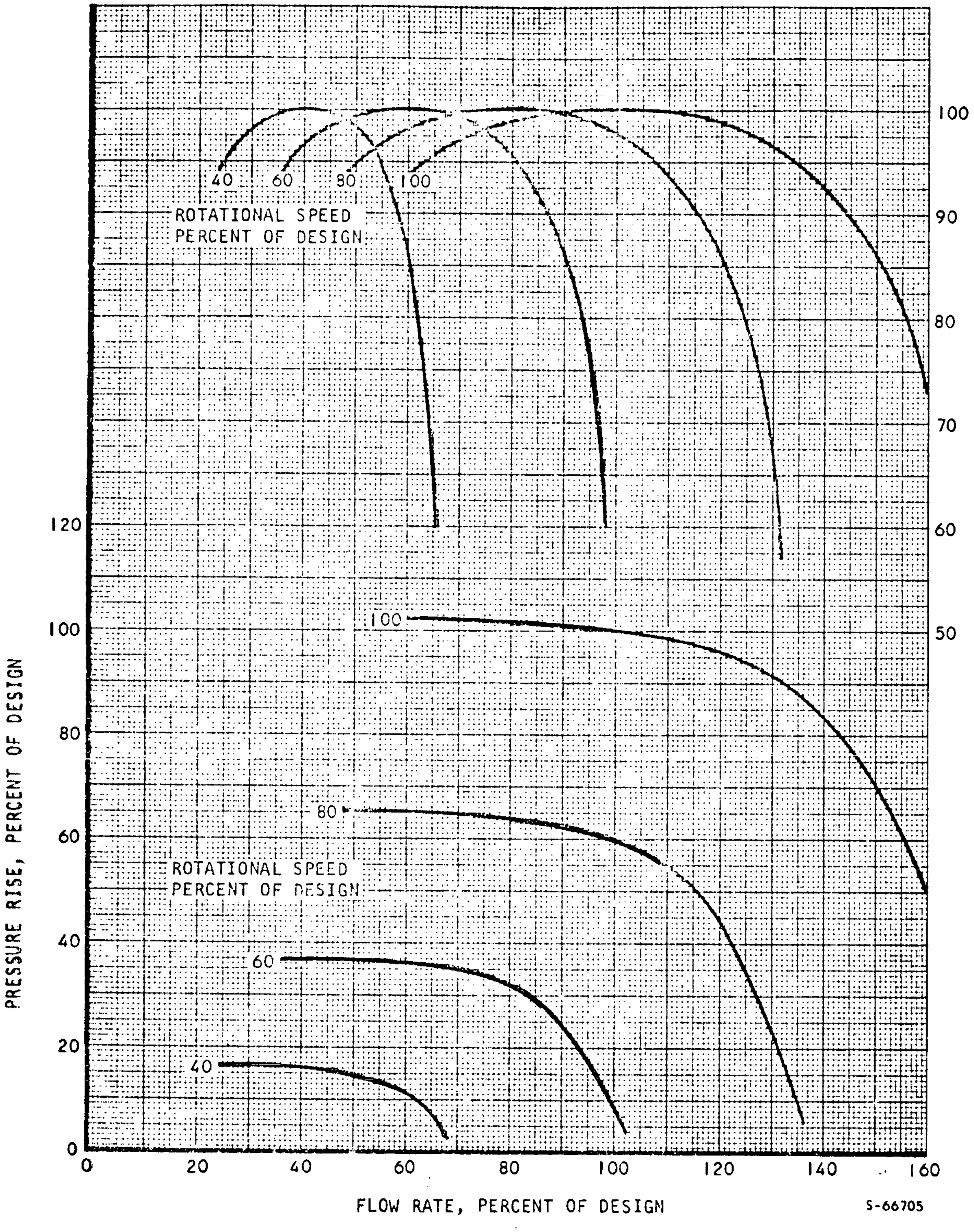


Figure 2-54. Off-Design Performance of Pumps Operating at a Design Specific Speed of 1000 rpm

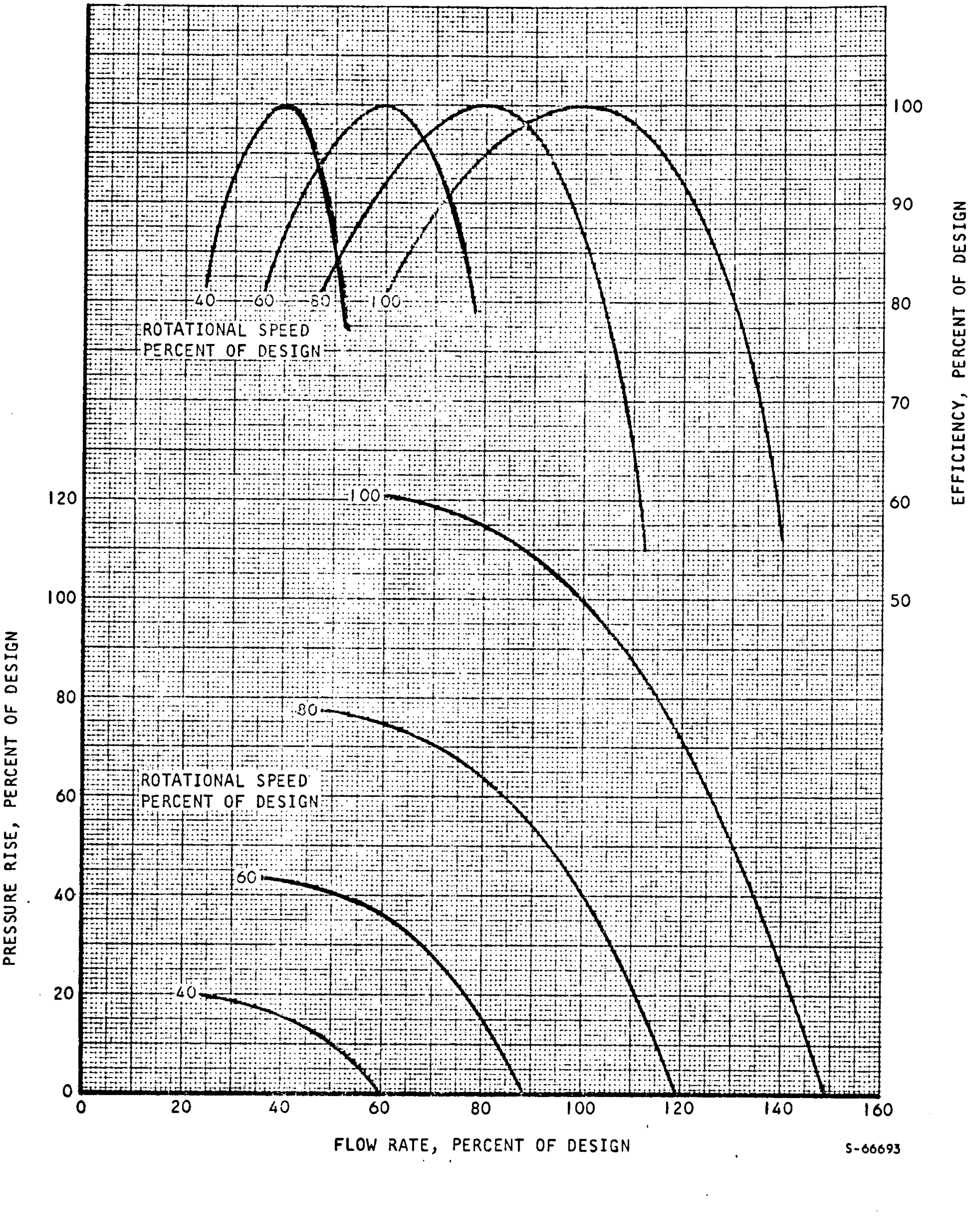


Figure 2-55. Off-Design Performance of Pumps Operating at a Design Specific Speed of 4000 rpm

(c) Input values of N_s and input two of the three parameters which follow:

W_X, ΔP_X, N_X :

$$N_s = \frac{(N)\left(449\,\frac{W}{\rho}\right)^{0.5}}{\left(\frac{144\,\Delta P}{n}\right)^{0.75}}$$

Subscript X denotes off-design condition.
Absence of subscript X denotes design condition.

(d) Calculate percent of design conditions:

Percent design flow rate $= 100\left(\frac{W_X}{W}\right)$ = percent W

Percent design pressure rise $= 100\left(\frac{\Delta P_X}{\Delta P}\right)$ = percent ΔP

Percent design rotational speed $= 100\left(\frac{N_X}{N}\right)$ = percent N

(e) Using N_s and the two available off-design parameters, interpolate between curves on Figs. 2-53, 2-54, and 2-55 as necessary to accommodate N_s , and find the value of the third off-design parameter and the off-design percent efficiency. (Interpolate linearly between N_s values and between N values).

(f) Check for acceptability of off-design operation at the point specified:

(1) If $(NPSP)_{A_X} = 0$:

Is $\left(\frac{W_X}{W}\right)^{0.5} \left(\frac{N_X}{N}\right) \leq 1.0$

$W_X = (\% \ W)\ (W/100)$

$N_X = (\% \ N)\ (N/100)$

If not, the pump cannot be operated at the off-design point specified.

(2) If $(NPSP)_{A_X} > 0$:

(a) Find $(NPSP)_{R_X}$:

$$(NPSP)_{R_X} = (NPSP)_R \left(\frac{W_X}{W}\right)^{0.666} \left(\frac{N_X}{N}\right)^{1.333}$$

(b) If $(NPSP)_{R_X} > (NPSP)_{A_X}$:

Is $\frac{W_X}{W}^{0.5} \frac{N_X}{N} \leq 1.0$

If not, the pump cannot be operated at the off-design point specified.

(c) If $(NPSP)_{R_X} \leq (NPSP)_{A_X}$:

Operation at the specified off-design point is permitted.

(3) If operation at the specified off-design point is acceptable, go to operation 24g.

(g) Calculation of off-design pump parameters:

(1) If percent ΔP was not an input for the off-design point, find

$$\Delta P_X = (\% \ \Delta P) \left(\frac{\Delta P}{100}\right)$$

(2) Find η_{t_X} :

$$\eta_{t_X} = (\% \ \eta_t) \left(\frac{\eta_t}{100}\right)$$

(3) Find pump power:

$$E_X = \frac{W_X \ (144 \ \Delta P_X)}{550 \ \rho \ \eta_{t_X}}$$

2.25 AiResearch Supplied Data

The AiResearch data supplied as curves in Ref. 1.9-6, are presented in the following pages. For use in the program, this data was reduced to equation form through the use of curve fitting routines.

MATH MODEL FOR SUBROUTINE TCOND

PURPOSE OF SUBROUTINE

To provide an integrated subprogram package which can compute the heat leak flux per unit cover for a variety of cryogenic insulation materials over the ranges of cryogen fluid and space-vehicle-ambient temperatures of interest in cryogenic systems analysis. Specifically, the subroutine is to encompass the following insulation materials:

DOUBLE ALUMINIZED MYLAR - SILK NET
DOUBLE GOLDIZED MYLAR - SILK NET
DOUBLE ALUMINIZED MYLAR - TISSUE GLASS
CRINKLED-DOUBLE ALUMINIZED MYLAR - TISSUE GLASS
NRC-2 CRINKLED SINGLE ALUMININZED MYLAR
SUPERFLOC
MICROSPHERES
POLYURETHANE FOAM
FIBERGLASS BATTING - HELIUM PURGED

SYMBOLS REFERENCED IN MATH MODEL

K_E	Effective Thermal Conducitivity (BTu/Hr.-Ft^2°R)
$\overline{N}$	Number of Radiation Shields Per Inch thickness of Insulation (layered material)
T_M	Mean Temperature (°R)
σ	Steten-Boltzman Constant ($0.1713*10^{-8}$ BTU/Hr-Ft^2-°R^4)
T_H	Hot Boundary Temperature (°R)
T_C	Cold Boundary Temperature (°R)
t	Apparent Insulation Thickness (FT)
N	Total Number of Radiation Shields $(12t*\overline{N})$
ϵ, ϵ_a, ϵ_b	Mean Emittance of the sides of the radiation shields
q	Heat leak flux per unit area (BTU/Hr-Ft^2)

The Math Model Equations

For a detailed discussion of the derivation of the general form of the equations which follow, the reader is referred to Reference 1.9-10. Specific sources for each of the following equations is given with the equation.

The equations given below are termed "installed insulation heat flux equations" since the data employed in the equations reflects test data from installed systems of insulation.

1. DOUBLE ALUMINIZED MYLAR/SILK NET (DAM/SN) SYSTEM: (Ref. 1.9-10)

$$K_E = 2.22 \times 10^{-9} \bar{N}T_M + \frac{\sigma (T_H^2+T_C^2)(T_H+T_C)t}{(N-1)\left(\frac{2}{\epsilon} - 1\right)}$$

Emittance: (Ref. 1.9-9, Fig. 4-2)

$$\epsilon_{DAM} = 4.40 \times 10^{-4} (T_M)^{0.667}$$

Heat Flux:

$$q = K_E \frac{T_H - T_C}{t}$$

2. DOUBLE GOLDIZED MYLAR/SILK NET (DGM/SN) SYSTEM: (Ref. 1.9-10)

$$K_E = 2.22 \times 10^{-9} \bar{N}T_M + \frac{\sigma (T_H^2+T_C^2)(T_H+T_C)\, t}{(N-1)\left(\frac{2}{\epsilon} - 1\right)}$$

Emittance: (Ref. 1.9-9, Fig. 4-3)

$$\epsilon_{DGM} = 8.76 \times 10^{-4} (T_M)^{0.509}$$

Heat Flux:

$$q = K_E \frac{T_H - T_C}{t}$$

3. DOUBLE ALUMINIZED MYLAR/TISSUE GLASS (DAM/TG) SYSTEM: (Ref. 1.9-10, Append. J)

$$K_E = 7.0 \times 10^{-12}(\overline{N})^2 T_M + \frac{1.7\sigma(T_H^2+T_C^2)\,(T_H+T_C)\,t}{(N-1)\,(\frac{2}{\epsilon} - 1)}$$

Emittance: (Ref. 1.9-9, Fig. 4-2)

$$\epsilon_{DAM} = 4.40 \times 10^{-4}\,(T_M)^{0.667}$$

Heat Flux:

$$q = K_E\,\frac{(T_H-T_C)}{t}$$

4. CRINKLED DOUBLE ALUMINIZED MYLAR/TISSUE GLASS (CDAM/TG) SYSTEM: (Ref. 1.9-10, Append. J)

$$K_E = 8.8 \times 10^{-12}(\overline{N})^2 T_M + \frac{1.7\,\sigma(T_H^2+T_C^2)\,(T_H+T_C)\,t}{(N-1)\,(\frac{2}{\epsilon} - 1)}$$

Emittance: (Ref. 1.9-9, Fig. 4-5)

$$\epsilon_{CDAM} = 4.90 \times 10^{-4}(T_M)^{0.67}$$

Heat Flux:

$$q = K_E \cdot \frac{(T_H-T_C)}{t}$$

5. NRC-2, CRINKLED SINGLE ALUMINIZED MYLAR (CSAM) SYSTEM: (Ref. 1.9-10, Append. J)

$$K_E = 2.0 \times 10^{-10}\,(\overline{N})^2 T_M + \frac{\sigma(T_H^2+T_C^2)\,(T_H+T_C)\,t}{(N-1)\,(\frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} - 1)}$$

Emittance:

$$\epsilon_a = \epsilon_{CSAM} = 4.90 \times 10^{-4}(T_M)^{0.67}$$ (Ref. 1.9-9, Fig. 45-)

$$\epsilon_b = \epsilon_{MYLAR} = 5.58 \times 10^{-3}(T_M)^{0.67}$$ (Ref. 1.9-9, Fig. 4-4)

Heat Flux:

$$q = K_E\,\frac{(T_H-T_C)}{t}$$

6. SUPERFLOC SYSTEM: (Ref. 1.9-10, Append. J)
(With constant modified to account for degradation)

$$K_E = 15.4 \times 10^{-11}(\overline{N})^2 T_M + \frac{\sigma(T_H^2+T_C^2)\ (T_H+T_C)\ t}{(N-1)\ (\frac{1}{\epsilon_a} + \frac{1}{\epsilon_b} -1)}$$

Emittance:

$\epsilon_a = \epsilon_{ALUM} = 4.40 \times 10^{-4}(T_M)^{0.667}$ (Ref. 1.9-9, Fig. 4-2)

$\epsilon_b = \epsilon_{NRS} = 0.41$ (Ref. CONVAIR supplied data)

Heat Flux:

$$q = K_E \frac{(T_H-T_C)}{t}$$

7. MICROSPHERES: (104 to 135 Dia. - = 5. lb/ft^3) (Ref. 1.9-12)

$$K_E = 1.56 \times 10^{-13}(T)^3 \left(1+ \frac{T_C}{T_H}\right) \left(1 + \frac{T_C^2}{T_H{}^2}\right)$$

Heat Flux:

$$q = K_C \frac{(T_H-T_C)}{t}$$

8. POLYURETHANE FOAM: (ρ = 2.0 lbs/ft^3) (Ref. 1.9-11, Sec 8.3.2, Figs. 8.3.2-1 through 8.3.2-6)

$$K_E = 1.1295 \times 10^{-3} + 3.4810 \times 10^{-5}(T_M)$$

Heat Flux:

$$q = K_E \frac{(T_H-T_C)}{t}$$

9. FIBERGLAS BATTING - HELIUM PURGED: (Ref. 1.9-11, Sec. 8.3.2, Figs. 8.3.2-10, 11, 12)

$$K_E = 1.3836 \times 10^{-3} (T_M)^{0.662}$$

Heat Flux:

$$q = K_E \frac{(T_H - T_C)}{t}$$

NOTE: Additional information relating to Microsphere insulation may be found in Ref. 1.9-13.

MATH MODEL FOR SUBROUTINE TANK

PURPOSE OF SUBROUTINE

Subroutine TANK provides in one subroutine the equations and iterative procedural steps which generate for all coast and burn periods, in the mission duty cycle, the tank pressure history, pressurization and vent requirements, propellant quantity history, and liquid and gas residuals quantities, from which the final tank size can be determined. The subroutine provides three pressurization options, as follows:

1. Self Pressurization
2. Cold Helium Pressurization
3. Vaporized Propellant

The subroutine performs the complete set of computations for the oxidizer tank subsystem first and then reports the entire cycle for the fuel tank subsystemm thus providing separate histories abd utilization data for each tank.

SUBPROGRAMS AND SYMBOLS REFERENCED IN MATH MODEL

Subroutines, functions, and data look-up Table numbers are referenced with the using equations contained in this math model. The asterisk (*) is used to imply multiplication, the slash (/) denotes division and the paranthesis ( ) serve to group a set of mathematical terms.

THE GENERALIZED MATH MODEL

The model presented herein is generalized to eliminate the many intermediate calculations which are readily discernible from the subroutine listing given in Appendix B, pages 277 through 287. The model is illustrated for each of the three pressurization options given above.

GENERALIZED INPUT REQUIREMENTS

P_i - Tank Pressure

T_i - Tank Temperature

V_i - Volume of Tank - Initial Est.

W_{pt} - Weight Liquid and Weight of Gas

τ_1 - Coast Interval One

θ_1 - Burn Interval One

$\dot{Q}$ - Heat Flux Into Tank

$\dot{w}$ - Fluid Flow Rate out of Tank

P_v - Tank Vent Pressure

P_{op} - Tank Operating Pressure

T_{PG} - Temperature of Pressurant Gas

e - Specific Internal Energy

1.0 SYSTEM 1 - SELF PRESSURIZATION:

1.1 Calculate Initial Effective Tank Density:

$$\rho_i = \frac{W_{PT}}{V}$$

1.2 Look-up Initial Energy Level:

$$e_i' = f\ (Pi,\ Pi)$$

Table 33 for O_2

Table 34 for H_2

1.3 Do Energy Balance for First Coast, τ_1

$$e_{\tau_1} = e_i + \frac{\dot{Q}\ \tau_1}{(W_{PT})_i}$$

1.4 Look up Resulting Pressure: P_{τ_1}

$$P_{\tau_1} = f\ (\rho_i,\ e_{\tau_1})$$

Table 36 for O_2

Table 37 for H_2

Store P_{τ_1}

1.5 Determine if $P_{\tau_1} > Pv$:

If Yes:

(a) Call subroutine VENT for values of WP and WPV

$$Wv = WPT - WP - WPV$$

(b) Set $P_{\tau_1} = Pv$

Store new P_{τ_1}

(c) Calculator ρ_{τ_1} :

$$\rho_{\tau_1} = \frac{(Wpt)_i - (Wv)_{\tau_1}}{V} = \frac{(Wp)_{\tau_1}}{V}$$

(d) Look up New Energy Level e_{τ_1} :

$$e_{\tau_1} = f\ (\rho_{\tau_1},\ P_{\tau_1})$$

Table 33 for 02

Table 34 for H_2

If No:

(a) Continue to next duty cycle Segment θ_1

1.6 Do Energy Balance for First Burn θ_1:

$$E_{\theta_1} = e_{\tau_1}\ (W_{pt})_{\tau_1} - (H_L)_{\tau_1}\ (\dot{w})_{\theta_1}\ (\theta_1)$$

$$(H_L)_{\tau_1} = f\ (P_{\tau_1})$$

Table 39 for O_2

Table 40 for H_2

Weight Propellant after the burn $(W_p)_{\theta_1}$:

$$(W_p)_{\theta_1} = (Wp)_{\tau_1} - (\dot{w}_{\theta_1}) * \theta_1$$

Internal Energy after the burn e_{θ_1}:

$$e_{\theta_1} = \frac{E_\theta}{(W_p)_{\theta_1}}$$

1.7 Calculate

$$\rho_{\theta_1} = \frac{(W_p)_{\theta_1}}{V}$$

1.8 Look up Resulting Pressure P_{θ_1} :

$$P_{\theta_1} = f\ (\rho_{\theta_1},\ e_{\theta_1})$$

Table 36 for O_2

Table 37 for H_2

Store P_{θ_1}

1.9 Do Energy Balance for Second Coast τ_2:

$$e_{\tau_2} = e_{\theta_1} + \frac{\dot{Q}\ \tau_2}{(W_p)_{\theta_1}}$$

1.10 Look up Resulting Pressure P_{τ_2} :

$$P_{\tau_2} = f\ (\rho_{\theta_1},\ e_{\tau_2})$$

Table 36 for O_2

Table 37 for H_2

Store P_{τ_2}

1.11 Determine If $P_{\tau_2} > Pv$

Continue through coast and burn intervals; τ_2, θ_2; τ_3, θ_3, ... τ_f, θ_f in same steps as 1.1 through 1.11, each time storing

P_{τ_1} , P_{θ_1}, P_{τ_2}, P_{θ_2} ....P_{τ_f}, P_{θ_f}

and $(Wv)_{\tau_1}$, $(Wv)_{\tau_2}$ ....$(Wv)_{\tau_f}$

1.12 Sum (Wv) for Each Fluid Tank:

$$(Wv)_{ToT} = \sum_{J=1}^{f} (Wv)_J$$

1.13 Calculate Parent Gas Residuals:

$$(W_{GR})_{Tank} = \frac{144 * P_{\theta_f} * V}{Z_{\theta_f} * R_p * T_{\theta_f}}$$

$T_{\theta_f} = f\ (P_{\theta_f})$ Function TSAT

$Z_{\theta_f} = f\ (T_{\theta_f}, IG)$ Subroutine ZFIND

$R_p = f\ (IG)$ Function FINDR

2.0 SYSTEM 2 - COLD HELIUM PRESSURIZATION:

2.1 Calculate Initial Effective Density:

$$\rho_i = \frac{W_{PT}}{V}$$

for O_2 & H_2

2.2 Look up Initial Energy Level:

$$e_i = f\ (\rho_i, P_i)$$

Table 33 for O_2

Table 34 for H_2

2.3 Do Energy Balance for First Coast:

$$e_{\tau_1} = e_i + \frac{Q * \tau_1}{(W_p)_T}$$

2.4 Look up Resulting Pressure P_1:

$$P_{\tau_1} = f\ (\rho_i, e_{\tau_1})$$

Table 36 for O_2

Table 37 for H_2

Store P_{τ_1}

2.5 Determine If $P_{\tau_1} \geq P_v$:

If Yes:

(a) Call Subroutine VENT, for values of W_{HE}, W_P, W_{PV}

$$(W_v)_{\tau_1} = (W_{PT})_i - (W_P)_i - W_{PV}$$

(b) Set $P_{\tau_1} = P_v$

Store New P_{τ_1}

(c) Calculate

$$\rho_{\tau_1} = \frac{(W_{PT})_i - (W_v)_{\tau_1}}{V} = \frac{(W_P)_{\tau_1}}{V}$$

(d) Look up New Energy Level e :

$$e_{\tau_1} = f(\rho_{\tau_1}, P_{\tau_1})$$

Table 33 for O_2

Table 34 for H_2

If No:

(a) Continue to next duty cycle Segment θ_1

2.6 Do Energy Balance For First Burn θ_1:

$$E_{\theta_1} = e_{\tau_1} * (W_P)_{T_1} - (H_L)_1 * (\omega)_{\theta_1} * \theta_1$$

$$(H_L)_{\tau_1} = f(\rho_{\tau_1})$$

Table 39 for O_2

Table 40 for H_2

Weight Propellant after the Burn $(W_P)_{\theta_1}$:

$$(W_P)_{\theta_1} = (W_P)_{\tau_1} - (\dot{\omega})_{\theta_1} * \theta_1$$

$$e_{\theta_1} = \frac{E_{\theta_1}}{(W_P)_{\theta_1}}$$

2.7 Calculate ρ_{θ_1}:

$$\rho_{\theta_1} = \frac{(W_P)_{\theta_1}}{V}$$

2.8 Look up Resulting Pressure P_{θ_1} :

$$P_{\theta_1} = f\ (\rho_{\theta_1},\ e_{\theta_1})$$

Table 36 for O_2
Table 37 for H_2

Store P_{θ_1}

2.9 Find Pressurant Required for θ_1:

$$(\rho_G)_{\theta_1} = f\ (IG,\ T_{\theta_1},\ P_{\theta_1})$$

Call GSZDNS

$$(\rho_L)_{\theta_1} = f\ (T_{\theta_1},\ IG)$$

Call RHØLIQ

$$(Vull)_{\theta_1} = V * \frac{(\rho_L)_{\theta_1} - \rho_n}{(\rho_L)_{\theta_1} - (\rho_G)_{\theta_1}}$$

$$(\dot{\omega}_{HE})_{\theta_1} = \frac{144. * (Pop - P_{\theta_1}) * (Vull)_{\theta_1}}{Z_{HE} * R_{HE} * T_{\theta_1} * \theta_1}$$

$$Z_{HE} = f\ (T_{\theta_1},\ P_{HE},\ IG)$$

IG = 17
Subroutine ZFIND

$$R_{HE} = f\ (IG)$$ Function FINDR

$$T\theta_1 = f\ (P_{\theta_1})$$ Function TSAT

$$P_{HE} = P_{op} - P_{\theta 1}$$

Store P_{HE} and P_{θ_1}

2.10 Do Energy Balance for Second Coast τ_2 :

$$e_{\tau_2} = e_{\theta_1} + \frac{Q^* \tau_2}{(W_p)_{\theta_1}}$$

2.11 Look up Resulting Pressure P_{τ_2}:

$$P_{\tau_2} = f\ (\rho_{\theta_1}, e_{\tau_2})$$

Table 36 for O_2
Table 37 for H_2

Store P_{τ_2}

2.12 Determine If $P_{\tau_2} > P_v$:

.
.
.
.

Continue through coast and burn sequence τ_1, θ_1; τ_2, θ_2; -------- τ_f, θ_f using steps 2.1 through 2.11, storing

$P_{\tau 1}$, P_{θ_1}; $P_{\tau 2}$, P_{θ_2} --------$P_{\tau f}$, $P_{\theta f}$

$(P_{HE})_{\tau 1}$, $(P_{HE})_{\theta 1}$,------------$(P_{HE})_{\tau f}$, $(P_{HE})_{\theta f}$

$(\dot{\omega}_{HE})_{\theta_1}$ ------------------$(\dot{\omega}_{HE})_{\theta_f}$

2.13 Sum Wv for Each Fluid Tank:

$$(W_V)_{ToT} = \sum_{J=1}^{f} (W_v)_J$$

2.14 Calculate Parent Gas Residuals:

$$(W_{GR})_{Tank} = \frac{144. \times P_{\Theta_f} * V}{Z_{\Theta f} * R_p * T_{\Theta_f}}$$

$T_{\Theta_f} = f(P_{\Theta_f})$	Function TSAT
$Z_{\Theta_f} = f(T_{\Theta_f}, IG)$	Subroutine ZFIND
$R_p = f(IG)$	Function FINDR

2.15 Calculate Pressurization System Weight:

(a) Sum Helium Quantities:

$$(W_{HE})_{ToT} = \sum_{J=1}^{f} (\dot{w}_{HE})_{\Theta_j} * (\Theta_j)$$

(b) Compute Helium System Weight:

$$(W_{PG})_{System} = B * (W_{HE})_{ToT} + C$$

$B = 1.5$ Scaling Low Factor

$C = 40.$ = Hardware Scaling Low Constant

3.0 SYSTEM 3 - VAPORIZED PROPELLANT PRESSURIZATION:

3.1 Calculate Initial Effective Density:

$$\rho_i = \frac{W_{PT}}{V}$$

For O_2 and H_2

3.2 Look up Initial Energy Level:

$$e_i = f(\rho_i, P_i)$$

Table 33 for O_2

Table 34 for H_2

3.3 Do Energy Balance for First Coast: τ_1

$$e_{\tau_1} = e_i + \frac{Q * \tau_1}{(W_p)_T}$$

3.4 Look up Resulting Pressure P_{τ_1}:

$$P_{\tau_1} = f(\rho_i, e_{\tau_1})$$

Store P_{τ_1}

Table 36 for O_2
Table 37 for H_2

3.5 Determine If $P_{\tau_1} > Pv$:

If Yes:

(a) Call Subroutine VENT for values at W_P, W_{pv}, etc.

$$(W_v)_{\tau_1} = (W_{PT})_i - (W_p)_i - W_{PV}$$

(b) Set $P_{\tau_1} = Pv$:

Store new P_{τ_1}

(c) Calculate ρ_{τ_1}:

$$\rho_{\tau_1} = \frac{(W_p)_T - (Wv)_{\tau_1}}{V} = \frac{(W_p)_{\tau_1}}{V}$$

(d) Look up New Energy Level e_{τ_1}:

$$e_{\tau_1} = f(\rho_{\tau_1}, P_{\tau_1})$$

Table 33 for O_2
Table 34 for H_2

If No:

(a) Continue to Next Duty Cycle Segment θ_1:

Assumption: The greatest gaseous fluid-mass-flux is required if complete paper-pressure collapse is assumed. This is a conservative assumption, but probably realistic for the shuttle since propellant orientation is not fixed at all times.

3.6 Do Energy Balance for First Burn: θ_1

$$E_{\theta_1} = \epsilon_{\tau 1} * (W_p) - (H_L)_{\tau_1} * (\dot{\omega})_{\theta_1} * (\theta_1)$$

$$(H_L)_{\tau_1} = f\ (P_{\tau_1})$$

Table 39 for O_2

Table 40 for H_2

Weight Propellant After the Burn $(W_p)_{\theta_1}$:

$$(W_p)_{\theta_1} = (W_p)_{\tau_1} - (\dot{\omega})_{\theta_1} * \theta_1$$

3.7 Calculate ρ_{θ_1}:

$$\rho_{\theta_1} = \frac{(W_p)_{\theta_1}}{V}$$

3.8 Look up Energy Level as if Tank were Maintained at Pop:

$$e_{\theta_1} = f\ (\rho_{\theta_1}, \text{Pop})$$

Table 33 for O_2

Table 34 for H_2

3.9 Calculate Total Energy of Tank at Pop:

$$(E_{\theta_1})_{Pop} = (e_{\theta_1})_{pop} * (W_p)_{\theta_1}$$

3.10 Calculate Pressurant Gas Flow Rate:

$$(\dot{\omega}_{PG})_{\theta_1} = \frac{(E_{\theta 1})_{pop} - E\ \theta_1}{C_{P_{PG}} * \left[T_{PG} - (T_P)_{Pop}\right] * \theta_1}$$

where:

$$(T_{\theta_i}) = (T_P)_{P_{cp}} = f\,(P_{OP}) \quad \text{Function TSAT}$$

$$CP_{PG} = f\left(\frac{T_{PG} + (T_P)_{POP}}{2}, P_{OP}, IG\right)$$

Subroutine GSUBP

3.11 Calculate Vented Propellant for τ_2:

Call Subroutine VENT, for values of W_P, W_{PV}, etc.

$$(W_V)_{\tau_2} = (W_{PT})_{\theta_1} - (W_P)_{\theta_1} - (W_{PV})_{T_2}$$

$$\rho_{T_2} = \frac{(W_P)_{\theta_1} - (W_V)_{T_2}}{V} = \frac{(W_P)_{T_2}}{V}$$

3.12 Look Up Energy Level for τ_2:

$$e_{T_2} = (\rho_{T_2}, P_{T_2})$$

3.13 Do Energy Balance for Burn Two: θ_2

o

o

o

o

Repeat process continuing through Coast and Burn sequence,

τ_3, θ_3 - - - τ_f, θ_f

The same as described in preceeding steps, each time storing pressures, flow rates, propellant weights, densities, etc.

3.14 Sum W_V for Each Tank Fluid:

$$(W_V)_{TOT} = \sum_{j=1}^{f} (W_v)_j$$

3.15 Calculate Parent Gas Residuals:

$$\left(W_{GR}\right)_{Tank} = \frac{144 * P_{ef} * V}{Z_{ef} * R_{P} * T_{Of}}$$

$T_{Of} = f\ (P_{ef})$ Function TSAT

$Z_{Of} = f\ (T_{Of},\ IG)$ Subroutine Z FIND

$R_{P} = f\ (IG)$ Function FINDR

3.16 Find Maximum Flowrate of Pressurant Gas Occurring over Duty Cycle:

$$\left(\dot{\omega}_{PG}\right)_{Max} = f\left(\dot{\omega}_{PGMX}, \left(\dot{\omega}_{PG}\right)_{\theta_j}\right]_{\theta_j = 1}^{\theta_j = f}$$

f = AMAX 1

3.17 Calculate Heat Exchanger Weight:

Call Subroutine HEATEX for heat exchanger weight and ΔP.

3.18 Calculate Weight of Gas Generator Propellant Required:

$$\left(W_{GG_P}\right)_{PG} = f\ \left(T_{PG},\ T_{O_{GG}},\ \dot{\omega}_{PG_{\theta j}},\ (P_{\theta j} + \Delta P)\right)\Bigg]_{\theta_j = 1}^{\theta_j = f}$$

Table 11 for O_2

Table 12 for H_2

3.19 Calculate Gas Generator System Weight:

Call GASGEN, for gas generator weight.

3.20 Calculate Mayman Meter Horsepower Required:

$$(HP_{max})_{PG} = \frac{144. * (\Delta P_{CP}) * (\dot{\omega}_{PGMX})}{550. * (0.5) \rho_{LIG}}$$

where: $\eta_m * \eta_p = 0.5$

$\rho_{LIG} = f(T_P, IG)$ Subroutine RHOLIQ

3.21 Lock Up Motor Weight for Circulating Pump Drive:

$$(W_{Motor}) = f(HP_{max}, \text{Motor Speed})$$

Table 16, for
O_2 motor and H_2 motor

3.22 If Motor is Battery Powered, find Battery Weight:

$$K_j = \frac{144 * \Delta P_{CP} * 776}{550 * (0.5) * \rho_L * 3600}$$

$$W_{B_i} = 0.0$$

$$W_B = \Big[W_B + \dot{\omega}_{PGO_j} * \theta_j \Big]_{\theta_j = 1}^{\theta_j = f}$$

$$W_{Batt} = W_B / \rho_E$$

Where:
ρ_E = Power Density of Battery

3.23 Determine Pressurization Circulating Pump Weight:

$$W_{CPPC} = f(\eta_p, NPSH, \Delta P_{CP}, \dot{\omega}_{PGMAX})$$

Table 14 for O_2
Table 15 for H_2

3.24 Determine Pressurization System Weight:

$$W_{SYS\ PG} = W_{HEX} + W_{GG} + W_{Motor} + W_{Batt} + W_{CPPG}$$

3.25 Calculate Gas Generator Propellant Weight Required by Species:

$$W_{H2_{GG}} = \left(W_{GGP}\right)_{PG} * \frac{1}{GG\ MRAT - 1}$$

$$W_{\phi 2_{GG}} = \left(W_{GGP}\right)_{PG} - W_{H2_{GG}}$$

MATH MODEL FOR SUBROUTINE TURBN

PURPOSE OF SUBROUTINE

To provide for the computation of the weight of a turbine drive unit for the subcritical cryogenic pumps. The subroutine is based upon data developed for NASA by a study contractor (Ref. 1.9-14).

SYMBOLS AND CONSTANTS REFERENCED IN THE MATH MODEL

SYMBOLS:

Np – Pump speed (rpm)
N_{SS} – Suction specific speed
NPSH – Net positive suction head (ft)
Q – Flow rate (gal/min)
D_T – Turbine rotor mean diameter (in.)
U – Turbine mean blade speed (ft/sec)
W_{PT} – Weight of power transmission element (lb)
Hp – Horsepower required by pump
W_R – Weight of turbine rotor (lb)
W_n – Weight of inlet manifold and nozzle (lb)

<u>Constants:</u>

H_2 turbine, mean blade speed = 1000 ft/sec
O_2 turbine, mean blade speed = 650 ft/sec
H_2 turbine, power trans element weight factor = 84.0
O_2 turbine, power trans element weight factor = 121.0

INPUT REQUIRED FOR MATH MODEL

IGAS = Fluid identify index, 1 = O_2 ; 2 = H_2
PSPD = Pump speed (rpm)
PMPØW = Pump power (Hp)

TGGDC = Turbine gas generator chamber pressure (psia)
PSTAGE = Number of pump stages

THE MATH MODEL EQUATIONS

1. Compute Turbine Rotor Mean Diameter

$$D_T = \frac{229\ U}{N_p}$$

2. Compute Weight of Power Transmission Element

$$W_{PT} = F \left(\frac{HP}{N_p} \right)^{0.439}$$

where

$F = 84.0$ for LH_2
$= 121.0$ for LO_2

3. Compute Weight of Turbine Rotor

$$W_R = 0.286 \left(\frac{D_T}{2.935} \right)^3$$

where

0.286 = density of rotor material (lb/in.^{3})

4. Compute Weight of Inlet Manifold and Nozzle

$$W_M = L\ W_R \left(\frac{P_{Ti}}{500} \right)^{0.3}$$

where

P_{TI} = TGGPC = Turbine inlet gas pressure

5. Compute Weight of Inducer

$$W_{INDCR} = 5.0 \text{ lb (Defined)}$$

6. Compute Weight of Turbine

$$\text{Stage Multiplier} = Q = 1$$

If, PSTAGE is greater than 1, then Q = 2.

$$W_{TRBN} = W_{PT} + W_R \times Q + W_M \times Q + W_{INDCR}$$

Appendix D

THE HYDRAZINE APU ANALYSIS PROGRAM (HZPR0G)

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CONTENTS

ILLUSTRATIONS

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TABLES

Section D-1
THE HYDRAZINE APU SYSTEM ANALYSIS PROGRAM (HZPROG)

D-1.1 INTRODUCTION TO HZPR0G.

The Hydrazine APU System Analysis Program utilizes the basic structures of the cryogenic Integrated Math Model Program to permit the analysis of a storable fuel power system. Modifications consisted of the deletion of many of the cryogenic oriented subprograms and the inclusion of five new subprograms for the processing of a hydrazine system and system configuration.

Basically, the program logic is unchanged from the description given in Vol. V B-1, and only minor changes were required in a few PDP elements to accommodate additional variables and new input data READ statements. In general, then, the information contained in Vol. V B-1 is applicable to program HZPR0G.

The program will size the Hydrazine APU system to fit the operating demands and duty cycle constraints and produces as output the component and system hardware size and weight, propellant (or reactant) weight, pressurant gas weight, and such analytical information (i.e., computed performance values) as may be desired. The analytical results are displayed both as time dependent data tabulations and summary table data.

D-1.2 PROGRAM LOGIC MODIFICATION

The major change in program logic arises from the necessity of adding a new system name sequence to the five existing sequences. This required coding changes in Subroutine C0NTR0L, CRYC0N and ST0DTA as well as alterations to the Procedure Definition Processor elements CNAMES, CAPU, and CCNTRL. The Data Table allocations were increased from fifty to fifty-five tables requiring changes in the Procedure Definition Processors CTAB and TABL0K.

D-1.3 PROGRAM SEQUENCING MODIFICATION

With the addition of the sixth system "HZN-APU" it was necessary to provide additional sequencing capability for subroutine CRYCØN.

D-1.3.1 Hydrazine APU Calculational Sequence

The subprogram which characterizes the Hydrazine APU system is subroutine HZAPU. This nearly self contained subprogram performs the system sizing calculations based upon the mass and energy transfer requirements of the input performance and mission duty cycle constraints.

The individual fluid circuit components and line segments are sized and weighed by subroutine HZNCMP which additionally supplies pressure drop calculations for the main fluid circuits. HZCMP is called directly by HZAPU.

For a Hydrazine APU analysis, subroutine CRYCØN has the values assigned, via input data, for SYSNUM, SCRIT and KSUBC (SYSNUM, I), as follows:

SYSNUM = 6
SCRIT = 1

and KSUBC (6, I).

The preprogrammed data statement stored in core by subroutine STØDTA for this system analysis is, (KSUBC(6, I), I = 1, 9)/12, 0. 0, 0, 0, 0, 0, 0, 0/.

The order of sub-program execution is as given in the following table:

Table 1.3-1

CRYCØN EXECUTION SEQUENCE FOR A HYDRAZINE APU SYSTEM ANALYSIS

Loop Pass	JKM Value	GØ TØ Statement	Subprogram Called
1	12	950	HZAPU
2	0	2200	Terminates Loop

When the internal loop is terminated CRYCØN calls subroutine ØTPWSM, outputs the weight summaries and returns to CONTRL for a new case, or termination of the program.

D-1.4 INPUT DATA – CARD DEFINITION AND DESCRIPTION

D-1.4.1 Hydrazine APU Input Data Card

Gp(o) – Card 1

The following variables are input on the Hydrazine APU input data card:

NAPU	Integer Number of APUs Available
HPR	Herse Power Rating of Single APU
PTRBIN	Turbine Inlet Pressure
PRAT	Turbine Pressure Ratio
PCRSRV	Percent Reserve Fuel Required for Mission
SPGPRS	Pressurant Gas Storage Pressure

The single card is usually identified by placing APU-1 in card columns 76-80.

D-1.4.2 Input Data Card Illustration

The card is illustrated in Figure D-1.4-1.

Prepared by:	Date	LOCKHEED MISSILES & SPACE COMPANY, INC.	Page Temp. Perm.
Checked by:	Date	Title HYDRAZINE APU INPUT DATA CARD	Model
Approved by:	Date		Report No. D-1.4-2

CARD TYPE Gp(o) Card - 1

CARD FUNCTION HYDRAZINE APU INPUT DATA

READ BY SUBROUTINE CØMPIL

FORMAT (I5, 5X, 5F10.0)

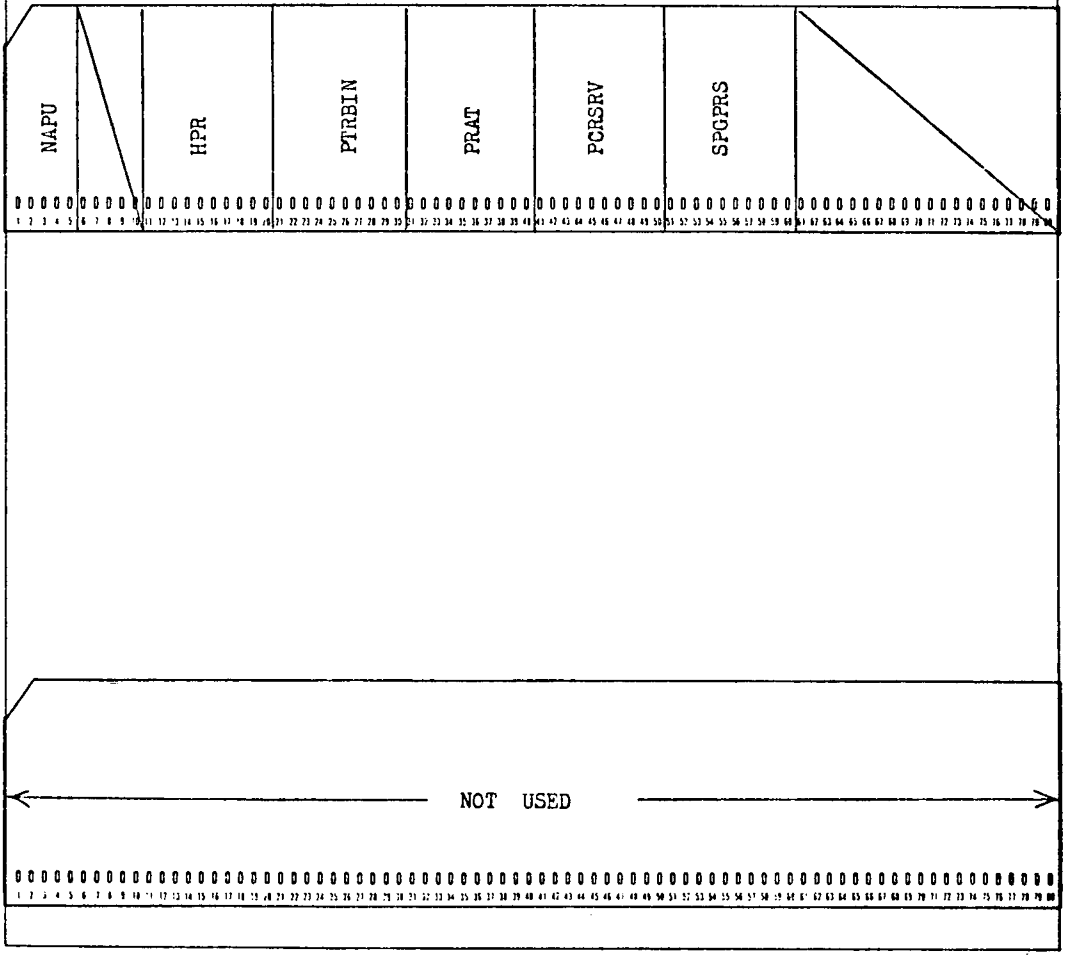

Figure D-1.4-1 Hydrazine APU Input Data Card

D-1.5 SUBROUTINE DESCRIPTIONS

This subsection contains the descriptions of the subroutines which are pertinent to the Hydrazine APU System Analysis. Subroutines not necessary to this analysis have been purged from the program file. The major subroutines for other systems have been dummied by retaining the element name and the RETURN and END statements. This procedure avoided extensive changes in the program basic structure.

D-1.5.1 SUBROUTINE HZAPU

DESCRIPTION

The subroutine contains the equations and computational techniques required for the characterization analysis of a positive expulsion hydrazine fueled APU system. The subroutine permits the computation of pertinent fuel and pressurant gas parameters required in the analysis and presents the calculated data in tabular format output. The following are the principal computations embodied in the subroutine:

a. Based upon the input APU duty cycle the subroutine determines for each duty cycle interval:

    Percent APU Power
    Rated Flow Rate
    Nominal Flow Rate
    Percent of Full Flow – Flowing
    Turbine Inlet Temperature
    Correction Factor for Nominal SPC
    Corrected Flow Rate Value
    Maximum Corrected Flow Rate

b. Total propellant consumed in mission

c. Propellant reserve for mission

d. Volume and surface area of propellant tank

e. Weight of tank pressure vessel, tank insulation and tank fluid expulsion device

f. Tank propellant and pressure history
g. Pressurant gas flow rate and quantity history
h. Weight of pressurant system by scaling law
i. Volume, surface area, diameter, weight of pressurant gas storage tank and tank insulation as calculated volumes.

System component weights and pressure drop calculations for the maximum propellant flow conditions are computed sequentially by subroutine HZNCMP, which is called by HZAPU.

Input data to subroutine HZAPU is read into the program by subroutine CØMPIL. The input data, required constants and computed parameter volumes are stored in labeled common preassigned storage areas defined by a set of Procedure Definition Processor elements. The labeled common groups employed for storage and data transfer are:

CØMMØN/CIAPU/
CØMMØN/CVAPU/
CØMMØN/CCNTRL/
CØMMØN/CDCYCL/
CØMMØN/CENG/
CØMMØN/CIØUNT/
CØMMØN/CMATRL/
CØMMØN/CTANK/
CØMMØN/TABLØK/
CØMMØN/CPAGE/

HZAPU MATHEMATICAL MODEL

The equations, mathematical procedures, necessary tables and constants required are presented in the HZAPU MATH MODEL, Section D-1.6.

CALLING SEQUENCE

Subroutine HZAPU is initiated via a simple call from Subroutine CRYCØN. No calling arguments are employed. Data transfer to HZAPU is accomplished through the use of INCLUDE statements as shown in the subroutine listing. Completion of the HZAPU calculations return sequential control of the program to CRYCØN.

SIGNIFICANT VARIABLES

Significant variables processed by subroutine HZAPU are as follows:

Name	Type	I/Ø	Dimension	Description
NAPU	I	I	1	Number of APU units
HPR	R	I	1	Horsepower rating of APU (HP)
TØTHPR	R	Ø	1	Total horsepower available (HP)
WD	R	Ø	20	Nominal propellant flow rate (lb/min)
PCTHP	R	Ø	20	Percent of total horsepower available (%)
PCWDØT	R	Ø	20	Percent of total flow rate (%)
WDØTR	R	Ø	20	Propellant flow rate at SPCR (lb/min)
SPCR	R	C	20	Specific propellant consumption at rated APU horsepower (lb/HP-hr)
SPCN	R	C	20	Specific propellant consumption at nominal APU horsepower (lb/HP-hr)
PTRBIN	R	I	1	Turbine inlet pressure (psia)
PRAT	R	I	1	Turbine pressure ratio
PAMB	R	I	20	APU outside ambient pressure (psia)
HP	R	I	20	Nominal APU horsepower/duty cycle interval
NEØP	I	I	20	Number of operating APU units
GGXTM	R	C	20	Turbine inlet temperature in given duty cycle interval (^{o}R)
CFSPC	R	C	20	Correction factor for propellant flow rate due to catalyst bed exit temperature
WDC	R	Ø	20	Corrected propellant flow rate (lb/min)
TIPWT	R	Ø	1	Total propellant for APU turbine (lbs)
WDØT	R	C	1	Max. propellant flow rate in all duty cycles (lb/min)
WDØTI	R	Ø	2	Max. fluid flow rate in all duty cycles (lb/min)
NDCYCL	R	I	100	Duty cycle intervals (min)
VØTNK	R	Ø	1	Volume – propellant tank (cu ft)
ARTNK	R	Ø	1	Surface area – propellant tank (sq ft)

Name	Type	I/0	Dimension	Description
WTPV	R	0	1	Weight of tank pressure vessel (lbs)
WTBLAD	R	0	1	Weight of expulsion device (lbs)
WTT0T	R	0	22	Weight of tank assembly (lbs)
TIWT	R	0	2	Tank insulation weight (lbs)
WTRES	R	C	1	Weight reserve fuel (lbs)
WPT0T	R	0	2	Total fluid loaded (lb)
RH0HZN	R	C	1	Density of hydrazine (lb/cu ft)
FTUX	R	C	1	Ultimate strength – tank material
RH0FTZ	R	C	1	Material density over F_{TU}
WPREM	R	0	20	Weight fuel removal in each duty cycle (lbs)
V0LDP	R	C	1	Volumatic fuel depletion each duty cycle (cu ft)
V0LDPS	R	C	1	Summed vol. fuel depletion (cu ft)
V0LRM	R	0	20	Volume fuel remaining each duty cycle (cu ft)
PHE	R	C	1	Helium pressure in expulsion device
THE	R	C	1	Helium temp. in expulsion device
WDTHE	R	0	20	Helium flow rate each duty cycle (lb/min)
WHEAD	R	0	20	Weight helium consumed each duty cycle (lb)
WHESUM	R	0	1	Total helium consumed (lb)
WDHEMX	R	0	1	Max. helium flow rate any duty cycle (lb/min)
WT0TPG	R	0	1	Pressurant gas system est. wgt from scaling law (lb)
V0TKHE	R	0	1	Volume helium tank (cu ft)
ARTKHE	R	0	1	Surface area helium tank (sq ft)
DITKHE	R	0	1	Diameter helium tank (inches)
WTHETK	R	0	1	Weight at helium tank (lb)

SUBPROGRAMS REFERENCED IN HZAPU

Name	Type	Purpose	Reference
MIPE	F	Table Data Extraction	Page B-221
PAGE	F	Controls Pagination and Line Count	Page B-239
FINTAB	S	Finds Designated Table at Data	Page B-147
ZFIND	S	Computes Compressibility of Desired Fluid at Specified Temp. and Pressure	Page B-334
FINDR	F	Finds Gas Constant for Specified Fluid	Page B-140
HZNCMP	S	Does Configuration Analysis for Hydrazine APU System	Page D-93

SUBPROGRAMS REFERENCING HZAPU

Name	Type	Purpose	Reference
CRYC0N	S	Sequential Control of Designated System Analysis	Page D-83

LISTING REFERENCE PAGE

A listing of Subroutine HZAPU will be found in Section D-3.0, page D-86.

FLOW CHART

The flow chart for Subroutine HZAPU will be found in Fig. D-1.5-1.

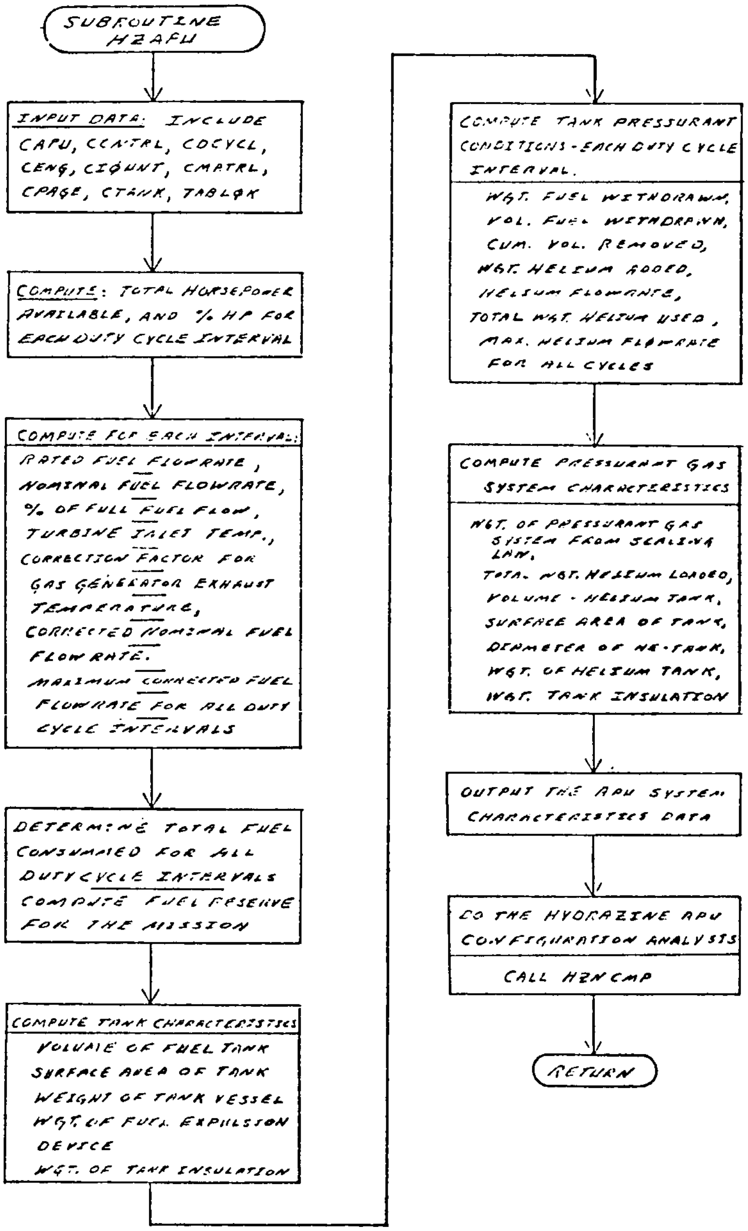

Figure D-1.5-1 Flow Chart for Subroutine HZAPU

D-1.5.2 SUBROUTINE HZNCMP

DESCRIPTION

Subroutine HZNCMP is coded to perform sizing and weight analysis for all of the component units which make up the hydrazine APU system configuration. The system configuration is defined as the computer image of the system main flow schematic diagram wherein all components and line segments are arranged in the normal logical sequence. The subroutine requires that each system or subsystem fluid segment begin with a data entry which flags the fluid kind and state and further requires that when a fluid state changes (i.e., gas to liquid), a second data entry flag must be available.

The subroutine is structured to process an APU system which utilizes Hydrazine and Helium as working fluids. The logic employed requires that the configuration data be entered starting with the fluid consumer and working back to the fluid storage tanks, thus permitting the accumulation of pressure drop data in an orderly fashion.

Subroutine HZNCMP is employed for the evaluation of a two fluid system and is arranged to process the fuel handling subsystem first, followed by the pressurization subsystem. It can, however, process either subsystem, or, just one subsystem, depending upon the setting of the input fluid flag variables. The program calls in required sub-programs as needed for the sizing and weighing of the individual components and line segments as they are encountered in the configuration sequence. The HZNCMP analysis procedure is based upon accomplishing a one-by-one analysis of the sequential component stream defined by the configuration table as read-in by subroutine CØMPIL. Based upon the input data, the subroutine accomplishes the computation of the individual component sizing, weight, pressure drop and flow constraint data and presents the calculated values in tabular formatted output as a "Summary of Computed System Configuration Parameters."

The principal computations accomplished in subroutine HZNCMP are as follows:

a. The subroutine first initializes a set of flag and summation variables and starts the configuration loop by calling for the decoding of first branching variable as entered from the first configuration data card. The primary branching control variables employed are CFUNCT and CFTYPE as defined in subroutine CØMPIL and PDP-CONFIG. The branching variable CFUNCT contains the coding for (in successive data entries), the fluid identification, consumer identification and, in turn, each component unit sequentially considered in the system. The secondary branching control variable CFTYPE successively contains the coding for, the fluid state, the consumer characteristic type, and, in turn, the controlling characteristics of each component unit sequentially considered in the system configuration. Subroutine branching to the specified component analysis region of the coding is accomplished via a computed GØ TØ statement, controlled by the variable CFUNCT.

b. The subroutine identifies the fluid to be considered and identifies its state condition and then initializes the sequential indices.

c. Identifies the fluid consumer and sets up the consumer fluid flowrate, fluid pressure and fluid temperature with their respective sequential indices. At this point the actual configuration analysis is begun.

d. The subroutine then processes a line segment (whenever called for by CFUNCT) through the sequence of the line analysis to compute – flow conditions, pressure drop and line weight. Fano-flow, velocity effects, as well as minimum wall thickness are all taken into consideration in the analysis.

e. Processes a control unit (valve, check valve, orifice, regulator, or flowmeter) through the sequence of the control analysis to compute flow conditions, pressure drop, and control weight. Mass characteristics as a function of pressure requirements for the control unit are specified in the "tens" digit of CFTYPE. Selection of the type of control unit is made via the "units" digit of CFTYPE, as defined in PDP-CCNFIG.

f. The subroutine processes a fitting or tap in much the same fashion as for the line segment analysis, taking into account the flow geometry effects. Computes the flow conditions, pressure drop and fitting or tap weight.

g. The subroutine then processes a fluid supply tank, first setting up the tank temperature and pressure. The actual tank weight for each fluid tank has been calculated previously in subroutine HZAPU, and subroutine HZNCMP simply retrieves the weight value from common storage. HZNCMP performs a check to see if the tank pressure is adequate for the system pressure drop total at the tank outlet.

h. The subroutine outputs the computed configuration component data in a tabular formatted output with all components identified and in the same sequence as given in the original system schematic.

Input data for use in subroutine HZNCMP is read-in at program initiation time via subroutine C0MPIL from the configuration data cards. Data from each card is stored in a packed array by subroutine ST0C0N using equivalenced array variables defined in the Procedure Definition Processor CCNFIG. Retrieval of the data is accomplished in HZNCMP via repeated calls to subroutine GETC0N which unpacks the data as needed.

The input data and subprogram computed parameter values are stored in various regions of the labeled C0MM0N storage defined by PDP elements. The labeled common storage employed by the subroutine are as follows:

C0MM0N/CAPU/
C0MM0N/CCNFIG/
C0MM0N/CCNTRL/
C0MM0N/CDCYCL/
C0MM0N/CENG/
C0MM0N/CI0UNT/
C0MM0N/CNAMES/
C0MM0N/C0NST/
C0MM0N/CPAGE/
C0MM0N/CTANK/
C0MM0N/TABL0K/

HZNCMP MATHEMATICAL MODEL

The math model for subroutine HZNCMP presenting the equations, math logic, and procedures are presented in Section D-1.6.

CALLING SEQUENCE

The subroutine is initiated by a simple call statement with no calling variables from subroutine HZAPU.

Data transfer to and from subroutine HZNCMP is effected through the use of INCLUDE statements which bring in the appropriate PDP elements defining the required labeled

C0MM0N storage areas. Upon completion of the HZNCMP computations, the program control returns to subroutine HZAPU.

SIGNIFICANT VARIABLES

Significant variables employed in, and processed by, subroutine HZNCMP are defined in the following list:

Name	Type	I/0	Dimension	Description
ICNF	I	I	1	Number of configuration data cards input
IDX	I	0	1	Configuration item index
ISIGN	I	0	1	Analysis directional index
CFUNCT	I	I	1	Integer Corresponding to Configuration Item Function
CFTYPE	I	I	1	Integer Corresponding to Function Type
CMTYPE	I	I	1	Integer Corresponding to Material Type
CITYPE	I	I	1	Integer Corresponding to Insulation Type
CN0PER	I	I	1	Number of APU units operating
CNSTBY	I	I	1	Number of APU units on standby
FRC0EF	R	C	100	Characteristic Friction Factor for Flow Region
L0D	R	I	100	Length over Diameter, or, Length
DIAM	R	I	100	Diameter
ITHIK	R	I	100	Insulation Thickness
NBAR	R	I	100	Number of Layers of Insulation per Inch
C0DE	R	I	100	Identification Code for Config. Unit
IGAS	I	I	1	Integer Corresponding to Fluid Kind (N_2H_4 or Helium)
GSTATE	I	I	1	Integer Corresponding to Fluid State (Gas or Liquid)
PRES	R	0	100	Fluid Pressure at Each Point in System
TEMP	R	0	100	Fluid Temp. at each point in System
WD0TN	R	0	100	Fluid Flowrate at each print in system
WD0TI	R	I	2	Input Fluid Max. Flow Rate at Consumer
FLD	R	0	1	$\frac{fL}{D}$ for Configuration Unit Considered

Name	Type	I/0	Dimension	Description
IDV	I	I	1	Integer Pointer for Control Mass Characteristic
LDV	I	I	1	Integer Pointer for Fitting and Tap Configuration
RH0	R	0	1	Fluid Density when a gas
DELP	R	0	1	Fluid Pressure Drop across Component
A	R	0	1	Cross Sectional Area of Flow Region
WEIGHT	R	0	1	Weight of Configuration Component Considered
INDXTK	I	0	2	Fluid Tank Index-Set to IDX
SIPRES	R	I	2, 1	Fluid Tank Initial Pressure
SITEMP	R	I	2, 1	Fluid Tank Initial Temperature
WTT0T	R	I	2	Fluid Tank Weight
MACH	R	0	100	Fluid Mach No.
MFLG	I	0	100	Fluid Mach No. Flag
S0PRES	R	I	2, 1	Tank Operating Pressure
SPGTEM	R	I	2, 1	Pressurant Gas Temperature
SPGPRS	R	I	1	Pressurant Gas Pressure
WTBLAD	R	C	1	Expulsion Device Weight
FLMU	R	C	1	Fluid Viscosity
VELCTY	R	C	1	Fluid Velocity
REYNUM	R	C	1	Reynold Number for Flow Conditions
RH0HZN	R	C	1	Density of Hydrazine
IDV	I	I	1	Flow Control Component Type Weight Classification Index
LDV	I	I	1	Flow Handling Component Geometry Description Index

SUBPROGRAMS REFERENCED IN HZNCMP

Name	Type	Purpose	Reference
PAGE	F	Controls Pagination and Line Count	Page B-239
GETC0N	S	Unpacks Configuration Data Records	Page B-174
AMINI	F	Finds Minimum of Two Real Values	System Library
VGVSHE	S	Computes Mach Number for Helium Fluid at Stated Fluid Density Using Velocity of Sound Equations	Page D-108

Name	Type	Purpose	Reference
LWEGHT	S	Computes Weight of a Line Segment Considering Minimum Wall Thicknesses	Page B-215
HZCVCW	F	Computes Weight of a Valve or Fitting as Specified	Page D-92
EXIT	S	Causes Program Termination – Used to Terminate from Error Condition	System Library
ABS	F	Computes Absolute Value of Defined Variable	System Library
FINTAB	S	Table Location and Look-up	Page B-147
MIPE	F	Table Data Extraction	Page B-221

DATA TABLES REFERENCED IN HZNCMP

Table Number	Title
51	Viscosity of Hydrazine
52	Viscosity of Helium

SUBPROGRAMS REFERENCING HZNCMP

Name	Type	Purpose	Reference
HZAPU	S	Analysis of Hydrazine APU	Page D-86

LISTING REFERENCE PAGE

The subroutine Listing will be found in Section D-3.0, page D-93.

FLOW CHART

A flow chart for subroutine HZNCMP is presented in Figure D-1.5-2.

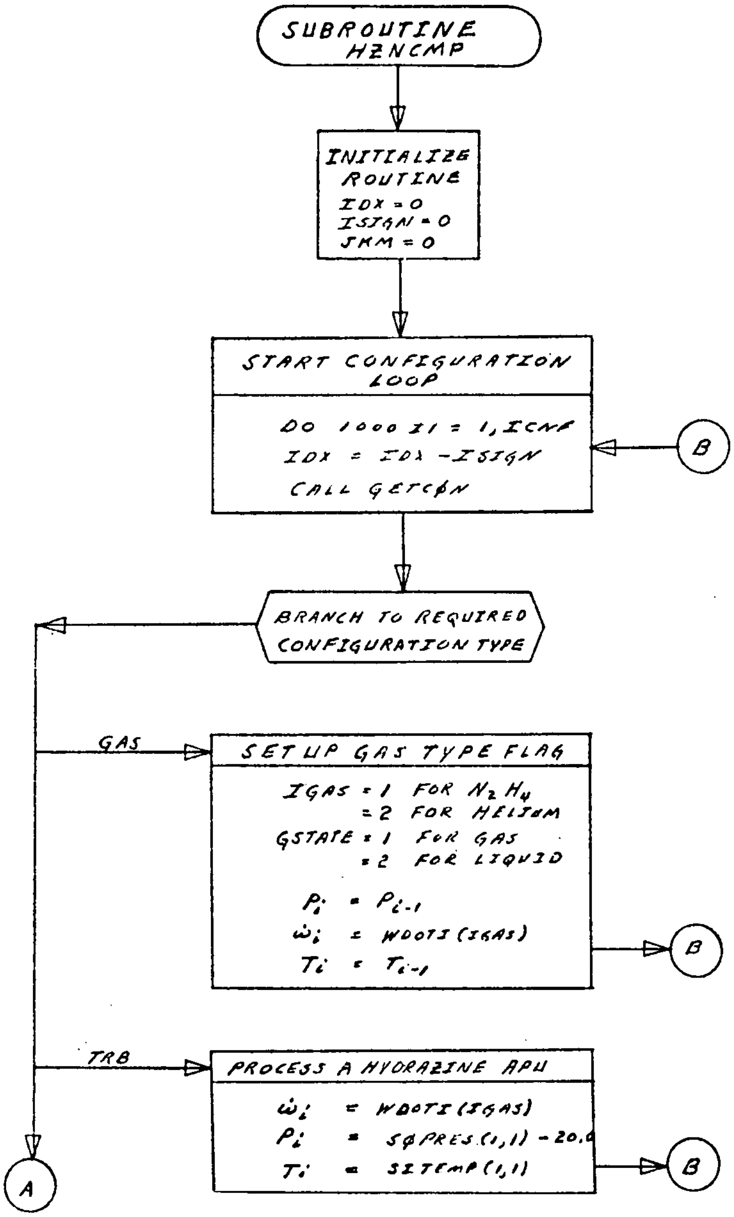

Figure D-1.5-2 Flow Chart for Subroutine HZNCMP (Sheet 1)

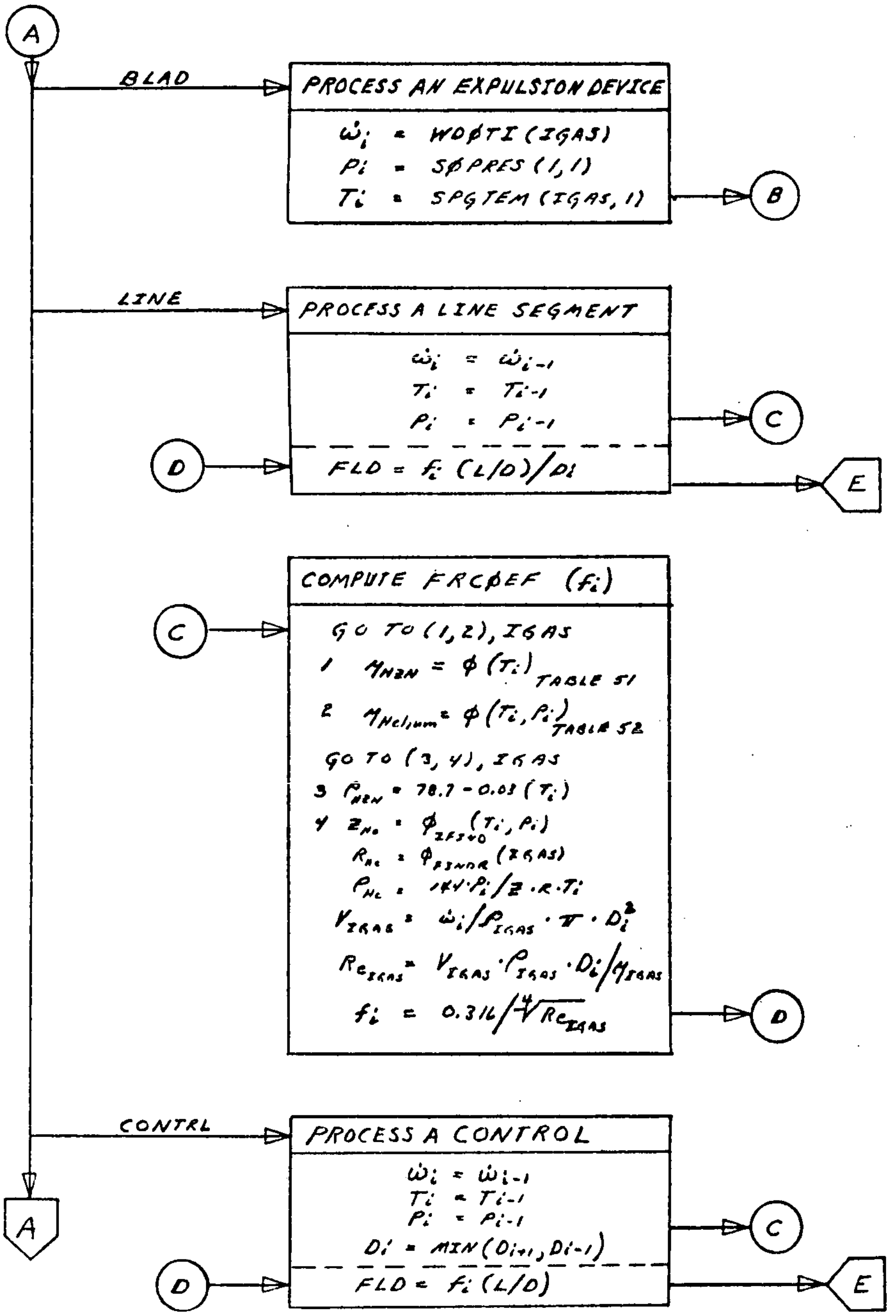

Figure D-1.5-2 Flow Chart for Subroutine HZNCMP
(Sheet 2)

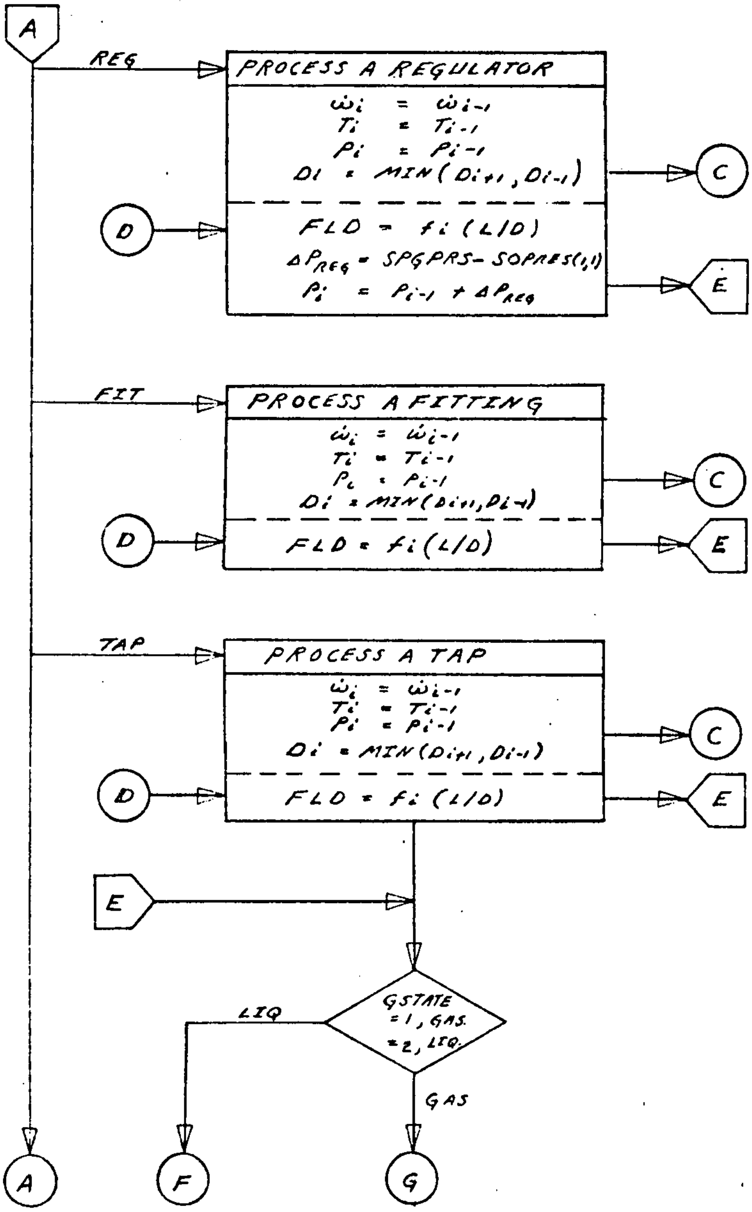

Figure D-1.5-2 Flow Chart for Subroutine HZNCMP (Sheet 3)

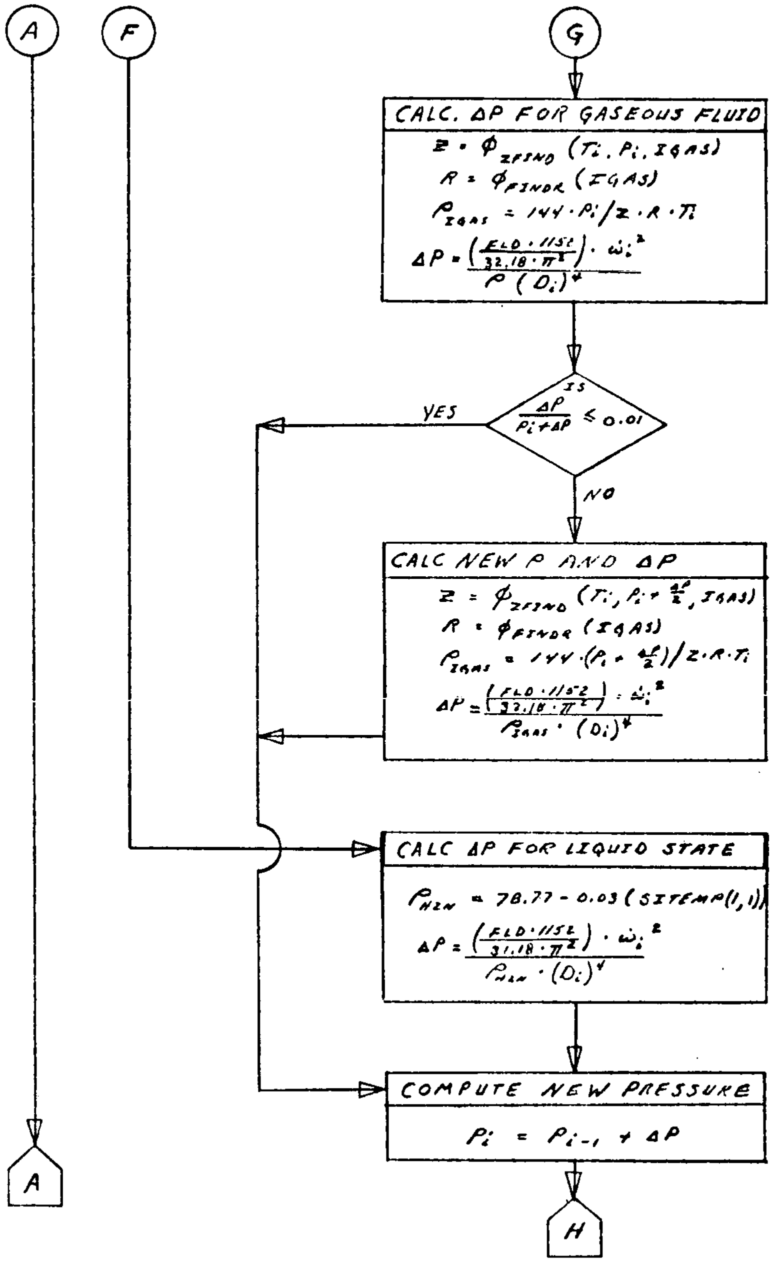

Figure D-1.5-2 Flow Chart for Subroutine HZNCMP (Sheet 4)

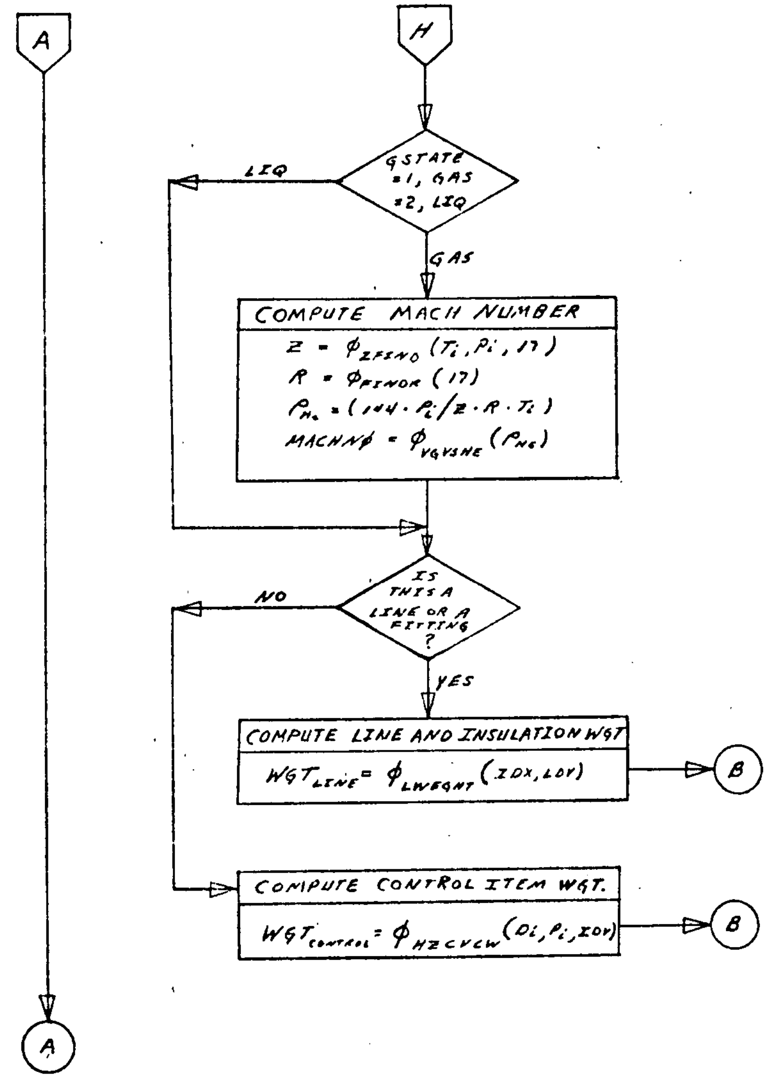

Figure D-1.5-2 Flow Chart for Subroutine HZNCMP (Sheet 5)

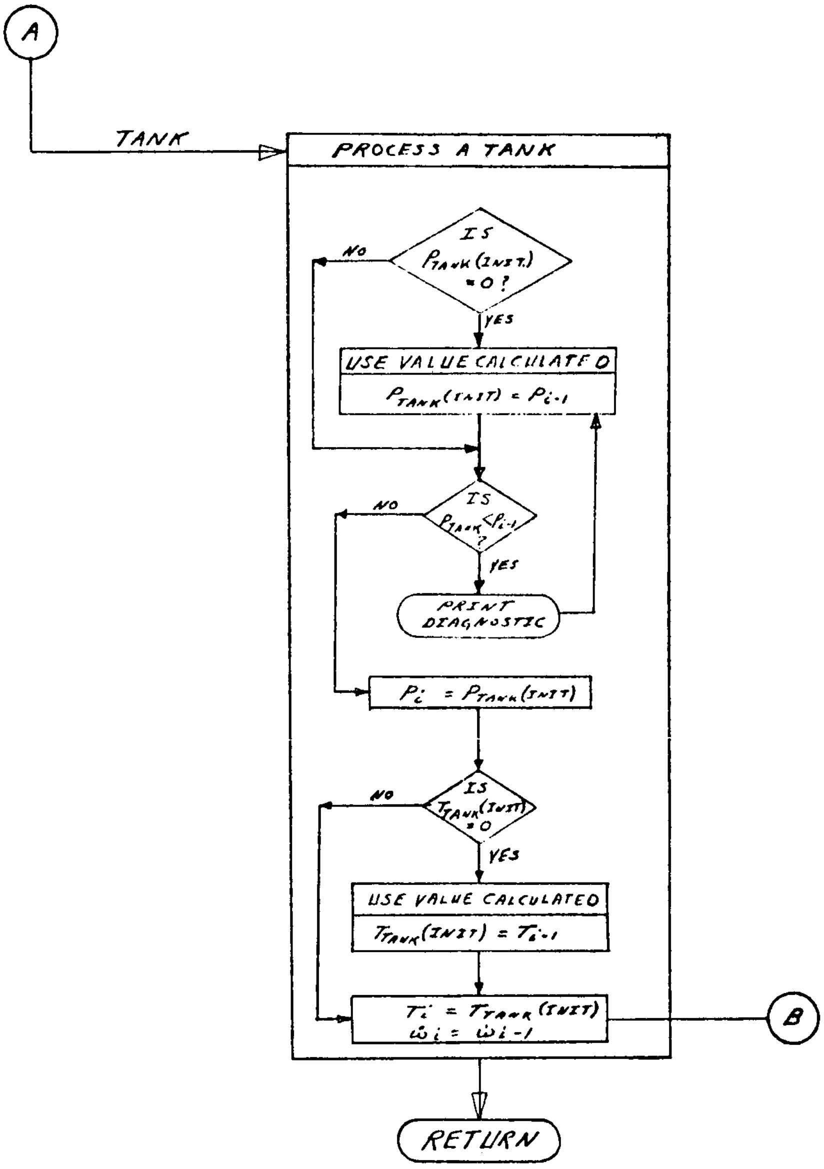

Figure D-1.5-2 Flow Chart for Subroutine HZNCMP (Sheet 6)

D-1.5.3 FUNCTION HZCVCW

DESCRIPTION

The function subprogram generates weight values for hydrazine valves, regulators and connectors. The function utilizes two equations devised from empirical hydrazine valve data. The basic data treats valves rated at two levels of pressure, below one thousand psia and above one thousand psia. The data were plotted, as shown in Figure D-1.5-3, and equations derived from curve fitting procedures. The equations are as follows:

For pressures up to 1000 psia;

$$\text{Valve Wgt.} = 0.669405 \text{ X } e^{(0.89646 \text{ X DIAM.})}$$

For pressures greater than 1000 psia;

$$\text{Valve Wgt.} = 1.195686 \text{ X } e^{(0.9104 \text{ X DIA.})}$$

In order to accommodate such components as check valves, regulators and disconnects for line sizes up to 3.5 inches, a set of adjusting factors for the equations were developed using weight ratios from standard equivalent diameter components. The basic valve weight equations with the adjusting factors are felt to yield reasonably close weight values for the span of hydrazine flow control components currently being considered. The function may be easily modified to accommodate more advanced data when such data becomes available. The function requires only the component port size, the operating service pressure and the component related type index, all of which are input to the function in the calling arguments. No access to common storage is required.

HZCVCW MATHEMATICAL MODEL

No math model is provided since the given equations derived from Figure D-1.5-3 are empirical data. The weight adjusting factors for check valves, etc., are simple weight ratios derived from standard component data.

CALLING SEQUENCE

The function subprogram is initiated by setting the weight variable equal to the function and providing the necessary three function arguments for data transfer. The function returns the desired component weight in pounds.

SIGNIFICANT VARIABLES

Significant variables employed in, and processed by function HZCVCW are defined as follows:

Name	Type	I/O	Dimension	Description
D	R	I	1	Port Diameter (Inches)
P	R	I	1	Service Operating Pressure (Psia)
IDV	I	I	1	Flow Control Component Weight Classification Index
C1	R	D	4	Weight Adjusting Factor for Pressures Less Than 1000 Psia
C2	R	D	4	Weight Adjusting Factor for Pressures Greater Than 1000 Psia

SUBPROGRAMS REFERENCED IN HZCVCW

None referenced.

SUBPROGRAMS REFERENCING HZCVCW

Name	Type	Purpose	Reference
HZNCMP	S	Hydrazine System Configuration Analysis	Page D-93

LISTING REFERENCE PAGE

The function listing will be found in Section D-3.0, page D-92.

FLOW CHART

No flow chart is presented for this subprogram.

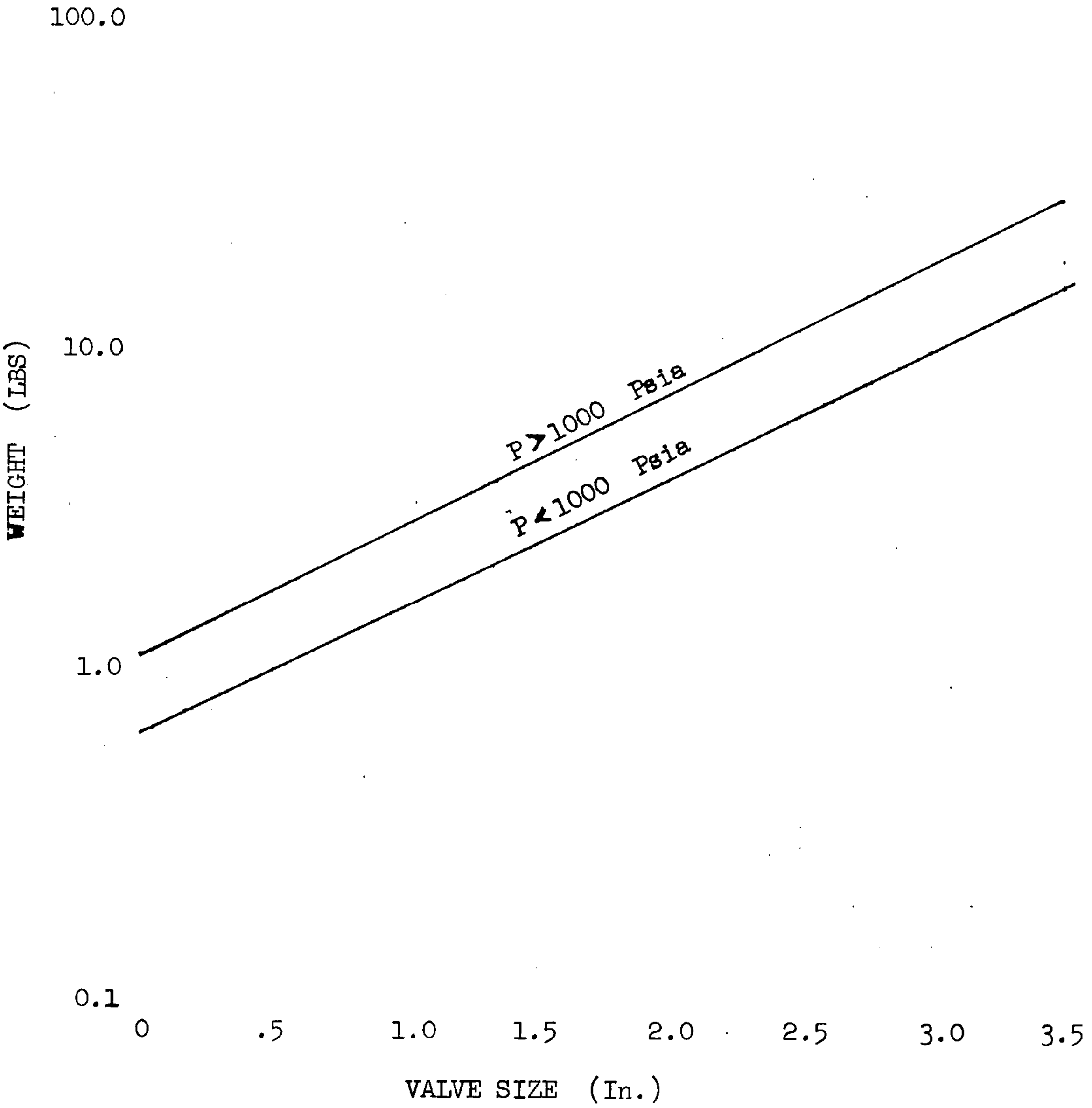

FIGURE D-1.5-3 BASIC HYDRAZINE VALVE WEIGHT DATA.

D-1.5.4 SUBROUTINE VGVSHE

DESCRIPTION

The subroutine computes the velocity of Helium gas flowing in a line fitting, tee or elbow, and the velocity of sound in the Helium gas at the temperature under consideration. It then computes a MACH Number and tests the Mach Number to see if it is greater than 0.3 or greater than 0.95. If the Mach Number is greater than 0.3 but less than 0.95 the subroutine causes one asterisk to be printed beside the MACH Number value printed in the system configuration output. If the MACH Number is greater than 0.95 then six asterisks are output in the configuration data output. If the MACH Number is less than 0.3, no asterisks are output and the column is blank. The purpose of the asterisks is to call attention to the MACH Number value which is directly related to line size (diameter) and fluid flow rate.

For the range of temperature and pressure of interest in the hydrazine APU system, the C_p and C_v values for Helium change very little and are therefore treated as constants of an average value over the range of 500 to 600°R, and 500 to 3500 psia. If the subroutine is to be utilized over a wider temperature range, it will be necessary to incorporate look-up tables for C_p and C_v as a function of temperature and density.

The principal computation accomplished in the subroutine is the determination of the MACH Number for the Helium employed as the pressurant gas in the hydrazine APU system.

Input data utilized by the subroutine is transmitted via access to common storage and through the calling arguments. The labeled common storage areas accessed by the subroutine are as follows:

```
COMMON/CCNFIG/
COMMON/CONST/
```

C.4

VGVSHE MATHEMATICAL MODEL

The equations employed by the subroutine for computing the MACH Number are standard handbook equations and need no further elaboration. No Math Model is presented for the subroutine.

CALLING SEQUENCE

The subroutine is initiated by a simple call statement with two calling arguments, the component configuration index and the fluid density. Data transfer to and from the routine is accomplished through the use of INCLUDE statements which bring in the appropriate PDP elements defining the required COMMON storage areas.

SIGNIFICANT VARIABLES

Significant variables employed in, and processed by, subroutine VGVSHE are defined as follows:

Name	Type	I/O	Dimension	Description
IDX	I	I	1	Configuration Table Index
RH0	R	I	1	Fluid Density (Lb/Cu. Ft.)
MFLG	I	C	1	MACH Number Flag
WD0TN	R	I	100	Fluid Flow Rate (Lb/sec)
PI	R	D	1	3.14159265
DIAM	R	I	100	Line or Part Diameter (In.)
VG	R	C	1	Velocity of Fluid (Ft/Sec)
CPGAS	R	D	1	C_p for Fluid (Btu/Lb-^oR)
CVGAS	R	D	1	C_v for Fluid (Btu/Lb-^oF)
GRAVTY	R	D	1	32.172 (Ft/Sec-Sec)
TEMP	R	I	100	Fluid Temp. (^oR)
VS	R	C	1	Velocity of Sound (Ft/Sec)
MACH	R	C	100	VG/VS

SUBPROGRAMS REFERENCED IN VGVSHE

Name	Type	Purpose	Reference
SQRT	F	Finds Square Root of Argument	System Routine

SUBPROGRAMS REFERENCING VGVSHE

Name	Type	Purpose	Reference
HZNCMP	S	System Configuration Analysis	Page D-93

LISTING REFERENCE PAGE

The subroutine listing will be found in Section D-3.0, page D-108.

FLOW CHART

None presented.

D-1.6 MATHEMATICAL MODELS

This subsection contains the math models for the major new subprograms employed in the Hydrazine APU system analysis.

D-1.6.1 MATH MODEL FOR SUBROUTINE HZAPU

PURPOSE OF SUBROUTINE

Subroutine HZAPU performs the basic system analysis computations for a Hydrazine fueled APU. The routine establishes the basic flow requirements for the system to a specified duty cycle and computes the total fuel requirements for the mission. The flow rate data generated is based on Rocketdyne specific fuel consumption versus percent of peak horsepower output data (Ref. D-1), and is corrected for the turbine inlet temperature and turbine exhaust pressure, at the horsepower requirement specified in the input duty cycle intervals. The routine generates a fuel tank and pressurant supply history keyed to the specified duty cycle. After computing the system performance characteristics, the routine sizes the fuel and pressurant tankage and the fuel expulsion device. The routine outputs the computed data and calls in subroutine HZNCMP to perform the sizing of the components specified in the system configuration.

THE MATH MODEL EQUATIONS

The equations and computational procedures required for the subroutine are given in the following subparagraphs.

1. DATA REQUIREMENTS

An important part of the analysis of the Hydrazine Auxiliary Power Unit Analyses is the determination of the propellant quantity for propellant tank sizing. It was assumed in these analyses that the required data will be collected by the APU contractor in a particular format.

The basic data required for the Hydrazine APU analysis is as follows:

a. Percent of peak horsepower output vs. specific propellant consumption as a function of turbine exit pressure

These data will be generated for specific:

Turbine Maximum Horsepower
Turbine Inlet Temperature – Reference
Turbine Exit Pressure
Turbine Pressure Ratio

Typical data derived from Ref. D-1 are presented in Table D-2 of Section D-2.0 as Data Table – 47.

b. Gas generator exit temperature vs. fraction of design flowrate

Typical data for the gas generator exit temperature (assumed to be the Turbine Inlet Temperature) will be found in Table D-2 (Section D-2.0) as Data Table – 49.

c. Turbine inlet temperature vs. correction factor for specific propellant consumption

Typical correction factor data will be found also in Table D-2 (Section D-2.0) as Data Table – 50.

d. Viscosity of hydrazine

See Table D-2 (Section D-2.0), Data Table – 51.

e. Viscosity of helium

See Table D-2 (Section D-2.0), Data Table – 52.

2. SYMBOLS USED IN THE MATH MODEL

The symbols employed in the Math Model are defined in the following list. (Note – Interval meams a Duty Cycle Interval)

SYMBOL	DEFINITION
HP_{TOT}	Total Horsepower Available
HP_{RATED}	APU Horsepower Rating
N_{APU}	Number of APU's Available
$\% \, HP_i$	% HP Required in Interval (i)
N_{op}	Number APU's operating
HP_i	HP Level in Interval (i)
$SPCR_i$	Rated Specific Fuel Consumption (SPC) in Interval (i)
$SPCN_i$	Nominal SPC in Interval (i)
PT_{IN}	Inlet Turbine Pressure
P_{RATIO}	Turbine Pressure Ratio
P_{AMB_i}	Ambient Altitude Pressure – Interval (i)
$\dot{\omega}_{R_i}$	Rated Flow Rate – Interval (i)
$\dot{\omega}_{N_i}$	Nominal Flow Rate – Interval (i)
$GGXTM_i$	Gas Gen. Exit Temp. – Interval (i)
$CFSPL_i$	SPC Correction Factor – Interval (i)
$\dot{\omega}_{c_i}$	Corrected Flow Rate – Interval (i)
$\dot{\omega}_{MAX}$	Maximum Flow Rate any Interval
FWC	Total Fuel Consumed in all Intervals
FWR	Weight of Fuel Reserves
FWTOT	Total Fuel Loaded in Tank

SYMBOL	DEFINITION
ρ_F	Density of Hydrazine
V_{TNK}	Volume of Fuel Tank
A_{TNK}	Surface Area of Fuel Tank
F_{TU}	Ultimate Stress – Tank Material
ρ_M	Density of Tank Material
WTPV	Weight of Tank Pressure Vessel
WTED	Weight of Expulsion Device
WTINS	Weight of Insulation
WTTOT	Total Weight – Tank Assy.
F_{OUT}	Fuel Withdrawn in Interval (i)
F_{RM_i}	Fuel Remaining in Interval (i)
V_{DP}	Volume Depletion of Fuel – Interval (i)
V_{DPS}	Volume Increase for Helium – Interval (i)
V_{RM_i}	Volume Fuel Remaining – Interval (i)
Z_{HEB}	Compressibility of Helium in Expulsion Device
ρ_{HEP}	Density of Helium in Expulsion Device
P_{HEB}	Pressure of Helium in Expulsion Device
T_{HEB}	Temperature of Helium in Expulsion Device
WH	Weight Helium in Expulsion Device – Interval (i)
$\dot{\omega}_{HE_i}$	Flow Rate of Helium in Interval (i)
$WHEADD_i$	Weight Helium Added in Interval (i)
WHESUM	Cum. Total of Helium by Weight for Interval (i)
$(\dot{\omega}_{HE})_{MAX}$	MAX Flow Rate – Helium in any Interval

SYMBOL	DEFINITION
WTOTPG	Total Weight – Pressurant Gas System
Z_{HE}	Compressibility of Helium in Storage Tank
T_{HE}	Temperature of Helium in Storage Tank
ρ_{HE}	Pressure of Helium in Storage Tank
ρ_{HE}	Density of Helium in Storage Tank
WTOTHE	Total Helium Including Reserves
V_{TKHE}	Volume of Helium Tank
A_{TKHE}	Surface Area of Helium Tank
D_{TKHE}	Diameter of Helium Tank
WTHETH	Weight of Helium Tank

3. THE CALCULATIONS

A. CHARACTERIZE THE SYSTEM

Total Horsepower Available –

$$HP_{TOT} = H\rho_{RATED} \times N_{APU}$$

Percent Power for Each Duty Cycle Period (i) –

$$\% HP_i = (N_{op} \times HP_i)/HP_{TOT}$$

Rated Flow Rate for Each Duty Cycle Period (i) –

$$SPCR_i = \phi\,(\rho T_{in}, P_{ratio}, P_{amb_i}, 100\%)$$

$$\phi = \text{Data Table 47}$$

$$\dot{\omega}_{R_i} = SPCR_i \times HP_i \times N_{op_i}$$

Nominal Flow Rate for Each Duty Cycle Period (i) –

$$SPCN_i = \phi(PT_{IN}, P_{ratio}, P_{amb_i}, \%\ HP_i)$$

$$\phi = \text{Data Table} - 47$$

$$\bar{\omega}_{N_i} = SPCN_i \times HP_i \times N_{op_i}$$

Percent of Full Flow the Duty Cycle Period (i) –

$$\%\dot{\omega}_i = \dot{\omega}_{R_i} / \dot{\omega}_{N_i}$$

Gas Generator Exit Temperature Each Interval (i) –

$$GGXTM_i = \phi(\%\ \dot{\omega}_i)$$

$$\phi = \text{Data Table} - 49$$

Correction Factor for Gas Generator Exit Temperature in Each Duty Cycle Period (i) –

$$CFSPC_i = \phi(GGXTM_i)$$

$$\phi = \text{Data Table} - 50$$

Corrected Flow Rate in Each Interval (i) –

$$\dot{\omega}_{c_i} = \dot{\omega}_i \times CFSPC_i$$

Maximum Flow Rate and Total Fuel Consumed –

$$\dot{\omega}_{MAX} = MAX(\dot{\omega}_{c_i})$$

$$FWC = \sum_{i=1}^{i = K\ CYCLE} \dot{\omega}_{c_i}$$

K CYCLE = Total Number of Duty Cycles

B. SIZE THE FUEL TANK

Reserve Fuel Required –

$$FWR = FWC \times (\%\ FR/100.0)$$

Total Fuel Loaded

$$FWTOT = FWC + FWR$$

Density of Hydrazine Fuel in Tank –

$$\rho_F = 78.77326 - 0.03\ T_F$$

T_F = Fuel Temperature

Density Equation was derived
from data given in Ref. D-1.

Volume of Fuel Tank –

$$V_{TNK} = \frac{FWTOT}{\rho_F} \times 1.02$$

1.02 Considers Volume of Expulsion Device

Surface Area of Fuel Tank –

$$A_{TNK} = 4.84 \times V_{TNK}^{0.667}$$

Ultimate Strength of Fuel Tank Material –

$$F_{TU} = \phi\,(T_F,\ MATRL)$$

ϕ = Data Table -22, 23, 24, 25, 26
Depending Upon Material

Density of Tank Material –

$\rho_m = \phi$ (Material Type)

ϕ = RH0L (An Imbedded Data Statement – See ST0DTA and PDP – CMATRL)

Weight of the Fuel Tank Pressure Vessel –

$$\mathrm{WTPV} = 7000. \times \frac{\mathrm{FWTOT}}{\rho_F} \times P_{op} \times \frac{\rho_m}{F_{TU}} \times \frac{1}{1728}$$

Weight of the Expulsion Device in Fuel Tank –

$$\mathrm{WTED} = 0.14 \times A_{TNK}$$

Sealing Law for Bladder Device

Weight of Tank Insulation –

$\rho_I = \phi$ (Insulation Type)

ϕ = RH0I (An Imbedded Data Statement – See ST0DTA and PDP – CMATRL)

$$\mathrm{WTINS} = A_{TNK} \times \rho_I \times I_{THK} \times \frac{1}{12}$$

Total Weight of Fuel Tank Assembly –

$$\mathrm{WT}_{TOT} = \mathrm{WTPV} + \mathrm{WTED} + \mathrm{WTINS}$$

C. SIZE THE PRESSURANT SYSTEM

Helium Flow Rate Required Each Duty Cycle Interval –

Set F_{TOT} = FWTOT initially – then do all computations in loop for all duty cycle intervals.

$$F_{OUT} = \ddot{\omega}_{c_i} \times \mathrm{DCYCLE}_i$$

$$F_{TOT} = F_{TOT} - F_{OUT}$$

$$F_{RM_i} = FTOT$$

$$V_{DP} = F_{OUT}/\rho_F$$

$$V_{DPS} = V_{DPS} + V_{DP}$$

$$V_{RM_i} = V_{TNK} - V_{DPS}$$

$$Z_{HEB} = \phi \,(P_{HEB1}\ T_{HEB})$$

$$\phi = \text{S.R. ZFIND}$$

$$\rho_{HEB} = \frac{144.\ \text{x}\ \rho_{HEB}}{Z_{HEB}\ \text{x}\ R_{HE}\ \text{x}\ T_{HEB}}$$

$$W_H = \rho_{HEB}\ \text{x}\ V_{DPS}$$

$$\dot{\omega}_{HE_i} = (W_H - WHE)/D\ CYCLE_i$$

$$WHEADO_i = WHEADD_i$$

$$WHE = WD$$

$$WHESUM = WHESUM + WHEADD_i$$

$$(\dot{\omega}_{HE})_{MAX} = MAX\ (\dot{\omega}_{HE_i})$$

Weight of Pressurant System from Scaling Law –

$$WTOTPG = 1.5\ \text{x}\ WHESUM + 40.0$$

D. SIZE THE HELIUM TANK

Density of Helium in Tank –

$$Z_{HE} = \phi_{ZFIND}\ (T_{HE},\ \rho_{HE})$$

$$\rho_{HE} = \frac{144. \times \rho_{HE}}{Z_{HE} \times R_{HE} \times T_{HE}}$$

Volume of Helium Tank –

WTOTHE = WHESUM + 0.2 x WHESUM
(Assume 20% Reserves)

$$V_{TKHE} = \frac{WTOTHE}{\rho_{HE}}$$

Surface Area of Helium Tank –

$$A_{TKHE} = 4.84 \times V_{TKHE}^{0.667}$$

Diameter of Helium Tank –

$$D_{TKHE} = \left(\frac{1.9098 \times FWTOT}{\rho_{HE}}\right)^{0.333} \times \frac{1}{12}$$

Weight of the Helium Tank –

Ultimate Strength of Tank Material:

$$F_{TU} = \phi\,(T_{HE})$$

ϕ = Data Table – 22, 23, 24, 25, 26
(Depending upon Material Type
See PDP – CMATRL)

Density of Tank Material:

$$\rho_m = \phi\,(\text{Material Type})$$

ϕ = RHØL (As Defined in B.)

$$WTHETK = 7000. \times \frac{FWTOT}{HE} \times P_{HE} \times \frac{\rho_m}{F_{TU}} \times \frac{1}{1728}$$

Weight at Helium Tank Insulation –

$\rho_I = \phi$ (Insulation Type)

ϕ = RHØI (As Defined in B.)

$$WTINS_{HETK} = A_{TKHE} \times \rho_I \times I_{THK} \times \frac{1}{12}$$

D. MATH MODEL CONFIGURATION

The system configuration concept upon which the Hydrazine APU Math Model is based is illustrated in Figure D-1.6-1.

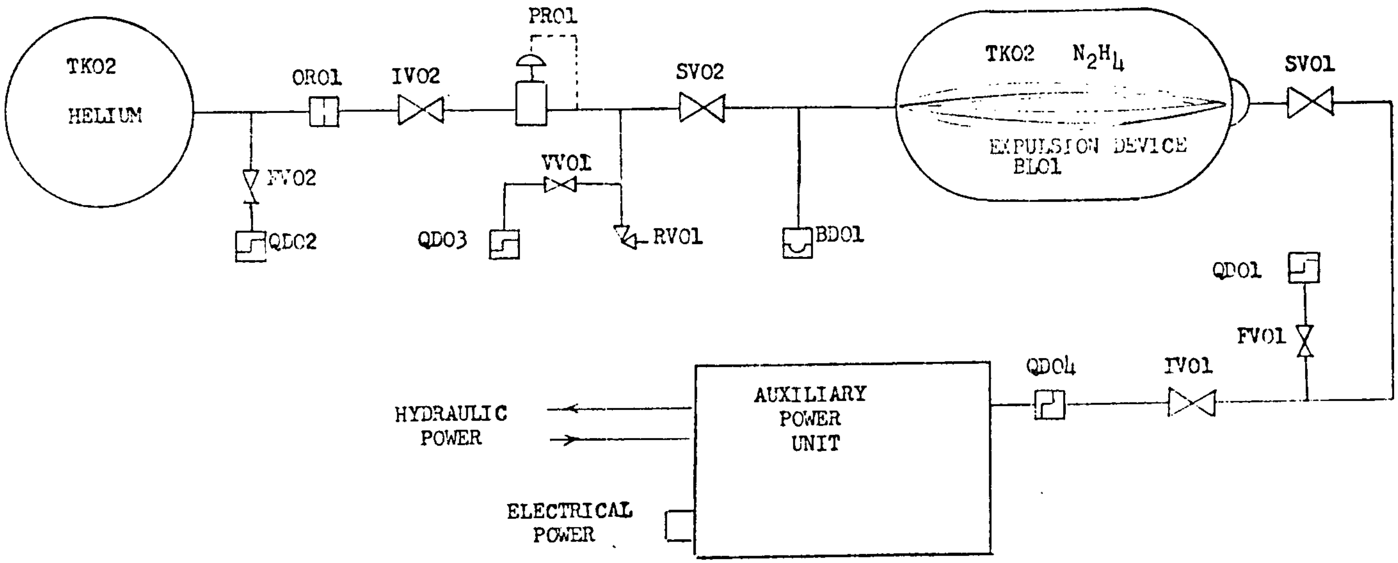

FIGURE D-1.6-1 HYDRAZINE APU CONFIGURATION SCHEMATIC

D-1.6.2 MATH MODEL FOR SUBROUTINE HZNCMP

PURPOSE OF SUBROUTINE

The subroutine provides the same kinds of calculations for configuration analysis as does subroutine CMPCAL described in Appendix C. Revisions are chiefly hydrazine and helium properties data. The reader is referred to the math modal for CMPCAL given in Vol. V B-3 Appendix C, page C-110 for the general form of the configuration analysis.

Section D-2.0
HZ PROG SAMPLE PROBLEM

To illustrate and checkout the hydrazine APU system analysis programs, a sample problem was assembled from data provided in Reference D-1 and D-2.

D-2.1 PROBLEM DESCRIPTION

The Hydrazine APU Fuel Supply System employed in the problem is an ambient temperature helium pressurized, positive fuel expulsion type of fuel storage system . The expulsion device employed is an elastomeric type bladder assumed to be non-permeable to helium. All components involves in the catalytic breakdown and gasification of the hydrazine are considered to be part of a GFE-APU. (Ref D-2) Hence, the program essentially treats a storage and fuel delivery system using data provided by the APU contractor.

The system configuration employed in the sample problem is illustrated in Fig. D-1.6-1.

D-2.2 SAMPLE PROBLEM INPUT DATA

Conversion of the system characterization data derived from Reference D-1 and D-2 into the problem input data deck was accomplished in the manner previously described in Sections 1.5 and 2.0 of Vol. V B-1.

The new data tables required for the Hydrazine APU analysis were constructed in the manner previously described in Section 1.5.3 of Vol. V B-1.

A listing of the sample problem input data deck is given in Table D-1. The list is organized as a "DATA" file called "HZAPUDATA.", permiting the placement of the input deck into mass storage for repetitive use. Changes to the data can then be effected through the use of "change cards". Similarly, a listing of the data tables employed by the program is provided in Table D-2. Again the list is organized as a DATA file, with a file name of "HZTABDATA." The file contains eleven tables.

D-2.3 SAMPLE PROBLEM DATA DECK SETUP

Setup for the data input decks may be accomplished in the following two ways.

a) Assuming the input data deck and data table deck are to entered as cards and the program is an file, the deck would be:

```
@ RUN
@ LID
@ ASG, A       HZPROG.
@ COPY, P      HZPROG., TPF$.
@ FREE         HZPROG.
@ PRT, T       TPF$.
@ XQT
   USER I. D. CARD
   TITLE CARD
   TABLE ECHO CONTROL CARD
   DATA TABLE DECK (GOES HERE)
   SYSTEM DEFINITION CARD
   DATA DECK INPUT DATA CARDS
@ PMD, BARE
@ FIN
```

(Note that a blank card must end the data table deck set)

b) Assuming that input data deck and data table deck are both in storage in DATA files and "HZPRØG." is a program file, the run deck would be:

```
@ RUN
@ LID
@ ASG, A       HZPRØG.
```

```
@COPY, P       HZPRØG., TPF$
@FREE          HZPRØG.
@PRT, T        TPF$
@ASG, A        HZAPUDATA.
@ASG, A        HZTABDATA.
@XQT
@ADD, P        HZTABDATA.
@PMD, BARE
@FIN
```

TABLE D-1 HYDRAZINE APU DATA INPUT DECK SET UP AS A DATA FILE

```
@DATA,IL            HZAPUDATA.
DATA006-RLIBLMSC18 06/08-11:25:42
000001       USERS NAME    6213    104 30235
000002                 TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT
000003               10    1     1
000004       @ADD,P       HZTABDATA.
000005       HZN-APU     SUBCRITICAL       LAST CARD                                 000000000000
000006       GAS       1   2     0                                         HZ-LIQ        CONFIG 1
000007       TRBINE    0   1     0                                         APU-1                2
000008       LINE     10   1     0    1        24.    1.   5   1.  70.     LN01                 3
000009       VALVE    21   1     0    1       100.                         IV01                 4
000010       LINE     10   1     0    1        10.    1.   5   1.  70.     LN02                 5
000011       TEE      31   1     0    1        20.                         FT01                 6
000012       LINE     10   1     0    1        10.    1.   5   1.  70.     LN03                 7
000013       VALVE    21   1     0    1       100.                         SV01                 8
000014       LINE     10   1     0    1        20.    1.   5   1.  70.     LN04                 9
000015       TANK      0   1     0    1                    6   2.  30.     TK01                10
000016       GAS       2   1     0                                         HE-GAS              11
000017       BLAD      0   1     0    1                                    BL01                12
000018       LINE     10   1     0    1        40.   .25   8   1.          LN11                13
000019       TEE      31   1     0    1        20.                         FT11                14
000020       LINE     10   1     0    1        20.   .25   8   1.          LN12                15
000021       VALVE    31   1     0    1       100.                         SV02                16
000022       LINE     10   1     0    1        24.   .25   8   1.          LN13                17
000023       TEE      31   1     0    1        20.                         FT12                18
000024       LINE     10   1     0    1        10.   .25   8   1.          LN14                19
000025       REG      32   1     0    1       394.                         PR01                20
000026       LINE     10   1     0    1        10.   .25   8   1.          LN15                21
000027       VALVE    31   1     0    1       100.                         IV02                22
000028       LINE     10   1     0    1        12.   .25   8   1.          LN16                23
000029       CONTRL   33   1     0    1       900.                         OR01                24
000030       LINE     10   1     0    1        12.   .25   8   1.          LN17                25
000031       TEE      31   1     0    1        20.                         FT13                26
000032       LINE     10   1     0    1        10.   .25   8   1.          LN18                27
000033       TANK      0   1     0    5                    6   1.  30.     TK02                28
000034       END                                                                         ENDCFG29
000035              10.5         0.             1       56.4      14.7                   DCYCLE 1
000036               1.5         0.             1       56.4       5.9                          2
000037               7.0         0.             1       57.0       .34                          3
000038               5.0         0.             1       57.0      .001                          4
000039               2.0         0.             1       56.1      .001                          5
000040               4.0      9900.             1       40.1     .0001                          6
000041              26.0         0.             1       40.1       .01                          7
000042               9.0         0.             1       42.0       6.0                          8
000043               3.0         0.             1      132.6     10.11                          9
000044              20.0         0.             1       71.1      14.7                         10
000045                      -1.                                                          ENDINPUT
000046           1            250.      600.        20.        10.     3000.            APUIN   1
000047           1    1    5    1     2                                                  STOTK HZ
000048              520.      600.      520.       600.       700.         .3        2.         .
000049                1.       5.                                                               .
000050               30.                                                                        .
000051           1    1    6    5     2                                                  STOTK --
000052              520.     3000.      520.      3000.      3500.         .4        1.         .
000053                0.       2.                                                               .
000054               30.                                                                        .
000055           1     0                                                                 IWOP N 1
```

TABLE D-2 DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
@DATA,IL           HZTABDATA.
DATA006-RLIBLMSC18 06/08-11:30:05
000001      FTU OF 321/347 ST.STEEL       2     3          22
000002      EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF 321/347 STAINLESS STEEL
000003      REF. SEC.8-LMSC A981608,PAGE 8.1.1-8
000004
000005      TEMPERATURE (R)   ULT.STRENGTH (PSI)
000006          14     1     2
000007        36.7       266500.      59.7       251000.     159.7       207000.
000008       259.7       173000.     359.7       143000.     459.7       121000.
000009       559.7       108000.     659.7        91000.     859.7        75000.
000010      1059.7        70000.    1259.7        66000.    1459.7        63000.
000011      1659.7        50000.    1859.7        32000.
000012      FTU OF 2219-T87 ALUM.         2     3          23
000013      EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF 2219-T87 ALUMINUM
000014      REF. SEC.8-LMSC A981608,PAGE 8.1.1-8
000015
000016      TEMPERATURE (R)   ULT.STRENGTH (PSI)
000017          16     1     2
000018        36.7        94000.     100.0        82400.     150.0        76000.
000019       200.0        72000.     250.0        68500.     300.0        67800.
000020       350.0        67000.     400.0        66300.     450.0        65000.
000021       500.0        63800.     550.0        62000.     600.0        60000.
000022       650.         58000.     859.7        38400.    1059.7        16600.
000023      1259.7         6400.
000024      FTU OF 6061-T6 ALUMINUM       2     3          24
000025      EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF 6061-T6 ALUMINUM ALLOY
000026      REF. MIL HANDBOOK -5
000027
000028      TEMPERATURE (R)   ULT.STRENGTH (PSI)
000029          13     1     3
000030        36.7        63840.     100.0        57330.     150.0        53340.
000031       200.0        50610.     250.0        48384.     300.0        46830.
000032       350.0        45696.     400.0        44940.     450.0        43848.
000033       500.0        42840.     550.0        41496.     600.0        40152.
000034       650.0        38556.
000035      FTU OF INCONEL-718            2     3          25
000036      EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF INCONEL-718
000037      REF. MIL HANDBOOK -5.
000038
000039      TEMPERATURE (R)   ULT.STRENGTH (PSI)
000040          13     1     3
000041        36.7       219600.     100.0       213660.     150.0       210240.
000042       200.0       206100.     250.0       201240.     300.0       196200.
000043       350.0       193140.     400.0       189000.     450.0       185400.
000044       500.0       182160.     550.0       179460.     600.0       177300.
000045       650.0       175140.
000046      FTU OF TI-6AL-4V              2     3          26
000047      EFFECT OF TEMPERATURE ON THE TENSILE STRENGTH OF TITANIUM TI-6AL-4V
000048      REF. MIL HANDBOOK -5.
000049
000050      TEMPERATURE (R)   ULT.STRENGTH (PSI)
000051          13     1     3
000052        36.7       288320.     100.        261600.     150.        244480.
000053       200.0       226880.     250.        212800.     300.        200960.
000054       350.0       190720.     400.        181280.     450.        173120.
000055       500.0       165280.     550.        158720.     600.        154240.
000056       650.0       145600.
```

TABLE D-2 (CONT'D) DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
000057     HZAPU -HP VS SPC TABLE          5      6             47
000058      ***
000059       ** THIS TABLE PRESENTS PEAK HORSEPOWER VS SPECIFIC PROPELLANT        **
000060       ** CONSUMPTION AS A FUNCTION OF TURBINE INLET PRESSURE, TURBINE      **
000061       ** PRESSURE RATIO, TURBINE OUTLET PRESSURE. THE DATA IS MODELED      **
000062       ** FROM THE ROCKETDYNE DESIGN HANDBOOK (R-8887) (PRELIMINARY)        **
000063      ***
000064          PTIN(I)             4      300.        400.        600.       1000.
000065          PRAT(I)             4        5.         10.         20.         40.
000066          PTOUT(I)            4        0.         10.        14.7         20.
000067     PERCENT HORSEPOWER  SPC
000068          9      1      2
000069        .05           7.70       .10        6.82         .15          6.50
000070        .20           6.36       .30        6.20         .40          6.13
000071        .60           6.05       .80        6.00        1.00          5.96
000072          9      1      2
000073        .05          11.7        .10        9.6          .15          8.3
000074        .20           7.65       .30        6.85         .40          6.46
000075        .60           6.15       .80        6.05        1.00          5.99
000076          9      1      2
000077        .075         11.5        .10       10.6          .15          9.32
000078        .20           8.43       .30        7.48         .40          6.90
000079        .60           6.38       .80        6.14        1.00          6.04
000080          8      1      2
000081        .10          11.4        .15       10.18         .20          9.23
000082        .30           8.13       .40        7.42         .60          6.70
000083        .80           6.35      1.00        6.15
000084          9      1      2
000085        .05           6.57       .10        5.88         .20          5.50
000086        .30           5.41       .40        5.35         .50          5.31
000087        .60           5.30       .80        5.25        1.00          5.21
000088          9      1      2
000089        .075         12.4        .10       10.3          .20          7.5
000090        .30           6.54       .40        6.06         .50          5.80
000091        .60           5.61       .80        5.40        1.00          5.31
000092          9      1      2
000093        .10          12.4        .15       10.05         .20          9.75
000094        .30           7.38       .40        6.68         .50          6.26
000095        .60           6.0        .80        5.67        1.00          5.45
000096          9      1      2
000097        .15          12.05       .20       10.25         .25          9.2
000098        .30           8.3        .40        7.35         .50          6.8
000099        .60           6.45       .80        5.95        1.00          5.60
000100         10      1      2
000101        .05           6.27       .10        5.55         .15          5.30
000102        .20           5.20       .30        5.15         .40          5.10
000103        .50           5.06       .60        5.04         .80          4.96
000104       1.00           4.87
000105         10      1      2
000106        .75          12.5        .10       11.5          .15          9.55
000107        .20           8.34       .30        6.93         .40          6.20
000108        .50           5.8        .60        5.58         .80          5.28
000109       1.00           5.06
000110          8      1      2
000111        .15          11.7        .20       10.1          .30          8.14
000112        .40           7.15       .50        6.5          .60          6.08
000113        .80           5.60      1.00        5.35
000114          7      1      2
```

TABLE D-2 (CONT'D) DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
000115        .20       12.15       .30       9.55       .40       8.22
000116        .50        7.31       .60       6.8        .80       6.11
000117       1.00        5.70
000118        11     1     2
000119        .05        5.5        .10       5.06       .15       4.85
000120        .20        4.65       .25       4.55       .30       4.50
000121        .40        4.45       .50       4.40       .60       4.31
000122        .80        4.29      1.00       4.28
000123        10     1     2
000124        .10       12.8        .15       9.8        .20       8.5
000125        .25        7.7        .30       7.3        .40       6.8
000126        .50        6.4        .60       6.25       .80       6.06
000127       1.00        5.8
000128         9     1     2
000129        .15       12.5        .20      10.4        .25       9.3
000130        .30        8.45       .40       7.52       .50       7.1
000131        .60        6.6        .80       6.27      1.00       5.98
000132         8     1     2
000133        .20       14.6        .25      12.4        .30      10.9
000134        .40        9.85       .50       7.50       .60       7.2
000135        .80        6.6       1.00       6.24
000136        10     1     2
000137        .05        7.6        .10       6.8        .15       6.5
000138        .20        6.35       .30       6.21       .40       6.12
000139        .50        6.06       .60       6.04       .80       6.02
000140       1.00        6.0
000141        10     1     2
000142        .05       11.15       .10       8.7        .15       7.6
000143        .20        7.1        .30       6.5        .40       6.2
000144        .50        6.07       .60       6.04       .80       6.02
000145       1.00        6.0
000146        10     1     2
000147        .075      11.0        .10       9.75       .15       8.4
000148        .20        7.7        .30       6.9        .40       6.55
000149        .50        6.32       .60       6.20       .80       6.07
000150       1.00        6.0
000151         9     1     2
000152        .10       11.1        .15       9.32       .20       8.4
000153        .30        7.4        .40       6.87       .50       6.56
000154        .60        6.34       .80       6.12      1.00       6.0
000155        10     1     2
000156        .05        6.6        .10       5.9        .15       5.63
000157        .20        5.5        .30       5.4        .40       5.34
000158        .50        5.3        .60       5.27       .80       5.25
000159       1.00        5.23
000160        10     1     2
000161        .075      10.75       .10       8.8        .15       7.4
000162        .20        6.75       .30       6.07       .40       5.7
000163        .50        5.55       .60       5.44       .80       5.35
000164       1.00        5.27
000165        10     1     2
000166        .09       11.5        .10      10.5        .15       8.55
000167        .20        7.6        .30       6.6        .40       6.06
000168        .50        5.81       .60       5.69       .80       5.50
000169       1.00        5.36
000170         9     1     2
000171        .10       12.0        .15       9.9        .20       8.63
000172        .30        7.27       .40       6.55       .50       6.20
```

TABLE D-2 (CONT'D) DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
000173          .60         6.0         .80        5.73       1.00       5.53
000174          11      1    2
000175          .05         6.0         .10        5.35        .15       5.17
000176          .20         4.98        .25        4.9         .30       4.85
000177          .40         4.80        .50        4.76        .60       4.755
000178          .80         4.75       1.00        4.74
000179          10      1    2
000180          .10        11.05        .15        8.7         .20       7.5
000181          .25         6.73        .30        6.27        .40       5.7
000182          .50         5.38        .60        5.17        .80       4.91
000183         1.00         4.8
000184          10      1    2
000185          .125       11.6         .15       10.75        .20       9.1
000186          .25         8.06        .30        7.3         .40       6.4
000187          .50         5.91        .60        5.5         .80       5.26
000188         1.00         5.0
000189           9      1    2
000190          .15        12.2         .20       10.9         .25       9.65
000191          .30         8.63        .40        7.3         .50       6.63
000192          .60         6.18        .80        5.57       1.00       5.20
000193          11      1    2
000194          .05         5.5         .10        5.06        .15       4.85
000195          .20         4.65        .25        4.55        .30       4.50
000196          .40         4.45        .50        4.40        .60       4.31
000197          .80         4.29       1.00        4.28
000198          11      1    2
000199          .075       13.7         .10       10.8         .15       8.2
000200          .20         7.1         .25        6.5         .30       6.1
000201          .40         5.6         .50        5.4         .60       5.25
000202          .80         5.06       1.00        4.8
000203          10      1    2
000204          .10        13.4         .15       10.45        .20       8.8
000205          .25         7.75        .30        7.05        .40       6.32
000206          .50         5.9         .60        5.5         .80       5.17
000207         1.00         4.98
000208           9      1    2
000209          .15        13.45        .20       12.4         .25      10.4
000210          .30         9.1         .40        8.25        .50       6.3
000211          .60         5.99        .80        5.5        1.00       5.23
000212          10      1    2
000213          .05         7.5         .10        6.7         .15       6.4
000214          .20         6.25        .30        6.11        .40       6.02
000215          .50         5.96        .60        5.94        .80       5.92
000216         1.00         5.90
000217          10      1    2
000218          .05         9.75        .10        8.0         .15       7.3
000219          .20         6.9         .30        6.4         .40       6.15
000220          .50         6.05        .60        6.04        .80       6.02
000221         1.00         6.0
000222          10      1    2
000223          .05        11.1         .10        9.0         .15       8.0
000224          .20         7.4         .30        6.8         .40       6.45
000225          .50         6.3         .60        6.2         .80       6.05
000226         1.00         6.02
000227          10      1    2
000228          .05        12.75        .10       10.0         .15       8.8
000229          .20         8.05        .30        7.25        .40       6.8
000230          .50         6.5         .60        6.34        .80       6.11
```

TABLE D-2 (CONT'D) DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
000231          1.00        6.06
000232          11      1     2
000233          .05         6.65        .075      6.15        .10       5.9
000234          .15         5.64        .20       5.51        .25       5.45
000235          .30         5.38        .40       5.30        .60       5.25
000236          .80         5.23        1.00      5.20
000237          11      1     2
000238          .05         10.3        .075      8.4         .10       7.4
000239          .15         6.55        .20       6.1         .25       5.83
000240          .30         5.65        .40       5.42        .60       5.29
000241          .80         5.25        1.00      5.22
000242          11      1     2
000243          .06         11.35       .075      10.0        .10       8.6
000244          .15         7.2         .20       6.6         .25       6.23
000245          .30         5.97        .40       5.70        .60       5.40
000246          .80         5.30        1.00      5.24
000247          10      1     2
000248          .075        11.15       .10       9.75        .15       8.03
000249          .20         7.23        .25       6.72        .30       6.4
000250          .40         5.95        .60       5.55        .80       5.35
000251          1.00        5.26
000252          11      1     2
000253          .05         6.0         .075      5.6         .10       5.35
000254          .15         5.12        .20       4.98        .25       4.90
000255          .30         4.85        .40       4.80        .60       4.75
000256          .80         4.72        1.00      4.70
000257          11      1     2
000258          .06         11.0        .075      10.15       .10       8.3
000259          .15         6.85        .20       6.35        .25       5.70
000260          .30         5.43        .40       5.1         .60       4.8
000261          .80         4.73        1.00      4.71
000262          10      1     2
000263          .075        12.2        .10       10.3        .15       8.1
000264          .20         7.12        .25       6.46        .30       6.0
000265          .40         5.5         .60       5.0         .80       4.85
000266          1.00        4.78
000267          10      1     2
000268          .075        12.4        .10       11.3        .15       9.5
000269          .20         8.12        .25       7.25        .30       6.65
000270          .40         6.0         .60       5.35        .80       5.08
000271          1.00        4.9
000272          10      1     2
000273          .05         5.65        .10       5.00        .15       4.75
000274          .20         4.68        .25       4.60        .30       4.56
000275          .40         4.50        .60       4.45        .80       4.39
000276          1.00        4.35
000277          10      1     2
000278          .075        12.5        .10       9.75        .15       7.5
000279          .20         6.5         .25       5.9         .30       5.5
000280          .40         5.1         .60       4.75        .80       4.6
000281          1.00        4.4
000282           9      1     2
000283          .10         12.2        .15       9.5         .20       8.0
000284          .25         7.05        .30       6.45        .40       5.75
000285          .60         5.0         .80       4.7         1.00      4.55
000286           9      1     2
000287          .125        12.25       .15       11.3        .20       9.5
000288          .25         8.3         .30       7.5         .40       6.5
```

TABLE D-2 (CONT'D) DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
000289          .60            5.45      .80       5.0        1.00       4.76
000290          10      1       2
000291          .05            7.4       .10       6.6         .15       6.3
000292          .20            6.15      .30       6.01        .40       5.95
000293          .50            5.92      .60       5.90        .80       5.87
000294         1.00            5.85
000295          10      1       2
000296          .05            8.0       .10       6.85        .15       6.46
000297          .20            6.25      .30       6.06        .40       6.00
000298          .50            5.96      .60       5.92        .80       5.89
000299         1.00            5.86
000300          10      1       2
000301          .05            9.0       .10       7.23        .15       6.73
000302          .20            6.44      .20       6.13        .40       6.02
000303          .50            5.98      .60       5.94        .80       5.90
000304         1.00            5.87
000305          10      1       2
000306          .05           10.0       .10       7.73        .15       7.06
000307          .20            6.71      .20       6.30        .40       6.09
000308          .50            6.00      .60       5.96        .80       5.91
000309         1.00            5.88
000310          11      1       2
000311          .05            6.65      .075      6.1         .10       5.87
000312          .15            5.65      .20       5.50        .25       5.43
000313          .30            5.38      .40       5.32        .60       5.28
000314          .80            5.25     1.00       5.21
000315          11      1       2
000316          .05            8.4       .075      7.1         .10       6.5
000317          .15            5.9       .20       5.7         .25       5.55
000318          .30            5.42      .40       5.35        .60       5.29
000319          .80            5.26     1.00       5.22
000320          11      1       2
000321          .05            9.6       .075      8.0         .10       7.15
000322          .15            6.3       .20       5.9         .25       5.7
000323          .30            5.55      .40       5.86        .60       5.30
000324          .80            5.27     1.00       5.23
000325          11      1       2
000326          .05           11.0       .075      8.8         .10       7.9
000327          .15            6.85      .20       6.3         .25       6.0
000328          .30            5.75      .40       5.5         .60       5.31
000329          .80            5.28     1.00       5.24
000330          10      1       2
000331          .05            6.0       .075      5.6         .10       5.35
000332          .15            5.1       .20       4.97        .30       4.84
000333          .40            4.77      .60       4.72        .80       4.70
000334         1.00            4.67
000335          10      1       2
000336          .05            9.2       .075      7.25        .10       6.5
000337          .15            5.7       .20       5.3         .30       4.9
000338          .40            4.78      .60       4.73        .80       4.71
000339         1.00            4.68
000340          10      1       2
000341          .06           10.5       .075      9.05        .10       7.6
000342          .15            6.4       .20       5.8         .30       5.25
000343          .40            4.97      .60       4.84        .80       4.76
000344         1.00            4.69
000345           9      1       2
000346          .075          11.6       .10       9.0         .15       7.1
```

TABLE D-2 (CONT'D) DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
000347        .20        6.4         .30        5.6         .40        5.14
000348        .60        4.89        .80        4.78       1.00        4.70
000349        11     1     2
000350        .05        5.5         .075       5.06        .10        4.85
000351        .15        4.65        .20        4.55        .25        4.50
000352        .30        4.45        .40        4.40        .60        4.31
000353        .80        4.29       1.00        4.28
000354        11     1     2
000355        .05       12.25        .075       9.25        .10        7.75
000356        .15        6.3         .20        5.6         .25        5.15
000357        .30        4.85        .40        4.56        .60        4.42
000358        .80        4.38       1.00        4.32
000359        10     1     2
000360        .075      12.25        .10        9.9         .15        7.6
000361        .20        6.5         .25        5.9         .30        5.45
000362        .40        4.97        .60        4.58        .80        4.42
000363       1.00        4.36
000364        10     1     2
000365        .085      12.25        .10       11.5         .15        9.25
000366        .20        7.75        .25        6.8         .30        6.2
000367        .40        5.45        .60        4.83        .80        4.55
000368       1.00        4.40
000369     HYDRAZINE VAPOR PRESS.       2     4          48
000370        ***
000371          * HYDRAZINE VAPOR PRESSURE AS A FUNCTION OF TEMPERATURE.
000372          * REFERENCE - ROCKETDYNE DESIGN HANDBOOK. R-8887
000373        ***
000374     TEMP. (DEG.R)      VAP.PRES. (PSIA)
000375        14     1     2
000376      480.          .039     492.          .052     510.          .11
000377      520.          .16      540.          .33      560.          .63
000378      580.         1.13      600.         1.92      620.         3.30
000379      640.         5.00      660.         7.65      680.        11.30
000380      700.        16.50      720.        23.90
000381     GAS.GEN. EXIT TEMP.          2     4          49
000382        *** GAS GENERATOR EXIT TEMPERATURE AS A FUNCTION OF
000383          * FRACTION OF DESIGN FLOWRATE . REFERENCE - ROCKETDYNE
000384          X DESIGN HANDBOOK R-8887
000385        ***
000386     (WDOT/WDOT DES.)  TEMP.(DEG.R)
000387        14     1     2
000388        .025        1660.       .092        1760.       .150       1813.
000389        .200        1849.       .300        1900.       .400       1940.
000390        .500        1971.       .600        1996.       .700       2015.
000391        .800        2033.      1.000        2060.      1.200       2085.
000392       1.400        2106.      1.600        2125.
000393     TURBN.IN.TEMP.CORR.FACT.     2     4          50
000394        *** TURBINE INLET TEMPERATURE CORRECTION FACTOR FOR SPECIFIC
000395          * PROPELLANT CONSUMPTION.  REFERENCE - ROCKETDYNE DESIGN
000396          * HANDBOOK R-8887.
000397        ***
000398      T.I.T.(DEG-R)     SPC(T)/SPC(REF)
000399        17     1     2
000400        1660.      1.127      1710.      1.10        1760.      1.087
000401        1810.      1.067      1860.      1.05        1910.      1.034
000402        1960.      1.019      2010.      1.005       2060.       .992
000403        2110.       .9797     2160.       .9675      2210.       .9565
000404        2260.       .947      2310.       .9384      2360.       .931
```

TABLE D-2 (CONT'D) DATA TABLES FOR HYDRAZINE APU PRØBLEM – SET UP AS A DATA FILE

```
000405         2410.         .9239        2460.        .9175
000406      VISCOSITY OF HYDRAZINE        2      3            51
000407         *** VISCOSITY OF HYDRAZINE VERSUS TEMPERATURE FROM
000408           * ROCKETDYNE DESIGN HANDBOOK R-8887.
000409         ***
000410      TEMPERATURE(DEG.R)VISCOSITY(LB/S-FT)
000411          11      1      2
000412       492.            8.830 E-4 500.             8.165 E-4 510.            7.513 E-4
000413       520.            6.895 E-4 530.             6.364 E-4 540.            5.901 E-4
000414       550.            5.484 E-4 560.             5.107 E-4 570.            4.731 E-4
000415       580.            4.388 E-4 590.             3.763 E-4
000416      VISCOSITY OF HELIUM           3      4            52
000417         *** VISCOSITY OF HELIUM VS. PRESSURE  AND TEMPERATURE
000418           * FROM 1000 TO 5000 PSIA AND 500 TO 600 DEG.RANKINE
000419           * REF. NBS-TN-622.
000420         ***
000421       PRESSURE                5      500.      1000.     2000.      3000.     4000.
000422      TEMP.(DEG.R)       VISCOSITY
000423          3       1      2
000424        400.        .0000111      500.       .0000128     600.       .0000145
000425          3       1      2
000426        400.        .0000112      500.       .0000129     600.       .0000161
000427          3       1      2
000428        400.        .0000115      500.       .0000131     600.       .0000147
000429          3       1      2
000430        400.        .0000117      500.       .0000132     600.       .0000148
000431          3       1      2
000432        400.        .0000119      500.       .0000134     600.       .0000149
000433                                                                          END TABLES

@FIN
```

D-2.4 SAMPLE PROBLEM DATA OUTPUT

This subsection presents the entire output for the Hydrazine APU sample problem. The output, which follows, is indexed by page number in the header-box top left corner. This index will be used in describing the several output sections produced in the run.

D-2.4.1 Output Description

Page 1	Table Data Input Summary – Lists the tables loaded for the program run.
Page 2	System Input Verification – Verifies the system name called for on System Definition Card.
Pages 3, 4	System Configuration and Duty Cycle Data – Echo of data in Input Data Deck.
Pages 5, 6	Echo of Major System Component Data – From Input Data Deck.
	Start of Program Calculations:
Page 7	Computed Hydrazine APU Parameters – Characterizes Fuel Storage Subsystem. Presents tank size and weight data based upon detailed calculation of fluid requirements over integrated mission duty cycle span.
Page 8	Characterizes Pressurant Gas Storage Subsystem Presents pressurant tank size and weight data based upon detailed calculation of fluid requirements over the integrated mission duty cycle span.
Pages 9, 10	Computer System Configuration Parameters – Presents computed temperature, pressure, flowrate, flow condition and weight for each component item in system configuration.
Page 11	Component Weight Summary and System Weight Summary – Presents a summary of individual component weights and corresponding insulation weights. Presents subsystem and systems weight totals.

The following pages present the detailed sample problem output.

```
NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * * * PAGE      1
DEPT 6213         *       THE INTEGRATED MATH MODEL        * DATE 08 JUN 73
EXT. 30235        *                                        * TIME 10:14:16
BLD. 104          *                AT4307                  * CASE      1
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
            TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

                                    TABLE INPUT SUMMARY

 TABLE       TITLE OF TABLE                NUMBER OF      NUMBER OF      NUMBER OF
NUMBER                                     DIMENSIONS     SUBTABLES         WORDS

   22  FTU OF 321/347 ST.STEEL                 2              1               32
   23  FTU OF 2219-T87 ALUM.                   2              1               36
   24  FTU OF 6061-T6 ALUMINUM                 2              1               30
   25  FTU OF INCONEL-718                      2              1               30
   26  FTU OF TI-6AL-4V                        2              1               30
   47  HZAPU -HP VS SPC TABLE                  5             64             1470
   48  HYDRAZINE VAPOR PRESS.                  2              1               32
   49  GAS.GEN. EXIT TEMP.                     2              1               32
   50  TURBN.IN.TEMP.CORR.FACT.                2              1               38
   51  VISCOSITY OF HYDRAZINE                  2              1               26
   52  VISCOSITY OF HELIUM                     3              5               52

                                           TOTAL TABLE STORAGE =  1808




NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * * * PAGE      2
DEPT 6213         *       THE INTEGRATED MATH MODEL        * DATE 08 JUN 73
EXT. 30235        *                                        * TIME 10:14:32
BLD. 104          *                AT4307                  * CASE      1
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
            TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT


                 ***  YOU HAVE CALLED FOR THE SYSTEM HZN-APU  ***
```

```
NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * * PAGE      3
DEPT 6213         *        THE INTEGRATED MATH MODEL        * DATE 08 JUN 73
EXT. 30235        *                                         * TIME 10:14:32
BLD. 104          *                  AT4307                 * CASE      1
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
            TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

                     ***** S Y S T E M   C O N F I G U R A T I O N *****

 COMP    COMP    FUNC.  NUMB.  NUMB.  MATRL.  FLOW FRICTION   LINE LENGTH    LINE     INSULATION   INSULATION   NO. LAYERS
 NAME    CODE    TYPE   OPER.  STBY.  TYPE     COEFICIENT    OR L-OVER-D   DIAMETER      TYPE       THICKNESS   INSULATION

GAS     HZ-LIQ    1       2      0      0     .00000000           .00         .00          0            .00          .0
TRBINE  APU-1     0       1      0      0     .00000000           .00         .00          0            .00          .0
LINE    LN01     10       1      0      1     .00000000         24.00        1.00          5           1.00        70.0
VALVE   IV01     21       1      0      1     .00000000        100.00         .00          0            .00          .0
LINE    LN02     10       1      0      1     .00000000         10.00        1.00          5           1.00        70.0
TEE     FT01     31       1      0      1     .00000000         20.00         .00          0            .00          .0
LINE    LN03     10       1      0      1     .00000000         10.00        1.00          5           1.00        70.0
VALVE   SV01     21       1      0      1     .00000000        100.00         .00          0            .00          .0
LINE    LN04     10       1      0      1     .00000000         20.00        1.00          5           1.00        70.0
TANK    TK01      0       1      0      1     .00000000           .00         .00          6           2.00        30.0
GAS     HE-GAS    2       1      0      0     .00000000           .00         .00          0            .00          .0
BLAD    BL01      0       1      0      1     .00000000           .00         .00          0            .00          .0
LINE    LN11     10       1      0      1     .00000000         40.00         .25          8           1.00          .0
TEE     FT11     31       1      0      1     .00000000         20.00         .00          0            .00          .0
LINE    LN12     10       1      0      1     .00000000         20.00         .25          8           1.00          .0
VALVE   SV02     31       1      0      1     .00000000        100.00         .00          0            .00          .0
LINE    LN13     10       1      0      1     .00000000         24.00         .25          8           1.00          .0
TEE     FT12     31       1      0      1     .00000000         20.00         .00          0            .00          .0
LINE    LN14     10       1      0      1     .00000000         10.00         .25          8           1.00          .0
REG     PR01     32       1      0      1     .00000000        394.00         .00          0            .00          .0
LINE    LN15     10       1      0      1     .00000000         10.00         .25          8           1.00          .0
VALVE   IV02     31       1      0      1     .00000000        100.00         .00          0            .00          .0
LINE    LN16     10       1      0      1     .00000000         12.00         .25          8           1.00          .0
CONTRL  OR01     33       1      0      1     .00000000        900.00         .00          0            .00          .0
LINE    LN17     10       1      0      1     .00000000         12.00         .25          8           1.00          .0
TEE     FT13     31       1      0      1     .00000000         20.00         .00          0            .00          .0
LINE    LN18     10       1      0      1     .00000000         10.00         .25          8           1.00          .0
TANK    TK02      0       1      0      5     .00000000           .00         .00          6           1.00        30.0
END               0       0      0      0     .00000000           .00         .00          0            .00          .0
```

```
                    NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * * PAGE      4
                    DEPT 6213         *       THE INTEGRATED MATH MODEL         * DATE 08 JUN 73
                    EXT. 30235        *                                         * TIME 10:14:33
                    BLD. 104          *                  AT4307                 * CASE      1
                    * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                              TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

                                      ***** D U T Y   C Y C L E   D A T A *****

OPER.TIME       NON-OPERATING    MIB-DEGRAD.    UNITS OPER.  HORSEPOWER      AMB.PRESSURE     POWER-KW      REPRES.TIME

.10500000+02    .00000000        .00000000          1          .56400000+02   .14700000+02    .00000000       .00000000
.15000000+01    .00000000        .00000000          1          .56400000+02   .59000000+01    .00000000       .00000000
.70000000+01    .00000000        .00000000          1          .57000000+02   .34000000+00    .00000000       .00000000
.50000000+01    .00000000        .00000000          1          .57000000+02   .10000000-02    .00000000       .00000000
.20000000+01    .00000000        .00000000          1          .56100000+02   .10000000-02    .00000000       .00000000
.40000000+01    .99000000+04     .00000000          1          .40100000+02   .10000000-03    .00000000       .00000000
.26000000+02    .00000000        .00000000          1          .40100000+02   .10000000-01    .00000000       .00000000
.90000000+01    .00000000        .00000000          1          .42000000+02   .60000000+01    .00000000       .00000000
.30000000+01    .00000000        .00000000          1          .13260000+03   .10110000+02    .00000000       .00000000
.20000000+02    .00000000        .00000000          1          .71100000+02   .14700000+02    .00000000       .00000000
.00000000      -.10000000+01     .00000000          0          .00000000      .00000000       .00000000       .00000000
```

```
NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * PAGE     5
DEPT 6213         *       THE INTEGRATED MATH MODEL       * DATE 08 JUN 73
EXT. 30235        *                                       * TIME 10:14:33
BLD. 104          *                 AT4307                * CASE     1
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
            TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

             *****   H Y D R A Z I N E   A P U   D A T A   *****


                          1  NUMBER OF APU UNITS
                 .25000000+03  HORSEPOWER PER UNIT
                 .60000000+03  TURBINE INLET PRESSURE
                 .20000000+02  TURBINE PRESSURE RATIO
                 .10000000+02  PER-CENT RESERVE FUEL
                 .30000000+04  PRESSURANT GAS PRESSURE
```

```
NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * PAGE     6
DEPT 6213         *       THE INTEGRATED MATH MODEL       * DATE 08 JUN 73
EXT. 30235        *                                       * TIME 10:14:33
BLD. 104          *                 AT4307                * CASE     1
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
            TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

                      ***** T A N K   D A T A *****


            1               1         NUMBER OPERATING (NOP)
            1               1         ACQUISITION TYPE
            5               6         INSULATION TYPE
            1               5         MATERIAL TYPE
            2               2         PRESSURIZATION TYPE
     .52000000+03   .52000000+03   INITIAL TEMPERATURE (R)
     .60000000+03   .30000000+04   INITIAL PRESSURE
     .52000000+03   .52000000+03   PRESSURANT GAS TEMP. (R)
     .60000000+03   .30000000+04   OPERATING PRESS. (PSIA)
     .70000000+03   .35000000+04   VENTING PRESSURE
     .30000000+00   .40000000+03   HEAT FLUX (BTU/HR-FT**2)
     .20000000+01   .10000000+01   INSULATION THICKNESS
     .00000000      .00000000      INITIAL FLUID LOAD (OPT)
     .10000000+01   .00000000      PERCENT ULLAGE VOLUME
     .50000000+01   .20000000+01   MAXIMUM DIAMETER (FT)
     .00000000      .00000000      HEX OUTLET TEMP. (R)
     .00000000      .00000000      HEX DELTA PRESS. (PSIA)
     .00000000      .00000000      PUMP DELTA PRESS. (PSIA)
     .00000000      .00000000      GAS GEN OUTLET TEMP (R)
     .00000000      .00000000      P SUB C OF GAS GEN (PSIA
     .00000000      .00000000      GAS GEN MIXTURE RATIO
     .30000000+02   .30000000+02   NUMBER INSULATION LAYERS

                 1                 TANK WEIGHT-CONFIGURATION OPTION CONSIDERED
                 0                 NUMBER OF TANK SHAPES IN CONFIGURATION
```

```
                        NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * * PAGE     7
                        DEPT 6213         *       THE INTEGRATED MATH MODEL         * DATE 08 JUN 73
                        EXT. 30235        *                                         * TIME 10:14:34
                        BLD. 104          *                  AT4307                 * CASE     1
                        * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                              TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT


                             *** INITIATE PROGRAM AND CHARACTERIZE CONSUMER PARAMETERS ***


                         **********      INITIAL HYDRAZINE APU PROGRAM CALCULATIONS       **********

PARAMETER   CYCLE-1      CYCLE-2      CYCLE-3      CYCLE-4      CYCLE-5      CYCLE-6      CYCLE-7      CYCLE-8      CYCLE-9     CYCLE-10


COMPUTE THE PCT. HP REQD.-EACH DUTY CYCLE- AND TOTAL HP AVAILABLE

  PCTHP =     22.560       22.560       22.800       22.800       22.440       16.040       16.040       16.800       53.040       28.440
  TOTHPR=     250.00

COMPUTE THE SPECIFIC FUEL CONSUMPTION AND FLOWRATES FOR THE RATED AND NOMINAL CONDITIONS

  SPCR   =     4.780        4.706        4.700        4.700        4.700        4.700        4.700        4.706        4.712        4.780
  WDOTR =    19.9167      19.6079      19.5847      19.5833      19.5833      19.5833      19.5834      19.6083      19.6318      19.9167
  SPCN   =     6.782        5.575        4.971        4.935        4.941        5.091        5.093        6.030        4.911        6.144
  WD     =    6.3752       5.2406       4.7224       4.6885       4.6199       3.4024       3.4035       4.2209      10.8527       7.2801
  PCWDOT=     32.009       26.727       24.113       23.941       23.591       17.374       17.380       21.526       55.281       36.553

COMPUTE THE CORRECTED AND MAX. FLOWRATES FOR THE APU UNITS

  GGXTM =    1908.04      1883.31      1869.97      1869.10      1867.31      1830.09      1830.13      1856.78      1984.20      1926.21
  CFSPC =     1.0346       1.0425       1.0468       1.0471       1.0477       1.0602       1.0602       1.0511       1.0122       1.0291
  WDC    =    6.5959       5.4636       4.9434       4.9093       4.8401       3.6071       3.6082       4.4365      10.9853       7.4922
  WDOT(MAX)=    10.98532  LB.PER MINUTE
  WDOTI =      .183089  LB.PER SECOND

COMPUTE THE TOTAL FUEL CONSUMED AND THE TOTAL LOADED

  TOTAL PROPELLANT CONSUMED =       477.255  LBS.OF HYDRAZINE.
  TOTAL PROPELLANT LOADED =         524.980

COMPUTE THE FUEL TANK CHARACTERISTIC PARAMETERS

  DENSITY OF HYDRAZINE     =        63.17326
  VOLUME OF STORAGE TANK   =          8.4764
  SURFACE AREA OF TANK     =         20.1355
  TANK PRESS.VESSEL WGT.   =         89.4459
  TANK BLADDER ASSY WGT.   =          2.8190
  TOTAL TANK ASSY. WEIGHT =          92.2648
  TANK INSULATION WEIGHT   =          1.9800
```

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                         NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * PAGE     8
                         DEPT 6213         *        THE INTEGRATED MATH MODEL      * DATE 08 JUN 73
                         EXT. 30235        *                                       * TIME 10:14:34
                         BLD. 104          *                 AT4307                * CASE     1
                         * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                                     TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT
                           **********      HYDRAZINE APU CALCULATIONS CONTINUED            **********

PARAMETER   CYCLE-1     CYCLE-2     CYCLE-3     CYCLE-4     CYCLE-5     CYCLE-6     CYCLE-7     CYCLE-8     CYCLE-9     CYCLE-10


COMPUTE THE PRESSURANT GAS PARAMETERS


  WPREM =   455.723     447.528     412.924     388.377     378.697     364.269     270.454     230.525     197.569      47.725
  VOLREM =   7.3801      7.2503      6.7026      6.3140      6.1608      5.9324      4.4474      3.8153      3.2936       .9217
  WDOTHE =    .043710     .036206     .032759     .032533     .032075     .023904     .023911     .029400     .072798     .049650
  WHEADD =    .458958     .054310     .229316     .162667     .064149     .095616     .621696     .264604     .218395     .992995

  MAX. HELIUM FLOWRATE =            .001213

  TOTAL HELIUM CONSUMED  =         3.162704

  TOTAL HELIUM LOADED =            3.795245

COMPUTE THE PRESSUPANT GAS SYSTEM WEIGHT FROM THE SCALING LAW


  PRESS.GAS SYSTEM WGT.  =         44.74406

COMPUTE THE PRESSURANT GAS TANK WEIGHT BY ACTUAL VALUES

  DENSITY OF HELIUM IN TANK =      1.890716
  VOL. OF HELIUM TANK                2.0073
  SURF. AREA OF HELIUM TANK          7.6981
  DIAMETER OF HELIUM TANK           18.7724
  WEIGHT OF HELIUM TANK             41.5043
  HELIUM TANK INSULATION WGT. =       .4170
```

```
                                  NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * PAGE     9
                                  DEPT 6213         *       THE INTEGRATED MATH MODEL       * DATE 08 JUN 73
                                  EXT. 30235        *                                       * TIME 10:14:34
                                  BLD. 104          *                   AT4307              * CASE     1
                                  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                                        TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

                                      *** SUMMARY OF COMPUTED SYSTEM CONFIGURATION PARAMETERS ***

 F    CODE    FT  NO  NS  IS IDX   G  GS   FCOEF       L/D        DIAM  ITHICK     PRES      TEMP    WDOT  WEIGHT     MACH     MFLAG

GAS  HZ-LIQ   1   2   0   1   1    1   2  .000000       .0000     .0000   .0000      .0000     .00  .0000      .000  .0000000
TRB  APU-1    0   1   0   1   2    1   2  .000000       .0000     .0000   .0000   580.0000  520.00  .1831      .000  .0000000
LIN  LN01     0   1   0   1   3    1   2  .039594     24.0000    1.0000  1.0000   580.0018  520.00  .1831      .437  .0000000
VAL  IV01     1   1   0   1   4    1   2  .039594    100.0000    1.0000   .0000   580.0094  520.00  .1831     1.541  .0000000
LIN  LN02     0   1   0   1   5    1   2  .039594     10.0000    1.0000  1.0000   580.0102  520.00  .1831      .182  .0000000
TEE  FT01     1   1   0   1   6    1   2  .039594     20.0000    1.0000   .0000   580.0117  520.00  .1831      .085  .0000000
LIN  LN03     0   1   0   1   7    1   2  .039594     10.0000    1.0000  1.0000   580.0125  520.00  .1831      .182  .0000000
VAL  SV01     1   1   0   1   8    1   2  .039594    100.0000    1.0000   .0000   580.0201  520.00  .1831     1.541  .0000000
LIN  LN04     0   1   0   1   9    1   2  .039594     20.0000    1.0000  1.0000   580.0216  520.00  .1831      .364  .0000000
TAN  TK01     0   1   0   1  10    1   2  .000000       .0000     .0000  2.0000   600.0000  520.00  .1831    92.265  .0000000
```

```
                           NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * PAGE     10
                           DEPT 6213         *       THE INTEGRATED MATH MODEL       * DATE 08 JUN 73
                           EXT. 30235        *                                       * TIME 10:14:35
                           BLD. 104          *                AT4307                 * CASE     1
                           * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                                       TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

                                *** SUMMARY OF COMPUTED SYSTEM CONFIGURATION PARAMETERS - CONTD. ***

 F    CODE    FT  NO  NS  IS IDX   G  GS   FCOEF        L/D        DIAM  ITHICK     PRES     TEMP    WDOT  WEIGHT     MACH     MFLAG

GAS  HE-GAS   2   1   0   1  11    2   1  .000000       .0000     .0000   .0000     .0000      .00  .0000    .000  .0000000
BLA  BL01     0   1   0   1  12    2   1  .000000       .0000     .0000   .0000  600.0000   520.00  .0012   2.819  .0000000
LIN  LN11     0   1   0   1  13    2   1  .036514     40.0000     .2500  1.0000  600.0191   520.00  .0012    .182  .0025936
TEE  FT11     1   1   0   1  14    2   1  .036514     20.0000     .2500   .0000  600.0215   520.00  .0012    .005  .0025936
LIN  LN12     0   1   0   1  15    2   1  .036514     20.0000     .2500  1.0000  600.0310   520.00  .0012    .091  .0025936
VAL  SV02     1   1   0   1  16    2   1  .036514    100.0000     .2500   .0000  600.0429   520.00  .0012    .838  .0025935
LIN  LN13     0   1   0   1  17    2   1  .036514     24.0000     .2500  1.0000  600.0544   520.00  .0012    .109  .0025935
TEE  FT12     1   1   0   1  18    2   1  .036514     20.0000     .2500   .0000  600.0567   520.00  .0012    .005  .0025934
LIN  LN14     0   1   0   1  19    2   1  .036514     10.0000     .2500  1.0000  600.0615   520.00  .0012    .046  .0025934
REG  PR01     2   1   0   1  20    2   1  .036514    394.0000     .2500   .0000 2999.0000   520.00  .0012   1.801  .0000000
LIN  LN15     0   1   0   1  21    2   1  .036720     10.0000     .2500  1.0000 2999.0010   520.00  .0012    .080  .0005745
VAL  IV02     1   1   0   1  22    2   1  .036720    100.0000     .2500   .0000 2999.0037   520.00  .0012   1.801  .0005745
LIN  LN16     0   1   0   1  23    2   1  .036720     12.0000     .2500  1.0000 2999.0049   520.00  .0012    .096  .0005745
CON  OR01     3   1   0   1  24    2   1  .036720    900.0000     .2500   .0000 2999.0288   520.00  .0012   1.801  .0005745
LIN  LN17     0   1   0   1  25    2   1  .036720     12.0000     .2500  1.0000 2999.0301   520.00  .0012    .096  .0005745
TEE  FT13     1   1   0   1  26    2   1  .036720     20.0000     .2500   .0000 2999.0306   520.00  .0012    .009  .0005745
LIN  LN18     0   1   0   1  27    2   1  .036720     10.0000     .2500  1.0000 2999.0316   520.00  .0012    .080  .0005745
TAN  TK02     0   1   0   1  28    2   1  .000000       .0000     .0000  1.0000 3000.0000   520.00  .0012  41.504  .0000000


                        ***** THE HYDRAZINE APU CALCULATIONS HAVE BEEN COMPLETED *****
```

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                 NAME R.F.HAUSMAN  * * * * * * * * * * * * * * * * * * * * * PAGE     11
                 DEPT 6213         *       THE INTEGRATED MATH MODEL       * DATE 08 JUN 73
                 EXT. 30235        *                                       * TIME 10:14:36
                 BLD. 104          *                 AT4307                * CASE      1
                 * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
                             TEST CASE FOR HYDRAZINE APU PROGRAM CHECKOUT

                                        *** COMPONENT WEIGHT SUMMARY ***

                ...PROPELLANT...                                            ...HELIUM...
                    --------                                                    ----
                           COMPONENT     INSULATION                                    COMPONENT     INSULATION
COMPONENT       CODE       WT. (LBS)     WT. (LBS)           COMPONENT     CODE        WT. (LBS)     WT. (LBS)

  LINE          LN01            .437          .039      .     LINE          LN11            .182          .120
  VALVE         IV01           1.541          .000      .     TEE           FT11            .005          .000
  LINE          LN02            .182          .016      .     LINE          LN12            .091          .060
  TEE           FT01            .085          .000      .     VALVE         SV02            .838          .000
  LINE          LN03            .182          .016      .     LINE          LN13            .109          .072
  VALVE         SV01           1.541          .000      .     TEE           FT12            .005          .000
  LINE          LN04            .364          .032      .     LINE          LN14            .046          .030
  TANK          TK01          92.265         1.980      .     REG           PR01           1.801          .000
                                                        .     LINE          LN15            .080          .030
                                                        .     VALVE         IV02           1.801          .000
                                                        .     LINE          LN16            .096          .036
                                                        .     CONTRL        OR01           1.801          .000
                                                        .     LINE          LN17            .096          .036
                                                        .     TEE           FT13            .009          .000
                                                        .     LINE          LN18            .080          .030
                                                        .     TANK          TK02          41.504          .417

                                    *** COMPONENT WEIGHT SUMMARY TOTALS ***

                   CONSUMER WEIGHT - LBS                    .000000
                   OXIDYZER SYSTEM WT. -LBS                 .965977+02
                   OXID INSULATION WT - LBS                 .208296+01
                   FUEL SYSTEM WT. - LBS                    .485447+02
                   FUEL INSULATION WT - LBS                 .830953+00
                   TOTAL SYSTEM WT. - LBS                   .148056+03

@FIN
```

Section D-3

THE HYDRAZINE APU ANALYSIS PROGRAM (HZPRØG)

D-3.1 PROGRAM LISTING

The program listing presented in the following pages was produced using the EXEC-8 LISTALL processor which lists a file in alphabetical order. Since the processor does not differentiate between subroutines, functions and Procedure Definition Processors (PDPs), each subprogram has been relabeled to clearly identify the type of symbolic listing presented. The alphabetical listing permits rapid list scanning when searching for a particular subprogram.

The file "HZPRØG." contains a total of sixty-eight FØRTRAN elements of which thirty are Procedure Definition Processor elements and thirty-eight are subroutines, functions and the main driver routine.

The listing contained in this subsection presents five PDP elements and nine FORTRAN subprograms of which four are new subprograms coded for the Hydrazine APU analysis. The other five subprograms and the five PDP elements are modified versions of the originals as previously listed in Appendix B.

There are in the file, thirteen dummy elements, which are present only because it is simpler to dummy out a subprogram rather than change basic coding structure. The thirteen dummy elements are:

ACCRES
ACQWT
APUFLØ
APUSUB
APUSUP
CØNSUM
ECLSS
FUELCL
CMPCAL
LIQRES
TANK
TSIZEI
WTACC

Other subprograms contained in the "HZPRØG." file are the following sixteen elements:

DIAG
FINDR
FINTAB
GETCØN
INTAB
LØCATE
LWEIGHT
MIPE
ØUTPUT
PAGE
STØCØN
TCØND
TEL
YLGINT
YLNTRP
ZFIND

Listings for these elements will be found in Appendix B along with the remaining twenty-five PDP elements. The file table of contents given in D-3.2 may be used to identify the remaining PDP elements.

While symbolic listings are quite useful in understanding the coding of a particular subprogram, it is recommended that the program user create and maintain a standard compiler listing output file, since the additional information provided by the compiler is very useful in troubleshooting and debugging changes to the basic coding.

The program list file follows:

* PRØCEDURE DEFINITIØN PRØCESSØR CAPU

```
635717*TPF$.CAPU
CAPU* PROC
C
      PARAMETER  LAPU = 20
C
      REAL KK, MRGGCH, MRGGCO
C
      COMMON /CIAPU/ M      ,NAPU  ,DELPCP,FMR   ,FMRG  ,HPR   ,MRGGCH,
     1 MRGGCO,PFH   ,PFO   ,PGG   ,RRFP  ,TD    ,TDGGH ,TDGGO ,TENV  ,
     2 TFH   ,TFO   ,TG    ,TIT   ,TME   ,TVH   ,TVO   ,EQAP1(5),
     3 EQAP2(11,2),EQAP3(11,2),LAPU1(4,8),LAPU2(4,11),LAPU3(4,11)
     4,PRAT  ,PCRSRV,SPGPRS,WTBLAD,PTRBIN
C
      COMMON /CVAPU/KK(LAPU), RR(LAPU), WD(LAPU), D (LAPU), TE(LAPU),
     1              CPE(LAPU),TTH(LAPU),TTO(LAPU),WDA(LAPU),WDB(LAPU),
     2              WDC(LAPU),WDD(LAPU),WDE(LAPU),WDF(LAPU),WDG(LAPU),
     3              WDJ(LAPU),WGH(LAPU),WTH(LAPU),WTO(LAPU),HTH(LAPU),
     4              HTO(LAPU),
     5              WDRH  (LAPU),WDRO  (LAPU), PCTHP (LAPU), WGGH  (LAPU)
     6             ,WGGO  (LAPU),WDFC  (LAPU), WGHC  (LAPU), WGOC  (LAPU)
     7             ,WDBC  (LAPU),WDCC  (LAPU), WDEC  (LAPU), DELH  (LAPU)
     8             ,DWDH  (LAPU),DQODWH(LAPU), DQODWO(LAPU), Q1HDOT(LAPU)
     9             ,Q1ODOT(LAPU),Q2HDOT(LAPU), Q2ODOT(LAPU), Q3HDOT(LAPU)
     T             ,Q3ODOT(LAPU),TTH2WD(LAPU), TTO2WD(LAPU), PCH2WD(LAPU)
     1             ,PCO2WD(LAPU),Q2HDTC(LAPU), Q2ODTC(LAPU), Q3HDTC(LAPU)
     2             ,Q3ODTC(LAPU),Q4HDOT(LAPU), Q5HDOT(LAPU), Q6ODOT(LAPU)
     3             ,Q7ODOT(LAPU),RHOCH2(LAPU), RHOCO2(LAPU), DQDWTH(LAPU)
     4             ,DQDWTO(LAPU),TSIN  (LAPU), CPH   (LAPU)
     5             ,CSUBVO(LAPU),CSUBVH(LAPU), PHIO2 (LAPU), PHIH2 (LAPU)
     6             ,QINTKO(LAPU),QINTKH(LAPU), CPBH  (LAPU), WSUM  (LAPU)
     7             ,SPCR (LAPU),WDOTR (LAPU),SPCN  (LAPU),PCWDOT(LAPU)
     8             ,GGXTM(LAPU),CFSPC (LAPU),WPREM (LAPU),VOLRM (LAPU)
     9             ,WHEAD(LAPU),WDTHE (LAPU)
C
      EQUIVALENCE        (EQAP1   ,TPF   ),(EQAP1(2),WDO   ),
     1 (EQAP1(3),WDH   ),(EQAP1(4),WDT   ),(EQAP1(5),WTBURN)
     2,(EQAP2      ,WOCOMP),(EQAP2( 1,2),WHCOMP),(EQAP2( 2,1),WTGO  ),
     3 (EQAP2( 2,2),WTGH  ),(EQAP2( 3,1),VTO   ),(EQAP2( 3,2),VTH   ),
     4 (EQAP2( 4,1),ATO   ),(EQAP2( 4,2),ATH   ),(EQAP2( 5,1),WGTOT ),
     5 (EQAP2( 5,2),WGTHT ),(EQAP2( 6,1),WVHO2 ),(EQAP2( 6,2),WVHH2 ),
     6 (EQAP2( 7,1),WRO   ),(EQAP2( 7,2),WRH   ),(EQAP2( 8,1),WAO   ),
     7 (EQAP2( 8,2),WAH   ),(EQAP2( 9,1),WSO   ),(EQAP2( 9,2),WSH   ),
     8 (EQAP2(10,1),WRAO  ),(EQAP2(10,2),WRAH  ),(EQAP2(11,1),WOTOT ),
     9 (EQAP2(11,2),WHTOT )
C
      EQUIVALENCE           (EQAP3      ,TGGCO ),(EQAP3( 1,2),TGGCH ),
     1 (EQAP3( 2,1),WTGGO ),(EQAP3( 2,2),WTGGH ),(EQAP3( 3,1),AREATO),
     2 (EQAP3( 3,2),AREATH),(EQAP3( 4,1),VSTO  ),(EQAP3( 4,2),VSTH  ),
     3 (EQAP3( 5,1),QTODOT),(EQAP3( 5,2),QTHDOT),(EQAP3( 6,1),WSVHO ),
     4 (EQAP3( 6,2),WSVHH ),                     (EQAP3( 7,2),WSVH  ),
     5 (EQAP3( 8,1),WPTTO ),(EQAP3( 8,2),WPTTH ),(EQAP3( 9,1),WSRO  ),
     6 (EQAP3( 9,2),WSRH  ),(EQAP3(10,1),WSOB  ),(EQAP3(10,2),WSHB  ),
     7 (EQAP3(11,1),WRSAO ),(EQAP3(11,2),WRSAH )
C
C
C         *****
C             * NAPU  - NUMBER OF APU UNITS
C             * HPR   - HORSEPOWER RATING EACH APU
```

```
********     CAPU     ********

     C              * FMR    - APU TURBINE MIXTURE RATIO
     C              * PGG    - APU GAS GEN. INLET GAS PRESSURE
     C              * TIT    - TURBINE INLET TEMP
     C              * TO     - EXHAUST TEMP FOR HEAT EXCHANGER
     C              * FMRG   - FUEL MIXTURE-RATIO FOR SUPPLEMENTAL GAS GEN.
     C              * PFH    - FINAL H2 TANK PRESSURE
     C              * PFO    - FINAL O2 TANK PRESSURE
     C              * TFH    - FINAL H2 TANK TEMPERATURE
     C              * TFO    - FINAL O2 TANK TEMPERATURE
     C              * TG     - TEMP. OF EXHAUST PRODUCTS - SUPPL. GAS GEN.
     C              * DELCP  - DELTA-P OF TANK CIRCULATING PUMP
     C              * KK     - COR.FACTOR-REF.PROP.FLOW RATE FOR 2060 TIT.
     C              * RR     - REF.PROP.FLOW RATE (LBS/MIN)
     C              * WD     - DELIVERED FLOW RATE OVER INTERVAL (I)(LBS/MIN)
     C              * D      - HEAT OF COMBUSTION PRODUCTS (BTU/LB)
     C              * TE     - APU TURBINE EXHAUST TEMP.
     C              * CPE    - EXHAUST SPEC.HT. AT(TE AND FMR)
     C              * TTH    - TEMP. OF H2 IN TANK DURING INTERVAL(I)
     C              * TTO    - TEMP. OF O2 IN TANK DURING INTERVAL(I)
     C              * WDA    - APU EXHAUST FLOW THRU H2-HEX (ACCUM TO GAS GEN)
     C              * WDB    - APU EXHAUST FLOW THRU H2-HEX (TANK TO ACCUM)
     C              * WDC    - APU EXHAUST FLOW THRU H2-TANK HEX
     C              * WDD    - APU EXHAUST FLOW THRU O2-HEX (ACCUM TO GAS GEN)
     C              * WDE    - APU EXHAUST FLOW THRU O2-HEX (TANK TO ACCUM)
     C              * WDF    - APU EXHAUST FLOW THRU O2-TANK HEX
     C              * WDG    - APU EXHAUST FLOW THRU H2-HEX(SUBC.ACUM-GAS GEN)
     C              * WDJ    - APU EXHAUST FLOW THRU O2-HEX(SUBC.ACUM-GAS GEN)
     C              * WGH    - REF.H2 FLOWRATE TO SUPPLEMENTAL GAS GEN.
     C              * WTH    - H2 FLOW TO ACCUM DURING INTERVAL (I)
     C              * WTO    - O2 FLOW TO ACCUM DURING INTERVAL (I)
     C              * HTH    - ENTHALPY OF H2 IN TANK AT INTERVAL(I)
     C              * HTO    - ENTHALPY OF O2 IN TANK AT INTERVAL(I)
     C              * WDRH   - WGT.RATE OF H2 FLOWING-INTERVAL(I), (LBS/MIN).
     C              * WDRO    - WGT.RATE OF O2 FLOWING-INTERVAL(I), (LBS/MIN)
     C              * PCTHP   - PERCENT HORSEPOWER REQD.-INTERVAL(I)
     C              * WGGH    - H2 FLOW RATE TO COND.GAS GENS.-INTERVAL(I)
     C              * WGGO    - O2 FLOW RATE TO COND.GAS GENS.-INTERVAL(I)
     C              * WDFC    - CORRECTED WDF(I) FOR FLOW RATE CHANGE
     C              * WGHC    - REF.H2 FLOW TO SUPPLEMENTAL GAS GEN.
     C              * WGOC    - REF.O2 FLOW TO SUPPLEMENTAL GAS GEN.
     C              * WDBC    - CORRECTED VALUES OF HEX EXHAUST REQMTS.(WDB(I))
     C              * WDCC    - CORRECTED VALUES OF HEX EXHAUST REQMTS.(WDC(I))
     C              * WDEC    - CORRECTED VALUES OF HEX EXHAUST REQMTS.(WDE(I))
     C              * DELH    - TOTAL ENTHALPY INCREMENT FROM SUPPL.GAS GEN.
     C              * DWDB    - REF.REDUCTION IN WDB FOR  APU EXHAUST AVAIL.
     C              * TSIN    - T-COLD-IN FOR SUPPLEMENTARY GAS GENERATOR
     C              * CPH     - SPECIFIC HEAT OF COLD FLUID INTO SUP.GAS GEN.
     C              * DQODWH - HT.XFER.INTO O2 TANK DURING INTERVAL(I)
     C              * DQODWO - HT.XFER.INTO H2 TANK DURING INTERVAL(I)
     C              * Q1HDOT - HT.XFER.INTO HEX BETWEEN H2 ACCUM -APU GAS GEN.
     C              * Q1ODOT - HT.XFER.INTO HEX BETWEEN O2 ACCUM -APU GAS GEN.
     C              * Q2HDOT - HT.XFER.INTO HEX BETWEEN H2 TANK - H2 ACCUM.
     C              * Q2ODOT - HT.XFER.INTO HEX BETWEEN O2 TANK - O2 ACCUM.
     C              * Q3HDOT - HT.XFER.INTO H2 TANK - INTERVAL(I)
     C              * Q3ODOT - HT.XFER.INTO O2 TANK - INTERVAL(I)
     C              * Q2HDTC - CORRECTED VALUE OF Q2HDOT DUE TO SUPPL.GAS GEN.
     C              * Q2ODTC - CORRECTED VALUE OF Q2ODOT DUE TO SUPPL.GAS GEN.
     C              * Q3HDTC - CORRECTED VALUE OF Q3HDOT DUE TO SUPPL.GAS GEN.
```

```
*********     CAPU     *********

              C                * Q30DTC - CORRECTED VALUE OF Q30DOT DUE TO SUPPL.GAS GEN.
              C                * Q4HDOT - HT.XFER.INTO HEX BETWEEN H2 ACCUM -APU GAS GEN.
              C                * Q5HDOT - HT.XFER.INTO HEX BETWEEN H2 PUMP  - H2 ACCUM.
              C                * Q60DOT - HT.XFER.INTO HEX BETWEEN O2 ACCUM -APU GAS GEN.
              C                * Q70DOT - HT.XFER.INTO HEX BETWEEN O2 PUMP  - O2 ACCUM.
              C                * TTH2WD - TOTAL USABLE H2 WITHDRAWN TO END INTERVAL(I)
              C                * TTO2WD - TOTAL USABLE O2 WITHDRAWN TO END INTERVAL(I)
              C                * PCH2WD - PERCENT USABLE H2 WITHDRAWN TO END INTERVAL(I)
              C                * PCO2WD - PERCENT USABLE O2 WITHDRAWN TO END INTERVAL(I)
              C                * RHOCH2 - DENSITY OF H2 IN STORAGE TANK
              C                * RHOCO2 - DENSITY OF O2 IN STORAGE TANK
              C                * DQDWTH - DQ/DW * WTH(I)
              C                * DQDWTO - DQ/DW * WTO(I)
              C           *****
              C
               END
```

PRØCEDURE DEFINITIØN PRØCESSØR CCNTRL

```
635717*TPFS.CCNTRL
CCNTRL* PROC
C
      PARAMETER  NBRSR=9, NBRSY=6
C
      INTEGER  SCRIT,SYSNUM
C
      COMMON /CCNTRL/ INBLK(NBRSY,5,2),NAMSYS(NBRSY),SCRIT,SYSNUM
     I ,INTGSY,MDTRC(12),KSUBC(NBRSY,NBRSR),LREPT,JAPUS(2,2)
C
C                 INBLK   -  CONTROLS INPUT SELECTION IN COMPIL
C                 SCRIT  =  1  FOR SUB-CRITICAL
C                        =  2  FOR SUPER-CRITICAL
C                 SYSNUM =  1  ACPS
C                        =  2  APU
C                        =  3  EC/LSS
C                        =  4  FUEL CELL
C                        =  5  OMS
C                        =  6  HZN  (HYDRAZINE APU)
C
C    CARD COL.    MDTRC( ) - DIAGNOSTIC TRACE SWITCH FOR CRYCON (OFF=0)
C       (69)           (1) = 1   TURN ON ACCRES
C       (70)           (2) = 1   TURN ON ACQWT
C       (71)           (3) = 1   TURN ON APUSUB OR APUSUP
C       (72)           (4) = 1   TURN ON CMPCAL
C       (73)           (5) = 1   TURN ON FUELCL
C       (74)           (6) = 1   TURN ON CONSUM
C       (75)           (7) = 1   TURN ON ECLSS
C       (76)           (8) = 1   TURN ON LIQRES
C       (77)           (9) = 1   TURN ON TANK
C       (78)          (10) = 1   TURN ON TSIZEI
C       (79)          (11) = 1   TURN ON WTACC
C       (80)          (12) = 1   TURN ON HZAPU
C
C                 MDTRC(1) IS CARD COL 69,--- MDTRC(12) IS CARD COL 80
C                   OF THE SYSTEM SPECIFICATION CARD
C
C
C     ****************************************************************
C
C     *******  THIS SUBPROGRAM HAS BEEN MODIFIED FOR USE WITH THE ******
C     *******             HYDRAZINE APU PROGRAM                   ******
C     *******       **    DO NOT USE WITH TCIMM    **             ******
C
C     ****************************************************************
C
C
 END
```

PROCEDURE DEFINITION PROCESSOR CNAMES

```
635717*TPFS.CNAMES
CNAMES* PROC
C
      INTEGER FNAME
C
      COMMON /CNAMES/ FNAME(19), L0(9,16), L1(21,2), L2(3,7), L3(4,3),
     1 L4(4,11), L5(4,5), L6(4,4), L7(4,23), L8(4,3), L9(4,5), L10(4,5),
     2 L11(4,24), L12(4,28), L13(4,28), JFLUID(2,3), KFLUID(2,2)
C
C        NAMES ARE GIVEN IN S.R. STODTA
C
C     ******************************************************************
C
C     *******  THIS SUBPROGRAM HAS BEEN MODIFIED FOR USE WITH THE ******
C     *******                HYDRAZINE APU PROGRAM                ******
C     *******           **    DO NOT USE WITH TCIMM   **          ******
C
C     ******************************************************************
C
C
 END
```

SUBRØUTINE CØMPIL

```
635717*TPFS.COMPIL
C                 * * * * * * * * * * * * * ** * * * * * * * * * * *
C                 * ROUTINE NAME - DATA INPUT, VERIFY AND ECHO *
C                 * ROUTINE LANG - FORTRAN V UNIVAC 1108 EXEC 2*
C                 * PROGRAMMER   - R. BOLLINGER 1943 102 26933 *
C                 * DATE CODED   - APRIL FOOLS DAY 1970        *
C                 * REVISED      - JANUARY 11,1972             *
C                 * REVISED      - JULY  1972                  *
C                 * PROGRAMMER   - J. MCKAY  D1943  201  45178 *
C                 * * * * * * * * * * * * * ** * * * * * * * * * * *
C
C
C      *********************************************************************
C
C      *******  THIS SUBPROGRAM HAS BEEN MODIFIED FOR USE WITH THE ******
C      *******              HYDRAZINE APU PROGRAM                  ******
C      *******        **    DO NOT USE WITH TCIMM    **            ******
C
C      *********************************************************************
C
       SUBROUTINE COMPIL
C
       LOGICAL JP,PAGE
C
       INCLUDE CACCUM
       INCLUDE CAPU
       INCLUDE CCNFIG
       INCLUDE CCNTRL
       INCLUDE CDCYCL
       INCLUDE CECLSS
       INCLUDE CENG
       INCLUDE CFUEL
       INCLUDE CHEX
       INCLUDE CHSORC
       INCLUDE CIOUNT
       INCLUDE CMOTOR
       INCLUDE CNAMES
       INCLUDE CPAGE
       INCLUDE CPUMP
       INCLUDE CTANK
       INCLUDE CTURBN
       INCLUDE  TANKWT
C
  5010 FORMAT(A6,I4,3I5,3F5.0,I5,2F5.0,5X,A6)
  5020 FORMAT(I5,6F10.0)
  5030 FORMAT(3I5/7F10.0/F10.0)
  5039 FORMAT(I5)
  5040 FORMAT(11F6.0,6X,A6)
  5050 FORMAT(I5,4F10.0/I5,4F10.0/4F10.0/4F10.0/5F10.0/5F10.0)
  5060 FORMAT (5I5/8F10.0/8F10.0/F10.0)
  5062 FORMAT (2I5,7F10.0)
  5070 FORMAT(F10.0)
  5080 FORMAT(3F10.0,I5,3F10.0,F7.0)
  5090 FORMAT(I5,5X,4F10.0)
  5100 FORMAT(I5,5X3F10.0)
  5110 FORMAT(8F10.0)
  5120 FORMAT(I5,5X,5F10.0)
  5130 FORMAT(7F10.0)
```

```
********     COMPIL     *********

      5140 FORMAT(10F7.0)
      5141 FORMAT(2I5,6F10.0)
      5150 FORMAT(4I5,5F10.0/(7F10.0))
      5151 FORMAT(7F10.0/5F10.0)
     C
      6000 FORMAT('0',38X9A6//21A6/21A6/' ')
      6010 FORMAT(3XA6, 2XA6,1XI4,2XI5,2XI5,2XI5,2X,E15.8,6XF7.2,6XF6.2,5XI5,
          1 9XF6.2,7XF5.1)
      6020 FORMAT('0 *DIAGNOSTIC* THE ABOVE FUNCTION CODE IS ILLEGAL')
      6030 FORMAT('0',38X9A6/' ')
      6031 FORMAT('0',T55,'SUBCRITICAL APU DATA'//)
      6032 FORMAT('0',T53,'SUPERCRITICAL APU DATA'//)
      6040 FORMAT(54XI5,2X3A6/(46XE13.8,2X3A6))
      6050 FORMAT('0',38X9A6//)
      6051 FORMAT(T18,'- 1 -',T36,'- 2 -',T54,'- 3 -',T72,'- 4 -',T90,'- 5 -'
          1 ,T103,'HEAT EXCHANGER NUMBER'/T13,'OXYGEN  HYDROGEN  OXYGEN  HYDR
          2OGEN  OXYGEN  HYDROGEN  OXYGEN  HYDROGEN  OXYGEN  HYDROGEN'/)
      6052 FORMAT(/////T18,'- 6 -',T36,'- 7 -',T54,'- 8 -',T72,'- 9 -',T90,
          1 '- 10 -',T103,'HEAT EXCHANGER NUMBER'/T13,'OXYGEN  HYDROGEN  OXYG
          2EN  HYDROGEN  OXYGEN  HYDROGEN  OXYGEN  HYDROGEN  OXYGEN  HYDROGEN
          3'/)
      6060 FORMAT (41XI5,10XI5,7X4A6)
      6062 FORMAT ('0'//38X'*'9A6/ 39X'TANK'8X'FLUID'9X'. . . D I M E N S I O
          1 N S . . .'/ 39X'SHAPE'7X'TYPE'22X'(FEET)'/)
      6064 FORMAT (30X 2I12,6X 3F12.4)
      6069 FORMAT(T48,'NUMBER OF HEAT EXCHANGERS INPUT =',I5//)
      6070 FORMAT(9X10F9.1,3X4A6)
      6080 FORMAT(42XI4,10XI5,7X4A6/4(36X2E15.8,2X4A6/),'0',38X9A6///4(36X2E1
          15.8 ,2X4A6/),'0',38X9A6/// (36X2E15.8,2X4A6))
      6090 FORMAT (36X2E15.8,2X4A6)
      6091 FORMAT('0',47X,I5,15X,'TANK WEIGHT-CONFIGURATION OPTION CONSIDERED
          1 '/48X,I5,15X,'NUMBER OF TANK SHAPES IN CONFIGURATION')
      6100 FORMAT('0'38X9A6/' ')
      6101 FORMAT('0',T10,'OPER.TIME',T24,'NON-OPERATING',T40,'MIB-DEGRAD.',
          1 T54,'UNITS OPER.',T67,'HORSEPOWER',T81,'AMB.PRESSURE',T98,
          2 'POWER-KW',T110,'REPRES.TIME'/)
      6110 FORMAT(T7,3E15.8,I8,5X,4E15.8)
      6120 FORMAT ('0 * ERROR * DUTY CYCLE INPUT TOO LONG'/)
      6127 FORMAT(//T18,'- 6 -',T36,'- 7 -',T54,'- 8 -',T72,'- 9 -',T90,
          1 '- 10 -',T103,'HEAT SOURCE NUMBER'/T13,
          2                                     'OXYGEN  HYDROGEN  OXYGEN  HYDR
          3OGEN  OXYGEN  HYDROGEN  OXYGEN  HYDROGEN  OXYGEN  HYDFOGEN'/)
      6128 FORMAT(T49,'NUMBER OF HEAT SOURCES INPUT =',I5//)
      6129 FORMAT(T18,'- 1 -',T36,'- 2 -',T54,'- 3 -',T72,'- 4 -',T90,'- 5 -'
          1 ,T103,'HEAT SOURCE NUMBER'/T13,'OXYGEN  HYDROGEN OXYGEN  HYDROGEN
          2  OXYGEN  HYDROGEN  OXYGEN  HYDROGEN  OXYGEN  HYDROGEN'/)
      6130 FORMAT(9X10I9,3X4A6/(9X10F9.1,3X4A6))
      6140 FORMAT(T52,I15,T70,'MOTOR TYPE'/T52,E15.8,T70,'MOTOR EFFICIENCY',
          1 /T52,E15.8,T70,'MOTOR SPEED'/T52,E15.8,T70,'BATTERY POWER DENSITY
          2')
      6150 FORMAT(54XI5,2X4A6/(46XE13.8,2X4A6))
      6160 FORMAT(54XI5,2X4A6/54XI5,2X4A6/54XI5,2X4A6/54XI5,2X4A6,
          1 /(46XE13.8,2X4A6))
     C
     C   ******************************************************************
     C
     C      *****  CHECK 'NBLK' BEFOR DATA SETUP - INCLUDE ALL DATA BLOCKS  *****
     C      *****  REQUIRED FOR THE SYSTEM BEING STUDIED.                   *****
```

```
********     COMPIL     ********

C
C  ************************************************************************
C
      NIENTH = 0.0
C
C
C          ***** INPUT THE CONFIGURATION TARLE
C
      IF(PAGE(0)) WRITE(6,6000) (LO(I,1),I=1,9),((L1(I,J),I=1,21),J=1,2)
      JP = PAGE(5)
C
      IERR = 0
      DO 30 II=1,ICNF
      READ (IIN,5010) CFUNCT, CFTYPE, CNOPER, CNSTBY, CMTYPE, FRCOEF(II)
     1                , LOD(II), DIAM(II), CITYPE, ITHICK(II), NRAR(II),
     2                  CODE(II)
      IF(PAGE(1)) WRITE(6,6000) (LO(I,1),I=1,9),((L1(I,J),I=1,21),J=1,2)
      WRITE (IOT,6010) CFUNCT, CODE(II), CFTYPE, CNOPER, CNSTBY, CMTYPE,
     1                   FRCOEF(II), LOD(II), DIAM(II), CITYPE,
     2                   ITHICK(II), NBAR(II)
C
C          ***** SEARCH FOR THE CONFIGURATION NAME.
C
      DO 10 I2 = 1,19
      IF(CFUNCT.EQ.FNAME(I2)) GO TO 20
   10 CONTINUE
C
      WRITE(6,6020)
      IERR = IERR + 1
      GO TO 30
C
   20 CFUNCT = I2
      CALL STOCON(II)
      IF(CFUNCT.EQ.19) GO TO 35
   30 CONTINUE
C
C          ***** INPUT THE DUTY CYCLE DATA
C
   35 CONTINUE
      IF (IERR .GT. 0) CALL EXIT
      IF(PAGE(0)) WRITE(6,6100) (LO(I,6),I=1,9)
      WRITE (IOT,6101)
      DCYCLT = 0.0
      NDCYCL = 0
      II = 0
      DO 100 I1=1,ICDL2,2
      NDCYCL = NDCYCL + 2
      II = II + 1
      READ (IIN,5080) DCYCLE(I1), DCYCLE(I1+1), PSI(II), NEOP(II),
     1                 HP(II), PAMR(II), PKW(II), RPRTIM(II)
      IF(PAGE(1)) WRITE(6,6100) (LO(I,6),I=1,9)
      WRITE (IOT,6110) DCYCLE(I1), DCYCLE(I1+1), PSI(II), NEOP(II),
     1                  HP(II), PAMB(II), PKW(II), RPRTIM(II)
      DCYCLT = DCYCLT + DCYCLE(I1)
      KCYCLE = II - 1
      IF(DCYCLE(I1+1)) 90,,
      IF(DCYCLE(I1)),100,100
      NDCYCL = NDCYCL - 1
```

```
*********     COMPIL     *********

   90 NDCYCL = NDCYCL - 1
      GO TO 110
  100 CONTINUE
C
      WRITE(6,6120)
      CALL EXIT
C
C         ***** INPUT THE CONSUMER DATA
C
  110 CONTINUE
      GO TO (111,112,120,130,111,140), SYSNUM
  111 CONTINUE
C
C         ***** READ IN THE ENGINE CONSUMER DATA
C
      IF(PAGE(0)) WRITE(6,6030) (L0(I,2),I=1,9)
      READ(5,5020) NENG,GITEMP,GIPRES,THRUST,PSUBC,EXPRAT,MIXRAT
      WRITE(6,6040) NENG,(L2(I,1),I=1,3),
     1            GITEMP,(L2(I,2),I=1,3),
     2            GIPRES,(L2(I,3),I=1,3),
     3            THRUST,(L2(I,4),I=1,3),
     4            PSUBC ,(L2(I,5),I=1,3),
     5            EXPRAT,(L2(I,6),I=1,3),
     6            MIXRAT,(L2(I,7),I=1,3)
C
      GO TO 113
C
  112 CONTINUE
C
C         ***  READ IN THE APU CONSUMER DATA
C
      IF(PAGE(0))WRITE (IOT,6030) (L0(I,13),I=1,9)
C
      READ (IIN,5120) NAPU, HPR, FMR, PGG, TIT, TD
      GO TO (114,115),SCRIT
  114 CONTINUE
      WRITE (IOT,6031)
      READ (IIN,5130) MRGGCH, MRGGCO, TDGGH, TDGGO, TVH, TVO, TENV
C
      WRITE (IOT,6150) NAPU, (L11(I,1),I=1,4), HPR, (L11(I,2),I=1,4),
     1                 FMR , (L11(I,3),I=1,4), PGG, (L11(I,4),I=1,4),
     2                 TIT , (L11(I,5),I=1,4), TD , (L11(I,6),I=1,4),
     3                MRGGCH,(L11(I,7),I=1,4),MRGGCO,(L11(I,8),I=1,4),
     4                TDGGH ,(L11(I,9),I=1,4),TDGGO ,(L11(I,10),I=1,4),
     5                TVH   ,(L11(I,11),I=1,4),TVO   ,(L11(I,12),I=1,4),
     6                TENV  ,(L11(I,13),I=1,4)
C
      GO TO 113
C
  115 CONTINUE
      WRITE (IOT,6032)
      READ (IIN,5130) FMRG, PFH, PFO, TFH, TFO, TG, DELPCP, TENV
C
      WRITE (IOT,6150) NAPU, (L11(I,1),I=1,4),HPR   , (L11(I,2),I=1,4),
     1                 FMR , (L11(I,3),I=1,4),PGG   , (L11(I,4),I=1,4),
     2                 TIT , (L11(I,5),I=1,4),TD    , (L11(I,6),I=1,4),
     3                 FMRG,(L11(I,14),I=1,4),PFH   ,(L11(I,15),I=1,4),
     4                 PFO ,(L11(I,16),I=1,4),TFH   ,(L11(I,17),I=1,4),
```

```
********     COMPIL     *********

     5                TFO ,(L11(I,18),I=1,4),TG     ,(L11(I,19),I=1,4),
     6              DELPCP,(L11(I,20),I=1,4),TENV   ,(L11(I,13),I=1,4)
C
      GO TO 113
C
  120 CONTINUE
C
C          *** READ IN LIFE SUPPORT SYSTEM CONSUMER DATA
C
      IF(PAGE(0)) WRITE (IOT,6050) (LO(I,15),I=1,9)
C
      READ (IIN,5150) MDAYS,NCREW,NRPRES,NDARES,O2FNOM,GLKRAT,TLSNOM(1),
     1 TLSNOM(2),RHOBEG(1),RHOBEG(2),TKFTEM(1),TKFTEM(2),TKFPRS(1),
     2 TKFPRS(2),TENVR,CABVOL
C
      READ (IIN,5151) LINDIA(1), LINDIA(2), HTRFLX(1), HTRFLX(2),
     1                PLSNOM(1), PLSNOM(2), HTRDIA(1), HTRDIA(2),
     2                HTRLNG(1), HTRLNG(2), PSET1, PSET2
C
      WRITE (IOT,6160) MDAYS,(L13(I, 1),I=1,4),
     1     NCREW    ,(L13(I, 2),I=1,4),NRPRES   ,(L13(I, 3),I=1,4),
     2     NDARES   ,(L13(I, 4),I=1,4),O2FNOM   ,(L13(I, 5),I=1,4),
     3     GLKRAT   ,(L13(I, 6),I=1,4),TLSNOM(1),(L13(I, 7),I=1,4),
     4     TLSNOM(2),(L13(I, 8),I=1,4),RHOBEG(1),(L13(I, 9),I=1,4),
     5     RHOBEG(2),(L13(I,10),I=1,4),TKFTEM(1),(L13(I,11),I=1,4),
     6     TKFTEM(2),(L13(I,12),I=1,4),TKFPRS(1),(L13(I,13),I=1,4),
     7     TKFPRS(2),(L13(I,14),I=1,4),TENVR    ,(L13(I,15),I=1,4),
     8     CABVOL   ,(L13(I,16),I=1,4),LINDIA(1),(L13(I,17),I=1,4),
     9     LINDIA(2),(L13(I,18),I=1,4),HTRFLX(1),(L13(I,19),I=1,4),
     T     HTRFLX(2),(L13(I,20),I=1,4),PLSNOM(1),(L13(I,21),I=1,4),
     A     PLSNOM(2),(L13(I,22),I=1,4),HTRDIA(1),(L13(I,23),I=1,4),
     B     HTRDIA(2),(L13(I,24),I=1,4),HTRLNG(1),(L13(I,25),I=1,4),
     C     HTRLNG(2),(L13(I,26),I=1,4),PSET1    ,(L13(I,27),I=1,4),
     D     PSET2    ,(L13(I,28),I=1,4)
C
      GO TO 113
C
  130 CONTINUE
C
C          *** READ IN FUEL CELL CONSUMER DATA
C
      IF(PAGE(0)) WRITE(IOT,6050) (LO(I,14),I=1,9)
C
      READ (IIN,5140) MRFC, SRCFC, QDTFC, SPWTFC, TFCNOM(1),TFCNOM(2),
     1                TF21IN, TF21OU, TFOFC, TFHFC
      READ (IIN,5140) PFOFC, PFHFC, RHOFIL(1), RHOFIL(2), WOVENT,WHVENT,
     1                DELTCP, TENV, PRFCOP, POWNOM
      READ (IIN,5141) NFCOP, NFCSTB, PLSET1, PLSET2, VJANUL(1),
     1                VJANUL(2),TKMXDI(1),TKMXDI(2)
      READ (IIN,5130) FCVOLT, PRGRAT(1), PRGRAT(2), PRGTIM(1),
     1                           PRGTIM(2), PRGINT(1), PRGINT(2)
C
      WRITE (IOT,6150) NFCOP  ,(L12(I, 1),I=1,4),MRFC,(L12(I, 2),I=1,4),
     1         SRCFC    ,(L12(I, 3),I=1,4),QDTFC    ,(L12(I, 4),I=1,4),
     2         SPWTFC   ,(L12(I, 5),I=1,4),TFCNOM(1),(L12(I, 6),I=1,4),
     3         TFCNOM(2),(L12(I, 7),I=1,4),TF21IN   ,(L12(I, 8),I=1,4),
     4         TF21OU   ,(L12(I, 9),I=1,4),TFOFC    ,(L11(I,18),I=1,4),
     5         TFHFC    ,(L11(I,17),I=1,4),PFOFC    ,(L11(I,16),I=1,4),
```

```
     6          PFHFC    ,(L11(I,15),I=1,4),RHOFIL(1),(L12(I,10),I=1,4),
     7          RHOFIL(2),(L12(I,11),I=1,4),WOVENT   ,(L12(I,12),I=1,4),
     8          WHVENT   ,(L12(I,13),I=1,4),DELTCP   ,(L11(I,20),I=1,4),
     9          TENV     ,(L11(I,13),I=1,4),PRFCOP   ,(L12(I,14),I=1,4),
     T          POWNOM   ,(L12(I,15),I=1,4),PLSET1   ,(L12(I,16),I=1,4),
     A          PLSET2   ,(L12(I,17),I=1,4),VJANUL(1),(L12(I,18),I=1,4),
     B          VJANUL(2),(L12(I,19),I=1,4),TKMXDI(1),(L12(I,20),I=1,4),
     C          TKMXDI(2),(L12(I,21),I=1,4),FCVOLT   ,(L12(I,22),I=1,4),
     D          PRGRAT(1),(L12(I,23),I=1,4),PRGRAT(2),(L12(I,24),I=1,4),
     E          PRGTIM(1),(L12(I,25),I=1,4),PRGTIM(2),(L12(I,26),I=1,4),
     F          PRGINT(1),(L12(I,27),I=1,4),PRGINT(2),(L12(I,28),I=1,4)
C
      GO TO 113
C
  140 CONTINUE
C
C          *** READ IN HYDRAZINE APU CONSUMER DATA
C
      IF(PAGE(0)) WRITE(IOT,6050) (L0(I,16),I=1,9)
C
      READ (IIN,5120) NAPU, HPR, PTRBIN, PRAT, PCRSRV, SPGPRS
C
      WRITE (IOT,6150) NAPU,(L11(I, 1),I=1,4),HPR    ,(L11(I, 2),I=1,4),
     1                PTRBIN,(L11(I,24),I=1,4),PRAT   ,(L11(I,21),I=1,4),
     2                PCRSRV,(L11(I,22),I=1,4),SPGPRS,(L11(I,23),I=1,4)
C
      GO TO 113
C
C
  113 CONTINUE
C
C          ***** INPUT TANK DATA
C
      IF (PAGE(0)) WRITE (IOT,6050) (L0(I,12),I=1,9)
C
      J = 1
      READ (IIN,5060) (NOP   (I,J),SATYPE(I  ),SITYPE(I,J),SMTYPE(I,J),
     1     SPTYPE(I,J),SITEMP(I,J),SIPRES(I,J),SPGTEM(I,J),SOPRES(I,J),
     2     SVPRES(I,J),SHFLUX(I,J),SITHIK(I,J),FLDLOD(I  ),SULGPC(I  ),
     3     SMDIAM(I,J),SHOTEM(I,J),SHDELP(I,J),SPDELP(I,J),SGOTEM(I,J),
     4     SGGPC (I,J),SGMRAT(I,J),SNBAR (I  ),I=1,2)
      WRITE (IOT,6060) (NOP   (I,J),I=1,2),(L7(I,22),I=1,4),
     1                 (SATYPE(I  ),I=1,2),(L7(I,12),I=1,4),
     2                 (SITYPE(I,J),I=1,2),(L7(I,10),I=1,4),
     3                 (SMTYPE(I,J),I=1,2),(L7(I, 9),I=1,4),
     4                 (SPTYPE(I,J),I=1,2),(L7(I,13),I=1,4)
C
      WRITE (IOT,6090) (SITEMP(I,J),I=1,2),(L7(I, 6),I=1,4),
     1                 (SIPRES(I,J),I=1,2),(L7(I, 7),I=1,4),
     2                 (SPGTEM(I,J),I=1,2),(L7(I,15),I=1,4),
     3                 (SOPRES(I,J),I=1,2),(L7(I,14),I=1,4),
     4                 (SVPRES(I,J),I=1,2),(L7(I, 8),I=1,4),
     5                 (SHFLUX(I,J),I=1,2),(L7(I, 5),I=1,4),
     6                 (SITHIK(I,J),I=1,2),(L7(I,11),I=1,4),
     7                 (FLDLOD(I  ),I=1,2),(L7(I, 3),I=1,4),
     8                 (SULGPC(I  ),I=1,2),(L7(I, 4),I=1,4),
     9                 (SMDIAM(I,J),I=1,2),(L7(I, 2),I=1,4),
     A                 (SHOTFM(I,J),I=1,2),(L7(I,18),I=1,4),
```

```
********     COMPIL    ********

     B                  (SHDELP(I,J),I=1,2),(L7(I,16),I=1,4),
     C                  (SPDELP(I,J),I=1,2),(L7(I,17),I=1,4),
     D                  (SGOTEM(I,J),I=1,2),(L7(I,20),I=1,4),
     E                  (SGGPC (I,J),I=1,2),(L7(I,19),I=1,4),
     F                  (SGMRAT(I,J),I=1,2),(L7(I,21),I=1,4),
     G                  (SNBAR (I  ),I=1,2),(L7(I,23),I=1,4)
C
      READ (IIN,5062) IWOP,NOSHAP
C
      WRITE (IOT,6091) IWOP, NOSHAP
C
C                   CHECK FOR GENERAL TANK CONFIGURATION
      IF (IWOP .LT. 2 .OR. NOSHAP .EQ. 0) GO TO 210
      WRITE (IOT,6062) (LO(I,10),I=1,9)
C                   READ IN GENERAL TANK CONFIGURATION
      DO 200 I=1,NOSHAP
      READ (IIN,5062) JTKTYP(I),JFLTP(I),XD(I),YD(I),ZD(I)
  200 WRITE(IOT,6064) JTKTYP(I),JFLTP(I),XD(I),YD(I),ZD(I)
  210 CONTINUE
C
      DO 2000 JSIM=1,5
C
      IF (INBLK(SYSNUM,JSIM,SCRIT) .EQ. 0) GO TO 2000
      GO TO (1100,1200,1300,1400,1500),JSIM
C
C          ***** INPUT THE ACCUMULATOR DATA
C
 1100 CONTINUE
      IF(PAGE(0)) WRITE(6,6050) (LO(I,3),I=1,9)
C
      READ (IIN,5030) (NAOP(I),AITYPE(I),AMTYPE(I),ATEMP(I),APRES(I),
     1      AHFLUX(I),AITHIK(I),AVOL(I),ADIAM(I),ANDELP(I),
     2      ANBAR (I),I=1,2)
C
      WRITE (IOT,6060) (NAOP  (I),I=1,2),(L7(I,22),I=1,4),
     1                 (AITYPE(I),I=1,2),(L7(I,10),I=1,4),
     2                 (AMTYPE(I),I=1,2),(L7(I, 9),I=1,4)
C
      WRITE (IOT,6090) (ATEMP (I),I=1,2),(L3(I, 1),I=1,4),
     1                 (APRES (I),I=1,2),(L7(I,14),I=1,4),
     2                 (AHFLUX(I),I=1,2),(L7(I, 5),I=1,4),
     3                 (AITHIK(I),I=1,2),(L7(I,11),I=1,4),
     4                 (AVOL  (I),I=1,2),(L3(I, 2),I=1,4),
     5                 (ADIAM (I),I=1,2),(L7(I, 2),I=1,4),
     6                 (ANDELP(I),I=1,2),(L3(I, 3),I=1,4),
     7                 (ANBAR (I),I=1,2),(L7(I,23),I=1,4)
      GO TO 2000
C
C          ***** INPUT THE HEX DATA
C
 1200 CONTINUE
      IF(PAGE(0)) WRITE(IOT,6050) (LO(I,4),I=1,9)
      READ(IIN,5039) NUMHEX
      READ(IIN,5040)((HEXHIT(I,J),HEXHOT(I,J),HEXCIT(I,J),HEXCOT(I,J),
     1               HEXHIP(I,J),HEXHOP(I,J),HEXCIP(I,J),HEXCOP(I,J),
     2               HXHDLP(I,J),HXCDLP(I,J),HXMRAT(I,J),HXCODE(I,J),
     3               J=1,2),I=1,NUMHEX)
      WRITE(IOT,6069) NUMHEX
```

```
*********     COMPIL     *********

      WRITE(IOT,6051)
      WRITE(IOT,6070)((HEXHIT(I,J),J=1,2),I=1,5),(L4(I, 1),I=1,4),
     1               ((HEXHOT(I,J),J=1,2),I=1,5),(L4(I, 2),I=1,4),
     2               ((HEXCIT(I,J),J=1,2),I=1,5),(L4(I, 3),I=1,4),
     3               ((HEXCOT(I,J),J=1,2),I=1,5),(L4(I, 4),I=1,4),
     4               ((HEXHIP(I,J),J=1,2),I=1,5),(L4(I, 5),I=1,4),
     5               ((HEXHOP(I,J),J=1,2),I=1,5),(L4(I, 6),I=1,4),
     6               ((HEXCIP(I,J),J=1,2),I=1,5),(L4(I, 7),I=1,4),
     7               ((HEXCOP(I,J),J=1,2),I=1,5),(L4(I, 8),I=1,4),
     8               ((HXHDLP(I,J),J=1,2),I=1,5),(L4(I, 9),I=1,4),
     9               ((HXCDLP(I,J),J=1,2),I=1,5),(L4(I,10),I=1,4),
     T               ((HXMRAT(I,J),J=1,2),I=1,5),(L4(I,11),I=1,4)
      IF (NUMHEX .LE. 5) GO TO 2000
      WRITE (IOT,6052)
      WRITE(IOT,6070)((HEXHIT(I,J),J=1,2),I=6,10),(L4(I, 1),I=1,4),
     1               ((HEXHOT(I,J),J=1,2),I=6,10),(L4(I, 2),I=1,4),
     2               ((HEXCIT(I,J),J=1,2),I=6,10),(L4(I, 3),I=1,4),
     3               ((HEXCOT(I,J),J=1,2),I=6,10),(L4(I, 4),I=1,4),
     4               ((HEXHIP(I,J),J=1,2),I=6,10),(L4(I, 5),I=1,4),
     5               ((HEXHOP(I,J),J=1,2),I=6,10),(L4(I, 6),I=1,4),
     6               ((HEXCIP(I,J),J=1,2),I=6,10),(L4(I, 7),I=1,4),
     7               ((HEXCOP(I,J),J=1,2),I=6,10),(L4(I, 8),I=1,4),
     8               ((HXHDLP(I,J),J=1,2),I=6,10),(L4(I, 9),I=1,4),
     9               ((HXCDLP(I,J),J=1,2),I=6,10),(L4(I,10),I=1,4),
     T               ((HXMRAT(I,J),J=1,2),I=6,10),(L4(I,11),I=1,4)
      GO TO 2000
C
C          ***** INPUT THE PUMP DATA
C
 1300 CONTINUE
      IF(PAGE(0)) WRITE(6,6050) (L0(I,5),I=1,9)
      READ(5,5050)(PTYPE(I),PEFF(I),PNPSH(I),PSSPED(I),EPDELP(I),I=1,2),
     1            (TPEFF(I),TPNPSH(I),TPDELP(I),TPWDOT(I),I=1,2),
     2            (TEFF(I),TITEMP(I),TOTEMP(I),TMRATO(I),TGGPC(I),
     3 I=1,2)
      WRITE(6,6080)(PTYPE (I),I=1,2),(L5(I,1),I=1,4),
     1             (PEFF  (I),I=1,2),(L5(I,2),I=1,4),
     2             (PNPSH (I),I=1,2),(L5(I,3),I=1,4),
     3             (PSSPED(I),I=1,2),(L5(I,4),I=1,4),
     4             (EPDELP(I),I=1,2),(L5(I,5),I=1,4),
     5             (L0(I,11),I=1,9),
     6             (TPEFF (I),I=1,2),(L6(I,1),I=1,4),
     7             (TPNPSH(I),I=1,2),(L6(I,2),I=1,4),
     8             (TPDELP(I),I=1,2),(L6(I,3),I=1,4),
     9             (TPWDOT(I),I=1,2),(L6(I,4),I=1,4),
     T             (L0(I,8),I =1,9),
     1             (TEFF  (I),I=1,2),(L9(I,1),I=1,4),
     2             (TITEMP(I),I=1,2),(L9(I,2),I=1,4),
     3             (TOTEMP(I),I=1,2),(L9(I,3),I=1,4),
     4             (TMRATO(I),I=1,2),(L9(I,4),I=1,4),
     5             (TGGPC (I),I=1,2),(L9(I,5),I=1,4)
      GO TO 2000
C
C          ***** INPUT THE HEAT SOURCE DATA
C
 1400 CONTINUE
      IF (PAGE(0)) WRITE (IOT,6100) (L0(I,7),I=1,9)
      READ (IIN,5039) NUMHSO
```

```
      READ (IIN,5090) ((HSTYPE(I,J),HSMRAT(I,J),HSOTEM(I,J),HSAEE (I,J),
     1                   HSPRES(I,J),J=1,2),I=1,NUMHSO)
      WRITE (IOT,6128) NUMHSO
      WRITE (IOT,6129)
      WRITE (IOT,6130) ((HSTYPE(I,J),J=1,2),I=1, 5),(L10(I,1),I=1,4),
     1                 ((HSMRAT(I,J),J=1,2),I=1, 5),(L10(I,2),I=1,4),
     2                 ((HSOTEM(I,J),J=1,2),I=1, 5),(L10(I,3),I=1,4),
     3                 ((HSAEE (I,J),J=1,2),I=1, 5),(L10(I,4),I=1,4),
     4                 ((HSPRES(I,J),J=1,2),I=1, 5),(L10(I,5),I=1,4)
      IF (NUMHSO .LE. 5) GO TO 2000
      WRITE (IOT,6127)
      WRITE (IOT,6130) ((HSTYPE(I,J),J=1,2),I=6,10),(L10(I,1),I=1,4),
     1                 ((HSMRAT(I,J),J=1,2),I=6,10),(L10(I,2),I=1,4),
     2                 ((HSOTEM(I,J),J=1,2),I=6,10),(L10(I,3),I=1,4),
     3                 ((HSAEE (I,J),J=1,2),I=6,10),(L10(I,4),I=1,4),
     4                 ((HSPRES(I,J),J=1,2),I=6,10),(L10(I,5),I=1,4)
      GO TO 2000
C
C         ***** INPUT THE MOTOR DATA
C
 1500 CONTINUE
      IF (PAGE(0)) WRITE (IOT,6100) (LO(I,9),I=1,9)
      READ(5,5100) MTYPE,MEFF,MSS,PDNSTY
      WRITE (IOT,6140) MTYPE,MEFF,MSS,PDNSTY
C
 2000 CONTINUE
C
      RETURN
      END
```

MAIN DRIVER PRØGRAM CØNTRL

```
635717*TPFS.CONTRL
C
      LOGICAL PAGE
C
      INCLUDE CCNTRL
      INCLUDE CIOUNT
      INCLUDE CKEYS
      INCLUDE CPAGE
C
      DATA NSPC / 'SUP' / ILST / 'LAS' /
C
 5000 FORMAT(2A6,2XA4,3XA3,1XA5/12A6)
 5001 FORMAT(A3,A6,3X,A3,14X,A3,36X,12I1)
 6000 FORMAT ('0'19X '***  SYSTEM NAME STARTING 'A3,' IS IN ERROR  ***')
 6001 FORMAT ('0'/// 44X'***  YOU HAVE CALLED FOR THE SYSTEM 'A3,A6,
     1 '***')
C
C                         INITIALIZE DATA STORAGE ROUTINES
C
      CALL STODTA
      CALL OTUNIT (IOT)
C
C
      CALL DATE (9,DOR)
C
C                         READ NAME AND TITLE INFORMATION
C
      READ(5,5000) NAME,DEPT,BLD,EXT,CTITLE
      NCASE = 1
      INTGSY = 1
C
C                         READ TABLE INPUT DATA  (ONLY ONCE)
C
      CALL INTAB
C
    1 CONTINUE
      KEY1 = 1
      KEY2 = 0
      IF(INTGSY.EQ.1) GO TO 5
      READ (5,5000) NAME,DEPT,BLD,EXT,CTITLE
    5 CONTINUE
      READ (IIN,5001) NSYS,N1,NCRIT,INTGR,MDTRC
      DO 10 I=1,NBRSY
      IF (NSYS .EQ. NAMSYS(I)) GO TO 20
   10 CONTINUE
      WRITE (IOT,6000) NSYS
      CALL EXIT
   20 SYSNUM = I
      IF (PAGE(0)) WRITE (IOT,6001) NSYS,N1
      SCRIT = 1
      IF (NCRIT .EQ. NSPC) SCRIT = 2
      INTGSY = 2
      IF (INTGR .EQ. ILST) INTGSY = 1
C
C                         READ COMPONENT INPUT DATA
C
      CALL COMPIL
C
C                         DO SYSTEM CALCULATIONS FOR THE GIVEN SYSTEM
C
      CALL CRYCON
C
C                         IF THIS IS AN INTEGRATED SYSTEM - GO READ NEXT
C                         SYSTEM NAME
C                         IF IT IS A LAST CARD EXIT
C
      IF (INTGSY .EQ. 2) GO TO 1
      CALL EXIT
      END
```

SUBRØUTINE CRYCØN

```
635717*TPFS.CRYCON
C
C
C     ******************************************************************
C
C     *******  THIS SUBPROGRAM HAS BEEN MODIFIED FOR USE WITH THE ******
C     *******                HYDRAZINE APU PROGRAM                ******
C     *******           **   DO NOT USE WITH TCIMM    **          ******
C
C     ******************************************************************
C
      SUBROUTINE CRYCON
C
      LOGICAL DIAG,JP
C
      INCLUDE CCNTRL
      INCLUDE CKEYS
C
      KEY1 = 1613
C
      K = 0
C
      IF(SYSNUM.NE.2) GO TO 10
      DO 6 I = 1,2
    6 KSUBC(2,I+1) = JAPUS(SCRIT,I)
C
   10 I = 1
      K = 0
      LREPT = 0
C
   20 JKM = KSUBC(SYSNUM,I)
C
C                   IF ZERO HAVE REACHED END OF CALLING SEQUENCE
      IF (JKM .EQ. 0) GO TO 2200
C                   MDTRC - IS DIAGNOSTIC TRACE SWITCH (INPUT IN CONTRL)
      IF (MDTRC(JKM) .EQ. 0) GO TO 50
C                   TURN ON DIAG. TRACE
      JP = DIAG (-1,6HCRYCON)
C                   CALL ROUTINES DEPENDING ON SYSTEM SPECIFIED (SYSNUM)
  50  GO TO (100,200,300,400,450,500,550,600,700,800,900,950,1000),JKM
C
  100 CALL ACCRES
      GO TO 2000
C
  200 CALL ACQWT
      GO TO 2000
C
  300 GO TO (310,350),SCRIT
C
  310 CALL APUSUB
      GO TO 2000
C
  350 CALL APUSUP
      GO TO 2000
C
  400 CALL CMPCAL
      GO TO 2000
C
```

```
********     CRYCON     ********

        450 CALL FUELCL
            GO TO 2000
      C
        500 CALL CONSUM
            GO TO 2000
      C
        550 CALL ECLSS
            GO TO 2000
      C
        600 CALL LIQRES
            GO TO 2000
      C
        700 CALL TANK
            GO TO 2000
      C
        800 K = K + 1
            IF (SYSNUM .EQ. 2) K = 2
      C
            CALL TSIZEI (K)
            GO TO 2000
      C
        900 CALL WTACC
      C
        950 CALL HZAPU
      C
       1000 CONTINUE
      C
       2000 CONTINUE
            IF(LREPT) 10,2001,10
      C
       2001 IF(MDTRC(JKM) .EQ. 0) GO TO 2100
      C
      C                      TURN OFF DIAGNOSTIC TRACE SENTINEL
      C
            JP = DIAG (-2,6HCRYCON)
      C
       2100 I = I + 1
            IF(I-9) 20,20,2200
      C                      END OF PROCESS THIS SYSTEM
       2200 CONTINUE
      C
      C                      PRINT COMPONENT WEIGHT SUMMARY
            CALL OTPWSM
      C
            RETURN
            END
```

PRØCEDURE DEFINITIØN PRØCESSOR CTAB

```
635717*TPF$.CTAB
      CTAB*   PROC
      C
            PARAMETER  NTBN = 55, NSBZ = 40
      C
            INTEGER TLA,TYPE
      C
            COMMON /CTAB/ TLA(NTBN),NV,TYPE,NIP,ND,XTAB(NSBZ),YTAB(NSBZ),
           1 TAB(6,5),JTABID,NLTBL
      C
            DIMENSION ITAB(6,5)
      C
            EQUIVALENCE (ITAB,TAB)
      C
      C         ***** CTAB VARIABLE DEFINITION
      C
      C               TLA  - TABLE LOCATION ARRAY
      C                      THIS ARRAY CONTAINS THE BEGINNING DRUM ADDRESS
      C                      - 1, FOR UP TO 50 TABLES
      C
      C               NV   - NUMBER OF VALUES IN THE INPUT TABLE (NV<101).
      C
      C               TYPE - TYPE OF THE INPUT TABLE (0 = COEFICIENT,
      C                                                1 = DESCRETE  ).
      C
      C               NIP  - NUMBER OF TABLE VALUES TO BE USED IN
      C                      INTERPOLATION (NIP<NV).
      C
      C               ND   - NUMBER OF DIMENSIONS FOR THE INPUT TABLE
      C                      (ND<7).
      C
      C               XTAB - ARRAY OF COEFICIENTS FOR POLYNOMIAL EVALUATION
      C                      OR ARRAY OF VALUES OF THE INDEPENDENT VARIABLE
      C                      FOR INTERPOLATION.
      C
      C               YTAB - ARRAY OF VALUES OF THE DEPENDENT VARIABLE
      C                      FOR INTERPOLATION.
      C
      C                TAB - ARRAY OF VALUES OF THE REMAINING ND-2
      C               ITAB   INDEPENDENT VARIABLES FOR INTERPOLATION.
       END
```

SUBRØUTINE HZAPU

```
635717*TPFS.HZAPU
      SUBROUTINE HZAPU
C
      INCLUDE CAPU
      INCLUDE CCNTRL
      INCLUDE CDCYCL
      INCLUDE CENG
      INCLUDE CIOUNT
      INCLUDE CMATRL
      INCLUDE CPAGE
      INCLUDE CTANK
      INCLUDE TABLOK
C
      LOGICAL JP,PAGE
C
C     FIND PERCENT POWER FOR EACH DUTY CYCLE POINT
C
      TOTHPR = HPR * NAPU
C
      DO 10 I = 1,KCYCLE
      PCTHP(I) = (NEOP * HP(I))/TOTHPR            @FRALTION OF TOTAL
C
C     FIND RATED FLOW RATE FOR EACH DUTY CYCLE POINT
C
      CALL FINTAB (NTBID(47))
      XTAB(1)      = PTRBIN
      XTAB(2)      = PRAT
      XTAB(3)      = PAMB(I)
      XTAB(4)      = 1.0
      SPCR(I) = MIPE(4,XTAB)                      @ LB/HP-HR.
C
      WDOTR(I) = (SPCR(I) * TOTHPR)/60.0                @LBS.PER MIN.
C
C     FIND NOM.FLOW RATE FOR EACH DUTY CYCLE PERIOD
C
      CALL FINTAB (NTBID(47))
      XTAB(1)      = PTRBIN
      XTAB(2)      = PRAT
      XTAB(3)      = PAMB(I)
      XTAB(4)      = PCTHP(I)
      SPCN(I) = MIPE(4,XTAB)
C
      WD(I)    = (SPCN(I)*HP(I)*NEOP(I))/60.0           @LBS.PER MIN.
C
C     THE PERCENT OF FULL FLOW FOR THE INTERVAL IS -
C
      PCWDOT(I) =  WD(I)/WDOTR(I)
C
C     THE GAS GENERATOR EXIT TEMPERATURE FOR THE INTERVAL IS -
C
      CALL FINTAB (NTBID(49))
      XTAB(1) = PCWDOT(I)
      GGXTM(I) = MIPE(1,XTAB)
C
C     THE CORRECTION FACTOR FOR THE NOM SPC IS -
C
      CALL FINTAB (NTBID(50))
      XTAB(1) = GGXTM(I)
```

```
      CFSPC(I) = MIPE(1,XTAB)
C
      WDC(I) =  WD(I) *  CFSPC(I)                         @ LB PER MIN.
C
C     THE CORRECTED FLOW RATE FOR EACH INTERVAL IS -
C
   10 CONTINUE
C
C     COMPUTE THE MAX FLOWRATE AND TOTAL PROPELLANT CONSUMED.
C
      TIPWT = 0.0
      WDOT  = 0.0
      I     = 0
      DO 20 I1 = 1,NDCYCL,2
      I = I +1
      WDOT = AMAX1(WDOT,WDC(I))
C
      WDOTI(1) = WDOT/60.0                             @ LB PER SECOND.
C
      TIPWT = TIPWT + WDC(I)* DCYCLE(I1)
C
   20 CONTINUE
C
C     OUTPUT THE DATA TO THIS POINT.
C
C
      JP = PAGE(0)
C
      WRITE (IOT,6000)
 6000 FORMAT(//T38,'*** INITIATE PROGRAM AND CHARACTERIZE CONSUMER PARAM
     1ETERS ***'//)
      WRITE (IOT,6001)
 6001 FORMAT(T30,'***********',T46,'INITIAL HYDRAZINE APU PROGRAM CALCULA
     1TIONS',T95,'***********'//T2,'PARAMETER',T14,'CYCLE-1',T26,'CYCLE-2
     2',T38,'CYCLE-3',T50,'CYCLE-4',T62,'CYCLE-5',T74,'CYCLE-6',T86,
     3'CYCLE-7',T98,'CYCLE-8',T110,'CYCLE-9',T121,'CYCLE-10'/)
      JP = PAGE(6)
      WRITE (IOT,6046)
 6046 FORMAT(/T2,'COMPUTE THE PCT. HP REQD.-EACH DUTY CYCLE- AND TOTAL H
     1P AVAILABLE'/)
      WRITE (IOT,6002) ((PCTHP(J)*100.0),J=1,KCYCLE)
 6002 FORMAT(T4,'PCTHP =',T13,10(F8.3,4X))
      WRITE (IOT,6003) TOTHPR
 6003 FORMAT(T4,'TOTHPR=',T13,F8.2)
      WRITE (IOT,6047)
 6047 FORMAT(/T2,'COMPUTE THE SPECIFIC FUEL CONSUMPTION AND FLOWRATES FO
     1R THE RATED AND NOMINAL CONDITIONS'/)
      WRITE (IOT,6004) (SPCR(J),J=1,KCYCLE)
 6004 FORMAT(T4,'SPCR  =',T13,10(F8.3,4X))
      WRITE (IOT,6005) (WDOTR(J),J=1,KCYCLE)
 6005 FORMAT(T4,'WDOTR =',T13,10(F8.4,4X))
      WRITE (IOT,6006) (SPCN(J),J=1,KCYCLE)
 6006 FORMAT(T4,'SPCN  =',T13,10(F8.3,4X))
      WRITE (IOT,6007) (WD(J),J=1,KCYCLE)
 6007 FORMAT(T4,'WD    =',T13,10(F8.4,4X))
      WRITE (IOT,6009) ((PCWDOT(J)*100.),J=1,KCYCLE)
 6009 FORMAT(T4,'PCWDOT=',T13,10(F8.3,4X))
      WRITE (IOT,6048)
```

```
 6048 FORMAT(/T2,'COMPUTE THE CORRECTED AND MAX. FLOWRATES FOR THE APU U
     1NITS'/)
      WRITE (IOT,6010) (GGXTM(J),J=1,KCYCLE)
 6010 FORMAT(T4,'GGXTM =',T13,10(F8.2,4X))
      WRITE (IOT,6011) (CFSPC(J),J=1,KCYCLE)
 6011 FORMAT(T4,'CFSPC =',T13,10(F8.4,4X))
      WRITE (IOT,6012) (WDC(J),J=1,KCYCLE)
 6012 FORMAT(T4,'WDC   =',T13,10(F8.4,4X))
      WRITE (IOT,6013)  WDOT
 6013 FORMAT(T4,'WDOT(MAX)=',T15,F10.5,T27,'LB.PER MINUTE')
      WRITE (IOT,6014)  WDOTI(1)
 6014 FORMAT(T4,'WDOTI =',T13,F10.6,T25,'LB.PER SECOND')
      WRITE (IOT,6040)
 6040 FORMAT(/T2,'COMPUTE THE TOTAL FUEL CONSUMED AND THE TOTAL LOADED',
     1 /)
      WRITE (IOT,6015) TIPWT
 6015 FORMAT(T4,'TOTAL PROPELLANT CONSUMED =',T35,F10.3,T47,'LBS.OF HYDR
     1AZINE.')
C
C       TOTAL PROPELLANT LOADED
C
        WTRES = TIPWT * (PCRSRV/100.)
        WPTOT(1) = TIPWT + WTRES
C
C       VOLUME AND AREA OF STORAGE TANK
C
        RHOHZN = 78.77326 - 0.03 * SITEMP(1,1)
C
        VOTNK = (WPTOT(1)/RHOHZN) * 1.02
C
        ARTNK = 4.84 * (VOTNK**0.667)
C
C       COMPUTE THE TANK WEIGHT
C
        MATL1 = SMTYPE(1,1)
        CALL FINTAB(NTBID(9)+MATL1)
        FTUX = MIPE(1,SITEMP(1,1))
        RHOFTZ = RHOL(MATL1)/1728.0/FTUX
C
        WTPV = 7000.0 * WPTOT(1)/RHOHZN * SOPRES(1,1) * RHOFTZ
C
        WTBLAD = 0.14 * ARTNK
C
        WTTOT(1) = WTPV + WTBLAD
C
C       TANK INSULATION WEIGHT
C
        TIWT(1,1) = ARTNK * RHOI(SITYPE(1,1)) * SITHIK(1,1)/12.0
C
C
C       COMPUTE TANK PROPELLANT HISTORY
        WHESUM = 0.0
        WDHEMX = 0.0
        WHE =0.0
        VOLDPS       = 0.0
        WTOT = WPTOT(1)
        I = 0
        DO 30 I2 = 1,NDCYCL,2
```

```
*********    HZAPU    *********

      I = I +1
      WOUT =  WDC(I) *  DCYCLE(I2)
      WTOT = WTOT - WOUT
      WPREM(I) = WTOT
      VOLDP          = WOUT/RHOHZN
      VOLDPS         = VOLDPS + VOLDP
      VOLRM(I)       = VOTNK - VOLDPS
      PHE = SOPRES(1,1)
      THE = SITEMP(1,1)
      CALL ZFIND(THE,PHE,17,ZHE)
      RHOGT          = 144.0 * PHE/(ZHE * FINDR(17) * THE)
      WH             = RHOGT * VOLDPS                         $ LBS
      WDTHE(I) = (WH - WHE)/DCYCLE(I2)
      WDHEMX = AMAX1(WDHEMX,WDTHE(I))
      WHEAD(I)  =  WH - WHE
      WHE = WH
      WHESUM  =  WHESUM + WHEAD(I)
   30 CONTINUE
C
      WDOTI(2) = WDHEMX/60.0
C
C     WEIGHT OF PRESSURANT GAS SYSTEM
C
      WTOTPG =  1.5 * WHESUM + 40.0
C
C        TOTAL HELIUM LOADED
C
      WPTOT(2) = WHESUM + 0.2 * WHESUM
C
C        VOLUME, AREA, DIAMETER OF HELIUM TANK
C
      THE            = SITEMP(2,1)
      PHE            = SOPRES(2,1)
C
      CALL ZFIND(THE,PHE,17,ZHE)
      RHOHE          = 144.0 * PHE/(ZHE * FINDR(17) * THE)
C
      VOTKHE = (WPTOT(2))/RHOHE
C
       ARTKHE = 4.84 * (VOTKHE**0.666)
C
      DITKHE = ((1.9098*(WPTOT(2)/RHOHE))**0.333) * 12.0
C
C        WEIGHT OF HELIUM TANK
C
      MATL2          = SMTYPE(2,1)
      CALL FINTAB(NTAID(9)+MATL2)
      FTUX1 = MIPE(1,SITEMP(2,1))
      RHOFTX = RHOL(MATL2)/1728.0/FTUX1
C
      WTHETK         = 7000.0 * WPTOT(2)/RHOHE * PHE * RHOFTX
C
      WTTOT(2) = WTHETK
C
      TIWT(2,1)      = ARTKHE * RHOI(SITYPE(2,1)) * SITHIK(2,1)/12.0
C
C     OUTPUT THE HISTORY DATA  AND TANK WEIGHT
C
```

```
********     HZAPU     ********

      WRITE (IOT,6016)  WPTOT(1)
 6016 FORMAT(T4,'TOTAL PROPELLANT LOADED =',T35,F10.3)
      WRITE (IOT,6041)
 6041 FORMAT(/T2,'COMPUTE THE FUEL TANK CHARACTERISTIC PARAMETERS'/)
      WRITE (IOT,6017)  RHOHZN
 6017 FORMAT(T4,'DENSITY OF HYDRAZINE     =',T35,F10.5)
      WRITE (IOT,6018)  VOTNK
 6018 FORMAT(T4,'VOLUME OF STORAGE TANK  =',T35,F10.4)
      WRITE (IOT,6019)  ARTNK
 6019 FORMAT(T4,'SURFACE AREA OF TANK     =',T35,F10.4)
      WRITE (IOT,6020)  WTPV
 6020 FORMAT(T4,'TANK PRESS.VESSEL WGT.  =',T35,F10.4)
      WRITE (IOT,6021)  WTBLAD
 6021 FORMAT(T4,'TANK BLADDER ASSY WGT.  =',T35,F10.4)
      WRITE (IOT,6022)  WTTOT(1)
 6022 FORMAT(T4,'TOTAL TANK ASSY. WEIGHT =',T35,F10.4)
      WRITE (IOT,6023)  TIWT(1,1)
 6023 FORMAT(T4,'TANK INSULATION WEIGHT  =',T35,F10.4)
C
      JP = PAGE(0)
C
      WRITE (IOT,6045)
 6045 FORMAT(T30,'***********',T46,'HYDRAZINE APU CALCULATIONS CONTINUED'
     1,        T95,'***********'//T2,'PARAMETER',T14,'CYCLE-1',T26,'CYCLE-2
     2',T38,'CYCLE-3',T50,'CYCLE-4',T62,'CYCLE-5',T74,'CYCLE-6',T86,
     3'CYCLE-7',T98,'CYCLE-8',T110,'CYCLE-9',T121,'CYCLE-10'/)
      JP = PAGE(6)
C
      WRITE (IOT,6042)
 6042 FORMAT(/T2,'COMPUTE THE PRESSURANT GAS PARAMETERS'/)
      WRITE (IOT,6024) (WPREM(J),J=1,KCYCLE)
 6024 FORMAT(/T4,'WPREM =',T13,10(F8.3,4X))
      WRITE (IOT,6025) (VOLRM(J),J=1,KCYCLE)
 6025 FORMAT(T4,'VOLREM =',T13,10(F8.4,4X))
      WRITE (IOT,6026) (WDTHE(J),J=1,KCYCLE)
 6026 FORMAT(T4,'WDOTHE =',T13,10(F10.6,2X))
      WRITE (IOT,6027) (WHEAD(J),J=1,KCYCLE)
 6027 FORMAT(T4,'WHEADD =',T13,10(F10.6,2X))
      WRITE (IOT,6037) WDOTI(2)
 6037 FORMAT(/T4,'MAX. HELIUM FLOWRATE =',T35,F10.6)
      WRITE (IOT,6028)  WHESUM
 6028 FORMAT(/T4,'TOTAL HELIUM CONSUMED  =',T35,F10.6)
      WRITE (IOT,6038) WPTOT(2)
 6038 FORMAT(/T4,'TOTAL HELIUM LOADED =',T35,F10.6)
      WRITE (IOT,6043)
 6043 FORMAT(/T2,'COMPUTE THE PRESSURANT GAS SYSTEM WEIGHT FROM THE SCAL
     1ING LAW'/)
      WRITE (IOT,6029)  WTOTPG
 6029 FORMAT(/T4,'PRESS.GAS SYSTEM WGT.  =',T35,F10.5)
      WRITE (IOT,6044)
 6044 FORMAT(/T2,'COMPUTE THE PRESSURANT GAS TANK WEIGHT BY ACTUAL VALUE
     1S'/)
      WRITE (IOT,6039) RHOHE
 6039 FORMAT(T4,'DENSITY OF HELIUM IN TANK =',T35,F10.6)
      WRITE (IOT,6032) VOTKHE
 6032 FORMAT(T4,'VOL. OF HELIUM TANK',T35,F10.4)
      WRITE (IOT,6033) ARTKHE
 6033 FORMAT(T4,'SURF. AREA OF HELIUM TANK',T35,F10.4)
```

```
********    HZAPU    ********

      WRITE (IOT,6034) DITKHE
 6034 FORMAT(T4,'DIAMETER OF HELIUM TANK',T35,F10.4)
      WRITE (IOT,6035) WTHETK
 6035 FORMAT(T4,'WEIGHT OF HELIUM TANK',T35,F10.4)
      WRITE (IOT,6036) TIWT(2,1)
 6036 FORMAT(T4,'HELIUM TANK INSULATION WGT. =',T35,F10.4)
C
C     DO THE HYDRAZINE APU CONFIGURATION ANALYSIS
C
      CALL HZNCMP
C
      WRITE (IOT,6030)
 6030 FORMAT(////T25,'***** THE HYDRAZINE APU CALCULATIONS HAVE BEEN COM
     1PLETED *****')
C
      RETURN
C
      END
```

FUNCTION HZCVCW

```
635717*TPF$.HZCVCW
      FUNCTION HZCVCW(D,P,IDV)
C
C        *** PROGRAM GENERATES WEIGHTS FOR HYDRAZINE
C        *** VALVES, REGULATORS AND CONNECTORS
C
      DIMENSION  C1(4), C2(4)
C
          DATA C1/-.20, -.1, 0.0, .25/
          DATA C2/-.30, 0.0, 0.3,0.50/
C
      IF (IDV.EQ.0) IDV = 4
      IF (P.LT.1000.0) GO TO 10
      IF (P.GE.1000.0) GO TO 20
C
   10 HZCVCW = 0.66940552 * EXP(0.896463 * D) + C1(IDV)
      RETURN
C
   20 HZCVCW = 1.1956857 * EXP(0.9104158 * D) + C2(IDV)
      RETURN
C
      END
```

SUBRØUTINE HZNCMP

```
635717*TPF$.HZNCMP
      SUBROUTINE HZNCMP
C
      INTEGER GSTATE
      LOGICAL PAGE, JP
C
      INCLUDE CAPU
      INCLUDE CCNFIG
      INCLUDE CCNTRL
      INCLUDE CDCYCL
      INCLUDE CENG
      INCLUDE CIOUNT
      INCLUDF CNAMFS
      INCLUDE CONST
      INCLUDE CPAGE
      INCLUDE CTANK
      INCLUDE TABLOK
C
C     INITIALIZE ROUTINE
C
      IDX   =  0
      ISIGN = 1
      JKM    = 0
      CI    = 1152.0/(GRAVTY*PI**2)
      IF(PAGE(0)) WRITE (IOT,6050)
      WRITE (IOT,6020)
      JP    = PAGE (3)
C
C     START CONFIGURATION LOOP
C
      DO 1000 II =1,ICNF
      IDX           = IDX + ISIGN
      MACH(IDX)     = 0.0
      MFLG(IDX)     = 6H
      CALL GETCON(IDX)
C
C     **** BRANCH TO REQUIRED CONFIGURATION TYPE
C
      GO TO (100,200,300,400,450,500,450,450,400,405,600,700,800,900,
     1 230,250,270,280,1100), CFUNCT
C
C         **** SET UP THE GAS TYPE ****
C
  100 IGAS          = CFTYPE
      GSTATE        = ICNFIG(5)
      IF(IGAS.EQ.JKM) GO TO 110
      JKM           = IGAS
      ISIGN         = 1
      ISTRT(IGAS)   = IDX + 1
  110 CONTINUE
C
      IF(IGAS.EQ.2.AND.GSTATE.EQ.1) GO TO 111
      GO TO 112

  111 IF(PAGE(0)) WRITE (IOT,6051)
      WRITE (IOT,6020)
      JP = PAGE(3)
C
```

```
  112 CONTINUE
C
      IF(II.EQ.1) GO TO 999
      IF(IGAS.EQ.2.AND.GSTATE.EQ.1) GO TO 999
C
      PRES(IDX)     = PRES(IDX - ISIGN)
      WDOTN(IDX)    = WDOTN(IDX - ISIGN)
      TEMP(IDX)     = TEMP(IDX - ISIGN)
      GO TO 999
C
  200 GO TO 1000
C
C     ***  PROGESS A HYDRAZINE APU TURBINE UNIT
C
  230 WDOTN(IDX)    = WDOTI(IGAS)
      PRES(IDX)     = SOPRES(1,1) - 20.0
      TEMP(IDX)     = SITEMP(1,1)
      GO TO 999
C
  250 GO TO 1000
C
  270 GO TO 1000
C
C
C     ***  PROCESS A BLADDER ASSY
C
  280 WDOTN(IDX)    = WDOTI(IGAS)
      PRES(IDX)     = SOPRES(1,1)
      TEMP(IDX)     = SITEMP(IGAS,1)
      WEIGHT(IDX)   = WTBLAD
      GO TO 999
C
C          ***** PROCESS A LINE *****
C
  300 WDOTN(IDX) = WDOTN(IDX-ISIGN)
      TEMP(IDX)  = TEMP(IDX-ISIGN)
      PRES(IDX)    = PRES(IDX-ISIGN)
      GO TO (301,302),IGAS
C
  301 CALL FINTAH (NTBID(51))
      FLMU    = MIPE(1,TEMP(IDX))
      GO TO 303
  302 CALL FINTAB (NTBID(52))
      XTAB(1) = PRES(IDX)
      XTAB(2) = TEMP(IDX)
      FLMU    = MIPE(2,XTAB)
C
  303 GO TO (304,305),IGAS
C
  304 RHO     = 78.77326 - 0.03002 * TEMP(IDX)
      GO TO 306
  305 CALL ZFIND(TEMP(IDX),PRES(IDX),17,ZHE)
      RHO     = 144.0 * PRES(IDX)/(ZHE * FINDR(17) * TEMP(IDX))
C
  306 VELCTY  = 576.0 * WDOTN(IDX)/(RHO * PI * (DIAM(IDX)**2))
C
      REYNUM  = VELCTY * RHO * DIAM(IDX)/(12.0 * FLMU)
C
```

```
********    HZNCMP    ********

      FRCOEF(IDX) =  0.316/(REYNUM**0.25)
C
      FLD          = FRCOEF(IDX) * LOD(IDX)/DIAM(IDX)
      LDV           = CFTYPE/10
      CFTYPE       = CFTYPE - LDV*10
      GO TO 510
C
C         ***** PROCESS A CONTROL *****
C
  400 WDOTN(IDX) = WDOTN(IDX-ISIGN)
      TEMP(IDX)  = TEMP(IDX-ISIGN)
      PRES(IDX)     = PRES(IDX-ISIGN)
      DIAM(IDX)     = AMIN1(DIAM(IDX+1),DIAM(IDX-1))
      GO TO (401,402),IGAS
C
  401 CALL FINTAB (NTBID(51))
      FLMU    = MIPE(1,TEMP(IDX))
      GO TO 403
  402 CALL FINTAB (NTBID(52))
      XTAB(1) = PRES(IDX)
      XTAB(2) = TEMP(IDX)
      FLMU    = MIPE(2,XTAB)
C
  403 GO TO (404,410),IGAS
C
  404 RHO      = 78.77326 - 0.03002 * TEMP(IDX)
      GO TO 411
  410 CALL ZFIND(TEMP(IDX),PRES(IDX),17,ZHE)
      RHO      = 144.0 * PRES(IDX)/(ZHE * FINDR(17) * TEMP(IDX))
C
  411 VELCTY  = 576.0 * WDOTN(IDX)/(RHO * PI * (DIAM(IDX)**2))
C
      REYNUM  = VELCTY * RHO * DIAM(IDX)/(12.0 * FLMU)
C
      FRCOEF(IDX) =  0.316/(REYNUM**0.25)
C
      FLD           = FRCOEF(IDX)*LOD(IDX)
      IDV           = CFTYPE/10
      CFTYPE       = CFTYPE - IDV*10
      GO TO 510
C
C         ***** PROCESS A REGULATOR *****
C
  405 WDOTN(IDX) = WDOTN(IDX-ISIGN)
      TEMP(IDX)  = TEMP(IDX-ISIGN)
      PRES(IDX)     = PRES(IDX-ISIGN)
      DIAM(IDX)     = AMIN1(DIAM(IDX+1),DIAM(IDX-1))
      GO TO (421,422),IGAS
C
  421 CALL FINTAB (NTBID(51))
      FLMU    = MIPE(1,TEMP(IDX))
      GO TO 423
  422 CALL FINTAB (NTBID(52))
      XTAB(1) = PRES(IDX)
      XTAB(2) = TEMP(IDX)
      FLMU    = MIPE(2,XTAB)
C
  423 GO TO (424,425),IGAS
```

```
********    HZNCMP    ********

C
  424 RHO     = 78.77326 - 0.03002 * TEMP(IDX)
      GO TO 426
  425 CALL ZFIND(TEMP(IDX),PRES(IDX),17,ZHE)
      RHO     = 144.0 * PRES(IDX)/(ZHE * FINDR(17) * TEMP(IDX))
C
  426 VELCTY  = 576.0 * WDOTN(IDX)/(RHO * PI * (DIAM(IDX)**2))
C
      REYNUM  = VELCTY * RHO * DIAM(IDX)/(12.0 * FLMU)
C
      FRCOEF(IDX) =  0.316/(REYNUM**0.25)
C
      FLD          = FRCOEF(IDX)*LOD(IDX)
      IDV          = CFTYPE/10
      CFTYPE      = CFTYPE - IDV*10
C
      IX           = IDX - ISIGN
      DLPREG       = (SOPRES(IGAS,1)-1.0) - PRES(IDX)
      PRES(IDX)    = PRES(IX) + ISIGN*DLPREG
      GO TO 561
C
C         ***** PROCESS A FITTING *****
C
  450 WDOTN(IDX) = WDOTN(IDX-ISIGN)
      TEMP(IDX)  = TEMP(IDX-ISIGN)
      PRES(IDX)    = PRES(IDX-ISIGN)
      DIAM(IDX)    = AMIN1(DIAM(IDX+1),DIAM(IDX-1))
      GO TO (451,452),IGAS
C
  451 CALL FINTAB (NTBID(51))
      FLMU    = MIPE(1,TEMP(IDX))
      GO TO 453
  452 CALL FINTAB (NTBID(52))
      XTAB(1) = PRES(IDX)
      XTAB(2) = TEMP(IDX)
      FLMU    = MIPE(2,XTAB)
C
  453 GO TO (454,455),IGAS
C
  454 RHO     = 78.77326 - 0.03002 * TEMP(IDX)
      GO TO 456
  455 CALL ZFIND(TEMP(IDX),PRES(IDX),17,ZHE)
      RHO     = 144.0 * PRES(IDX)/(ZHE * FINDR(17) * TEMP(IDX))
C
  456 VELCTY  = 576.0 * WDOTN(IDX)/(RHO * PI * (DIAM(IDX)**2))
C
      REYNUM  = VELCTY * RHO * DIAM(IDX)/(12.0 * FLMU)
C
      FRCOEF(IDX) =  0.316/(REYNUM**0.25)
C
      FLD          = FRCOEF(IDX)*LOD(IDX)
      LDV          = CFTYPE/10
      CFTYPE      = CFTYPE - LDV*10
      GO TO 510
C
C         ***** PROCESS A TAP *****
C
  500 WDOTN(IDX) = WDOTN(IDX-ISIGN)
```

```
*********     HZNCMP     *********
      TEMP(IDX)  = TEMP(IDX-ISIGN)
      PRES(IDX)     = PRES(IDX-ISIGN)
      DIAM(IDX)     = AMIN1(DIAM(IDX+1),DIAM(IDX-1))
      GO TO (501,502),IGAS
C
  501 CALL FINTAB (NTBID(51))
      FLMU     = MIPE(1,TEMP(IDX))
      GO TO 503
  502 CALL FINTAB (NTBID(52))
      XTAB(1) = PRES(IDX)
      XTAB(2) = TEMP(IDX)
      FLMU     = MIPE(2,XTAB)
C
  503 GO TO (504,505),IGAS
C
  504 RHO      = 78.77326 - 0.03002 * TEMP(IDX)
      GO TO 506
  505 CALL ZFIND(TEMP(IDX),PRES(IDX),17,ZHE)
      RHO      = 144.0 * PRES(IDX)/(ZHE * FINDR(17) * TEMP(IDX))
C
  506 VELCTY  = 576.0 * WDOTN(IDX)/(RHO * PI * (DIAM(IDX)**2))
C
      REYNUM  = VELCTY * RHO * DIAM(IDX)/(12.0 * FLMU)
C
      FRCOEF(IDX) =  0.316/(REYNUM**0.25)
C
      FLD           = FRCOEF(IDX)*LOD(IDX)
      LDV           = CFTYPE/10
      CFTYPE       = CFTYPE - LDV*10
      GO TO 510
C
C          *****  COMPUTE LINE, CONTROL, FITTING OR TAP DELTA PRESSURE.
C
  510 IX            = IDX - ISIGN
C
      GO TO(520,550),GSTATE
C
C          ***** DELTA PRESSURE WHEN GASEOUS
C
  520 CALL ZFIND(TEMP(IX),PRES(IX),17,Z)
      RHO = 144.0*PRES(IX)/(Z*FINDR(  17)*TEMP(IX))
      DELP = C1*FLD*(WDOTN(IX)/CNOPER)**2/(RHO*DIAM(IDX)**4)
C
C        ***** IF THE PERCENT OF PRESSURE CHANGE EXCEEDS 1 PCT. RECOMP-
C        ***** UTE THE DELTA-P. IF NOT COMPUTE THE NEW PRESSURE.
C
      IF(DELP/(PRES(IX) + DELP) - 0.01)560,560,530
C
C                       CALCULATE NEW RHO OF GAS
C
  530 CALL ZFIND(TEMP(IX),PRES(IX)+DELP/2.0,17,Z)
      RHO = 144.0*PRES(IX)/(Z*FINDR(  17)*TEMP(IX))
      DELP = C1*FLD*(WDOTN(IX)/CNOPER)**2/(RHO*DIAM(IDX)**4)
C
      GO TO 560
C
C     DELTA-P FOR LIQUID STATE
C
```

```
*********     HZNCMP     *********

      550 CONTINUE
          RHOHZN        = 78.77326 - 0.03002 * SITEMP(1,1)
          DELP          = C1*FLD*(WDOTN(IX)**2)/(RHOHZN*DIAM(IDX)**4)
    C
    C          ***** COMPUTE NEW PRESSURE
    C
      560 PRES(IDX) = PRES(IX) + ISIGN*DELP
    C
    C          ***** COMPUTE THE GAS MACH NUMBER
    C
          IF(GSTATE.EQ.2) GO TO 561
    C
    C                          CALCULATE NEW GAS DENSITY
          CALL ZFIND(TEMP(IX),PRES(IDX),17,Z)
          RHO = 144.0*PRES(IDX)/(Z*FINDR(   17)*TEMP(IX))
    C
          IF(GSTATE.EQ.1) CALL VGVSHE(IDX,RHO)
    C
      561 CONTINUE
    C          ***** COMPUTE LINE WEIGHT *****
    C
          IF(CFUNCT.EQ.3) GO TO 562
          IF(CFUNCT.EQ.5) GO TO 562
          IF(CFUNCT.EQ.6) GO TO 562
          IF(CFUNCT.EQ.7) GO TO 562
          IF(CFUNCT.EQ.8) GO TO 562
          GO TO 570
    C
      562 CALL LWEGHT(IDX,LDV)
          GO TO 999
    C
    C          ***** COMPUTE CONTROL WEIGHT *****
    C
      570 WEIGHT(IDX)= HZCVCW(DIAM(IDX),PRES(IDX),IDV)
          GO TO 999
    C
      600 GO TO 1000
    C
    C          ***** PROCESS A TANK OR SUPPLY *****
    C
      700 INDXTK(1)     = IDX
          IF(SIPRES(IGAS,1)) 720,710,720
    C
    C     IF NO TANK INPUT PRESSURE - USE CALCULATED VALUE
    C
      710 SIPRES(IGAS,1)  = PRES(IDX-ISIGN)
          GO TO 740
    C
    C     **** CHECK INPUT TANK PRES. AGAINST REQD.CALCULATED PRESSURE.
    C        * IF INPUT TANK PRES. IS LESS THAN CALC.VALUE - WRITE MESSAGE.
    C        * SET TANK INPUT PRESSURE EQUAL TO REQD. PRESSURE.
    C     **** IF NOT, CONTINUE WITH CALCULATIONS.
    C
      720 IF(SIPRES(IGAS,1) - PRES(IDX-ISIGN)) 730,740,740
    C
      730 WRITE (IOT,6000) SIPRES(IGAS,1), PRES(IDX-ISIGN)
          GO TO 710
    C
```

```
********     HZNCMP     ********
      740 PRES(IDX)     = SIPRES(IGAS,I)
C
C         **** ALSO CHECK TANK TEMPERATURE
C
          IF(SITEMP(IGAS,I)) 760,750,760
      750 SITEMP(IGAS,I) = TEMP(IDX-ISIGN)
C
      760 TEMP(IDX)     = SITEMP(IGAS,I)
C
          WDOTN(IDX)    = WDOTN(IDX-ISIGN)
C
          WEIGHT(IDX) = WTTOT(IGAS)
          WI(IDX) = TIWT(IGAS,I)
          GO TO 999
C
      800 GO TO 1000
C
      900 GO TO 1000
C
C              ***** END OF CONFIGURATION PROCESSING LOOP *****
C
      999 CONTINUE
C
          IF(.NOT.PAGE(I)) GO TO 1998
C
     1998 CONTINUE
C
          KFUNCT        = FNAME(CFUNCT)
C
          WRITE (IOT,6030) KFUNCT, CODE(IDX), CFTYPE, CNOPER, CNSTBY, ISIGN,
         1                 IDX, IGAS, GSTATE, FRCOEF(IDX), LOD(IDX),
         2                 DIAM(IDX), ITHICK(IDX),PRES(IDX), TEMP(IDX),
         3                 WDOTN(IDX), WEIGHT(IDX), MACH(IDX), MFLG(IDX)
C
          IF(PRES(IDX).GE.0. .AND. TEMP(IDX).GE.0. ) GO TO 998
C
          WRITE (IOT,6040)
          CALL EXIT
C
      998 CONTINUE
     1000 CONTINUE
     1100 CONTINUE
C
C         FOR WEIGHT SUMMARY
C
          KHEND         = IDX-1
          KOEND         = IHSTT-2
C
          RETURN
C
C         OUTPUT FORMATS
C
     6000 FORMAT('0 *DIAGNOSTIC* TANK INPUT PRESSURE IS LESS THAN THE REQUIR
         1ED PRESSURE. TANK PRESSURE SET = REQUIRED PRESSURE.'/15X,'TANK INP
         2UT PRESSURE =',F7.2,', REQUIRED PRESSURE = ',F7.2)
C
     6020 FORMAT('0  F    CODE    FT  NO  NS  IS IDX   G  GS    FCOEF      L/D
         1           DIAM  ITHICK    PRES      TEMP    WDOT  WEIGHT    MACH    M
         2FLAG'/' ')
C
     6030 FORMAT(2XA3,2XA6,I3,6I4,F9.6,F12.4,2F8.4,F10.4,F8.2,F7.4,F9.3,
         1 F10.7,3X,A6)
C
     6040 FORMAT(T44,'*** TERMINATE - NEGATIVE TEMP. OR PRESSURE. ***')
C
     6050 FORMAT(/T38,'*** SUMMARY OF COMPUTED SYSTEM CONFIGURATION PARAMETE
         1RS ***')
     6051 FORMAT(/T32,'*** SUMMARY OF COMPUTED SYSTEM CONFIGURATION PARAMETE
         1RS - CONTD. ***')
C
          END
```

SUBRØUTINE ØTRTNS

```
635717*TPF$.OTRTNS
C
C                    GENERAL OUTPUT ROUTINES
C
      SUBROUTINE OTPHEX
C
C
C     ******************************************************************
C
C     *******  THIS SUBPROGRAM HAS BEEN MODIFIED FOR USE WITH THE ******
C     *******               HYDRAZINE APU PROGRAM                 ******
C     *******          **   DO NOT USE WITH TCIMM    **           ******
C
C     ******************************************************************
C
      LOGICAL  JP,PAGE
C
      INCLUDE CACCUM
      INCLUDE CAPU
      INCLUDE CCNFIG
      INCLUDE CECLSS
      INCLUDE CENG
      INCLUDE CFLRAT
      INCLUDE CFUEL
      INCLUDE CHEX
      INCLUDE CHSORC
      INCLUDE CIOUNT
      INCLUDE CNAMES
      INCLUDE CPUMP
      INCLUDE CTANK
      INCLUDE CTURBN
C
      DATA  IDMHX/ MHX/
C
 6110 FORMAT(1H0,T51,'*** COMPONENT WEIGHT SUMMARY ***'//T27,'...PROPELL
     1ANT...',T87,'...HELIUM...'/ T31,'---------',T91,'----'/ T38,'COMPON
     2ENT'T52,'INSULATION'T98,'COMPONENT'T112,'INSULATION' / T11,'COMPON
     3ENT'T27,'CODF'T38,'WT. (LBS)'T52,'WT. (LBS)'T71,'COMPONENT'T87,
     4'CODE'T98,'WT. (LBS)'T112,'WT. (LBS)'/)
 6112 FORMAT(1H0,T47,'*** COMPONENT WEIGHT SUMMARY TOTALS ***')
C
      NIENTH = 0.0
C
      ENTRY OTPWSM
C                    OUTPUT WEIGHT SUMMARY DATA
      IF (PAGE( 0)) WRITE (IOT,6110)
      JP = PAGE ( 8)
      I1 = IOSTT
      I2 = IHSTT
      KH2 = 1
      KO2 = 1
      MVL = 3
      NCPH = KHEND - IHSTT
      NCPO = KOEND - IOSTT
      MXCP = NCPO
      IF (MXCP .LT. NCPH) MXCP = NCPH
      H2IWT = 0.
      H2SWT = 0.
```

```
********     OTRTNS     ********

              O2IWT = 0.
              O2SWT = 0.
      C
              DO 770 I=1,MXCP
              GO TO (700,730),KO2
      C                         SET UP OXIDYZER SIDE
          700 I1 = I1 + 1
              IF (I1 .LE. KOEND) GO TO 710
              KO2 = 2
              MVL = MVL - 1
              GO TO 730
          710 CALL GETCON (I1)
              IF (CFUNCT .EQ. 1) GO TO 700
              KONAM = FNAME(CFUNCT)
              O2IWT = O2IWT + WI(I1)
              O2SWT = O2SWT + WEIGHT(I1)
      C
          730 GO TO (740,760),KH2
      C                         SET UP FUEL SIDE
          740 I2 = I2 + 1
              IF (I2 .LE. KHEND) GO TO 750
              KH2 = 2
              MVL = MVL - 2
              GO TO 760
          750 CALL GETCON (I2)
              IF (CFUNCT .EQ. 1) GO TO 740
              KHNAM = FNAME(CFUNCT)
              H2IWT = H2IWT + WI(I2)
              H2SWT = H2SWT + WEIGHT(I2)
      C
          760 IF (MVL .EQ. 0) GO TO 780
              IF (PAGE( 1))WRITE (IOT,6110)
      C                         PRINT A LINE
              CALL OUTPW (MVL,KONAM,CODE(I1),WEIGHT(I1),WI(I1),
             1                   KHNAM,CODE(I2),WEIGHT(I2),WI(I2))
          770 CONTINUE
      C
          780 CONTINUE
              JP = PAGE ( 9)
              CALL SPACE
              WRITE (IOT,6112)
              TTLSWT = ENGWT + H2SWT + H2IWT + O2SWT + O2IWT
              CALL SPACE
      C                         PRINT SYSTEM WT. TOTALS
              CALL OUTPF1 (4,LCNF1,ENGWT)
              DO 790 I=1,5
              CALL OUTPF1 (4,LCNF1(1,I+1),WTOFSY(I))
          790 CONTINUE
              RETURN
      C
      C
              END
```

SUBRØUTINE STØDTA

```
635717*TPFS.STODTA
C
C
C     ******************************************************************
C
C     *******  THIS SUBPROGRAM HAS BEEN MODIFIED FOR USE WITH THE ******
C     *******                HYDRAZINE APU PROGRAM                 ******
C     *******           **   DO NOT USE WITH TCIMM    **           ******
C
C     ******************************************************************
C
      SUBROUTINE STODTA
C
      INCLUDE CAPU
      INCLUDE CCNFIG
      INCLUDE CCNTRL
      INCLUDE CECLSS
      INCLUDE CFLRAT
      INCLUDE CHEX
      INCLUDE CHSORC
      INCLUDE CIOUNT
      INCLUDE CMATRL
      INCLUDE CNAMES
      INCLUDE CONST
      INCLUDE CPAGE
      INCLUDE CPUMP
      INCLUDE CTANK
      INCLUDE CTURBN
      INCLUDE TABLOK
C
C                  *****   PDP CAPU     *****
C
      DATA ((LAPU1(I,J),I=1,4),J=1,8)  /    'PROPELLANT TEMP. (DEG-R)',
     1   'OXYGEN LOADED        (LBS)'   ,    'HYDROGEN LOADED     (LBS)',
     2   'TOTAL LOADED         (LBS)'   ,    'PROP. USED BY APU  (LBS)',
     3   'OXY. MAX. FLOW  (LB/SEC)'     ,    'HYD. MAX. FLOW  (LB/SEC)',
     4   'WDOT OX-TURB-GG (LB/SEC)'     /
C
      DATA ((LAPU2(I,J),I=1,4),J=1,11) /    'WT. OF CIRCL. COMPRESSOR',
     1   'GAS GEN. CONSUMPTION    '     ,    'VOLUME OF STORAGE TANK  ',
     2   'AREA OF STORAGE TANK    '     ,    'WEIGHT OF STORAGE TANK  ',
     3   'H2 VENT - ABSORB TK LEAK'     ,    'WT. OF RESIDUAL IN TANK ',
     4   'WT. OF ACCUMULATOR TANK '     ,    'CAPACITY OF ACCUMULATOR ',
     5   'WT. OF RESID. IN ACCUM. '     ,    'TOT. WT. OF PROPL. REQD.'/
C
      DATA ((LAPU3(I,J),I=1,4),J=1,11) /    'TEMP. OF G.G. EXHAUST   ',
     1   'WTG. OF FLUID TO G.G.   '     ,    'SURF. AREA OF STO. TANK ',
     2   'VOLUME OF STORAGE TANK  '     ,    'HEAT LEAK INTO STO. TANK',
     3   'WT H2-ABSRB TK+PMP HT LK'     ,    'TOT.H2-VENTED FOR HT.LK.',
     4   'TOTAL WT. OF PROPELLANT '     ,    'STORAGE TANK RESIDUAL   ',
     5   'ACCUMULATOR CAPACITY    '     ,    'ACCUMULATOR TANK RESIDUL'/
C
C                  *****  PDP CCNFIG  *****
C
      DATA ((LCNF1(I,J),I=1,4),J=1,6) / 'CONSUMER WEIGHT - LBS    ' ,
     1      'OXIDYZER SYSTEM WT. -LBS' , 'OXID INSULATION WT - LBS' ,
     2      'FUEL SYSTEM WT. - LBS   ' , 'FUEL INSULATION WT - LBS' ,
     3      'TOTAL SYSTEM WT. - LBS  ' /
```

```
********     STODTA     *********

C
C                    *****   PDP CCNTRL   *****
C
C                                                 SUB CRIT.    SUPER CRIT.
      DATA ((INBLK(1,I,J),I=1,5),J=1,2) / 1,1,1,1,0,   1,1,0,1,0 /
      DATA ((INBLK(2,I,J),I=1,5),J=1,2) / 1,1,1,1,1,   1,1,0,1,0 /
      DATA ((INBLK(3,I,J),I=1,5),J=1,2) / 0,0,0,0,0,   0,1,0,0,0 /
      DATA ((INBLK(4,I,J),I=1,5),J=1,2) / 0,1,0,1,0,   0,1,1,0,1 /
      DATA ((INBLK(5,I,J),I=1,5),J=1,2) / 1,1,1,1,0,   0,0,0,0,0 /
      DATA ((INBLK(5,I,J),I=1,5),J=1,2) / 0,0,0,0,0,   0,0,0,0,0 /
      DATA (KSUBC(1,I),I=1,NBRSR) / 6, 4, 10, 9, 8, 1, 10, 11, 2/
      DATA (KSUBC(2,I),I=1,NBRSR) / 6, 3, 4, 10,11, 2,  0,  0, 0/
      DATA (KSUBC(3,I),I=1,NBRSR) / 7, 0, 0,  0, 0, 0,  0,  0, 0/
      DATA (KSUBC(4,I),I=1,NBRSR) / 5, 4, 0,  0, 0, 0,  0,  0, 0/
      DATA (KSUBC(5,I),I=1,NBRSR) / 6, 4, 10, 9, 8, 1, 10, 11, 2/
      DATA (KSUBC(6,I),I=1,NBRSR) /12, 0, 0,  0, 0, 0,  0,  0, 0/
      DATA JAPUS(1,1),JAPUS(1,2) / 4, 3/
      DATA JAPUS(2,1),JAPUS(2,2) / 3, 4/
      DATA NAMSYS / 'ACP','APU','EC/','FUE','OMS','HZN' /
C
C                    *****   PDP CFLRAT   *****
C
      DATA ((LFRT(I,J),I=1,3),J=1,7)/
     1   'WDOT OX-TURB.-G.G.','WDOT HY-TURB.-G.G.','WDOT BOTH TURB.-GG',
     2   'WDOT OXY HEX.-G.G.','WDOT HYD HEX.-G.G.','WDOT BOTH HEX.-G.G',
     3   'TOTAL FLOWRATE  **'/
C
C                    *****   PDP CHEX     *****
C
      DATA  ((UNAM(I,J),I=1,2),J=1,4) /
     1  '   BOILING  ','SUP-CRITICAL','PARALLEL-FLO','COUNTER-FLOW'/
      DATA  ((LHX1(I,J),I=1,4),J=1,10)/
     1   'THERML CONDUCTANCE RATIO','HOT FLUID FLOW RATE      ',
     2   'COLD FLUID DELTA - P    ','CAPACITY RATIO           ',
     3   'NUMBER OF TRANSFER UNITS','COMPUTED VALUE OF UA     ',
     4   'COMPUTED VALUE OF W/UA  ','WEIGHT OF SUBUNIT        ',
     5   'WEIGHT OF HEAT EXCHANGER','HEX SUBUNIT TYPE  ***    '/
      DATA  ((LHX2(I,J),I=1,4),J=1,14)/
     1   'COLD FLUID INLET TEMP   ','COLD FLUID OUTLET TEMP  ',
     2   'COLD FLUID SPECIFIC HEAT','COLD FLUID FLOW RATE    ',
     3   'HOT FLUID INLET TEMP    ','HOT FLUID OUTLET TEMP   ',
     4   'HOT FLUID SPECIFIC HEAT ','HOT FLUID FLOW RATE     ',
     5   'COLD SIDE EFFECTIVENESS ','HOT SIDE EFFECTIVENESS  ',
     6   'TOTAL EFFECTIVENESS     ','HEAT EXCHANGER UA/A-WALL',
     7   'HEAT EXCHANGER DIAMETER ','HEAT EXCHANGER LENGTH   '/
      DATA LHX3 / 'HEAT EXCHANGER CHARACTERISTICS' /
C
C                    *****   PDP CHSORC   *****
C
      DATA ((LHS1(I,J),I=1,5),J=1,6) /
     1'GAS GENERATOR CHARACTERISTICS ','GAS GEN. FLOW RATE - (LB/SEC) ',
     2'GAS GEN. PROPELLANT WGT.-(LBS)','GAS GENERATOR WEIGHT - (LBS)  ',
     3'CUMULATIVE GAS GEN. PROP. WTG.','WEIGHT OF HEX-GAS GEN. ASSY.  '/
C
      DATA ((LHS2(I,J),I=1,5),J=1,14) /
     1'SPEC.HEAT AVAILABLE-(BTU/LB-R)','TOTAL HEAT REQUIRED - (BTU)   ',
     2'HOT FLUID REQUIRED - (LBS)    ','CUMULATIVE HEAT REQD. - (BTU) ',
     3'CUMULATIVE HOT FLUID - (LBS)  ','WASTE HEAT UTILIZATION DATA   ',
```

```
*********     STODTA     *********

     4'MAX HOT FLUID FLO-RATE(LBS/HR)','CYCLE MAX REQD ENERGY - O2 HEX',
     5'CYCLE MAX REQD ENERGY - N2 HEX','CYCLE MAX REQD ENERGY- O2 TANK',
     6'CYCLE MAX REQD ENERGY- N2 TANK','TOTAL MAX ENERGY - HEX + TANKS',
     7'TOTAL ENERGY FOR MISSION SPAN ','TOTAL ENERGY REQMT - KW/HRS   '/
C
C                    *****   PDP CIOUNT   *****
C
      DATA IOUNIT/14,21,22,23,19,29,15,16,17,18,25,26,27,28/
      DATA  IIN,IOT / 5,6 /
C
C                    *****   PDP CMATRL   *****
C
      DATA(RHOL(I),I=1,5)/501.120,176.256,169.344,511.488,276.480/
      DATA (RHOI(I),I=1,9)/2.14,2.45,2.80,0.836,0.59,0.65,5.0,2.2,1.0/
      DATA (RHOIS(I),I=1,9)/0.0428,0.0490,0.0280,0.027867,0.01475,
     1 0.021667,5.0,2.20,1.0/
      DATA(MINTHK(I),I=1,15)/0.020,0.025,0.028,0.020,0.016,0.035,0.058,
     1                  0.065,0.042,0.020,0.049,0.083,0.095,0.049,0.035/
C
C                    *****   PDP CNAMES   *****
C
      DATA(FNAME(I),I=1,19)/'GAS   ','ENGINE','LINE  ','CONTRL','FITING'
     1                     ,'TAP   ','TEE   ','ELBOW ','VALVE ','REG   '
     2                     ,'ACCUM ','TANK  ','PUMP  ','HEX   ','TRBINE'
     3                     ,'F-CELL','EC/LSS','BLAD  ','END   '/
C
      DATA ((LO(I,J),I=1,9),J=1,16)/
     1          ' ***** S Y S T E M   C O N F I G U R A T I O N ***** ',
     2          '           ***** E N G I N E   D A T A *****          ',
     3          '      ***** A C C U M U L A T O R   D A T A *****     ',
     4          '    ***** H E A T   E X C H A N G E R   D A T A ***** ',
     5          '  ***** H I G H   P R E S   P U M P   D A T A *****   ',
     6          '       ***** D U T Y   C Y C L E   D A T A *****      ',
     7          '       ***** H E A T   S O U R C E   D A T A *****    ',
     8          '          ***** T U R B I N E   D A T A *****         ',
     9          '            ***** M O T O R   D A T A *****           ',
     T          '*** T A N K   C O N F I G U R A T I O N   D A T A ****',
     1          '   ***** L O W   P R E S   P U M P   D A T A *****    ',
     2          '            ***** T A N K   D A T A *****             ',
     3          ' ***** A U X I L I A R Y   P O W E R   U N I T ***** ',
     4          '        ***** F U E L   C E L L   D A T A *****       ',
     5          '           ***** E C / L S S   D A T A *****          ',
     6          ' *****    H Y D R A Z I N E   A P U   D A T A   ***** '/
C
      DATA ((L1(I,J),I=1,21),J=1,2)/'    COMP   COMP    FUNC.  NUMB.  NU
     1MB.  MATRL.  FLOW FRICTION   LINE LENGTH    LINE     INSULATION
     2 INSULATION   NO. LAYERS ','     NAME   CODE    TYPE   OPER.  STBY.
     3  TYPE     COEFICIENT     OR L-OVER-D   DIAMETER      TYPE        T
     4HICKNESS   INSULATION '/
C
      DATA ((L2(I,J),I=1,3),J=1,7)/'NUMBER OF ENGINES ',
     1         'GAS INLET TEMP.   ','GAS INLET PRES.   ',
     2         'ENGINE THRUST     ','CHAMBER PRES.     ',
     3         'EXPANSION RATIO   ','MIXTURE RATIO     '/
C
      DATA ((L3(I,J),I=1,4),J=1,3)     /     'OPERATING TEMP. (DEG R) ',
     1    'TANK VOLUME (CU. FT.)   '     ,     'NOMINAL OPER. DELTA PRES'/
C
```

```
********     STODTA     ********

          DATA((L4(I,J),I=1,4),J=1,11)/ 'HEX HOT INLET TEMP.       ',
         1   'HEX HOT OUTLET TEMP.      ','HEX COLD INLET TEMP.      ',
         2   'HEX COLD OUTLET TEMP.     ','HEX HOT INLET PRES.       ',
         3   'HEX HOT OUTLET PRES.      ','HEX COLD INLET PRES.      ',
         4   'HEX COLD OUTLET PRES.     ','HEX HOT SIDE DELTA-P      ',
         5   'HEX COLD SIDE DELTA-P     ','HEX GAS GEN. O/F RATIO    '/
C
          DATA ((L5(I,J),I=1,4),J=1,5)/ 'TYPE                      ',
         1   'EFFICIENCY                ','NET + SUCTION HEAD        ',
         2   'SHAFT SPEED               ','ESTIMATED DELTA PRES.     '/
C
          DATA ((L6(I,J),I=1,4),J=1,4)/ 'PUMP EFFICIENCY           ',
         1   'NET POS. SUCTION HEAD     ','PUMP PRESSURE RISE        ',
         2   'PUMP FLOW RATE            '/
C
          DATA ((L7(I,J),I=1,4),J=1,23)     /
         1   '                          '     ,    'MAXIMUM DIAMETER (FT)    ',
         2   'INITIAL FLUID LOAD (OPT)  '     ,    'PERCENT ULLAGE VOLUME    ',
         3   'HEAT FLUX (BTU/HR-FT**2)  '     ,    'INITIAL TEMPERATURE (R)  ',
         4   'INITIAL PRESSURE          '     ,    'VENTING PRESSURE         ',
         5   'MATERIAL TYPE             '     ,    'INSULATION TYPE          ',
         6   'INSULATION THICKNESS      '     ,    'ACQUISITION TYPE         ',
         7   'PRESSURIZATION TYPE       '     ,    'OPERATING PRESS. (PSIA)  ',
         8   'PRESSURANT GAS TEMP. (R)  '     ,    'HEX DELTA PRESS. (PSIA)  ',
         9   'PUMP DELTA PRESS. (PSIA)  '     ,    'HEX OUTLET TEMP. (R)     ',
         T   'P SUB C OF GAS GEN (PSIA  '     ,    'GAS GEN OUTLET TEMP (R)  ',
         1   'GAS GEN MIXTURE RATIO     '     ,    'NUMBER OPERATING (NOP)   ',
         2   'NUMBER INSULATION LAYERS  '     /
C
          DATA ((L8(I,J),I=1,4),J=1,3)/ '( ENG. DEG. DUE TO MIB    ',
         1   ' ACTIVE         INACTIVE  ','  TIME            TIME    '/
C
          DATA ((L9(I,J),I=1,4),J=1,5)/ 'TURBINE EFFICIENCY        ',
         1   'TURBINE INLET TEMP.       ','TURBINE OUTLET TEMP.      ',
         2   'TURBINE MIXTURE RATIO     ','TURBINE GAS GEN. PSUBC    '/
C
          DATA((L10(I,J),I=1,4),J=1,5)/ 'HEAT SOURCE TYPE          ',
         1   'HEAT SOURCE MIX. RATIO    ','HEAT SOURCE OUTLET TEMP.  ',
         2   'HEAT SOURCE AVAIL.ENERGY  ','HEAT SOURCE PRESSURE      '/
C
          DATA((L11(I,J),I=1,4),J=1,24)/'NUMBER OF APU UNITS       ',
         1   'HORSEPOWER PER UNIT       ','TURBINE MIXTURE RATIO     ',
         2   'APU GAS GEN. INLET PRESS  ','TURBINE INLET TEMP.       ',
         3   'HEX EXHAUST DISCHGE.TEMP  ','H2-SUP.GAS GEN.MIX-RATIO  ',
         4   'O2-SUP.GAS GEN.MIX-RATIO  ','H2-SUP.GAS GEN.EXIT TEMP  ',
         5   'O2-SUP.GAS GEN.EXIT TEMP  ','H2-TANK RESID.VAP.TEMP.   ',
         6   'O2-TANK RESID.VAP.TEMP.   ','SYSTEM ENVIRONMENT TEMP.  ',
         7   'FUEL MIX-RAT.SUP.GAS-GEN  ','FINAL H2 TANK PRESSURE    ',
         8   'FINAL O2 TANK PRESSURE    ','FINAL H2 TANK TEMP.       ',
         9   'FINAL O2 TANK TEMP.       ','TEMP.EX.PROD.SUP.GAS-GEN  ',
         T   'DELTA-P TANK CIRC. PUMP   ','TURBINE PRESSURE RATIO    ',
         A   'PER-CENT RESERVE FUEL     ','PRESSURANT GAS PRESSURE   ',
         B   'TURBINE INLET PRESSURE    '/
C
          DATA((L12(I,J),I=1,4),J=1,28)/'NUMBER OF FUEL CELLS OP.  ',
         1   'FUEL CELL MIXTURE RATIO   ','SP.REACTANT CONSUMPTION   ',
         2   'F.C.HEAT REJECTION RATE   ','SP.WGT. OF FUEL CELL      ',
         3   'FUEL CELL NOM. TEMP.- O2  ','FUEL CELL NOM. TEMP.- H2  ',
```

```
     4   'HOT FLUID INLET TEMP.   ','HOT FLUID OUTLET TEMP.  ',
     5   'O2 TANK FILL DENSITY    ','H2 TANK FILL DENSITY    ',
     6   'EST. O2 TANK VENT QUANT.','EST. H2 TANK VENT QUANT.',
     7   'FUEL CELL OPER. PRESSURE','NOM.FUEL CELL OPER.POWER',
     8   'O2 TANK LO-PRES. SETTING','H2 TANK LO-PRES. SETTING',
     9   'O2 TANK VAC.JAC. ANNULUS','H2 TANK VAC.JAC. ANNULUS',
     T   'O2 TANK MAXIMUM DIAMETER','H2 TANK MAXIMUM DIAMETER',
     A   'FUEL CELL VOLTAGE (AVG) ','FUEL CELL O2 PURGF RATE ',
     B   'FUEL CELL H2 PURGE RATE ','FUEL CELL O2 PURGF TIME ',
     C   'FUEL CELL H2 PURGE TIME ','O2 PURGE INTERVAL-AMPHRS',
     D   'H2 PURGE INTERVAL-AMPHRS'/
C
      DATA((L13(I,J),I=1,4),J=1,28)/'MISSION DURATION - DAYS ',
     1   'NUMBER OF MEN IN CREW   ','AIRLOCK REPRESSURIZINGS ',
     2   'DAYS SUPPLY RESERVE GAS ','O2 CONSUMED PER MAN-DAY ',
     3   'VEHICLE GAS LEAKAGE RATE','DELIVERED O2 NOM. TEMP. ',
     4   'DELIVERED N2 NOM. TEMP. ','O2 FILL DENSITY         ',
     5   'N2 FILL DENSITY         ','O2 TANK FINAL TEMP      ',
     6   'N2 TANK FINAL TEMP.     ','O2 TANK FINAL PRESSURE  ',
     7   'N2 TANK FINAL PRESSURE  ','LSS ENVIRONMENT TEMP.   ',
     8   'CABIN OR AIRLOCK VOLUME ','O2-HEX INLET LINE DIAM. ',
     9   'N2-HEX INLET LINE DIAM. ','HEX HEATER ENERGY RATING',
     T   'TNK HEATER ENERGY RATING','DELIVERED O2 PRESSURE   ',
     A   'DELIVERED N2 PRESSURE   ','O2 TANK HEATER DIAMETER ',
     B   'N2 TANK HEATER DIAMETER ','O2 TANK HEATER LENGTH   ',
     C   'N2 TANK HEATER LENGTH   ','O2 TANK LOW-PRESS. LIMIT',
     D   'N2 TANK LOW-PRESS. LIMIT'/
C
      DATA ((JFLUID(I,J),I=1,2),J=1,3)/'   OXYGEN   ','  HYDROGEN  ',
     1                                 '  NITROGEN  '/
      DATA ((KFLUID(I,J),I=1,2),J=1,2)/'  OXIDYZER  ','    FUEL    '/
C
C                  *****   PDP CONST    *****
C
      DATA GRAVTY,PI,PI203 / 32.172 ,3.14159265 ,2.0943951 /
C
C                  *****   PDP CPAGE    *****
C
      DATA MAXLIN,JNUM  ,OPTLUN/50,'AT4307',6 /
      DATA PTITLE/'     THE INTEGRATED MATH MODEL       '/
C
C                  *****   PDP CPUMP    *****
C
      DATA ((LPP1(I,J),I=1,3),J=1,6) /
     1'TEMPERATURE       ','PRESSURE          ','FLOW RATE         ',
     2'DELTA-PRESSURE    ','NPSH AVIALABLE    ','DENSITY OF FLUID  '/
      DATA LPP2 / 'NUMBER OF STAGES REQD.  ' /
      DATA ((LPP3(I,J),I=1,3),J=1,6) /
     1'COMPUTED NPSP REQD','COMPUTED PUMP EFF.','COMPUTED PUMP VOL.',
     2'COMPUTED PUMP WGT.','COMPUTED PUMP PWR.','COMPUTED PUMP SPD.'/
      DATA LPP4 / 'SELECTED PUMP OPTION    ' /
      DATA LPP5 / 'PUMP CHARACTERISTICS    '/
C
C                  *****   PDP CTANK    *****
C
      DATA ((LTZ1(I,J),I=1,3),J=1,14)/
     1   'NUMBER OF TANKS   ','MATERIAL TYPE      ','INSULATION TYPE   ',
     2   'FLUID WGT. (TOTAL)','FLUID VOLUME /TANK','DIAMETER (FT)/TANK',
```

```
*********     STODTA     *********

           3   'SURFACE AREA /TANK','TANK VOLUME / TANK','TANK WGT. (LB) TOT',
           4   'INSUL. THICKNESS  ','INSUL. WT (LB) TOT','HEAT LEAK BTU/H/FT',
           5   'GAS RESIDUALS WT. ','HGT ADDED CYL SECT'/
            DATA ((LTZ2(I,J),I=1,2),J=1,3)
           1        / 'SURF TENSION' , 'POSITV DISPL' , 'DIELCTROPHOR' /
            DATA ((LTZ3(I,J),I=1,3),J=1,4)                /'TYPE ACQ. DEVICE  ',
           1   'DEVICE WT. (LBS)  ','TRAPPED BY DEVICE ','RESID. PROPELLANT '/
      C
      C                  *****   PDP CTURBN   *****
      C
            DATA LTBN1 /'TURBINE CHARACTERISTICS '/
            DATA ((LTBN2(I,J),I=1,5),J=1,6) /
           1'TURBINE ROTOR MEAN DIAMETER   ','WGT. OF PWR. TRANSMISSION ASSY',
           2'WGT. OF TURBINE ROTOR         ','WGT. OF MANIFOLD AND NOZZLE   ',
           3'WEIGHT OF INDUCER             ','WEIGHT OF TURBINE ASSY.       '/
      C
      C                  *****   PDP TABLOK   *****
      C
            DATA  NTBID / 1, 2, 7, 8, 4, 3, 6, 5,21, 9,
           1              10,10,17,13,13,16,13,21,27,28,
           2              29,30,31,32,21,32,35,32,38,35,
           3              10,13,16,13,41,41,32,32,41,18,
           4              19,20,21,44,45,46,47,48,49,50,
           5              51,52, 0, 0, 0/
            MIPE = 0.
            NIENTH = 0.0
      C
            RETURN
      C
            END
```

PRØCEDURE DEFINITIØN PRØCESSOR TABLOK

```
635717*TPF$.TABLOK
TABLOK* PROC
C
      REAL  MIPE
C
          COMMON /TABLOK/ XTAB(7), NTBID(55)
C
 END
```

SUBRØUTINE VGVSHE

```
635717*TPF$.VGVSHE
      SUBROUTINE VGVSHE(IDX,RHO)
C
C         ** IDX  -  INDEX OF CONFIGURATION TABLE
C         **  RHO  -  DENSITY OF THE GAS
C
      INCLUDE CCNFIG
      INCLUDE CONST
C
      DATA IBLNK,IAST1,IAST6/'      ','*     ','*******'/
C
C         **  COMPUTE THE VELOCITY OF THE GAS
C
      MFLG(IDX) = IBLNK
      VG = 576. * WDOTN(IDX)/(PI * DIAM(IDX)**2 * RHO)
C
C         **  COMPUTE THE VELOCITY OF SOUND IN GAS
C
      CPGAS = 1.242
      CVGAS = 0.747
C
      VS = SQRT(GRAVTY*CPGAS*FINDR(17)*TEMP(IDX)/CVGAS)
C
C         ** COMPUTE MACH NUMBER
C
      MACH(IDX) = VG/VS
C
C         ** CHECK MACH NUMBER, FLAG MACH GREATER THAN .3 WITH ONE
C         ** ASTERISK, FLAG MACH NUMBER GREATER THAN 0.95 WITH
C         ** 6 ASTERISKS.
C
      IF(MACH(IDX) - 0.3) 40,40,10
   10 IF(MACH(IDX) - 0.95) 20,30,30
   20 MFLG(IDX) = IAST1
      GO TO 40
   30 MFLG(IDX) = IAST6
   40 RETURN
C
      END
```

D-3.2 PROGRAM FILE ELEMENT TABLE OF CONTENTS

The next several pages contain the program file table of contents, also known as the PRT, T index. The table is printed when called for by a@PRT, T control card. The output contains the "element table," "procedure tables," and, if a@PREP card has preceeded the PRT card, the "entry point table."

The column headings given at the beginning of the element table have the following meanings:

D-FLAG	an asterisk means that the entry is deleted from the file.
NAME	name of synbolic/relocatable/absolute element.
VERSION	version of element.
TYPE	if the element is symbolic, the processor which created it is indicated.
DATE, TIME	time that element was added to the file.
SEQUENCE NO.	position of the element in the file. This is sequentially issued as elements are added to the file.
PRE-SIZE	for relocatable elements, the preamble length is given in sectors (28 words per sector)
TEXT-SIZE	this is the text size in sectors.
CYCLE WORD	the cycle word is broken up into three separate parameters; starting from left to right, they are: 1) the number of cycles the system will maintain 2) the number of the most current cycles (absolute scale) 3) the number of cycles currently being maintained.
LOCATION	refers to the sector position relating to the start of the file (1792 is the base).

It should be noted that the entry point table is fugitive in the sense that it must be recreated each time a change is made in the program, and is subject to the following constraints:

1) Destroyed when an update is made to any element in a program file.
2) Destroyed when program file is put on magnetic tape.
3) Is not re-established when file is copied from tape to drum.

4) Contains externalized labels.
5) Is created by the @PREP statement which will prepare or re-establish an entry point table for a specified program file.

ELEMENT TABLE ØF FILE HZPRØG.

```
D NAME          VERSION         TYPE         DATE        TIME       SEQ #  SIZE-PRE,TEXT (CYCLE WORD) PSRMODE  LOCATION
  CACCUM                        FOR PROC     06 JUN 73   17:35:21       1             14   1    0   1              1792
  CAPU                          FOR PROC     06 JUN 73   17:35:29       2             52   1    0   1              1806
  CCNFIG                        FOR PROC     06 JUN 73   17:35:38       3             43   1    0   1              1858
  CDCYCL                        FOR PROC     06 JUN 73   17:35:48       4             10   1    0   1              1901
  CECLSS                        FOR PROC     06 JUN 73   17:35:50       5             19   1    0   1              1911
  CENG                          FOR PROC     06 JUN 73   17:35:52       6             10   1    0   1              1930
  CFLRAT                        FOR PROC     06 JUN 73   17:35:54       7              3   1    0   1              1940
  CFLUID                        FOR PROC     06 JUN 73   17:35:54       8              1   1    0   1              1943
  CFUEL                         FOR PROC     06 JUN 73   17:35:57       9             13   1    0   1              1944
  CHEX                          FOR PROC     06 JUN 73   17:35:58      10             22   1    0   1              1957
  CHTX                          FOR PROC     06 JUN 73   17:36:00      11              4   1    0   1              1979
  CHSORC                        FOR PROC     06 JUN 73   17:36:01      12             13   1    0   1              1983
  CIOUNT                        FOR PROC     06 JUN 73   17:36:25      13              5   1    0   1              1996
  CKEYS                         FOR PROC     06 JUN 73   17:36:26      14              1   1    0   1              2001
  CMATRL                        FOR PROC     06 JUN 73   17:36:27      15             17   1    0   1              2002
  CMOTOR                        FOR PROC     06 JUN 73   17:36:28      16              2   1    0   1              2019
  CNAMES                        FOR PROC     06 JUN 73   17:36:29      17              5   1    0   1              2021
  CONST                         FOR PROC     06 JUN 73   17:36:30      18              2   1    0   1              2026
  CPAGE                         FOR PROC     06 JUN 73   17:36:34      19              8   1    0   1              2028
  CPUMP                         FOR PROC     06 JUN 73   17:36:37      20             20   1    0   1              2036
  CSYSWT                        FOR PROC     06 JUN 73   17:36:42      21              6   1    0   1              2056
  CTAB                          FOR PROC     06 JUN 73   17:36:47      22             10   1    0   1              2062
  CTABA                         FOR PROC     06 JUN 73   17:36:48      23              2   1    0   1              2072
  CTANK                         FOR PROC     06 JUN 73   17:37:01      24             19   1    0   1              2074
  CTURBN                        FOR PROC     06 JUN 73   17:37:11      25             13   1    0   1              2093
  DUMMY                         FOR PROC     06 JUN 73   17:37:12      26              3   1    0   1              2106
  SPUMP                         FOR PROC     06 JUN 73   17:37:16      27              2   1    0   1              2109
  TABLOK                        FOR PROC     06 JUN 73   17:37:17      28              1   1    0   1              2111
  TANKWT                        FOR PROC     06 JUN 73   17:37:18      29              3   1    0   1              2112
  ACCRES                        RELOCATABLE  06 JUN 73   17:37:24      30      1       1                             2115
  ACCRES                        FOR SYMB     06 JUN 73   17:37:24      31              1   5    0   1              2117
  ACQWT                         RELOCATABLE  06 JUN 73   17:37:30      32      1       1                             2118
  ACQWT                         FOR SYMB     06 JUN 73   17:37:31      33              1   5    0   1              2120
  APUFLO                        RELOCATABLE  06 JUN 73   17:37:36      34      1       1                             2121
  APUFLO                        FOR SYMB     06 JUN 73   17:37:36      35              1   5    0   1              2123
  APUSUB                        RELOCATABLE  06 JUN 73   17:37:37      36      1       1                             2124
  APUSUB                        FOR SYMB     06 JUN 73   17:37:38      37              1   5    0   1              2126
  APUSUP                        RELOCATABLE  06 JUN 73   17:37:40      38      1       1                             2127
  APUSUP                        FOR SYMB     06 JUN 73   17:37:40      39              1   5    0   1              2129
  CMPCAL                        RELOCATABLE  06 JUN 73   17:37:43      40      1       1                             2130
  CMPCAL                        FOR SYMB     06 JUN 73   17:37:43      41              1   5    0   1              2132
  COMPIL                        RELOCATABLE  06 JUN 73   17:38:12      42      6     172                             2133
  COMPIL                        FOR SYMB     06 JUN 73   17:38:12      43            143   5    0   1              2311
  CONSUM                        RELOCATABLE  06 JUN 73   17:38:14      44      1       1                             2454
  CONSUM                        FOR SYMB     06 JUN 73   17:38:15      45              1   5    0   1              2456
  CRYCON                        RELOCATABLE  06 JUN 73   17:38:20      46      3       9                             2457
  CRYCON                        FOR SYMB     06 JUN 73   17:38:21      47             17   5    0   1              2469
  DIAG                          RELOCATABLE  06 JUN 73   17:38:22      48      1       5                             2486
  DIAG                          FOR SYMB     06 JUN 73   17:38:23      49             11   5    0   1              2492
  ECLSS                         RELOCATABLE  06 JUN 73   17:38:25      50      1       1                             2503
  ECLSS                         FOR SYMB     06 JUN 73   17:38:25      51              1   5    0   1              2505
  FINDR                         RELOCATABLE  06 JUN 73   17:38:37      52      1       3                             2506
  FINDR                         FOR SYMB     06 JUN 73   17:38:37      53              2   5    0   1              2510
  FINTAB                        RELOCATABLE  06 JUN 73   17:38:42      54      2       9                             2512
  FINTAB                        FOR SYMB     06 JUN 73   17:38:42      55             12   5    0   1              2523
  FUELCL                        RELOCATABLE  06 JUN 73   17:38:49      56      1       1                             2535
  FUELCL                        FOR SYMB     06 JUN 73   17:38:49      57              1   5    0   1              2537
  GETCON                        RELOCATABLE  06 JUN 73   17:38:55      58      2       4                             2538
  GETCON                        FOR SYMB     06 JUN 73   17:38:56      59              8   5    0   1              2544
```

```
   INTAB                         RELOCATABLE  06 JUN 73   17:39:11     60     2     57                         2552
   INTAB                         FOR SYMB     06 JUN 73   17:39:12     61           66    5    0    1          2611
   LIQRES                        RELOCATABLE  06 JUN 73   17:39:25     62     1      1                         2677
   LIQRES                        FOR SYMB     06 JUN 73   17:39:25     63            1    5    0    1          2679
   LOCATE                        RELOCATABLE  06 JUN 73   17:39:36     64     2      9                         2680
   LOCATE                        FOR SYMB     06 JUN 73   17:39:37     65           13    5    0    1          2691
   LWEGHT                        RELOCATABLE  06 JUN 73   17:39:45     66     2     16                         2704
   LWEGHT                        FOR SYMB     06 JUN 73   17:39:59     67           24    5    0    1          2722
   MIPE                          RELOCATABLE  06 JUN 73   17:40:22     68     2     21                         2746
   MIPE                          FOR SYMB     06 JUN 73   17:40:23     69           28    5    0    1          2769
   OTRTNS                        RELOCATABLE  06 JUN 73   17:41:06     70     5     16                         2797
   OTRTNS                        FOR SYMB     06 JUN 73   17:41:10     71           22    5    0    1          2818
   OUTPUT                        RELOCATABLE  06 JUN 73   17:41:13     72     2     21                         2840
   OUTPUT                        FOR SYMB     06 JUN 73   17:41:14     73           13    5    0    1          2863
   PAGE                          RELOCATABLE  06 JUN 73   17:41:18     74     2      7                         2876
   PAGE                          FOR SYMB     06 JUN 73   17:41:19     75           31    5    0    1          2885
   STOCON                        RELOCATABLE  06 JUN 73   17:41:22     76     1      3                         2916
   STOCON                        FOR SYMB     06 JUN 73   17:41:23     77            7    5    0    1          2920
   STODTA                        RELOCATABLE  06 JUN 73   17:41:43     78     4     78                         2927
   STODTA                        FOR SYMB     06 JUN 73   17:41:45     79          108    5    0    1          3009
   TANK                          RELOCATABLE  06 JUN 73   17:42:00     80     1      1                         3117
   TANK                          FOR SYMB     06 JUN 73   17:42:00     81            1    5    0    1          3119
   TCOND                         RELOCATABLE  06 JUN 73   17:42:07     82     1     17                         3120
   TCOND                         FOR SYMB     06 JUN 73   17:42:07     83           22    5    0    1          3138
   TEL                           RELOCATABLE  06 JUN 73   17:42:11     84     2      9                         3160
   TEL                           FOR SYMB     06 JUN 73   17:42:12     85           15    5    0    1          3171
   TSIZEI                        RELOCATABLE  06 JUN 73   17:42:14     86     1      1                         3186
   TSIZEI                        FOR SYMB     06 JUN 73   17:42:14     87            1    5    0    1          3188
   WTACC                         RELOCATABLE  06 JUN 73   17:42:16     88     1      1                         3189
   WTACC                         FOR SYMB     06 JUN 73   17:42:17     89            1    5    0    1          3191
   YLGINT                        RELOCATABLE  06 JUN 73   17:42:21     90     1     16                         3192
   YLGINT                        FOR SYMB     06 JUN 73   17:42:22     91           42    5    0    1          3209
   YLNTRP                        RELOCATABLE  06 JUN 73   17:42:25     92     1      1                         3251
   YLNTRP                        FOR SYMB     06 JUN 73   17:42:25     93            3    5    0    1          3253
   ZFIND                         RELOCATABLE  06 JUN 73   17:42:31     94     2     35                         3256
   ZFIND                         FOR SYMB     06 JUN 73   17:42:31     95           33    5    0    1          3293
   CCNTRL                        FOR PROC     08 JUN 73   01:49:36     96           13    1    0    1          3326
   CONTRL                        RELOCATABLE  08 JUN 73   01:49:39     97     3     10                         3339
   CONTRL                        FOR SYMB     08 JUN 73   01:49:39     98           13    5    0    1          3352
   HZNCMP                        RELOCATABLE  08 JUN 73   01:50:07     99     4     65                         3365
   HZNCMP                        FOR SYMB     08 JUN 73   01:50:08    100           84    5    0    1          3434
   HZCVCW                        RELOCATABLE  08 JUN 73   01:50:40    101     1      5                         3518
   HZCVCW                        FOR SYMB     08 JUN 73   01:50:40    102            5    5    0    1          3524
   VGVSHE                        RELOCATABLE  08 JUN 73   01:50:42    103     2      5                         3529
   VGVSHE                        FOR SYMB     08 JUN 73   01:50:43    104            8    5    0    1          3536
   HZAPU                         RELOCATABLE  08 JUN 73   10:08:05    105     4     65                         3544
   HZAPU                         FOR SYMB     08 JUN 73   10:08:06    106           70    5    0    1          3613
NEXT AVAILABLE LOCATION-                                                                                         3683

ASSEMBLER PROCEDURE TABLE EMPTY

COBOL PROCEDURE TABLE EMPTY

                         FORTRAN PROCEDURE TABLE

D NAME              LOCATION        LINK    D NAME              LOCATION        LINK    D NAME              LOCATION        LINK
  CACCUM                50178         1       CAPU                  50570         2       CCNFIG                52026         3
  CCNTRL                93130        96       CDCYCL                53230         4       CECLSS                53510         5
```

```
CENG                54042      6      CFLRAT              54322      7      CFLUID              54406      8
CFUEL               54434      9      CHEX                54798     10      CHSORC              55526     12
CHTX                55414     11      CIOUNT              55890     13      CKEYS               56030     14
CMATRL              56058     15      CMOTOR              56534     16      CNAMES              56590     17
CONST               56730     18      CPAGE               56786     19      CPUMP               57010     20
CSYSHT              57570     21      CTAB                57738     22      CTABA               58018     23
CTANK               58074     24      CTURBN              58606     25      DUMMY               58970     26
SPUMP               59054     27      TABLOK              59110     28      TANKWT              59138     29

                    ENTRY POINT TABLE

D NAME            LINK   D NAME            LINK   D NAME            LINK   D NAME            LINK   D NAME            LINK
  ACCRES            30     ACQWT             32     APUFLO            34     APUSUB            36     APUSUP            38
  CMPCAL            40     COMPIL            42     CONSUM            44     CRYCON            46     DIAG              48
  ECLSS             50     FINDR             52     FINTAB            54     FUELCL            56     GETCON            58
  HZAPU            105     HZCVCW           101     HZNCMP            99     INTAB             60     LIQRES            62
  LOCAT             64     LWEGHT            66     MIPE              68     OTPHEX            70     OTPWSM            70
  OTUNIT            72     OUTPA             72     OUTPF             72     OUTPF1            72     OUTPI             72
  OUTPW             72     PAGE              74     RVMIPE            68     SPACE             72     STOCON            76
  STODTA            78     TANK              80     TCOND             82     TEL               84     TSIZEI            86
  VGVSHE           103     WTACC             88     YLGINT            90     YLNTRP            92     ZFIND             94


@FREE        HZPROG.
```

D-3.3 CROSS REFERENCE OF PROGRAM FILE

It is often of interest to know which subprograms call a specific routine in a given program sequence. This kind of information for program file HZPR0G is presented in the following pages. An explanation of the XREF processor which generates the cross reference listing is given below.

XREF (Cross Reference Listing of Relocatable Elements): The XREF processor generates a cross reference listing of all entry points and undefined symbols in the specified program file that has been PACKed and PREP'D. The names of the relocatable elements are listed alphabetically. Beside each element name, the names of the element entry points are listed. Beside each entry point name, the names of all relocatable elements in the program file which reference this entry point are listed. An element entry point is the result of an assembly or compilation and specifies the location at which execution of the program element commences. A compiled FORTRAN V subroutine or function has one entry point corresponding to the name of the subroutine or function. An undefined symbol (or external reference) is the result of a subroutine call or reference to an array not contained within the element. Any external FORTRAN reference creates an undefined symbol.

CRØSS REFERENCE OF FILE HZPRØG.

```
@XREF*XREF.XREF     TPFS.
 XREF OF FILE 635717*TPFS
 ACCRES         01  (000004) (ACCRES) ,CRYCON
 ACQWT          01  (000004) (ACQWT) ,CRYCON
 APUFLO         01  (000004) (APUFLO)
 APUSUB         01  (000004) (APUSUB) ,CRYCON
 APUSUP         01  (000004) (APUSUP) ,CRYCON
 CMPCAL         01  (000004) (CMPCAL) ,CRYCON
 COMPIL         01  (005254) (COMPIL) ,CONTRL
 CONSUM         01  (000004) (CONSUM) ,CRYCON
 CRYCON         01  (000205) (CRYCON) ,CONTRL
 DIAG           01  (000062) (DIAG) ,MIPE,LWEGHT,LOCATE,GETCON,FINTAB,CRYCON
 ECLSS          01  (000004) (ECLSS) ,CRYCON
 FINDR          01  (000014) (FINDR) ,HZNCMP,VGVSHE,HZAPU
 FINTAB         01  (000163) (FINTAB) ,LWEGHT,HZNCMP,HZAPU
 FUELCL         01  (000004) (FUELCL) ,CRYCON
 GETCON         01  (000053) (GETCON) ,OTRTNS,HZNCMP
 HZAPU          01  (001234) (HZAPU) ,CRYCON
 HZCVCW         01  (000055) (HZCVCW) ,HZNCMP
 HZNCMP         01  (002036) (HZNCMP) ,HZAPU
 INTAB          01  (001510) (INTAB) ,CONTRL
 LIQRES         01  (000004) (LIQRES) ,CRYCON
 LOCAT          01  (000167) (LOCATE) ,MIPE
 LWEGHT         01  (000353) (LWEGHT) ,HZNCMP
 MIPE           01  (000506) (MIPE) ,LWEGHT,HZNCMP,HZAPU
 OTPHEX         01  (000333) (OTRTNS)
 OTPWSM         01  (000336) (OTRTNS) ,CRYCON
 OTUNIT         01  (000512) (OUTPUT) ,CONTRL
 OUTPA          01  (000425) (OUTPUT)
 OUTPF          01  (000344) (OUTPUT)
 OUTPFI         01  (000371) (OUTPUT) ,OTRTNS
 OUTPI          01  (000402) (OUTPUT)
 OUTPW          01  (000450) (OUTPUT) ,OTRTNS
 PAGE           01  (000121) (PAGE) ,OTRTNS,CONTRL.INTAB,HZNCMP,DIAG,HZAPU,COMPIL
 RVMIPE         01  (000521) (MIPE)
 SPACE          01  (000507) (OUTPUT) ,OTRTNS
 STOCON         01  (000040) (STOCON) ,COMPIL
 STODTA         01  (000006) (STODTA) ,CONTRL
 TANK           01  (000004) (TANK) ,CRYCON
 TCOND          01  (000371) (TCOND)
 TEL            01  (000161) (TEL) ,MIPE
 TSIZEI         01  (000004) (TSIZEI) ,CRYCON
 VGVSHE         01  (000067) (VGVSHE) ,HZNCMP
 WTACC          01  (000004) (WTACC) ,CRYCON
 YLGINT         01  (000405) (YLGINT) ,TEL
 YLNTRP         01  (000007) (YLNTRP)
 ZFIND          01  (000436) (ZFIND) ,HZNCMP,HZAPU
 **DONE**
```

Section D-4

REFERENCES

D-1 Auxiliary Power Unit – Rocketdyne Design Handbook, Preliminary, R-8887, Rocketdyne Div. of North American Rockwell Corp. (No Date).

D-2 Block Diagram – Functional Integrated Auxiliary Power Units, Dwg. No. VL 72-000011, Sheet-5, Space Division, North American Rockwell Corp., 10-27-72.